Environmental impact assessment of rail freight intermodality in Belgium using a Life Cycle Assessment approach

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Abstract

Freight transport is a crucial sector for the development of the economy and society, but it also produces negative impacts on the environment and the human health that must be considered. Intermodal freight transport represents an opportunity to achieve a transport of goods with enhanced environmental and competitive characteristics. Hence, intermodal freight transport consists in the transport of goods by at least two modes of transport, in the same loading unit (e.g. container), without handling the goods themselves when changing modes in an intermodal terminal. Intermodal freight transport leads to the shifting of road freight transport in long distances to others modes of transport with improved environmental performance such as rail freight transport and inland waterways transport.

This thesis is concerned with a study of the environmental impacts of rail freight intermodality using a life cycle approach. The purpose of this research is to analyse the environmental impacts of the different inland freight transport modes in Belgium (focusing on rail freight transport), and their use in intermodal freight transport routes in Belgium and Europe. In this framework, the Life Cycle Assessment (LCA) methodology constitutes an effective tool to assess the environmental impact of the inland freight transport modes. The system perspective of the LCA methodology implies the need to analyse not only the direct processes related to the transport activity such as energy consumption and exhaust emissions, but also the processes connected with the electricity and fuel production, vehicles (e.g. locomotives and wagons, barges and lorries) and infrastructure (e.g. railway, inland waterways and road).

This thesis studies the inland freight transport in Belgium from the period 2006 to 2012. It has been carried out the LCA of rail freight transport (distinguishing between electric and diesel traction), inland waterways transport and road freight transport independently. A comparison between the environmental impacts of these inland freight transport modes has been performed as well. Within rail freight transport, the environmental impacts of electric trains using the electricity supply mix of different European countries have been compared. Moreover, a detailed study of the life cycle phases of construction, maintenance and disposal of railway infrastructure has been conducted. Furthermore, the influence of load factor and emission engine technology in the environmental performance of road transport have been studied.

In addition, a study of the environmental impacts of consolidated intermodal freight transport routes in Belgium and Europe have been carried out. The aim of this analysis is the comparison of the environmental impacts of these intermodal routes depending on the transport mode chosen for the major part of the intermodal route.

Finally, this thesis studies the environmental impact of the modal splits of inland freight transport in Belgium for several scenarios such as the increase of rail freight transport as a result of the possible development of the intermodal rail freight transport or the optimization of the operational costs. It has been analysed how the change of the modal split and the improvement of the technology used by the different transport modes affects the environmental impacts of inland freight transport in Belgium.

Résumé

Le transport de marchandises est un secteur crucial pour le développement de l'économie et de la société, mais il produit également des impacts négatifs sur l'environnement et la santé humaine qui doivent être pris en compte. Le transport intermodal de marchandises représente une opportunité de parvenir à un transport de marchandises présentant des caractéristiques environnementales et compétitives améliorées. Par conséquent, le transport intermodal de marchandises consiste dans le transport de marchandises par au moins deux modes de transport, dans la même unité de chargement (par exemple, un conteneur), sans manipulation des marchandises elles-mêmes lors du changement de mode dans un terminal intermodal. Le transport intermodal de marchandises entraîne le déplacement du fret routier sur de longues distances par rapport à d'autres modes de transport à performance environnementale améliorée, tels que le fret ferroviaire et le transport fluvial.

Cette thèse porte sur une étude des impacts environnementaux du transport intermodal de fret ferroviaire en utilisant une approche de cycle de vie. Le but de cette recherche est d'analyser les impacts environnementaux des différents modes de transport de fret terrestre en Belgique (en se concentrant sur le transport de fret ferroviaire), ainsi que leur utilisation sur les itinéraires de transport de fret intermodal en Belgique et en Europe. Dans ce cadre, la méthodologie d'Analyse du Cycle de Vie (ACV) constitue un outil efficace pour évaluer l'impact environnemental des modes de transport utilisées dans le trafic intérieur de marchandises. L'approche système de la méthodologie d'ACV implique la nécessité d'analyser non seulement les processus directs liés aux activités de transport, tels que la consommation d'énergie et les émissions de gaz d'échappement, mais également les processus liés à la production d'électricité et de carburant, aux véhicules (par exemple, locomotives et wagons, barges et camions) et des infrastructures (par exemple, chemins de fer, voies navigables et routes).

Cette thèse étudie le transport de fret intérieur en Belgique de 2006 à 2012. Il a été réalisé l'ACV du transport de fret ferroviaire (en faisant la distinction entre traction électrique et diesel), du transport fluvial et du transport routier des marchandises. Une comparaison entre les impacts environnementaux de ces modes de transport de fret intérieur a également été réalisée. Dans le transport de fret ferroviaire, les impacts environnementaux des trains électriques utilisant le mix électrique de différents pays européens ont été comparés. En outre, une étude détaillée des phases du cycle de vie de la construction, de la maintenance et de la fin de vie des infrastructures ferroviaires a été réalisée. De plus, l'influence des facteurs de charge et des technologies pour réduire les émissions des moteurs du transport routier a été étudiée.

En outre, une étude des impacts environnementaux des routes de transport intermodal de marchandises consolidées en Belgique et en Europe a été réalisée. Le but de cette analyse est de comparer les impacts environnementaux de ces routes intermodales en fonction du mode de transport choisi pour la majeure partie de la route intermodale.

Enfin, cette thèse étudie l'impact sur l'environnement de la répartition modale des transports de fret intérieurs en Belgique dans plusieurs scénarios, tels que l'augmentation du transport de fret ferroviaire résultant du développement du transport intermodal ou l'optimisation des coûts opérationnels. Il a été analysé comment le changement de la répartition modale et l'amélioration de la technologie utilisée par les différents modes de transport affectent les impacts environnementaux du transport de fret intérieur en Belgique.

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To my parents, my idea of going through life

A mis padres, mi idea de pasar por la vida

Chaque chose que nous voyons en cache une autre, nous désirons toujours voir ce qui est caché par ce que nous voyons. Il y a un intérêt pour ce qui est caché et que le visible ne nous montre pas. Cet intérêt peut prendre la forme d'un sentiment assez intense, une sorte de combat dirais-je, entre le visible caché et le visible apparent. - René Magritte

Table of Contents

Part I: Introduction

Part I: Introduction	
Chapter 1. Introduction: inland freight transport	Chapter 2. The Life Cycle Assessment methodology

Part II: Life Cycle Assessment of inland freight transport in Belgium		
Chapter 3. LCA of rail freight transport	Chapter 4. LCA of inland waterways transport	Chapter 5. LCA of road freight transport
Chapter 6. Comparison of the environmental impacts of the inland freight transport modes		

Part III: Environmental impact assessment of freight transport	
Chapter 7. Study of intermodal freight transport routes	Chapter 8. Study of the modal split of inland freight transport in Belgium

Part IV: Conclusions and perspectives
Chapter 9. Conclusions and perspectives

Chapter 1. Introduction: inland freight transport

Transport plays a fundamental role in the economy and in the society, but it also may have an adverse impact on the climate, the natural environment and the human health. Moreover, these negative impacts can occur from a local level (e.g. air pollution, noise, congestion or accidents), through regional levels (e.g. electricity production or land transformation for transport infrastructures) to a global level (e.g. climate change).

This research thesis focuses on the environmental impacts of the different inland freight transport modes: rail freight transport, inland waterways (IWW) transport and road freight transport. In the European Union (EU-28), road transport is the dominant mode of inland freight transport. In 2012, 75.3% of the total inland freight expressed in tonne-kilometres (tkm) were transported by road in the year 2012 (see Figure 1.1), 18.1% by rail and 6.7% by IWW (Eurostat statistics, 2017).

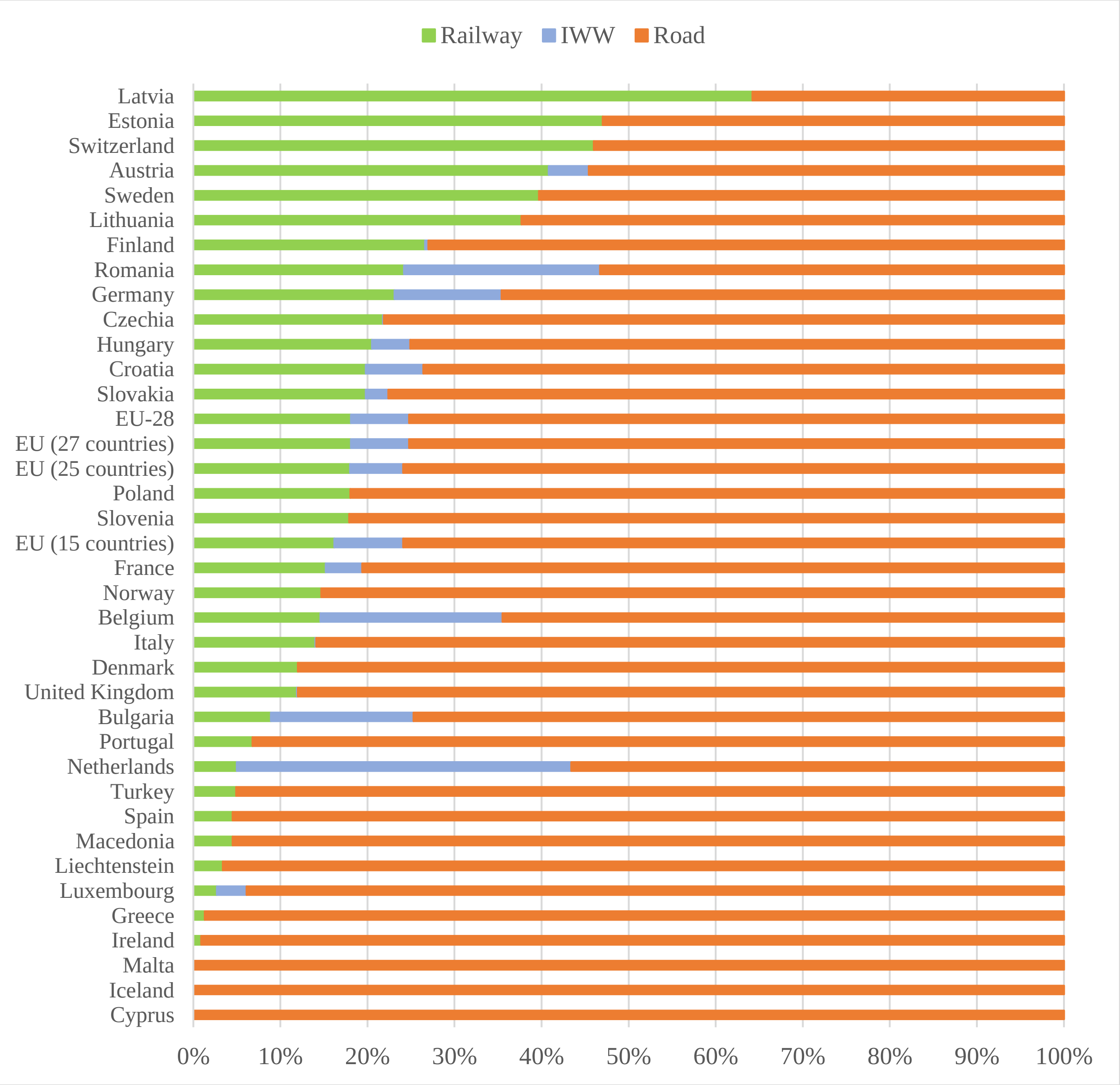


Figure 1.1. Modal split of inland freight transport in Europe in the year 2012. Source: Eurostat statistics, 2017

In the case of Belgium, as shown in Table 1.1, road transport was responsible for 64.5% of the total inland freight expressed in tkm in Belgium in the year 2012 (i.e. 32 105 million tkm), representing the dominant mode of the three major inland transport modes. IWW accounts for 20.9% (10 420 million tkm) and rail transport for 14.6% (7 279 million tkm) (Eurostat statistics, 2017).

Table 1.1. Modal split and inland freight transport in Belgium. Source: Eurostat statistics, 2017

		2005	2006	2007	2008	2009	2010	2011	2012
Modal split (%)	**Railway**	13.4	15.4	15.3	15.9	12.8	14.5	15.2	14.6
	IWW	14.1	14.5	14.9	15.6	14.3	17.6	18.5	20.9
	Road	72.4	70.1	69.7	68.5	72.9	67.9	66.3	64.5
Freight transport (million tkm)	**Railway**	8 141[1]	9 461[1]	9 258	8 927	6 374	7 476	7 593	7 279[1]
	IWW	8 566	8 908	9 006	8 746	7 087	9 070	9 251	10 420
	Road	43 847	43 017	42 085	38 356	36 174	35 002	33 107	32 105
	TOTAL	60 554	61 386	60 386	56 029	49 635	51 548	49 951	49 804

[1]Values calculated using the modal split

Figure 1.2 presents the results in modal split and inland freight transport in Belgium of the period from 2005 to 2012 indicated in Table 1.1. According to Eurostat statistics, from 2005 to 2012 there has been a decrease of 10 750 million tkm of total inland freight transport in Belgium. However, this decline has affected differently the inland freight transport modes. Thereby, while road transport has decreased in 11 742 million tkm and 7.9% of modal split, IWW transport has increased in 1 874 million tkm and 6.8% of modal split. Otherwise, rail freight transport has experienced a decline in absolute terms of 862 million tkm but a growth in relative terms of 1.2% of modal split. It must be borne in mind that rail freight transport experiences strong competition from IWW transport to attract the goods moved by road transport in Belgium.

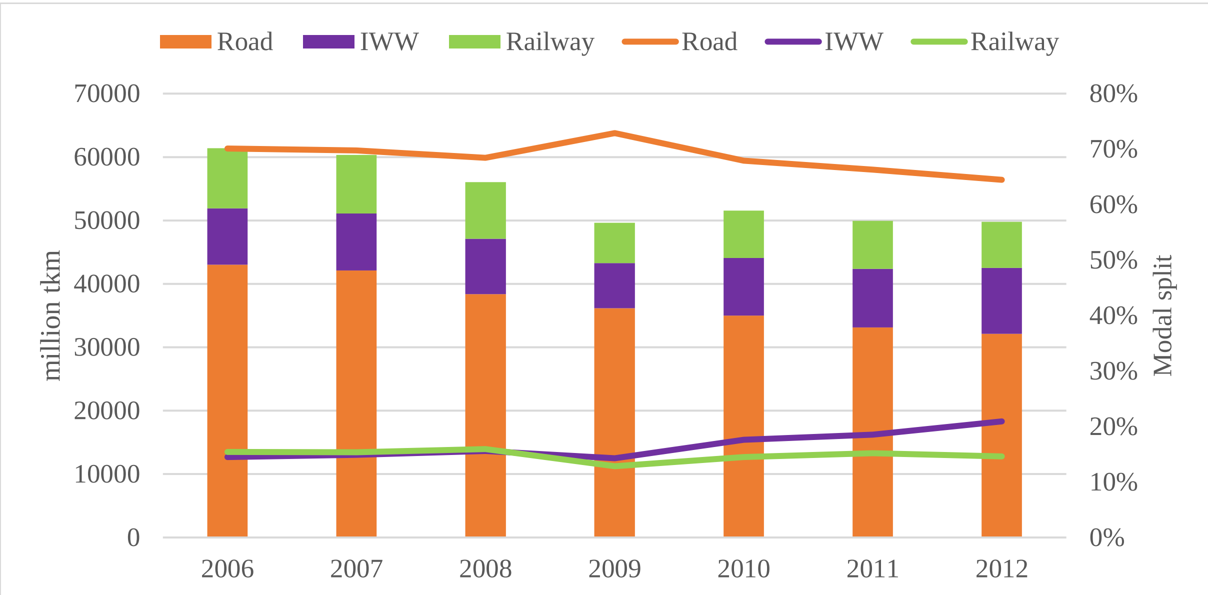


Figure 1.2. Inland freight transport (million tkm) and modal split (%) in Belgium. Source: Eurostat statistics, 2017

1.1. The contribution of transport to climate change, air pollution and energy consumption

In recent years, climate change is considered as one of the most important environmental problems by the society. As shown in Table 1.2, the transport sector is responsible for 24.2% and 34.3% of the total greenhouse gas (GHG) emissions (excluding emissions or removals from land use, land use change and forestry (LULUCF)) in the European Union (EU-28) and Belgium in the year 2012, respectively. If international aviation and navigation GHG emissions are excluded, a decrease to 19.5% in the EU-28 and 21% in Belgium is produced. In Belgium, international navigation contributed by 13.87% of total GHG emissions due to the presence of the Port of Antwerp, which is the second port in Europe in total maritime freight volume (Antwerp Port Authority, 2016). Within transport sector, road transport represents 72% and 50% of the transport GHG emissions in the EU-28 and Belgium in the year 2012, respectively. If GHG emissions from international bunkers are excluded, road transport produces most of the GHG emissions of the transport sector, accounting for 95% in the EU-28 and 97% in Belgium.

Table 1.2. Greenhouse gas emissions (excluding LULUCF) in the EU-28 and Belgium in the year 2012. Source: Eurostat statistics, 2017

	Including international bunkers		Excluding international bunkers	
	EU-28	**Belgium**	**EU-28**	**Belgium**
Non-transport sectors	75.77%	65.73%	80.46%	78.95%
International aviation	2.77%	2.88%	-	-
International navigation	3.06%	13.87%	-	-
Cars	10.51%	10.08%	11.16%	12.11%
Light duty lorries	2.12%	1.99%	2.25%	2.39%
Heavy duty lorries and buses	4.55%	4.81%	4.83%	5.78%
Motorcycles	0.22%	0.12%	0.23%	0.14%
Other road transport	0.01%	-	0.01%	-
Railways	0.15%	0.09%	0.16%	0.10%
Domestic aviation	0.34%	0.01%	0.36%	0.01%
Domestic navigation	0.37%	0.29%	0.39%	0.35%
Other transport	0.13%	0.13%	0.14%	0.16%

Population exposure to particulate matter and tropospheric ozone is considered as a major environmental health problem in most cities. In the EU-28, 391 000 premature deaths in 2015 were caused by the long-term exposure to $PM_{2.5}$ (particulate matter of a diameter of 2.5 µm or less), 76 000 due to NO_2 (nitrogen dioxide) and 16 400 due to tropospheric ozone. In Belgium, the premature deaths in 2015 attributed to $PM_{2.5}$, NO_2 and tropospheric ozone are 7 400, 1 500, and 220, respectively (European Environment Agency, 2018). Transport represents an important source of air pollution, especially for particulate matter and nitrogen oxides (NO_X). Particulate matter can be emitted directly from vehicles (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as sulphur oxides (SO_X), NO_X, ammonia (NH_3) or Volatile Organic Compounds (VOC). The tropospheric ozone is formed from other precursor pollutants such as NO_X and Non-Methane Volatile Organic Compounds (NMVOC) by photochemical reaction under the influence of solar radiation. It should be noted that stratospheric ozone layer is beneficial to the environment because it filters ultraviolet radiation from the sun.

As can be seen in Table 1.3, road transport was the main source of NO_X emissions in 2012, representing 38.13% and 48.33% of the total emissions in the EU-28 and Belgium, respectively. Moreover, transport was a major source of NMVOC with 12.02% in the EU-28 and 7.89% in Belgium of the total emissions. For primary $PM_{2.5}$, transport constitutes 14.27% and 18.22% of the total emissions in the EU-28 and Belgium, respectively. For particles with a diameter of 10 µm or less (PM_{10}), transport accounts for 12.86% in the EU-28 and 17.65% in Belgium of the total emissions. For SO_X, transport constitutes 2.01% and 1.95% of the total emissions in the EU-28 and Belgium, respectively. The non-road transport emissions of SO_X are bigger than road transport emissions in both EU-28 and Belgium, as a result of the highest sulphur content in the gas-oil used in navigation. For NH_3, road transport accounts for 1.71% in the EU-28 and 1.41% in Belgium of the total emissions. In Belgium, road transport was responsible for 17% of the total emissions of carbon monoxide (CO) in 2012, accounting for 1% the other modes of transport (European Environment Agency, 2014). The mentioned pollutants are produced during fuel combustion, but other non-exhaust emissions of particulate matter, including $PM_{2.5}$ and PM_{10}, are emitted from the wear of brakes, tyres and road surface in road transport and the abrasion of brakes, wheels and rails in rail transport. The air pollutant emissions from road transport have decreased over the years as a result of the implement of the "Euro" emission standards, which are promoted enhancements of the emission control technologies.

Table 1.3. Air pollution in the EU-28 and Belgium in the year 2012. Source: Eurostat statistics, 2017

		NO_X	NMVOC	$PM_{2.5}$	PM_{10}	SO_X	NH_3
EU-28	**Non-transport sectors**	54.60%	87.98%	85.73%	87.14%	97.99%	98.28%
	Road transport	38.13%	10.88%	12.29%	11.26%	0.14%	1.71%
	Non-road transport	7.27%	1.13%	1.98%	1.60%	1.87%	0.01%
Belgium	**Non-transport sectors**	46.11%	92.11%	81.78%	82.35%	98.05%	98.59%
	Road transport	48.33%	7.34%	16.22%	15.81%	0.25%	1.41%
	Non-road transport	5.55%	0.55%	1.99%	1.84%	1.70%	0.00%

Additionally, transport is the sector with the highest energy consumption in the EU-28 and the second in Belgium with a 31.7% and 28.3% of the final energy consumption in the year 2012, respectively (see Table 1.4). Within transport sector, road transport constitutes 81.6% in the EU-28 and 82.4% in Belgium of the transport final energy consumption. The large amount of energy consumed by transport, together with the use of other resources such as land and raw materials for the transport infrastructures and vehicles, could lead to problems of resource scarcity.

Table 1.4. Final energy consumption in the EU-28 and Belgium in the year 2012. Source: Eurostat statistics, 2017

	Non-transport sectors	Road	Rail	Intl. aviation	Domestic aviation	Domestic navigation	Pipeline	Non-specified
EU-28	68.27%	25.90%	0.63%	3.95%	0.50%	0.46%	0.14%	0.15%
Belgium	71.72%	23.31%	0.53%	3.86%	0.01%	0.43%	0.16%	-

In light of these observations, the search for more environmentally and health friendly, energy-efficient and competitive transport systems becomes necessary. In this framework, intermodal freight transport represents an opportunity to achieve all these goals through the shifting of road freight transport in long distances to others modes of transport with improved environmental performance such as rail freight transport and IWW transport.

The glossary for transport statistics defines the intermodal freight transport as the transport of goods by at least two different modes of transport, in one and the same Intermodal Transport Unit (ITU) without handling the goods themselves when changing modes (ITF, Eurostat, UNECE, 2009). The major part of the journey is done by rail, IWW or sea (main haulage) while road transport is used for the shortest possible initial and final parts of the transport chain (pre- and post-haulage) (Tawfik and Limbourg, 2018). At the intermodal terminal, the ITUs (container, swap body or road vehicle) are transferred between modes of transport. Thereby, intermodal terminals act as a point of collection, sorting, transhipment and distribution of goods (ITF, Eurostat, UNECE, 2009). Figure 1.3 shows and example of an intermodal freight transport route, which includes the processes of pre-haulage by road, the transhipment in an intermodal terminal, the main haulage by train or barge, the transhipment in another intermodal terminal and finally a post-haulage by road.

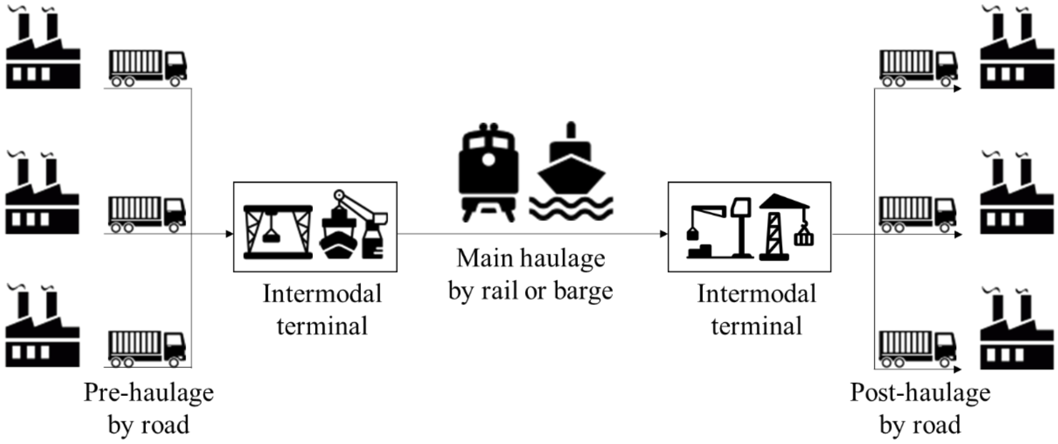


Figure 1.3. Example of intermodal freight transport system

1.2. Difficulties in achieving a modal shift from road to rail freight transport

Environmental impact studies on freight transport show that rail freight transport is the land transport option that has the highest environmental performance compared to intermodal road-rail and all-road transport (Fries and Hellweg, 2014; Facanha and Horvath, 2006), especially when electrified railway is used (Spielmann and Scholz, 2005). Although IWW transport is the inland freight transport with highest energy-efficiency, it is strongly limited by geographical conditions. Nevertheless, road transport is more flexible with a more extended network and direct links, causing the dominant use of all-road or road-rail intermodal transport (Demir et al., 2015).

Despite the inherent advantages of rail freight transport in long distances such as the reduced cost that can be obtained due to the high payload capacity of trains and the reduced externalities compared to road transport due to decrease of emissions and improvement of road safety (Crozet et al., 2014), rail freight transport presents some features that may hinder the shift from road transport. For instance, rail freight transport is small compared to rail passenger transport. Passenger trains constitutes 86.5% of the total rail traffic (measured in train-km) in Belgium in the year 2009 (Eurostat statistics, 2017) and this, together with the traffic priority over rail freight that passenger traffic receives from European transport managers, results in a preference of the investment in the infrastructure destined to passenger transport. Moreover, the high operating costs and investments needed for rail freight transport compared to road transport, and the possibility of a monopoly or duopoly by well-established companies in the railway market could hamper the shift from road transport (Vanelslander et al., 2015). Thereby, among the 12 rail freight operators present in Belgium, one held a market share of 86.62% of tkm in 2012 (Van de Voorde and Vanelslander, 2014). However, the liberalization of the Belgian rail freight market started in 2005 could lead to an increase in the competitiveness of the railway sector, involving a modal shift from road transport to rail freight transport. Another factor to be considered is the smaller length of the railway network compared to the road network. This causes both a weak access and a mass use of the rail infrastructure, resulting in a lack of direct rail links and a poor flexibility of the rail freight market, respectively (Vanelslander et al., 2015).

In view of the above, some relevant factors that might influence the possible development of rail freight transport are the improvement of both rail infrastructure and interoperability between rail networks of different countries acting on the infrastructure, signalling, traffic management and rolling stock that lead to higher speed of rail freight transport. Alternatively, policy measures that promote a modal shift from road transport to rail freight transport such as subsidies for rail freight transport, road pricing or environmental zoning could be applied. Particularly, all this measures could allow a development of rail freight transport in long distances (Den Boer et al., 2011).

Intermodal rail freight transport can increase the share of rail freight transport through the consolidation of freight flows that would otherwise be transported by road. Thus, besides the traditionally heavy bulk goods transported by train, other products could be transported by road through the use of containers. In order to perform the modal shift from road transport in long distances to rail freight transport, it is necessary to have a connected European railway network. Belgium is both an exporter and importer country as a result of the large activity of its seaports. Therefore, the creation of a single European transport area promoted by the European Commission's White Paper on transport (2011) through the Trans-European Transport Network (TEN-T) would increase the transport of goods by train from seaports to the rest of Europe. The competitiveness of rail freight transport would increase due to the removal of border barriers and the standardization and interoperability of the intermodal rail freight transport on the European continent.

Additionally, a strategic target to improve the rail market share in Belgium are seaports. For example, in the port of Antwerp road transport was the main mode of transport for containers in 2015 with a 58% of the share, a 35% of container were transported by barge and a 7% by train (Antwerp Port Authority, 2016). It should be noted that IWW transport has been clearly chosen over rail. However, a shift from road to rail transport could be encouraged with the implementation of measures to promote the rail freight transport. Furthermore, a greater integration of the different transport modes, especially road-rail intermodal transport, would lead to an increase of the rail market share. The strong presence and competiveness of IWW transport in Belgium makes it an alternative to road and rail freight transport.

A research conducted for the European Parliament's Committee on Transport and Tourism has reviewed several studies to assess the potential shift from road to rail transport. The chosen studies estimate a modal shift ranging from 1-14%, emphasizing the competitiveness of rail freight transport in distances from 300 km. Moreover, this study evaluates the potential actions that could be adopted to achieve the shifting from road to rail transport such as reducing the access charges to the railway network, the internalization of external cost through road pricing, increasing the competition in the rail freight market and finally, not systematically prioritizing passenger transport over goods transport and therefore increasing the flexibility of rail freight transport. Furthermore, investments in the railway infrastructure to improve the interoperability between countries and the construction of intermodal terminals to facilitate the intermodal transport would encourage companies to use rail freight transport (Gleave et al., 2015).

1.3. Modal shift from road to rail freight transport within the Green Logistics framework

McKinnon has developed a Green Logistic framework for freight transport based on the ASIF (Activity Structure Intensity Fuel) framework of the IPCC (McKinnon, 2016). The Green Logistic framework encompasses a series of decarbonisation measures and strategies to reduce the carbon emissions of freight transport comprehend in five spheres of activity. Based on the study of McKinnon (2016) on the possible decarbonisation of logistics through a speed reduction in transport, it has been analysed how the modal shift from road to rail freight transport in long distance as a result of the intermodal rail-road transport would influence freight transport within the ASIF and Green Logistics frameworks (see Table 1.5).

Table 1.5. Contribution of the modal shift from road transport in long distances to rail freight transport. Source: based on McKinnon, 2016

ASIF framework	Green Logistics framework	Contribution of modal shift from road to rail freight transport	Nature of influence
Activity	Supply chain configuration	Possible expansion of the supply chain	Indirect
Structure	Freight modal split	Increased rail freight transport	Direct
Intensity	Vehicle utilization	Higher payload capacity of trains	Indirect
Intensity	Energy efficiency	Higher energy efficiency of trains	Direct
Fuel	Carbon content of the energy	Use of electricity by trains	Direct

The first strategy of the Green Logistics framework is the reduction of freight transport activity through a reconfiguration of the supply chain of goods by reducing transport distances (e.g. from global to regional level). It must be borne in mind that transport is an important stage of every product life cycle, but shorter transport distances do not necessarily imply better environmental characteristics of a product. It is necessary to consider all the life cycle stages of a product to determine the most sustainable way to produce it. Thereby, the production stage presents usually a greater environmental burden than the transport stage, thus distant producers can assure highest environmental performances of a product despite the largest distance. Therefore, a Life Cycle Assessment (LCA) of the product has to be carried out to stablish if shortening transport distances is worthwhile from an environmental point of view (McKinnon, 2010). If we analyse the influence of the modal shift from road to rail freight transport on this strategy, this would be indirect as an increase of the use of rail freight transport for long distances could promote the expansion of the supply chain, at least at the European level (favoured by the TEN-T).

The second strategy is the change of the modal split in freight transport towards freight transport modes with improved environmental performance such as rail freight transport and IWW transport (McKinnon, 2010). Therefore, the modal shift from road to rail freight transport in long distance directly influences this strategy.

The third and fourth strategies are related to the reduction of the freight transport intensity by increasing both the use of the transport vehicles by enhancing their load factor and the energy efficiency of freight transport, respectively (McKinnon, 2010). The modal shift from road to rail freight transport in long distance would indirectly influence the third strategy. For instance, the higher payload capacity of trains promotes their shared use by several companies, which would improve the load factor and a reduction of the transport intensity. Moreover, the higher operating costs of rail freight transport entails the optimization of the load factor to make it profitable (Tawfik, 2018). Concerning the fourth strategy, rail freight transport is more energy-efficient than road transport as will be shown hereafter, thus the shifting from road to rail transport has a direct influence on this strategy. Furthermore, the energy efficiency in the railway sector, and therefore its competiveness, can improve in the future. Some points to improve the efficiency of the rail freight transport will be the weight reduction through new materials of locomotives and wagons (Helms and Lambrecht, 2006). This would allow the saving of the energy consumed during transport activity, but also energy consumed in the manufacture and disposal of rail vehicles. Moreover, the development of new engines for locomotives more energy-efficient and with more restrictive emissions standards, the energy recovery systems from braking, the energy-efficient driving through the control of speed and improved aerodynamics in rolling stock, will lead to a reduction in the energy consumption (IEA/UIC, 2015).

Finally, the fifth strategy is the reduction of the carbon content of the energy used in freight transport. Thereby, the use of cleaner energy such as electricity from renewable sources or replacing diesel by other sources of cleaner energy as biodiesel, will lead to the reduction of environmental impacts. It should be noted that the use of biodiesel produces advantages in terms of CO_2 emissions, but analysing the life cycle of the biodiesel the pollution could be transferred from air when combustion to soil and water during crop production. Thus, the environmental advantages of the use of biodiesel depend on the specific type and source of the biodiesel. Moreover, the use of biodiesel does not affect exhaust emissions dependent on engine technology such as NO_X or particles for example. The modal shift from road to rail freight transport in long distance directly influences this strategy.

Even though the use of diesel is present in rail freight transport in Belgium, the use of electric traction is much greater. Table 1.6 presents the rail freight traction share in Flanders (Belgium). The data are obtained from the Flemish Environment Agency (VMM) and they are calculated only for the Flemish region, but this value can be considered as representative for Belgium in general. The rail freight traction share of years 2006 and 2010 have been calculated using linear interpolation. It should be noted that the use of diesel traction is decreasing in Belgium, which means that only a small part of the rail freight produces exhaust emissions.

Table 1.6. Electric and diesel rail freight traction share in Flanders (Belgium). Sources: Flemish Environment Agency (VMM, 2008, 2009, 2010, 2012, 2013)

Year	1990	2006	2007	2008	2009	2010	2011	2012
Electric traction	61%	76.33%	76%	78.2%	83.1%	83.45%	83.8%	86.3%
Diesel traction	39%	23.67%	24%	21.8%	16.9%	16.55%	16.2%	13.7%

1.4.Environmental impact assessment studies on transport

The main goals of this research thesis is to analyse the environmental impacts of the different inland freight transport modes in Belgium (focusing on rail freight transport), and their use in intermodal freight transport routes in Belgium and Europe. In this framework, the Life Cycle Assessment (LCA) methodology constitutes an effective tool to assess the environmental impact of the inland freight transport modes. The system perspective of the LCA methodology implies the need to analyse not only the direct processes related to the transport activity such as energy consumption and exhaust emissions, but also the processes connected with the electricity and fuel production, vehicles and infrastructure. Further discussion on the LCA methodology is developed in Chapter 2.

Several studies have already applied the LCA methodology to transport, either passengers or goods and in different transport modes such as rail, IWW, road and air transport. However, no LCA study has focused on the environmental impact of inland freight transport in Belgium. As shown in Table 1.7, the LCA applied to transport has been investigated in several papers; among the most important contributions, let us mention: Spielmann and Scholz (2005), Facanha and Horvath (2006, 2007), Chester and Horvath (2009), Spielmann et al. (2007), Stripple and Uppenberg (2010), Van Lier and Macharis (2014) and Fries and Hellweg (2014). Furthermore, it should be mentioned some articles that have analysed the environmental impact of high-speed rail from a life-cycle perspective: Von Rozycki et al. (2003), Chester and Horvath (2010), Yue et al. (2015) and Jones et al. (2017).

Table 1.7. LCA studies applied to transport

Year	Authors	Country	Area of study
2003	Von Rozycki et al.	Germany	High-speed rail
2005	Spielmann and Scholz	Switzerland	Inland freight transport
2006	Facanha and Horvath	U.S.	Rail, road and air freight transport
2007	Facanha and Horvath	U.S.	Rail, road and air freight transport
2007	Spielmann et al.	Switzerland	Freight and passenger transport
2009	Chester and Horvath	U.S.	Rail, road and air passenger transport
2010	Chester and Horvath	U.S.	High-speed rail
2010	Stripple and Uppenberg	Sweden	Rail transport
2011	Åkerman	Sweden	High-speed rail
2014	Fries and Hellweg	Switzerland	Rail and road freight transport
2014	Van Lier and Macharis	Belgium	IWW transport
2015	Yue et al.	China	High-speed rail
2015	Banar and Özdemir	Turkey	Rail passenger transport
2017	Jones et al.	Portugal	High-speed rail

Spielmann and Scholz (2005) analysed the environmental life-cycle performance of rail, IWW and road transport in Europe, concluding that for gaseous emissions rail or IWW transport presented 92% and 65% less gaseous emissions compared to road transport, respectively. Moreover, they did a comparison of the LCA of rail transport in Switzerland and Europe. On the one hand, the Swiss rail transport is performed only by electric trains powered almost exclusively by hydroelectric energy, using diesel trains only for shunting activity. On the other hand, European rail transport is a mix of diesel and electric traction (as in the case of Belgium). While in both cases the energy consumption was almost the same, the environmental life-cycle performance of Swiss rail transport was better as a result of the use of trains powered by hydroelectric energy. In addition, they showed the importance of infrastructure in the LCA of transport systems.

Facanha and Horvath (2006, 2007) performed an environmental assessment of the life-cycle of rail, road and air freight transport in the U.S. They considered that rail freight transport in the U.S. is predominantly performed by diesel traction and the rail infrastructure is only dedicated to good transport. Their results showed that rail freight transport presents less emissions of CO_2, NO_X, CO and PM_{10} than road transport. Moreover, they concluded that transport operation is the more important transport life-cycle phase for CO_2 emissions in every transport mode and the infrastructure is an important source of PM_{10}. They highlighted the importance of considering the life-cycle emissions in new transport policies. For passenger transport, Chester and Horvath (2009) performed an environmental assessment of the life-cycle of automobiles, buses, trains, and airplanes in the U.S. They also emphasize the importance of considering the entire life-cycle when analysing the energy consumption, GHG emissions and air pollution in transport.

Spielmann et al. (2007) carried out the most complete life cycle inventory on transport for both passengers and goods. This study was used to develop the transport processes in the Ecoinvent database and therefore it has been adopted as a model for our research. Further discussion on the use of the Ecoinvent database is developed in Chapter 3 for rail freight transport, Chapter 4 for IWW transport and Chapter 5 for road freight transport.

Stripple and Uppenberg (2010) investigated the LCA of a newly constructed railway line in Sweden, used by both passenger and freight transport. Considering a life of 60 years for the infrastructure and that trains are powered by hydroelectric energy, the train traffic (which includes the stages of transport operation and rail equipment) accounts for 56.7% and the rail infrastructure for 43.3% of the total primary energy consumption. For Global Warming Potential, the train traffic accounts for 6.7% and the rail infrastructure for 93.3%. The small GHG emissions of train traffic is a result of the use of hydroelectric power as energy traction and the main GHG emissions of rail infrastructure are due to the production of materials, being the contribution of the infrastructure construction works smaller.

Fries and Hellweg (2014) performed a LCA of rail and road freight transport in Switzerland and some European transport routes. Their results showed that rail freight transport is the land transport option that has the highest environmental performance compared to intermodal road-rail and all-road transport.

1.5.Main contributions and structure of the thesis

This research has been carried out in the framework of the BRAIN-TRAINS project. In order to increase the rail share in the modal split of freight transport in Belgium, the Belgian Federal Government initiated the BRAIN-TRAINS project, which approached the possible development of rail freight intermodality in Belgium from an interdisciplinary perspective, focusing on five main subjects: optimal corridors and hub development, macro-economic impact of intermodality, effective market regulation, governance and organization for a well-functioning intermodality, and environmental sustainability of intermodal rail freight transport. The objective of increasing the rail freight transport is linked to the European Commission's White Paper on transport (2011), which aims to shift the 30% of road freight over 300 km to other modes of transport more energy-efficient such as rail or waterborne transport by 2030. This shift of road freight transport may represent a challenging target to the rail freight sector due to the high amount of goods that this implies. Therefore, the aim of the BRAIN-TRAINS project was to analyse the current situation of intermodal transport in Belgium to allow policymakers to take decisions for the development of intermodal transport.

This thesis is concerned with a study of the environmental impacts of rail freight intermodality using a life cycle approach. As shown in Figure 1.4, this thesis is organized in four parts. Part I provides and introduction to inland freight transport and the LCA methodology. Part II presents the results of the LCA of the different inland freight transport modes in Belgium. Part III assess the environmental impact of intermodal freight transport routes and the modal splits for Belgium using the LCA results obtained in Part II. Finally, Part IV presents the main conclusions retrieved from Part II and Part III and possible research perspectives.

<u>Part I: Introduction</u>

Chapter 1 presents an introduction to inland freight transport and the alternative solution of intermodal freight transport to improve the environmental performance of freight transport.

Chapter 2 provides and explanation of the concept and main characteristics of LCA and the strength and limitations of applying the LCA methodology to determine the environmental impacts of transport.

<u>Part II: Life Cycle Assessment of inland freight transport in Belgium</u>

Part II develops the LCA of rail freight transport, IWW transport and road freight transport independently. Furthermore, a comparison between the environmental impacts of these inland freight transport modes has been performed.

Chapter 3 focuses on the LCA of rail freight transport in Belgium. This chapter includes the assessment of diesel trains, electric trains using the electricity supply mix in Belgium corresponding to the appropriate year and rail freight transport considering the Belgian traction mix. Moreover, a comparison of the environmental impacts of electric trains using the electricity supply mix of different European countries has been performed. Furthermore, a detailed study of the life cycle phases of construction, maintenance and disposal of railway infrastructure has been conducted. Specific information related to the Belgian rail infrastructure has been collected from literature sources and directly from Infrabel, the Belgian railway infrastructure manager. The following questions have been studied in this chapter: what type of rail traction (diesel or electric) in Belgium has a better environmental life cycle performance?

What role does the railway infrastructure play in the environmental impact of rail transport in Belgium? Does it vary in importance depending on the type of traction used? How does the electricity supply mix affect the environmental impact of electric trains in different countries? Could an electric train, depending on the type of electricity used, have a greater or lesser impact than a diesel train?

Chapter 4 presents an analysis of the environmental performance of IWW transport in Belgium for several years. Thereby, it has been studied, among other characteristics, the following question: how does the sulphur content of the fuel used by barges influence the environmental impacts of IWW transport?

Chapter 5 focuses on the LCA of road freight transport in Belgium for several years. The influence of load factor and emission engine technology in the environmental performance of road transport have been studied for an average road transport in Belgium and for an articulated lorry 34-40 tonnes. The following questions have been studied in this chapter: how the emission engine technology does affects the environmental impact of road freight transport? How important is the load factor and therefore the fuel consumption in the environmental impacts of road transport?

Chapter 6 compares the environmental impacts of the different inland freight transport modes in Belgium (i.e. rail freight transport, IWW transport and road freight transport). The main question studied in this chapter is: Which inland freight transport mode has a better environmental performance and for what impact categories?

Part III: Environmental impact assessment of freight transport

In Part III, the results obtained previously in Part II have been used to carry out the assessment of the life cycle environmental impacts related to different alternative solutions of intermodal freight transport. For this, several consolidated intermodal routes in Belgium and Europe have been analysed, allowing the comparison of the environmental impacts of these intermodal routes depending on the freight transport mode chosen. Moreover, it has been analysed how the increase of rail freight transport as a result of the possible development of the intermodal rail freight transport affects the environmental impacts of the modal split of inland freight transport in Belgium. Furthermore, the environmental impacts of the modal splits obtained for the optimization of both operational costs and environmental factors in Belgium have been studied.

Chapter 7 provides the assessment of the life cycle environmental impacts related to different alternative solutions of intermodal freight transport routes in both Belgium and Europe. Some questions studied in this chapter are: road transport is usually the shortest possible route, but is it worth from an environmental point of view? How does the electricity supply mix of the different countries through which the intermodal route passes affect the environmental impact of electric trains? Could an electric train, depending on the type of electricity used, have a greater or lesser impact than road transport?

Chapter 8 presents a study of the environmental impact of the modal splits of inland freight transport in Belgium for several scenarios such as the increase of rail freight transport or the optimization of the operational costs and environmental factors. The main question studied in this chapter is: which one of the following two measures would have a greater influence in the environmental impacts of inland freight transport, reducing the share of road transport in the modal split or improving the technology thus achieving a reduction of the energy consumption and direct emissions from road transport?

Part IV: Conclusions and perspectives

Chapter 9 is the final chapter of this thesis, and presents the main conclusions retrieved from this research thesis and possible research perspectives.

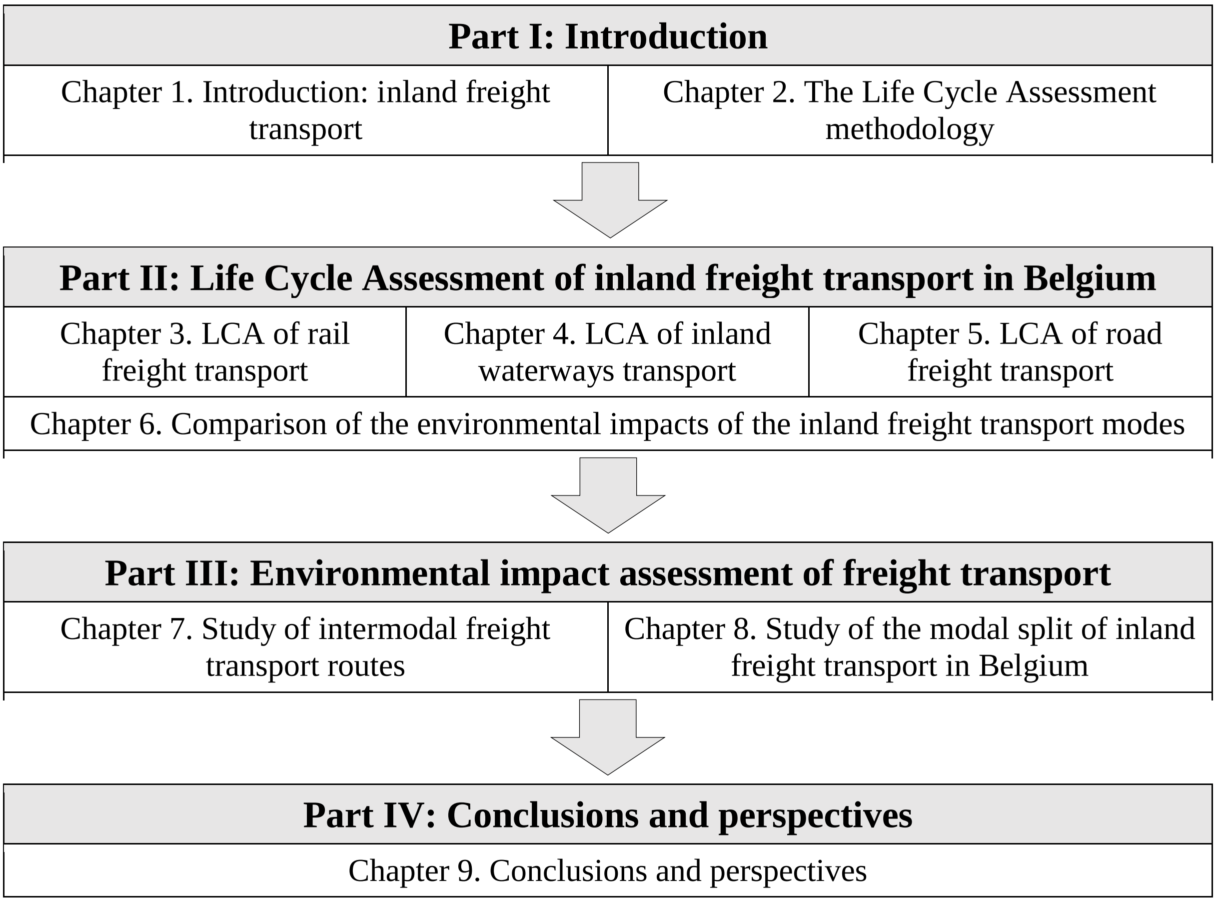


Figure 1.4. Structure of this research thesis

Chapter 2. The Life Cycle Assessment methodology

2.1. Introduction

The Life Cycle Assessment (LCA) methodology constitutes an effective tool to quantitatively analyse and compare the environmental impacts of products or activities (as transport for example) from raw material extraction, through materials use, and finally to disposal. What does this mean? If we take for example a car (see Figure 2.1), we do not only analyse the energy consumption and exhaust emissions during the use of the vehicle, but we also consider all the energy consumption and emissions (including wastes) between the raw material extraction (e.g. metals and oil), through the materials production (e.g. steel and plastics), components manufacturing and car assembling until the end-of-life of the car. At the end-of-life stage, we take into account in the assessment the recyclable materials of the car that will be reintroduce to the loop to produce new products, the materials that will be sent to energy recovery (i.e. to generate electricity or heat through combustion or to produce combustibles) or landfills and finally the parts of the car that can be reused and therefore its life span can be extended.

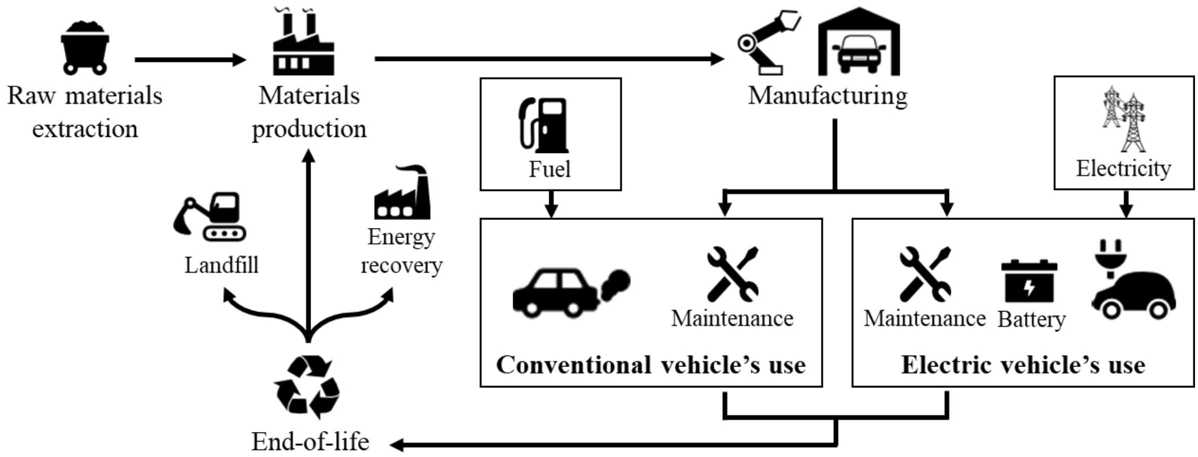


Figure 2.1. Representation of the system boundaries for the Life Cycle Assessment of a car

2.1.1. Identification of hotspots to improve the environmental performance

As mentioned above, one of the main characteristics of the LCA is that it is a quantitative methodology (and science-based), allowing the comparison of the environmental impact of several products (or in our research transport alternatives) for several environmental issues. For instance, through the analysis of different scenarios we can identify the hotspots of the life cycle of a vehicle to improve its environmental performance. Thereby, we can compare what energy source has a greater environmental performance in the transport operation stage of a car (electricity or fossil fuels for example). Furthermore, we can analyse several scenarios such as the use of different types of fuels in a conventional vehicle (e.g. fossil fuels such as petrol, diesel or natural gas or biofuels), the use of different energy sources (renewable, nuclear or coal for example) for the generation of electricity used by an electric vehicle, the use of different materials for the manufacturing of batteries,…

2.1.2. Identification of pollution transfers

Since the LCA has a "cradle-to-grave" approach (i.e. it encompasses all the stages of the life cycle of a system), the application of the LCA methodology can avoid pollution transfer between stages of the life cycle of a product (e.g. minimising the environmental impact in the use phase but increasing it in the production phase). Continuing the example of a vehicle, Figure 2.2 shows how important it is to consider all the life cycle stages of a vehicle to determine its environmental impact. In this way, although we can opt for an electric vehicle instead of a conventional vehicle to completely eliminate the CO_2 exhaust emissions, in the stage of production of electricity the CO_2 emissions can increase depending on the type of electricity used. On the one hand, the life cycle CO_2 emissions of a vehicle are considerably reduced by using renewable electricity. On the other hand, the life cycle CO_2 emissions of a vehicle can increase using only electricity produced by coal power plants. Thus, an electric vehicle that uses electricity produced from coal can emit more CO_2 than a conventional vehicle using petrol considering the complete life cycle.

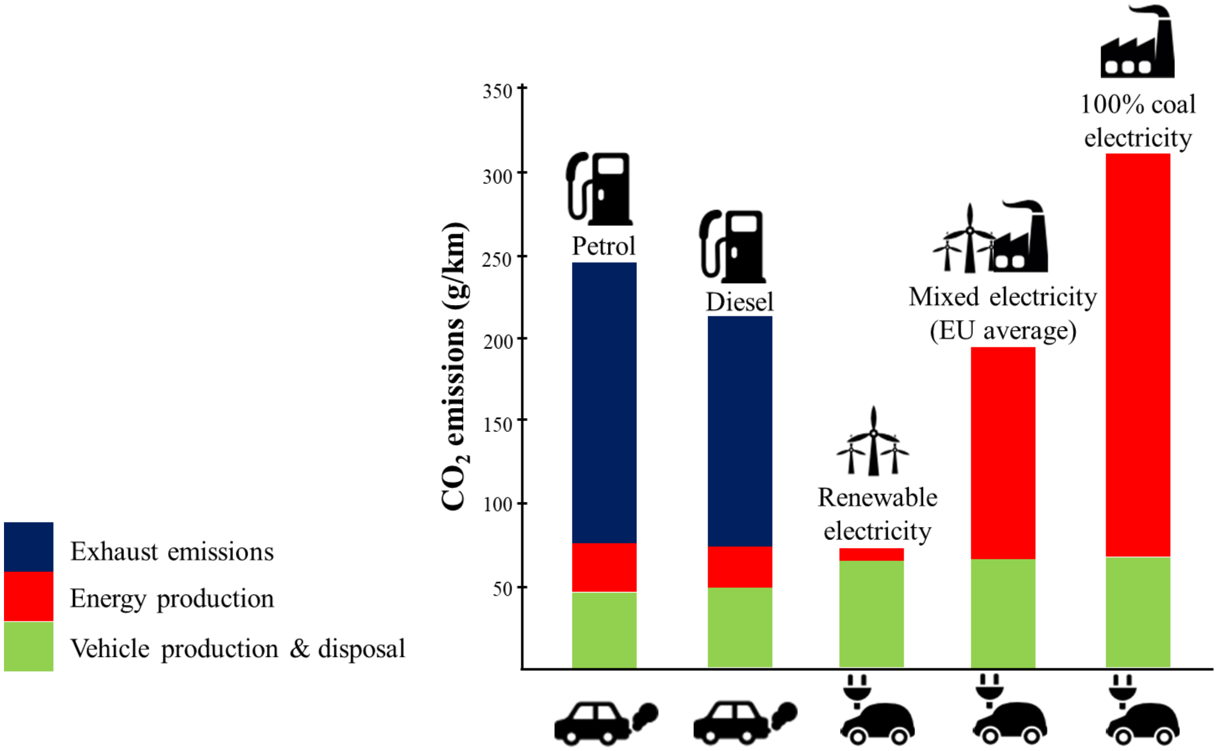


Figure 2.2. Life cycle CO_2 emissions for different vehicles and energy sources. Source: based on European Environment Agency, 2016

Moreover, a major feature of the LCA methodology is that it uses a set of environmental impact categories to determine the environmental impact of a product, thus identifying the possible pollution transfers between impact categories. For instance, when using a diesel car instead of a petrol car, on the one hand we can decrease the impact on the climate change indicator during the use phase due to the lower CO_2 emissions, but on the other hand the impact on the photochemical ozone formation indicator can increase as a result of the higher NO_X emissions.

Furthermore, burden shifting can be identified between geographic regions due to the assessment of the complete supply chain of a product. For example, the lithium-ion batteries normally used in electric vehicles contain minerals such as nickel that lead to environmental and health issues in mining. Thus, the air pollution in cities during the electric vehicle's use is avoided but the environmental impact is produced during the raw material extraction in other regions.

In conclusion, the "cradle-to-grave" approach and the inclusion of various environmental categories in the assessment of the environmental impact makes the LCA a comprehensive methodology. This allows us to have a holistic view of the environmental impacts that a product or system produces and in most cases leads us to understand that no technology or product is the silver bullet to solve all the environmental issues, avoiding that image of good and evil.

2.2.History and development of the Life Cycle Assessment methodology

We can distinguish two stages throughout the history of the development of the LCA methodology. The first stage is characterized by the emergence and development of the LCA methodology and its lack of harmonization. A first phase of this stage would be the one that goes from the late 1960s to the early 1970s, in which the first studies that could be considered LCA took place. These studies arise from the incipient concern in society about issues related to the environment such as raw materials and energy scarcity and the increase in the production of pollution and waste. At this time, the first LCA study is the one commissioned by the Coca-Cola Company in 1969 to analyse the material and energy consumption and environmental impact of different packaging using a life cycle approach (Guinée, 2016). A second phase took place between the 1970s and 1990s. In this period of time the LCA methodology is not yet homogeneous, thus the results obtained differ enormously as a consequence of the different methods. However, the LCA methodology continues to develop as a consequence of the greater interest in environmental problems on the part of the scientific and industrial community (Guinée, 2016).

A second stage in the history of the LCA methodology occurs in the 1990s, when the LCA methodology is harmonised based on the different methods previously developed (Guinée, 2016). The consensus among the scientific community started in 1990 with the definition of the term "Life Cycle Assessment". In this period of time there was an increase in international collaboration to develop the different aspects of the LCA methodology (e.g. Life Cycle Impact Assessment methodologies). Due to the homogenization of the LCA methodology and the development of LCA databases and software (the first versions of GaBi (Thinkstep) and SimaPro (Pré) were released in 1989 and 1990, respectively), the industry and the administration opted for its use as a tool to determine the environmental impact of products and activities. An important milestone is the creation of the International Journal of Life Cycle Assessment in the year 1996 (Bjørn et al., 2018a).

In order to achieve the harmonization of the different methods used in LCA, between 1997 and 2000 several ISO standards were developed such as ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000. In the year 2006, these standards were grouped and updated into the ISO 14040:2006 that establishes the guidelines for carrying out a LCA and the ISO 14044:2006 (with an amendment in 2017) that develops the different stages of a LCA. As shown in Table 2.1, other standards emerged later to complement ISO 14040:2006 and ISO 14044:2006 for specific applications. For instance, ISO 14025:2006 establishes the principles and specifies the procedures for developing Type III environmental declarations such as

Environmental Product Declarations (EPDs), ISO 14045:2012 stablishes the guidelines for Eco-efficiency Assessment, ISO/TS 14072:2014 provides additional requirements and guidelines for Organizational Life Cycle Assessment (O-LCA) and ISO/TS 14067:2013 and ISO 14046:2014 specify the guidelines related to carbon footprint and water footprint, respectively.

Table 2.1. Compilation of most important ISO standards related to LCA

ISO number	Name
ISO 14040:2006	Environmental management - Life cycle assessment - Principles and framework
ISO 14044:2006	Environmental management - Life cycle assessment - Requirements and guidelines
ISO 14025:2006	Environmental labels and declarations - Type III environmental declarations - Principles and procedures
ISO 14045:2012	Environmental management - Eco-efficiency assessment of product systems - Principles, requirements and guidelines
ISO/TS 14072:2014	Environmental management - Life cycle assessment - Requirements and guidelines for organizational life cycle assessment
ISO/TS 14067:2013	Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication
ISO 14046:2014	Environmental management - Water footprint - Principles, requirements and guidelines

Among the international organizations involved in the development and harmonisation of the LCA methodology, we should highlight the International Organization for Standardization (ISO), the Society of Environmental Toxicology and Chemistry (SETAC), the United Nations Environment Programme (UNEP) and the European Platform on Life Cycle Assessment (EPLCA). The Life Cycle Initiative launched by the SETAC and the PNUE in 2002 has developed and disseminated several works (based on the ISO 14040) with a LCA approach (UNEP/SETAC Life Cycle Initiative, 2007, 2009, 2011, 2013, 2015). At the European level, the EPLCA implemented by the European Commission’s Joint Research Centre has played an important role in the development and use of the LCA. It has launched important initiatives like the ILCD Handbook (2010), the ILCD impact assessment method (2011) or the Environmental Footprint project started in 2013 (Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF)).

In recent years, new approaches have been developed concerning the LCA methodology. Thereby, the Life Cycle Sustainability Assessment (LCSA) has been developed based on the concept of sustainability, which includes the environmental, economic and social aspects of a product using a life cycle approach. Moreover, the "Footprint" indicators have emerged, which use a single impact category (e.g. carbon footprint or water footprint) instead of a set of impact categories (Klöpffer, 2014). Finally, there have been other methodological developments based on the LCA framework. We can highlight the following: consequential LCA, Input-output LCA (IO-LCA), hybrid LCA, Eco-efficiency assessment, Resource efficiency assessment, Material Flow Analysis (MFA), Organizational LCA (O-LCA) and Life Cycle Management (LCM) (Finkbeiner, 2016).

2.2.1. Life Cycle Sustainability Assessment

In 1987, the Brundtland Commission (officially called World Commission on Environment and Development) of the United Nations published the report “Our common future”, in which the most commonly used definition of sustainable development appears: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own need" (WCED, 1987). This definition implies that economic and social development must take into account the capacity of the earth to generate resources. In 1997, Elkington (1997) proposed the concept of "triple bottom line" to explain that the industry has to include the environmental and social aspects at the same level as economic profit to achieve the sustainability. Therefore, as shown in Figure 2.3, sustainable development can only be achieved by taking into account all three dimensions of sustainability: environmental, economic and social.

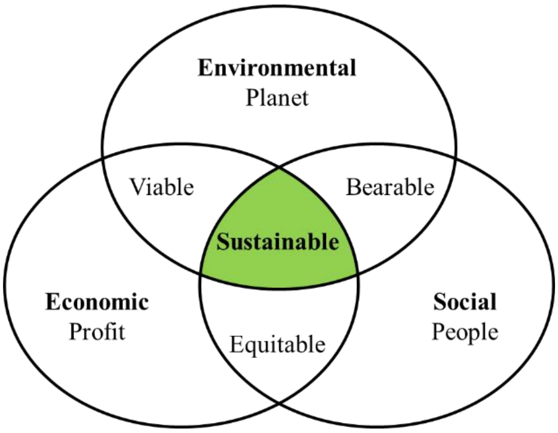


Figure 2.3. Diagram of sustainable development as a result of the integration of the three dimensions of sustainability

Similarly to the sustainable development concept, the Life Cycle Sustainability Assessment (LCSA) integrates the environmental, economic and social dimensions of sustainability. Since the LCA only deals with the environmental dimension, it is necessary the development of life cycle methodologies to analyse the economic and social dimensions of a product sustainability. Klöpffer (2008) proposed the following equation to explain the concept of LCSA:

$$LCSA = LCA + LCC + SLCA$$

Where:

- LCSA: Life Cycle Sustainability Assessment
- LCA: Life Cycle Assessment
- LCC: Life Cycle Costing
- SLCA: Social Life Cycle Assessment

Fundamentally, Life Cycle Costing (LCC) methodology aims to add all the costs related to the life cycle of a product from the raw materials extraction to end of life. Similarly, Social Life Cycle Assessment (SLCA) methodology allows the analysis of the social aspects related to the life cycle of a product. One of the main challenges for the development of the LCSA are the lack of development of the SLCA methodology (e.g. databases and impact indicators are still at an early stage).

In order to carry out the LCSA, it is necessary that the system boundaries of the LCA, LCC and SLCA be equal or at least compatible and that no weighting takes place between the results of the three dimensions. Furthermore, no weighting between the results of the three dimensions must be carried out (Klöpffer, 2008). Therefore, the goal of the LCSA is to consider the results obtained in the three life cycle methodologies in equality to fully understand the sustainability of a product. It should be noted that this thesis only focuses on the LCA of rail freight intermodality, therefore the economic and social aspects are not considered.

2.2.2. Footprint indicators

Footprint indicators analyse one particular environmental problem using a life cycle approach. Examples include carbon footprint (ISO/TS 14067:2013), water footprint (ISO 14046:2014) or Cumulative Energy Demand. Therefore, footprint indicators could be defined as a LCA that focuses on one impact category (e.g. global warming potential would be the equivalent of carbon footprint) instead of using a selection of environmental impact categories. Considering that one of the main characteristics and strengths of the LCA methodology is that several impact categories have to be considered to analyse the environmental impact of a product, the use of footprint indicators contradicts one of the fundamental aspects of the LCA (Klöpffer, 2014).

The rise in the use of footprint indicators could be explained by the fact that by addressing just one environmental problem, its application is easier (need to collect less data than an LCA) and the subsequent communication of results for the general public is much simpler. However, the use of a single environmental impact category causes the greatest weakness of the footprint indicators, the lack of identification of possible pollution transfers between impact categories since all possible environmental impacts have not been considered. Thereby, when considering a single impact category other impacts that can be asserted equal or more important are omitted.

2.2.3. Other sustainability assessment methods

The growing interest on the part of the scientific community and society (including industry, and public authorities) to understand and manage the environmental impact that human activities have on the planet, has led to the birth and development of various tools and concepts. Figure 2.4 presents a graphic representation of the positioning of LCA among other sustainability assessment methods. Depending on the objective and field of application one sustainability assessment method or another will be used.

LCA is positioned as a tool (i.e. it can be used in a practical and straightforward manner) at the value chain level. Nowadays, since value chains are global, the LCA of a product involves companies around the world. Along with the LCA methodology, we could include other LCA-based tools such as LCSA (including LCC and SLCA), carbon and water footprint, IO-LCA, hybrid LCA, and MFA for example. Moreover, at the tool level we find the eco-design, which enables the designing of products considering its environmental impact taking a life cycle approach (eco-labelling could be included at the same level).

At the value chain level, but with a lowest level of concreteness we find the Life Cycle Management (LCM), which is a management system applied to an organization (a company for example) based on a life cycle approach and using a toolbox of different sustainability assessment methods, like those shown in Figure 2.4 (Sonnemann et al., 2015; UNEP/SETAC, 2007). And as a concept, we find the Life Cycle Thinking (LCT), which includes the notion of always taking the life cycle approach in environmental studies.

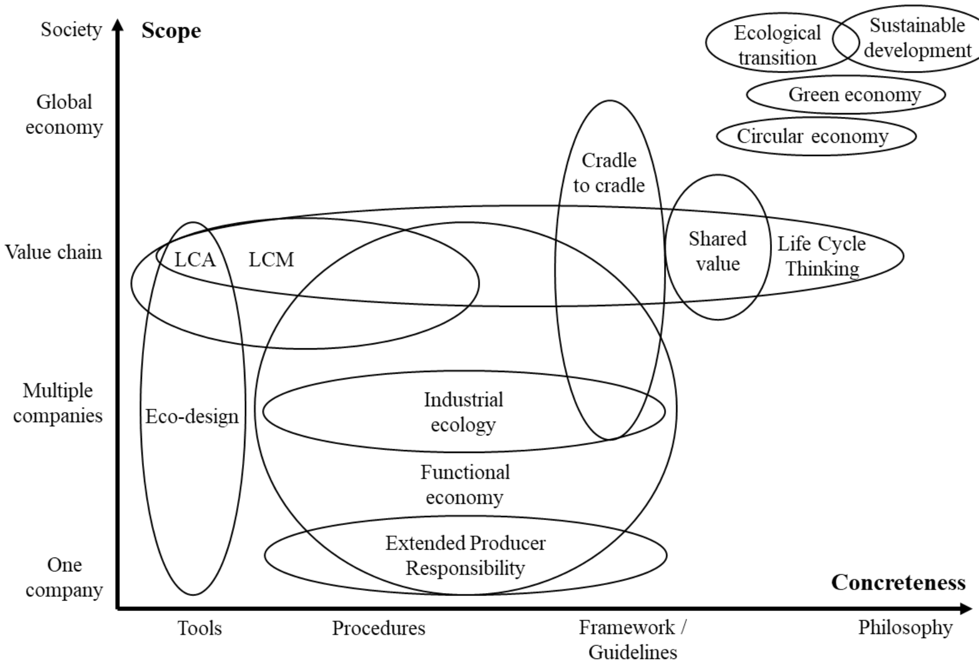


Figure 2.4. Tools for environmental impact assessment. Source: Beaulieu et al., 2015

2.3.Life Cycle Assessment methodology

Life Cycle Assessment is a structured methodology standardised by ISO Standards 14040:2006 and 14044:2006 (International Organization for Standardization, 2006) at the international level. Moreover, at the European level the Joint Research Centre has developed the ILCD Handbook (European Commission, 2010), which is a reference to perform a LCA. As shown in Figure 2.5, a LCA study comprises four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. LCA is an iterative methodology, which means that we can move from one phase to another as best suited to the development of the study. For example, if new relevant elements are found during the inventory phase, we can redefine the objective and field of the study to adapt them to the new situation.

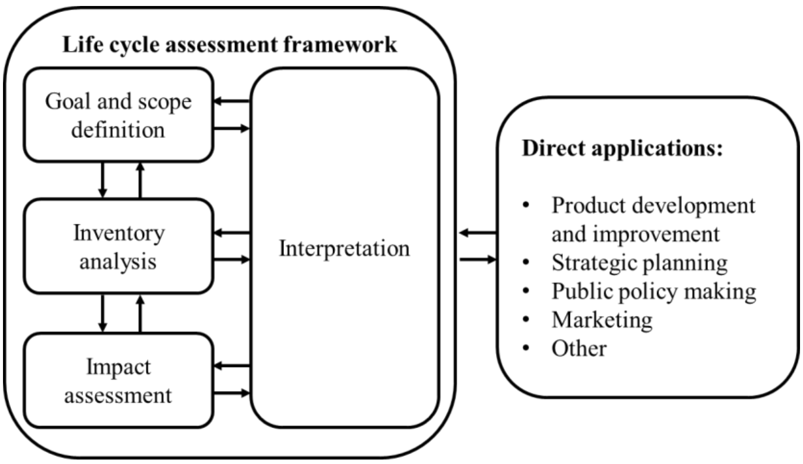


Figure 2.5. Stages of a Life Cycle Assessment. Source: ISO 14040:2006

Companies can use LCA as a decision making tool in various situations. For instance, LCA enables to compare the environmental impact of several products or activities with the same function to identify which has a best environmental performance. Moreover, LCA can be used to support decision for the eco-design of a product through the identification and improvement of both processes (e.g. most energy efficient technologies or supply chains) and materials (e.g. substances with a lower environmental impact in their extraction or end of life) with lower environmental costs throughout its life cycle. Furthermore, the LCA results form the basis for the certification (EPDs or ecolabels for example) and marketing of products and services. In the case of public authorities, they can launch policy initiatives integrating LCA to improve the sustainability of products or activities considering their full life cycle. For example, policymakers can use LCA to develop policies related to resource management, eco-labelling, electricity supply mix or waste management. With regard to transport, both companies and public authorities can use LCA to achieve a sustainable transport taking a life cycle approach.

2.3.1. Goal and scope definition

The first stage of a LCA is the goal and scope definition. In order to set the goal of the LCA, we have to define the possible applications of the results we obtain, that is, if we want to compare the environmental impact of several products or we want to improve the environmental performance of a given product, for example. Moreover, we have to understand the reasons why the LCA is performed. The reasons (why do we perform a LCA?) have to be linked to the intended applications (what do we perform a LCA for?) (Bjørn et al., 2018b). For instance, we want to carry out a LCA to compare the environmental performance of electric and conventional cars. On the one hand, if the study is commissioned by a car company the reason of performing a LCA could be to study the best techniques to manufacture a new electric car. On the other hand, if the study is commissioned by the government the reason of performing a LCA could be to give support to the government to define new transport policies. Other aspects related with the communication of the results that must be taken into account when setting the goals of the LCA are the limitations of the study due to methodological choices and the audience to which the results will be communicated (Bjørn et al., 2018b).

Once the goal of the study is fixed, we can define the scope of the study (i.e. the system boundaries) depending on the goal. The scope of the LCA must include the life cycle processes that are relevant to determine the environmental impact of the product or system studied. We have to clearly define the life cycle stages (i.e. raw material extraction, production, use and end of life) of the product. Processes that do not significantly contribute to the environmental impact of the product or system studied can be excluded of the system boundaries by defining cut-off criteria.

During the goal and scope definition stage, the ILCD Handbook (European Commission, 2010) identifies three different decision contexts situations depending on whether the LCA results will be used for decision support (situations A and B) or not (situation C). The situation A concerns micro-level decision support related to product issues and involving small modifications. The situation B concerns meso/macro-level decision support at strategic levels and involving large scale modifications. The situation C relates to a purely descriptive accounting of the analysed system, without the results being used to support decisions. We distinguish the situations C1 and C2 depending on whether interactions with other systems are considered or not, respectively (European Commission, 2010).

In addition to the goal and scope of the study, another important element to be defined is the functional unit, which is the reference unit to which the material and energy flows included in the life cycle processes are referenced. The functional unit allows the comparison of the LCA results of different products with the same function. Along with the “cradle-to-grave” approach, Klöpffer (2014) considers the functional unit as the most characteristic elements of the LCA methodology, which makes it different from other environmental impact assessment methods.

Following the example of cars, we could use as a functional unit "one km distance travelled" or "one passenger-km" for example. Thereby, we could compare the environmental impact of different types of cars. But we have to be very careful, since depending on the functional unit the conclusions may vary widely. Thereby, using the functional unit "one km distance travelled", we only compare the environmental performance of the vehicle, but using the functional unit "one passenger-km", we take into account the capacity to transport passengers. In this last case, it is necessary to specify how many passengers the car transport, as the environmental impact will vary depending on the occupancy ratio. Another example, if we want to compare the environmental impact of organic and conventional crops, we could use as a functional unit "one kg of product" or "one hectare of crop field". Using the functional unit "one kg of product", organic farming should show better environmental performance, but using the functional unit "one hectare of crop field", conventional farming could show a better environmental performance since it has a higher yield.

Finally, it is recommended to choose the Life Cycle Impact Assessment (LCIA) method that we are going to use in the LCIA stage of the LCA. Although it is not required to use a certain LCIA method, the use of one or the other method has to be justified (Curran, 2017).

2.3.2. Life Cycle Inventory analysis

The second stage of a LCA is the Life Cycle Inventory (LCI) analysis, which consists in the collection and compilation of data on the life cycle processes included in the scope of the study (e.g. input of materials, energy consumption or waste production).

To facilitate the collection of data, the system to be studied is divided into processes such as electricity consumption for example. The result obtained from the LCI is a list of the input and output flows of materials and energy. Due to the large amount of work involved in preparing the LCI, it is usually the stage that most times consumes in an LCA.

Figure 2.6 presents a graphic representation of the LCI for the LCA of one kilometre of transport using a conventional car. From a practical point of view, commercial databases as Ecoinvent (Weidema et al., 2013) have been developed to allow an easier access to the inventory of numerous processes such as an average transport in a passenger car during one kilometre for example. These databases can be used to perform a preliminary search to guide us in identifying the most influential factors in the environmental impact of the product system. (Spielmann and Scholz, 2005).

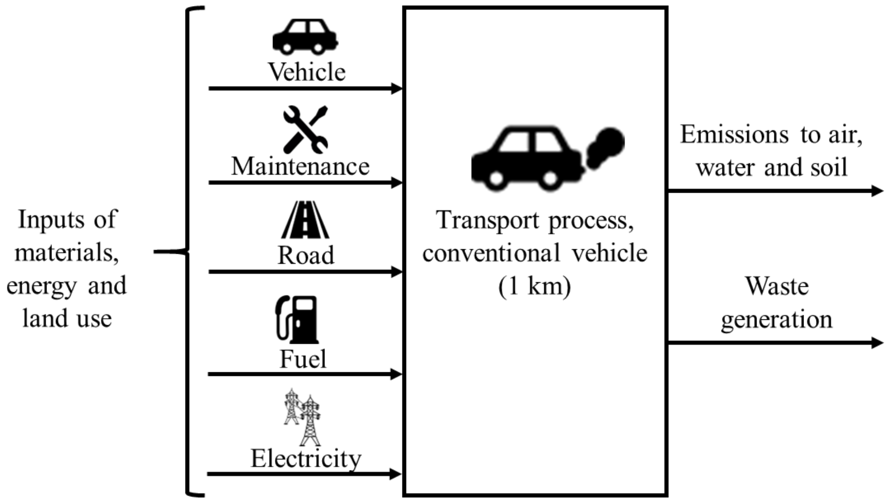


Figure 2.6. Representation of input and output processes of the LCI of one km of transport in a conventional vehicle

2.3.2.1. Allocations

Certain processes have several functions, which means that they produce several products or by-products or they serve in several product systems. For example, roads are used by a multitude of vehicles (including both passenger and goods transport), thus the environmental impacts related to the construction, maintenance and disposal of the road must be allocated proportionally to the use each vehicle makes.

When we are faced to a process with several functions, the ISO 14040:2006 standard recommends different solutions. The first solution would be the subdivision of the process into smaller processes to separate the different functions. The second option is the expansion of the system, that is, if we want to compare two processes, we can expand a process until it becomes similar to the other process (Bjørn et al., 2018c). If the subdivision or expansion of the system does not solve the problem, we have to resort to the allocation of environmental impacts. The allocation of the environmental impact between the different functions must first be performed using a relevant physical parameter such as mass or volume of by-products, for example. When we do not find a physical parameter, we can perform an allocation using other criteria such as the economic value (Bjørn et al., 2018c). For instance, we can allocate the environmental impacts related to the road infrastructure using the distance travelled by a vehicle between the total distances covered in a year by all the vehicles.

2.3.3. Life Cycle Impact Assessment

The third stage of a LCA is the Life Cycle Impact Assessment (LCIA), where the information collected in the LCI is translated into environmental impacts through the use of science-based models. As shown in Figure 2.7, ISO 14040:2006 requires three mandatory stages within the LCIA (selection of impact categories, classification of elementary flows from the LCI between the different impact categories and characterisation of the elementary flows using quantitative models to translate them into environmental impact) and two optional stages (normalisation and weighting).

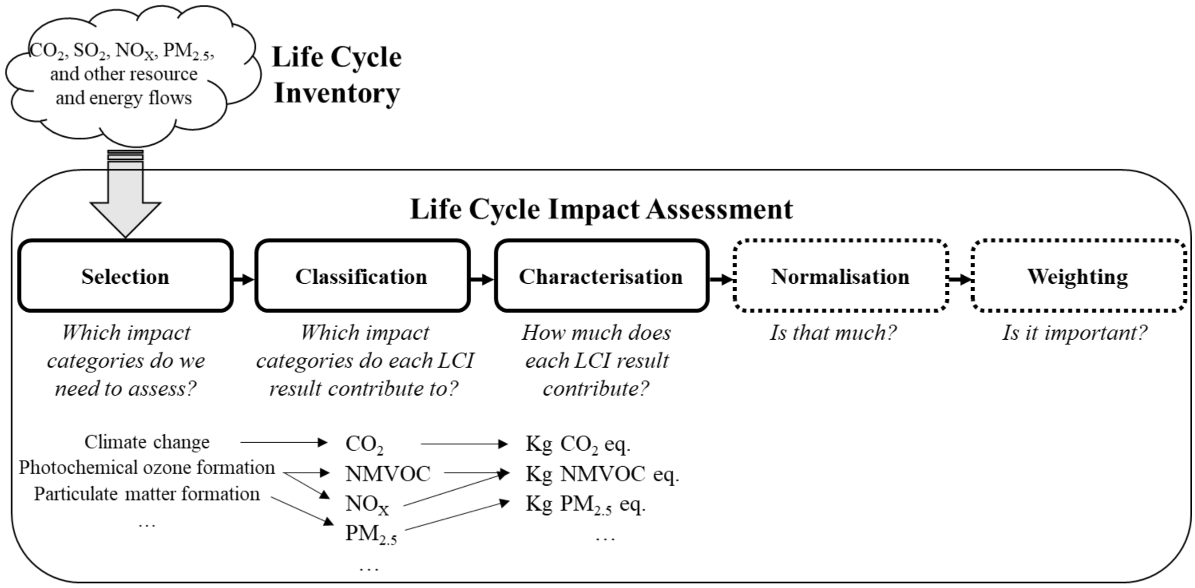


Figure 2.7. Schema of the stages of the Life Cycle Impact Assessment. Sources: Based on Hauschild and Huijbregts, 2015; Rosenbaum et al., 2018

2.3.3.1. Selection of impact categories

In the first step of the LCIA, we do a selection of impact categories, which include category indicators and characterisation models (Hauschild and Huijbregts, 2015). When choosing the impact categories, it must be taken into account that the impact categories must cover the most relevant environmental problems for the analysed product system, being desirable that there are not too many categories and that these be independent among them to avoid double counting. According to ISO 14040:2006, the terms related to the LCIA are defined as follows:

- Impact category: class representing environmental issues of concern. For example, some environmental impact categories relevant to transport are climate change, particulate matter formation and photochemical ozone formation.
- Impact category indicator: quantifiable representation of an impact category. For example, radiative forcing as Global Warming Potential (kg CO_2 equivalents) for climate change, intake fraction for fine particles (kg $PM_{2.5}$ equivalents) for particulate matter formation and tropospheric ozone concentration increase (kg NMVOC equivalents) for photochemical ozone formation.
- Characterisation model: it reflects the environmental mechanism by describing the relationship between the LCI results, category indicators and, in some cases, category endpoints. The characterisation model is used to derive the characterisation factors, which are applied to convert an assigned LCI result to the common unit of the category indicator.

The impact category indicators can be midpoint or endpoint depending on the level of the impact pathway at they are placed. According to Rosenbaum et al. (2018), the impact pathway is the cause-effect chain of an environmental mechanism. ISO 14040 defines the environmental mechanism as the system of physical, chemical and biological processes for a given impact category, linking the LCI results to category indicators and to category endpoints.

Figure 2.8 shows an example of impact pathway model for the impact category climate change, from the LCI flow to endpoint categories such as damage to human health and damage to ecosystem diversity.

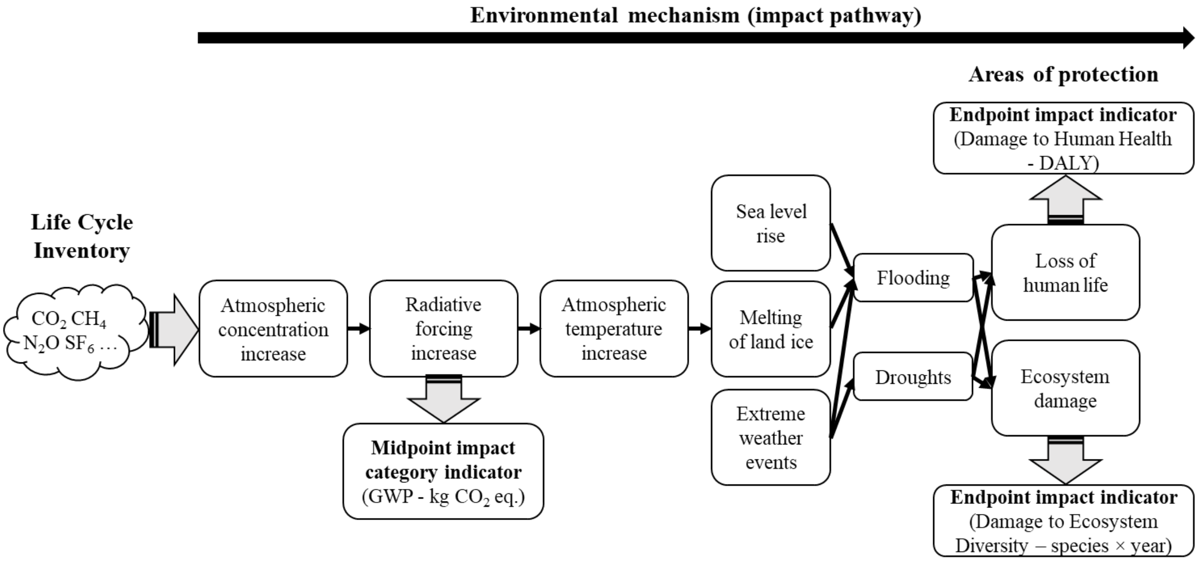


Figure 2.8. Example of an impact pathway model for the impact category climate change. Source: Based on Hauschild and Huijbregts, 2015

Therefore, the midpoint impact indicators are placed in a point of the impact pathway (i.e. the cause-effect chain of an environmental mechanism) between the LCI flow and the endpoint categories such as damage to human health, damage to ecosystem diversity and damage to resource availability, which are related to the areas of protection of human health, natural environment and natural resources, respectively. Since the endpoint categories characterise the damage to the areas of protection, the characterisation factors used in this point of the impact pathway are called damage factors.

Impact category indicators based on specific characterisation models and factors are grouped into LCIA methods such as "ILCD 2011 Midpoint+" (see Section 2.5.3.1) or "ReCiPe 2008" (see Section 2.5.3.2). For instance, the LCIA method "ILCD 2011 Midpoint+" includes 16 impact categories at the midpoint level and the LCIA method "ReCiPe 2008" includes 18 midpoint impact categories and 3 endpoint impact categories.

Overall, the elementary flows from the LCI (e.g. pollutants or resources and energy flows) can be characterised using specifics characterisation factors (which belong to a characterisation model) and therefore converted into midpoint impact category indicators related to midpoint impact categories (e.g. climate change, particulate matter formation or photochemical ozone formation). The midpoint category indicators can be multiplied by damage factors and aggregated into endpoint impact category indicators (e.g. damage to human health, damage to ecosystem diversity and resource scarcity). Figure 2.9 presents the framework of the LCIA method "ReCiPe 2008" for the impact category climate change. It should be noted that the impact category climate change influences both areas of protection human health and natural environment.

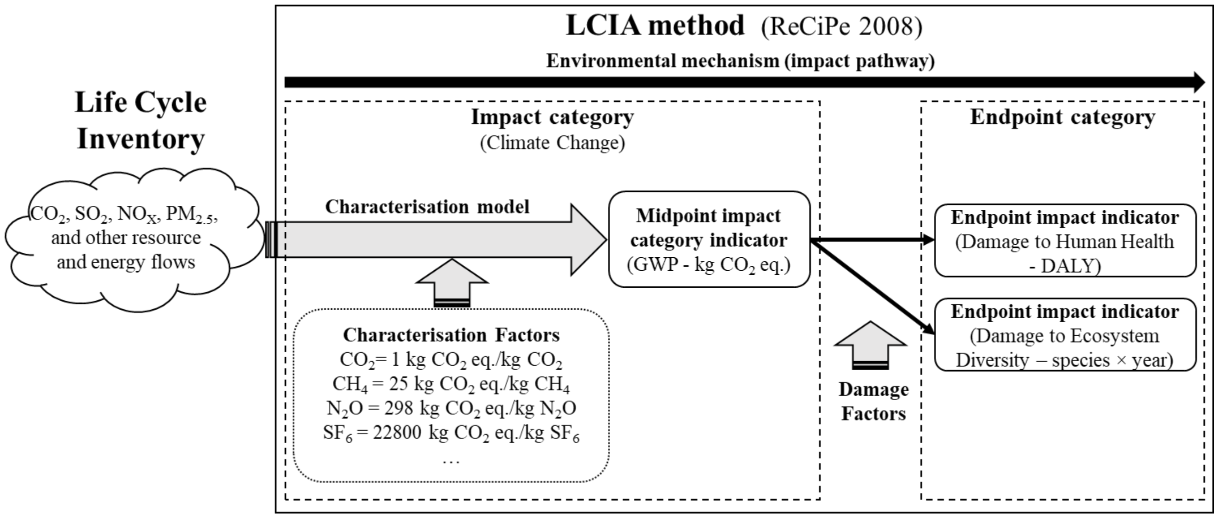


Figure 2.9. Framework of the LCIA method "ReCiPe 2008" for the impact category climate change. Note that the characterisation factors for the Global Warming Potential (GWP) are for a time horizon of 100 years (IPCC 2007)

Commercial LCA software such as SimaPro and GaBi make different LCIA methods available to the LCA practitioner. Figure 2.10 shows the LCIA methods appeared since 2000 and their updates. These LCIA methods have different number of impact categories, impact pathway (i.e. they can be midpoint or endpoint methods), characterisation models or geographical scale.

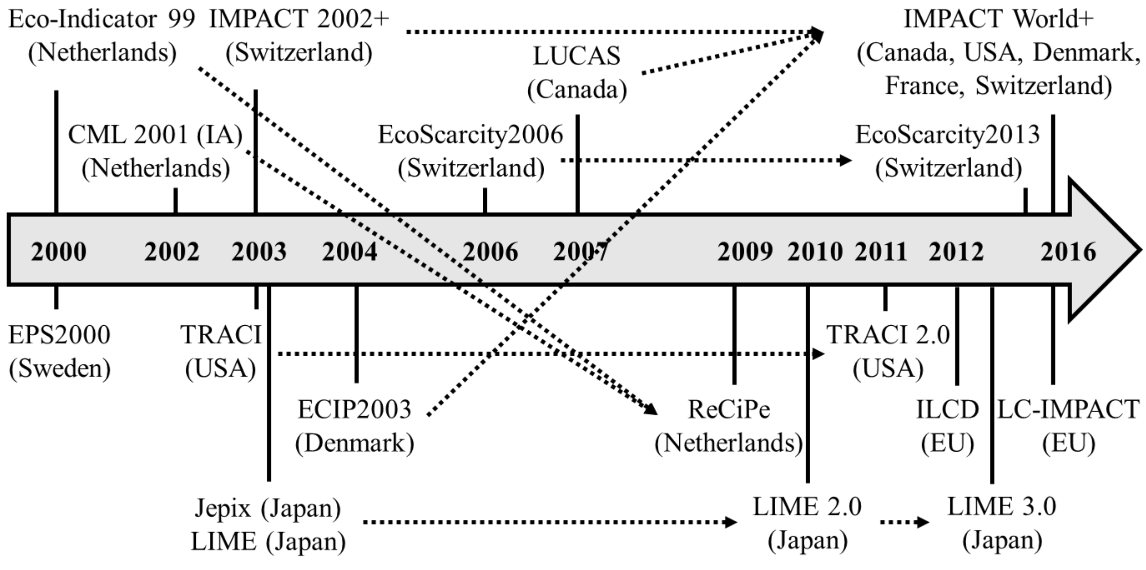


Figure 2.10. Appearance of different LCIA methods since 2000 and their updates (dotted arrows). Source: Rosenbaum, 2017

2.3.3.2. Classification

The classification of the processes inventoried in the LCI is performed grouping them into impact categories according to their contribution to the chosen indicator. For example, in the LCA of a conventional car, the exhaust GHG emissions are allocated to the impact category climate change. From a practical point of view, this stage is carried out by the LCA software applying a LCIA method such as ILCD 2011 Midpoint+ (Rosenbaum et al., 2018).

2.3.3.3. *Characterisation*

During this stage of the LCIA, the inventory flows assigned to the different impact categories are transformed into environmental impact values. As mentioned above, we obtain the quantitative values of the impact category indicators through the application of characterisation factors to the inventory flows. The impact category indicators express in a specific unit the impact of the product system studied in that impact category. For example, the GHGs emitted during the life cycle of the product are transformed into "kg of CO_2 equivalent" by applying the characterization factors of the Global Warming Potential model. This quantitative result on "kg of CO_2 equivalent" constitutes the environmental impact on climate change of the life cycle product system.

The characterization models (to which the characterization factors belong) are based on scientific models. Some of these models are more mature than the others, therefore some impact category indicators have greater reliability than others. For instance, the models for the impact category climate change are rather solid, but other models such as for the impact categories related to toxicity present a higher degree of uncertainty.

2.3.3.4. *Normalisation*

According to ISO 14040:2006, normalisation is the calculation of the magnitude of impact category indicator results relative to reference information. The objective of normalisation is the identification of the most relevant impact categories in our LCA study by comparing with references from our study (internal normalisation) or from outside our study (external normalisation). The normalisation stage allows the analysis of the order of magnitude of the impact category indicators results when compared with other internal or external references, which can help to identify errors. Moreover, through the normalisation we can translate the impact category indicators (which are expressed in different units) to the same metric, what facilitates the interpretation and communication of the LCA results. It should be noted that normalisation can be applied to midpoint and endpoint impact indicators. However, it must be borne in mind that there may be a bias in the conclusions of the LCA study depending on the references that are chosen in the normalization stage (Pizzol et al., 2017 and Laurent and Hauschild, 2015).

Internal normalisation allows the comparison of the environmental impacts between different alternatives within a LCA study. Thereby, the scores of the different category impact indicators obtained from different product alternatives can be divided by one of the alternatives, by the maximum score or the sum of all the scores, allowing the comparison and facilitating the communication of the results (Pizzol et al., 2017 and Laurent and Hauschild, 2015).

Besides internal normalisation, we can carry out the normalisation of LCA results through the use of independent references from the product system under study. The geographic scale of these external references can be global or limited by the territory belonging to the product system. When we stay at the geographical or physical limits of the product system, we can apply a production-based approach (we include all the activities of the territory, except those associated with imports) or a consumption-based approach (we exclude all the activities of the territory except those related to consumption and includes activities related to imports that are carried out outside the limits of the reference system) (Pizzol et al., 2017 and Laurent and Hauschild, 2015).

It must be borne in mind that the LCI of the external reference may not have the same modelling approach. Thereby, the external reference can use different system boundaries, inventory flows (it may not consider relevant products of our product system for example), allocation procedures or even characterisation models (Pizzol et al., 2017).

2.3.3.5. Weighting

After the normalisation stage, we can carry out the weighting stage. According to ISO 14040:2006, weighting is the conversion and possibly aggregation of the indicator results across impact categories using numerical factors based on value-choices. The main goal of the weighting stage is to facilitate the choice between several alternatives in a LCA study when the results between impact categories do not allow a clear choice of which alternative has a better environmental performance. For example, an alternative may have a low impact on climate change but a high impact on particle emission and another alternative may be the reverse, that is, a high impact on climate change and a low impact on particle emission.

Therefore, when a trade-off between impact categories appears, thought the application of weighting factors we can make a selection between alternatives. However, the application of weighting factors on the impact category indicators is not a science-based method since the prioritisation of the impact categories is a subjective choice, thus influencing the ethical values of the LCA practitioner. Thereby, ISO 14044:2006 does not recommend the use of the weighting stage when the results of the LCA study are presented in public (Pizzol et al., 2017; Hauschild and Huijbregts, 2015 and Rosenbaum et al., 2018).

2.3.4. Life Cycle Interpretation

Finally, the fourth stage of a LCA is the interpretation of the results obtained in the LCIA. Through the analysis of the LCI and LCIA results we must solve the questions formulated in the goal and scope definition at the beginning of the LCA study. When the normalization and weighting of results is carried out, these LCIA phases could be considered as preparatory stages for the interpretation of results. In order to make the conclusions and recommendations of the study more robust, the interpretation can be accompanied by sensitivity analysis and uncertainty analysis (Hauschild, 2018).

When analysing the LCIA results, an empirical approach can be carried out to determine whether the difference of impact between various scenarios is significant. Hence, a difference of less than 10% in the categories related to climate change and energy consumption may not be considered significant due to uncertainties in the LCIA results. For the categories related to respiratory inorganics, acidification and eutrophication, the difference must be greater than 30%. For categories related to toxicity, a difference of one or two orders of magnitude it is necessary to be considered significant (Jolliet et al., 2010).

2.4. Why to use the Life Cycle Assessment methodology to analyse the environmental impact of freight transport?

The LCA methodology constitutes an effective tool to assess complex systems like freight transport, providing a system perspective analysis that allows assessing environmental impacts through all the stages of the transport system (transport operation, vehicles and infrastructure) including their related supply chains, from raw material extraction, through production and use, and finally disposal (i.e. a cradle-to-grave assessment). Moreover, LCA methodology allows the quantification of all relevant emissions and consumptions, as well as the related environmental and health impacts and resource depletion issues that are associated with transport. Therefore, the comprehensive analysis of the LCA methodology due to the cradle-to-grave approach and the inclusion of a set of environmental impact categories allows the identification of possible pollution transfer between the life cycle stages of a transport mode, geographic regions and environmental impact categories.

The application of the LCA methodology in a study on the environmental impact of transport avoids focusing all the attention in the transport operation stage (i.e. the transport activity), allowing also to consider other stages such as energy production (e.g. diesel refining or electricity generation), infrastructure and vehicles. Moreover, as a result of the LCA methodology, we can analyse the connections between different industrial sectors such as the energy and the transport sector. For instance, the LCA perspective becomes determinant in the case of electric trains, where the production of electricity is a major hotspot to improve the environmental performance of rail freight transport.

The standardisation at the international level by ISO 14040:2006 and 14044:2006 of the LCA methodology enables it to be a structured environmental assessment tool. The framework provided by the LCA methodology allows the collection of information and its analysis in a rigorous and methodological manner, improving the robustness of the results obtained.

The development and continuous application of the LCA methodology has allowed the creation of specialized software and databases. Moreover, the LCA methodology has already been applied to environmental transport issues in several studies. Therefore, the available software and commercial databases enable a preliminary screening to identify the most important processes in the transport activity.

However, some weaknesses of the LCA methodology need to be addressed such as enhancing midpoint impact categories related to transport such as accidents damage, noise impact or land use. Moreover, some impact category indicators are not fully mature as those related to human toxicity and ecotoxicity for example, which means that some substances are not fully considered in the characterisation models and therefore their contribution to the impact indicator results is not reflected. It must be borne in mind that these and other indicators are currently being developed and improved.

The holistic approach of LCA requires a large amount of data related to freight transport to develop the flow inventory, which implies that the creation of the LCI becomes a time-consuming activity. We also have to consider that since our research focus on inland freight transport in Belgium, the missing specific data in commercial databases may be a limiting factor. Moreover, the existence of several freight operators (e.g. twelve rail freight operators in Belgium) and the regionalization of data complicate the collection of specific data concerning the state-of-the-art for Belgian freight transport including transport emissions. In contrast, we have the opportunity to improve the existing LCA commercial databases and to develop a Belgian specific database with the obtained results.

For all the aforementioned, LCA methodology is a perfect tool to find clues about how to improve the environmental performance of transport.

2.5.Life Cycle Assessment of inland freight transport in Belgium

2.5.1. Goal and scope definition of this research thesis

The overall goals and scope of this research thesis are:

- to analyse and compare the environmental impacts of the different inland freight transport modes in Belgium (i.e. rail freight transport, IWW transport and road freight transport),
- to analyse the environmental impacts of intermodal freight transport routes using different inland freight transport modes in both Belgium and Europe and,
- to study the environmental impacts of the modal splits of inland freight transport in Belgium obtained as a result of the possible development of the intermodal rail freight transport and due to the optimization of operational costs and environmental factors.

The functional unit chosen is “one tonne-kilometre (tkm) of freight transported” in the different modes of inland freight transport, which represents the transport of one tonne of goods over a distance of one kilometre.

According to the ILCD Handbook (European Commission, 2010), the decision context of the LCA performed in the framework of this thesis is assigned to a situation C. This study is of a descriptive nature, analysing the environmental performance of the different inland freight transport modes in Belgium. Moreover, the LCA results obtained in this study will not be used for decision support, thus it could not be framed in a situation A or B. Since, the transport system of our study presents interactions with other systems, a situation C1 has been considered.

This thesis studies the inland freight transport in Belgium from the period 2006 to 2012. This is because the most recent data available on energy consumption for rail freight transport in Belgium is from 2012. Therefore, although for IWW and road transport there is data available until 2014, it has been decided to analyse until 2012 in order to be coherent with rail freight transport.

Figure 2.11 shows the system boundaries considered in our study for LCA of rail, IWW and road freight transport. Looking at the year 2012, road transport was the dominant mode of the three major inland freight transport modes in Belgium, accounting for 64.5% of the total inland freight expressed in tonnes-kilometres. Rail transport was responsible for 14.6% and IWW accounted for 20.9% of the total inland freight transported in Belgium (Eurostat statistics, 2017).

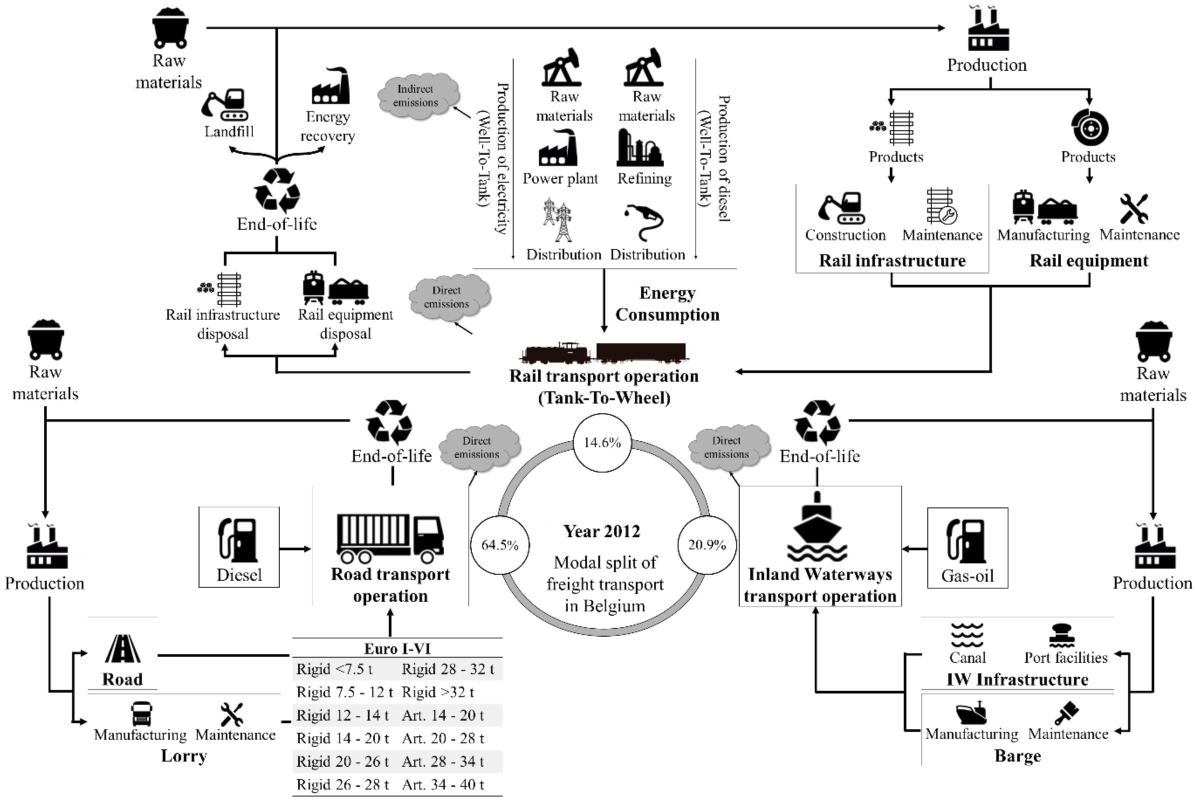


Figure 2.11. Boundaries considered in the Life Cycle Assessment of the inland freight transport system

A division of the processes related to the energy consumption in transport can be made. On the one hand, Well-To-Tank (WTT) processes such as primary energy consumption and indirect emissions are produced at the upstream energy processes, which start with the raw materials extraction, continue with the diesel refining or electricity production and end with the energy distribution to the traction unit (locomotive, barge or lorry in our study). On the other hand, the Tank-To-Wheel (TTW) processes such as the final energy consumption and the exhaust emissions are produced during the transport activity. Finally, the Well-To-Wheel (WTW) processes are the sum of the WTT processes and the TTW processes.

In our study, the LCA approach have been used, taking into consideration the overall life cycle of the energy carrier. LCA methodology can provide complete information of the environmental impacts related to a process, and not only providing information on energy consumption and emissions produced but also on raw materials consumption. Furthermore, the application of LCA methodology on transport allows the analysis of not only the transport emissions related to the energy consumption during the transport operation, but also the emissions related to the construction of rail infrastructure, IWW infrastructure and road infrastructure and the manufacturing of vehicles such as locomotives, wagons, barges or lorries. Moreover, the maintenance and disposal of both infrastructure and vehicles is also considered (Spielmann et al., 2007).

Table 2.2 compares direct and indirect energy consumptions between the different modes of inland freight transport extracted from Messagie et al. (2014a). For rail transport, the TTW stage is only responsible for 19% of the total energy consumption while WTT stage accounts for 50%. These proportions represent a European average with a mixed use of mainly electricity and the remaining part of diesel. The manufacture, maintenance and disposal of the rail equipment accounts for 12% and the construction, maintenance and disposal of the rail infrastructure accounts for 19% of the total energy consumption. Concerning IWW transport, in the case of a M4 barge (i.e. a vessel of the category "Dortmund-Ems Canal" with a load capacity from 650 t to 1 000 t, see Table 4.11) on CEMT VI waterway (classification of European IWW, see Table 4.11) in Belgium, barge operation is responsible for 67%, WTT stage for 20%, manufacture, maintenance and disposal of the M4 barge for 2% and construction, maintenance and disposal of the CEMT VI waterway for 11% of the total energy consumption. For road transport, the TTW stage accounts, on average, for 75% of the total energy consumption, 11% for fuel production, 6% for manufacture, maintenance and disposal of the lorry and 8% for the construction, maintenance and disposal of the road infrastructure (Messagie et al., 2014a). While the shares of energy consumption showed in Table 2.2 are only indicative and dependent on specific assumptions, they highlight the importance of all the stages of transport in the total energy consumption of freight transport.

Table 2.2. Direct and indirect energy consumptions in different modes of transport. Source: Messagie et al., 2014a

Average energy consumption	WTT	TTW	Vehicle	Infrastructure
Rail transport[1]	50%	19%	12%	19%
IWW transport[2]	20%	67%	2%	11%
Road transport[1]	11%	75%	6%	8%

[1]Source: Spielmann and Scholz, 2005; [2]Source: Van Lier and Macharis, 2014

2.5.2. Life Cycle Inventory of this research thesis

As mentioned above, commercial databases as Ecoinvent (Weidema et al., 2013) have been developed to allow an easier access to the inventory of numerous processes such as the transport of one tonne-kilometre by train for example. However, there is no Belgian specific commercial transport database and current databases should be improved and updated. It has been taken as a model for our research the Swiss transport database included in Ecoinvent, which is the most comprehensive transport database available (Spielmann et al., 2007). The existing Swiss database has allowed us to perform a preliminary search to guide us in identifying the most influential factors in the environmental impact of rail, IWW and road freight transport (Spielmann and Scholz, 2005). Once these have been identified, we have been able to collect the most significant data of inland freight transport in Belgium. Currently, there is no publication relative to the state-of-the-art for inland freight transport in Belgium, having a lack of technical data (e.g. locomotive types or infrastructure characteristics for example) for the assessment of inland freight transport impacts. For data collection, more reliable sources of information have been identified and we have collected information through interviews with different stakeholders (see Appendix A).

A detailed study of the rail freight transport has been conducted, collecting data directly from Infrabel (the Belgian railway infrastructure manager) and B-Logistics (rebranded to LINEAS, April 2017), which is the main rail freight operator in Belgium. The rail freight system has been divided in three sub-systems: rail transport operation, rail infrastructure and rail equipment.

For the rail transport operation sub-system, the specific energy consumption of electric and diesel trains has been determined separately. Upstream emissions related to the production and distribution of the energy to the traction unit and the direct emissions during the rail transport activity have been determined. In the case of indirect emissions from electric trains, in order to adjust as closely as possible the environmental impact related to the yearly electricity consumption, and since the electricity supply mix varies widely over the years, our LCA study uses the electricity supply mix in Belgium corresponding to the appropriate year. Three types of direct emissions produced during the rail transport operation have be distinguished: the exhaust emissions to air related to the diesel combustion in locomotives, the direct emissions to soil from abrasion of brake linings, wheels and rails and the sulphur hexafluoride (SF_6) emissions to air during conversion of electricity at traction substations.

The subsystem rail infrastructure includes the processes that are connected with the construction, maintenance and disposal of the railway infrastructure. We have collected data from Infrabel and literature sources relative to the Belgian railway infrastructure. This comprises information on the materials and energy used in the construction of the railway network (including track, tunnels and bridges) such as rails, sleepers, fastening systems, switches and crossings, track bedding or overhead contact system for example. The maintenance of the Belgian railway infrastructure has been analysed as well. Therefore, the maintenance works such as rail grinding, rail renewal, sleeper and fastening system renewal, switches and crossing renewal, ballast tamping, ballast renewal, ballast cleaning and weed control are taken into account. We have considered in the maintenance of railway infrastructure both the fuel consumption and exhaust emissions from the machinery used in the maintenance and the new materials used in the track renewal. We have also included in our study the end-of-life of the railway infrastructure and the land use in the Belgian railway network. Most of the elements are recycled such as the ballast that is reused as material for backfill and the wooden sleepers that are incinerated with energy recovery.

The life cycle phases of manufacturing, maintenance and disposal of rail equipment (locomotives and wagons) are taken into account in our study as well. Table 2.3 presents the main data used to develop the LCI of rail freight transport.

Table 2.3. Main data used to develop the LCI of rail freight transport

Sub-system	Data	Main sources
Transport operation	Total annual energy consumption	SNCB (2009, 2013, 2015)
	Rail freight traction share	Vlaamse Milieumaatschappij (VMM) (2008, 2009, 2010, 2012, 2013)
	Electricity supply mix	Eurostat statistics (2017)
	Emission factors for direct emissions	Spielmann et al. (2007)
	Sulphur content of diesel	EU Fuel Quality Monitoring (2012)
Railway Infrastructure	Length of railway lines in Belgium	Eurostat statistics (2017)
	Transport performance (tkm)	SNCB (2009, 2013, 2015)
	Operating performance (Gtkm)	Eurostat statistics (2017)
	Kilometric performance (train-km)	Eurostat statistics (2017)
	Construction, maintenance and disposal	IBGE (2011); Infrabel (2007, 2011, 2014 and questionnaires); Kiani et al. (2008); Schmied and Mottschall (2013); Spielmann et al. (2007); Tuchschmid et al. (2011) and UIC (2013)
Rolling stock	Population of locomotives and wagons	Eurostat statistics (2017) and SNCB (questionnaires)
	Manufacturing, maintenance and disposal	Ecoinvent database (2013)

Analogously to the rail transport system, for the LCA of IWW transport, all life cycle phases of IWW transport operation, IWW infrastructures (including canals and the Port of Antwerp as reference), and manufacturing and maintenance of the vessels are included. Information relative to the total annual freight moved by IWW transport in Belgium by barge type, fuel consumption in the vessel transport operation and waterways infrastructure characteristics for several years have been collected. Table 2.4 presents the main data used to develop the LCI of IWW transport.

Table 2.4. Main data used to develop the LCI of IWW transport

Sub-system	Data	Main sources
Transport operation	Class specific fuel consumption of barges	Service Public de Wallonie (2014)
	Carrying capacity of each vessel class	Institut pour le Transport par Batellerie (ITB) (2007, 2008, 2009, 2010, 2012 and 2013)
	Emission factors for direct emissions	Spielmann et al., (2007)
IWW and Port	Length of IWW	Eurostat statistics (2017)
	Transport performance (tkm)	Eurostat statistics (2017)
	Incoming and outgoing Port of Antwerp	Antwerp Port Authority (2016)
	Construction, maintenance and disposal	Ecoinvent database (2013)
Barges	Population of barges	Institut pour le Transport par Batellerie (ITB) (2006, 2007, 2008, 2009, 2010, 2011 and 2012)
	Manufacturing, maintenance and disposal	Ecoinvent database (2013)

For the LCA of road transport, all life cycle phases of road transport operation, road infrastructure, and manufacturing and maintenance of the lorries are included. Information relative to the total annual freight moved by road transport in Belgium by weight classification and heavy duty vehicle technology type, fuel consumption in the road transport operation and road infrastructure characteristics for several years have been collected. Table 2.5 presents the main data used to develop the LCI of road freight transport.

Table 2.5. Main data used to develop the LCI of road freight transport

Sub-system	Data	Main sources
Transport operation	Average diesel consumption	TRACCS database (2013) and EcoTransIT (2014)
	Maximum payload	TRACCS database (2013)
	Transport performance (tkm)	COPERT (2016)
	Emission factors for direct emissions	Spielmann et al. (2007) and EMEP/EEA (2013)
Road infrastructure	Length of road infrastructure	Eurostat statistics (2017)
	Construction, maintenance and disposal	Ecoinvent database (2013)
Lorries	Population of lorries	COPERT (2016)
	Manufacturing, maintenance and disposal	Ecoinvent database (2013)

2.5.3. Life Cycle Impact Assessment of this research thesis

As discussed before, in the Life Cycle Impact Assessment (LCIA) stage the information collected in the LCI is translated into environmental impacts through the use of quantitative models with the assistance of specialised LCA software. For this research study, all calculations of the LCIA stage have been performed with the SimaPro 8.0.5 software. Within the LCIA methods available in this commercial LCA software, it has been selected two LCIA methods: ILCD 2011 Midpoint+ and ReCiPe 2008.

2.5.3.1. ILCD 2011 Midpoint+

The LCIA method ILCD 2011 Midpoint+ is the method recommended by the European Commission (European Commission, 2010). It has been used the version V1.06 / EU27 2010. As shown in Table 2.6, ILCD 2011 Midpoint+ is a midpoint method including 16 environmental impact categories. The European Commission – Joint Research Centre analysed several LCIA methods and selected the impact category indicators with the highest quality for each impact category in order to harmonise a methodology. Moreover, the selected characterisation methods (models and associated characterisation factors) have been classified according to their quality into three levels (European Commission, 2011):

- Level I: Recommended and satisfactory. The characterisation methods of this level are defined by European Commission (2011) as "*recommended for all types of life cycle based decision support. Although further research needs may have been identified, these are not preventing the models/factors being seen as satisfactory given the current state-of-the art. However, updating and improvement via established mechanisms, such as e.g. the IPCC, should be followed also for these methods and factors*".
- Level II: Recommended but in need of some improvements. The characterisation methods of this level are defined by European Commission (2011) as "*recommended for all types of life cycle based decision support. The uncertainty of models and the resulting characterisation factors is to be more strongly highlighted. The impact on results and interpretation has to be more carefully evaluated, especially in published comparisons. The need for dedicated further research is identified for these methods/factors to further improve them in terms of precision, differentiation, coverage of elementary flows etc.*"
- Level III: Recommended, but to be applied with caution. The characterisation methods of this level are defined by European Commission (2011) as "*recommended to be used but only with caution given the considerable uncertainty, incompleteness and/or other shortcomings of the models and factors. These models/factors are in need of further research and development before they can be used without reservation for decision support especially in comparative assertions*".

Furthermore, the impact category "Ionising radiation - ecosystems" has been considered interim, since although the recommended characterisation method is the best among the analysed methods for this impact category, the method is not yet mature for recommendation (European Commission, 2011).

Table 2.6. Classification of the midpoint impact categories and their recommended characterisation methods (models and associated characterisation factors) used in ILCD 2011 Midpoint+. Sources: European Commission, 2011; Pré, 2015

Level of quality	Impact category	Recommended default LCIA method	Indicator	Unit
Level I (recommended and satisfactory)	Climate change	Baseline model of 100 years of the IPCC 2007	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq.
	Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	kg CFC-11 eq.
	Particulate matter / Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al., 2007	Intake fraction for fine particles (kg $PM_{2.5}$ eq./kg)	kg $PM_{2.5}$ eq.
Level II (recommended but in need of some improvements)	Ionising radiation, human health	Human health effect model as developed by Dreicer et al., 1995 (Frischknecht et al., 2000)	Human exposure efficiency relative to U235	kBq U235 eq.
	Photochemical ozone formation	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	kg NMVOC eq.
	Acidification	Accumulated Exceedance (Seppâlâ et al., 2006, Posch et al., 2008)	Accumulated Exceedance	molc H+ eq.
	Terrestrial eutrophication			molc N eq.
	Freshwater eutrophication	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.
	Marine eutrophication		Fraction of nutrients reaching marine end compartment (N)	kg N eq.
	Mineral, fossil and renewable resource depletion[1]	CML 2002 (Guinée et al., 2002)	Scarcity	kg Sb eq.
Level II / III	Human toxicity, cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for humans (CTU_h)	CTU_h
	Human toxicity, non-cancer effects			
	Freshwater ecotoxicity		Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e
Level III (recommended, but to be applied with caution)	Land use	Model based on Soil Organic Matter (SOM) (Milà i Canals et al., 2007)	Soil Organic Matter	kg C deficit
	Water resource depletion	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al., 2008)	Water use related to local scarcity of water	m^3 water eq.
Interim	Ionising radiation, ecosystems	No methods recommended	-	CTU_e

[1]Depletion of renewable resources is included in the analysis but none of the analysed methods is mature for recommendation

With regard to endpoint impact categories, the LCIA method ILCD 2011 Midpoint+ does not have a complete selection of characterisation methods to translate all the midpoint impact categories to endpoint categories as a result of the immaturity of the current endpoint characterisation methods (European Commission, 2011). However, as can be seen in Figure 2.12, the influence of the midpoint categories to endpoint categories such as damage to human health, damage to ecosystem diversity and resource scarcity could be evaluated in the future. These endpoint categories are related to the areas of protection of human health, natural environment and natural resources, respectively (European Commission, 2010).

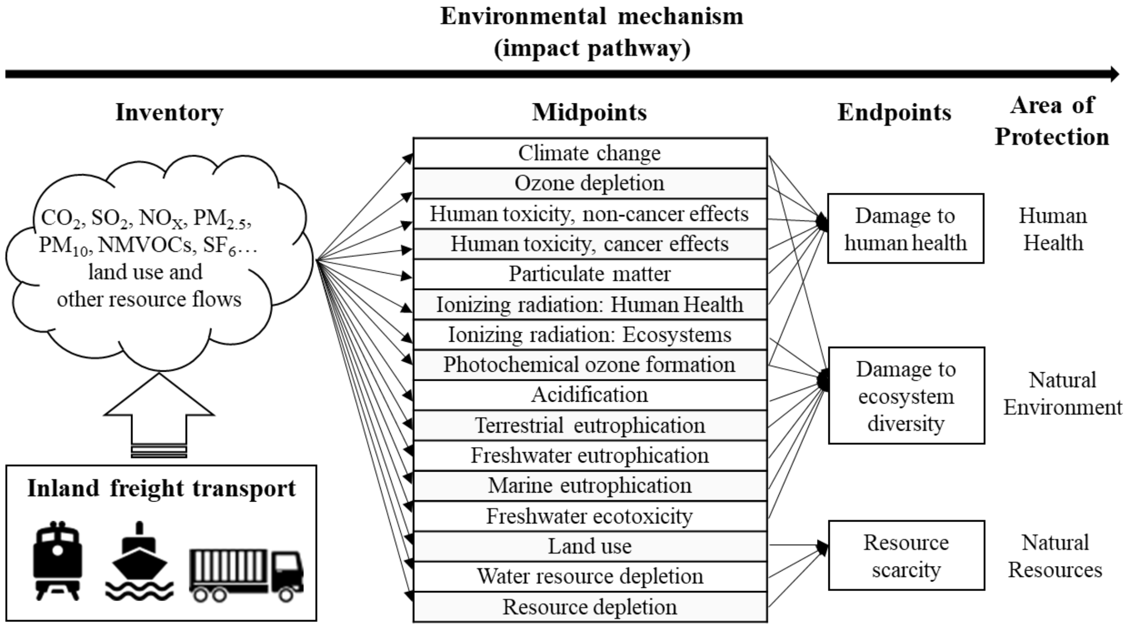


Figure 2.12. Diagram of the Life Cycle Impact Assessment methodology applied on inland freight transport. Source: European Commission, 2010

In order to facilitate the interpretation of LCIA results, in this study it has been used only the midpoint impact categories with a level of quality I (climate change, ozone depletion and particulate matter), and II (ionizing radiation – human health, photochemical ozone formation, acidification, terrestrial and freshwater eutrophication and mineral, fossil and renewable resource depletion). Moreover, the impact category marine eutrophication has not been included since the system boundaries of our study are limited to inland freight transport.

I. Climate change

The climate change is produced by the emission of greenhouse gases (GHG) such as CO_2, methane (CH_4) or nitrous oxide (N_2O) for example, which have the capacity to absorb infrared radiation, increasing the radiative forcing in the atmosphere and therefore causing the increase of the global temperature of the planet.

The GHGs are classified according to their Global Warming Potential (GWP), which is calculated with respect to CO_2. Moreover, the GWP of the GHGs are calculated for different time horizons (e.g. 20 or 100 years) due to variable lifespan of GHGs in the atmosphere. For example, CH_4 has lower GWP over 100 years than over 20 years due to its lower life span in the atmosphere, and conversely, SF_6 has a higher GWP over 100 years than over 20 years.

The category impact indicator used by ILCD 2011 Midpoint+ method is the GWP, which calculates the radiative forcing over a time horizon of 100 years using the characterisation model and factors of the IPCC (2007). For example, the GWP over a time horizon of 100 years of CO_2 is 1 kg CO_2 eq./kg CO_2, for CH_4 is 25 kg CO_2 eq./kg CH_4, for N_2O is 298 kg CO_2 eq./kg N_2O and for SF_6 is 22 800 kg CO_2 eq./kg SF_6 (IPCC, 2007). It should be noted that these values have been updated in the successive reports of the IPCC. This model and factors are also applied in the ReCiPe method (European Commission, 2011; Pré, 2015).

II. Ozone depletion

The stratospheric ozone depletion is an environmental issue produce for the destruction of the stratospheric ozone layer due to the action of anthropogenic pollutants. The stratospheric ozone layer is beneficial to the environment because it filters ultraviolet radiation from the sun. The category impact indicator used by ILCD 2011 Midpoint+ method is the Ozone Depletion Potential (ODP), which calculates the destructive effects on the stratospheric ozone layer over a time horizon of 100 years. This method has been published by the World Meteorological Organisation (WMO) in 1999 and is also applied in the ReCiPe method (European Commission, 2011; Pré, 2015).

III. Particulate matter

Population exposure to particulate matter is considered as a major environmental health problem in most cities. Transport represents an important source of air pollution, especially for particulate matter and NO_X. Particulate matter can be emitted directly from vehicles (primary particulate matter) or be formed in the atmosphere (secondary particulate matter) from precursor pollutants such as SO_X, NO_X, NH_3 or VOC. The category impact indicator used by ILCD 2011 Midpoint+ method is RiskPoll (Rabl and Spadaro, 2004), which determines the impact of premature death or disability that particulate matter (including primary and secondary particulate matter) has on the population, being calculated with respect to $PM_{2.5}$ (European Commission, 2011; Pré, 2015).

IV. Ionizing radiation – human health

The category impact indicator used by ILCD 2011 Midpoint+ method is the human health effect model (Frischknecht et al. 2000), which quantifies the impact of ionizing radiation on the population compared to Uranium 235 (U235). This model and factors are also applied in the ReCiPe method (European Commission, 2011; Pré, 2015).

V. Photochemical ozone formation

The tropospheric ozone formation in cities represents a significant concern for human health and the environment. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC (both pollutants emitted by the transport sector) by photochemical reaction under the influence of solar radiation. The category impact indicator used by ILCD 2011 Midpoint+ method is the LOTOS-EUROS model (van Zelm et al, 2008) as applied in the ReCiPe method for the midpoint impact category photochemical ozone formation (European Commission, 2011; Pré, 2015).

VI. Acidification

Terrestrial acidification is produced for the emission to the atmosphere of SO_2, NO_X, NH_3 or inorganic acids as HCl for example, causing the deposition of acidifying compounds in terrestrial and aquatic ecosystems through the "acid rain". The category impact indicator used by ILCD 2011 Midpoint+ method is Accumulated Exceedance (Seppälä et al. 2006 and updated characterisation factors by Posch et al. 2008), which characterise the deposit of acidifying substances in terrestrial and freshwater ecosystems (European Commission, 2011; Pré, 2015).

VII. Terrestrial eutrophication

Terrestrial eutrophication is the result of deposition from the atmosphere of nitrogen compounds (e.g. NO_X or NH_3) in the soil, which produces a change in terrestrial ecosystems. The category impact indicator used by ILCD 2011 Midpoint+ method is Accumulated Exceedance (Seppälä et al. 2006 and updated characterisation factors by Posch et al. 2008), which characterise the deposit of nitrogen substances in terrestrial ecosystems (European Commission, 2011; Pré, 2015).

VIII. Aquatic eutrophication

Aquatic eutrophication is produced by the enrichment of the aquatic ecosystems with an excess of nutrients leading to an intense biomass production and resulting in the degradation and change in the species composition of the aquatic ecosystem. The category impact indicator used by ILCD 2011 Midpoint+ method is the EUTREND model (Struijs et al., 2009) as applied in the ReCiPe method, considering only phosphorus component for freshwater eutrophication and nitrogen components for marine eutrophication (European Commission, 2011; Pré, 2015).

IX. Mineral, fossil and renewable resource depletion

The category impact indicator used by ILCD 2011 Midpoint+ method is the CML 2002 (Guinée et al., 2002), which determines the abiotic depletion potential of resources (e.g. oil or minerals) through the use of characterisation factors and using as reference element the antimony (the unit of this indicator is kg of Sb eq.) (European Commission, 2011; Pré, 2015).

X. Human toxicity and Ecotoxicity

In addition to the preceding impact categories, there are other impact categories related to toxicity that, although important, have not been included because they have been classified as categories with a quality level II / III. The category impact indicators for human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity used by ILCD 2011 Midpoint+ method are the USEtox model developed by Rosenbaum et al., 2008 (European Commission, 2011)

2.5.3.2. ReCiPe 2008

ReCiPe 2008 is a LCIA method including 18 midpoint impact categories with their respective characterisation models and factors and midpoint impact category indicators. Moreover, most of these midpoint impact indicators can be multiplied by damage factors and aggregated into three endpoint impact categories. Therefore, through the application of ReCiPe, the resources consumed and contribution of the pollutants emitted by freight transport and determined in the LCI can be analysed using midpoint impact categories (e.g. climate change, particulate matter formation or photochemical oxidant formation). Then, the influence of most of these midpoint impact categories can be evaluated (i.e. all except marine eutrophication and water depletion) in terms of endpoint impact categories such as damage to human health, damage to ecosystem diversity and damage to resource availability, which are related to the areas of protection of human health, natural environment and natural resources, respectively (Goedkoop et al., 2013).

Figure 2.13 represents the relations between the LCI, the 18 midpoint impact categories and related indicators, and the three endpoint impact categories and associated indicators of the LCIA method ReCiPe 2008.

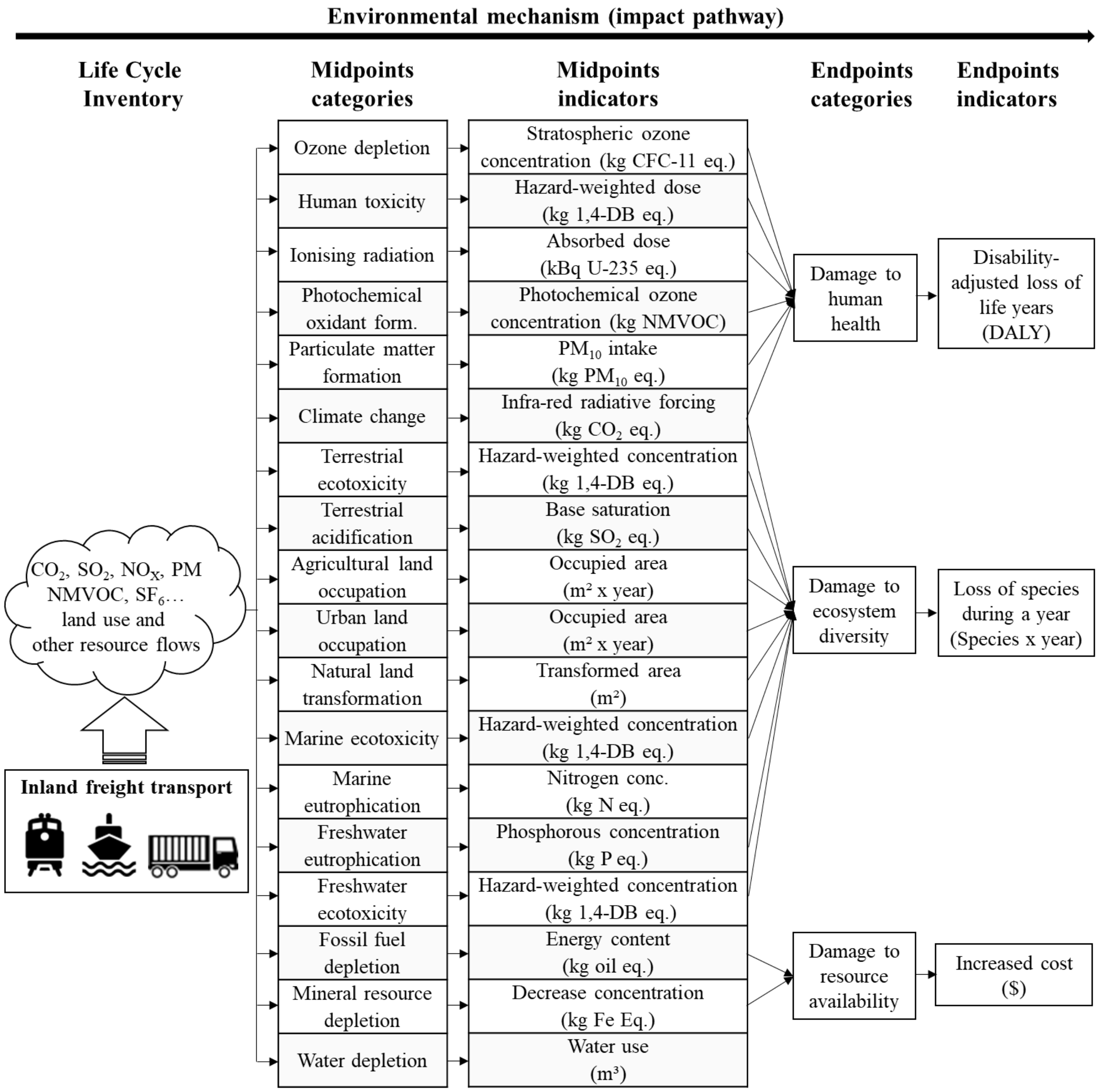


Figure 2.13. Diagram of the Life Cycle Impact Assessment method ReCiPe 2008 applied on inland freight transport. Source: Adapted from Goedkoop et al., 2013

LCA studies applied to transport mainly focused on air emissions, especially CO_2, CO, NO_X, SO_2, NMVOC and particulate matter (Spielmann and Scholz, 2005; Facanha and Horvath, 2006, 2007; Chester and Horvath, 2009, 2010; Van Lier and Macharis, 2014; Jones et al., 2017). Therefore, it has been considered that the following midpoint environmental impact categories are relevant for our study on freight transport: climate change (kg CO_2 eq.), photochemical oxidant formation (kg NMVOC eq.) and particulate matter formation (kg PM_{10} eq.).

Moreover, ReCiPe 2008 allows us the study of the environmental impacts of freight transport at the endpoint level. Hence, the endpoint categories damage to human health (DALY), damage to ecosystem diversity (species × year), damage to resource availability ($) have been analysed as well. It must be borne in mind when comparing endpoint categories that they present a greater uncertainty than midpoint categories due to a more complete modelling of impact pathways (Kägi et al., 2016). Therefore, these results on endpoint damages should be interpreted with caution due to the uncertainty of the methodology.

ReCiPe 2008 assesses damage to human health using the indicator disability-adjusted loss of life years (DALY), which encompass the number of years of life lost and the number of years of life disable. The damage to ecosystem diversity is assessed using the indicator loss of species in a certain area during a year (species × year). The damage to resource availability is assessed using the indicator increased cost, which is expressed in a monetary unit ($) and it is based on the surplus costs of future resource production in the future (Goedkoop et al., 2013).

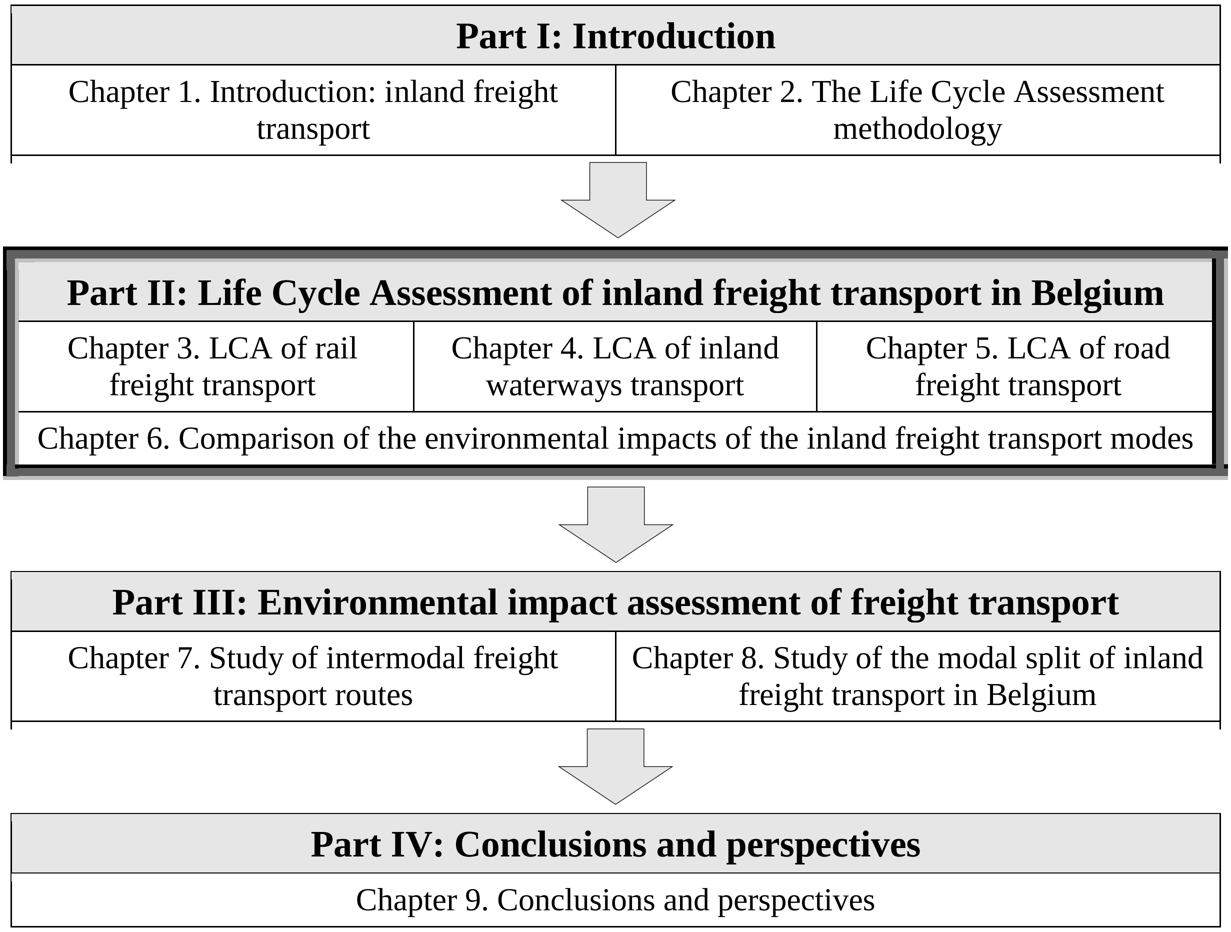
ReCiPe 2008 groups different sources of uncertainty and choices in three cultural perspectives (individualist, hierarchist and egalitarian), classifying similar types of assumptions and choices to manage the uncertainty of the characterisation models (Goedkoop et al., 2013; Rosembaum et al., 2018). Table 2.7 presents the cultural perspectives used in ReCiPe 2008.

Table 2.7. Cultural perspectives used in ReCiPe 2008. Source: Rosembaum et al., 2018

	Time perspective	**Manageability**	**Required level of evidence**
Individualist	Short term	Technology can avoid many problems	Only proven effects
Hierarchist	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
Egalitarian	Long term	Problems can lead to catastrophe	All possible effects

In our study, the hierarchist perspective has been used (ReCiPe 2008 version V1.12 / Europe), since it gives an average value of the environmental impact obtained.

Part II: Life Cycle Assessment of inland freight transport in Belgium



Chapter 3. Life Cycle Assessment of rail freight transport

3.1. Introduction

It has been collected specific information related to the rail freight transport system in Belgium from both literature sources and directly through the use of questionnaires from Infrabel (the Belgian railway infrastructure manager) and B-Logistics (rebranded to LINEAS, April 2017), which is the main rail freight operator in Belgium with a market share of 86.62% of tonne-kilometres (tkm) in 2012 (Van de Voorde and Vanelslander, 2014).[1]

The system boundaries considered in our study for the rail freight transport are shown in Figure 3.1. The rail freight transport system has been divided in three sub-systems: rail transport operation, rail equipment (locomotives and wagons) and rail infrastructure. The sub-system rail transport operation includes the processes that are directly connected with the train activity. In diesel trains, it takes into account the exhaust emissions to air from diesel locomotives and the indirect emissions from diesel production. In electric trains, it encompasses both the sulphur hexafluoride (SF_6) emitted during conversion at traction substations related to electricity consumption and the indirect emissions from electricity generation. Since the electricity supply mix plays a fundamental role in the environmental impacts of electric trains, the electricity supply mix used for the electric trains in Belgium has been determined for each year. Moreover, the rail transport operation includes the direct emissions to soil from abrasion of brake linings, wheels, rails and overhead contact lines in both types of traction. Furthermore, the application of the LCA methodology on transport allows the analysis of the environmental impacts related to the manufacturing, maintenance and disposal of rail equipment (i.e. locomotive and wagons) and the construction, maintenance and disposal of the railway infrastructure (Spielmann et al., 2007).

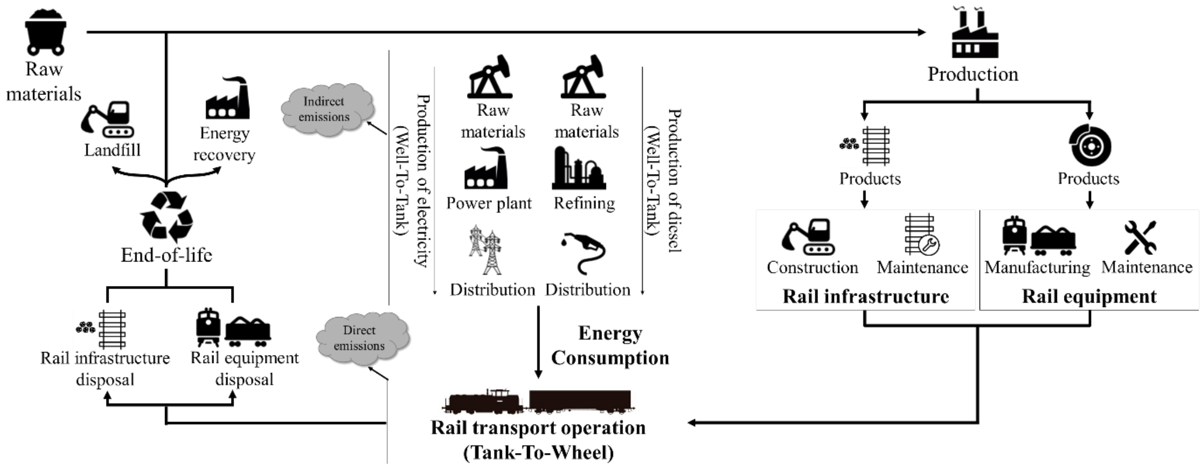


Figure 3.1. Rail freight transport system boundaries considered in our study. Source: Based on Spielmann et al., 2007

[1] The results presented in this chapter have been submitted for publication in Merchan et al. (2018)

3.2. Rail transport operation

The main processes included in the sub-system rail transport operation can be divided in two stages. On the one hand, the Well-To-Tank (WTT) stage comprises the primary energy consumption and indirect emissions produced at the upstream energy processes, which start with the raw materials extraction, continue with the diesel refining or electricity production and end with the energy distribution to the train. The analysis of the electricity supply mix used by electric trains is included in this stage. On the other hand, the Tank-To-Wheels (TTW) stage encompasses the energy consumption of electric and diesel trains during the transport activity and the direct emissions such as the exhaust emissions to air from diesel locomotives, the SF_6 emissions from electricity conversion at traction substations and the direct emissions to soil from abrasion. The Well-To-Wheels (WTW) processes would be the sum of the WTT processes and the TTW processes. Besides the assessment of the environmental impacts related to the overall life cycle of the energy carrier, the LCA approach followed in our study includes the emissions and energy and raw material consumptions from the construction or manufacturing, maintenance and end of life of rail infrastructure and vehicles.

3.2.1. Energy consumption (Tank-To-Wheel) of rail freight transport

The energy consumption during the rail transport activity of electric and diesel trains has been determined separately on the basis of the total annual energy consumption of electricity and diesel and the total annual rail freight moved by each energy traction from the period 2006 to 2012, using the data in Table 3.1. The annual data on energy consumption (TTW) of trains from SNCB include the energy consumed by trains, such as the empty returns, shunting activity, maintenance of trains, as well as electrical losses in catenary (SNCB, 2009, 2013, 2015).

Table 3.1. Rail freight transport performance and energy consumption (TTW) in Belgium. Sources: SNCB, 2009, 2013, 2015

Year	2006	2007	2008	2009	2010	2011	2012
Rail freight (millions tkm)	8 442	8 148	7 882	5 439	5 729	5 913	5 220
Electric traction consumption (TJ)	3 489	3 261	3 382	2 472	2 092	2 248	1 922
Diesel traction consumption (TJ)	1 449	1 339	1 282	739	721	582	465
Total consumption (TJ)	4 939	4 600	4 664	3 211	2 813	2 830	2 387
Energy consumption (kJ/tkm)	585	565	592	590	491	479	457

The energy consumption for the Belgian rail freight transport has been calculated as 457 kJ/tkm in 2012. However, no differentiation can be made between electric and diesel traction. The rail freight traction share in Figure 3.2 has been used to calculate the rail freight moved by electric and diesel traction, enabling to determine the specific energy consumption of electric and diesel trains separately. Table 3.2 shows the values of energy consumption of electric and diesel trains calculated in our study from the period 2006 to 2012. If we take year 2012 as an example, 86.3% of the 5 220 million tkm of rail freight in Belgium were moved with electric traction, resulting in 4 505 million tkm. The total electricity consumed in 2012 was 1 922 TJ, therefore the specific energy consumption of electric trains was 427 kJ/tkm. Similarly, 13.7% of the 5 220 million tkm of rail freight in Belgium were moved with diesel traction, resulting in 715 million tkm. The total diesel consumed in 2012 was 465 TJ, including the diesel consumption of the shunting activity, thus the specific energy consumption of diesel trains was 650 kJ/tkm.

Table 3.2. Energy consumption (TTW) of rail freight transport in Belgium

Year	2006	2007	2008	2009	2010	2011	2012
Energy consumption of electric trains (kJ/tkm)	541	527	549	547	438	454	427
Energy consumption of diesel trains (kJ/tkm)	725	685	746	804	760	608	650

According to EcoTransIT (2008), electric and diesel trains present an energy consumption of 456 kJ/tkm and 530 kJ/tkm, respectively. These values represent European averages of the year 2005 and comprise both the final energy consumption during transport operation and the energy consumption of the generation of diesel and electricity, i.e. WTW energy consumption (EcoTransIT, 2008). By comparing the values used in EcoTransIT (2008) with the energy consumptions obtained in our study for the year 2006, our results for Belgium show higher energy consumptions with 541 kJ/tkm and 725 kJ/tkm of electricity and diesel consumed (including shunting activity), respectively. Electric trains present in our study lower energy consumptions after the year 2010 and the values calculated for diesel trains (including shunting activity) show higher energy consumptions than the values of EcoTransIT (2008). Therefore, electric trains are more energy efficient than diesel trains.

Furthermore, the energy consumption of the Belgian traction mix using the energy consumption of electric and diesel trains and the rail freight traction share has been calculated. Since the rail freight traction share for Belgium was not available, the data used is for the Flemish region (Belgium), but this value can be considered as representative for Belgium in general. The rail freight traction share of years 2006 and 2010 have been calculated using linear interpolation. It should be noted that even though the use of diesel is present in rail freight transport in Belgium, the use of electric traction is much greater. Moreover, the use of diesel traction is decreasing in Belgium, which means that only a small part of the rail freight produces exhaust emissions. Figure 3.2 shows the values of energy consumption (TTW) of electric and diesel trains and the Belgian traction mix calculated in our study from the period 2006 to 2012.

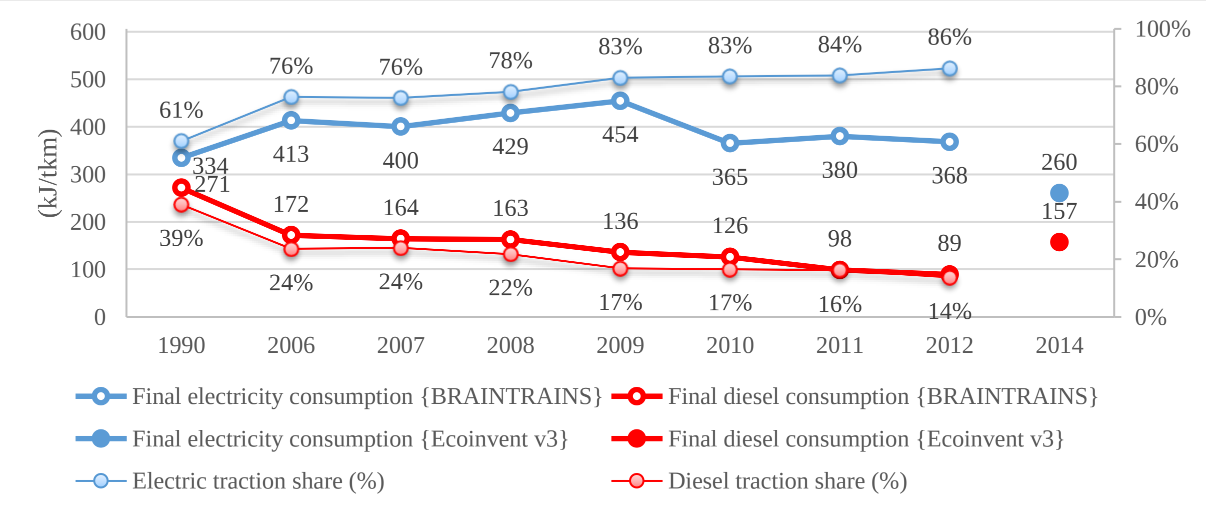


Figure 3.2. Energy consumption (TTW) of the Belgian traction mix in Belgium. Source: Flemish Environment Agency (VMM, 2008, 2009, 2010, 2012, 2013)

In the case of the energy consumption in the Belgian traction mix, Ecoinvent v3 database (Weidema et al., 2013) present a consumption of 260 kJ of electricity and 157 kJ of diesel to move one tkm of rail freight in Belgium in the year 2014. By comparing with our results, 368 kJ of electricity and 89 kJ of diesel (including shunting activity) were needed to move one tkm in Belgium in the year 2012. As in our study, the values of energy consumption extracted from the Ecoinvent v3 database represent the final energy consumption during transport operation (i.e. TTW energy consumption). The results of final electricity consumption from our study are always higher than the value used by Ecoinvent v3. However, since the year 2009, the final diesel consumption from our study shows values lower than the value from Ecoinvent v3. The discrepancies between the values of our study and those of Ecoinvent v3 should be highlighted, since they point out a need for updating the Ecoinvent v3 database.

The energy consumption of rail transport is influenced by external factors to the train as the orography and factors related to the train characteristics such as speed, acceleration, length and total weight (Spielmann et al., 2007). In Belgium, the energy consumption depends on whether the rail transport takes place in the flat terrain near the coast or is performed in the hilliest area of the south, where actual consumptions are higher. Moreover, the energy consumption of a freight train decreases per tonne-kilometre with a low average speed and making few stops along the route (Infrabel, 2014).

Furthermore, the longer the train and the heavier the cargo, rail freight transport becomes more energy efficient (Messagie et al., 2014a). In the Belgian network, the length of freight trains is limited to 750 m and the maximum permitted load is 3600 t with an axle load up to 22.5 t on flat terrain, decreasing in mountainous terrain (Service Public Wallonie, 2012). The maximum authorised load is fixed considering the characteristics of the line section (e.g. gradient, curves or number of tracks) and the train (e.g. adhesion and power) (Infrabel, 2014). The average load of freight trains in Belgium were 569 t, 575 t and 584 t in the years 2006, 2007 and 2008, respectively (SNCB, 2009). It should be noted that the use of electric locomotives rather than diesel locomotives enables to transport heavier loads.

Some measures that will lead to a reduction in the energy consumption in rail freight transport are the development of more energy-efficient engines for locomotives with more restrictive emissions standards, the energy recovery systems from braking, the energy-efficient driving through the control of speed, the improvement of aerodynamics in rolling stock (IEA/UIC, 2015) and the weight reduction through new materials of locomotives and wagons (Helms and Lambrecht, 2006).

3.2.2. Direct emissions (Tank-To-Wheel) of rail freight transport

It must be borne in mind that the direct emissions do not yet represent environmental impact categories such as climate change or acidification. These direct emissions during transport operation are part of the inventory analysis and this, together with the energy consumption during transport operation and the emissions, energy and material consumptions from the vehicle and infrastructure stages, constitute the required elements to model the freight transport system. It is necessary to consider all the elements from the inventory analysis to evaluate the contribution of the freight transport to environmental impact categories. Therefore, this section presents pollutant emissions as substances produced during the transport activity and not as environmental impacts.

The direct emissions produced during the Tank-To-Wheel stage of the rail freight transport have been calculated using the emission factors of Spielmann et al. (2007), which do a selection of emission factors from others authors (see Table 3.3). The uncertainty of these emission factors has been calculated using the pedigree matrix developed by Weidema and Wesnæs (1996). To do this, it is assumed a lognormal distribution of the values, which is characterised by the standard deviation (SD). It should be noted that the square of the geometric standard deviation covers the 95% confidence interval (i.e. 95% of all measures values are within the range). If we take the SD of CO_2 emissions to air as an example, 95% of all measures values are between the mean value times 1.12 and the mean value divided by 1.12. Therefore, the closer the SD is to one, the lower is the uncertainty (Pré, 2013). The pedigree matrix allows the estimation of the SD on the basis of five criteria (reliability, completeness, temporal correlation, geographical correlation and further technological correlation) and a basic uncertainty factor (Pré, 2013). Table 3.3 includes the SD used in our study from the Ecoinvent database. The uncertainty of the emission factors varies depending of the pollutant. Thereby, the emission factor for CO_2 presents the lowest uncertainty. Since the basic uncertainty factor for heavy metals (5.00), CO (5.00) and $PM_{2.5}$ (3.00) is high, the uncertainty for these emission factors is greater (Pré, 2013).

Table 3.3. Emission factors used to determine the direct emissions of rail freight transport. Sources: Spielmann et al., 2007; Weidema et al., 2013

Emissions to air	Emission factor (g/kg diesel)	SD	Emissions to air	Emission factor (g/kg diesel)	SD
CO_2	3 146	1.12	**$PM_{2.5}$**	1.28	3.07
Cd	0.00001	5.19	**PM_{10}**	0.0549	1.53
Cu	0.0017	5.19	**PM_{10} > PM > $PM_{2.5}$**	0.107	2.03
Cr	0.00005	5.19	**Methane**	0.13	1.64
Ni	0.00007	5.19	**Toluene**	0.04	2.13
Se	0.00001	5.19	**Benzene**	0.1	2.13
Zn	0.001	5.19	**Xylene**	0.04	2.13
Pb	0.00000011	5.19	**NMVOC**	5.07	1.64
Hg	0.00000002	5.19	**NH_3**	0.02	1.64
CO	15.8	5.04	**N_2O**	0.1	1.64
NO_X	55	1.52	**-**	-	-

Three types of direct emissions have been distinguished. Firstly, the exhaust emissions to air related to the diesel combustion in diesel locomotives have been calculated using the diesel consumption. Spielmann et al. (2007) give a value of NMVOC emissions containing emissions of xylene, benzene and toluene, resulting in an emission factor of 5.25 g/kg diesel. In order to facilitate the calculation, the emission factors of toluene (0.04 g/kg diesel), benzene (0.1 g/kg diesel) and xylene (0.04 g/kg diesel) have been subtracted, resulting in an emission factor for NMVOC of 5.07 g/kg diesel.

To determine particle emissions, it is necessary to add the particles produced as exhaust emission from diesel locomotives to those produced by the abrasion of wheels and rails. Firstly, the emission factors of 0.0549 g PM_{10}/kg diesel and 0.107 g PM/kg diesel from Spielmann et al. (2007) have been used to determine the particles produced as exhaust emission. Secondly, to estimate the particles produced from wheel and rail abrasion, Spielmann et al. (2007) assume

167.5 t PM_{10}/year (25% of for wheel and rail abrasion) and 71.973 t PM/year. To obtain the quantity per tkm, it has been divided by the 10 786 million tkm of Switzerland in the year 2000 (Spielmann et al., 2007), resulting in 1.55×10^{-5} kg PM_{10}/tkm and 6.67×10^{-6} kg PM/tkm from wheel and rail abrasion. We consider that the emissions from wheel and rail abrasion in Switzerland are similar to those produced in Belgium. Finally both the particles produced as exhaust emission and produced by the abrasion have been added.

The emissions of SO_2 are dependent on the sulphur concentration in the diesel. According to Ntziachristos and Samaras (2000), the SO_2 emissions are given by Equation (1).

$$\boxed{SO_2\ emission\ (kg) = 2 \times\ k_{S,m} \times Diesel\ consumption} \qquad (1)$$

The emissions of SO_2 in Equation (1) are estimated by assuming that all sulphur in the fuel is transformed completely into SO_2. The $k_{S,m}$ factor is the weight related to sulphur content in fuel (kg/kg diesel) (Ntziachristos and Samaras, 2000). The diesel trains in Belgium uses conventional road-transport diesel, which is regulated by Directive 2003/17/EC, establishing a low sulphur content with a maximum limit of 10 ppm sulphur by mass from 2009. However, as shown in Table 3.4, diesel in Belgium has an average sulphur content of 8 ppm since 2008. For the years 2006 and 2007, the sulphur content in diesel in Belgium was 24 ppm and 9 ppm, respectively (Twisse and Scott, 2012).

Table 3.4. Concentration of sulphur in diesel in ppm. Sources: Vanherle et al., 2007; Twisse and Scott, 2012

Year	Sulphur content (ppm)	SO_2 emissions (g/kg)	Year	Sulphur content (ppm)	SO_2 emissions (g/kg)
1990	1 700	3.4	**2001**	269	0.538
1991 - 1995	1 300	2.6	**2002**	47	0.094
1996	600	1.2	**2003 - 2004**	40	0.080
1997	480	0.960	**2005**	31	0.062
1998	440	0.880	**2006**	24	0.048
1999	406	0.812	**2007**	9	0.018
2000	294	0.588	**2008 - 2012**	8	0.016

According to Equation (1), the SO_2 emission factor for diesel used since 2009 with a concentration of sulphur of 10 ppm ($k_{S,m}$ = 0.00001 kg/kg) is 0.02 g SO_2/kg diesel. Because sulphur concentration varies throughout years, the corresponding emission factor for each year has been calculated. For this study, the SO_2 emission factors of 0.048 g/kg, 0.018 g/kg and 0.016 g/kg have been used for the years 2006, 2007 and the period from 2008 to 2012, respectively. It should be noted that Ecoinvent assumes a sulphur content of 300 ppm resulting in an emission factor of 0.6 g/kg. This highlights the need to update the Ecoinvent v3 database.

Secondly, the sulphur hexafluoride (SF_6) emissions to air produced during conversion of electricity at traction substations have been determined using the electricity consumption. A SF_6 emission factor of 4.40×10^{-5} g/kWh electricity has been used following Spielmann et al. (2007). Finally, in order to estimate the emissions to soil of iron from abrasion of brake linings, wheels, rails and overhead contact lines, the value from Ecoinvent has been taken equal to 1.78×10^{-5} kg/tkm of iron emitted to soil. Since emissions to soil are not related to energy consumption, the same value is maintained every year.

Table 3.5 presents the direct emissions of rail freight transport in Belgium using the Belgian traction mix of diesel and electric traction showed in Figure 3.2. Moreover, the reference process of Ecoinvent v3 database "Transport, freight train {BE}| processing | Alloc Rec, U" is used as reference values.

Table 3.5. Direct emissions (g/tkm) of rail freight transport (Belgian traction mix of diesel and electric traction) in Belgium

Rail transport (Belgian traction mix) (g/tkm)	2006	2007	2008	2009	2010	2011	2012	Ecoinvent v3[1] 2014
CO_2	12.62	12.08	11.95	9.99	9.25	7.23	6.55	11.55
SO_2	1.93×10^{-4}	6.91×10^{-5}	6.08×10^{-5}	5.08×10^{-5}	4.70×10^{-5}	3.68×10^{-5}	3.33×10^{-5}	2.20×10^{-3}
Cd	4.01×10^{-8}	3.84×10^{-8}	3.80×10^{-8}	3.17×10^{-8}	2.94×10^{-8}	2.30×10^{-8}	2.08×10^{-8}	3.67×10^{-8}
Cu	6.82×10^{-6}	6.53×10^{-6}	6.46×10^{-6}	5.40×10^{-6}	5.00×10^{-6}	3.91×10^{-6}	3.54×10^{-6}	6.24×10^{-6}
Cr	2.01×10^{-7}	1.92×10^{-7}	1.90×10^{-7}	1.59×10^{-7}	1.47×10^{-7}	1.15×10^{-7}	1.04×10^{-7}	1.84×10^{-7}
Ni	2.81×10^{-7}	2.69×10^{-7}	2.66×10^{-7}	2.22×10^{-7}	2.06×10^{-7}	1.61×10^{-7}	1.46×10^{-7}	2.57×10^{-7}
Se	4.01×10^{-8}	3.84×10^{-8}	3.80×10^{-8}	3.17×10^{-8}	2.94×10^{-8}	2.30×10^{-8}	2.08×10^{-8}	3.67×10^{-8}
Zn	4.01×10^{-6}	3.84×10^{-6}	3.80×10^{-6}	3.17×10^{-6}	2.94×10^{-6}	2.30×10^{-6}	2.08×10^{-6}	3.67×10^{-6}
Pb	4.41×10^{-10}	4.22×10^{-10}	4.18×10^{-10}	3.49×10^{-10}	3.23×10^{-10}	2.53×10^{-10}	2.29×10^{-10}	4.04×10^{-10}
Hg	8.02×10^{-11}	7.68×10^{-11}	7.60×10^{-11}	6.35×10^{-11}	5.88×10^{-11}	4.60×10^{-11}	4.16×10^{-11}	7.32×10^{-11}
CO	6.34×10^{-2}	6.07×10^{-2}	6.00×10^{-2}	5.02×10^{-2}	4.65×10^{-2}	3.63×10^{-2}	3.29×10^{-2}	5.80×10^{-2}
NO_X	2.21×10^{-1}	2.11×10^{-1}	2.09×10^{-1}	1.75×10^{-1}	1.62×10^{-1}	1.26×10^{-1}	1.14×10^{-1}	2.02×10^{-1}
$PM_{2.5}$	5.14×10^{-3}	4.92×10^{-3}	4.86×10^{-3}	4.06×10^{-3}	3.76×10^{-3}	2.94×10^{-3}	2.66×10^{-3}	4.71×10^{-3}
PM_{10}	2.20×10^{-4}	2.21×10^{-4}	2.09×10^{-4}	1.74×10^{-4}	1.61×10^{-4}	1.26×10^{-4}	1.14×10^{-4}	1.60×10^{-2}
PM_{10}[2]	1.55×10^{-2}							
$PM_{10} > PM > PM_{2.5}$	4.29×10^{-4}	4.11×10^{-4}	4.06×10^{-4}	3.40×10^{-4}	3.15×10^{-4}	2.46×10^{-4}	2.23×10^{-4}	7.07×10^{-3}
$PM_{10} > PM > PM_{2.5}$[2]	6.67×10^{-3}							
Methane	5.22×10^{-4}	4.99×10^{-4}	4.94×10^{-4}	4.13×10^{-4}	3.82×10^{-4}	2.99×10^{-4}	2.71×10^{-4}	4.77×10^{-4}
Toluene	1.60×10^{-4}	1.54×10^{-4}	1.52×10^{-4}	1.27×10^{-4}	1.18×10^{-4}	9.20×10^{-5}	8.33×10^{-5}	1.47×10^{-4}
Benzene	4.01×10^{-4}	3.84×10^{-4}	3.80×10^{-4}	3.17×10^{-4}	2.94×10^{-4}	2.30×10^{-4}	2.08×10^{-4}	3.67×10^{-4}
Xylene	1.60×10^{-4}	1.54×10^{-4}	1.52×10^{-4}	1.27×10^{-4}	1.18×10^{-4}	9.20×10^{-5}	8.33×10^{-5}	1.47×10^{-4}
NMVOC	2.03×10^{-2}	1.95×10^{-2}	1.93×10^{-2}	1.61×10^{-2}	1.49×10^{-2}	1.17×10^{-2}	1.06×10^{-2}	1.86×10^{-2}
NH_3	8.02×10^{-5}	7.68×10^{-5}	7.60×10^{-5}	6.35×10^{-5}	5.88×10^{-5}	4.60×10^{-5}	4.16×10^{-5}	7.32×10^{-5}
N_2O	4.01×10^{-4}	3.84×10^{-4}	3.80×10^{-4}	3.17×10^{-4}	2.94×10^{-4}	2.30×10^{-4}	2.08×10^{-4}	3.67×10^{-4}
SF_6 from electricity	5.05×10^{-6}	4.89×10^{-6}	5.24×10^{-6}	5.55×10^{-6}	4.46×10^{-6}	4.65×10^{-6}	4.50×10^{-6}	3.18×10^{-6}
Emissions to soil of Fe	1.78×10^{-2}							1.78×10^{-2}

[1]Source: Weidema et al., 2013; [2]Particles produced from wheel and rail abrasion

By comparing the direct emissions used in Ecoinvent v3 with the values obtained in our study, our results for Belgium show lower direct emissions since the year 2009. This is because the final diesel consumption from our study presents values lower than the value from Ecoinvent v3 since 2009 (see Figure 3.2).

As mentioned above, the emissions of SO_2 are dependent on the sulphur content in the diesel. Therefore, as Ecoinvent v3 considers a sulphur concentration of 300 ppm for the diesel used in rail freight transport, it presents higher SO_2 emissions than our results for Belgium. For this study, a sulphur content of 24 ppm, 9 ppm and 8 ppm have been considered for the years 2006, 2007 and the period from 2008 to 2012, respectively.

The SF_6 to air from electric traction are higher in our study than in Ecoinvent v3 as a result of the greater electric consumption considered in our study compared to Ecoinvent v3. Finally, the same emissions to soil of iron from abrasion of brake linings, wheels, rails and overhead contact lines extracted from the Ecoinvent v3 database has been used in our study.

Table 3.6 presents the direct emissions of diesel trains including shunting activity in Belgium using the diesel consumption showed in Table 3.2.

Table 3.6. Direct emissions (g/tkm) of diesel trains (including shunting activity) in Belgium

Diesel trains (including shunting activity) (g/tkm)	2006	2007	2008	2009	2010	2011	2012
CO_2	53.33	50.34	54.82	59.10	55.90	44.66	47.79
SO_2	8.14×10^{-4}	2.88×10^{-4}	2.79×10^{-4}	3.01×10^{-4}	2.84×10^{-4}	2.27×10^{-4}	2.43×10^{-4}
Cd	1.70×10^{-7}	1.60×10^{-7}	1.74×10^{-7}	1.88×10^{-7}	1.78×10^{-7}	1.42×10^{-7}	1.52×10^{-7}
Cu	2.88×10^{-5}	2.72×10^{-5}	2.96×10^{-5}	3.19×10^{-5}	3.02×10^{-5}	2.41×10^{-5}	2.58×10^{-5}
Cr	8.48×10^{-7}	8.00×10^{-7}	8.71×10^{-7}	9.39×10^{-7}	8.88×10^{-7}	7.10×10^{-7}	7.60×10^{-7}
Ni	1.19×10^{-6}	1.12×10^{-6}	1.22×10^{-6}	1.31×10^{-6}	1.24×10^{-6}	9.94×10^{-7}	1.06×10^{-6}
Se	1.70×10^{-7}	1.60×10^{-7}	1.74×10^{-7}	1.88×10^{-7}	1.78×10^{-7}	1.42×10^{-7}	1.52×10^{-7}
Zn	1.70×10^{-5}	1.60×10^{-5}	1.74×10^{-5}	1.88×10^{-5}	1.78×10^{-5}	1.42×10^{-5}	1.52×10^{-5}
Pb	1.86×10^{-9}	1.76×10^{-9}	1.92×10^{-9}	2.07×10^{-9}	1.95×10^{-9}	1.56×10^{-9}	1.67×10^{-9}
Hg	3.39×10^{-10}	3.20×10^{-10}	3.49×10^{-10}	3.76×10^{-10}	3.55×10^{-10}	2.84×10^{-10}	3.04×10^{-10}
CO	2.68×10^{-1}	2.53×10^{-1}	2.75×10^{-1}	2.97×10^{-1}	2.81×10^{-1}	2.24×10^{-1}	2.40×10^{-1}
NO_X	9.32×10^{-1}	8.80×10^{-1}	9.58×10^{-1}	1.03	9.77×10^{-1}	7.81×10^{-1}	8.36×10^{-1}
$PM_{2.5}$	2.17×10^{-2}	2.05×10^{-2}	2.23×10^{-2}	2.40×10^{-2}	2.27×10^{-2}	1.82×10^{-2}	1.94×10^{-2}
PM_{10}	7.73×10^{-4}	7.23×10^{-4}	7.85×10^{-4}	8.10×10^{-4}	7.50×10^{-4}	5.49×10^{-4}	5.62×10^{-4}
PM_{10}[1]	1.55×10^{-2}						
$PM_{10} > PM > PM_{2.5}$	1.51×10^{-3}	1.41×10^{-3}	1.53×10^{-3}	1.58×10^{-3}	1.46×10^{-3}	1.07×10^{-3}	1.09×10^{-3}
$PM_{10} > PM > PM_{2.5}$[1]	6.67×10^{-3}						
Methane	2.20×10^{-3}	2.08×10^{-3}	2.27×10^{-3}	2.44×10^{-3}	2.31×10^{-3}	1.85×10^{-3}	1.97×10^{-3}
Toluene	6.78×10^{-4}	6.40×10^{-4}	6.97×10^{-4}	7.51×10^{-4}	7.11×10^{-4}	5.68×10^{-4}	6.08×10^{-4}
Benzene	1.70×10^{-3}	1.60×10^{-3}	1.74×10^{-3}	1.88×10^{-3}	1.78×10^{-3}	1.42×10^{-3}	1.52×10^{-3}
Xylene	6.78×10^{-4}	6.40×10^{-4}	6.97×10^{-4}	7.51×10^{-4}	7.11×10^{-4}	5.68×10^{-4}	6.08×10^{-4}
NMVOC	8.59×10^{-2}	8.11×10^{-2}	8.84×10^{-2}	9.52×10^{-2}	9.01×10^{-2}	7.20×10^{-2}	7.70×10^{-2}
NH_3	3.39×10^{-4}	3.20×10^{-4}	3.49×10^{-4}	3.76×10^{-4}	3.55×10^{-4}	2.84×10^{-4}	3.04×10^{-4}
N_2O	1.70×10^{-3}	1.60×10^{-3}	1.74×10^{-3}	1.88×10^{-3}	1.78×10^{-3}	1.42×10^{-3}	1.52×10^{-3}
Emissions to soil of Fe	1.78×10^{-2}						

[1]Particles produced from wheel and rail abrasion

Table 3.7 presents the direct emissions of electric trains in Belgium using the electricity consumption showed in Table 3.2. The only direct emissions produced by electric locomotives are the direct emissions from abrasion of brake linings, wheels and rails. Moreover, it has been considered as direct emissions the SF_6 emissions to air during conversion of electricity at traction substations.

Table 3.7. Direct emissions (g/tkm) of electric trains in Belgium

Electric trains (g/tkm)	2006	2007	2008	2009	2010	2011	2012
SF_6	6.62×10^{-6}	6.44×10^{-6}	6.71×10^{-6}	6.68×10^{-6}	5.35×10^{-6}	5.55×10^{-6}	5.21×10^{-6}
PM_{10}	1.55×10^{-2}						
PM_{10} > PM > $PM_{2.5}$	6.67×10^{-3}						
Emissions to soil of Fe	1.78×10^{-2}						

3.2.3. Electricity supply mix of Belgium

In order to analyse the environmental sustainability of the rail freight transport using the LCA methodology, the overall chain of the energy carrier has to be considered. For electric trains, to adjust as closely as possible the environmental impacts related to the yearly electricity consumption, and since the electricity supply mix varies over the years, our LCA study uses the electricity supply mix in Belgium corresponding to the appropriate year. We consider the environmental impacts related to electricity from the raw materials extraction (coal, oil, gas or uranium for example) and its transport to the power plant, continuing with electricity production at the power plant (including its construction and disposal) and ending with the electricity distribution (including transforming and cable loses) to the traction unit. The Belgian high voltage network has distribution losses of 5% (The World Bank, 2017) and the railway network has transmission losses of 7% (Infrabel, 2014).

As shown in Figure 3.3, the domestic production mix and the supply mix of electricity have been distinguished. The domestic production mix is the country specific production without taking into account exports or imports of electricity, and the supply mix is the domestic production including exports and imports of electricity. Therefore, the electricity supply mix of a country have a different energy split than the domestic production, because the different energy split of the exporting countries. Analogously to Belgium, the electricity imports from The Netherlands, France and Luxembourg have been modelled considering the supply mix of the exporting countries.

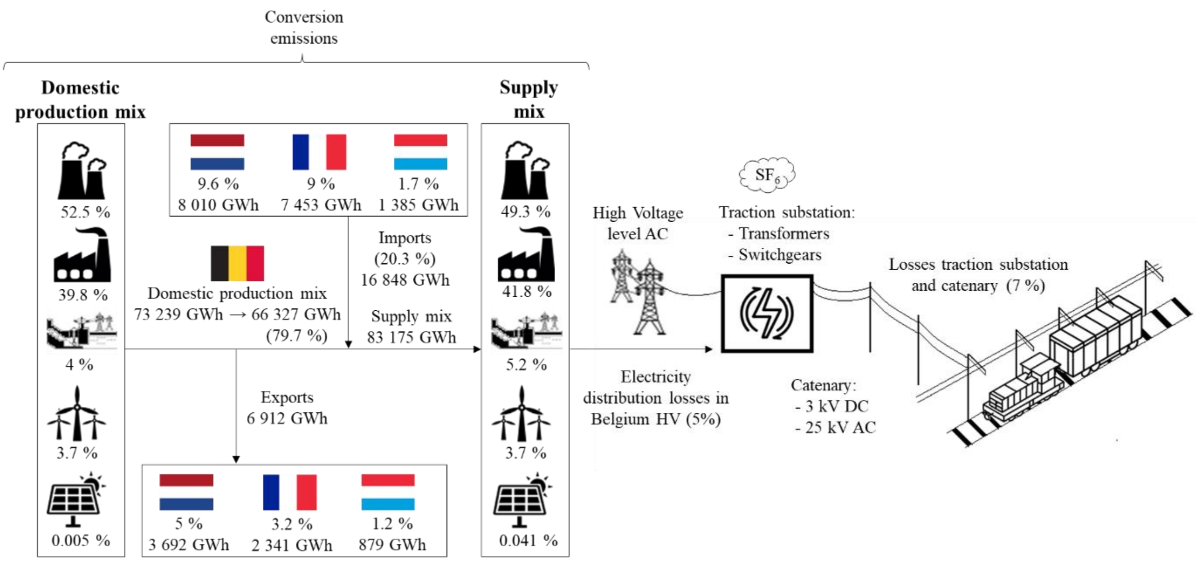


Figure 3.3. Belgian electricity production system and distribution to rail electric system in the year 2012. Sources: Eurostat statistics, 2017; Infrabel, 2014

The electricity supply mix for every year has been calculated using the domestic production of Belgium and exports and imports of electricity according to Eurostat data, which allows distinguishing between autoproducers of electricity (which generate electricity for their own use) and main activity producers, which generates electricity and transfer it through the high voltage network. Therefore, only the electricity generated by main activity producers can be used by rail transport, since the rail network uses high voltage electricity. Moreover, It has also been included the production of 3 GWh and 3.8 GWh of solar energy by Infrabel in the years 2011 and 2012, respectively.

In order to facilitate the understanding of the methodology used to calculate the supply mix of Belgium, we will take the year 2012 as an example. According to the Eurostat statistics nuclear power was responsible for 52.5% (38 464 GWh) of the total Belgian domestic production mix (73 239 GWh), representing the main energy source. Combustible fuels (i.e. coal, natural gas, oil and renewables and wastes) accounted for 39.8% (29 136 GWh), hydroelectric for 4% (2 943 GWh), wind for 3.7% (2 692 GWh) and other energies but mainly solar for 0.005% (4 GWh). A part (6 912 GWh) of the Belgian domestic production mix was exported to The Netherlands (3 692 GWh), to France (2 341 GWh) and to Luxembourg (879 GWh). Moreover, an import of electricity of 16 848 GWh (representing the 20.3% of the Belgian supply mix) from The Netherlands (8 010 GWh and 9.6% of the Belgian supply mix), from France (7 453 GWh and 9% of the Belgian supply mix) and from Luxembourg (1 385 GWh and 1.7% of the Belgian supply mix) was performed at the same time.

As mentioned above, to calculate the supply mix, the electricity imports from The Netherlands, France and Luxembourg have been modelled considering the supply mix of the exporting countries. For this purpose the energy split of the exporting countries (i.e. The Netherlands, France and Luxembourg) has been modelled in the same way as Belgium. Thus, first domestic production minus exports has been modelled and then imports from other countries have been added. Table 3.8 shows the domestic production mix of Belgium, The Netherlands, France and Luxembourg. However, it should be noted that the electricity mix has been used in the final modelling.

Table 3.8. Domestic production mix of electricity in Belgium, France, The Netherlands and Luxembourg. Source: Eurostat statistics, 2017

2012	Belgium		The Netherlands		France		Luxembourg	
	GWh	Share	GWh	Share	GWh	Share	GWh	Share
Nuclear	38 464	52.5 %	3 741	5 %	404 880	77.1 %	0	-
Combustible Fuels[1]	29 136	39.8 %	67 451	89.5 %	37 266	7.1 %	2 342	50.8 %
Hydroelectric	2 943	4 %	104	0.1 %	66 987	12.8 %	2 194	47.6 %
Wind	2 692	3.7 %	4 060	5.4 %	14 029	2.7 %	77	1.7 %
Other, mainly solar	4	0.005 %	27	0.004 %	1 939	0.4 %	0	-
Total net domestic production	73 239	100 %	75 383	100 %	525 101	100 %	4 613	100 %

[1]Coal, natural gas, oil and renewables and wastes

The first column of Table 3.9 shows the Belgian domestic production minus exports. Based on the 66 327 GWh available, the new proportions of each source of energy have been calculated. Thus, taking the case of nuclear energy as an example, the 66 327 GWh available have been multiplied by 52.5% of energy supplied by nuclear power (see Table 3.8), resulting in 34 834 GWh. In a second step, the energy split of the electricity imported from France, The

Netherlands and Luxembourg has been calculated. Thus, taking the electricity imported from The Netherlands as an example, the 8 010 GWh imported have been multiplied by 5% of energy supplied by nuclear power in The Netherlands, resulting in 398 GWh. Finally, electricity imports distinguishing power source from every country have been added to the Belgian domestic production mix without exports. Therefore, taking the case of nuclear energy as an example, to the 34 834 GWh supplied by nuclear power has been added 398 GWh from The Netherlands and 5 747 GWh from France, resulting in 40 978 GWh of electricity from combustible fuels in the Belgian supply mix, representing the 49.3% of the total supply mix.

Table 3.9. Calculation process to obtain the Belgian supply mix. Source: Eurostat statistics, 2017

Year 2012 (GWh)	Belgian domestic production minus exports	Belgian imports from			Belgian supply mix	
		The Netherlands	France	Luxembourg		
Nuclear	34 834	398	5 747	0	40 978	49.3 %
Combustible Fuels[1]	26 386	7 167	529	703	34 786	41.8 %
Hydroelectric	2 665	11	951	659	4 286	5.2 %
Wind	2 438	431	199	23	3 092	3.7 %
Other, mainly solar	4	3	28	0	34	0.041 %
Total	66 327	8 010	7 453	1 385	83 175	100 %

[1]Coal, natural gas, oil and renewables and wastes

Table 3.10 presents the energy split used in our study, which consist of the domestic production mix (taking into account only the electricity generated by main activity producer) minus exports, the electricity imported from France, The Netherlands and Luxembourg and the production of solar energy by Infrabel in the years 2011 and 2012.

Table 3.10. Electricity supply mix in Belgium. Source: Eurostat statistics, 2017

Energy source (%)	2006	2007	2008	2009	2010	2011	2012
Nuclear, pressure water reactor	43.08	44.83	43.93	46.71	44.78	47.51	41.88
Natural gas	23.26	24.12	23.34	26.31	25.88	22.19	22.18
Hard coal	5.24	5.43	5.25	5.92	5.82	4.99	4.99
Oil	0.38	0.40	0.38	0.43	0.43	0.37	0.37
Treatment blast furnace gas	1.53	1.58	1.53	1.72	1.70	1.45	1.45
Treatment of coal gas	0.07	0.07	0.07	0.08	0.08	0.06	0.06
Hydro, pumped storage	1.23	1.26	1.36	1.48	1.32	1.26	1.41
Hydro, run-of-river	1.57	1.63	1.77	1.81	1.61	1.46	1.79
Wind, <1MW turbine, onshore	0.01	0.01	0.02	0.03	0.04	0.07	0.09
Wind, >3MW turbine, onshore	0.03	0.05	0.06	0.10	0.12	0.23	0.29
Wind, 1-3MW turbine, onshore	0.29	0.40	0.53	0.85	1.05	1.98	2.47
Wind, 1-3MW turbine, offshore	0.01	0.01	0.02	0.03	0.04	0.07	0.09
Co-generation, biogas	0.45	0.46	0.45	0.50	0.50	0.43	0.43
Co-generation, wood chips	2.35	2.43	2.35	2.65	2.61	2.24	2.24
Imports from France	11.72	9.27	8.18	2.19	3.58	8.50	8.96
Imports from Luxembourg	2.70	2.28	1.80	2.24	2.09	1.82	1.67
Imports from The Netherlands	6.10	5.76	8.96	6.93	8.36	5.37	9.63
Infrabel (solar energy)	0	0	0	0	0	0.003	0.004

The process “Electricity, high voltage {BE}| market for | Alloc Rec, U” from Ecoinvent v3 database (Weidema et al., 2013) has been taken as a model to translate the data from Eurostat on energy sources to the technologies used in the electricity production.

The rail emissions produced by electric traction are calculated using the average electricity split production per year and country (EcoTransIT, 2008). However, these emission factors change as result of a variation in the energy split of the country. For example, Messagie et al. (2014b) estimates an average emission factor for the Belgian electricity production in the year 2011 of 184 g CO_2eq/kWh. This value varies from a minimum of 102 g CO_2eq/kWh to a maximum of 262 g CO_2eq/kWh throughout the year. The contribution of each energy source varies every day, reaching even day/night variations. For instance, nuclear plants do maintenance in February, decreasing the contribution of nuclear energy to the domestic production mix. Furthermore, increased imports of electricity is required, entailing as mentioned above an increase in losses because electricity has to circulate longer distances. Overall, emission factors for electricity production varies widely.

Table 3.11 presents the most relevant emission factors for the electricity used by electric trains in Belgium from the period 2006 to 2012. These values have been calculated using the electricity supply mix in Belgium from Table 3.10. EcoTransIT considers an average emission factors for the Belgian electricity supply for rail transport of 253 g CO_2/kWh for 2005 (EcoTransIT, 2008), 392 g CO_2eq/kWh for 2007 (EcoTransIT, 2014) and 234 g CO_2eq/kWh for 2013 (EcoTransIT, 2016). By comparing the values used in EcoTransIT (2008, 2014, 2016) with the emission factors on g CO_2eq/kWh obtained in our study, our results for Belgium show higher emission factors than EcoTransIT for the years 2005 and 2013 but lower for 2007.

Table 3.11. Emission factors per kWh of the electricity supply mix in Belgium used by railway transport in our study

	2006	2007	2008	2009	2010	2011	2012
g CO_2eq/kWh	304	306	315	328	334	281	314
g NO_X/kWh	0.353	0.355	0.360	0.376	0.381	0.330	0.378
g SO_2/kWh	0.343	0.343	0.336	0.350	0.352	0.320	0.382
g NMVOC/kWh	0.029	0.028	0.028	0.029	0.029	0.027	0.118
g PM_{10}/kWh	0.098	0.096	0.099	0.097	0.098	0.093	0.163

Regarding other pollutants, EcoTransIT (2008) considers an average emission factors for the Belgian electricity in 2005 of 0.49 g NO_X/kWh, 0.6 g SO_2/kWh, 0.051 g NMVOC/kWh and 0.045 g PM_{10}/kWh. By comparing the values used in EcoTransIT (2008) with the emission factors obtained in our study, our results for the Belgian electricity present lower values in all the emission factors except for PM_{10}. Moreover, EcoTransIT (2014) considers an average emission factors in 2007 of 0.77 g NO_X/kWh, 1.321 g SO_2/kWh, 0.054 g NMVOC/kWh and 0.104 g PM_{10}/kWh. By comparing the values from EcoTransIT (2014) with the emission factors obtained in our study for the year 2007, our results show lower emission factors with 0.355 g NO_X/kWh, 0.343 g SO_2/kWh, 0.028 g NMVOC/kWh and 0.096 g PM_{10}/kWh. Furthermore, EcoTransIT (2016) considers an average emission factors in 2013 of 0.428 g NO_X/kWh, 0.212 g SO_2/kWh, 0.022 g NMHC/kWh and 0.068 g PM_{10}/kWh. By comparing the values used in EcoTransIT (2016) with the emission factors obtained in our study, our results for Belgium present lower values for NO_X but higher for SO_2, NMVOC and PM_{10}.

3.2.4. Diesel refining

In order to obtain diesel emission factors with an LCA approach, the overall chain of the diesel energy carrier has to be considered. The energy chain of fuel production comprises the crude oil material extraction and its transport to the refineries, the oil refining process and the diesel distribution to filling station.

Belgium is fully dependent on crude oil imports, which are mainly performed using the Rotterdam-Antwerp pipeline (RAPL) and oil tankers (see Figure 3.4). Meanwhile, Belgium is a net exporter of refined products. The only four refineries operate in the petrochemical cluster of the port of Antwerp (Total, ExxonMobil, IBR and ATPC). The refinery products are stored in tanks, and then transported by pipeline (mainly the Central European Pipeline System), railway, IWW or road to the over 40 oil storage facilities in Belgium (IEA, 2014). Refinery products such as gasoline and diesel can be delivered directly to refuelling stations. B-Logistics uses conventional road-transport diesel. Refuelling facilities for B-Logistics are the ports of Zeebrugge, Ghent, Antwerp, Liège and Charleroi. There are also suppliers that bring fuel to the tracks in tanker trucks.

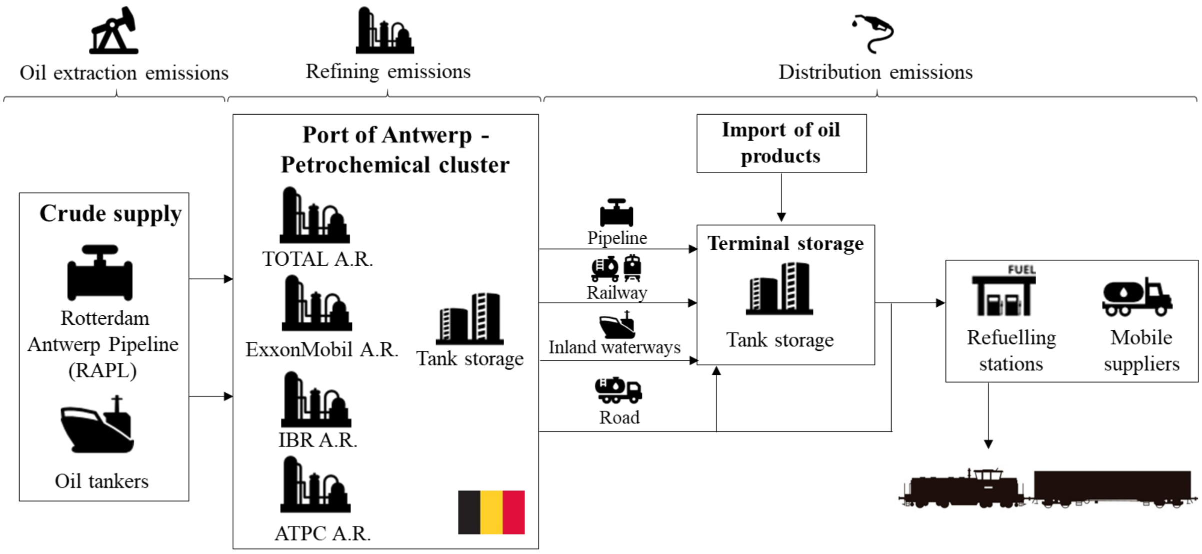


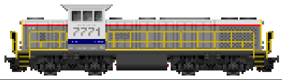
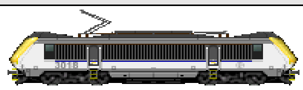
Figure 3.4. Graphic representation of Well-To-Tank stage (refining and distribution of diesel) in Belgium for diesel rail transport. Source: Based on Trozzi and Klimont, 2013

3.3. Rail equipment

For the manufacturing, maintenance and disposal of locomotives and wagons, instead of collecting new data specific to Belgium such as material composition or energy consumption in maintenance work for example, the Ecoinvent v3 database has been used. Unfortunately, the information related to these aspects was unavailable. Therefore, the Ecoinvent v3 database has been taken as representative for Belgium.

Table 3.12 presents the number of locomotives used by B-Logistics (LINEAS) in the years 2015 and 2016. Since no data is available for the period from 2006 to 2012, the population of locomotives of the year 2015 has been used. Therefore, it has been considered 201 locomotives for freight transport, being 86 electric locomotives and 115 diesel locomotives. The population of goods wagons have been extracted from Statistics Belgium (2017). Since the number of wagons used in diesel and electric traction separately is not available, the same wagon demand in both energy tractions have been used.

Table 3.12. Locomotives of B-Logistics (LINEAS)

Type locomotive			2015	2016	Manufacturer	Energy consumption	Power
Diesel locomotives	**Class 57**		5	0	Vossloh	-	-
	Class 66		0	1	General Electrics	5 L/km	2.5 MW
	HLD 77 / 78		110	110	Siemens - Vossloh	25 L/hour[1] or 2.5 L/km	1.1 MW
	Total diesel locomotives		115	111	-	-	-
Electric locomotives	**HLE 13**		45	42	Alstom	16 Wh/tkm[2]	5.2 MW
	HLE 21		6	0	BN/ACEC	-	3.3 MW
	HLE 28		30	33	Bombardier	13 Wh/tkm	5.6 MW
	HLE 29		5	7	Bombardier	13 Wh/tkm	5.6 MW
	Total electric locomotives		86	82	-	-	-
Total locomotives			201	193	-	-	-

[1]Energy consumption for shunting activity; [2]Estimated by Infrabel, the actual consumption can be lower (the eco-driving project allows saving between 15 and 30% of energy)

As shown in Equation (2), the locomotive and wagons demand has been determined on the basis of the total annual transport performance of freight transport (i.e. tonnes-kilometres, see Table 3.1), the number of locomotives and goods transport wagons used in Belgium by each energy traction and a life span of 40 years for both locomotives and wagons. If we take year 2012 as an example, we consider that the 5 220 million tkm of rail freight were moved using 201 locomotives with a life span of 40 years, resulting in 9.63×10^{-10} locomotives per tkm. In the same way for the wagons, 11 612 goods wagons were used in 2012, resulting in a goods wagon demand of 5.56×10^{-8} wagons per tkm.

$$Vehicle\ demand\ \left(\frac{unit}{tkm}\right) = \frac{1}{\left(\frac{tkm}{population\ vehicle}\right) \times life\ span\ (year)} \qquad (2)$$

The rail freight traction share (see Figure 3.2) has been used to calculate the rail freight moved by electric and diesel traction, enabling to determine the locomotive demand of electric and diesel trains separately. For 2012, 86.3% of the 5 220 million tkm of rail freight in Belgium were moved with electric traction, resulting in 4 505 million tkm. It has been considered 86 electric locomotives of B-Logistics and a life span of 40 years for every year, therefore the locomotive demand for electric trains was 4.77×10^{-10} unit/tkm. Similarly, 13.7% of the 5 220 million tkm of rail freight in Belgium were moved with diesel traction, resulting in 715 million tkm. It has been considered 115 diesel locomotives of B-Logistics (including the locomotives for shunting activity) and a life span of 40 years for every year, therefore the locomotive demand for diesel trains was 4.02×10^{-9} unit/tkm. Note that all the environmental interventions are referred to one vehicle (unit).

Table 3.13 presents the values of goods wagon and locomotive demand of rail freight transport (i.e. Belgian traction mix), electric trains and diesel trains calculated in our study from the period 2006 to 2012. Moreover, the reference process of Ecoinvent v3 database "Transport, freight train {BE}| processing | Alloc Rec, U" is used as reference values. In the case of Ecoinvent v3 database, it considers a population of 19 791 goods transport wagons and 307 locomotives for freight transport in Switzerland in the year 2000, resulting in a goods wagon demand of 4.59×10^{-8} wagons per tkm and 7.11×10^{-10} locomotives per tkm. By comparing the values obtained in our study with the values from Ecoinvent v3 database, our results for Belgium show similar wagon and locomotive demands.

Table 3.13. Locomotive and goods wagon demand for rail freight transport in Belgium

	2006	2007	2008	2009	2010	2011	2012	Ecoinvent v3[2]
Goods transport wagons[1]	11 003	10 616	9 454	11 612	11 612	11 612	11 612	19 791
Wagons demand (unit/tkm)	3.26×10^{-8}	3.26×10^{-8}	3.00×10^{-8}	5.34×10^{-8}	5.07×10^{-8}	4.91×10^{-8}	5.56×10^{-8}	4.59×10^{-8}
Locomotive demand (unit/tkm)	5.95×10^{-10}	6.17×10^{-10}	6.38×10^{-10}	9.24×10^{-10}	8.77×10^{-10}	8.50×10^{-10}	9.63×10^{-10}	7.11×10^{-10}
Electric locomotive demand (unit/tkm)	3.34×10^{-10}	3.47×10^{-10}	3.49×10^{-10}	4.76×10^{-10}	4.50×10^{-10}	4.34×10^{-10}	4.77×10^{-10}	-
Diesel locomotive demand (unit/tkm)	1.44×10^{-9}	1.47×10^{-9}	1.67×10^{-9}	3.13×10^{-9}	3.03×10^{-9}	3.00×10^{-9}	4.02×10^{-9}	-

[1]Source: Statistics Belgium, 2017; [2]Source: Weidema et al., 2013

3.4.Railway infrastructure

For the sub-system rail infrastructure, a detailed study of the life cycle phases of construction, maintenance and disposal of infrastructure has been conducted. According to Eurostat, the Belgian railway network is classified in both one track railway lines and two or more tracks railway lines. All the processes included in the sub-system rail infrastructure have been calculated using a two tracks line as reference. As shown in Table 3.14, the length of one track lines has been converted in two tracks lines, and adding the length of two or more tracks lines, the total length of the Belgian railway network in two track lines has been obtained. The values of one and two tracks lines for years 2011 and 2012 have been calculated using linear interpolation.

Table 3.14. Length of railway lines in Belgium (km). Source: Eurostat statistics, 2016

	2005	2006	2007	2008	2009	2010[1]	2011	2012
Total standard gauge	3 544	3 560	3 568	3 513	3 578	3 582	-	-
One track railway lines	820	825	828	744	796	722	718	713
Two tracks or more railway lines	2 724	2 735	2 740	2 769	2 782	2 860	2 876	2 891
Total two-ways tracks calculated	3 134	3 148	3 154	3 141	3 180	3 221	3 235	3 248

[1]Source: Statistics Belgium, 2017

3.4.1. Allocation factors of the railway infrastructure between freight and passenger transport

Since the railway infrastructure is shared between passenger and freight transport, an allocation of the environmental impacts related to the construction, maintenance and disposal of infrastructure has to be performed. On the one hand, the allocation of construction and disposal of the rail infrastructure has been calculated using the transport performance (tkm) and operating performance (Gtkm, i.e. transport of one tonne of hauled vehicles and content, thus including the weight of the wagons, over a distance of one kilometre) for freight and passenger transport in Belgium. It should be noted that data on traction performance (GGtkm, i.e. transport of one tonne of railway vehicle, thus including the weight of the load, wagons and locomotive, over a distance of one kilometre) is not available. On the other hand, the allocation of operation and maintenance of the railway infrastructure has been calculated using the transport performance (tkm) and kilometric performance (train-km, i.e. the movement of a train over a distance of one kilometre) for freight and passengers transport in Belgium.

Table 3.15 shows data on transport, operating and kilometric performance for freight and passenger transport in Belgium. The values of operating performance for the years 2011 and 2012 have been obtained considering that the variation of Gtkm is approximately the same as the variation of tkm or pkm. Moreover, the values of kilometric performance for the years 2010 and 2012 have been calculated using linear interpolation (in red in Table 3.15).

Table 3.15. Goods and passenger transport in Belgium. Sources: Eurostat statistics, 2017; Statistics Belgium, 2017; SNCB, 2009, 2013, 2015; UIC, 2010

		2005	2006	2007	2008	2009	2010	2011	2012
Transport performance (million tkm and pkm)	**Freight**	8 130	8 442	8 148	7 882	5 439	5 729	5 913	5 220
	Passenger	9 150	9 607	9 932	10 403	10 426	10 609	10 848	10 857
Operating performance (million Gtkm)	**Total**	46 664	46 381	45 940	45 663	40 595	42 835	43 921	42 417
	Freight	20 363	20 014	18 987	18 794	12 995	12 645	13 051	11 522
	Passenger	25 544	25 664	26 308	26 287	27 001	30 190	30 870	30 896
	Other trains[1]	757	703	645	582	599	-	-	-
Kilometric performance (million train-km)	**Total**	97	96	97	96	93	93	95	94
	Freight	16	15	15	15	12	13	12	12
	Passenger	77	78	80	80	81	81	82	83
	Other trains[1]	4	3	3	3	3	-	-	-

[1]Trains moving only for the requirements of the railway enterprise

As shown in Equation (3), the allocation factors of infrastructure construction and disposal for the Belgian railway infrastructure have been calculated in three steps. Firstly, the length of the Belgian railway network in two tracks lines has been divided by the total operating performance (Gtkm) of freight and passenger transport. Secondly, the ratio Gtkm/tkm for freight transport and Gtkm/pkm for passenger transport has been obtained. Thirdly, the values determined in the first and second step have been multiplied to obtain the rail infrastructure demand per tkm referred to one meter and year (m×a) for freight transport ((m×a)/tkm) and passenger transport ((m×a)/pkm). Therefore, the allocation principle for the construction and disposal of rail infrastructure is the train weigh (Spielmann et al., 2007).

$$\boxed{Infrastructure\ construction\ \left(\frac{m \times a}{tkm}\right) = \frac{Length\ railway\ (m)}{Total\ Gtkm\ (freight + passenger)} \times \frac{Gtkm\ freight}{tkm\ freight}} \quad (3)$$

The allocation factors of infrastructure maintenance and operation have been calculated using the same methodology (see Equation (4)), but instead of the total operating performance has been used the total kilometric performance (train-km), and the ratios Gtkm/tkm and Gtkm/pkm have been replaced by the ratios train-km/tkm for freight transport and train-tkm/pkm for passenger transport. Thus, the allocation principle for the maintenance and operation of rail infrastructure is the temporal occupation of the infrastructure (Spielmann et al., 2007).

$$\boxed{Infrastructure\ maintenance\ \left(\frac{m \times a}{tkm}\right) = \frac{Length\ railway\ (m)}{Total\ train{-}km\ (freight + passenger)} \times \frac{train{-}km\ freight}{tkm\ freight}} \quad (4)$$

Table 3.16 presents the different demand factors for the Belgian railway infrastructure. The demand factors of infrastructure construction and maintenance are the same for rail freight transport (i.e. Belgian traction mix), electric trains and diesel trains.

Table 3.16. Railway infrastructure demand for rail transport in Belgium

		2005	2006	2007	2008	2009	2010	2011	2012
Construction and disposal	**Freight ((m×a)/tkm)**	1.68×10^{-4}	1.61×10^{-4}	1.60×10^{-4}	1.64×10^{-4}	1.87×10^{-4}	1.66×10^{-4}	1.63×10^{-4}	1.69×10^{-4}
	Passengers ((m×a)/pkm)	1.87×10^{-4}	1.81×10^{-4}	1.82×10^{-4}	1.74×10^{-4}	2.03×10^{-4}	2.14×10^{-4}	2.10×10^{-4}	2.18×10^{-4}
Operation and maintenance	**Freight ((m×a)/tkm)**	6.24×10^{-5}	5.73×10^{-5}	6.01×10^{-5}	6.18×10^{-5}	7.31×10^{-5}	7.77×10^{-5}	7.12×10^{-5}	7.74×10^{-5}
	Passengers ((m×a)/pkm)	2.74×10^{-4}	2.66×10^{-4}	2.60×10^{-4}	2.51×10^{-4}	2.64×10^{-4}	2.65×10^{-4}	2.59×10^{-4}	2.62×10^{-4}

Since the main use of the Belgian railway infrastructure is passenger transport, rail freight transport presents a lower railway infrastructure demand than passenger transport in both the construction and disposal of railway infrastructure and the operation and maintenance of railway infrastructure. It should be noted that the difference on railway infrastructure demand between passenger and freight transport is much greater in the operation and maintenance than in the construction and disposal of railway infrastructure. This is because passenger transport presents a more intensive use of the railway infrastructure (between five and seven times more than rail freight transport, see the values on kilometric performance in Table 3.15), but the transported mass of passenger and goods are more similar (see the values on operating performance in Table 3.15).

3.4.2. Life Cycle Inventory of the railway construction

A detailed analysis of the Belgian railway infrastructure has been carried out. As shown in Figure 3.5, the subsystem railway infrastructure includes the processes that are connected with the construction, maintenance and disposal of the railway infrastructure. The LCI of the Belgian railway infrastructure includes tunnels, bridges, track bedding, rails, sleepers, fastening system, switches and crossings, and the overhead contact system.

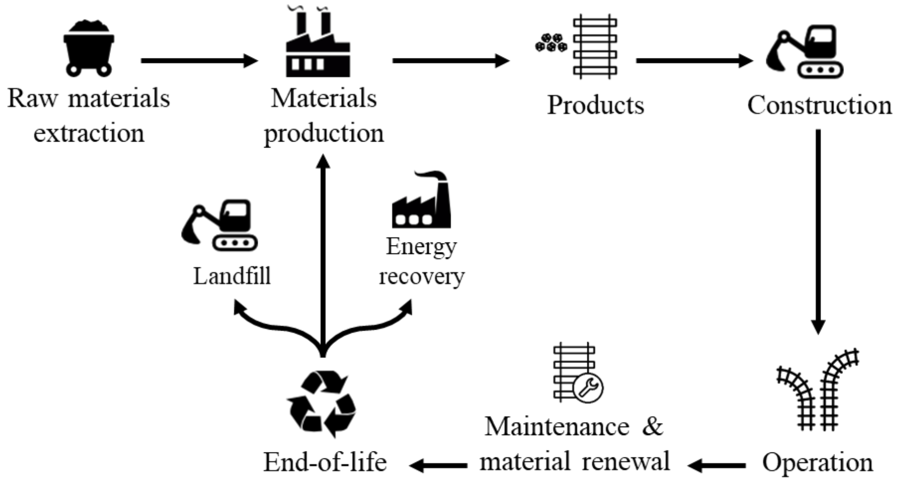


Figure 3.5. Life Cycle Assessment of the railway infrastructure

3.4.2.1. Tunnels and bridges

The material demand for the construction of tunnels and bridges has been calculated using data from Schmied and Mottschall (2013), which analyse the German railway infrastructure (see Table 3.17). Two types of tunnels have been distinguished with different material demand requirements. The mined tunnels are constructed by drilling and blasting or using tunnel boring machines, and the trenched tunnels are built through an open excavation, which is refilled once is completed. The difference in energy consumption between mined and trenched tunnels is the use of tunnel boring machines in the former (Schmied and Mottschall, 2013). Moreover, Table 3.17 shows the material demand for tunnel and bridge construction from Von Rozycki et al. (2003), which focus on the German high-speed rail infrastructure and has been used by Spielmann et al. (2007) to develop the rail freight transport processes in the Ecoinvent v3 database.

Table 3.17. Material consumed in the construction of an average German two-tracks railway tunnel and bridge

	German railway infrastructure[1]					German high-speed rail infrastructure[2]			
	Tunnel		Bridge			Tunnel		Bridge	
	Mined	Trenched	Viaducts	Concrete	Iron	Mined	Trenched	Rail glen	Railroad and roadway
Share of tunnel type	75%	25%	-	-	-	61%	29%	-	-
Life span (years)	60	60	60	60	60	100	100	100	50
Concrete (m³/m)	37. 2	49	31.6	14	-	44 t/m	71 t/m	55 t/m	89 t/m
Steel (t/m)	1.6	6.1	3.51	1.5	7.2	2.1	2.8	3	4.9
Excavation soil (m³/m)	127.9	300	26.17	5.234	5.234	270 t/m	700 t/m	-	-
Electricity (MWh/m)	2.2	0.5	-	-	-	-	-	-	-
Diesel (L/m)	140	100	8.4	6.1	6.1	-	-	-	-

[1]Source: Schmied and Mottschall, 2013; [2]Source: Von Rozycki et al., 2003

Tuchschmid et al. (2011) considered for the Belgian railway network in the year 2008 a share of 25% and 75% for trenched tunnels and mined tunnels, respectively. Since no data is available for Belgium, they used the same proportion as the German railway network, which is based in an assumption of Schmied and Mottschall (2013). Tuchschmid et al. (2011) use for the Belgian railway network a share of 26% for viaducts, 57% for concrete bridges and 17% for iron bridges. Table 3.18 presents the material demand for tunnel and bridge construction using the parameters of construction from Schmied and Mottschall (2013) and the reference values from Spielmann et al. (2007).

Table 3.18. Material demand for tunnel and bridge construction

	Belgium		Switzerland[2]	
	Tunnel	Bridge	Tunnel	Bridge
Concrete, high exacting ($m^3/(m×a)$)	0.669	0.27	0.261	0.306
Reinforcing steel (kg/(m×a))	45.417	49.86	24.5	36.8
Excavation soil (kg/(m×a))	2.849 $m^3/(m×a)$	0.178	4 850	-
Gravel, crushed (kg/(m×a))	583	-	583	-
Diesel (MJ/(m×a))[1]	77.9	4	135	-
Electricity (kWh/(m×a))	29.6	-	56.9	-

[1]Considering that the density of diesel is 0.84 kg/L and diesel net calories are 42.8 MJ/kg;
[2]Source: Spielmann et al., 2007

The material demand from tunnel and bridge construction in the Belgian railway network has been calculated considering the share of tunnels and bridges. The Belgian railway network has 132 tunnels and 4 800 bridges. The total length of tunnels is 95 km, which represents approximately 27 metres of tunnel per kilometre or 2.6 % of the Belgian railway network. Tuchschmid et al. (2011) considered for the Belgian railway network a share of 1.3% of tunnels in the year 2008. Since the total length of bridges is unavailable, it has been used a share of bridges for the Belgian railway network of 2.2% from Tuchschmid et al. (2011). Spielmann et al. (2007) used a share of 7% of tunnels and 3% of bridges for the Swiss railway network. Table 3.19 presents the material demand from tunnel and bridge construction in the Belgian railway network considering the share of tunnels and bridges, and the reference values from Spielmann et al. (2007).

Table 3.19. Material demand for tunnel and bridge construction considering the share of tunnels and bridges in the Belgian railway network

	Belgium		Switzerland[2]	
	Tunnel	Bridge	Tunnel	Bridge
Share in the railway network	2.6%	2.2%	7%	3%
Concrete, high exacting ($m^3/(m×a)$)	0.018	0.006	0.018	0.009
Reinforcing steel (kg/(m×a))	1.201	1.097	1.715	1.104
Excavation soil ($m^3/(m×a)$)	0.075	0.004	340 kg/(m×a)	-
Gravel, crushed (kg/(m×a))	15.419	-	41	-
Diesel (MJ/(m×a))[1]	2.060	0.088	9.45	-
Electricity (kWh/(m×a))	0.782	-	3.98	-

[1]Considering that the density of diesel is 0.84 kg/L and diesel net calories are 42.8 MJ/kg;
[2]Source: Spielmann et al., 2007

3.4.2.2. Track bedding, rails, sleepers and fastening system

The railway track foundation for a single track used in the Belgian railway network is composed on average for a single track of an upper base of 3 200 kg/m, a subbase of 3 550 kg/m and a subgrade of 7 100 kg/m. Considering a life span of 40 years, a material demand of 692.5 kg/(m×a) of gravel for a two-ways railway track is obtained. Only ballasted tracks have been considered in our study (see Figure 3.6).

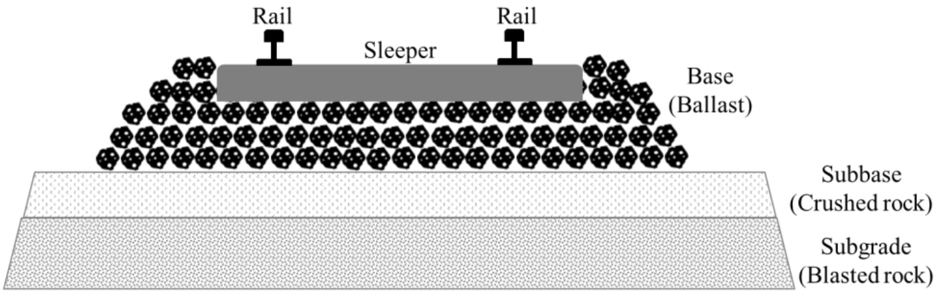


Figure 3.6. Example of a ballasted track

Two main types of rails profiles have been taken into account in our study, the rail 50E2 (50 kg/m) and the rail 60E1 (60 kg/m), with an average share in Belgium of 53% and 47%, respectively. Moreover, the use of three splice bars per km has been included (piece of steel that joins two rails, see Figure 3.7), considering the use of continuously welded rails of 300 meters long. The weight of the splice bars for the rails 50E2 and 60E1 is 13.9 kg/unit and 19 kg/unit, respectively. The theoretical threshold used at Infrabel to trigger the renewal of rails is 450 million tonnes for the rail 50E2 and 750 million tonnes for the rail 60E1, but it has been considered a life span of 30 years for the rails and splice bars. Therefore, the material demand for a two-ways railway track is 7.29 kg/(m×a) of steel from rails and 0.0072 kg/(m×a) of steel from splice bars, resulting in 7.3 kg/(m×a) of steel.

The distance between sleepers stated by Infrabel for the Belgian railway network in continuous welded rails 50E2 and 60E1 in main lines is 0.6 m, thus an average of 1.67 sleepers/m is used. For continuous welded rails 50E2 in side lines, the sleepers are installed at 0.75 m spacing, resulting in an average of 1.3 sleeper/m (Infrabel, 2007). The spacing of 0.6 m is similar to those of the main Swiss railway lines (Künniger and Richter, 1998) and the Swedish railway lines (Stripple and Uppenberg, 2010). Bolin and Smith (2013) describe a spacing between wooden and plastic composite sleepers of 0.495m, and for concrete sleepers of 0.61 m for the U.S. railway network.

According to a manufacturer of concrete sleepers for the Belgian railway network, concrete sleepers type M41 have a total weight of 294 kg, including 286.2 kg of concrete and 7.8 kg of steel reinforcement (PREFER, 2006). As shown in Table 3.20, Künniger and Richter (1998) describe the concrete sleepers used in the main Swiss railway lines made of 258 kg of concrete and 14 kg of reinforcement steel; Ueda et al. (1999) describe the use of concrete sleepers in the Japanese railway network made of 155 kg of concrete and 4.8 kg of reinforcing steel; Stripple and Uppenberg (2010) describe the use in a new constructed single-track railway in Sweden of concrete sleepers made of 250 kg of concrete and 6.1 kg of steel reinforcement and Bolin and Smith (2013) describe the use of concrete sleepers of 318 kg in U.S., including the reinforcing steel. As mentioned above, Ecoinvent v3 database takes the values from Von Rozycki et al. (2003), which performed a study of a high-speed railway track in Germany, considering a material use due to concrete sleepers of 990 t of concrete and 39 t of steel per rail track kilometre in a two-way line. If a distance between sleepers of 0.6 m (1.67 sleeper/m) is considered, it results in 297 kg of concrete and 11.7 kg of steel per sleeper. By comparing the concrete sleeper considered in our study, a greater material consumption is considered than Stripple and Uppenberg (2010), Ueda et al. (1999) and Künniger and Richter (1998) with the exception of the steel reinforcement used in the main Swiss railway lines. Bolin and Smith (2013) and the calculations made by von Rozycki et al. (2003) show highest material demand than our study.

Table 3.20. Comparison of material profile of sleepers from different sources

	Material	Belgium (kg/sleeper)	Switzerland[1] (kg/sleeper)	Japan[2] (kg/sleeper)	Sweden[3] (kg/sleeper)	U.S.[4] (kg/sleeper)	Germany[5] (2-way track)
Concrete sleeper	Concrete	286.2	258	155	250	318	990 t/km
	Steel	7.8	14	4.8	6.1		39 t/km
	Life span	40	35-45	50	-	40	30
Wooden sleeper	Wood	80	62	56-58	-	0.093-0.11 m³/sleeper	-
	Creosote	5.07	15.2	14	-	88 kg/m³	-
	Life span	25	24-30	15		35	-
Steel sleeper	Steel	70	91	55	-	-	-
	Life span	35	30-45	50	-	-	-

[1]Source: Künniger and Richter, 1998; [2]Source: Ueda et al., 1999; [3]Source: Stripple and Uppenberg, 2010; [4]Source: Bolin and Smith, 2013; [5]Source: Von Rozycki et al., 2003

The wooden sleepers used in the Belgian railway network are made of 80 kg of oak (*Quercus petraea* or *Quercus robur*) with a life span of 25 years. The use of beech is no longer permitted. The wood for manufacturing sleepers is produced in a framework of sustainable forest management certified by an independent body, such as the certifications FSC and PEFC for example (Infrabel, 2011). The wooden sleepers are dried and creosoted to preserve the wood in the Wondelgem workshop of Infrabel. The creosote required to protect the oak wood is 50 kg/m³ (IBGE, 2011). The wooden sleepers used by Infrabel have a rectangular cross-section in the Form E1 and E2 group 2 according to EN 13145, that is 150 mm high by 260 mm wide (British Standards, 2001) with a length fixed at 2 600 mm (Infrabel, 2011). Thus, the volume of a standard wooden sleeper is 0.1014 m³, resulting in a treatment with creosote of 5.07 kg per sleeper. By comparing with Künniger and Richter (1998), Ueda et al. (1999) and Bolin and Smith (2013), a lower quantity of creosote is considered in our study.

Infrabel uses several techniques to fix the rails to the sleepers. As shown in figure 3.7, the most representative elements of the fastening system have been identified for every technique, such as clips for attachment, bolts, screw spikes and base plates for wooden sleepers, and rubber pad for concrete sleepers.

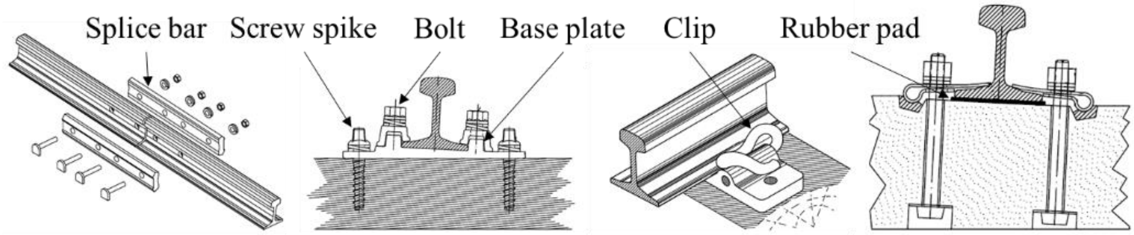


Figure 3.7. Elements of the fastening system and splice bar. Source: Infrabel, 2007

For concrete sleepers, six methods have been identified, and in the case of wooden sleepers, four and six methods have been identifies for main and side lines, respectively (Infrabel, 2007).

As shown in Table 3.21, the average amount of representative elements for concrete and wooden sleepers in main and side lines has been calculated.

Table 3.21. Material profile of some representative elements of the fastening system and average amount used in the Belgian railway network. Source: Infrabel, 2007

	Material	Weight (kg/unit)	Life span	Concrete sleeper (unit/sleeper)	Wooden sleeper	
					Main track (unit/sleeper)	Side track (unit/sleeper)
Screw spike	**Steel**	1.1	30-35	-	5	6.5
Clip	**Steel**	1	35-40	4	4.5	1
Bolt	**Steel**	0.3	30-35	4	1	1
Base plate	**Steel**	3.5	40	-	1.5	1.5
Rubber pad	**Rubber**	0.6	20-25	2	-	-

Table 3.22 shows the values of annual material demand from sleepers of main and side lines, including fastening system, in the Belgian railway network. It should be noted that our study does not include the manufacturing processes of sleepers or fastening system. As mentioned above, the Belgian railway network presents an average of 1.67 sleepers/m in main lines and 1.3 sleeper/m in side lines (Infrabel, 2007). Moreover, the Belgian railway network presented in the year 2010 a ratio between wooden and concrete sleepers in the main tracks of 21% and 79%, respectively. For side tracks, the rate was a 65% of wooden sleepers and a 35 % of concrete sleepers. In the switches, the distribution was a 95% of wooden sleepers and a 5% of concrete sleepers (UIC, 2013). The greater use of wooden sleepers in the switches is due to the flexibility of wooden sleepers to create custom-made sleepers (IBGE, 2011).

Table 3.22. Annual material demand from sleepers and fastening system of main and side lines in the Belgian railway network

Type	Material or element	Infrabel		Main lines					Side lines				
		kg / sleeper	life span	unit / sleeper	sleeper / m	kg/(m×a)	Rate	kg/(m×a)	unit / sleeper	sleeper / m	kg/(m×a)	Rate	kg/(m×a)
Sleeper Concrete M41	**Concrete**	286.2	40	-	1.67	11.95	79%	9.42	-	1.3	9.54	35%	3.34
	Steel	7.8		-		0.33		0.26	-		0.26		0.09
	Clip	1	35 – 40	4		0.19		0.15	4		0.15		0.05
	Bolt	0.3	30 – 35	4		0.07		0.05	4		0.05		0.02
	Rubber pad	0.6	20 - 25	2		0.10		0.08	2		0.08		0.03
Wooden sleeper	**Oak Wood**	80	25	-		5.34	21%	1.12	-		4.27	65%	2.77
	Creosote	5.07		-		0.34		0.07	-		0.27		0.18
	Screw spike	1.1	30 – 35	5		0.31		0.06	6.5		0.32		0.21
	Clip	1	35 – 40	4.5		0.21		0.05	1		0.04		0.02
	Bolt	0.3	30-35	1		0.02		0.004	1		0.01		0.01
	Base plate	3.5	40	1.5		0.22		0.05	1.5		0.17		0.11

The ratio between main and side lines from the Table 3.23 has been used to calculate the annual material demand from sleepers and fastening system of the Belgian railway network.

Table 3.23. Ratio between main and lines in the Belgian railway network

	2006	2007	2008	2009	2010	2011	2012	2013	2014
Main lines share (%)	69.18	69.19	69.49	72.87	72.58	71.61	72.07	74.22	74.11
Side lines share (%)	30.82	30.81	30.51	27.13	27.42	28.39	27.93	25.78	25.89

Table 3.24 presents the annual material demand from sleepers and fastening system of the Belgian railway network for a two-ways track.

Table 3.24. Annual material demand (kg/(m×a)) from sleepers and fastening system of the Belgian railway network for a two-ways track

		2006	2007	2008	2009	2010	2011	2012
Sleeper Concrete M41	**Concrete ($m^3/(m\times a)$)**	6.19×10^{-3}	6.19×10^{-3}	6.20×10^{-3}	6.37×10^{-3}	6.36×10^{-3}	6.31×10^{-3}	6.33×10^{-3}
	Steel reinforcement	4.11×10^{-1}	4.11×10^{-1}	4.12×10^{-1}	4.24×10^{-1}	4.23×10^{-1}	4.19×10^{-1}	4.21×10^{-1}
	Clip (Steel)	2.41×10^{-1}	2.41×10^{-1}	2.42×10^{-1}	2.48×10^{-1}	2.48×10^{-1}	2.46×10^{-1}	2.47×10^{-1}
	Bolt (Steel)	8.44×10^{-2}	8.44×10^{-2}	8.46×10^{-2}	8.69×10^{-2}	8.67×10^{-2}	8.60×10^{-2}	8.64×10^{-2}
	Rubber pad	1.27×10^{-1}	1.27×10^{-1}	1.27×10^{-1}	1.30×10^{-1}	1.30×10^{-1}	1.29×10^{-1}	1.30×10^{-1}
Wooden sleeper	**Oak Wood**	3.26	3.26	3.25	3.14	3.15	3.18	3.16
	Creosote	2.07×10^{-1}	2.07×10^{-1}	2.06×10^{-1}	1.99×10^{-1}	1.99×10^{-1}	2.01×10^{-1}	2.00×10^{-1}
	Screw spike (Steel)	2.16×10^{-1}	2.16×10^{-1}	2.15×10^{-1}	2.06×10^{-1}	2.06×10^{-1}	2.09×10^{-1}	2.08×10^{-1}
	Clip (Steel)	7.75×10^{-2}	7.75×10^{-2}	7.77×10^{-2}	7.90×10^{-2}	7.89×10^{-2}	7.85×10^{-2}	7.87×10^{-2}
	Bolt (Steel)	1.02×10^{-2}	1.02×10^{-2}	1.02×10^{-2}	9.80×10^{-3}	9.83×10^{-3}	9.93×10^{-3}	9.89×10^{-3}
	Base plate (Steel)	1.34×10^{-1}	1.34×10^{-1}	1.33×10^{-1}	1.29×10^{-1}	1.29×10^{-1}	1.30×10^{-1}	1.30×10^{-1}

3.4.2.3. Switches and crossings

Switch and crossing systems play a key role in the connections between different tracks, establishing a railway network that allows the rail transport. The switches and crossing used by Infrabel are manufactured in Belgium. As shown in Figure 3.8, the most relevant parts of the switch and crossing system considered in our study are the common crossing, switch rails, outside rails, check rails and breather switch.

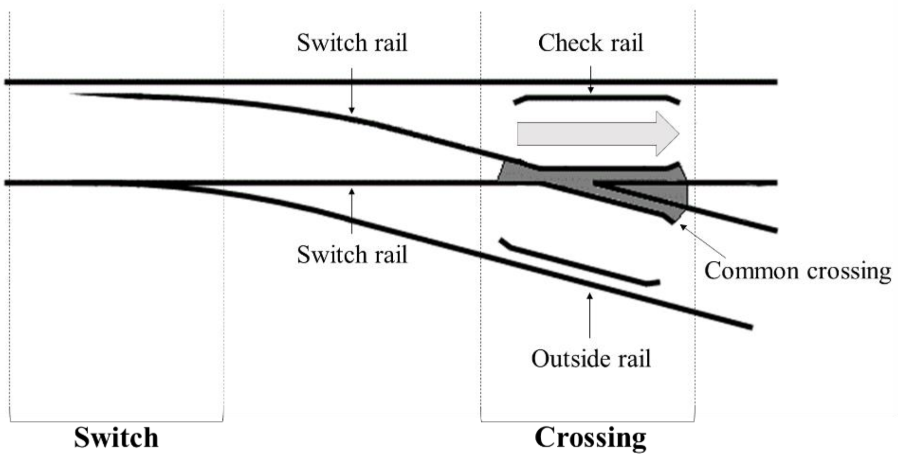


Figure 3.8. Switch and crossing system

Infrabel uses three types of common crossings in the Belgian railway network (Infrabel, 2007), being the ratio between monobloc, assembled and machined common crossings of 65%, 19% and 16%, respectively. Table 3.25 presents the average weight of the different components per switch and crossing system. Since the life span of the switches is not available, the same life span than the rails has been considered (i.e. 30 years).

Table 3.25. Average weight and number of the different switches' elements. Source: Infrabel, 2007

Switch and crossing system elements	Weight (kg/unit)	unit/switch	Weight (kg/switch)
Common crossing - Monobloc	1 423	65%	-
Common crossing - Assembled	588	19%	-
Common crossing - Machined	934	16%	-
Average common crossing	1 186	1	1 186
Average switch rail	1 373	2	2 746
Average outside rail	445	2	890
Average breather switch	729	1	729
Check rail	88	2	176

The annual material demand from switches and crossings of the Belgian railway network has been calculated using the total number of switches in the main and side lines (see Table 3.26).

Table 3.26. Number of switches in main and side lines in the Belgian railway network

	2006	2007	2008	2009	2010	2011	2012	2013	2014
Main lines	4 446	4 438	4 510	4 526	4 513	4 488	4 470	4 348	4 309
Side lines	8 378	8 161	7 904	7 692	7 588	7 519	7 327	5 712	5 522

In order to calculate the annual material demand from the switch and crossing system of the complete Belgian railway network (see Table 3.27), the ratio between main and side lines from the Table 3.23 has been used. It should be noted that our study does not include the manufacturing processes of the switches and crossings.

Table 3.27. Annual material demand (kg/(m×a)) from switch and crossing system of the Belgian railway network for a two-ways track

	2006	2007	2008	2009	2010	2011	2012	2013	2014
Common crossing	1.12×10^{-1}	1.10×10^{-1}	1.08×10^{-1}	1.09×10^{-1}	1.08×10^{-1}	1.05×10^{-1}	1.04×10^{-1}	9.12×10^{-2}	8.83×10^{-2}
Switch rail	2.60×10^{-1}	2.56×10^{-1}	2.50×10^{-1}	2.53×10^{-1}	2.50×10^{-1}	2.44×10^{-1}	2.41×10^{-1}	2.11×10^{-1}	2.05×10^{-1}
Outside rail	8.42×10^{-2}	8.29×10^{-2}	8.09×10^{-2}	8.21×10^{-2}	8.09×10^{-2}	7.91×10^{-2}	7.80×10^{-2}	6.85×10^{-2}	6.63×10^{-2}
Breather switch	6.89×10^{-2}	6.79×10^{-2}	6.62×10^{-2}	6.72×10^{-2}	6.62×10^{-2}	6.48×10^{-2}	6.39×10^{-2}	5.60×10^{-2}	5.43×10^{-2}
Check rail	1.66×10^{-2}	1.64×10^{-2}	1.60×10^{-2}	1.62×10^{-2}	1.60×10^{-2}	1.57×10^{-2}	1.54×10^{-2}	1.35×10^{-2}	1.31×10^{-2}
Total Steel	5.42×10^{-1}	5.33×10^{-1}	5.20×10^{-1}	5.28×10^{-1}	5.21×10^{-1}	5.09×10^{-1}	5.02×10^{-1}	4.40×10^{-1}	4.26×10^{-1}

3.4.2.4. *Overhead contact system*

Three main types of overhead contact line systems have been identified in the Belgian railway network. The main overhead contact lines have a power supply of 3 kV DC, of which the type compound have a length of 4 330 km and the type R3 is 490 km long. The overhead high speed lines (HSL) with a power supply of 25 kV AC are 450 km long.

The most relevant parts of the overhead contact lines considered in our study are showed in Figure 3.9. A mast with a length from 7 to 15 meters and made of galvanised steel supports the overhead contact line. The bracket system is attached to the mast supporting the catenary wire. An earth wire is attached to the mast. The feeder supply the electricity to the overhead contact line. The catenary wire supports the contact wires through the use of droppers. The contact wires are composed of two wires, which transmits the electricity to the trains by the pantograph fixed on the top of the train. The insulators isolate the electric parts from the structural elements such as the mast.

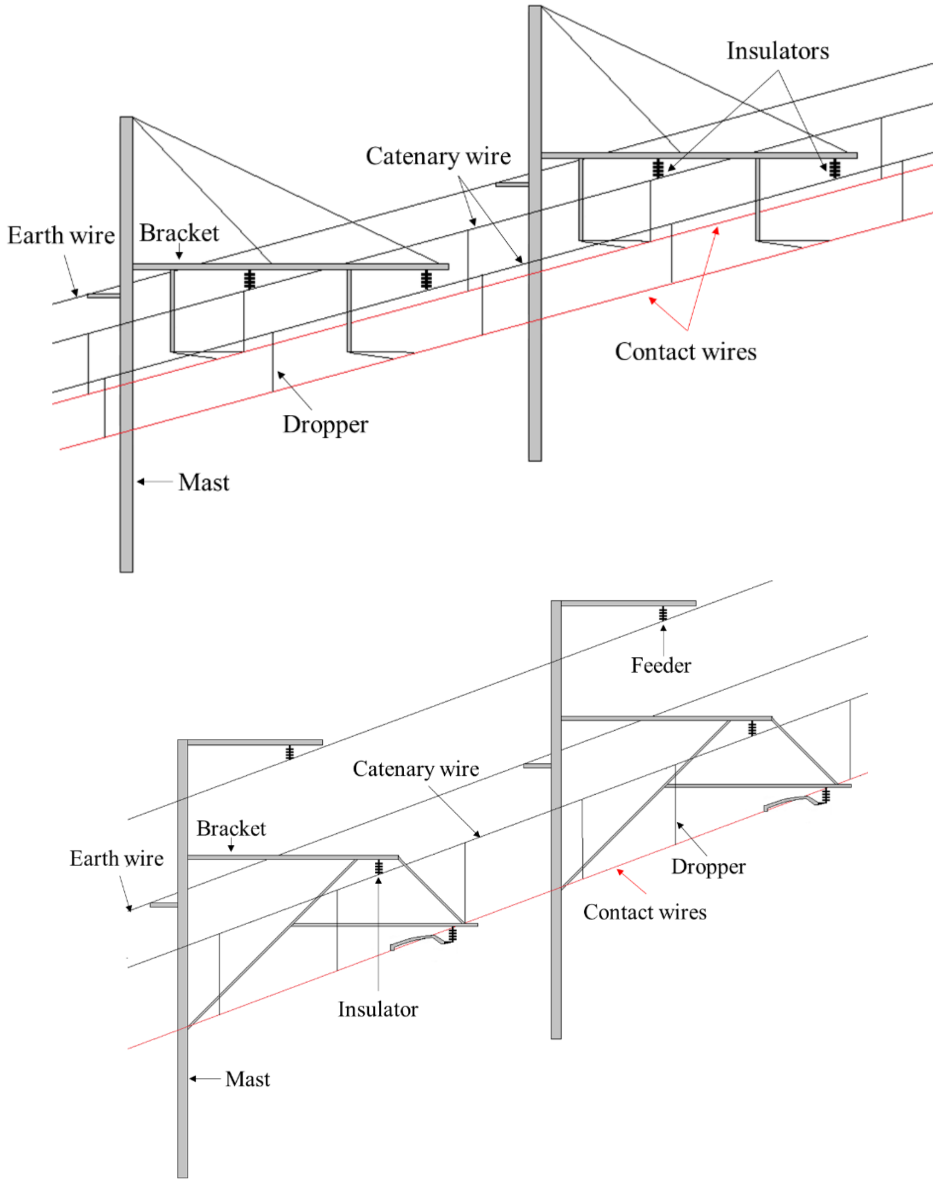


Figure 3.9. Examples of overhead compound lines (above) and overhead R3 lines (below)

Table 3.28 shows the material composition of the overhead contact system of the Belgian railway network collected from Infrabel through the use of questionnaires.

Table 3.28. Material composition of the overhead contact system of the Belgian railway network

OCL type	Component	Material	Unit	Belgium	Life span	Average unit/km	Additional data
Compound - R3 - HSL	Mast	Steel	kg/unit	830	60	45	Depending on the length and section
		Zinc	kg/unit	Negligible	20-40		
Compound	Bracket system	Galvanised steel	kg/unit	20	60	45	Depending on the bracket length
R3 - HSL	Bracket system	Aluminium	kg/unit	35	60	45	
Compound	Contact wire 107 mm^2	Cu Ag	kg/m	0.951	15	2 wires	Weight varies +/- 3%
	Main catenary wire 95 mm^2	Cu Cd Sn	kg/m	0.855	60	1 wire	Weight varies to +4%
	Auxiliary catenary wire 104 mm^2	Cu Cd Sn	kg/m	0.924	60	1 wire	-
	Earth wire 75 mm^2	Almelec[1]	kg/m	0.213	60	1 wire	-
R3	Contact wire 120 mm^2	Cu Ag	kg/m	1.067	20	2 wires	Weight varies +/- 3%
	Catenary wire 95 mm^2	Cu Cd Sn	kg/m	0.855	60	1 wire	Weight varies to +4%
	Feeder 366 mm^2	Almelec[1]	kg/m	1.051	60	1 wire	-
	Earth wire 75 mm^2	Almelec[1]	kg/m	0.213	60	1 wire	-
HSL	Contact wire 150 mm^2	Cu Mg	kg/m	1.333	25	1 wire	Weight varies +/- 3%
	Catenary wire 95 mm^2	Cu Cd or Cu Mn	kg/m	0.830	60	1 wire	-
	Feeder 288 mm^2	Almelec[1]	kg/m	0.828	60	1 wire	-
	Aerial earth wire 117 mm^2	Almelec[1]	kg/m	0.330	60	1 wire	-
	Underground earth wire 35 mm^2	Cu	kg/m	0.311	60	1 wire	-
Compound - R3	Suspension insulators	Fixation: steel or Al Body: glass fibre	kg/unit	1.4	30	45	-
Compound	Insulator of registration arm		kg/unit	2.44	30	45	-
R3	Insulator of registration arm		kg/unit	3.85	30	45	-
R3	Suspension insulators Feeder		kg/unit	1.4	30	45	-
HSL	Bracket insulators		kg/unit	5.9	30	85	-
HSL	Suspension insulators Feeder		kg/unit	1.71	30	45	-
-	Compact insulators[2]	Glass fibre and Cu	kg/unit	60	30	0.83	-

[1]Aluminium alloy with small proportions of magnesium and silicon; [2]Approximately 5 000 units in an electrified network of 6 000 km

The annual material demand due to the overhead contact line system has been calculated in three steps. Firstly, the material demand of the three types of overhead contact line (i.e. compound, R3 and HSL) present in the Belgian railway network has been calculated separately. For some components such as mast, bracket systems and insulators it has been calculated the average units of these components per meter of overhead contact line. Secondly, the material demand for an average overhead contact line has been calculated considering a share of 82.16%, 9.30% and 8.54% for the compound, R3 and HSL overhead contact lines, respectively. The components of the overhead contact system made of the same material have been grouped, such as the masts and bracket systems made of steel and the insulators made of glass fibre for example. Thirdly, since the Belgian railway network is not completely electrified, the contribution of material demand from the overhead contact system has been calculated for the Belgian railway network considering both electrified and non-electrified network. Table 3.29 shows the length of electrified and non-electrified tracks in the Belgian railway network for several years.

Table 3.29. Length of the tracks in the Belgian railway network. Source: Eurostat statistics, 2017

	2005	2006	2007	2008	2009
Electrified tracks (km)	5 444	5 462	5 454	5 601	5 661
Non-electrified tracks (km)	771	605	507	682	775
Electrified tracks share (%)	87.59	90.03	91.49	89.15	87.96
Non-electrified tracks share (%)	12.41	9.97	8.51	10.85	12.04

Using the average material demand of the overhead contact system and the share of electrified and non-electrified network, the contribution of material demand from the overhead contact system has been calculated for the Belgian railway network from 2005 to 2009 (see Table 3.30).

Table 3.30. Material demand (kg/(m×a)) from the overhead contact system considering both electrified tracks and non-electrified tracks in a railway line with two-tracks

Component Source	Material	2005	2006	2007	2008	2009
Mast & Bracket system	**Steel**	1.11	1.14	1.16	1.13	1.12
Bracket systems	**Al**	8.20×10^{-3}	8.43×10^{-3}	8.57×10^{-3}	8.35×10^{-3}	8.24×10^{-3}
Contact wires	**Cu Ag**	2.00×10^{-1}	2.05×10^{-1}	2.09×10^{-1}	2.03×10^{-1}	2.01×10^{-1}
Contact wires	**Cu Mg**	7.98×10^{-3}	8.20×10^{-3}	8.33×10^{-3}	8.12×10^{-3}	8.01×10^{-3}
Catenary & Aux. Catenary wires	**Cu Cd Sn**	4.50×10^{-2}	4.62×10^{-2}	4.70×10^{-2}	4.58×10^{-2}	4.52×10^{-2}
Catenary wire	**Cu Cd or Cu Mn**	2.07×10^{-3}	2.13×10^{-3}	2.16×10^{-3}	2.11×10^{-3}	2.08×10^{-3}
Earth wires & Feeder	**Almelec**	1.14×10^{-2}	1.17×10^{-2}	1.19×10^{-2}	1.16×10^{-2}	1.15×10^{-2}
Earth wires underground	**Cu**	6.98×10^{-5}	7.17×10^{-5}	7.29×10^{-5}	7.10×10^{-5}	7.01×10^{-5}
Insulators	**Glass fibre**	1.61×10^{-2}	1.66×10^{-2}	1.68×10^{-2}	1.64×10^{-2}	1.62×10^{-2}

3.4.2.5. Life Cycle Inventory of railway construction

Table 3.31 shows the LCI for the construction of an average railway two-tracks in Belgium. The material demand for the track construction is considered in the complete railway network, adding the material demand for the construction of tunnels and bridges considering by their respective railway network share. The components of same material have been grouped such as the concrete for tunnels and bridge construction and the manufacturing of concrete sleepers, for example. Furthermore, two more processes from Spielmann et al. (2007) not considered previously have been included in the railway track construction, such as 1.2 $m^3/(m\times a)$ of excavation by a skid-steer loader and 0.05 MJ/(m×a) of diesel.

By comparing the values obtained in our study with the values from Spielmann et al. (2007), our results for Belgium show a lower material consumption on concrete (high exacting) and reinforcing steel. Moreover, a lower energy consumption on diesel and electricity is obtained in our research as a result of both the lower energy consumption in the tunnel construction and the lower share of tunnel in the railway network considered in our study compared to Spielmann et al. (2007). Furthermore, our results for the Belgian railway infrastructure present a higher material consumption on gravel, steel (low-alloyed) and aluminium. It should be noted that our LCI for the railway construction presents a larger number of elements such as wood, creosote and rubber pad from the sleeper system and other materials from the overhead contact system.

Table 3.31. Life Cycle Inventory for the construction of an average railway two-tracks in Belgium

	2005	2006	2007	2008	2009	2010	2011	2012	Switzerland[2]
Concrete, high exacting (m^3/(m×a))	-	3.00×10^{-2}	2.99×10^{-2}	3.02×10^{-2}	3.01×10^{-2}	3.00×10^{-2}	3.00×10^{-2}	3.00×10^{-2}	4.31×10^{-2}
Reinforcing steel (kg/(m×a))	-	11.33	11.31	11.32	11.31	11.30	11.29	11.28	13.5
Wood (kg/(m×a))	-	3.26	3.26	3.25	3.14	3.15	3.18	3.16	-
Creosote (kg/(m×a))	-	2.07×10^{-1}	2.07×10^{-1}	2.06×10^{-1}	1.99×10^{-1}	1.99×10^{-1}	2.01×10^{-1}	2.00×10^{-1}	-
Rubber pad (kg/(m×a))	-	1.27×10^{-1}	1.27×10^{-1}	1.27×10^{-1}	1.30×10^{-1}	1.30×10^{-1}	1.29×10^{-1}	1.30×10^{-1}	-
Gravel, crushed (kg/(m×a))	708.13	708.06	708.02	708.27	707.98	707.96	707.94	707.92	571
Steel, low-alloyed (kg/(m×a))	1.11	1.14	1.16	1.13	1.12	-	-	-	5.60×10^{-1}
Al (kg/(m×a))	8.20×10^{-3}	8.43×10^{-3}	8.57×10^{-3}	8.35×10^{-3}	8.24×10^{-3}	-	-	-	6.00×10^{-3}
CuAg (kg/(m×a))	2.00×10^{-1}	2.05×10^{-1}	2.09×10^{-1}	2.03×10^{-1}	2.01×10^{-1}	-	-	-	5.50×10^{-2}
CuMg (kg/(m×a))	7.98×10^{-3}	8.20×10^{-3}	8.33×10^{-3}	8.12×10^{-3}	8.01×10^{-3}	-	-	-	-
CuCdSn (kg/(m×a))	4.50×10^{-2}	4.62×10^{-2}	4.70×10^{-2}	4.58×10^{-2}	4.52×10^{-2}	-	-	-	-
CuMn (kg/(m×a))	2.07×10^{-3}	2.13×10^{-3}	2.16×10^{-3}	2.11×10^{-3}	2.08×10^{-3}	-	-	-	-
Almelec (kg/(m×a))	1.14×10^{-2}	1.17×10^{-2}	1.19×10^{-2}	1.16×10^{-2}	1.15×10^{-2}	-	-	-	-
Cu (kg/(m×a))	6.98×10^{-5}	7.17×10^{-5}	7.29×10^{-5}	7.10×10^{-5}	7.01×10^{-5}	-	-	-	-
Glass fibre (kg/(m×a))	1.61×10^{-2}	1.66×10^{-2}	1.68×10^{-2}	1.64×10^{-2}	1.62×10^{-2}	-	-	-	-
Excavation soil (m^3/(m×a))	8.03×10^{-2}	7.99×10^{-2}	7.98×10^{-2}	8.10×10^{-2}	7.96×10^{-2}	7.95×10^{-2}	7.94×10^{-2}	7.93×10^{-2}	340
Excavation (m^3/(m×a)	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Diesel (MJ/(m×a))	2.23	2.22	2.21	2.240	2.21	2.20	2.20	2.20	9.50
Electricity (kWh/(m×a))	7.93×10^{-1}	7.89×10^{-1}	7.88×10^{-1}	8.00×10^{-1}	7.85×10^{-1}	7.85×10^{-1}	7.84×10^{-1}	7.82×10^{-1}	3.98

[1]Source: Spielmann et al., 2007

3.4.3. Life Cycle Inventory of the railway maintenance

The maintenance of the Belgian railway infrastructure has been analysed as well. Therefore, the maintenance works on renewing rails, sleepers, switches and crossings systems, and ballast and maintenance works such as rail grinding, ballast tamping, ballast profiling, ballast stabilisation, ballast cleaning and weed control are taken into account. It has been considered in the maintenance of railway infrastructure both the fuel consumption and exhaust emissions from the machinery used in the maintenance and the new materials used in the track renewal. Table 3.32 shows the maintenance works in the Belgian railway network.

Table 3.32. Maintenance works in the Belgian railway network

	2006	2007	2008	2009	2010	2011	2012
Rails renewal in main lines (km/year)	61	100	140	212	99	121	119
Sleepers renewal in main lines (km/year)	147	171	170	150	175	90	110
Switches renewal (units)	62	86	100	82	62	65	72
Ballast renewal (km/year)	59	96	110	115	59	31	22

Table 3.33 presents the LCI of the Belgian railway infrastructure maintenance. An electricity consumption from ventilation of tunnel operation of 837 kWh/(m×a) has been considered (Spielmann et al., 2007), which has been multiplied by the tunnel share of every year.

Table 3.33. Material demand for the railway maintenance of an average Belgian railway track two-ways

Maintenance	Material or Energy source	2006	2007	2008	2009	2010	2011	2012
Tunnel ventilation	Electricity (kWh/(m×a)	22.34	22.29	22.63	22.22	22.20	22.17	22.14
Rail and Splice bar renewal	Reinforcing steel (kg/(m×a))	7.07×10^{-2}	1.16×10^{-1}	1.63×10^{-1}	2.43×10^{-1}	1.12×10^{-1}	1.37×10^{-1}	1.34×10^{-1}
	Diesel (MJ/(m×a))	1.29×10^{-1}	2.11×10^{-1}	2.96×10^{-1}	4.43×10^{-1}	2.04×10^{-1}	2.49×10^{-1}	2.44×10^{-1}
Rail grinding	Diesel (MJ/(m×a))	9.41	9.39	9.43	9.31	9.19	9.15	9.12
	Water (L/(m×a))	1.65×10^{-1}	1.65×10^{-1}	1.65×10^{-1}	1.63×10^{-1}	1.61×10^{-1}	1.60×10^{-1}	1.60×10^{-1}
Sleeper renewal - Sleepers	Concrete (m³/(m×a))	1.80×10^{-4}	2.09×10^{-4}	2.09×10^{-4}	1.82×10^{-4}	2.10×10^{-4}	1.07×10^{-4}	1.31×10^{-4}
	Reinforcing steel (kg/(m×a))	1.20×10^{-2}	1.39×10^{-2}	1.39×10^{-2}	1.21×10^{-2}	1.40×10^{-2}	7.14×10^{-3}	8.70×10^{-3}
	Wood (kg/(m×a))	5.23×10^{-2}	6.07×10^{-2}	6.06×10^{-2}	5.28×10^{-2}	6.09×10^{-2}	3.12×10^{-2}	3.79×10^{-2}
	Creosote (kg/(m×a))	3.32×10^{-3}	3.85×10^{-3}	3.84×10^{-3}	3.35×10^{-3}	3.86×10^{-3}	1.98×10^{-3}	2.40×10^{-3}
	Diesel (MJ/(m×a))	1.18×10^{-1}	1.36×10^{-1}	1.36×10^{-1}	1.19×10^{-1}	1.37×10^{-1}	7.00×10^{-2}	8.52×10^{-2}
Sleeper renewal - Fastening system	Reinforcing steel (kg/(m×a))	1.69×10^{-2}	1.96×10^{-2}	1.96×10^{-2}	1.71×10^{-2}	1.97×10^{-2}	1.01×10^{-2}	1.23×10^{-2}
	Rubber pad (kg/(m×a))	3.69×10^{-3}	4.28×10^{-3}	4.28×10^{-3}	3.73×10^{-3}	4.29×10^{-3}	2.20×10^{-3}	2.68×10^{-3}
Switches and crossings renewal	Reinforcing steel (kg/(m×a))	3.76×10^{-3}	5.21×10^{-3}	6.08×10^{-3}	4.92×10^{-3}	3.67×10^{-3}	3.84×10^{-3}	4.23×10^{-3}
	Electricity (kWh/(m×a))	1.13	1.12	1.09	1.11	1.09	1.07	1.05
	Lubricating oil (kg/(m×a))	9.25×10^{-3}	9.11×10^{-3}	8.89×10^{-3}	9.02×10^{-3}	8.89×10^{-3}	8.69×10^{-3}	8.57×10^{-3}
Ballast renewal	Gravel, crushed (kg/(m×a))	1.50	2.44	2.80	2.89	1.47	7.67×10^{-1}	5.42×10^{-1}
	Ballast spreading machine (MJ/(m×a))	8.09×10^{-2}	1.31×10^{-1}	1.51×10^{-1}	1.56×10^{-1}	7.90×10^{-2}	4.13×10^{-2}	2.92×10^{-2}
	Ballast tamping machine (MJ/(m×a))	3.23×10^{-1}	5.25×10^{-1}	6.04×10^{-1}	6.24×10^{-1}	3.16×10^{-1}	1.65×10^{-1}	1.17×10^{-1}
	Ballast changing machine (MJ/(m×a))	1.72×10^{-1}	2.79×10^{-1}	3.21×10^{-1}	3.32×10^{-1}	1.68×10^{-1}	8.79×10^{-2}	6.21×10^{-2}
	Ballast cleaning machine (MJ/(m×a))	1.72×10^{-1}	2.79×10^{-1}	3.21×10^{-1}	3.32×10^{-1}	1.68×10^{-1}	8.79×10^{-2}	6.21×10^{-2}
Weed control	Glyphosate (kg/(m×a))	1.41	1.41	1.41	1.39	1.38	1.37	1.37
	Clopyralide (kg/(m×a))	2.99×10^{-3}	2.98×10^{-3}	2.99×10^{-3}	2.96×10^{-3}	2.92×10^{-3}	2.91×10^{-3}	2.89×10^{-3}
	Fluroxypyr (kg/(m×a))	5.97×10^{-3}	5.96×10^{-3}	5.99×10^{-3}	5.91×10^{-3}	5.84×10^{-3}	5.81×10^{-3}	5.79×10^{-3}
	MCPA (kg/(m×a))	1.77×10^{-1}	1.77×10^{-1}	1.77×10^{-1}	1.75×10^{-1}	1.73×10^{-1}	1.72×10^{-1}	1.72×10^{-1}
	Diflufenican (kg/(m×a))	8.17×10^{-2}	8.15×10^{-2}	8.18×10^{-2}	8.08×10^{-2}	7.98×10^{-2}	7.94×10^{-2}	7.91×10^{-2}
	Tryclopyr (kg/(m×a))	2.38×10^{-1}	2.37×10^{-1}	2.38×10^{-1}	2.35×10^{-1}	2.32×10^{-1}	2.31×10^{-1}	2.30×10^{-1}
	2,4 D (kg/(m×a))	3.55×10^{-1}	3.54×10^{-1}	3.55×10^{-1}	3.51×10^{-1}	3.46×10^{-1}	3.45×10^{-1}	3.44×10^{-1}
	Flazasulfuron (kg/(m×a))	1.10×10^{-2}	1.09×10^{-2}	1.10×10^{-2}	1.08×10^{-2}	1.07×10^{-2}	1.07×10^{-2}	1.06×10^{-2}

3.4.3.1. Maintenance of rails

The steel demand of the rails renewal has been calculated using the kilometres per year of rail removed from Infrabel and the previously calculated 7.3 kg/(m×a) of steel from rails in the railway infrastructure construction. The diesel consumption of the rail laying machine used in the rail renewal has been calculated using a construction speed of 37 h/km and a diesel consumption of 5 L/h from Kiani et al. (2008). Considering that the density of diesel is 0.84 kg/L and the diesel net calories are 42.8 MJ/kg (Frischknecht et al., 2007), results in a diesel consumption of the machinery of 179.76 MJ/h.

Rail grinding is a maintenance process to improve the rail surface. It avoids a further deterioration of the rails, removing the surface corrosion, deformities and damages from the rail and restoring the rail profile (Krezo et al., 2016), which reduces the iron abrasion of the rails and wheels, enhances the quality of the ride and it reduces the noise emissions from rail transport. Rail grinding produces particle emissions from both the rail and the grinding stone. Moreover, the exhaust emissions and energy consumption of the vehicle and the water consumed for collecting the grinding particles have to be considered (Barton et al., 2010).

Barton et al. (2010) did a Material Flow Analysis (MFA) of the rail grinding process of 1 km of tunnel single track using a small metro grinder with a grinding depth of 1 mm at the gauge corner. Although they explained that their results should not be compared to rail grinding on main railway lines (because the grinding machines used in main lines are different in their conception and grinding power), the lack of available data and the goal of achieving a comprehensive study of the maintenance of the railway infrastructure, lead us to use the diesel consumption of the machinery and the water consumed in the rail grinding maintenance process.

Barton et al. (2010) estimated a consumption for 1 km of track of 666.4 kg/a of diesel from the rail grinding machine and 500 L/a of water used by the grinding particles collection system. Moreover, they estimated a grinding shift with a length of 100 m and 3.5 hours long, resulting in a construction speed of 35 h/km. Therefore, considering that the density of diesel is 0.84 kg/L and the diesel net calories are 42.8 MJ/kg (Frischknecht et al., 2007), a diesel consumption of 22.67 L/h or 814.91 MJ/h for rail grinding is obtained.

In the year 2014, a length of 1 038 km of the Belgian railway network were rail grinded. Since a regular rail grinding schedule (Milford and Allwood, 2010) is considered, this value for every year had been used. It should be noted that the higher amount of kilometres of rail grinding every year in the railway network compared with other maintenance works. This results in a great energy consumption from this maintenance process. Thereby, most of the diesel consumption from the maintenance works are due to rail grinding.

3.4.3.2. Maintenance of sleepers

The material demand of the sleeper renewal has been calculated using the kilometres per year of sleeper removed in main lines from Infrabel. Moreover, the previously calculated material demand of concrete (9.42 kg/(m×a)) and steel (0.26 kg/(m×a)) from concrete sleepers and oak wood (1.12 kg/(m×a)) and creosote (0.07 kg/(m×a)) from wooden sleepers (considering a ratio between wooden and concrete sleepers in the main tracks of 21% and 79%, respectively) in the railway infrastructure construction has been used.

The material demand of the fastening system used to fix the rail to the sleepers in the main lines has been calculated. The previously calculated material demand from clips (0.15 kg/(m×a)), bolts (0.05 kg/(m×a)) and rubber pads (0.08 kg/(m×a)) from concrete sleepers and screw spikes (0.06 kg/(m×a)), clips (0.05 kg/(m×a)), bolts (0.004 kg/(m×a)) and base plates (0.05 kg/(m×a)) from wooden sleepers (considering a ratio between wooden and concrete sleepers in the main tracks of 21% and 79%, respectively) in the railway infrastructure construction has been used.

The diesel consumption from the machinery used in the sleeper renewal has been calculated using a construction speed of 14 h/km and a diesel consumption of 5 L/h from Kiani et al. (2008). Considering that the diesel has a density of 0.84 kg/L and its net calories are 42.8 MJ/kg (Frischknecht et al., 2007), a diesel consumption of the machinery of 179.76 MJ/h is obtained.

3.4.3.3. Maintenance of switches and crossings

The material demand of the switch and crossing renewal has been calculated using the unit per year of switches and crossings removed in main and side lines and an average weight of 5 727 kg/unit of steel from switches and crossings. An electricity consumption of 400 kWh/switch per year for heating switches and a lubricating oil consumption of 3.88 L/switch per year have been considered (Spielmann et al., 2007). The distribution per metre of switches has been used to obtain the electricity and lubricating demand from switch and crossing system of main and side lines in the Belgian railway network. Moreover, the ratio between main and side lines has been used to calculate the annual electricity and lubricating oil demand of the complete Belgian railway network.

3.4.3.4. Maintenance of ballast

The ballast demand of the ballast maintenance has been calculated using the km per year of ballast removed from Infrabel and a ballast consumption of 160 kg/(m×a) from the upper base. The diesel consumption from the machinery used in the ballast maintenance has been calculated using data from Kiani et al. (2008). Four processes have been considered in the ballast maintenance: ballast spreading with a construction speed of 12 h/km and a diesel consumption of 10 L/h, ballast tamping with a construction speed of 32 h/km and a diesel consumption of 15 L/h, and ballast changing and ballast cleaning with a construction speed of 17 h/km and a diesel consumption of 15 L/h. The density of diesel is 0.84 kg/L and the diesel net calories are 42.8 MJ/kg (Frischknecht et al., 2007), resulting in a diesel consumption of the machinery of 359.52 MJ/h for ballast spreading and 539.28 MJ/h for ballast tamping, ballast changing and ballast cleaning.

3.4.3.5. Weed control

Table 3.34 shows the herbicides used for weed control in the Belgian railway network for main tracks in 2016 and secondary tracks such as tracks in stations and industrial lines in 2015. The weed control is made using a spray-train in main tracks. The total length usually sprayed (two campaigns) is 7 131 km with a surface usually treated of 1 200 ha. The weed control is performed by different contractors applying different chemicals.

Table 3.34. Use of herbicides for weed control in main tracks in 2016 and side tracks in 2015

Herbicide	Main tracks (kg)	Secondary tracks (kg)
Glyphosate	262	4 173
Clopyralide	-	9.4
Fluroxypyr	-	18.8
MCPA	-	557
Diflufenican	42	215
Tryclopyr	332	416
2,4 D	298	818
Flazasulfuron	7.5	-

3.5.Life Cycle Impact Assessment of rail freight transport in Belgium

As mentioned in Chapter 2, a LCA study comprises four stages. First, the goal and scope definition, which in this chapter is to determine the environmental impacts of rail freight transport in Belgium. The functional unit chosen is “one tonne-kilometre of freight transported by train”. The second stage of a LCA is the Life Cycle Inventory (LCI) analysis. We have collected data directly from Infrabel and B-Logistics (LINEAS) and complementing the information using literature sources and the Ecoinvent v3 database. The third stage is the Life Cycle Impact Assessment (LCIA). All calculations were made with the SimaPro 8.0.5 software using the LCIA method “ILCD 2011 Midpoint+” (version V1.06 / EU27 2010), which is the method recommended by the European Commission (European Commission, 2010). As mentioned above, “ILCD 2011 Midpoint+” is a midpoint method including 16 environmental impact indicators. However, in this analysis it has been used only the indicators with a level of quality “I” (climate change, ozone depletion and particulate matter), and “II” (ionizing radiation – human health, photochemical ozone formation, acidification, terrestrial and freshwater eutrophication and mineral, fossil and renewable resource depletion). Finally, the fourth stage is the assessment of the results obtained in the previous stages.

3.5.1. Life Cycle Impact Assessment of the Belgian traction mix

Figure 3.10 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by rail in Belgium using the Belgian traction mix of the year 2012 (i.e. 86.3% of electric traction and 13.7% of diesel traction). Therefore, to calculate the LCIA of one tonne-kilometre of rail freight transport in 2012 it is necessary to consider a wagon demand of 5.56×10^{-8} unit/tkm, a locomotive demand of 9.63×10^{-10} unit/tkm, a railway infrastructure demand of 1.69×10^{-4} (m×a)/tkm, a railway infrastructure maintenance demand of 7.74×10^{-5} (m×a)/tkm, a diesel consumption of 0.00208 kg/tkm (89 kJ/tkm), an electricity consumption of 0.10288 kWh/tkm (368 kJ/tkm) and the direct emissions to air and soil. The processes related to railway infrastructure have been modelled using specific data for Belgium and the electricity supply mix in Belgium corresponds to the appropriate year.

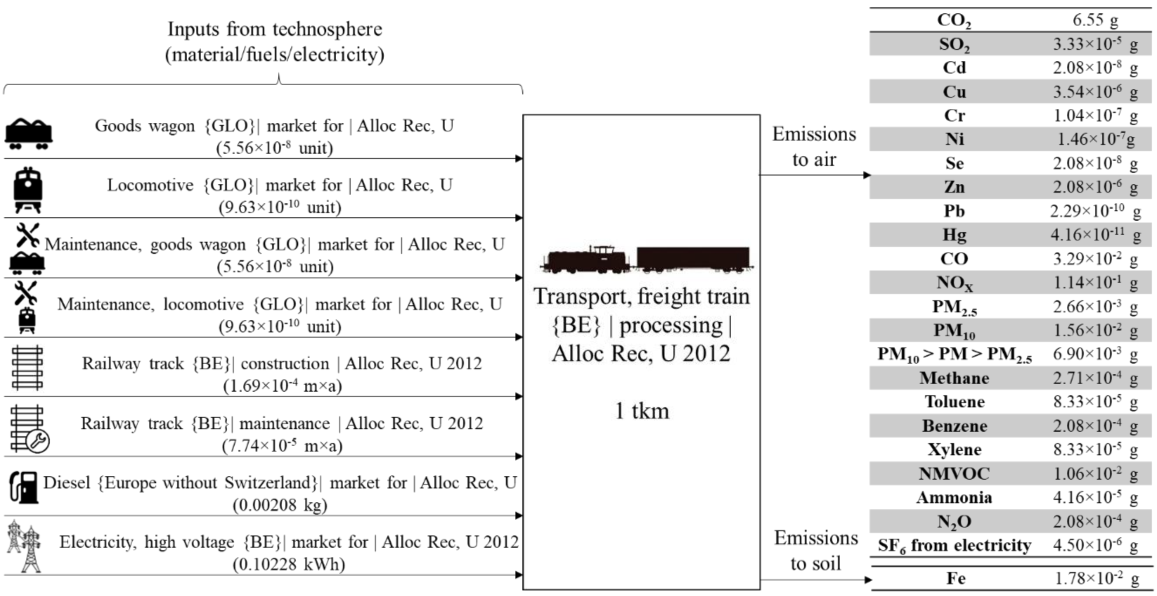


Figure 3.10. Inputs and outputs of 1 tkm of rail freight transport in Belgium in 2012

Table 3.35 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by rail in Belgium using the Belgian traction mix from 2006 to 2012, the average LCIA of Belgium taking as reference the period from 2006 to 2012 and the reference values of the process from Ecoinvent v3 "Transport, freight train {BE}| processing | Alloc Rec, U".

Table 3.35. LCIA of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012	Belgian average	Ecoinvent v3[1]
Climate change	kg CO_2 eq	6.97×10^{-2}	6.82×10^{-2}	7.17×10^{-2}	7.88×10^{-2}	6.83×10^{-2}	6.09×10^{-2}	6.42×10^{-2}	6.88×10^{-2}	5.37×10^{-2}
Ozone depletion	kg CFC-11 eq	1.38×10^{-8}	1.34×10^{-8}	1.39×10^{-8}	1.43×10^{-8}	1.22×10^{-8}	1.24×10^{-8}	1.19×10^{-8}	1.31×10^{-8}	9.01×10^{-9}
Particulate matter	kg $PM_{2.5}$ eq	3.35×10^{-5}	3.29×10^{-5}	3.32×10^{-5}	3.80×10^{-5}	3.42×10^{-5}	3.20×10^{-5}	3.55×10^{-5}	3.42×10^{-5}	2.86×10^{-5}
Ionizing radiation HH	kBq U235 eq	6.93×10^{-2}	6.66×10^{-2}	6.92×10^{-2}	7.07×10^{-2}	5.65×10^{-2}	6.55×10^{-2}	5.85×10^{-2}	6.52×10^{-2}	4.35×10^{-2}
Photochemical ozone formation	kg NMVOC eq	4.02×10^{-4}	3.89×10^{-4}	3.92×10^{-4}	3.80×10^{-4}	3.44×10^{-4}	2.96×10^{-4}	3.03×10^{-4}	3.58×10^{-4}	3.34×10^{-4}
Acidification	molc H+ eq	4.23×10^{-4}	4.13×10^{-4}	4.16×10^{-4}	4.37×10^{-4}	3.93×10^{-4}	3.51×10^{-4}	3.64×10^{-4}	3.99×10^{-4}	3.51×10^{-4}
Terrestrial eutrophication	molc N eq	1.47×10^{-3}	1.42×10^{-3}	1.43×10^{-3}	1.37×10^{-3}	1.24×10^{-3}	1.06×10^{-3}	1.04×10^{-3}	1.29×10^{-3}	1.23×10^{-3}
Freshwater eutrophication	kg P eq	1.62×10^{-5}	1.57×10^{-5}	1.64×10^{-5}	1.89×10^{-5}	1.70×10^{-5}	1.62×10^{-5}	1.96×10^{-5}	1.71×10^{-5}	9.99×10^{-6}
Resource depletion	kg Sb eq	2.12×10^{-6}	2.10×10^{-6}	2.14×10^{-6}	2.52×10^{-6}	2.25×10^{-6}	2.25×10^{-6}	2.34×10^{-6}	2.25×10^{-6}	1.24×10^{-6}

[1]Source: Weidema et al., 2013

Figure 3.11 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by rail in Belgium (from Table 3.35). Since each environmental impact indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the year with less impact and the highest value represents the maximum impact.

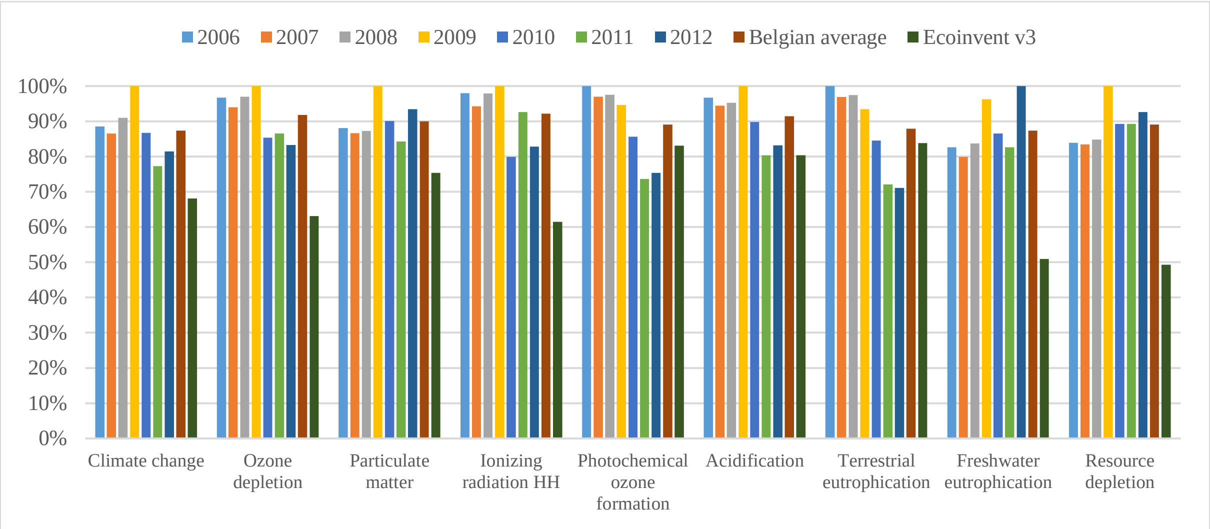
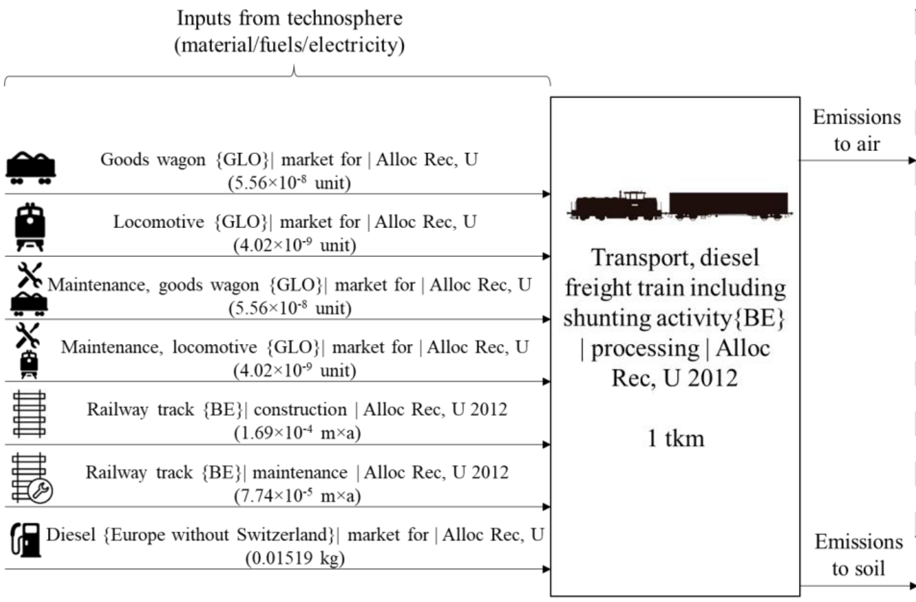


Figure 3.11. LCIA of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium and the reference values of the process from Ecoinvent v3 "Transport, freight train {BE}| processing | Alloc Rec, U"

The year 2009 presents the maximum impact in six indicators because this year presents a high energy consumption and a lower transport performance (tkm), resulting in a high demand of railway infrastructure and rail equipment. There are no significant differences in terms of impact among the years 2006, 2007 and 2008. However, the year 2006 presents the maximum impact due to the higher exhaust emissions produced by the diesel traction in the indicators photochemical ozone formation and terrestrial eutrophication. By comparing the environmental impacts of the average rail freight transport (from 2006 to 2012) with the values from Ecoinvent v3, our results for Belgium show a higher impact in all the indicators.

3.5.2. Life Cycle Impact Assessment of diesel trains in Belgium

Figure 3.12 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by rail in Belgium using diesel traction in the year 2012. In order to obtain the LCIA of one tonne-kilometre of rail freight transport using diesel traction in 2012 it is necessary to take into account a wagon demand of 5.56×10^{-8} unit/tkm, a diesel locomotive demand of 4.02×10^{-9} unit/tkm, a rail infrastructure demand of 1.69×10^{-4} (m×a)/tkm, a rai infrastructure maintenance demand of 7.74×10^{-5} (m×a)/tkm, a diesel consumption of 0.01519 kg/tkm (650 kJ/tkm) and the direct emissions to air and soil. As mentioned above, the processes related to railway infrastructure have been modelled using specific data for Belgium.



CO_2	47.79 g
SO_2	2.43×10^{-4} g
Cd	1.52×10^{-7} g
Cu	2.58×10^{-5} g
Cr	7.60×10^{-7} g
Ni	1.06×10^{-6} g
Se	1.52×10^{-7} g
Zn	1.52×10^{-5} g
Pb	1.67×10^{-9} g
Hg	3.04×10^{-10} g
CO	2.40×10^{-1} g
NO_X	8.36×10^{-1} g
$PM_{2.5}$	1.94×10^{-2} g
PM_{10}	1.64×10^{-2} g
$PM_{10} > PM > PM_{2.5}$	8.30×10^{-3} g
Methane	1.97×10^{-3} g
Toluene	6.08×10^{-4} g
Benzene	1.52×10^{-3} g
Xylene	6.08×10^{-4} g
NMVOC	7.70×10^{-2} g
Ammonia	3.04×10^{-4} g
N_2O	1.52×10^{-3} g

Fe	1.78×10^{-2} g

Figure 3.12. Inputs and outputs of 1 tkm transported by diesel trains in Belgium in 2012

Table 3.36 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by diesel trains (including shunting activity) in Belgium.

Table 3.36. LCIA of 1 tkm transported by diesel trains in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	8.38×10^{-2}	8.03×10^{-2}	8.59×10^{-2}	9.72×10^{-2}	9.14×10^{-2}	7.72×10^{-2}	8.32×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.44×10^{-8}	1.38×10^{-8}	1.48×10^{-8}	1.63×10^{-8}	1.55×10^{-8}	1.29×10^{-8}	1.38×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	5.62×10^{-5}	5.41×10^{-5}	5.74×10^{-5}	6.70×10^{-5}	6.28×10^{-5}	5.43×10^{-5}	5.89×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	7.04×10^{-3}	6.82×10^{-3}	7.23×10^{-3}	8.20×10^{-3}	7.80×10^{-3}	6.82×10^{-3}	7.27×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	1.18×10^{-3}	1.12×10^{-3}	1.21×10^{-3}	1.32×10^{-3}	1.25×10^{-3}	1.02×10^{-3}	1.09×10^{-3}
Acidification	**molc H+ eq**	9.59×10^{-4}	9.14×10^{-4}	9.83×10^{-4}	1.10×10^{-3}	1.03×10^{-3}	8.59×10^{-4}	9.25×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.43×10^{-3}	4.20×10^{-3}	4.55×10^{-3}	4.96×10^{-3}	4.68×10^{-3}	3.80×10^{-3}	4.07×10^{-3}
Freshwater eutrophication	**kg P eq**	1.28×10^{-5}	1.28×10^{-5}	1.31×10^{-5}	1.69×10^{-5}	1.58×10^{-5}	1.51×10^{-5}	1.69×10^{-5}
Resource depletion	**kg Sb eq**	1.93×10^{-6}	1.93×10^{-6}	1.97×10^{-6}	2.50×10^{-6}	2.30×10^{-6}	2.22×10^{-6}	2.45×10^{-6}

Figure 3.13 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by diesel trains in Belgium (from Table 3.36). The year 2009 presents the maximum impact in all the indicators mainly due to this year presents the highest energy consumption for diesel trains (804 kJ/tkm). It should be noted that there are no significant differences in terms of impact among the years 2006, 2007 and 2008.

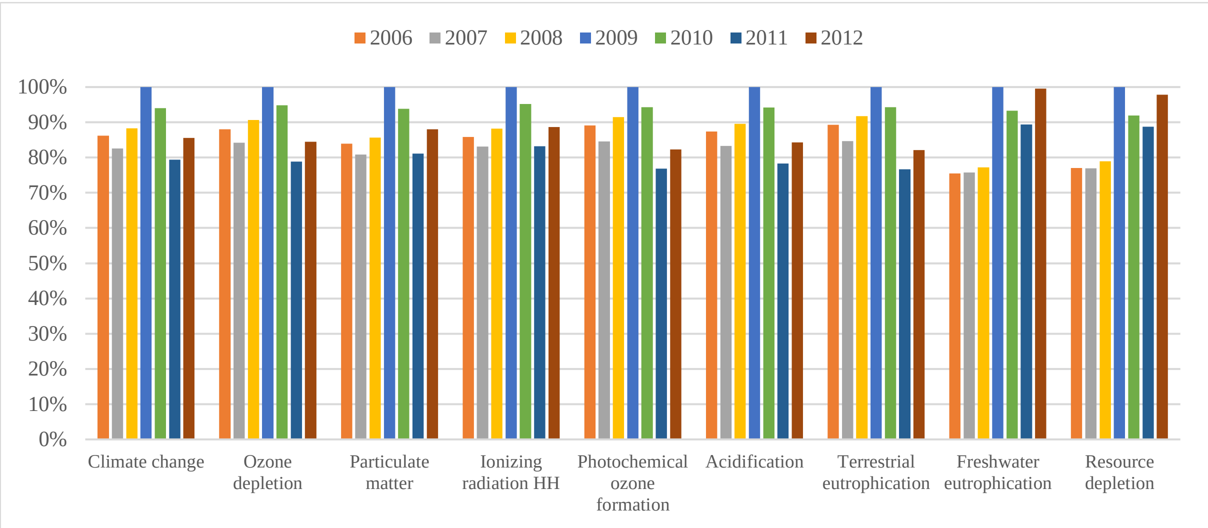


Figure 3.13. LCIA of 1 tkm transported by diesel trains in Belgium

3.5.3. Life Cycle Impact Assessment of electric trains in Belgium

Figure 3.14 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by rail in Belgium using electric traction in the year 2012. In order to obtain the LCIA of one tonne-kilometre of rail freight transport using electric traction in 2012 it is necessary to take into account a wagon demand of 5.56×10^{-8} unit/tkm, a locomotive demand of 4.77×10^{-10} unit/tkm, a railway infrastructure demand of 1.69×10^{-4} (m×a)/tkm, a railway infrastructure maintenance demand of 7.74×10^{-5} (m×a)/tkm, an electricity consumption of 0.1185 kWh/tkm (427 kJ/tkm) and the direct emissions to air and soil. As mentioned above, the processes related to railway infrastructure have been modelled using specific data for Belgium and the electricity supply mix in Belgium corresponds to the appropriate year.

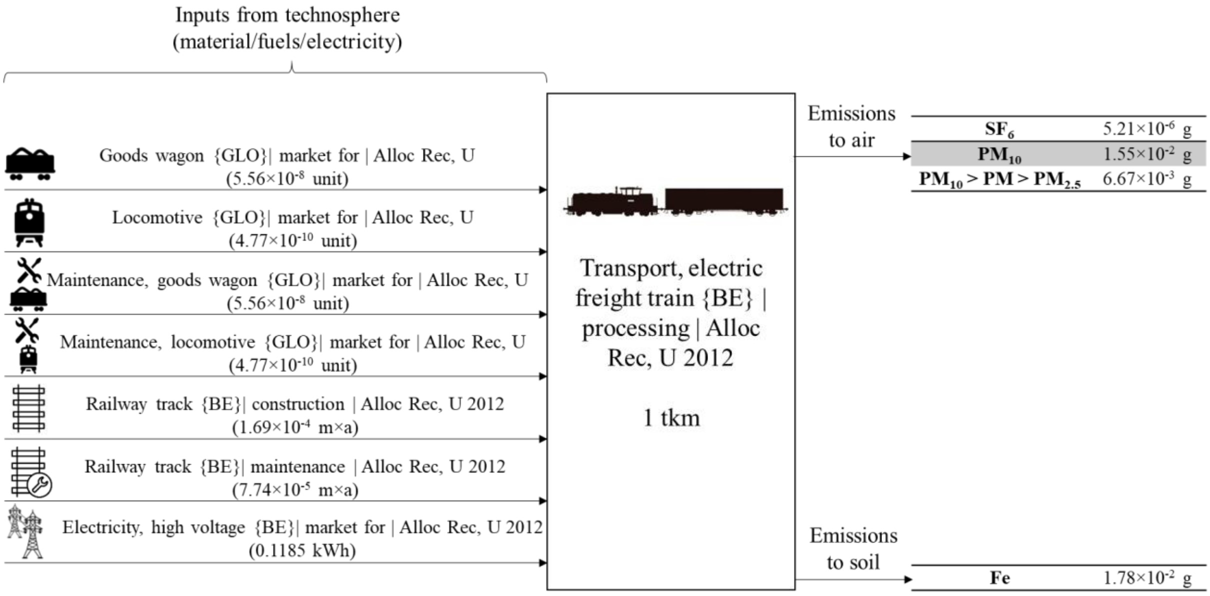


Figure 3.14. Inputs and outputs of 1 tkm transported by electric trains in Belgium in 2012

Table 3.37 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by electric trains in Belgium.

Table 3.37. LCIA of 1 tkm transported by electric trains in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	6.54×10^{-2}	6.44×10^{-2}	6.77×10^{-2}	7.50×10^{-2}	6.38×10^{-2}	5.77×10^{-2}	6.12×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.37×10^{-8}	1.33×10^{-8}	1.36×10^{-8}	1.39×10^{-8}	1.15×10^{-8}	1.23×10^{-8}	1.16×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	2.64×10^{-5}	2.62×10^{-5}	2.64×10^{-5}	3.21×10^{-5}	2.85×10^{-5}	2.77×10^{-5}	3.17×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	8.86×10^{-2}	8.55×10^{-2}	8.65×10^{-2}	8.34×10^{-2}	6.61×10^{-2}	7.68×10^{-2}	6.67×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	1.60×10^{-4}	1.59×10^{-4}	1.63×10^{-4}	1.88×10^{-4}	1.65×10^{-4}	1.56×10^{-4}	1.78×10^{-4}
Acidification	**molc H+ eq**	2.57×10^{-4}	2.54×10^{-4}	2.58×10^{-4}	3.03×10^{-4}	2.66×10^{-4}	2.53×10^{-4}	2.74×10^{-4}
Terrestrial eutrophication	**molc N eq**	5.48×10^{-4}	5.43×10^{-4}	5.60×10^{-4}	6.41×10^{-4}	5.58×10^{-4}	5.27×10^{-4}	5.62×10^{-4}
Freshwater eutrophication	**kg P eq**	1.73×10^{-5}	1.66×10^{-5}	1.74×10^{-5}	1.93×10^{-5}	1.72×10^{-5}	1.64×10^{-5}	2.00×10^{-5}
Resource depletion	**kg Sb eq**	2.18×10^{-6}	2.16×10^{-6}	2.19×10^{-6}	2.53×10^{-6}	2.24×10^{-6}	2.26×10^{-6}	2.32×10^{-6}

Figure 3.15 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by electric trains in Belgium (from Table 3.37). The year 2009 presents the maximum impact in seven indicators mainly due to this year presents a high energy consumption for electric trains (547 kJ/tkm). The year 2006 presents the maximum impact in the indicator ionizing radiation due to the high import of electricity from France, where the nuclear power is the main source of energy.

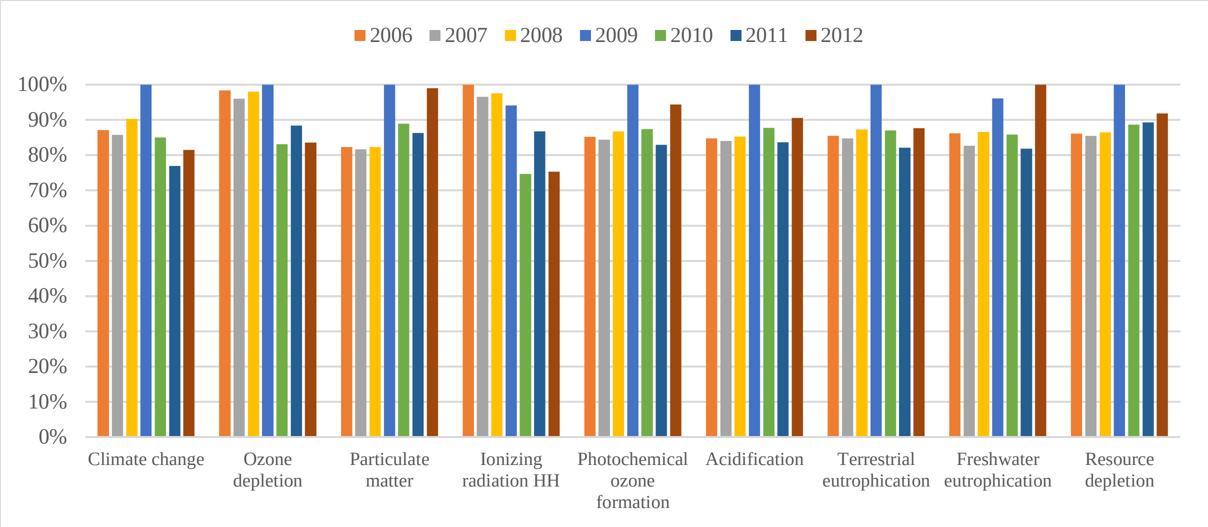


Figure 3.15. LCIA of 1 tkm transported by electric trains in Belgium

3.5.4. Contribution of the sub-systems rail transport operation, rail equipment and rail infrastructure to the environmental impact of rail freight transport

For the LCIA of the Belgian rail freight transport, all life cycle phases of rail freight transport operation (including the calculated electricity supply mix in Belgium corresponding to the appropriate year), rail equipment (i.e. locomotives and wagons) and rail infrastructure are considered. Table 3.38 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by rail in Belgium using the Belgian traction mix of 2012 (86.3% of electric traction and 13.7% of diesel traction).

Table 3.38. LCIA of 1 tkm transported by rail freight transport in Belgium in 2012

Impact category	Unit	Transport operation	Diesel production	Electricity supply mix	Rail track construction	Rail track maint.	Rail equip. mfg.	Rail equip. maint.	Total
Climate change	kg CO_2 eq	6.72×10^{-3}	1.20×10^{-3}	3.21×10^{-2}	1.36×10^{-2}	2.52×10^{-3}	4.44×10^{-3}	3.57×10^{-3}	6.42×10^{-2}
Ozone depletion	kg CFC-11 eq	0	1.44×10^{-9}	7.27×10^{-9}	1.39×10^{-9}	1.36×10^{-9}	2.58×10^{-10}	1.70×10^{-10}	1.19×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	3.51×10^{-6}	1.09×10^{-6}	8.06×10^{-6}	1.16×10^{-5}	2.01×10^{-6}	5.60×10^{-6}	3.62×10^{-6}	3.55×10^{-5}
Ionizing radiation HH	kBq U235 eq	0	5.54×10^{-4}	5.49×10^{-2}	1.16×10^{-3}	1.27×10^{-3}	3.82×10^{-4}	2.18×10^{-4}	5.85×10^{-2}
Photochemical ozone formation	kg NMVOC eq	1.25×10^{-4}	7.49×10^{-6}	5.63×10^{-5}	7.79×10^{-5}	8.55×10^{-6}	1.75×10^{-5}	9.76×10^{-6}	3.03×10^{-4}
Acidification	molc H+ eq	8.49×10^{-5}	1.38×10^{-5}	8.20×10^{-5}	1.03×10^{-4}	1.91×10^{-5}	3.62×10^{-5}	2.49×10^{-5}	3.64×10^{-4}
Terrestrial eutrophication	molc N eq	4.88×10^{-4}	1.69×10^{-5}	1.74×10^{-4}	2.53×10^{-4}	2.76×10^{-5}	5.23×10^{-5}	3.08×10^{-5}	1.04×10^{-3}
Freshwater eutrophication	kg P eq	0	1.27×10^{-7}	6.00×10^{-6}	7.42×10^{-6}	2.04×10^{-6}	3.12×10^{-6}	9.07×10^{-7}	1.96×10^{-5}
Resource depletion	kg Sb eq	0	1.73×10^{-8}	3.60×10^{-7}	1.37×10^{-6}	1.42×10^{-7}	4.27×10^{-7}	2.12×10^{-8}	2.34×10^{-6}

Table 3.39 shows the results obtained in the LCIA of one tonne-kilometre of freight transported by diesel trains (including shunting activity) in Belgium in 2012.

Table 3.39. LCIA of 1 tkm transported by diesel trains in Belgium in 2012

Impact category	Unit	Transport operation	Diesel production	Rail track construction	Rail track maint.	Rail equip. mfg.	Rail equip. maint.	Total
Climate change	kg CO_2 eq	4.83×10^{-2}	8.76×10^{-3}	1.36×10^{-2}	2.52×10^{-3}	5.98×10^{-3}	4.00×10^{-3}	8.32×10^{-2}
Ozone depletion	kg CFC-11 eq	0	1.05×10^{-8}	1.39×10^{-9}	1.36×10^{-9}	3.47×10^{-10}	1.97×10^{-10}	1.38×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	2.56×10^{-5}	7.98×10^{-6}	1.16×10^{-5}	2.01×10^{-6}	7.69×10^{-6}	4.07×10^{-6}	5.89×10^{-5}
Ionizing radiation HH	kBq U235 eq	0	4.04×10^{-3}	1.16×10^{-3}	1.27×10^{-3}	5.37×10^{-4}	2.56×10^{-4}	7.27×10^{-3}
Photochemical ozone formation	kg NMVOC eq	9.14×10^{-4}	5.47×10^{-5}	7.79×10^{-5}	8.54×10^{-6}	2.37×10^{-5}	1.13×10^{-5}	1.09×10^{-3}
Acidification	molc H+ eq	6.20×10^{-4}	1.01×10^{-4}	1.03×10^{-4}	1.91×10^{-5}	5.49×10^{-5}	2.80×10^{-5}	9.25×10^{-4}
Terrestrial eutrophication	molc N eq	3.56×10^{-3}	1.23×10^{-4}	2.53×10^{-4}	2.76×10^{-5}	7.17×10^{-5}	3.52×10^{-5}	4.07×10^{-3}
Freshwater eutrophication	kg P eq	0	9.27×10^{-7}	7.42×10^{-6}	2.04×10^{-6}	5.34×10^{-6}	1.15×10^{-6}	1.69×10^{-5}
Resource depletion	kg Sb eq	0	1.26×10^{-7}	1.37×10^{-6}	1.42×10^{-7}	7.61×10^{-7}	4.70×10^{-8}	2.45×10^{-6}

Table 3.40 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by electric trains in Belgium in 2012. The transport operation stage includes the direct emissions of SF_6 (a powerful GHG) during electricity conversion at traction substations and particles (PM_{10} and PM) from abrasion. On the one hand, the LCIA results shows an impact on climate change due to the SF_6 emissions. On the other hand, ILCD 2011 does not consider the particle emissions emitted to air from abrasion in the indicator particulate matter. A discussion of the indicator particulate matter is presented in Section 6.3.2 (see Figure 6.7).

Table 3.40. LCIA of 1 tkm transported by electric trains in Belgium in 2012

Impact category	Unit	Transport operation	Electricity supply mix	Rail track construction	Rail track maint.	Rail equip. mfg.	Rail equip. maint.	Total
Climate change	kg CO_2 eq	1.19×10^{-4}	3.72×10^{-2}	1.36×10^{-2}	2.52×10^{-3}	4.20×10^{-3}	3.51×10^{-3}	6.12×10^{-2}
Ozone depletion	kg CFC-11 eq	0	8.43×10^{-9}	1.39×10^{-9}	1.36×10^{-9}	2.44×10^{-10}	1.66×10^{-10}	1.16×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	0	9.35×10^{-6}	1.16×10^{-5}	2.01×10^{-6}	5.27×10^{-6}	3.55×10^{-6}	3.17×10^{-5}
Ionizing radiation HH	kBq U235 eq	0	6.37×10^{-2}	1.16×10^{-3}	1.27×10^{-3}	3.57×10^{-4}	2.12×10^{-4}	6.67×10^{-2}
Photochemical ozone formation	kg NMVOC eq	0	6.53×10^{-5}	7.79×10^{-5}	8.54×10^{-6}	1.65×10^{-5}	9.51×10^{-6}	1.78×10^{-4}
Acidification	molc H+ eq	0	9.50×10^{-5}	1.03×10^{-4}	1.91×10^{-5}	3.32×10^{-5}	2.44×10^{-5}	2.74×10^{-4}
Terrestrial eutrophication	molc N eq	0	2.02×10^{-4}	2.53×10^{-4}	2.76×10^{-5}	4.92×10^{-5}	3.01×10^{-5}	5.62×10^{-4}
Freshwater eutrophication	kg P eq	0	6.95×10^{-6}	7.42×10^{-6}	2.04×10^{-6}	2.77×10^{-6}	8.69×10^{-7}	2.00×10^{-5}
Resource depletion	kg Sb eq	0	4.17×10^{-7}	1.37×10^{-6}	1.42×10^{-7}	3.73×10^{-7}	1.71×10^{-8}	2.32×10^{-6}

Figure 3.16 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported by different modes of rail freight transport in Belgium in the year 2012: rail freight transport considering the Belgian traction mix of 2012 (see Table 3.38), diesel trains (see Table 3.39) and electric trains (see Table 3.40).

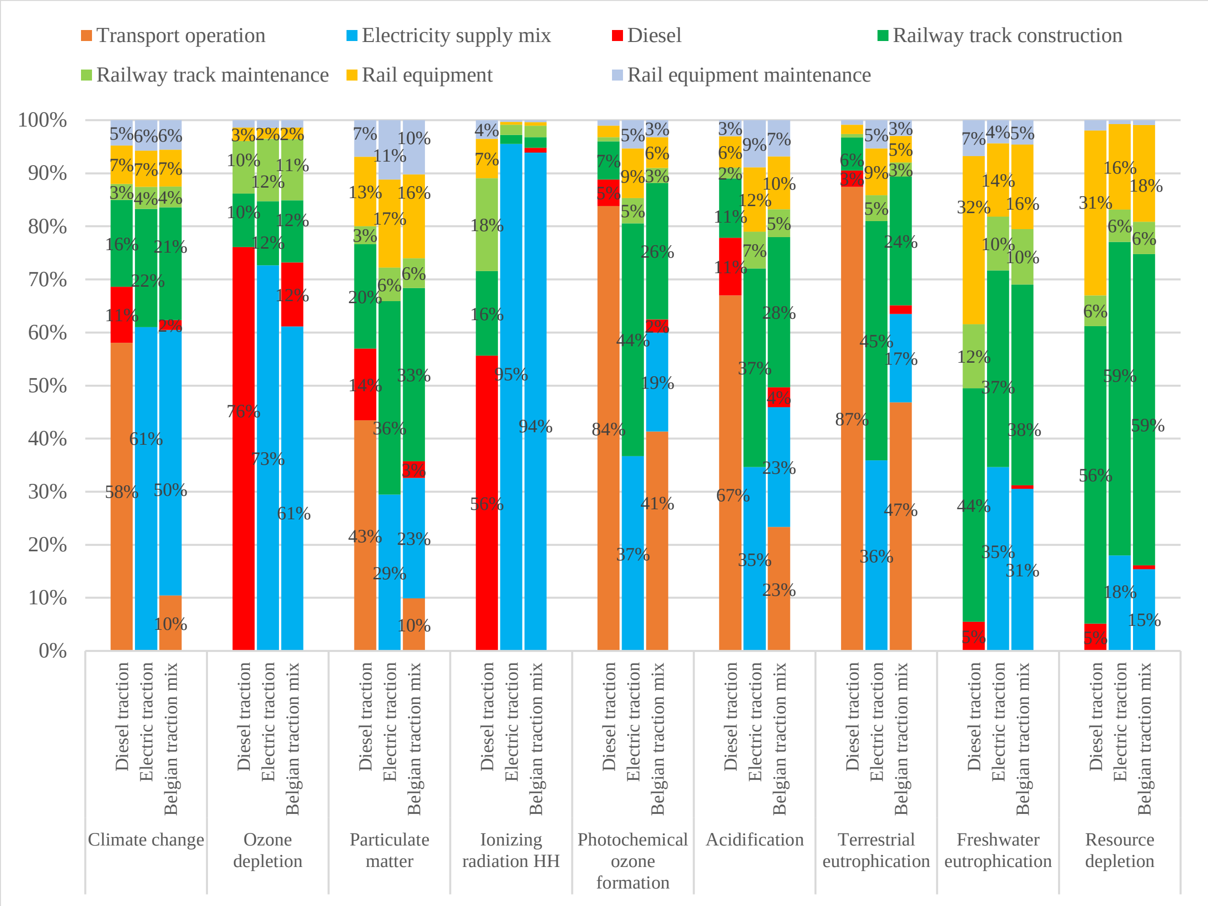


Figure 3.16. LCIA of 1 tkm of rail freight transport using diesel traction, electric traction and the Belgian traction mix of 2012

For diesel trains, the transport operation stage is the main source of impact in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions of diesel locomotives.

For the indicator climate change, the transport operation is the main source of GHG in diesel trains. For the indicator particulate matter, the exhaust emissions of $PM_{2.5}$, NO_X and SO_2 during the transport operation are the main source of impact. Particulate matter can be emitted directly from locomotives (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as SO_X, NO_X, NH_3 or VOC. Moreover, the exhaust emissions of NO_X and NMVOC are the main contributor in the indicator photochemical ozone formation. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC by photochemical reaction under the influence of solar radiation. Furthermore, the exhaust emissions of NO_X are the main source of impact in the indicators acidification (SO_2 emissions also have a great influence) and terrestrial eutrophication.

For the indicator ozone depletion, the main contributor of the impact in diesel trains is the emissions of bromotrifluoromethane ($CBrF_3$ or halon 1 301) to air during the petroleum refinery operation. This gas contributes to the depletion of the stratospheric ozone layer, which filters ultraviolet radiation from the sun.

For electric trains, the electricity generation is the most significant stage in terms of impact in the indicators climate change, ozone depletion and ionizing radiation. The GHG emitted by the natural gas and coal power plants represent the 22.7% and 10.7% of the total impact of electric trains in the indicator climate change, respectively. In Belgium, the natural gas power plants contributed 22.18% of the total electricity supply mix and the coal power plants were responsible for 4.99% in the year 2012. For the indicator ozone depletion, nuclear power is the main contributor due to the used of refrigerant gases in the uranium enrichment. For the indicator ionizing radiation (damage to human health), the nuclear power represent the 76% of the total impact of electric trains in this indicator.

Moreover, the electricity generation is an important contributor in the indicator freshwater eutrophication due to the hard coal and lignite mining. The hard coal and lignite power plants were responsible for 42.03% of the total electricity supply mix in Germany in the year 2012 and this, together that Germany was the main exporter of electricity to The Netherlands (24.39%) and Luxembourg (65.26%), which in turn were exporting countries of electricity to Belgium (9.63% from The Netherlands and 1.67% from Luxembourg), results in a higher impact in the indicator freshwater eutrophication of electric trains. Moreover, as mentioned above, the coal power plants contributed 4.99% of the total electricity supply mix in the year 2012.

The railway infrastructure construction is the main contributor in both indicators freshwater eutrophication due to the pollution from the production of primary copper and steel and resource depletion due to the consumption of materials such as gravel, steel and copper. Furthermore, the impact generated by the railway infrastructure construction is important in the indicator particulate matter due to the emissions of particles during the steel and gravel production and transport during the dismantling of the infrastructure. The railway infrastructure maintenance presents an important impact in the indicators ozone depletion, freshwater eutrophication and resource depletion as a result of the use of herbicides for weed control. For the indicator freshwater eutrophication, glyphosate represents the 9.6% and 8.1% of the total impact for diesel trains and electric trains, respectively.

Focusing on the rail equipment, the pollution from the production of the steel used in the wagons manufacturing is a main contributor in the indicators freshwater eutrophication and resource depletion in both diesel and electric trains. For diesel trains, the production of primary copper, lead and aluminium used in the locomotives is important in the indicator freshwater eutrophication, and the copper used in the locomotives is important in the indicator resource depletion. It should be noted the higher locomotive demand of diesel traction compared to electric traction.

3.5.5. Life Cycle Impact Assessment of electric trains using different electricity supply mix

The electricity supply mix used for electric trains plays an important role in determining their environmental impacts. Therefore, depending on the energy split of the country (i.e. the share of nuclear or natural gas power for example), the environmental impacts of the electric trains varies. In order to determine how the electricity supply mix affect the environmental impact of electric trains when they run through different countries in Europe, it has been used the electricity supply mix of Belgium, Germany, France, Italy, Luxembourg, The Netherlands and Poland corresponding to 2012 (see Table 3.41) according to Eurostat data (Eurostat statistics, 2017). The electricity supply mix for every country has been calculated using the domestic production of the different countries and exports and imports of electricity. The processes related to electricity supply mix of the corresponding countries from Ecoinvent v3 database (Weidema et al., 2013) has been taken as a model to translate the data from Eurostat on energy sources to the technologies used in the electricity production in our study.

Table 3.41. Electricity supply mix of Belgium {BE}, Germany {DE}, France {FR}, Italy {IT}, Luxembourg {LU}, The Netherlands {NL} and Poland {PL} in the year 2012. Sources: Eurostat statistics, 2017; Weidema et al., 2013

Energy source (%)	{BE}	{DE}	{FR}	{IT}	{LU}	{NL}	{PL}
Hard coal	4.99	18.81	2.84	10.67	-	14.19	49.23
Lignite	-	23.22	-	-	-	-	32.03
Hydro, pumped storage	1.41	1.02	0.90	0.66	5.21	-	0.28
Hydro, run-of-river	1.79	3.86	9.72	5.10	5.65	0.09	1.61
Hydro, reservoir, non-alpine region	-	0.76	-	-	-	-	-
Hydro, reservoir, alpine region	-	-	1.86	9.07	-	-	-
Natural gas	22.18	12.69	2.66	42.85	11.38	38.58	1.86
Natural gas, 10 MW	-	0.00	-	-	-	0.00	-
Nuclear, pressure water reactor	41.88	12.69	75.42	-	-	3.24	-
Nuclear, boiling water reactor	-	3.44	-	-	-	-	-
Oil	0.37	1.39	0.71	7.81		1.26	1.36
Wind, <1MW turbine, onshore	0.09	1.4	0.21	1.52	0.09	1.10	0.07
Wind, >3MW turbine, onshore	0.29	0.75	0.05	0.28	-	0.14	0.51
Wind, 1-3MW turbine, offshore	0.09	0.02	-	-	-	0.46	-
Wind, 1-3MW turbine, onshore	2.47	6.47	2.35	2.63	0.29	1.81	2.54
Geothermal	-	0.00	-	1.74	-	-	-
Co-generation, biogas	0.43	1.64	0.08	0.41	0.21	0.71	0.15
Co-generation, wood chips	2.24	1.35	0.18	0.68	-	1.58	1.88
Treatment of blast furnace gas	1.45	1.11	0.36	0.97	-	1.87	0.31
Treatment of coal gas	0.06	0.32	0.11	0.41	-	0.19	0.98
Import from Belgium	-	-	0.49	-	11.91	4.00	-
Import from France	8.96	2.59	-	4.21	0.00	0.00	-
Import from Luxembourg	1.67	0.00	-	-	-	-	-
Import from The Netherlands	9.63	0.15	-	-	-	-	-
Import from Germany	-	-	0.22	-	65.26	24.39	4.44
Import from Switzerland	-	0.74	0.71	8.47	-	-	-
Import from Italy	-	-	0.25	-	-	-	-
Import from Poland	-	0.03	-	-	-	-	-
Import from Austria	-	1.61	-	0.38	-	-	-
Import from Czech Republic	-	1.65	-	-	-	-	0.06
Import from Sweden	-	0.57	-	-	-	-	1.96
Import from United Kingdom	-	-	0.25	-	-	0.28	-
Import from Denmark	-	1.73	-	-	-	-	-
Import from Greece	-	-	-	0.85	-	-	-
Import from Slovenia	-	-	-	1.29	-	-	-
Import from Spain	-	-	0.63	-	-	-	-
Import from Norway	-	-	-	-	-	6.10	-
Import from Ukraine	-	-	-	-	-	-	0.74

Table 3.42 presents the results obtained in the LCIA of one kWh of electricity of Belgium, Germany, France, Italy, Luxembourg, The Netherlands and Poland in the year 2012 using the electricity supply mix of Table 3.41.

Table 3.42. LCIA of 1 kWh of electricity supply mix of Belgium {BE}, Germany {DE}, France {FR}, Italy {IT}, Luxembourg {LU}, The Netherlands {NL} and Poland {PL} in the year 2012

Impact category	Unit	{BE}	{DE}	{FR}	{IT}	{LU}	{NL}	{PL}
Climate change	**kg CO_2 eq**	3.14×10^{-1}	6.72×10^{-1}	8.84E-02	5.69×10^{-1}	6.25×10^{-1}	6.31×10^{-1}	1.07
Ozone depletion	**kg CFC-11 eq**	7.11×10^{-8}	4.01×10^{-8}	8.86×10^{-8}	7.65×10^{-8}	4.49×10^{-8}	3.64×10^{-8}	1.27×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	7.89×10^{-5}	7.60×10^{-5}	4.76×10^{-5}	1.94×10^{-4}	8.67×10^{-5}	5.81×10^{-5}	4.19×10^{-4}
Ionizing radiation HH	**kBq U235 eq**	5.37×10^{-1}	1.96×10^{-1}	7.98×10^{-1}	1.12×10^{-1}	2.50×10^{-1}	1.19×10^{-1}	3.46×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	5.51×10^{-4}	6.56×10^{-4}	2.21×10^{-4}	1.26×10^{-3}	6.94×10^{-4}	6.59×10^{-4}	2.29×10^{-3}
Acidification	**molc H+ eq**	8.02×10^{-4}	1.08×10^{-3}	4.91×10^{-4}	2.81×10^{-3}	1.34×10^{-3}	8.35×10^{-4}	7.27×10^{-3}
Terrestrial eutrophication	**molc N eq**	1.70×10^{-3}	2.33×10^{-3}	7.43×10^{-4}	4.06×10^{-3}	2.3×10^{-3}	2.48×10^{-3}	7.54×10^{-3}
Freshwater eutrophication	**kg P eq**	586×10^{-5}	7.71×10^{-4}	1.62×10^{-5}	1.06×10^{-4}	5.47×10^{-4}	2.26×10^{-4}	1.14×10^{-3}
Resource depletion	**kg Sb eq**	3.52×10^{-6}	2.32×10^{-6}	4.83×10^{-6}	1.80×10^{-6}	2.45×10^{-6}	1.63×10^{-6}	1.31×10^{-6}

Figure 3.17 shows a comparison of the results obtained in the environmental impact assessment of one kWh of electricity supply mix of Belgium, Germany, France, Italy, Luxembourg, The Netherlands and Poland in the year 2012 (from Table 3.42).

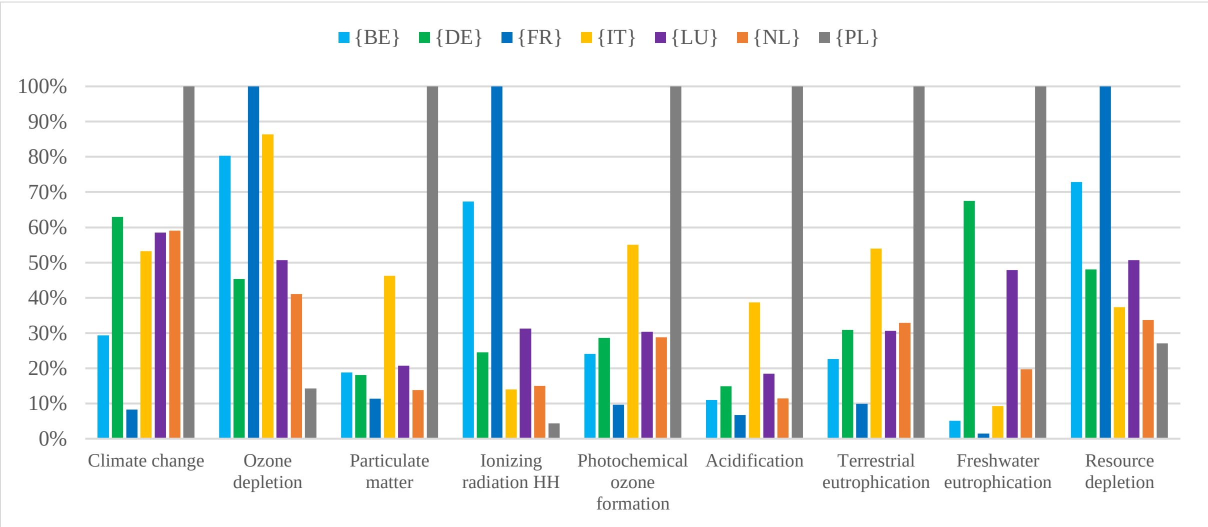


Figure 3.17. LCIA of 1 kWh of electricity supply mix of Belgium {BE}, Germany {DE}, France {FR}, Italy {IT}, Luxembourg {LU}, The Netherlands {NL} and Poland {PL} in the year 2012

The electricity supply mix of Poland presents the maximum impact in the indicators climate change, particulate matter, photochemical ozone formation, acidification, terrestrial eutrophication and freshwater eutrophication. This is due to the dominant use of hard coal and lignite in the electricity generation, generating large emissions from coal power plants of GHG, NO_X, SO_2 and particles. Moreover, the lignite mining is the most significant stage for the indicator freshwater eutrophication. The electricity supply mix of France shows the highest impact in the indicators ozone depletion due to the use of refrigerant gases in the uranium enrichment, ionizing radiation (damage to human health) due to the predominance of nuclear power and resource depletion due to the high amount of uranium used in nuclear power plants.

The purpose of the comparison of electric trains in different countries in Europe is to understand how the electricity supply mix affect the environmental impact of electric trains when they cross the border between countries. Therefore, since we assume that the train is the same, the processes related to the rail equipment and rail transport operation (except for electricity supply mix) such as energy consumption remains the same. However, it has been used the railway infrastructure process "Railway track {RoW}| market for | Alloc Rec, U" and demand from the Ecoinvent v3 database (Weidema et al., 2013). Thus, it has been taken into account a railway infrastructure demand of 8.63×10^{-5} m×a/tkm for Germany, 8.91×10^{-5} (m×a)/tkm for France, 6.29×10^{-5} (m×a)/tkm for Italy and 9.30×10^{-5} (m×a)/tkm for The Netherlands, Luxembourg and Poland (Weidema et al., 2013). Table 3.43 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by electric trains in Germany, France, Italy, Luxembourg, The Netherlands and Poland in the year 2012.

Table 3.43. LCIA of 1 tkm transported by electric trains in Germany {DE}, France {FR}, Italy {IT}, Luxembourg {LU}, The Netherlands {NL} and Poland {PL} in the year 2012

Impact category	Unit	{DE}	{FR}	{IT}	{LU}	{NL}	{PL}
Climate change	**kg CO_2 eq**	9.90×10^{-2}	3.03×10^{-2}	8.37×10^{-2}	9.51×10^{-2}	9.44×10^{-2}	1.47×10^{-1}
Ozone depletion	**kg CFC-11 eq**	6.13×10^{-9}	1.19×10^{-8}	1.02×10^{-8}	5.77×10^{-9}	6.78×10^{-9}	2.96×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	2.76×10^{-5}	2.45×10^{-5}	3.89×10^{-5}	2.62×10^{-5}	2.96×10^{-5}	6.90×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	2.53×10^{-2}	9.67×10^{-2}	1.49×10^{-2}	1.64×10^{-2}	3.18×10^{-2}	6.31×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	1.55×10^{-4}	1.05×10^{-4}	2.13×10^{-4}	1.59×10^{-4}	1.64×10^{-4}	3.52×10^{-4}
Acidification	**molc H+ eq**	2.66×10^{-4}	1.98×10^{-4}	4.49×10^{-4}	2.43×10^{-4}	3.03×10^{-4}	1.01×10^{-3}
Terrestrial eutrophication	**molc N eq**	5.28×10^{-4}	3.45×10^{-4}	6.86×10^{-4}	5.59×10^{-4}	5.38×10^{-4}	1.16×10^{-3}
Freshwater eutrophication	**kg P eq**	9.92×10^{-5}	9.84×10^{-6}	1.92×10^{-5}	3.49×10^{-5}	7.29×10^{-5}	1.44×10^{-4}
Resource depletion	**kg Sb eq**	1.35×10^{-6}	1.67×10^{-6}	1.10×10^{-6}	1.32×10^{-6}	1.42×10^{-6}	1.28×10^{-6}

Figure 3.18 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported by different modes of rail freight transport in Belgium in the year 2012, i.e. rail freight transport considering the Belgian traction mix (see Table 3.35), diesel trains (see Table 3.36) and electric trains (see Table 3.37), and electric trains in Germany, France, Italy, Luxembourg, The Netherlands and Poland corresponding to the year 2012 (see Table 3.43).

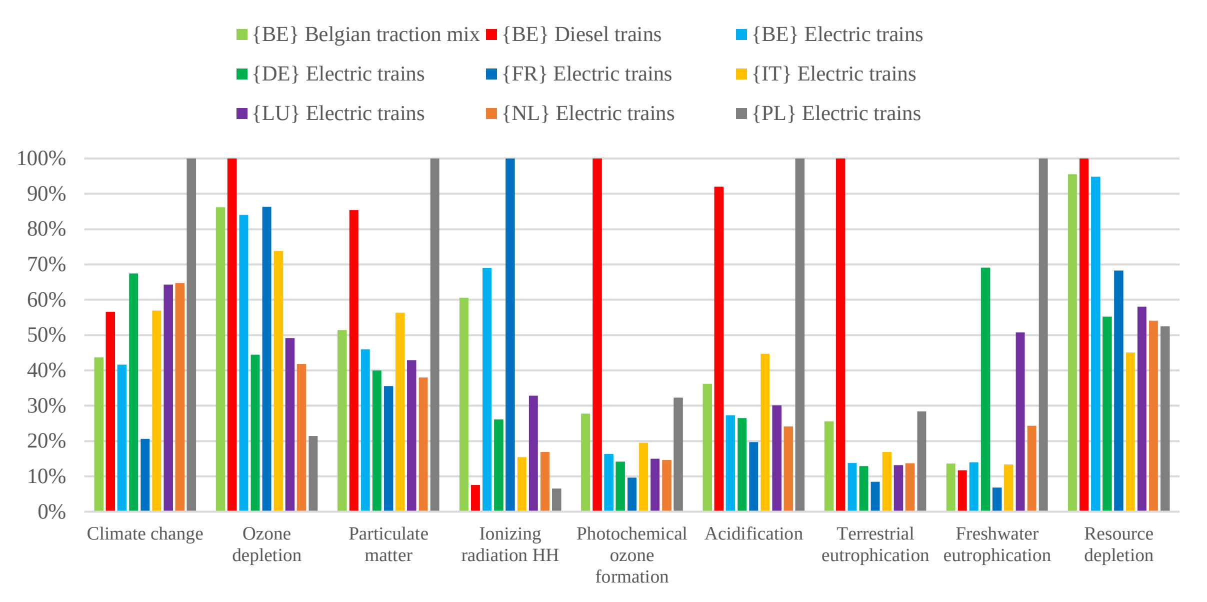


Figure 3.18. LCIA of 1 tkm transported by rail freight transport, diesel trains and electric trains in Belgium {BE}, and electric trains in Germany {DE}, France {FR}, Italy {IT}, Luxembourg {LU}, The Netherlands {NL} and Poland {PL} in the year 2012

Due to uncertainties regarding the LCIA results, a discussion of the most significant differences between scenarios has been performed. Diesel trains present the maximum impact in the indicators photochemical ozone formation and terrestrial eutrophication due to the exhaust emissions (especially NO_X and NMVOC direct emissions) produced in the diesel locomotives during the transport operation. This highlights the importance of upgrading the emission engine technology of diesel locomotives. However, the low rate of replacement of locomotives due to their longer life span causes a slow implementation of new engines with better emission technologies. Moreover, diesel trains show the maximum impact in the indicator ozone depletion due to the pollutant emissions to air during the petroleum refinery operation. Furthermore, diesel trains present the maximum impact in the indicator resource depletion, but with a similar value than the Belgian electric trains and Belgian traction mix as a result of the similar demand of gravel, steel and copper for the construction of the railway infrastructure and the steel demand for the manufacturing and rolling stock. It should be noted that while in the case of Belgium it has been performed a detailed study of the railway infrastructure has been performed, for the other countries the inventory and infrastructure demand from Ecoinvent v3 database has been used. This implies a higher material demand for the Belgian railway infrastructure due to the greater completeness of our study and therefore a higher environmental impact.

Electric trains using the electricity supply mix of Poland present the maximum impact in the indicators climate change, particulate matter, acidification and freshwater eutrophication due to the use of a 49.23% of hard coal and 32.03% of lignite in the electricity generation in Poland. Thereby, the large emissions from coal power plants of GHG have a great impact on climate change, SO_2 and particles emissions affect the indicator particulate matter and the SO_2 and NO_X emissions affect the indicator acidification. For the indicator freshwater eutrophication, the main impact is produced in the lignite mining.

As shown in Figure 3.18, an electric train using the electricity supply mix of Poland has almost twice the impact on climate change than a diesel train in Belgium. This highlights the importance of the electricity source that is used in electric trains. Therefore, the use of fossil energy in the generation of electricity can lead to rail freight transport using electric traction to be more polluting for climate change than rail freight transport using fossil energies such as diesel. It must be borne in mind that the use of electric trains leads to a reduction in local air pollution (NO_X, particles, NMVOC and SO_2 for example). Thereby, the use of electric trains avoids the population exposure to air pollutants emitted at ground level by diesel trains in highly populated areas.

Electric trains using the electricity supply mix of France show the maximum impact in the indicator ionizing radiation (damage to human health) due to the use of a 75.42% of nuclear power in the electricity production in France in 2012. Since the use of nuclear power in the electricity production is the determining factor in this indicator, the Belgian electric trains and the Belgian traction mix (with an 86.3% of electric trains) are the second and third with a higher impact, respectively. The nuclear power plants were responsible for 41.88% of the total electricity supply mix in Belgium in 2012. It should be noted that nuclear fission does not generate air emissions such as GHG that affect climate change, but instead it produces nuclear wastes with a high potential impact on human health and ecosystems.

3.5.6. Uncertainty analysis of the comparison of the results obtained in the LCIA of diesel and electric trains in Belgium in 2012

An uncertainty analysis performed with the Monte Carlo method has been conducted to compare the robustness of the LCIA results obtained for diesel and electric trains in Belgium. All calculations of this uncertainty analysis have been performed with the Monte Carlo implementation (set at 10 000 the number of iterations) of SimaPro 8.0.5 software (Pré, 2013). A further analysis of the uncertainty of diesel and electric trains is carried out in Section 6.4. Figure 3.19 shows the Monte Carlo results of the comparison of the LCIA of diesel and electric trains in Belgium in 2012.

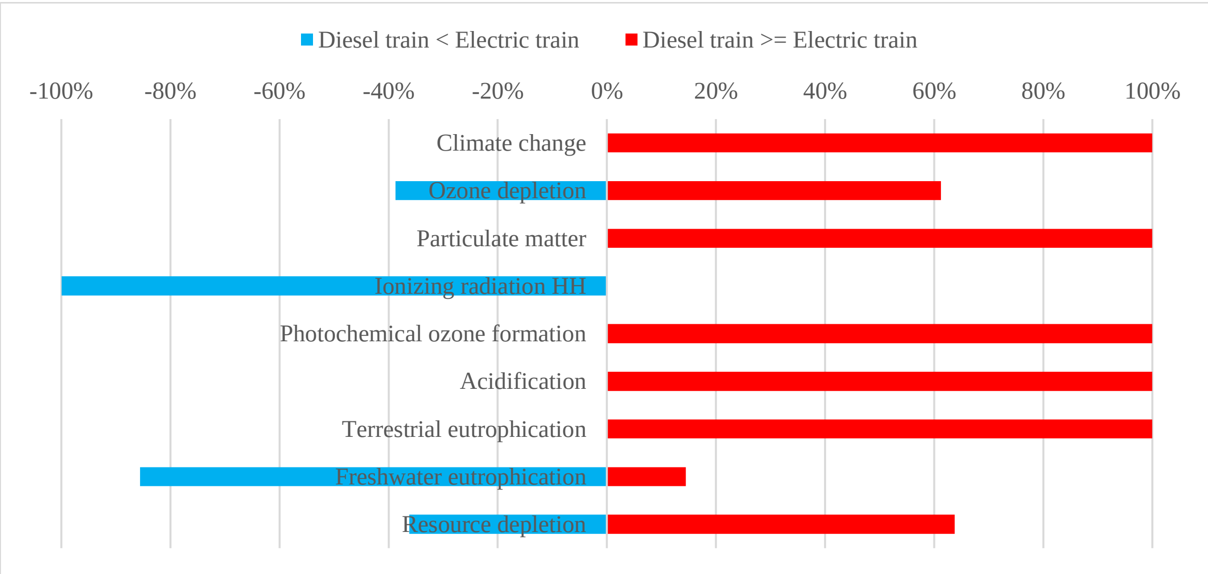


Figure 3.19. Monte Carlo results of the comparison of the LCIA of diesel and electric trains in Belgium in 2012

On the one hand, the blue bars represent the number of times the scenario where diesel trains had a lower impact than electric trains (left). On the other hand, the red bars represent the number of times the scenario where diesel trains had a higher impact than electric trains (right). There is a 100% chance diesel trains have a higher environmental impact than electric trains on the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. For the indicator ionizing radiation (damage to human health), electric trains present a 100% probability of having a higher score than diesel trains. For the indicators ozone depletion and resource depletion, diesel trains obtain a higher impact in the 61% and 64% of the iterations, respectively. Electric trains present a higher impact in the 86% of the iteration in the indicator freshwater eutrophication.

Chapter 4. Life Cycle Assessment of inland waterways transport

4.1. Introduction

Figure 4.1 presents the system boundaries considered in our study for inland waterways (IWW) transport. The IWW transport system has been divided in three sub-systems: IWW operation, vessel and IWW infrastructure (including canals and port facilities). The sub-system IWW operation includes the processes that are directly connected with the barge activity. Therefore, it takes into account the exhaust emissions to air from barges and the indirect emissions from fuel production. Moreover, the application of the LCA methodology involves the analysis of the environmental impacts related to the manufacturing, maintenance and disposal of the vessel and the construction, maintenance and disposal of the IWW infrastructure (Spielmann et al., 2007).

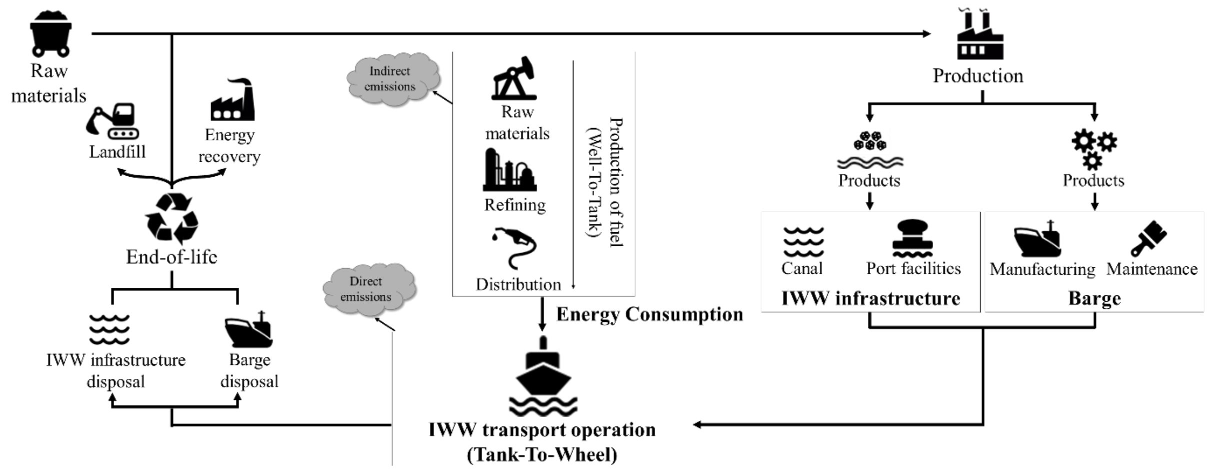


Figure 4.1. IWW transport system boundaries considered in our study. Source: Based on Spielmann et al., 2007

4.2. IWW transport operation

The main processes included in the sub-system IWW transport operation can be divided in two stages. On the one hand, the Well-To-Tank (WTT) stage comprises the primary energy consumption and indirect emissions produced at the upstream energy processes, which start with the crude oil extraction, continue with the fuel refining and end with the fuel distribution to the vessel. On the other hand, the Tank-To-Wheels (TTW) stage encompasses the energy consumption of barges and exhaust emissions to air during the transport activity. The Well-To-Wheels (WTW) processes would be the sum of the WTT processes and the TTW processes.

4.2.1. Energy consumption (Tank-To-Wheel) of IWW transport

The average energy consumption during the IWW transport activity has been determined using the class specific fuel consumption of barges in Wallonia from Service Public de Wallonie (2014) shown in Table 4.1. These specific fuel consumptions are based on the results obtained in the study of ADEME, VNF, TL&Associés (2006), which considers a load factor between 80% and 100% for IWW transport in northern France. Since the barge provides other functions such as home for the shippers, an allocation of the energy consumption could be performed. ADEME, VNF, TL&Associés (2006) estimate an annual average fuel consumption of 2 200 L of gas-oil for heating per barge. This energy consumption on heating has been decorrelated from the energy consumption related to freight transport (ADEME, VNF, TL&Associés, 2006). Therefore, we assume the exclusively use of fuel from Table 4.1 for freight transport. Regarding other literature sources, Van Lier and Macharis (2014) use for selected IWW in Flanders (Belgium) load factors in the range from 61.4% to 80.8%. Moreover, Table 4.1 presents the values used by Spielmann et al. (2007) to calculate the energy consumption of IWW transport used in Ecoinvent v3 considering a load factor of 71%. It should be noted that the values from Spielmann et al. (2007) are higher than the values for Belgium used in our study.

Table 4.1. Specific energy consumption (g/tkm) of IWW transport in Belgium. Source: Service Public de Wallonie, 2014

Vessel class	Loaded (g/tkm)			Empty (g/km)			Spielmann et al. (2007)[1] (g/tkm)
	Canal	River		Canal	River		
		Upstream	Downstream		Upstream	Downstream	
<250 t	10.25	11.51	10.08	3 864	2 940	1 596	23
250 t – 399 t	10.25	11.51	10.08	3 864	2 940	1 596	23
400 t – 649 t	9.49	9.74	9.32	4 452	3 612	2 772	10.4
650 t – 999 t	8.74	8.32	7.98	5 124	4 368	3 864	7
1 000 t – 1 499 t	8.06	4.79	4.03	5 880	4 452	3 864	8.2
1 500 t – 2 999 t	7.39	4.45	3.44	6 804	6 216	5 460	8.2
>3 000 t	4.20	3.78	3.11	8 232	8 568	6 636	8.2

[1]Source: Spielmann et al., 2007

Table 4.2 presents the specific energy consumptions of IWW transport in Europe (EcoTransIT, 2008). By comparing the values used in our study for Belgium with the values from EcoTransIT (2008) and Spielmann et al. (2007), they can vary widely depending on the vessel class. Therefore, it must be borne in mind that depending on the literature source used to calculate the energy consumption of IWW transport, the results may change significantly.

Table 4.2. Specific energy consumption (g/tkm) of IWW transport in Europe. Source: EcoTransIT, 2008

Vessel class	Loaded 100% (g/tkm)				Empty (g/km)			
	With sluices		Free flow		With sluices		Free flow	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
800 t	7.0	4.9	11.7	4.4	4 683	3 442	7 072	2 740
1 250 t	6.1	4.4	10.3	4.0	6 463	4 752	9 718	3 770
1 750 t	5.6	4.0	9.4	3.7	8 336	6 112	12 551	4 871
2 500 t	4.7	3.3	7.7	3.0	9 624	7 072	14 495	5 643

The chosen values regarding energy consumption from Service Public de Wallonie (2014) have been aggregated using the total carrying capacity of each vessel class by year from the period 2006 to 2012 (see Table 4.3) as allocation factor.

Table 4.3. Tonnage (t/year) of dry bulk barges in Belgium by vessel class. Sources: ITB, 2007, 2008, 2009, 2010, 2012, 2013

Vessel class	2006	2007	2008	2009	2010	2011	2012
<250 t	2 448	3 947	4 176	3 323	2 871	3 446	3 595
251 t – 450 t	115 068	103 812	96 513	91 662	87 596	78 726	72 071
451 t – 650 t	85 909	80 693	72 066	72 836	68 222	63 551	63 193
651 t – 850 t	77 600	71 358	64 625	61 135	58 988	54 852	50 646
851 t – 1 000 t	72 450	65 900	65 486	58 151	55 850	48 416	41 895
1 001 t – 1 500 t	320 440	325 035	317 936	296 911	280 938	268 805	263 778
1 501 t – 2 000 t	132 898	138 658	131 161	129 578	134 418	118 650	110 414
2 001 t – 2 500 t	160 131	144 527	141 009	138 400	136 363	128 367	137 369
2 501 t – 3 000 t	278 908	260 489	224 229	227 298	229 233	228 739	222 872
>3 000 t	265 451	321 592	393 622	445 115	498 284	510 206	511 032
TOTAL	1 511 303	1 516 011	1 510 823	1 524 409	1 552 763	1 503 758	1 476 865

Figure 4.2 shows the distribution by tonnage of dry bulk barges in Belgium by vessel class from Table 4.3. The share of the vessel class >3 000 t has grown from 18% in 2006 to 35% in 2012.

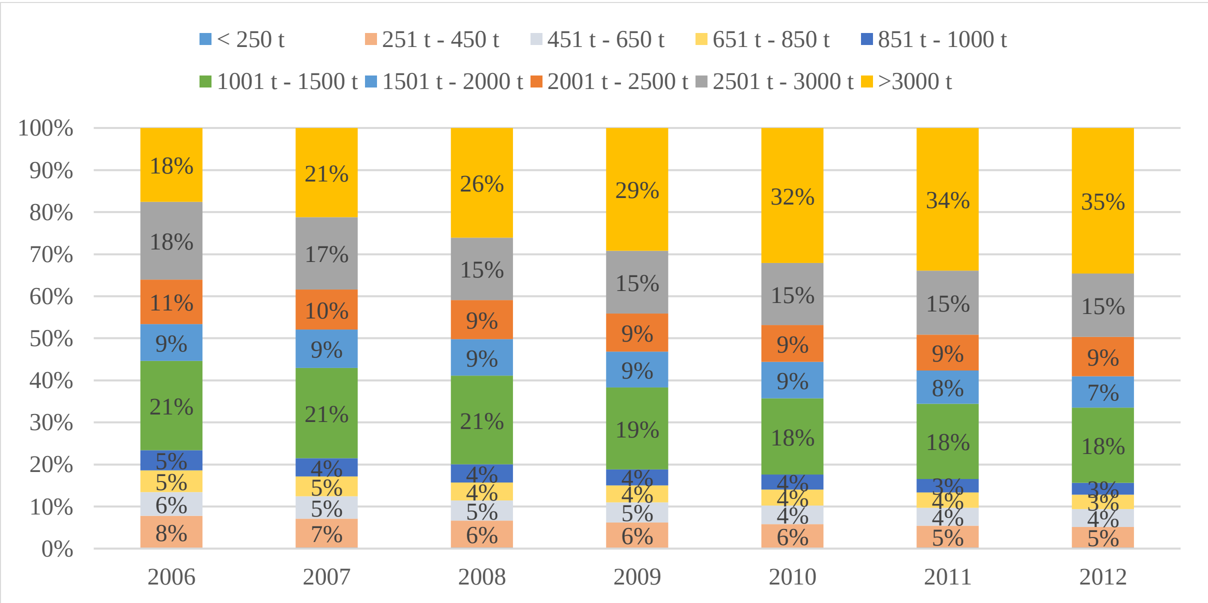


Figure 4.2. Distribution by tonnage of dry bulk barges in Belgium by vessel class

Table 4.4 shows the methodology used to calculate the average fuel consumption of IWW transport by weighted arithmetic mean each year taking as an example the specific fuel consumption in canals in the year 2012. The average fuel consumption of 2012 for dry bulk cargo in canals was 6.73 g/tkm or 288 kJ/tkm considering that diesel net calories are 42.8 MJ/kg.

Table 4.4. Average fuel consumption of dry bulk barges in canals in Belgium in 2012

Vessel class	Tonnage (t)[1]	Share	Class specific fuel consumption in canals (g/tkm)[2]	Contribution to average fuel consumption (g/tkm)
<250 t	3 595	0.24%	10.25	0.02
251 t – 450 t	72 071	5%	10.25	0.50
451 t – 650 t	63 193	4%	9.49	0.41
651 t – 850 t	50 646	3%	8.74	0.30
851 t – 1 000 t	41 895	3%	8.74	0.25
1 001 t – 1 500 t	263 778	18%	8.06	1.44
1 501 t – 2 000 t	110 414	7%	7.39	0.55
2 001 t – 2 500 t	137 369	9%	7.39	0.69
2 501 t – 3 000 t	222 872	15%	7.39	1.12
>3 000 t	511 032	35%	4.20	1.45
TOTAL	1 476 865	100%	-	6.73

[1]Source: ITB, 2013; [2]Source: Service Public de Wallonie, 2014

Table 4.5 shows the average fuel consumption of IWW transport calculated from the period 2006 to 2012. The values used in EcoTransIT (2008) are 727 kJ/tkm and 438 kJ/tkm for IWW transport upstream and downstream, respectively. These values represent European averages of the year 2005 and comprise both the final energy consumption during transport operation and the energy consumption of the generation of fuel, i.e. WTW energy consumption (EcoTransIT, 2008). By comparing the values used in EcoTransIT (2008) with the energy consumptions obtained in our study, our results for Belgium in the year 2006 show lower energy consumptions with 241 kJ/tkm and 206 kJ/tkm for IWW transport upstream and downstream, respectively. The great difference in energy consumption between the values of EcoTransIT (2008) and our results is mainly due to the higher specific energy consumptions used by EcoTransIT (2008) compared to those used in our study, especially for IWW transport upstream (see Table 4.2), and the inclusion of the primary energy consumption from fuel production.

Table 4.5. Average fuel consumption of IWW transport of dry bulk in Belgium

	Unit	2006	2007	2008	2009	2010	2011	2012
Canals	**g/tkm**	7.45	7.30	7.11	6.97	6.85	6.77	6.73
	kJ/tkm[1]	319	312	304	299	293	290	288
Upstream	**g/tkm**	5.64	5.51	5.40	5.32	5.23	5.16	5.11
	kJ/tkm[1]	241	236	231	228	224	221	219
Downstream	**g/tkm**	4.81	4.69	4.59	4.51	4.42	4.36	4.31
	kJ/tkm[1]	206	201	197	193	189	187	184

[1]Considering that diesel net calories are 42.8 MJ/kg

In the case of Ecoinvent v3 database, the energy consumption for IWW transport for the year 2014 is 402 kJ/tkm. This value represents a European average and considers only the final energy consumption during transport operation. By comparing the values obtained in our study with the values from Ecoinvent v3 database, our results for Belgium show lower energy consumptions. As mentioned above, the value of the Ecoinvent v3 database is calculated by Spielmann et al. (2007) using a higher specific energy consumption than those used in our study (see Table 4.1).

Figure 4.3 shows a comparison of the results obtained in average fuel consumption of one tonne-kilometre of freight transported by IWW transport in Belgium (from Table 4.5). The share of the vessel class >3 000 t has grown over the years and this, together the vessel class >3 000 t presents the lowest fuel consumption among all ship categories, results in a continuous decrease of the average fuel consumption of IWW transport from 2006 to 2012.

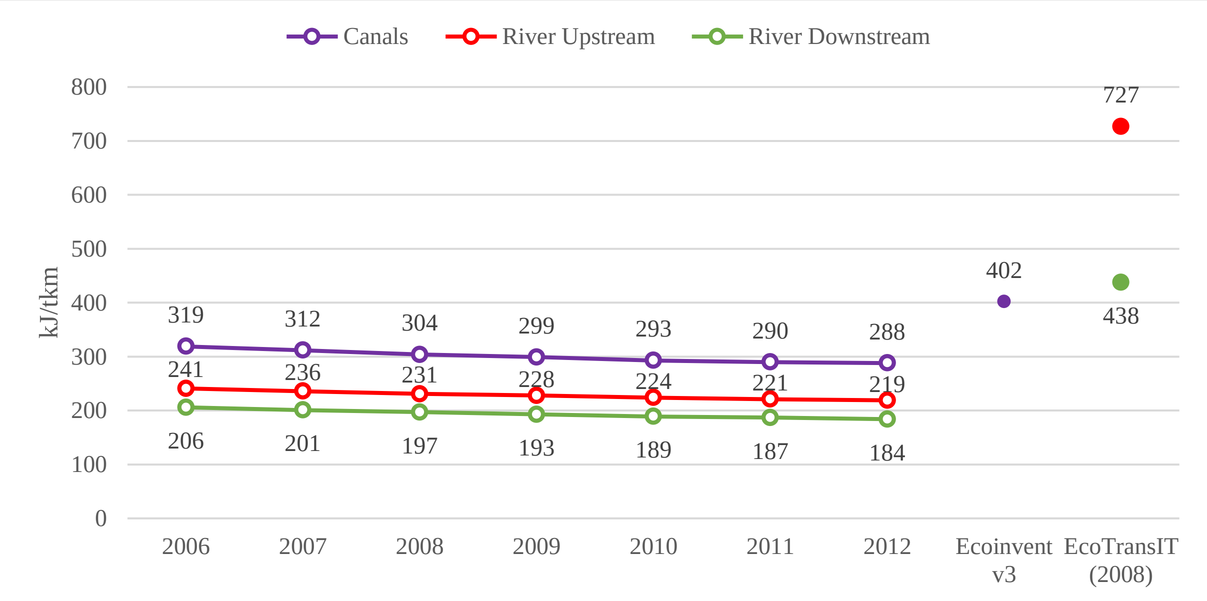


Figure 4.3. Average fuel consumption of IWW transport of dry bulk in Belgium

4.2.2. Direct emissions (Tank-To-Wheel) of IWW transport

As mentioned in Chapter 3 (Section 3.2.2), the direct emissions do not yet represent environmental impact categories such as climate change. These direct emissions during transport operation are part of the inventory analysis and this, together with the energy consumption during transport operation and the emissions, energy and material consumptions from the vehicle and infrastructure stages, constitute the required elements to model the freight transport system. It is necessary to consider all the elements from the inventory analysis to evaluate the contribution of the freight transport to environmental impact categories. Therefore, this section presents pollutant emissions as substances produced during the transport activity and not as environmental impacts.

The direct emissions produced during the IWW transport operation (Tank-To-Wheel stage) have been calculated using the emission factors of Spielmann et al. (2007), which do a selection of emission factors from others authors (see Table 4.6), and the calculated fuel consumption. The emission factors for NH_3 and hydrogen chloride (HCl) have been calculated from the process "Transport, freight, IWW, barge {RER} | processing | Alloc Rec, U" of the Ecoinvent v3 database.

As mentioned in Section 3.2.2, the uncertainty of these emission factors has been calculated using the pedigree matrix developed by Weidema and Wesnæs (1996). To do this, it is assumed a lognormal distribution of the values, which is characterised by the standard deviation (SD). It should be noted that the square of the geometric standard deviation covers the 95% confidence interval (i.e. 95% of all measures values are within the range). If we take the SD of CO_2

emissions to air as an example, 95% of all measures values are between the mean value times 1.49 and the mean value divided by 1.49. Therefore, the closer the SD is to one, the lower is the uncertainty (Pré, 2013). The pedigree matrix allows the estimation of the SD on the basis of five criteria (reliability, completeness, temporal correlation, geographical correlation and further technological correlation) and a basic uncertainty factor (Pré, 2013). Table 4.6 includes the SD used in our study from the Ecoinvent database. The uncertainty of the emission factors varies depending of the pollutant. Thereby, the emission factor for CO_2 presents the lowest uncertainty. Since the basic uncertainty factor for heavy metals (5.00), $PM_{2.5}$ (3.00) and Benzo(a)pyrene (3.00) is high, the uncertainty for these emission factors is greater (Pré, 2013).

Table 4.6. Emission factors used to determine the direct emissions of IWW transport. Sources: Spielmann et al., 2007; Weidema et al., 2013

Emissions to air	Emission factor (g/kg diesel)	SD	Emissions to air	Emission factor (g/kg diesel)	SD
CO_2	3 172	1.49	**$PM_{2.5}$**	0.923	3.21
Cd	0.00001	5.27	**PM_{10}**	0.039	1.76
Cu	0.0017	5.27	**PM_{10} > PM > $PM_{2.5}$**	0.077	2.23
Cr	0.00005	5.27	**Methane**	0.024	2.23
Ni	0.00007	5.27	**Toluene**	0.008	2.23
Se	0.00001	5.27	**Benzene**	0.019	2.23
Zn	0.001	5.27	**Xylene**	0.008	2.23
Pb	0.00000011	5.27	**NMVOC**	1	1.76
Hg	0.00000002	5.27	**NH_3**	0.00519	2.23
CO	2.7	2.23	**N_2O**	0.08	2.23
NO_X	50	1.76	**Benzo(a)pyrene**	0.0000077	3.21
HCl	0.00106	1.76	**-**	-	-

The emissions of SO_2 are dependent on the sulphur content in the fuel. The gas-oil used in barges has been regulated by several European Directives, such as the Directive 93/12/EC, establishing a sulphur content of gas-oil used in IWW transport of 2 000 ppm from 1994; Directive 1999/32/EC establishing a sulphur content of gas-oil of 1 000 ppm from 2008; and Directive 2009/30/EC establishing a sulphur content of gas-oil of 10 ppm from 2011.

The SO_2 emissions have been calculated using Equation (1) from Chapter 3 (Section 3.2.2). Table 4.7 presents the sulphur content of gas-oil and SO_2 emissions per kg of gas-oil used in our research. Since sulphur concentration varies throughout years, the corresponding emission factor for each year has been calculated. Therefore, the SO_2 emission factors of 4 g/kg, 2 g/kg and 0.02 g/kg have been used. Ecoinvent v3 assumes a sulphur concentration of 300 ppm for the fuel used in IWW transport resulting in an emission factor for SO_2 of 0.6 g/kg.

Table 4.7. Concentration of sulphur in gas-oil in ppm

	2006	2007	2008	2009	2010	2011	2012
Sulphur content (ppm)	2 000	2 000	1 000	1 000	1 000	10	10
SO_2 emissions (g/kg gas-oil)	4	4	2	2	2	0.02	0.02

Table 4.8 presents the direct emissions of barges in canals in Belgium using the fuel consumption showed in Table 4.5. Moreover, the reference process of Ecoinvent v3 database "Transport, freight, IWW, barge {RER} | processing | Alloc Rec, U" is used as reference values.

Table 4.8. Direct emissions (g/tkm) of IWW transport in canals in Belgium

IWW transport – Canal (g/tkm)	2006	2007	2008	2009	2010	2011	2012	Ecoinvent v3[1] 2014
CO_2	23.63	23.14	22.55	22.12	21.72	21.46	21.34	29.60
SO_2	2.98×10^{-2}	2.92×10^{-2}	1.42×10^{-2}	1.39×10^{-2}	1.37×10^{-2}	1.35×10^{-4}	1.35×10^{-4}	5.64×10^{-3}
Cd	7.45×10^{-8}	7.30×10^{-8}	7.11×10^{-8}	6.97×10^{-8}	6.85×10^{-8}	6.77×10^{-8}	6.73×10^{-8}	9.39×10^{-8}
Cu	1.27×10^{-5}	1.24×10^{-5}	1.21×10^{-5}	1.19×10^{-5}	1.16×10^{-5}	1.15×10^{-5}	1.14×10^{-5}	1.60×10^{-5}
Cr	3.72×10^{-7}	3.65×10^{-7}	3.55×10^{-7}	3.49×10^{-7}	3.42×10^{-7}	3.38×10^{-7}	3.36×10^{-7}	4.70×10^{-7}
Ni	5.21×10^{-7}	5.11×10^{-7}	4.98×10^{-7}	4.88×10^{-7}	4.79×10^{-7}	4.74×10^{-7}	4.71×10^{-7}	6.58×10^{-7}
Se	7.45×10^{-8}	7.30×10^{-8}	7.11×10^{-8}	6.97×10^{-8}	6.85×10^{-8}	6.77×10^{-8}	6.73×10^{-8}	9.39×10^{-8}
Zn	7.45×10^{-6}	7.30×10^{-6}	7.11×10^{-6}	6.97×10^{-6}	6.85×10^{-6}	6.77×10^{-6}	6.73×10^{-6}	9.39×10^{-6}
Pb	8.19×10^{-10}	8.02×10^{-10}	7.82×10^{-10}	7.67×10^{-10}	7.53×10^{-10}	7.44×10^{-10}	7.40×10^{-10}	1.88×10^{-7}
Hg	1.49×10^{-10}	1.46×10^{-10}	1.42×10^{-10}	1.39×10^{-10}	1.37×10^{-10}	1.35×10^{-10}	1.35×10^{-10}	6.58×10^{-10}
CO	2.01×10^{-2}	1.97×10^{-2}	1.92×10^{-2}	1.88×10^{-2}	1.85×10^{-2}	1.83×10^{-2}	1.82×10^{-2}	2.54×10^{-2}
NO_X	3.72×10^{-1}	3.65×10^{-1}	3.55×10^{-1}	3.49×10^{-1}	3.42×10^{-1}	3.38×10^{-1}	3.36×10^{-1}	4.70×10^{-1}
$PM_{2.5}$	6.88×10^{-3}	6.73×10^{-3}	6.56×10^{-3}	6.44×10^{-3}	6.32×10^{-3}	6.25×10^{-3}	6.21×10^{-3}	8.67×10^{-3}
PM_{10}	2.90×10^{-4}	2.85×10^{-4}	2.77×10^{-4}	2.72×10^{-4}	2.67×10^{-4}	2.64×10^{-4}	2.62×10^{-4}	3.71×10^{-4}
$PM_{10} > PM > PM_{2.5}$	5.74×10^{-4}	5.62×10^{-4}	5.47×10^{-4}	5.37×10^{-4}	5.27×10^{-4}	5.21×10^{-4}	5.18×10^{-4}	7.23×10^{-4}
Methane	1.79×10^{-4}	1.75×10^{-4}	1.71×10^{-4}	1.67×10^{-4}	1.64×10^{-4}	1.62×10^{-4}	1.61×10^{-4}	2.25×10^{-4}
Toluene	5.96×10^{-5}	5.84×10^{-5}	5.69×10^{-5}	5.58×10^{-5}	5.48×10^{-5}	5.41×10^{-5}	5.38×10^{-5}	7.52×10^{-5}
Benzene	1.42×10^{-4}	1.39×10^{-4}	1.35×10^{-4}	1.33×10^{-4}	1.30×10^{-4}	1.29×10^{-4}	1.28×10^{-4}	1.78×10^{-4}
Xylene	5.96×10^{-5}	5.84×10^{-5}	5.69×10^{-5}	5.58×10^{-5}	5.48×10^{-5}	5.41×10^{-5}	5.38×10^{-5}	7.52×10^{-5}
NMVOC	7.45×10^{-3}	7.30×10^{-3}	7.11×10^{-3}	6.97×10^{-3}	6.85×10^{-3}	6.77×10^{-3}	6.73×10^{-3}	9.39×10^{-3}
NH_3	3.86×10^{-4}	3.78×10^{-4}	3.69×10^{-4}	3.62×10^{-4}	3.55×10^{-4}	3.51×10^{-4}	3.49×10^{-4}	4.87×10^{-4}
N_2O	5.96×10^{-4}	5.84×10^{-4}	5.69×10^{-4}	5.58×10^{-4}	5.48×10^{-4}	5.41×10^{-4}	5.38×10^{-4}	3.11×10^{-3}
Benzo(a)pyrene	5.74×10^{-8}	5.62×10^{-8}	5.47×10^{-8}	5.37×10^{-8}	5.27×10^{-8}	5.21×10^{-8}	5.18×10^{-8}	7.24×10^{-11}
HCl	7.90×10^{-6}	7.73×10^{-6}	7.53×10^{-6}	7.39×10^{-6}	7.26×10^{-6}	7.17×10^{-6}	7.13×10^{-6}	9.95×10^{-6}

[1]Source: Weidema et al., 2013

By comparing the direct emissions used in Ecoinvent v3 with the values obtained in our study, our results for Belgium show lower direct emissions due to the lower energy consumptions obtained in our study. The only exception to this is the SO_2 emissions, which are dependent on the sulphur content in the fuel. Therefore, as Ecoinvent v3 considers a sulphur concentration of 300 ppm for the fuel used in IWW transport, it presents lower SO_2 emissions than our results for Belgium in the period from 2006 to 2010 (with a sulphur content of 2 000 ppm and 1 000 ppm, see Table 4.7), but higher SO_2 emissions than 2011 and 2012 (with a sulphur content of 10 ppm, see Table 4.7).

Table 4.9 presents the direct emissions of barges in upstream in Belgium using the fuel consumption showed in Table 4.5.

Table 4.9. Direct emissions (g/tkm) of IWW transport in upstream in Belgium

IWW transport – Upstream (g/tkm)	2006	2007	2008	2009	2010	2011	2012
CO_2	17.88	17.49	17.14	16.86	16.58	16.36	16.21
SO_2	2.26×10^{-2}	2.21×10^{-2}	1.08×10^{-2}	1.06×10^{-2}	1.05×10^{-2}	1.03×10^{-4}	1.02×10^{-4}
Cd	5.64×10^{-8}	5.51×10^{-8}	5.40×10^{-8}	5.32×10^{-8}	5.23×10^{-8}	5.16×10^{-8}	5.11×10^{-8}
Cu	9.59×10^{-6}	9.37×10^{-6}	9.19×10^{-6}	9.04×10^{-6}	8.89×10^{-6}	8.77×10^{-6}	8.69×10^{-6}
Cr	2.82×10^{-7}	2.76×10^{-7}	2.70×10^{-7}	2.66×10^{-7}	2.61×10^{-7}	2.58×10^{-7}	2.55×10^{-7}
Ni	3.95×10^{-7}	3.86×10^{-7}	3.78×10^{-7}	3.72×10^{-7}	3.66×10^{-7}	3.61×10^{-7}	3.58×10^{-7}
Se	5.64×10^{-8}	5.51×10^{-8}	5.40×10^{-8}	5.32×10^{-8}	5.23×10^{-8}	5.16×10^{-8}	5.11×10^{-8}
Zn	5.64×10^{-6}	5.51×10^{-6}	5.40×10^{-6}	5.32×10^{-6}	5.23×10^{-6}	5.16×10^{-6}	5.11×10^{-6}
Pb	6.20×10^{-10}	6.07×10^{-10}	5.94×10^{-10}	5.85×10^{-10}	5.75×10^{-10}	5.67×10^{-10}	5.62×10^{-10}
Hg	1.13×10^{-10}	1.10×10^{-10}	1.08×10^{-10}	1.06×10^{-10}	1.05×10^{-10}	1.03×10^{-10}	1.02×10^{-10}
CO	1.52×10^{-2}	1.49×10^{-2}	1.46×10^{-2}	1.44×10^{-2}	1.41×10^{-2}	1.39×10^{-2}	1.38×10^{-2}
NO_X	2.82×10^{-1}	2.76×10^{-1}	2.70×10^{-1}	2.66×10^{-1}	2.61×10^{-1}	2.58×10^{-1}	2.55×10^{-1}
$PM_{2.5}$	5.20×10^{-3}	5.09×10^{-3}	4.99×10^{-3}	4.91×10^{-3}	4.82×10^{-3}	4.76×10^{-3}	4.72×10^{-3}
PM_{10}	2.20×10^{-4}	2.15×10^{-4}	2.11×10^{-4}	2.07×10^{-4}	2.04×10^{-4}	2.01×10^{-4}	1.99×10^{-4}
$PM_{10} > PM > PM_{2.5}$	4.34×10^{-4}	4.25×10^{-4}	4.16×10^{-4}	4.09×10^{-4}	4.02×10^{-4}	3.97×10^{-4}	3.93×10^{-4}
Methane	1.35×10^{-4}	1.32×10^{-4}	1.30×10^{-4}	1.28×10^{-4}	1.25×10^{-4}	1.24×10^{-4}	1.23×10^{-4}
Toluene	4.51×10^{-5}	4.41×10^{-5}	4.32×10^{-5}	4.25×10^{-5}	4.18×10^{-5}	4.13×10^{-5}	4.09×10^{-5}
Benzene	1.07×10^{-4}	1.05×10^{-4}	1.03×10^{-4}	1.01×10^{-4}	9.93×10^{-5}	9.80×10^{-5}	9.71×10^{-5}
Xylene	4.51×10^{-5}	4.41×10^{-5}	4.32×10^{-5}	4.25×10^{-5}	4.18×10^{-5}	4.13×10^{-5}	4.09×10^{-5}
NMVOC	5.64×10^{-3}	5.51×10^{-3}	5.40×10^{-3}	5.32×10^{-3}	5.23×10^{-3}	5.16×10^{-3}	5.11×10^{-3}
NH_3	2.92×10^{-4}	2.86×10^{-4}	2.80×10^{-4}	2.76×10^{-4}	2.71×10^{-4}	2.68×10^{-4}	2.65×10^{-4}
N_2O	4.51×10^{-4}	4.41×10^{-4}	4.32×10^{-4}	4.25×10^{-4}	4.18×10^{-4}	4.13×10^{-4}	4.09×10^{-4}
Benzo(a)pyrene	4.34×10^{-8}	4.25×10^{-8}	4.16×10^{-8}	4.09×10^{-8}	4.02×10^{-8}	3.97×10^{-8}	3.93×10^{-8}
HCl	5.98×10^{-6}	5.85×10^{-6}	5.73×10^{-6}	5.64×10^{-6}	5.54×10^{-6}	5.47×10^{-6}	5.42×10^{-6}

Table 4.10 presents the direct emissions of barges in downstream in Belgium using the fuel consumption showed in Table 4.5.

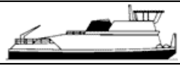
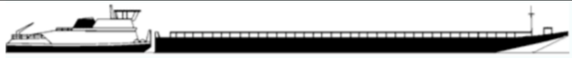
Table 4.10. Direct emissions (g/tkm) of IWW transport in downstream in Belgium

IWW transport – Downstream (g/tkm)	2006	2007	2008	2009	2010	2011	2012
CO_2	15.26	14.89	14.57	14.31	14.03	13.82	13.67
SO_2	1.92×10^{-2}	1.88×10^{-2}	9.19×10^{-3}	9.02×10^{-3}	8.85×10^{-3}	8.72×10^{-5}	8.62×10^{-5}
Cd	4.81×10^{-8}	4.69×10^{-8}	4.59×10^{-8}	4.51×10^{-8}	4.42×10^{-8}	4.36×10^{-8}	4.31×10^{-8}
Cu	8.18×10^{-6}	7.98×10^{-6}	7.81×10^{-6}	7.67×10^{-6}	7.52×10^{-6}	7.41×10^{-6}	7.32×10^{-6}
Cr	2.41×10^{-7}	2.35×10^{-7}	2.30×10^{-7}	2.25×10^{-7}	2.21×10^{-7}	2.18×10^{-7}	2.15×10^{-7}
Ni	3.37×10^{-7}	3.29×10^{-7}	3.22×10^{-7}	3.16×10^{-7}	3.10×10^{-7}	3.05×10^{-7}	3.02×10^{-7}
Se	4.81×10^{-8}	4.69×10^{-8}	4.59×10^{-8}	4.51×10^{-8}	4.42×10^{-8}	4.36×10^{-8}	4.31×10^{-8}
Zn	4.81×10^{-6}	4.69×10^{-6}	4.59×10^{-6}	4.51×10^{-6}	4.42×10^{-6}	4.36×10^{-6}	4.31×10^{-6}
Pb	5.29×10^{-10}	5.16×10^{-10}	5.05×10^{-10}	4.96×10^{-10}	4.87×10^{-10}	4.79×10^{-10}	4.74×10^{-10}
Hg	9.62×10^{-11}	9.39×10^{-11}	9.19×10^{-11}	9.02×10^{-11}	8.85×10^{-11}	8.72×10^{-11}	8.62×10^{-11}
CO	1.30×10^{-2}	1.27×10^{-2}	1.24×10^{-2}	1.22×10^{-2}	1.19×10^{-2}	1.18×10^{-2}	1.16×10^{-2}
NO_X	2.41×10^{-1}	2.35×10^{-1}	2.30×10^{-1}	2.25×10^{-1}	2.21×10^{-1}	2.18×10^{-1}	2.15×10^{-1}
$PM_{2.5}$	4.44×10^{-3}	4.33×10^{-3}	4.24×10^{-3}	4.16×10^{-3}	4.08×10^{-3}	4.02×10^{-3}	3.98×10^{-3}
PM_{10}	1.88×10^{-4}	1.83×10^{-4}	1.79×10^{-4}	1.76×10^{-4}	1.72×10^{-4}	1.70×10^{-4}	1.68×10^{-4}
$PM_{10} > PM > PM_{2.5}$	3.70×10^{-4}	3.61×10^{-4}	3.54×10^{-4}	3.47×10^{-4}	3.41×10^{-4}	3.36×10^{-4}	3.32×10^{-4}
Methane	1.15×10^{-4}	1.13×10^{-4}	1.10×10^{-4}	1.08×10^{-4}	1.06×10^{-4}	1.05×10^{-4}	1.03×10^{-4}
Toluene	3.85×10^{-5}	3.76×10^{-5}	3.67×10^{-5}	3.61×10^{-5}	3.54×10^{-5}	3.49×10^{-5}	3.45×10^{-5}
Benzene	9.14×10^{-5}	8.92×10^{-5}	8.73×10^{-5}	8.57×10^{-5}	8.40×10^{-5}	8.28×10^{-5}	8.19×10^{-5}
Xylene	3.85×10^{-5}	3.76×10^{-5}	3.67×10^{-5}	3.61×10^{-5}	3.54×10^{-5}	3.49×10^{-5}	3.45×10^{-5}
NMVOC	4.81×10^{-3}	4.69×10^{-3}	4.59×10^{-3}	4.51×10^{-3}	4.42×10^{-3}	4.36×10^{-3}	4.31×10^{-3}
NH_3	2.49×10^{-4}	2.43×10^{-4}	2.38×10^{-4}	2.34×10^{-4}	2.29×10^{-4}	2.26×10^{-4}	2.23×10^{-4}
N_2O	3.85×10^{-4}	3.76×10^{-4}	3.67×10^{-4}	3.61×10^{-4}	3.54×10^{-4}	3.49×10^{-4}	3.45×10^{-4}
Benzo(a)pyrene	3.70×10^{-8}	3.61×10^{-8}	3.54×10^{-8}	3.47×10^{-8}	3.41×10^{-8}	3.36×10^{-8}	3.32×10^{-8}
HCl	5.10×10^{-6}	4.98×10^{-6}	4.87×10^{-6}	4.78×10^{-6}	4.69×10^{-6}	4.62×10^{-6}	4.57×10^{-6}

4.3. Vessel

For the manufacturing, maintenance and disposal of vessels, it has been used the Ecoinvent v3 database instead of collecting new data specific to Belgium since this is outside the scope of this study. Table 4.11 shows the characteristics of the main dry bulk barges present in Belgium.

Table 4.11. Examples of dry bulk barge type characteristics. Source: ITB, 2018

Name	CEMT[1] class	Characteristics (m)	Load capacity	
Spits-Péniche	I	Length: 38.5 Width: 5.05 Draught: 2.2	250 t - 400 t ≈ 14 lorries	
Euro-barge (Kempenaar-Campinois)	II	Length: 50 - 63 Width: 6.60 Draught: 2.5	400 t - 600 t 24 TEU[2] ≈ 22 lorries	
Dortmund-Ems Canal (D.E.K.)	III	Length: 67 - 80 Width: 8.2 Draught: 2.5	650 t – 1 000 t ≈ 36 lorries	
Rhine-Herne Canal (R.H.K.)	IV	Length: 80 - 85 Width: 9.5 Draught: 2.5	1 000 t – 1 500 t 60 TEU[2] ≈ 60 lorries	
Big Rhine barge	Va, VIb	Length: 95 - 140 Width: 11.4 - 15 Draught: 2.5 - 3.9	1 500 t – 3 500 t 200 TEU[2] ≈ 140 lorries	
Pusher	-	Length: 5 - 40 Width: 5 - 11.4	-	
Barge Europe type I	-	Length: 70 Width: 9.5	1 500 t	
Barge Europe type II – IIa	-	Length: 76.5 Width: 11.4	2 000 t – 2 500 t	
Barge Europe type III	-	Length: 100 – 110 Width: 11.4	3 000 t – 4 500 t	
Pushed convoy - short formation	IV, Va, VIa	Length: 85 – 110 Width: 9. – 22.8	1 250 t – 6 000 t	
Pushed convoy - average formation	V, Vb, VIb, VIc	Length: 172 – 200 Width: 11.4 – 34.2	3 200 t – 18 000 t	
Pushed convoy - long formation	VIc, VII	Length: 270 - 285 Width: 22.8 – 34.2	9 600 t – 27 000 t	

[1]Classification of European IWW created by the Conférence Européenne des Ministres de Transport in 1992 (CEMT classes I-VII); [2]TEU: Twenty-foot equivalent unit

Table 4.12 shows the population of barges of Belgium by vessel class and year from the period 2006 to 2012.

Table 4.12. Population of dry bulk barges in Belgium by vessel class. Sources: ITB, 2007, 2008, 2009, 2010, 2012, 2013

Vessel class	2006	2007	2008	2009	2010	2011	2012
<250 t	16	23	24	19	16	18	19
251 t – 450 t	314	282	262	247	237	213	195
451 t – 650 t	150	141	126	128	120	111	110
651 t – 850 t	107	98	89	83	81	75	69
851 t – 1 000 t	78	71	70	61	60	52	45
1001 t – 1 500 t	261	264	258	241	230	220	216
1 501 t – 2 000 t	78	81	77	77	79	70	65
2 001 t – 2 500 t	70	63	61	60	59	56	60
2 501 t – 3 000 t	100	93	80	81	82	82	80
>3 000 t	76	92	110	122	137	141	141
TOTAL	1 250	1 208	1 157	1 119	1 101	1 038	1 000

Figure 4.4 shows the distribution by population of dry bulk barges in Belgium by vessel class from Table 4.12. The vessel class 251 t – 450 t (i.e. Spits-Péniche vessel) and 1 001 t – 1 500 t (i.e. Rhine-Herne Canal vessel) constitute between 46% and 41% of the total population of barges in the period from 2006 to 2012. This percentage decreases due to the increase of the population of the vessel class >3 000 t, which has grown from 6% in 2006 to 14% in 2012. This increase in population of vessel class >3 000 t is reflected in the growth of freight transported by this vessel class over the years (from 18% in 2006 to 35% in 2012, see Figure 4.2).

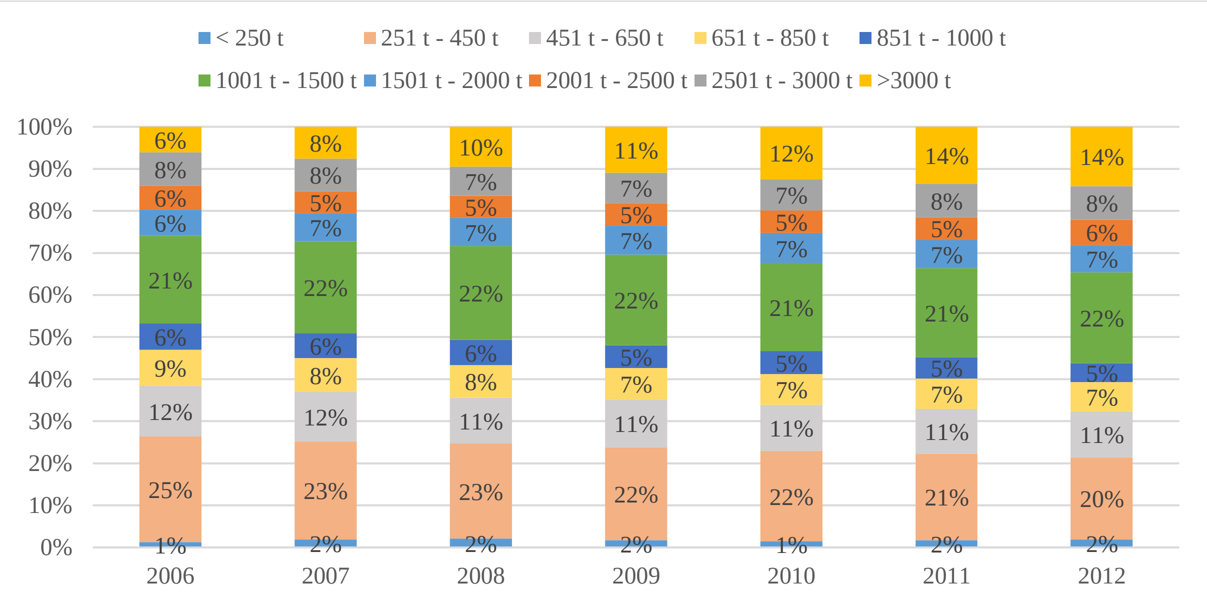


Figure 4.4. Distribution by population of dry bulk barges in Belgium by vessel class

Table 4.13 shows the average carrying capacity of dry bulk barges in Belgium calculated using the total tonnage (see Table 4.3) and the total population of vessels per year (see Table 4.12).

Table 4.13. Average carrying capacity (t/vessel) of dry bulk barges in Belgium

	2006	2007	2008	2009	2010	2011	2012
Average carrying capacity (t/vessel)	1 209	1 255	1 306	1 362	1 410	1 449	1 477

As shown in Equation (5), the vessel demand has been calculated in two steps. Firstly, it has been determined the lifetime kilometric performance per vessel (i.e. vkm/vessel) on the basis of the total annual vessel traffic, i.e. vehicle-kilometre (vkm), the population of barges present in Belgium per year and a life span of 46.5 years (Spielmann et al., 2007). If year 2010 is taken as an example, we consider that the total annual 19 218 thousand vkm (Eurostat statistics, 2017) of Belgium were performed by 1 101 barges (see Table 4.12) with a life span of 46.5 years, resulting in a lifetime kilometric performance of 811 659 vkm per vessel. Secondly, the lifetime transport performance (i.e. tkm/vessel) has been calculated using the average carrying capacity per vessel and the previously calculated lifetime kilometric performance. Continuing the example of 2010, an average carrying capacity of 1 410 t/vessel (see Table 4.13) has been considered, resulting in a life transport performance of 1 144 699 987 tkm/vessel and therefore, a vessel demand of 8.74×10^{-10} unit/tkm. Note that all the environmental interventions are referred to one vessel (unit).

$$Vessel\ demand\ \left(\frac{unit}{tkm}\right) = \frac{1}{\left(\left(\frac{vkm}{vessel \times year}\right) \times life\ span\ (year)\right) \times \left(\frac{t}{vehicle}\right)} \quad (5)$$

As shown in Table 4.14, the vessel demand has been calculated only for the years 2007, 2008 and 2010 since it is the only data available on total annual vessel traffic (i.e. vkm) for Belgium. Because of data limitations, the vessel demand of Ecoinvent v3 (1.05×10^{-9} unit/tkm) has been used for the years 2006, 2009, 2011 and 2012. The vessel demand used by Ecoinvent v3 presents a lower value than the vessel demands obtained for the years 2007 (1.24×10^{-9} unit/tkm) and 2008 (1.22×10^{-9} unit/tkm) in our study, but in the same order of magnitude. However, the vessel demand calculated for the year 2010 (8.74×10^{-10} unit/tkm) presents the lowest value, presenting a change of order of magnitude. Therefore, it has been decided to use the vessel demand from Ecoinvent v3 since it has the same order or magnitude than the years 2007 and 2008 and it is a most conservative value than the year 2010.

Table 4.14. Vessel demand for IWW transport in Belgium

Year	2007	2008	2010
Vessel traffic (vkm)[1]	16 646 000	15 586 000	19 218 000
Annual kilometric performance (vkm/vessel)	640 761	626 404	811 659
Transport performance per vehicle (tkm/vessel)	804 139 373	817 964 574	1 144 699 987
Vessel demand (unit/tkm)	1.24×10^{-9}	1.22×10^{-9}	8.74×10^{-10}

[1]Source: Eurostat statistics, 2017

4.4.IWW infrastructure

Similarly to the vessel demand, for the construction, maintenance and disposal of the infrastructure used for IWW transport, it has been used the Ecoinvent v3 database instead of collecting new data specific to Belgium since this is outside the scope of this study. Within infrastructure, port facilities and canals have been distinguished.

4.4.1. Port facilities

The Port of Antwerp (Belgium) has been used as reference to determine the port demand of the IWW transport. Ecoinvent v3 uses the Port of Rotterdam (The Netherlands) as reference, but both Port of Antwerp (12 068 ha) and Port of Rotterdam (12 643 ha) present approximately the same area. The port demand per tkm has been calculated on the basis of the total annual maritime cargo turnover of the Port of Antwerp, an average transport distance for dry-bulk barges of 250 km and a life span of 100 years (Spielmann et al., 2007). If year 2012 is taken as an example (see Table 4.15), a total annual throughput of 184 128 591 t in the Port of Antwerp (Port of Antwerp, 2016) is considered, resulting in a total port demand per transported tonne of 5.43×10^{-9} (unit×a)/t. A dry-bulk barge performs an average transport distance of 250 km and the life span of the port is assumed to be 100 years (Spielmann et al., 2007), therefore the port demand is 2.17×10^{-13} unit/tkm. Note that all the environmental interventions are referred to an entire port (unit).

Table 4.15. Port of Antwerp demand for IWW transport in Belgium

Year	2006	2007	2008	2009	2010	2011	2012
Total maritime cargo turnover (t)[1]	167 376 767	182 946 454	189 336 446	157 810 018	178 159 870	187 190 421	184 128 591
Port demand (unit/tkm)	2.39×10^{-13}	2.19×10^{-13}	2.11×10^{-13}	2.53×10^{-13}	2.25×10^{-13}	2.14×10^{-13}	2.17×10^{-13}

[1]Source: Port of Antwerp, 2016

In the case of Ecoinvent v3 database, the port demand for IWW transport (dry-bulk barges) for the year 2014 was 2.54×10^{-14} (m×a)/tkm. Our results present higher values than the port demand from Ecoinvent v3, presenting a different order of magnitude. This is due to the lower total annual maritime cargo turnover of the Port of Antwerp compared to the port of Rotterdam, which is used by Ecoinvent as reference.

4.4.2. Canals

Table 4.16 present the length of navigable IWW by vessel class in Belgium from 2006 to 2008. For our study, it has been assumed that the length of the navigable IWW for the period from 2009 to 2012 remains the same. Within the 1 516 km of navigable IWW in Belgium, 875 km are artificial canals and 641 km navigable rivers and lakes (Eurostat statistics, 2017).

Table 4.16. Navigable IWW (km) by carrying capacity of vessels. Source: Eurostat statistics, 2017

	Vessel class	2006	2007	2008
Navigable canals (km)	**<250 t**	0	0	0
	250 t – 399 t	156	156	156
	400 t – 649 t	213	213	213
	650 t – 999 t	0	0	0
	1 000 t – 1 499 t	221	221	221
	1 500 t – 2 999 t	86	86	86
	>3 000 t	199	199	199
	TOTAL	875	875	875
Navigable rivers and lakes (km)	**<250 t**	0	0	0
	250 t – 399 t	182	182	182
	400 t – 649 t	34	34	34
	650 t – 999 t	0	0	0
	1 000 t – 1 499 t	210	210	210
	1 500 t – 2 999 t	162	162	162
	>3 000 t	53	53	53
	TOTAL	641	641	641
TOTAL navigable IWW (km)		1 516	1 516	1 516

The canal demand per tkm has been calculated on the basis of the IWW transport performance and the length of artificial canals. The allocation of materials and energy consumption in the construction, maintenance and disposal of the IWW infrastructure has been carried out by differentiating between artificial canals and navigable rivers and lakes. Therefore, it has been considered that 58% of freight transported by barge is carried out in artificial canals and 42%

in natural waterways. If year 2012 is taken as an example (see Table 4.17), a 58% of the total annual transport performance (10 420 million tkm) of Belgium were performed in artificial canals, resulting in 6 014 million tkm. Thus, the annual transport performance per metre of artificial canal is 6 873 tkm/(m×a), resulting in 1.45×10^{-4} (m×a)/tkm of canal demand.

Table 4.17. Canals demand for IWW transport in Belgium

	2006	2007	2008	2009	2010	2011	2012
Transport performance (million tkm)[1]	8 908	9 006	8 746	7 087	9 070	9 251	10 420
Freight moved in canals (million tkm)	5 141	5 198	5 048	4 090	5 235	5 339	6 014
Transport performance (tkm/(m×a))	5 876	5 941	5 769	4 675	5 983	6 102	6 873
Canal demand ((m×a)/tkm)	1.70×10^{-4}	1.68×10^{-4}	1.73×10^{-4}	2.14×10^{-4}	1.67×10^{-4}	1.64×10^{-4}	1.45×10^{-4}

[1]Source: Eurostat statistics, 2017

In the case of Ecoinvent v3 database, the canal demand for IWW transport for the year 2014 was 1.16×10^{-4} (m×a)/tkm. Moreover, Spielmann et al. (2007) calculated a canal demand for IWW transport of 2.33×10^{-4} (m×a)/tkm. Our results are between the values from Ecoinvent v3 and Spielmann et al. (2007), showing the same order of magnitude.

Canals have other functions besides freight transport such as recreational boating or water management. Therefore, an allocation of the environmental impacts related to the construction, maintenance and disposal of canals could be performed. On the one hand, Van Lier and Macharis (2014) performed an economic allocation based on the estimate that 45% of expenses related to waterway management in Flanders (Belgium) are due to freight transport. On the other hand, Spielmann et al. (2007) does not consider an allocation of canals. Since the latter study was used to develop the transport processes in the Ecoinvent database and it has been adopted as a model for our research, for the sake of coherence with the rest of our study, it has been decided not to apply any allocation of the impact related to canals as proposed by Spielmann et al. (2007).

4.5.Life Cycle Impact Assessment of IWW transport in Belgium

The four stages of a LCA study described in Chapter 2 are applied to IWW transport. We restate them hereunder for completeness. First, the goal and scope definition, which in this chapter is to determine the environmental impacts of IWW transport in Belgium. The functional unit chosen is “one tonne-kilometre of freight transported by dry-bulk barge”. The second stage of a LCA is the Life Cycle Inventory (LCI) analysis. We have used the Ecoinvent v3 database and we have collected information specific to Belgium from several literature sources. The third stage is the Life Cycle Impact Assessment (LCIA). All calculations were made with the SimaPro 8.0.5 software using the LCIA method “ILCD 2011 Midpoint+” (version V1.06 / EU27 2010), which is the method recommended by the European Commission (European Commission, 2010). As mentioned above, “ILCD 2011 Midpoint+” is a midpoint method including 16 environmental impact indicators. However, in this analysis it has been used only the indicators with a level of quality “I” (climate change, ozone depletion and particulate matter), and “II” (ionizing radiation – human health, photochemical ozone formation, acidification, terrestrial and freshwater eutrophication and mineral, fossil and renewable resource depletion). Finally, the fourth stage is the assessment of the results obtained in the previous stages.

4.5.1. Life Cycle Impact Assessment of IWW transport in canal, upstream and downstream

Figure 4.5 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by dry-bulk barge in Belgium in canals in the year 2012. Therefore, to calculate the LCIA of one tonne-kilometre of IWW transport in canals in 2012 it is necessary to consider a vessel demand of 1.05×10^{-9} unit/tkm, a canal demand of 1.45×10^{-4} (m×a)/tkm, a port demand (considering the Port of Antwerp) of 2.17×10^{-13} unit/tkm, a fuel consumption of 0.00673 kg/tkm (288 kJ/tkm) and the direct emissions to air produced during the combustion of the fuel in the transport operation.

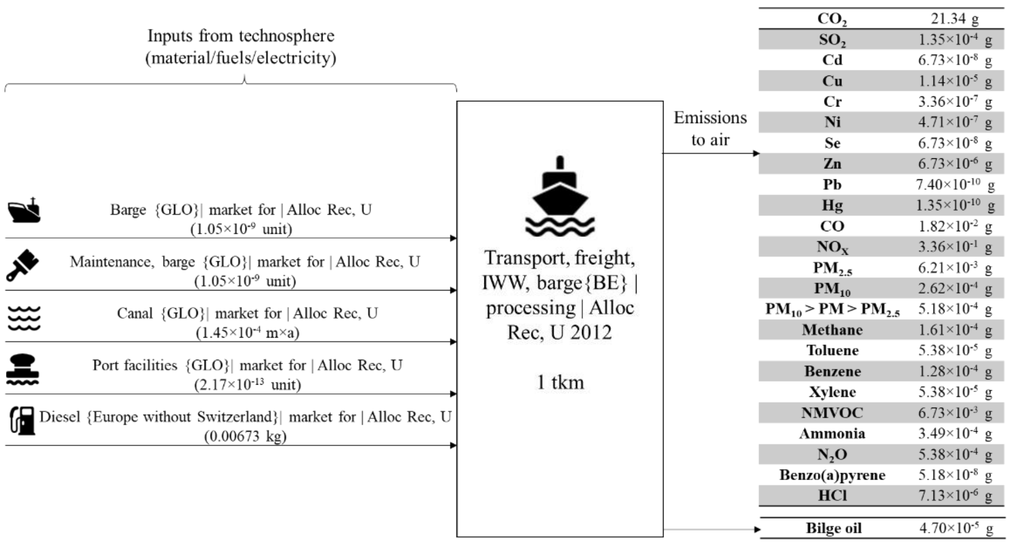


Figure 4.5. Inputs and outputs of 1 tkm transported by barge in canal in Belgium in 2012

Table 4.18 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canal in Belgium from 2006 to 2012, the average LCIA of Belgium taking as reference the period from 2006 to 2012 and the reference values of the process from Ecoinvent v3 "Transport, freight, IWW, barge {RER}| processing | Alloc Rec, U".

Table 4.18. LCIA of 1 tkm transported by IWW transport in canal in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012	Belgian average	Ecoinvent v3[1]
Climate change	kg CO_2 eq	8.32×10^{-2}	7.94×10^{-2}	7.78×10^{-2}	8.75×10^{-2}	7.81×10^{-2}	7.61×10^{-2}	7.47×10^{-2}	7.95×10^{-2}	5.17×10^{-2}
Ozone depletion	kg CFC-11 eq	8.67×10^{-9}	8.35×10^{-9}	8.15×10^{-9}	8.70×10^{-9}	8.07×10^{-9}	7.90×10^{-9}	7.81×10^{-9}	8.24×10^{-9}	7.40×10^{-9}
Particulate matter	kg $PM_{2.5}$ eq	5.44×10^{-5}	5.14×10^{-5}	4.93×10^{-5}	5.68×10^{-5}	5.02×10^{-5}	4.78×10^{-5}	4.74×10^{-5}	5.11×10^{-5}	2.21×10^{-5}
Ionizing radiation HH	kBq U235 eq	1.40×10^{-2}	1.30×10^{-2}	1.26×10^{-2}	1.47×10^{-2}	1.31×10^{-2}	1.26×10^{-2}	1.26×10^{-2}	1.32×10^{-2}	4.28×10^{-3}
Photochemical ozone formation	kg NMVOC eq	5.87×10^{-4}	5.74×10^{-4}	5.59×10^{-4}	5.80×10^{-4}	5.42×10^{-4}	5.35×10^{-4}	5.29×10^{-4}	5.58×10^{-4}	5.81×10^{-4}
Acidification	molc H+ eq	7.29×10^{-4}	6.99×10^{-4}	6.63×10^{-4}	7.21×10^{-4}	6.62×10^{-4}	6.28×10^{-4}	6.23×10^{-4}	6.75×10^{-4}	5.04×10^{-4}
Terrestrial eutrophication	molc N eq	2.20×10^{-3}	2.14×10^{-3}	2.09×10^{-3}	2.16×10^{-3}	2.04×10^{-3}	2.01×10^{-3}	1.98×10^{-3}	2.09×10^{-3}	2.25×10^{-3}
Freshwater eutrophication	kg P eq	2.15×10^{-5}	2.01×10^{-5}	1.96×10^{-5}	2.32×10^{-5}	2.03×10^{-5}	1.95×10^{-5}	1.94×10^{-5}	2.05×10^{-5}	5.25×10^{-6}
Resource depletion	kg Sb eq	7.38×10^{-7}	7.42×10^{-7}	7.43×10^{-7}	8.41×10^{-7}	6.95×10^{-7}	7.02×10^{-7}	6.62×10^{-7}	7.32×10^{-7}	4.83×10^{-7}

[1]**Source: Weidema et al., 2013**

Figure 4.6 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in canal in Belgium (from Table 4.18). Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the year with less impact and the highest value represents the maximum impact.

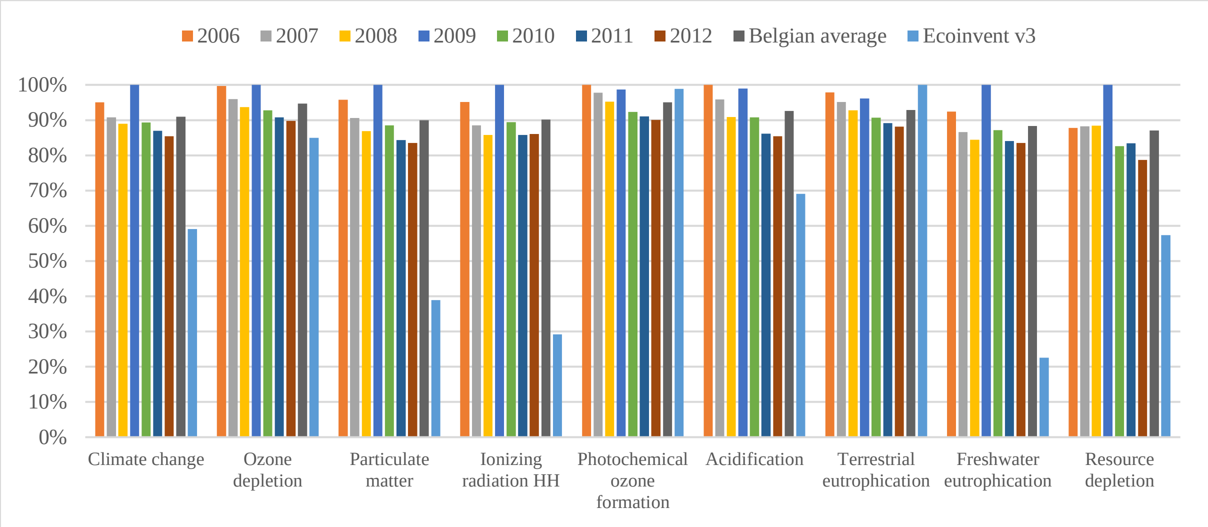


Figure 4.6. LCIA of 1 tkm transported by IWW transport in canal in Belgium and the reference values of the process from Ecoinvent v3 "Transport, freight, IWW, barge {RER}| processing | Alloc Rec, U"

The year 2009 presents the maximum impact in six indicators due to this year presents the lowest transport performance (tkm) and throughput (t) in the Port of Antwerp, resulting in a high demand of canals and port facilities, respectively. The year 2006 presents the maximum impact in the indicators photochemical ozone formation and acidification due to the higher exhaust emissions (especially NO_X) produced because of this year presents the highest energy consumption. Moreover, the high sulphur content of the gas-oil used in the year 2006 (2 000 ppm) generates large emissions of SO_2 as exhaust emissions, which has a great influence in the indicator acidification.

The process from Ecoinvent v3 presents the maximum impact in the indicator terrestrial eutrophication because of this process presents the highest NOx exhaust emissions as a result of the higher energy consumption (402 kJ/tkm) than the calculated in our research. Terrestrial eutrophication is the indicator where the exhaust emissions from the transport operation stage has a greater significance (see Figure 4.10). Thus, the process from Ecoinvent v3 presents the maximum impact in this indicator. It should be noted that in the indicator photochemical ozone formation, where the transport operation stage has a greater significance as well (see Figure 4.10), the process from Ecoinvent v3 does not present a significant difference with the years from 2006 to 2009. Furthermore, the transport operation stage is most significant in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication for the process from Ecoinvent v3 than for the processes of our study. This is due to the greater importance of the infrastructure subsystem (especially the port facilities demand) in our study than in the Ecoinvent v3 process.

By comparing the environmental impacts of the average IWW transport (from 2006 to 2012) with the values from Ecoinvent v3, our results for Belgium show a higher impact in all the indicators except the indicators photochemical ozone formation and terrestrial eutrophication.

In addition of the analysis of the environmental impact of IWW transport in canal, the environmental impact of transport by barge upstream and downstream have been studied. It should be noted that in the transport by barge in canal, upstream or downstream the vessel, canal and port demands remain the same. The change in the environmental impact is due to the different energy consumption and the related exhaust emissions to air generated. Table 4.19 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in upstream in Belgium.

Table 4.19. LCIA of 1 tkm transported by IWW transport in upstream in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	7.64×10^{-2}	7.27×10^{-2}	7.14×10^{-2}	8.13×10^{-2}	7.21×10^{-2}	7.00×10^{-2}	6.86×10^{-2}
Ozone depletion	**kg CFC-11 eq**	7.42×10^{-9}	7.12×10^{-9}	6.97×10^{-9}	7.56×10^{-9}	6.95×10^{-9}	6.79×10^{-9}	6.70×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	5.17×10^{-5}	4.88×10^{-5}	4.70×10^{-5}	5.45×10^{-5}	4.81×10^{-5}	4.59×10^{-5}	4.54×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.35×10^{-2}	1.25×10^{-2}	1.21×10^{-2}	1.42×10^{-2}	1.27×10^{-2}	1.22×10^{-2}	1.22×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	4.89×10^{-4}	4.76×10^{-4}	4.66×10^{-4}	4.89×10^{-4}	4.54×10^{-4}	4.48×10^{-4}	4.40×10^{-4}
Acidification	**molc H+ eq**	6.41×10^{-4}	6.12×10^{-4}	5.84×10^{-4}	6.44×10^{-4}	5.87×10^{-4}	5.58×10^{-4}	5.52×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.80×10^{-3}	1.75×10^{-3}	1.71×10^{-3}	1.80×10^{-3}	1.68×10^{-3}	1.65×10^{-3}	1.62×10^{-3}
Freshwater eutrophication	**kg P eq**	2.14×10^{-5}	2.00×10^{-5}	1.95×10^{-5}	2.31×10^{-5}	2.02×10^{-5}	1.94×10^{-5}	1.93×10^{-5}
Resource depletion	**kg Sb eq**	7.23×10^{-7}	7.27×10^{-7}	7.29×10^{-7}	8.27×10^{-7}	6.81×10^{-7}	6.88×10^{-7}	6.48×10^{-7}

Figure 4.7 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in upstream in Belgium (from Table 4.19). The year 2009 presents the maximum impact in almost all the indicators mainly due to this year presents the highest demand of canals and port facilities. The year 2006 presents the maximum impact in the indicator terrestrial eutrophication due to the higher NO_X exhaust emissions produced because of this year presents the highest energy consumption.

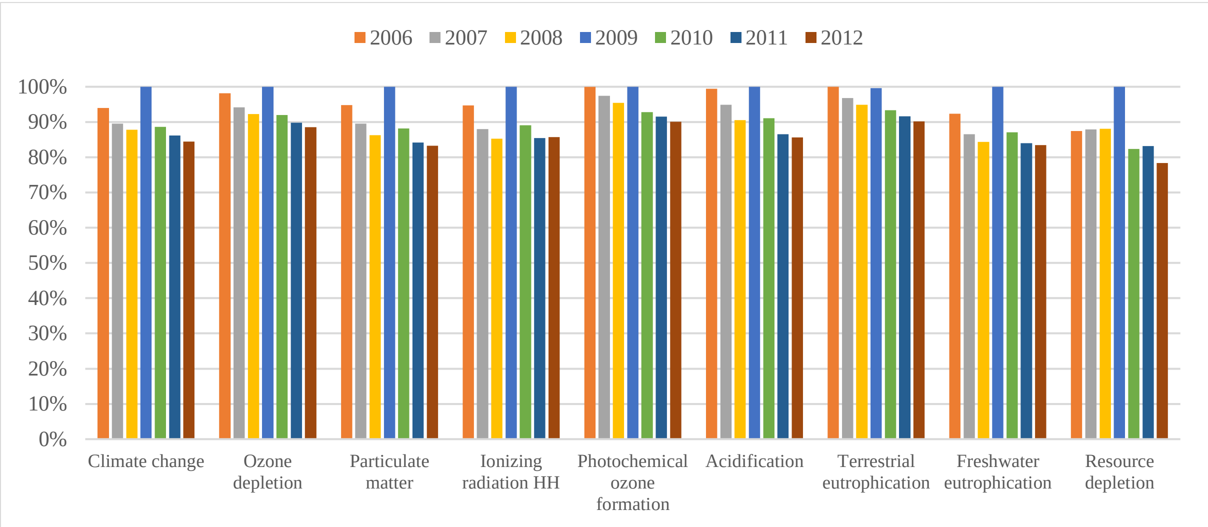


Figure 4.7. LCIA of 1 tkm transported by IWW transport in upstream in Belgium

Table 4.20 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in downstream in Belgium.

Table 4.20. LCIA of 1 tkm transported by IWW transport in downstream in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	7.33×10^{-2}	6.96×10^{-2}	6.84×10^{-2}	7.82×10^{-2}	6.90×10^{-2}	6.69×10^{-2}	6.56×10^{-2}
Ozone depletion	**kg CFC-11 eq**	6.85×10^{-9}	6.55×10^{-9}	6.41×10^{-9}	7.00×10^{-9}	6.39×10^{-9}	6.23×10^{-9}	6.14×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	5.05×10^{-5}	4.76×10^{-5}	4.60×10^{-5}	5.35×10^{-5}	4.70×10^{-5}	4.49×10^{-5}	4.45×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.32×10^{-2}	1.23×10^{-2}	1.19×10^{-2}	1.40×10^{-2}	1.25×10^{-2}	1.19×10^{-2}	1.20×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	4.43×10^{-4}	4.31×10^{-4}	4.22×10^{-4}	4.44×10^{-4}	4.10×10^{-4}	4.04×10^{-4}	3.97×10^{-4}
Acidification	**molc H+ eq**	6.00×10^{-4}	5.71×10^{-4}	5.46×10^{-4}	6.06×10^{-4}	5.49×10^{-4}	5.23×10^{-4}	5.17×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.62×10^{-3}	1.56×10^{-3}	1.53×10^{-3}	1.61×10^{-3}	1.50×10^{-3}	1.47×10^{-3}	1.45×10^{-3}
Freshwater eutrophication	**kg P eq**	2.13×10^{-5}	2.00×10^{-5}	1.95×10^{-5}	2.31×10^{-5}	2.01×10^{-5}	1.94×10^{-5}	1.93×10^{-5}
Resource depletion	**kg Sb eq**	7.17×10^{-7}	7.21×10^{-7}	7.22×10^{-7}	8.21×10^{-7}	6.75×10^{-7}	6.82×10^{-7}	6.42×10^{-7}

Figure 4.8 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in downstream in Belgium (from Table 4.20). The distribution between years of the different indicators is similar to the case of transport by barge in upstream (Figure 4.7). Therefore, the year 2009 presents the maximum impact in almost all the indicators and the year 2006 in the indicator terrestrial eutrophication.

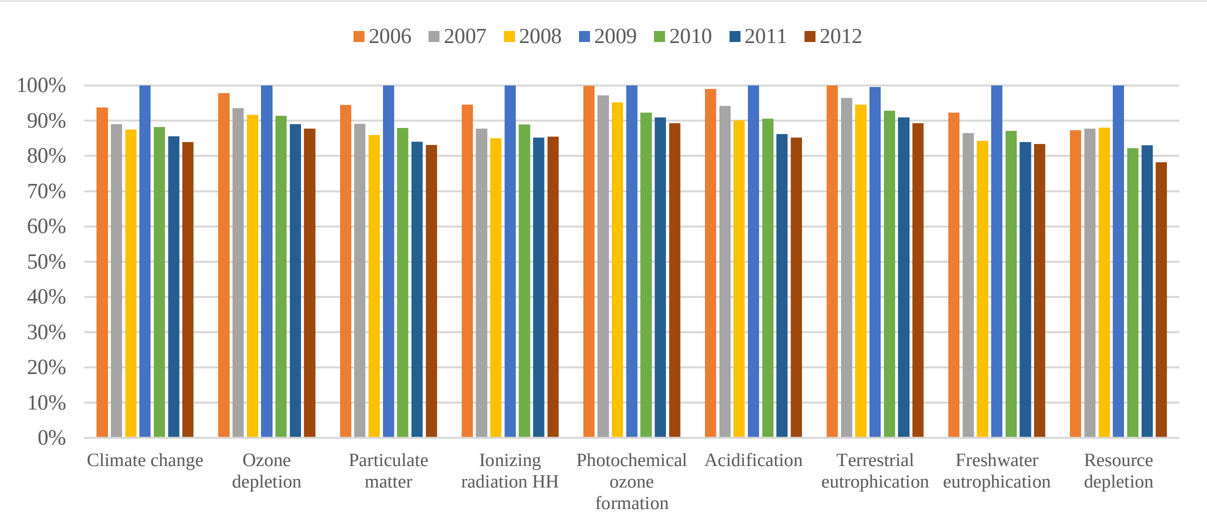


Figure 4.8. LCIA of 1 tkm transported by IWW transport in downstream in Belgium

4.5.2. Comparison of the environmental impacts of different IWW transport processes

This section compares the environmental performance of IWW transport in canals, upstream and downstream in Belgium. Furthermore, the environmental impacts of IWW transport using different energy consumption have been studied in Appendix B. Hence, the average energy consumption during the IWW transport operation has been determined using the class specific fuel consumption of barges from Spielmann et al. (2007) instead of the fuel consumption from Service Public de Wallonie (2014). It should be noted that the specific fuel consumptions from

Spielmann et al. (2007) are also used to calculate the energy consumption of the IWW transport process of Ecoinvent v3 database. By comparing the values obtained in our study in Section 4.2.1 for Belgium (see Table 4.5) with the values obtained in the sensitivity analysis from Appendix B (see Table B.1), the results for Belgium in Section 4.2.1 are lower than the results obtained in Appendix B.

The vessel, canal and port demands remain the same in the transport by barge in canal, upstream and downstream (Table 4.18, Table 4.19 and Table 4.20) and the transport by barge using the specific fuel consumption from Spielmann et al. (2007) from Appendix B (Table B.3). Therefore, the differences in the environmental impacts among these processes are due to the different energy consumptions and the related exhaust emissions to air generated.

Figure 4.9 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in canals (Table 4.18), upstream (Table 4.19) and downstream (Table 4.20) in Belgium in the year 2012. Moreover, it includes the transport by barge using the specific fuel consumption from Spielmann et al. (2007) in Belgium in the year 2012 (Table B.3). Finally, the reference values of the process from Ecoinvent v3 "Transport, freight, IWW, barge {RER}| processing | Alloc Rec, U" are presented as well.

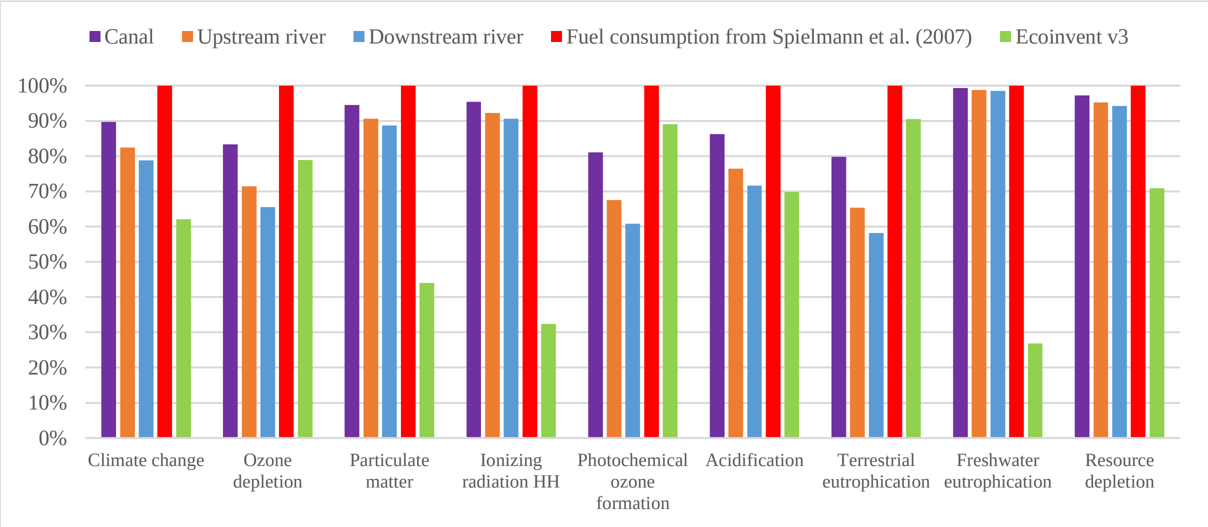


Figure 4.9. LCIA of 1 tkm transported by IWW transport in canal, upstream, downstream and the transport process using the fuel consumption from Spielmann et al. (2007) in Belgium in 2012 and the reference values from Ecoinvent

The transport process using the specific fuel consumption from Spielmann et al. (2007) shows the maximum impact in all the environmental impact indicators. Since the four types of IWW transport studied present the same vessel, canal and port demands, IWW transport using the specific fuel consumption from Spielmann et al. (2007) presents a higher impact than the others due to it has a higher average energy consumption and exhaust emissions. There are no significant differences among the four types of IWW transport of our study in the indicators particulate matter, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion because of the infrastructure subsystem is the most significant stage in terms of impact in these indicators.

The reference process from Ecoinvent v3 shows the second highest impact in the indicators photochemical ozone formation and terrestrial eutrophication because of this process has higher exhaust emissions on NO_X due to the higher energy consumption (402 kJ/tkm). As mentioned above, terrestrial eutrophication and photochemical ozone formation are the indicators where the exhaust emissions (especially NO_X emissions) from the transport operation stage has a greater significance (see Figure 4.10).

4.5.3. Contribution of the sub-systems IWW operation, vessel and IWW infrastructure to the environmental impact of IWW transport

For the LCIA of the Belgian IWW transport, all life cycle phases of IWW transport operation, hazardous waste incineration of bilge oil (liquid pumped from the bottom of ships containing wasted mineral and lubricating oil residues (Doka, 2007)), fuel production, vessel demand and IWW infrastructure including canal and port demand are taken into account.

Table 4.21 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canal in Belgium in 2012.

Table 4.21. LCIA of 1 tkm transported by barge in canal in Belgium in 2012

Impact category	Unit	Transport operation	Bilge oil	Fuel	Vessel mfg.	Vessel maint.	Canal	Port facilities	Total
Climate change	**kg CO_2 eq**	2.15×10^{-2}	1.39×10^{-4}	3.88×10^{-3}	1.14×10^{-3}	2.75×10^{-4}	1.26×10^{-2}	3.52×10^{-2}	7.47×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	3.07×10^{-12}	4.65×10^{-9}	6.31×10^{-11}	2.81×10^{-11}	6.74×10^{-10}	2.40×10^{-9}	7.81×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	4.64×10^{-6}	1.17×10^{-7}	3.53×10^{-6}	1.28×10^{-6}	2.03×10^{-7}	6.35×10^{-6}	3.13×10^{-5}	4.74×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	1.81×10^{-6}	1.79×10^{-3}	7.25×10^{-5}	2.37×10^{-5}	6.26×10^{-4}	1.01×10^{-2}	1.26×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	3.43×10^{-4}	2.08×10^{-7}	2.42×10^{-5}	5.35×10^{-6}	1.74×10^{-5}	4.07×10^{-5}	9.80×10^{-5}	5.29×10^{-4}
Acidification	**molc H+ eq**	2.50×10^{-4}	7.23×10^{-7}	4.45×10^{-5}	8.54×10^{-6}	1.89×10^{-6}	5.38×10^{-5}	2.63×10^{-4}	6.23×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.44×10^{-3}	5.37×10^{-7}	5.45×10^{-5}	1.23×10^{-5}	2.84×10^{-6}	1.38×10^{-4}	3.40×10^{-4}	1.98×10^{-3}
Freshwater eutrophication	**kg P eq**	0	4.15×10^{-8}	4.11×10^{-7}	6.63×10^{-7}	9.34×10^{-8}	2.56×10^{-6}	1.56×10^{-5}	1.94×10^{-5}
Resource depletion	**kg Sb eq**	0	2.36×10^{-10}	5.59×10^{-8}	7.06×10^{-8}	6.08×10^{-8}	3.19×10^{-7}	1.56×10^{-7}	6.62×10^{-7}

Table 4.22 shows the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in upstream in Belgium in 2012.

Table 4.22. LCIA of 1 tkm transported by barge in upstream in Belgium in 2012

Impact category	Unit	Transport operation	Bilge oil	Fuel	Vessel mfg.	Vessel maint.	Canal	Port facilities	Total
Climate change	**kg CO_2 eq**	1.63×10^{-2}	1.39×10^{-4}	2.95×10^{-3}	1.14×10^{-3}	2.75×10^{-4}	1.26×10^{-2}	3.52×10^{-2}	6.86×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	3.07×10^{-12}	3.53×10^{-9}	6.31×10^{-11}	2.81×10^{-11}	6.74×10^{-10}	2.40×10^{-9}	6.70×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	3.52×10^{-6}	1.17×10^{-7}	2.68×10^{-6}	1.28×10^{-6}	2.03×10^{-7}	6.35×10^{-6}	3.13×10^{-5}	4.54×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	1.81×10^{-6}	1.36×10^{-3}	7.25×10^{-5}	2.37×10^{-5}	6.26×10^{-4}	1.01×10^{-2}	1.22×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	2.60×10^{-4}	2.08×10^{-7}	1.84×10^{-5}	5.35×10^{-6}	1.74×10^{-5}	4.07×10^{-5}	9.80×10^{-5}	4.40×10^{-4}
Acidification	**molc H+ eq**	1.90×10^{-4}	7.23×10^{-7}	3.38×10^{-5}	8.54×10^{-6}	1.89×10^{-6}	5.38×10^{-5}	2.63×10^{-4}	5.52×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.09×10^{-3}	5.37×10^{-7}	4.14×10^{-5}	1.23×10^{-5}	2.84×10^{-6}	1.38×10^{-4}	3.40×10^{-4}	1.62×10^{-3}
Freshwater eutrophication	**kg P eq**	0	4.15×10^{-8}	3.12×10^{-7}	6.63×10^{-7}	9.34×10^{-8}	2.56×10^{-6}	1.56×10^{-5}	1.93×10^{-5}
Resource depletion	**kg Sb eq**	0	2.36×10^{-10}	4.25×10^{-8}	7.06×10^{-8}	6.08×10^{-8}	3.19×10^{-7}	1.56×10^{-7}	6.48×10^{-7}

Table 4.23 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in downstream in Belgium in 2012.

Table 4.23. LCIA of 1 tkm transported by barge in downstream in Belgium in 2012

Impact category	Unit	Transport operation	Bilge oil	Fuel	Vessel mfg.	Vessel maint.	Canal	Port facilities	Total
Climate change	**kg CO_2 eq**	1.38×10^{-2}	1.39×10^{-4}	2.48×10^{-3}	1.14×10^{-3}	2.75×10^{-4}	1.26×10^{-2}	3.52×10^{-2}	6.56×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	3.07×10^{-12}	2.98×10^{-9}	6.31×10^{-11}	2.81×10^{-11}	6.74×10^{-10}	2.40×10^{-9}	6.14×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	2.97×10^{-6}	1.17×10^{-7}	2.26×10^{-6}	1.28×10^{-6}	2.03×10^{-7}	6.35×10^{-6}	3.13×10^{-5}	4.45×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	1.81×10^{-6}	1.15×10^{-3}	7.25×10^{-5}	2.37×10^{-5}	6.26×10^{-4}	1.01×10^{-2}	1.20×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	2.19×10^{-4}	2.08×10^{-7}	1.55×10^{-5}	5.35×10^{-6}	1.74×10^{-5}	4.07×10^{-5}	9.80×10^{-5}	3.97×10^{-4}
Acidification	**molc H+ eq**	1.60×10^{-4}	7.23×10^{-7}	2.85×10^{-5}	8.54×10^{-6}	1.89×10^{-6}	5.38×10^{-5}	2.63×10^{-4}	5.17×10^{-4}
Terrestrial eutrophication	**molc N eq**	9.19×10^{-4}	5.37×10^{-7}	3.49×10^{-5}	1.23×10^{-5}	2.84×10^{-6}	1.38×10^{-4}	3.40×10^{-4}	1.45×10^{-3}
Freshwater eutrophication	**kg P eq**	0	4.15×10^{-8}	2.63×10^{-7}	6.63×10^{-7}	9.34×10^{-8}	2.56×10^{-6}	1.56×10^{-5}	1.93×10^{-5}
Resource depletion	**kg Sb eq**	0	2.36×10^{-10}	3.58×10^{-8}	7.06×10^{-8}	6.08×10^{-8}	3.19×10^{-7}	1.56×10^{-7}	6.42×10^{-7}

Figure 4.10 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canals (Table 4.21), upstream (Table 4.22) and downstream (Table 4.23) in Belgium in the year 2012. The values of transport operation and bilge oil have been clustered in the process transport operation. Moreover, the values of vessel maintenance and manufacturing have been grouped in the process vessel.

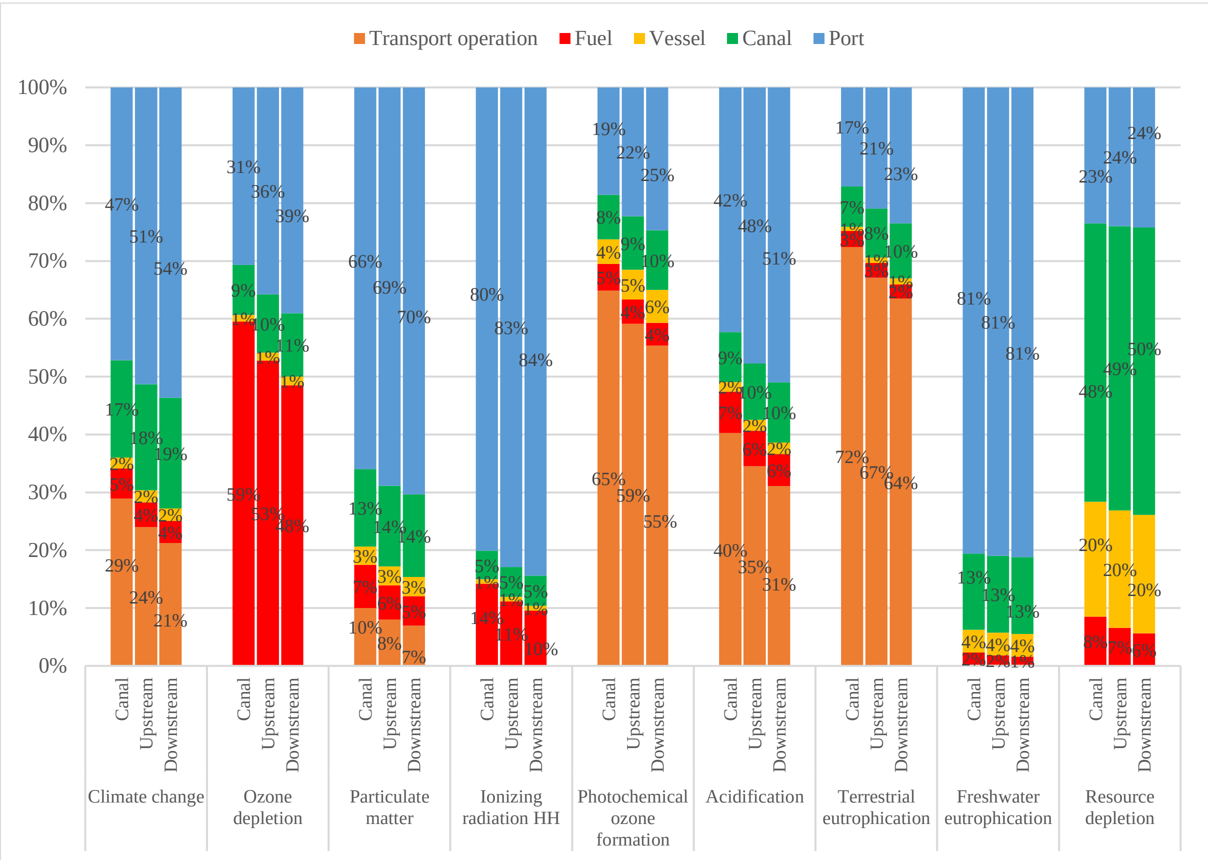


Figure 4.10. LCIA of 1 tkm of IWW transport in canal, upstream and downstream in Belgium in 2012

For IWW transport, the infrastructure sub-system (especially the port facilities demand) is the main source of impact in the indicators climate change, particulate matter, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion.

The main source of impact for the indicator climate change is related to the production of materials such as concrete and steel used in canals and port facilities. Moreover, the exhaust emissions from barges of GHG during the transport operation is a major source of impact in this indicator.

For the indicator particulate matter formation, the impact generated by the transport infrastructure (mostly from port facilities demand) is a major source of impact in this indicator due to the emissions of particles and SO_2 during the production of materials used in the transport infrastructure as steel and concrete. Moreover, the exhaust emissions of $PM_{2.5}$ and NO_X from barges are important in this indicator. It must be borne in mind that particulate matter can be emitted directly (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as SO_X, NO_X, NH_3 or VOC.

For the indicator ionizing radiation (damage to human health), the nuclear power used to generate the electricity for the production of materials (mainly steel and concrete) and the construction of the port facilities is the main source of impact. Similarly for the indicator freshwater eutrophication, the electricity generation for production of materials and the construction of the infrastructure is the source of the main impact due to the hard coal and lignite mining. Furthermore, the infrastructure construction is the main contributor in the indicator resource depletion due to the consumption of materials as concrete and steel.

For the indicator ozone depletion, the main contributor of the impact is the emissions of bromotrifluoromethane ($CBrF_3$ or halon 1 301) to air during the petroleum refinery operation. This gas contributes to the depletion of the stratospheric ozone layer, which filters ultraviolet radiation from the sun. The impact generated by the transport infrastructure comes from the electricity generation (especially from nuclear power, which uses refrigerant gases in the uranium enrichment) used in the production of concrete and steel.

The transport operation sub-system is the most important source of impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions of barges. For the indicator photochemical ozone formation, the exhaust emissions of mainly NO_X and to a lesser degree of NMVOC and SO_2 are the main contributor in this indicator. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC by photochemical reaction under the influence of solar radiation. For the indicator acidification, the exhaust emissions of NO_X and SO_2 are a major source of impact and for the indicator terrestrial eutrophication, the main source of impact are the exhaust emissions of NO_X.

4.5.4. Life Cycle Impact Assessment of IWW transport using different port facilities as reference

The port facilities demand has an important role in the environmental impact of IWW transport (see Figure 4.10). Therefore, a scenario analysis has been conducted to study how changes in port demand influences the total environmental impact of IWW transport. It has been used the Port of Rotterdam (The Netherlands), the Port of Liège (Belgian inland port) and the port demand used in Ecoinvent v3 to perform the scenario analysis. Table 4.24 shows the port demand calculated for the Port of Rotterdam and the Port of Liège using the methodology explained in Section 4.2.2.

Table 4.24. Port demand for IWW transport using the Port of Rotterdam and the Port of Liège

		2006	2007	2008	2009	2010	2011	2012
Total maritime cargo turnover (t)	**Rotterdam**[1]	381 753 000	409 086 000	421 136 000	386 957 000	430 159 000	434 551 000	441 527 000
	Liège[2]	14 413 738	15 788 667	16 027 486	13 219 445	15 452 240	13 893 382	13 343 538
Port demand (unit/tkm)	**Rotterdam**	1.05×10^{-13}	9.78×10^{-14}	9.50×10^{-14}	1.03×10^{-13}	9.30×10^{-14}	9.20×10^{-14}	9.06×10^{-14}
	Liège	2.78×10^{-12}	2.53×10^{-12}	2.50×10^{-12}	3.03×10^{-12}	2.59×10^{-12}	2.88×10^{-12}	3.00×10^{-12}

[1]Source: Port of Rotterdam, 2016; [2]Source: Port of Liège, 2017

In order to analyse how the variation in the port demand affects the LCIA results of IWW transport, it has been selected the values on energy consumption of loaded vessels in canals, the vessel demand and the canal demand of the year 2012. Table 4.25 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canal in Belgium in 2012 using the port demand of Port of Antwerp (2.17×10^{-13} unit/tkm), Port of Rotterdam (9.06×10^{-14} unit/tkm), Port of Liège (3.00×10^{-12} unit/tkm) and the port demand from Ecoinvent (2.54×10^{-14} unit/tkm).

Table 4.25. LCIA of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the port demand of Port of Antwerp, Port of Rotterdam, Port of Liège and the port demand used in Ecoinvent v3

Impact category	Unit	Port of Antwerp	Port of Rotterdam	Port of Liège	Port demand used in Ecoinvent v3
Climate change	**kg CO_2 eq**	7.47×10^{-2}	5.42×10^{-2}	5.26×10^{-1}	4.36×10^{-2}
Ozone depletion	**kg CFC-11 eq**	7.81×10^{-9}	6.42×10^{-9}	3.86×10^{-8}	5.70×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	4.74×10^{-5}	2.92×10^{-5}	4.49×10^{-4}	1.98×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.26×10^{-2}	6.74×10^{-3}	1.42×10^{-1}	3.70×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	5.29×10^{-4}	4.72×10^{-4}	1.79×10^{-3}	4.42×10^{-4}
Acidification	**molc H+ eq**	6.23×10^{-4}	4.69×10^{-4}	4.00×10^{-3}	3.90×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.98×10^{-3}	1.79×10^{-3}	6.34×10^{-3}	1.68×10^{-3}
Freshwater eutrophication	**kg P eq**	1.94×10^{-5}	1.03×10^{-5}	2.20×10^{-4}	5.60×10^{-6}
Resource depletion	**kg Sb eq**	6.62×10^{-7}	5.71×10^{-7}	2.66×10^{-6}	5.24×10^{-7}

Figure 4.11 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in canal in Belgium in 2012 by substituting the port demand (from Table 4.25). This scenario analysis shows that the port facilities used as reference influences the total impact of the IWW transport significantly. On the one hand, the transport process using the Port of Liège as reference presents the maximum impact in all the indicators with an important difference compared to the rest of the transport processes. On the other hand, there are no significant differences in the LCIA results between the other three processes.

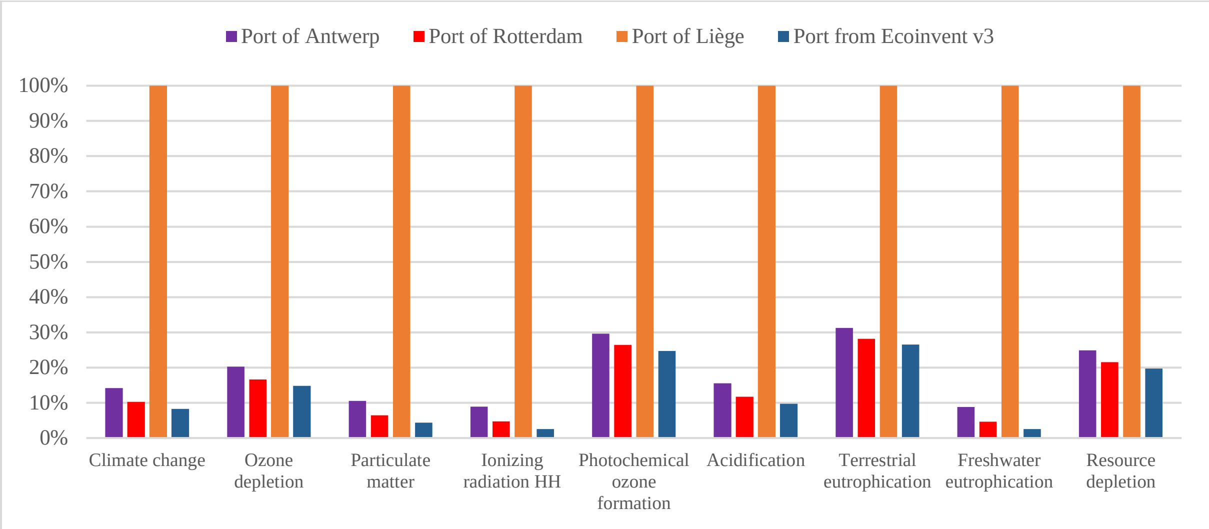


Figure 4.11. LCIA of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the port demand of Port of Antwerp, Port of Rotterdam, Port of Liège and the port demand used in Ecoinvent v3

Figure 4.12 analyses the distribution of the impact between the different life cycle phases (transport operation, fuel production, vessel, canal and port) of IWW transport in canal in Belgium in 2012 based on applying scenario analysis to the port demand (Port of Antwerp, Port of Rotterdam, Port of Liège and the port demand used in Ecoinvent v3).

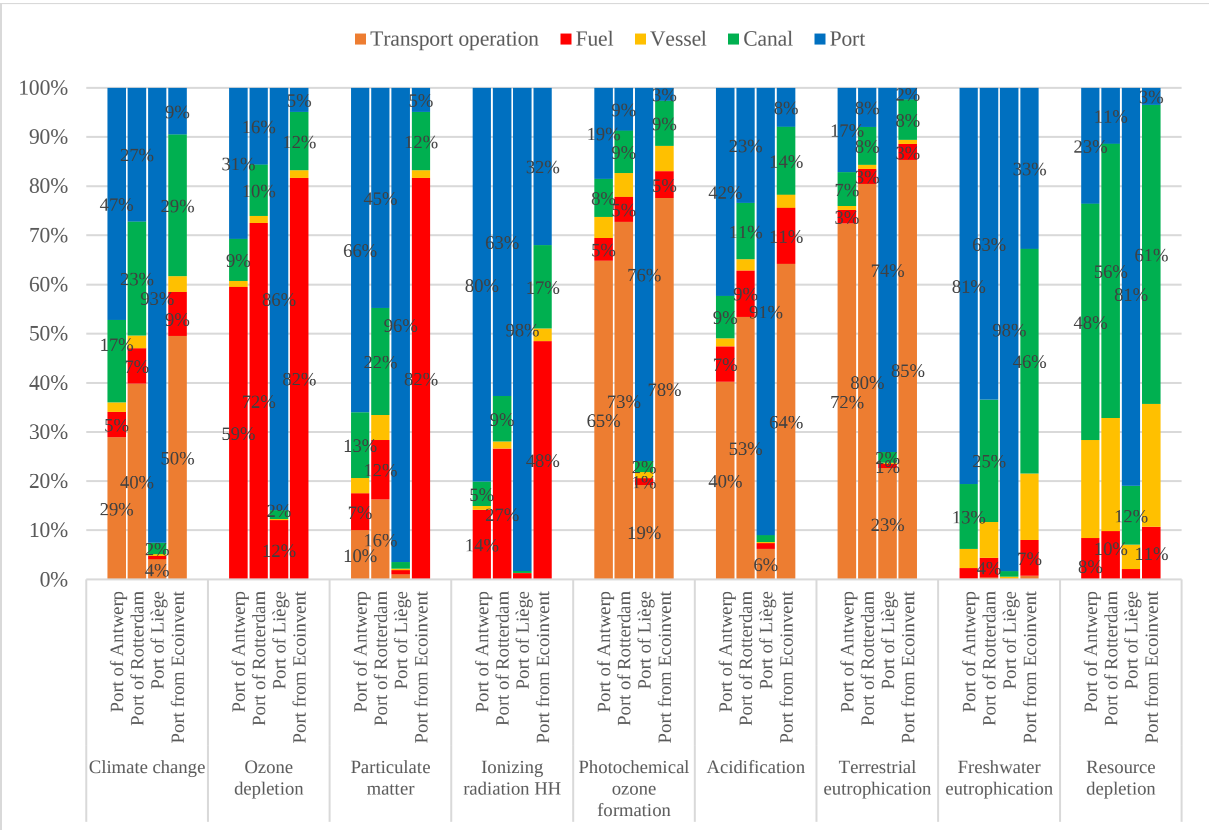


Figure 4.12. LCIA of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the port demand of Port of Antwerp, Port of Rotterdam, Port of Liège and the port demand used in Ecoinvent v3

As in the case of total impact (see Figure 4.11), the scenario analysis shows that the port demand also affects the distribution of the impact between the life cycle phases considerably. For IWW transport using the Port of Liège, the port facilities demand contributes the most to the impact. Within the other three processes, as the port demand decreases, the share of impact represented by the port demand also decreases. Therefore, for the process with the port demand from Ecoinvent v3 (which presents the lowest port demand analysed), the share of the impact from the port facilities is the lowest, then the process using the Port of Rotterdam and finally the process using the Port of Antwerp.

Chapter 5. Life Cycle Assessment of road freight transport

5.1. Introduction

Figure 5.1 presents the system boundaries considered in our study for road freight transport. The road freight transport system has been divided in three sub-systems: road transport operation, lorry and road infrastructure. The sub-system road transport operation includes the processes that are directly connected with the vehicle activity. Therefore, it takes into account the exhaust emissions to air from lorries and the indirect emissions from diesel production. Moreover, the application of the LCA methodology involves the analysis of the environmental impacts related to the manufacturing, maintenance and disposal of the vehicle and the construction, maintenance and disposal of the road infrastructure (Spielmann et al., 2007).

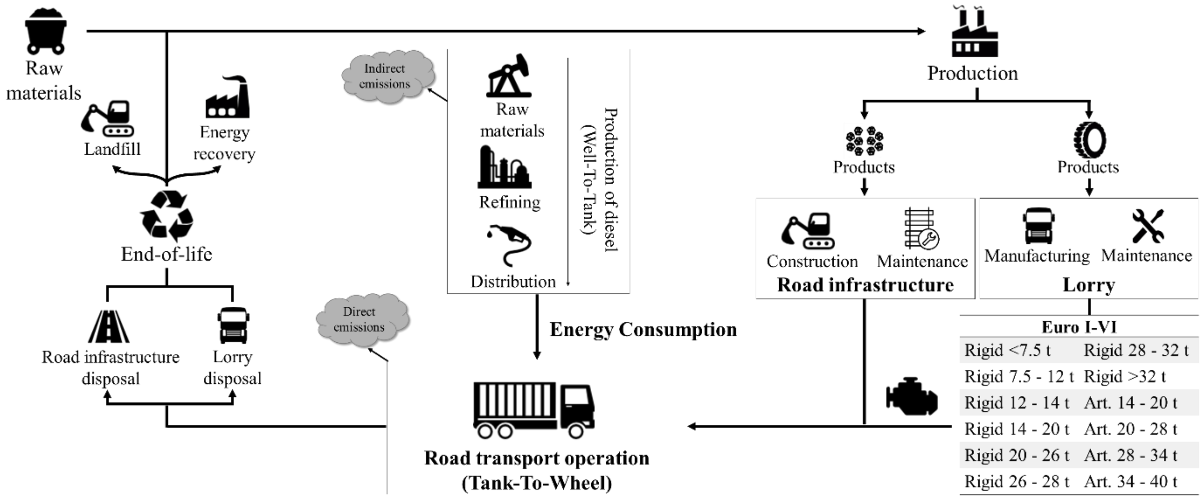


Figure 5.1. Road freight transport system boundaries considered in our study. Source: Based on Spielmann et al., 2007

5.2. Road transport operation

The main processes included in the sub-system road transport operation can be divided in two stages. On the one hand, the Well-To-Tank (WTT) stage comprises the primary energy consumption and indirect emissions produced at the upstream energy processes, which start with the crude oil extraction, continue with the diesel refining and end with the diesel distribution to the lorry. On the other hand, the Tank-To-Wheels (TTW) stage encompasses the energy consumption of lorries and direct emissions to air (exhaust emissions and non-exhaust emissions of particulate matter emitted from the wear of brakes, tyres and road surface) during the transport activity. The Well-To-Wheels (WTW) processes would be the sum of the WTT processes and the TTW processes.

5.2.1. Energy consumption (Tank-To-Wheel) of road freight transport

The energy consumption during the road freight transport activity has been calculated considering the influence of the load weight in the specific fuel consumption of the lorry. The average diesel consumption has been calculated in three stages. First, the specific fuel consumption per kilometre (g/km) has been calculated. Second, the fuel consumption per tonne-kilometre (g/tkm) has been determined. Third, the annual average fuel consumption of Belgium for the period from 2006 to 2012 has been obtained considering both the lorry gross vehicle weight (GVW) category and the emission engine technology.

5.2.1.1. Specific fuel consumption per kilometre (g/km)

In a first stage, the fuel consumption per kilometre of the vehicle (g/km) has been determined using the fuel consumption from EcoTransIT (2014) shown in Table 5.1. The energy consumption values have been converted to g/km considering that diesel net calories are 42.8 MJ/kg.

Table 5.1. Specific energy consumption of a lorry being empty or full. Source: EcoTransIT, 2014

Heavy Duty Lorry	Fuel Consumption (MJ/km)		Fuel Consumption (g/km)[1]	
	Empty lorry	Full lorry	Empty lorry	Full lorry
3.5 - 7.5 t	4.7	5.1	110	119
7.5 - 12 t	6.1	7.1	143	166
12 - 20 t	7	8.5	164	199
20 - 26 t	7.8	10.6	182	248
26 - 40 t	8.2	13.3	192	311

[1]Considering that diesel net calories are 42.8 MJ/kg

As shown in Figure 5.2, the fuel consumption factor of EcoTransIT (2014) has been translated from five lorry GVW categories to the twelve lorry GVW categories used in our study. This classification of twelve lorry categories has been used because it is the most recent one used by different databases such as COPERT, TRACCS, HBEFA or the ARTEMIS project.

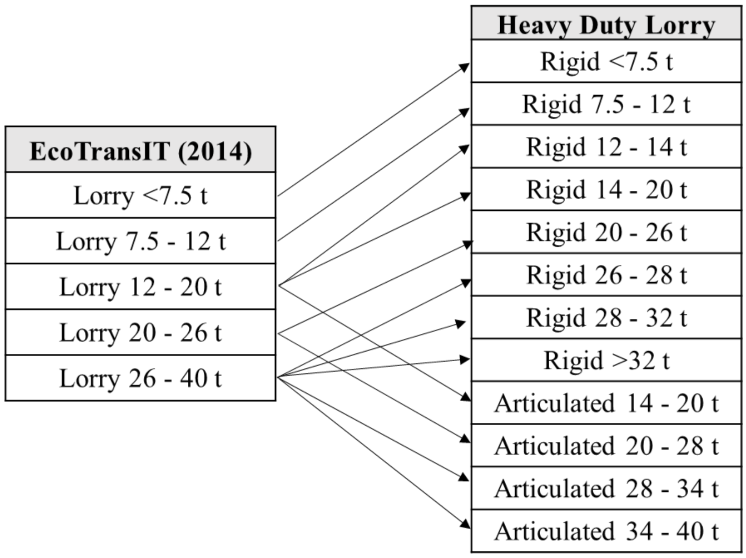


Figure 5.2. GVW classification of lorries used by EcoTransIT (2014) and the translation to the classification used in this thesis

Figure 5.3 shows the distribution of the population of heavy duty vehicles by lorry GVW category in Belgium in the period from 2006 to 2012.

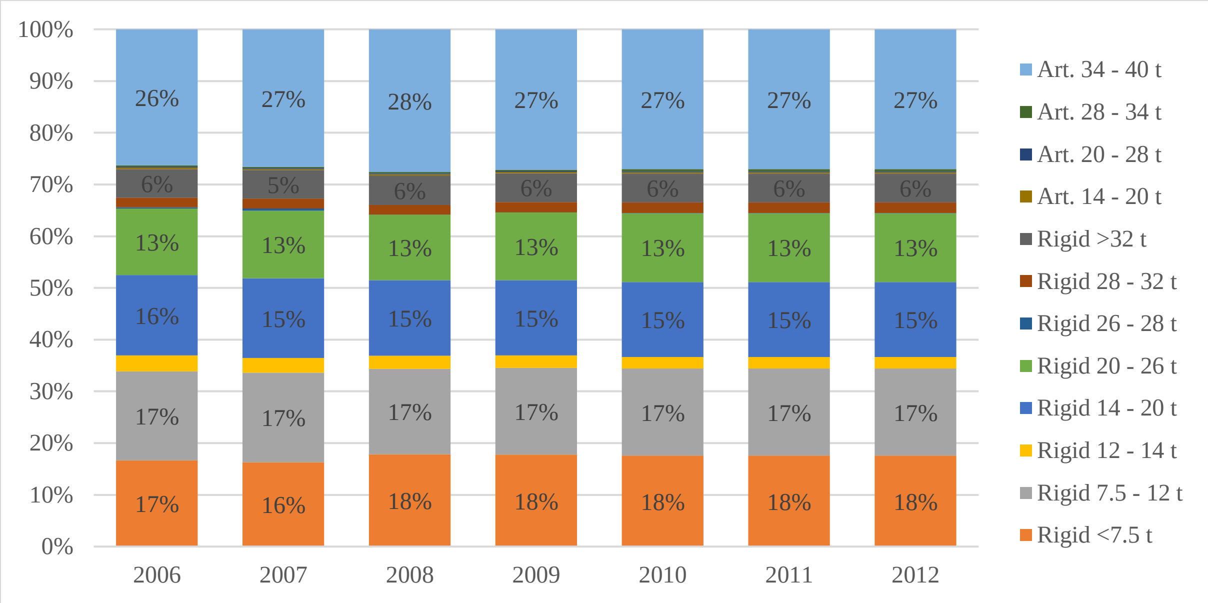


Figure 5.3. Heavy duty vehicles distribution by lorry GVW category in Belgium. Source: COPERT

Equation (6) from EcoTransIT (2014) has been used to calculate the specific fuel consumption (g/km) of a lorry for three scenarios with different load factors of 50%, 60% and 85%. These choices were made because the load factor of an average cargo in road transport including empty trips is 50% (EcoTransIT, 2008). Moreover, the load factors of intermodal road transport are 85% for the main haulage and 60% for the post-haulage (Janic, 2008).

$$Energy\ Consumption\ with\ actual\ load\ \left(\frac{g}{km}\right) = EC_{Empty} + \left(EC_{Full} - EC_{Empty}\right) \times LF\ (\%) \quad (6)$$

Table 5.2 presents the fuel consumption values calculated for the load factors of 50%, 60% and 85%.

Table 5.2. Specific fuel consumption (g/km) of a lorry depending on the load factors (LF) of 50%, 60% and 85%

Heavy Duty Lorry	LF 0% (Empty lorry)	LF 100% (Full lorry)	LF 50%	LF 60%	LF 85%
Rigid <7.5 t	110	119	114	115	118
Rigid 7.5 - 12 t	143	166	154	157	162
Rigid 12 - 14 t	164	199	181	185	193
Rigid 14 - 20 t	164	199	181	185	193
Rigid 20 - 26 t	182	248	215	221	238
Rigid 26 - 28 t	192	311	251	263	293
Rigid 28 - 32 t	192	311	251	263	293
Rigid >32 t	192	311	251	263	293
Art. 14 - 20 t	164	199	181	185	193
Art. 20 - 28 t	182	248	215	221	238
Art. 28 - 34 t	192	311	251	263	293
Art. 34 - 40 t	192	311	251	263	293

Table 5.3 presents the average fuel consumption (g/km) values from TRACCS database (Papadimitriou et al., 2013) for Belgium. By comparing with our results (see Table 5.2), the specific fuel consumptions obtained for a load factor of 50% in our study show similar values than those from TRACCS database for the lorry GVW category articulated 34-40 t (251 g/km in 2010), which might suggest that the values from TRACCS database have been obtained considering a load factor of approximately 50%.

Table 5.3. Fuel consumption (g/km) of road freight transport in Belgium from TRACCS database. Source: Papadimitriou et al., 2013

Heavy Duty Lorry	2005	2006	2007	2008	2009	2010
Rigid <7.5 t	109	109	109	109	109	109
Rigid 7.5 - 12 t	146	146	145	146	146	146
Rigid 12 - 14 t	153	154	154	154	154	154
Rigid 14 - 20 t	179	179	178	178	178	178
Rigid 20 - 26 t	215	214	213	213	213	213
Rigid 26 - 28 t	226	226	226	225	225	225
Rigid 28 - 32 t	260	260	260	260	260	260
Rigid >32 t	255	254	253	253	253	253
Art. 14 - 20 t	172	171	170	170	170	170
Art. 20 - 28 t	215	213	212	212	212	212
Art. 28 - 34 t	225	223	222	222	222	222
Art. 34 - 40 t	254	253	252	252	252	251

5.2.1.2. Fuel consumption per tonne-kilometre (g/tkm)

In a second stage, as shown in Equation (7), the energy consumption has been converted from g/km to g/tkm dividing by the actual payload of each GVW class. The actual payload of each lorry GVW class has been calculated multiplying the maximum payload by a load factor (see Equation (8)).

$$Fuel\ consumption\ \left(\frac{g}{tkm}\right) = \frac{Fuel\ consumption\ \left(\frac{g}{km}\right)}{Actual\ payload\ (t)} \quad (7)$$

$$Actual\ payload\ (t) = Maximum\ payload\ (t) \times Load\ factor\ (\%) \quad (8)$$

It should be noted that the fuel consumption in g/km increases with the size of the lorry (see Table 5.2), but in g/tkm decreases with the size of the lorry (see Table 5.4). This is due to increased payload with the GVW category. Furthermore, for the same GVW category, the higher the load factor and therefore the higher the actual payload implies a lower fuel consumption.

Table 5.4. Maximum payload, actual payload and fuel consumption (g/tkm) of road transport using the load factors (LF) of 50%, 60% and 85%

Heavy Duty Lorry	Maximum Payload (t/vehicle)[1]	Actual Payload (t/vehicle)			Fuel consumption (g/tkm)		
		LF 50%	LF 60%	LF 85%	LF 50%	LF 60%	LF 85%
Rigid <7.5 t	2	1.01	1.21	1.72	113	95	69
Rigid 7.5 - 12 t	5	2.51	3.01	4.27	61	52	38
Rigid 12 - 14 t	7	3.51	4.22	5.97	52	44	32
Rigid 14 - 20 t	9.7	4.85	5.82	8.24	37	32	23
Rigid 20 - 26 t	13.7	6.85	8.22	11.65	31	27	20
Rigid 26 - 28 t	16.4	8.19	9.83	13.92	31	27	21
Rigid 28 - 32 t	18.4	9.19	11.03	15.62	27	24	19
Rigid >32 t	19.7	9.86	11.83	16.76	25	22	17
Art. 14 - 20 t	12.6	6.32	7.58	10.74	29	24	18
Art. 20 - 28 t	17.1	8.54	10.25	14.52	25	22	16
Art. 28 - 34 t	21.5	10.76	12.91	18.29	23	20	16
Art. 34 - 40 t	25.3	12.66	15.20	21.53	20	17	14

[1]Source: Papadimitriou et al., 2013

5.2.1.3. Average fuel consumption per tonne-kilometre (g/tkm) in Belgium for the period from 2006 to 2012

Finally, in order to do an average energy consumption for every year, the annual tonne-kilometres moved by each lorry GVW category and emission engine technology in Belgium have been used to calculate a weighted arithmetic mean.

As shown in Equation (9), the annual transport performance has been calculated multiplying the vehicle-kilometres (i.e. vkm) by the actual payload of each GVW class and emission engine technology. The annual vehicle-kilometres have been determined using the population of heavy duty lorries and the mileage (km/a) of road freight transport in Belgium of each GVW class and emission engine technology (see Equation (10)). The values of population of heavy duty lorries and the mileage (km/a) of road freight transport in Belgium considering the lorry GVW category and the emission engine technology used in our research are in Appendix C (see Tables C.3 and C.4).

$$\boxed{Transport\ performance\ (tkm) = vkm \times Actual\ payload\ (t)} \qquad (9)$$

$$\boxed{vkm = Population\ of\ heavy\ duty\ lorries \times Mileage\ \left(\frac{km}{a}\right)} \qquad (10)$$

Table 5.5 shows the distribution by tkm of road freight transport in Belgium by GVW category from 2006 to 2012. The lorry GVW category articulated of 34-40 t represents approximately 75% of the road freight transport performance every year in Belgium. Therefore, this lorry GVW category has been used to compare the different inland freight transport modes and to study intermodal transport routes because it is representative and it presents the usual capacity for containers.

Table 5.5. Share of freight transport performance (% of tkm) in Belgium

Heavy Duty Lorry	2006	2007	2008	2009	2010	2011	2012
Rigid <7.5 t	0.62%	0.61%	0.65%	0.66%	0.65%	0.64%	0.65%
Rigid 7.5 - 12 t	1.90%	1.90%	1.77%	1.83%	1.83%	1.84%	1.84%
Rigid 12 - 14 t	0.32%	0.30%	0.26%	0.25%	0.23%	0.23%	0.24%
Rigid 14 - 20 t	3.48%	3.44%	3.18%	3.23%	3.20%	3.24%	3.26%
Rigid 20 - 26 t	4.88%	4.94%	4.68%	4.91%	4.97%	4.94%	4.95%
Rigid 26 - 28 t	0.12%	0.20%	0.02%	0.02%	0.03%	0.03%	0.03%
Rigid 28 - 32 t	1.18%	1.24%	1.15%	1.24%	1.28%	1.21%	1.21%
Rigid >32 t	11.60%	11.40%	11.54%	11.55%	11.48%	11.55%	11.58%
Art. 14 - 20 t	0.29%	0.26%	0.26%	0.26%	0.25%	0.27%	0.27%
Art. 20 - 28 t	0.21%	0.19%	0.20%	0.19%	0.19%	0.20%	0.20%
Art. 28 - 34 t	0.25%	0.22%	0.25%	0.23%	0.45%	0.47%	0.47%
Art. 34 - 40 t	75.12%	75.31%	76.04%	75.63%	75.45%	75.38%	75.31%
TOTAL	100%	100%	100%	100%	100%	100%	100%

Table 5.6 shows the methodology used to calculate the average fuel consumption of road freight transport each year taking as an example the year 2012. The average fuel consumption of 2012 for road freight transport in Belgium with a load factor of 50%, 60% and 85% was 23.22 g/tkm, 20.16 g/tkm and 15.65 g/tkm, respectively.

Table 5.6. Average fuel consumption (g/tkm) of road freight transport in Belgium in 2012

Heavy Duty Lorry	Share of tkm in 2012	Fuel consumption (g/tkm)			Contribution to average fuel consumption in 2012 (g/tkm)		
		LF 50%	LF 60%	LF 85%	LF 50%	LF 60%	LF 85%
Rigid <7.5 t	0.65%	113	95	69	0.73	0.61	0.44
Rigid 7.5 - 12 t	1.84%	61	52	38	1.13	0.96	0.70
Rigid 12 - 14 t	0.24%	52	44	32	0.12	0.10	0.08
Rigid 14 - 20 t	3.26%	37	32	23	1.22	1.03	0.76
Rigid 20 - 26 t	4.95%	31	27	20	1.55	1.33	1.01
Rigid 26 - 28 t	0.03%	31	27	21	0.01	0.01	0.01
Rigid 28 - 32 t	1.21%	27	24	19	0.33	0.29	0.23
Rigid >32 t	11.58%	25	22	17	2.95	2.58	2.02
Art. 14 - 20 t	0.27%	29	24	18	0.08	0.06	0.05
Art. 20 - 28 t	0.20%	25	22	16	0.05	0.04	0.03
Art. 28 - 34 t	0.47%	23	20	16	0.11	0.10	0.07
Art. 34 - 40 t	75.31%	20	17	14	14.94	13.04	10.25
TOTAL	100%	-	-	-	**23.22**	**20.16**	**15.65**

Table 5.7 presents the average energy consumption of both road freight transport (which considers all the GVW categories) and the lorry GVW category articulated of 34-40 t calculated from the period 2006 to 2012 in Belgium.

Table 5.7. Average energy consumption of road freight transport in Belgium using the load factors (LF) of 50%, 60% and 85%

		Unit	2006	2007	2008	2009	2010	2011	2012
Average road transport	LF 50%	(g/tkm)	23.29	23.26	23.14	23.21	23.20	23.21	23.22
		(kJ/tkm)	997	995	990	993	993	993	994
	LF 60%	(g/tkm)	20.21	20.19	20.09	20.15	20.14	20.15	20.16
		(kJ/tkm)	865	864	860	862	862	862	863
	LF 85%	(g/tkm)	15.69	15.68	15.61	15.65	15.64	15.65	15.65
		(kJ/tkm)	672	671	668	670	669	670	670
Articulated lorry of 34 - 40 t	LF 50%	(g/tkm)	19.83						
		(kJ/tkm)	849						
	LF 60%	(g/tkm)	17.31						
		(kJ/tkm)	741						
	LF 85%	(g/tkm)	13.60						
		(kJ/tkm)	582						

The energy consumption used in EcoTransIT (2008) for an articulated lorry of 34-40 t and emission engine technology Euro III for the year 2005 is 1 082 kJ/tkm (see Table 5.8). Therefore, the energy consumptions for an articulated lorry of 34-40 t obtained in our study are lower than the values from EcoTransIT (2008). It should be noted that the reference values represent European averages, whereas our results represent a Belgian average.

Table 5.8. Energy consumption for a European average articulated lorry of 34-40 t for motorway, average gradient for hilly countries for 2005. Source: EcoTransIT, 2008

Articulated lorry 34 - 40 t		Energy consumption (kJ/tkm)
Euro I	bulk	981
	average	1 086
	volume	1 673
Euro II	bulk	946
	average	1 044
	volume	1 592
Euro III	bulk	976
	average	1 082
	volume	1 665
Euro IV	bulk	947
	average	1 050
	volume	1 616
Euro V	bulk	899
	average	996
	volume	1 532

For Ecoinvent v3 database (see Appendix C, Table C.2), the energy consumption for a lorry of >32 t for the year 2014 is approximately 17 g/tkm (727 kJ/tkm), which is similar to our result for a rigid lorry >32 t with a load factor of 85%. As in the case of EcoTransIT (2008), the values from Ecoinvent v3 represent European averages, whereas our results represent a Belgian average.

5.2.2. Exhaust emissions (Tank-To-Wheel) of road freight transport

As mentioned in Chapter 3 (Section 3.2.2), the direct emissions do not yet represent environmental impact categories such as climate change or acidification. These direct emissions during transport operation are part of the inventory analysis and this, together with the energy consumption during transport operation and the emissions, energy and material consumptions from the vehicle and infrastructure stages, constitute the required elements to model the freight transport system. It is necessary to consider all the elements from the inventory analysis to evaluate the contribution of the freight transport to environmental impact categories. Therefore, this section presents pollutant emissions as substances produced during the transport activity and not as environmental impacts.

The exhaust emissions produced during the road transport operation have been determined using the calculated diesel consumption and the emission factors from two sources. For fuel dependent emissions such as CO_2 and heavy metals, the emission factors of Spielmann et al. (2007) have been used (see Table 5.9). The uncertainty of these emission factors has been calculated using the pedigree matrix developed by Weidema and Wesnæs (1996) (see Section 3.2.2). Table 5.9 includes the standard deviation (SD) used in our study from Ecoinvent v3.

Table 5.9. Emission factors used to determine the exhaust emissions of road freight transport. Sources: Spielmann et al., 2007; Weidema et al., 2013

Emissions to air	Emission factor (g/kg diesel)	SD	Emissions to air	Emission factor (g/kg diesel)	SD
CO_2	3 172	1.13	**Zn**	0.001	5.35
Cd	0.00001	5.35	**Pb**	0.00000011	5.35
Cu	0.0017	5.35	**Hg**	0.00000002	5.35
Cr	0.00005	5.35	**Cr (VI)**	0.0000001	5.35
Ni	0.00007	5.35	**As**	0.0000001	1.13
Se	0.00001	5.35	**-**	-	-

The emissions of SO_2 are dependent on the sulphur content in diesel. Conventional road-transport diesel is regulated by Directive 2003/17/EC, establishing a low sulphur content with a maximum limit of 10 ppm sulphur by mass from 2009. However, diesel in Belgium has an average sulphur content of 8 ppm since 2008. For the years 2006 and 2007, the sulphur content in diesel in Belgium was 24 ppm and 9 ppm, respectively (Twisse and Scott, 2012). The SO_2 emissions have been calculated using Equation (1) from Section 3.2.2. Table 5.10 presents the sulphur content of diesel and SO_2 emissions per kg of diesel used in our research. Since sulphur concentration varies throughout years, the corresponding emission factor for each year has been calculated. Thus, the SO_2 emission factors of 0.048 g/kg, 0.018 g/kg and 0.016 g/kg have been used. Ecoinvent v3 assumes a sulphur concentration of 300 ppm resulting in an emission factor of 0.6 g/kg. As already stated, this highlights the need to update the Ecoinvent v3 database.

Table 5.10. Concentration of sulphur in diesel in ppm. Source: Twisse and Scott, 2012

	2006	2007	2008	2009	2010	2011	2012
Sulphur content (ppm)	24	9	8	8	8	8	8
SO_2 emissions (g/kg diesel)	0.048	0.018	0.016	0.016	0.016	0.016	0.016

The road transport emissions dependent on the engine emission technology (CO, NMVOC, NO_X and PM for example) are delimited by the Euro emission standards, which are regulated by several European policies, such as the Directive 91/542/EEC (Euro I and Euro II), the Directive 1999/96/EC (Euro III, Euro IV and Euro V) and the EC Regulation 595/2009 (Euro VI).

As shown in Figure 5.4, the emission engine technologies presents in our study are the following: Conventional (cnv.), Euro I, Euro II, Euro III, Euro IV and Euro V. The emission engine technology Euro IV appears in the year 2006 in the Belgian heavy duty vehicle market, and the Euro V in the year 2009. The emission engine technology Euro VI appears in the year 2014. In the year 2012, the lorries with a conventional emission engine technology represented the 4% of the Belgian heavy duty market, the Euro I a 7%, the Euro II a 19%, the Euro III a 26%, the Euro IV a 21% and the Euro V a 22%.

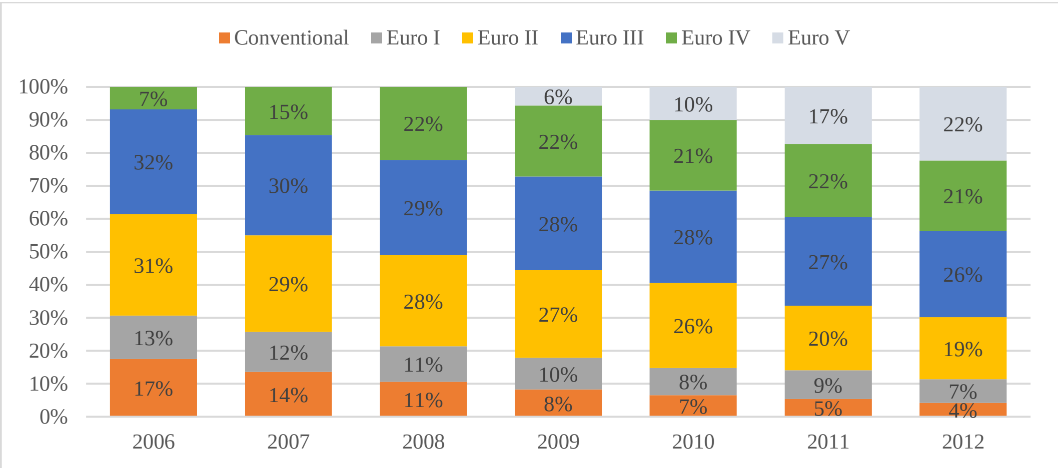


Figure 5.4. Heavy duty vehicle distribution by emission engine technology in Belgium. Source: COPERT

Within the category articulated lorry of 34-40 t in the year 2012 (see Figure 5.5), the lorries with a conventional emission engine technology represented the 13% of the Belgian lorries, the Euro I a 9%, the Euro II a 14%, the Euro III a 22%, the Euro IV a 20% and the Euro V a 21%.

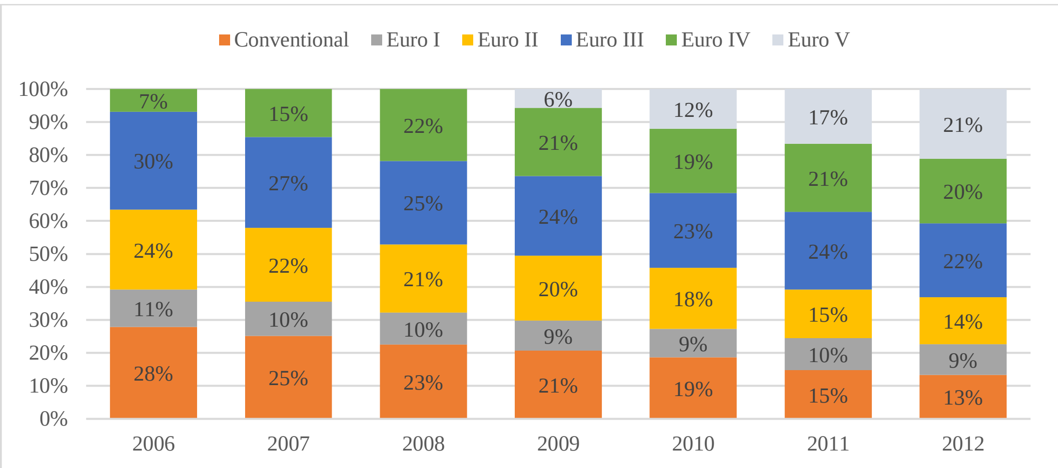


Figure 5.5. Heavy duty vehicle distribution within the lorry GVW category articulated lorry of 34-40 t by emission engine technology in Belgium. Source: COPERT

On the basis of the heavy duty vehicle population in the period from 2005 to 2010 in Belgium from TRACCS database (Papadimitriou et al., 2013), it has been calculated an average age of 9 years for heavy duty vehicles and an average age of 10 years for the vehicles of the GVW category articulated lorry 34-40 t. This explains that vehicles with older emission standards are present for several years on the Belgian heavy duty market.

The pollutant emissions dependent on the engine emission technology has been calculated using the tier 2 emission factors for heavy duty vehicles from EMEP/EEA air pollutant emission inventory guidebook 2013 (see Table 5.11). These emission factors represent European averages for different parameters such as driving speed, ambient temperatures, driving conditions (e.g. urban, rural or highway) or trip length for example (Ntziachristos and Samaras, 2014). Therefore, these emission factors may vary depending on the conditions considered. The emission factors from EMEP/EEA have been converted from g/km to g/tkm dividing by the actual payload (see Table 5.4) of each lorry gross vehicle weight (GVW) category.

Table 5.11. Emission factors (g/km) for pollutant emissions dependent on the engine emission technology of heavy duty vehicles. Source: Ntziachristos and Samaras, 2014

<table>
<tr><th>Heavy Duty Lorry</th><th>Technology</th><th>CO</th><th>NMVOC</th><th>NO_X</th><th>N_2O</th><th>NH_3</th><th>$PM_{2.5}$</th><th>indeno (1,2,3-cd) pyrene</th><th>benzo(k)fluoranthene</th><th>benzo(b)fluoranthene</th><th>benzo(a) pyrene</th></tr>
<tr><td rowspan="7"><7.5 t</td><td>Cnv.</td><td>1.850</td><td>1.070</td><td>4.70</td><td>0.029</td><td rowspan="5">0.0029</td><td>0.3330</td><td rowspan="28">1.40×10^{-6}</td><td rowspan="28">6.09×10^{-6}</td><td rowspan="28">5.45×10^{-6}</td><td rowspan="28">9.00×10^{-6}</td></tr>
<tr><td>Euro I</td><td>0.657</td><td>0.193</td><td>3.37</td><td>0.005</td><td>0.1290</td></tr>
<tr><td>Euro II</td><td>0.537</td><td>0.123</td><td>3.49</td><td>0.004</td><td>0.0610</td></tr>
<tr><td>Euro III</td><td>0.584</td><td>0.115</td><td>2.63</td><td>0.003</td><td>0.0566</td></tr>
<tr><td>Euro IV</td><td rowspan="3">0.047</td><td rowspan="3">0.005</td><td>1.64</td><td>0.006</td><td rowspan="2">0.0106</td></tr>
<tr><td>Euro V</td><td>0.933</td><td>0.017</td><td rowspan="2">0.0110</td></tr>
<tr><td>Euro VI</td><td>0.18</td><td>0.017</td><td>0.0005</td></tr>
<tr><td rowspan="7">7.5 - 16 t</td><td>Cnv.</td><td>2.130</td><td>0.776</td><td>8.92</td><td>0.029</td><td rowspan="5">0.0029</td><td>0.3344</td></tr>
<tr><td>Euro I</td><td>1.020</td><td>0.326</td><td>5.31</td><td>0.008</td><td>0.2010</td></tr>
<tr><td>Euro II</td><td>0.902</td><td>0.207</td><td>5.50</td><td>0.008</td><td>0.1040</td></tr>
<tr><td>Euro III</td><td>0.972</td><td>0.189</td><td>4.30</td><td>0.004</td><td>0.0881</td></tr>
<tr><td>Euro IV</td><td rowspan="3">0.071</td><td rowspan="3">0.008</td><td>2.65</td><td>0.012</td><td rowspan="2">0.0161</td></tr>
<tr><td>Euro V</td><td>1.51</td><td>0.034</td><td rowspan="2">0.0110</td></tr>
<tr><td>Euro VI</td><td>0.291</td><td>0.033</td><td>0.0008</td></tr>
<tr><td rowspan="7">16 - 32 t</td><td>Cnv.</td><td>1.930</td><td>0.486</td><td>10.70</td><td>0.029</td><td rowspan="5">0.0029</td><td>0.4180</td></tr>
<tr><td>Euro I</td><td>1.550</td><td>0.449</td><td>7.52</td><td>0.008</td><td>0.2970</td></tr>
<tr><td>Euro II</td><td>1.380</td><td>0.290</td><td>7.91</td><td>0.007</td><td>0.1550</td></tr>
<tr><td>Euro III</td><td>1.490</td><td>0.278</td><td>6.27</td><td>0.004</td><td>0.1300</td></tr>
<tr><td>Euro IV</td><td rowspan="3">0.105</td><td rowspan="3">0.010</td><td>3.83</td><td>0.012</td><td rowspan="2">0.0239</td></tr>
<tr><td>Euro V</td><td>2.18</td><td>0.034</td><td rowspan="2">0.0110</td></tr>
<tr><td>Euro VI</td><td>0.422</td><td>0.032</td><td>0.0012</td></tr>
<tr><td rowspan="7">>32 t</td><td>Cnv.</td><td>2.250</td><td>0.534</td><td>12.80</td><td>0.029</td><td rowspan="5">0.0029</td><td>0.4910</td></tr>
<tr><td>Euro I</td><td>1.900</td><td>0.510</td><td>9.04</td><td>0.012</td><td>0.3580</td></tr>
<tr><td>Euro II</td><td>1.690</td><td>0.326</td><td>9.36</td><td>0.012</td><td>0.1940</td></tr>
<tr><td>Euro III</td><td>1.790</td><td>0.308</td><td>7.43</td><td>0.007</td><td>0.1510</td></tr>
<tr><td>Euro IV</td><td rowspan="3">0.121</td><td rowspan="3">0.012</td><td>4.61</td><td>0.018</td><td rowspan="2">0.0268</td></tr>
<tr><td>Euro V</td><td>2.63</td><td>0.053</td><td rowspan="2">0.0110</td></tr>
<tr><td>Euro VI</td><td>0.507</td><td>0.049</td><td>0.0013</td></tr>
</table>

Figure 5.6 presents a comparison of the tier 2 emission factors for heavy duty vehicles from Table 5.11. Since the emission factors of the Polycyclic Aromatic Hydrocarbons (PAH) remain the same for all GVW and standard emission categories, they have not been included.

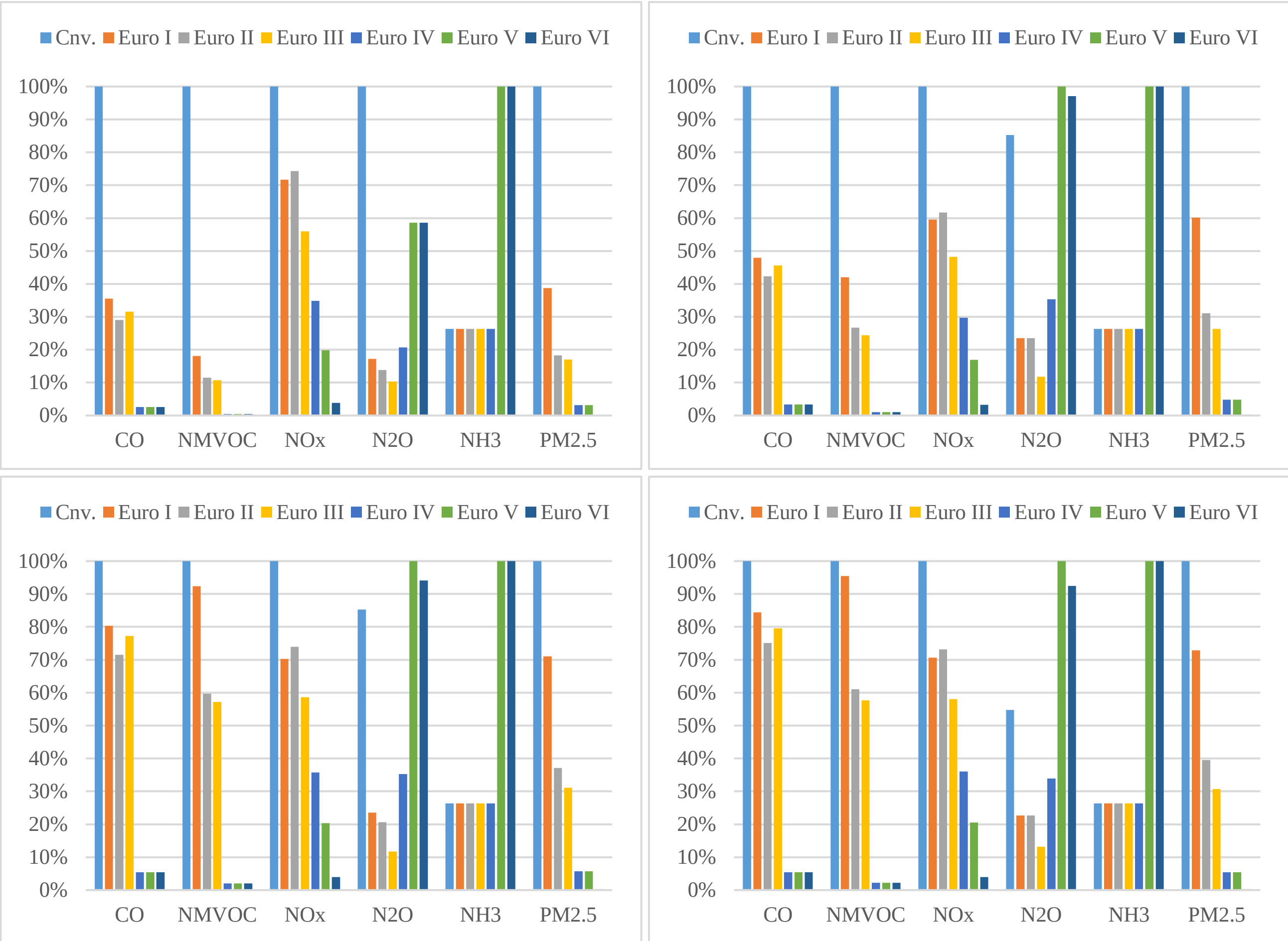


Figure 5.6. Comparison of the tier 2 emission factors for heavy duty vehicles from EMEP/EEA air pollutant emission inventory guidebook 2013. Top left: lorry <7.5 t. Top Right: lorry 7.5 – 16 t. Bottom left: lorry 16 – 32 t. Bottom right: lorry >32 t

The emission factors of CO show an increase between the emission standards Euro II and Euro III, then they decrease greatly from Euro IV an remain with the same value. In the case of NMVOC, the emission factors decrease with each new generation of emission standard but from Euro IV they drop considerably and remain with the same value.

The emission factors of NO_X decrease with each new generation of emission standard but between Euro I and Euro II there is an increase. For N_2O, the emission factors decrease from conventional engine to Euro III, then there is an increase in Euro IV and Euro V to finally lower again in Euro VI. However, the N_2O emissions factors are higher for the engines Euro V and Euro VI than in older emission engine technologies. This is due to the use of selective catalytic reduction systems (SCR) to abate NO_X exhaust emissions through the use of an ammonia carrier (urea), producing as by-products NH_3 and N_2O (Suarez-Bertoa et al., 2016).

All the GVW categories present an emission factor for NH_3 of 0.0029 g/km for the engines until Euro IV and the emission factor 0.011 g/km for the engines Euro V and Euro VI. Therefore, NH_3 emissions are higher for the engines Euro V and Euro VI than in older emission standards.

As for N_2O emissions, the increase of NH_3 emissions is due to the use of SCR systems to abate NO_X exhaust emissions, generating as by-products NH_3 and N_2O (Suarez-Bertoa et al., 2016).

The emission factor of $PM_{2.5}$ decrease with each new generation of emission standard due to the use of diesel particle filters (DPF). It should be noted the change of order of magnitude in the Euro VI standard due to a further decrease, causing that the value does not appear in the chart.

The emissions factor from EMEP/EEA are classified in four GVW categories. As shown in Figure 5.7, in order to be coherent with the energy consumption, it has been decided to translate the emission factor of EMEP/EEA from four lorry GVW categories to twelve lorry GVW categories. Since the emissions related to the engine technology are dependent on the lorry GVW category as well, 60 different types of lorries have been considered in the period from 2006 to 2008 (12 lorry GVW categories split in five emission standards) and 72 different types of lorries from 2009 to 2012 (12 lorry GVW categories split in six emission standards).

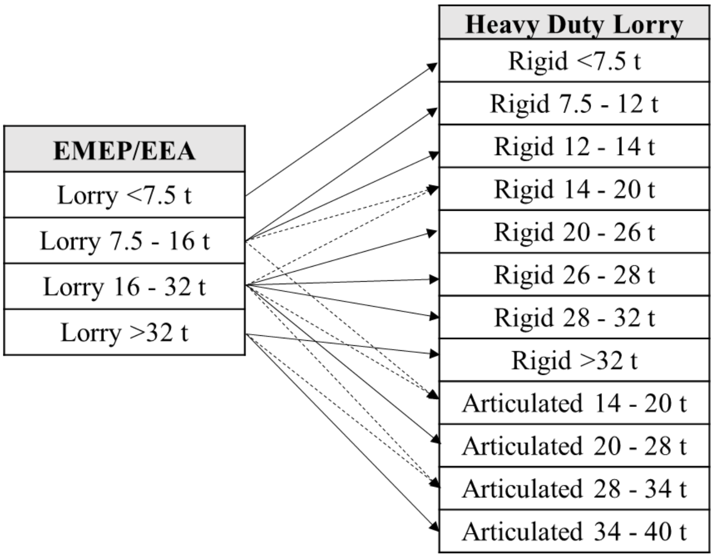


Figure 5.7. GVW classification of lorries used by EMEP/EEA (2013) and the translation to the classification used in this thesis

In order to determine an average emission for every year, following the same methodology as for energy consumption, the tonne-kilometres moved by each lorry GVW category and emission engine technology have been used to calculate a weighted arithmetic mean.

Table 5.12 shows the exhaust emissions produced during the road transport operation in Belgium with a load factor of 50%.

Table 5.12. Exhaust emissions (g/tkm) of road freight transport with a load factor of 50% in Belgium

Average road transport (g/tkm) – LF 50%	2006	2007	2008	2009	2010	2011	2012
CO_2	73.86	73.77	73.40	73.61	73.59	73.62	73.65
SO_2	1.12×10^{-3}	4.19×10^{-4}	3.70×10^{-4}	3.71×10^{-4}	3.71×10^{-4}	3.71×10^{-4}	3.72×10^{-4}
Cd	2.33×10^{-7}	2.33×10^{-7}	2.31×10^{-7}	2.32×10^{-7}	2.32×10^{-7}	2.32×10^{-7}	2.32×10^{-7}
Cu	3.96×10^{-5}	3.95×10^{-5}	3.93×10^{-5}	3.95×10^{-5}	3.94×10^{-5}	3.95×10^{-5}	3.95×10^{-5}
Cr	1.16×10^{-6}	1.16×10^{-6}	1.16×10^{-6}	1.16×10^{-6}	1.16×10^{-6}	1.16×10^{-6}	1.16×10^{-6}
Ni	1.63×10^{-6}	1.63×10^{-6}	1.62×10^{-6}	1.62×10^{-6}	1.62×10^{-6}	1.62×10^{-6}	1.63×10^{-6}
Se	2.33×10^{-7}	2.33×10^{-7}	2.31×10^{-7}	2.32×10^{-7}	2.32×10^{-7}	2.32×10^{-7}	2.32×10^{-7}
Zn	2.33×10^{-5}	2.33×10^{-5}	2.31×10^{-5}	2.32×10^{-5}	2.32×10^{-5}	2.32×10^{-5}	2.32×10^{-5}
Pb	2.56×10^{-9}	2.56×10^{-9}	2.55×10^{-9}	2.55×10^{-9}	2.55×10^{-9}	2.55×10^{-9}	2.55×10^{-9}
Hg	4.66×10^{-10}	4.65×10^{-10}	4.63×10^{-10}	4.64×10^{-10}	4.64×10^{-10}	4.64×10^{-10}	4.64×10^{-10}
Cr (VI)	2.33×10^{-9}	2.33×10^{-9}	2.31×10^{-9}	2.32×10^{-9}	2.32×10^{-9}	2.32×10^{-9}	2.32×10^{-9}
As	2.33×10^{-9}	2.33×10^{-9}	2.31×10^{-9}	2.32×10^{-9}	2.32×10^{-9}	2.32×10^{-9}	2.32×10^{-9}
CO	1.57×10^{-1}	1.40×10^{-1}	1.25×10^{-1}	1.15×10^{-1}	1.06×10^{-1}	9.46×10^{-2}	8.79×10^{-2}
NMVOC	3.34×10^{-2}	2.95×10^{-2}	2.60×10^{-2}	2.36×10^{-2}	2.14×10^{-2}	1.89×10^{-2}	1.73×10^{-2}
NO_X	8.11×10^{-1}	7.64×10^{-1}	7.21×10^{-1}	6.79×10^{-1}	6.40×10^{-1}	5.90×10^{-1}	5.62×10^{-1}
N_2O	1.27×10^{-3}	1.28×10^{-3}	1.29×10^{-3}	1.54×10^{-3}	1.77×10^{-3}	2.00×10^{-3}	2.19×10^{-3}
NH_3	2.97×10^{-4}	2.96×10^{-4}	2.94×10^{-4}	3.60×10^{-4}	4.17×10^{-4}	4.77×10^{-4}	5.25×10^{-4}
$PM_{2.5}$	2.15×10^{-2}	1.91×10^{-2}	1.70×10^{-2}	1.56×10^{-2}	1.42×10^{-2}	1.26×10^{-2}	1.16×10^{-2}
indeno(1,2,3-cd)pyrene	1.43×10^{-7}	1.43×10^{-7}	1.42×10^{-7}	1.43×10^{-7}	1.43×10^{-7}	1.43×10^{-7}	1.43×10^{-7}
benzo(k)fluoranthene	6.24×10^{-7}	6.22×10^{-7}	6.18×10^{-7}	6.21×10^{-7}	6.20×10^{-7}	6.21×10^{-7}	6.21×10^{-7}
benzo(b)fluoranthene	5.58×10^{-7}	5.57×10^{-7}	5.53×10^{-7}	5.56×10^{-7}	5.55×10^{-7}	5.56×10^{-7}	5.56×10^{-7}
benzo(a)pyrene	9.22×10^{-8}	9.20×10^{-8}	9.14×10^{-8}	9.18×10^{-8}	9.17×10^{-8}	9.17×10^{-8}	9.18×10^{-8}

Table 5.13 shows the exhaust emissions produced during the road transport operation in Belgium with a load factor of 60%.

Table 5.13. Exhaust emissions (g/tkm) of road freight transport with a load factor of 60% in Belgium

Average road transport (g/tkm) – LF 60%	2006	2007	2008	2009	2010	2011	2012
CO_2	64.11	64.04	63.73	63.90	63.89	63.91	63.94
SO_2	9.70×10^{-4}	3.63×10^{-4}	3.21×10^{-4}	3.22×10^{-4}	3.22×10^{-4}	3.22×10^{-4}	3.23×10^{-4}
Cd	2.02×10^{-7}	2.02×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.02×10^{-7}
Cu	3.44×10^{-5}	3.43×10^{-5}	3.42×10^{-5}	3.42×10^{-5}	3.42×10^{-5}	3.43×10^{-5}	3.43×10^{-5}
Cr	1.01×10^{-6}	1.01×10^{-6}	1.00×10^{-6}	1.01×10^{-6}	1.01×10^{-6}	1.01×10^{-6}	1.01×10^{-6}
Ni	1.41×10^{-6}	1.41×10^{-6}	1.41×10^{-6}	1.41×10^{-6}	1.41×10^{-6}	1.41×10^{-6}	1.41×10^{-6}
Se	2.02×10^{-7}	2.02×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.01×10^{-7}	2.02×10^{-7}
Zn	2.02×10^{-5}	2.02×10^{-5}	2.01×10^{-5}	2.01×10^{-5}	2.01×10^{-5}	2.01×10^{-5}	2.02×10^{-5}
Pb	2.22×10^{-9}	2.22×10^{-9}	2.21×10^{-9}	2.22×10^{-9}	2.22×10^{-9}	2.22×10^{-9}	2.22×10^{-9}
Hg	4.04×10^{-10}	4.04×10^{-10}	4.02×10^{-10}	4.03×10^{-10}	4.03×10^{-10}	4.03×10^{-10}	4.03×10^{-10}
Cr (VI)	2.02×10^{-9}	2.02×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.02×10^{-9}
As	2.02×10^{-9}	2.02×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.01×10^{-9}	2.02×10^{-9}
CO	1.31×10^{-1}	1.17×10^{-1}	1.04×10^{-1}	9.62×10^{-2}	8.84×10^{-2}	7.88×10^{-2}	7.32×10^{-2}
NMVOC	2.78×10^{-2}	2.46×10^{-2}	2.16×10^{-2}	1.97×10^{-2}	1.79×10^{-2}	1.58×10^{-2}	1.45×10^{-2}
NO_X	6.76×10^{-1}	6.37×10^{-1}	6.01×10^{-1}	5.66×10^{-1}	5.33×10^{-1}	4.92×10^{-1}	4.68×10^{-1}
N_2O	1.06×10^{-3}	1.07×10^{-3}	1.08×10^{-3}	1.29×10^{-3}	1.48×10^{-3}	1.67×10^{-3}	1.82×10^{-3}
NH_3	2.48×10^{-4}	2.47×10^{-4}	2.45×10^{-4}	3.00×10^{-4}	3.47×10^{-4}	3.98×10^{-4}	4.37×10^{-4}
$PM_{2.5}$	1.79×10^{-2}	1.60×10^{-2}	1.42×10^{-2}	1.30×10^{-2}	1.18×10^{-2}	1.05×10^{-2}	9.68×10^{-3}
indeno(1,2,3-cd)pyrene	1.20×10^{-7}	1.19×10^{-7}	1.18×10^{-7}	1.19×10^{-7}	1.19×10^{-7}	1.19×10^{-7}	1.19×10^{-7}
benzo(k)fluoranthene	5.20×10^{-7}	5.19×10^{-7}	5.15×10^{-7}	5.18×10^{-7}	5.17×10^{-7}	5.17×10^{-7}	5.18×10^{-7}
benzo(b)fluoranthene	4.65×10^{-7}	4.64×10^{-7}	4.61×10^{-7}	4.63×10^{-7}	4.63×10^{-7}	4.63×10^{-7}	4.63×10^{-7}
benzo(a)pyrene	7.68×10^{-8}	7.66×10^{-8}	7.61×10^{-8}	7.65×10^{-8}	7.64×10^{-8}	7.65×10^{-8}	7.65×10^{-8}

Table 5.14 shows the exhaust emissions produced during the road transport operation in Belgium with a load factor of 85%.

Table 5.14. Exhaust emissions (g/tkm) of road freight transport with a load factor of 85% in Belgium

Average road transport (g/tkm) – LF 85%	2006	2007	2008	2009	2010	2011	2012
CO_2	49.77	49.72	49.50	49.63	49.62	49.63	49.65
SO_2	7.53×10^{-4}	2.82×10^{-4}	2.50×10^{-4}	2.50×10^{-4}	2.50×10^{-4}	2.50×10^{-4}	2.50×10^{-4}
Cd	1.57×10^{-7}	1.57×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.57×10^{-7}
Cu	2.67×10^{-5}	2.66×10^{-5}	2.65×10^{-5}	2.66×10^{-5}	2.66×10^{-5}	2.66×10^{-5}	2.66×10^{-5}
Cr	7.85×10^{-7}	7.84×10^{-7}	7.80×10^{-7}	7.82×10^{-7}	7.82×10^{-7}	7.82×10^{-7}	7.83×10^{-7}
Ni	1.10×10^{-6}	1.10×10^{-6}	1.09×10^{-6}	1.10×10^{-6}	1.09×10^{-6}	1.10×10^{-6}	1.10×10^{-6}
Se	1.57×10^{-7}	1.57×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.56×10^{-7}	1.57×10^{-7}
Zn	1.57×10^{-5}	1.57×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.57×10^{-5}
Pb	1.73×10^{-9}	1.72×10^{-9}	1.72×10^{-9}	1.72×10^{-9}	1.72×10^{-9}	1.72×10^{-9}	1.72×10^{-9}
Hg	3.14×10^{-10}	3.14×10^{-10}	3.12×10^{-10}	3.13×10^{-10}	3.13×10^{-10}	3.13×10^{-10}	3.13×10^{-10}
Cr (VI)	1.57×10^{-9}	1.57×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.57×10^{-9}
As	1.57×10^{-9}	1.57×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.56×10^{-9}	1.57×10^{-9}
CO	9.22×10^{-2}	8.25×10^{-2}	7.37×10^{-2}	6.79×10^{-2}	6.24×10^{-2}	5.56×10^{-2}	5.17×10^{-2}
NMVOC	1.97×10^{-2}	1.73×10^{-2}	1.53×10^{-2}	1.39×10^{-2}	1.26×10^{-2}	1.11×10^{-2}	1.02×10^{-2}
NO_X	4.77×10^{-1}	4.50×10^{-1}	4.24×10^{-1}	4.00×10^{-1}	3.77×10^{-1}	3.47×10^{-1}	3.30×10^{-1}
N_2O	7.49×10^{-4}	7.53×10^{-4}	7.59×10^{-4}	9.07×10^{-4}	1.04×10^{-3}	1.18×10^{-3}	1.29×10^{-3}
NH_3	1.75×10^{-4}	1.74×10^{-4}	1.73×10^{-4}	2.12×10^{-4}	2.45×10^{-4}	2.81×10^{-4}	3.09×10^{-4}
$PM_{2.5}$	1.27×10^{-2}	1.13×10^{-2}	1.00×10^{-2}	9.15×10^{-3}	8.35×10^{-3}	7.39×10^{-3}	6.83×10^{-3}
indeno(1,2,3-cd)pyrene	8.44×10^{-8}	8.42×10^{-8}	8.36×10^{-8}	8.40×10^{-8}	8.39×10^{-8}	8.40×10^{-8}	8.40×10^{-8}
benzo(k)fluoranthene	3.67×10^{-7}	3.66×10^{-7}	3.64×10^{-7}	3.65×10^{-7}	3.65×10^{-7}	3.65×10^{-7}	3.65×10^{-7}
benzo(b)fluoranthene	3.28×10^{-7}	3.28×10^{-7}	3.25×10^{-7}	3.27×10^{-7}	3.27×10^{-7}	3.27×10^{-7}	3.27×10^{-7}
benzo(a)pyrene	5.42×10^{-8}	5.41×10^{-8}	5.37×10^{-8}	5.40×10^{-8}	5.39×10^{-8}	5.40×10^{-8}	5.40×10^{-8}

The exhaust emissions produced during the road transport operation of an articulated lorry of 34-40 t in Belgium has been calculated. It should be noted that every year has the same energy consumption when the same load factor in the same lorry GVW category (in this case an articulated lorry 34-40 t) is considered. Therefore, the fuel dependent emissions (i.e. CO_2 and heavy metals) per tkm are the same every year. The exhaust emissions on SO_2 are dependent on the sulphur content in diesel, thus the SO_2 emissions per tkm of the period from 2008 to 2012 are the same due to the sulphur content in diesel is the same (8 ppm). Furthermore, since the emission factors for the PAH (i.e. indeno(1,2,3-cd)pyrene, benzo(k)fluoranthene, benzo(b)fluoranthene and benzo(a)pyrene) does not vary between engine emission standards (see Table 5.11), the exhaust emissions on these pollutants do not change over the years.

Table 5.15 shows the exhaust emissions produced during the road transport operation of an articulated lorry of 34-40 t in Belgium with a load factor of 50%.

Table 5.15. Exhaust emissions (g/tkm) of an articulated lorry of 34-40 t with a load factor of 50% in Belgium

Art. lorry of 34-40 t (g/tkm) – LF 50%	2006	2007	2008	2009	2010	2011	2012
CO_2	62.92						
SO_2	9.52×10^{-4}	3.57×10^{-4}	3.17×10^{-4}				
Cd	1.98×10^{-7}						
Cu	3.37×10^{-5}						
Cr	9.92×10^{-7}						
Ni	1.39×10^{-6}						
Se	1.98×10^{-7}						
Zn	1.98×10^{-5}						
Pb	2.18×10^{-9}						
Hg	3.97×10^{-10}						
Cr (VI)	1.98×10^{-9}						
As	1.98×10^{-9}						
CO	1.36×10^{-1}	1.22×10^{-1}	1.10×10^{-1}	1.02×10^{-1}	9.31×10^{-2}	8.43×10^{-2}	7.88×10^{-2}
NMVOC	2.80×10^{-2}	2.51×10^{-2}	2.24×10^{-2}	2.06×10^{-2}	1.87×10^{-2}	1.68×10^{-2}	1.56×10^{-2}
NO_X	7.09×10^{-1}	6.70×10^{-1}	6.37×10^{-1}	6.00×10^{-1}	5.62×10^{-1}	5.22×10^{-1}	4.99×10^{-1}
N_2O	1.15×10^{-3}	1.17×10^{-3}	1.19×10^{-3}	1.42×10^{-3}	1.67×10^{-3}	1.81×10^{-3}	1.97×10^{-3}
NH_3	2.29×10^{-4}	2.29×10^{-4}	2.29×10^{-4}	2.80×10^{-4}	3.34×10^{-4}	3.69×10^{-4}	4.05×10^{-4}
$PM_{2.5}$	1.93×10^{-2}	1.74×10^{-2}	1.57×10^{-2}	1.45×10^{-2}	1.32×10^{-2}	1.18×10^{-2}	1.10×10^{-2}
indeno(1,2,3-cd)pyrene	1.11×10^{-7}						
benzo(k)fluoranthene	4.81×10^{-7}						
benzo(b)fluoranthene	4.30×10^{-7}						
benzo(a)pyrene	7.11×10^{-8}						

Table 5.16 shows the exhaust emissions produced during the road transport operation of an articulated lorry of 34-40 t in Belgium with a load factor of 60%.

Table 5.16. Exhaust emissions (g/tkm) of an articulated lorry of 34-40 t with a load factor of 60% in Belgium

Art. lorry of 34-40 t (g/tkm) – LF 60%	2006	2007	2008	2009	2010	2011	2012
CO_2	54.92						
SO_2	8.31×10^{-4}	3.12×10^{-4}	2.77×10^{-4}				
Cd	1.73×10^{-7}						
Cu	2.94×10^{-5}						
Cr	8.66×10^{-7}						
Ni	1.21×10^{-6}						
Se	1.73×10^{-7}						
Zn	1.73×10^{-5}						
Pb	1.90×10^{-9}						
Hg	3.46×10^{-10}						
Cr (VI)	1.73×10^{-9}						
As	1.73×10^{-9}						
CO	1.13×10^{-1}	1.02×10^{-1}	9.20×10^{-2}	8.49×10^{-2}	7.76×10^{-2}	7.02×10^{-2}	6.57×10^{-2}
NMVOC	2.33×10^{-2}	2.09×10^{-2}	1.87×10^{-2}	1.72×10^{-2}	1.56×10^{-2}	1.40×10^{-2}	1.30×10^{-2}
NO_X	5.90×10^{-1}	5.59×10^{-1}	5.31×10^{-1}	5.00×10^{-1}	4.69×10^{-1}	4.35×10^{-1}	4.16×10^{-1}
N_2O	9.55×10^{-4}	9.74×10^{-4}	9.92×10^{-4}	1.19×10^{-3}	1.39×10^{-3}	1.51×10^{-3}	1.64×10^{-3}
NH_3	1.91×10^{-4}	1.91×10^{-4}	1.91×10^{-4}	2.34×10^{-4}	2.78×10^{-4}	3.08×10^{-4}	3.37×10^{-4}
$PM_{2.5}$	1.61×10^{-2}	1.45×10^{-2}	1.31×10^{-2}	1.21×10^{-2}	1.10×10^{-2}	9.81×10^{-3}	9.16×10^{-3}
indeno(1,2,3-cd)pyrene	9.21×10^{-8}						
benzo(k)fluoranthene	4.01×10^{-7}						
benzo(b)fluoranthene	3.59×10^{-7}						
benzo(a)pyrene	5.92×10^{-8}						

Table 5.17 shows the exhaust emissions produced during the road transport operation of an articulated lorry of 34-40 t in Belgium with a load factor of 85%.

Table 5.17. Exhaust emissions (g/tkm) of an articulated lorry of 34-40 t with a load factor of 85% in Belgium

Art. lorry of 34-40 t (g/tkm) – LF 85%	2006	2007	2008	2009	2010	2011	2012
CO_2	43.15						
SO_2	6.53×10^{-4}	2.45×10^{-4}	2.18×10^{-4}				
Cd	1.36×10^{-7}						
Cu	2.31×10^{-5}						
Cr	6.80×10^{-7}						
Ni	9.52×10^{-7}						
Se	1.36×10^{-7}						
Zn	1.36×10^{-5}						
Pb	1.50×10^{-9}						
Hg	2.72×10^{-10}						
Cr (VI)	1.36×10^{-9}						
As	1.36×10^{-9}						
CO	8.01×10^{-2}	7.20×10^{-2}	6.49×10^{-2}	5.99×10^{-2}	5.48×10^{-2}	4.96×10^{-2}	4.63×10^{-2}
NMVOC	1.65×10^{-2}	1.47×10^{-2}	1.32×10^{-2}	1.21×10^{-2}	1.10×10^{-2}	9.87×10^{-3}	9.17×10^{-3}
NO_X	4.17×10^{-1}	3.94×10^{-1}	3.75×10^{-1}	3.53×10^{-1}	3.31×10^{-1}	3.07×10^{-1}	2.93×10^{-1}
N_2O	6.74×10^{-4}	6.88×10^{-4}	7.00×10^{-4}	8.38×10^{-4}	9.83×10^{-4}	1.06×10^{-3}	1.16×10^{-3}
NH_3	1.35×10^{-4}	1.35×10^{-4}	1.35×10^{-4}	1.65×10^{-4}	1.96×10^{-4}	2.17×10^{-4}	2.38×10^{-4}
$PM_{2.5}$	1.14×10^{-2}	1.02×10^{-2}	9.23×10^{-3}	8.52×10^{-3}	7.78×10^{-3}	6.93×10^{-3}	6.47×10^{-3}
indeno(1,2,3-cd)pyrene	6.50×10^{-8}						
benzo(k)fluoranthene	2.83×10^{-7}						
benzo(b)fluoranthene	2.53×10^{-7}						
benzo(a)pyrene	4.18×10^{-8}						

5.2.3. Non-exhaust emissions (Tank-To-Wheel) of road freight transport

The non-exhaust direct emissions considered in our study are those resulting from road, tyre and brake wear. These emissions are mainly dependent on the lorry size and the load factor, although other factors such as speed of the lorry, the chemical composition of the tyres or the characteristics of the road surface also influence (Grigoratos and Martini, 2014). The particle emissions from road and tyre wear are produced by the road surface friction with the tyres of the lorry. Moreover, particle emissions are produced by the mechanical abrasion of brake linings when the braking of the lorry.

The particles emissions from road, tyre and brake wear have been calculated using Equation (11). The emission factors for road wear is 7.00×10^{-9} kg/(kg GVW×km), for tyre wear is 8.06×10^{-8} kg/(kg GVW×km) and for brake wear is 8.13×10^{-9} kg/(kg GVW×km) (Weidema et al., 2013).

$$Non-exhaust\ emissions\ \left(\frac{kg}{tkm}\right) = \frac{Wear\ emissions\ \left(\frac{kg}{kg\ GVW\times km}\right)\times Actual\ GVW\ (kg)}{Atual\ payload\ (t)} \tag{11}$$

The Gross Vehicle Weight (GVW) is the maximum operating weight of the lorry, which includes the net vehicle weight and the maximum payload. Thus, the net vehicle weight is the GVW minus the maximum payload. As shown in Equation (12), the actual GVW for each lorry category has been calculated using the net vehicle weight (i.e. GVW minus the maximum payload) and the actual payload depending on the load factor.

$$Actual\ GVW\ (kg) = \left(GVW\ (kg) - Maximum\ payload\ (kg)\right) + Actual\ payload\ (kg) \quad (12)$$

Table 5.18 presents the actual GVW calculated for each lorry GVW category using the load factors of 50%, 60% and 85%.

Table 5.18. Actual GVW of road transport using the load factors of 50%, 60% and 85%

Heavy Duty Lorry	GVW (kg)	Maximum Payload (kg)[1]	Actual Payload (kg)			Actual GVW (kg)		
			LF 50%	LF 60%	LF 85%	LF 50%	LF 60%	LF 85%
Rigid <7.5 t	7 500	2 020	1 010	1 212	1 717	6 490	6 692	7 197
Rigid 7.5 - 12 t	12 000	5 025	2 512	3 015	4 271	9 488	9 990	11 246
Rigid 12 - 14 t	14 000	7 028	3 514	4 217	5 974	10 486	11 189	12 946
Rigid 14 - 20 t	20 000	9 699	4 849	5 819	8 244	15 151	16 121	18 545
Rigid 20 - 26 t	26 000	13 705	6 852	8 223	11 649	19 148	20 518	23 944
Rigid 26 - 28 t	28 000	16 376	8 188	9 825	13 919	19 812	21 450	25 544
Rigid 28 - 32 t	32 000	18 379	9 189	11 027	15 622	22 811	24 649	29 243
Rigid >32 t	33 200	19 714	9 857	11 828	16 757	23 343	25 314	30 243
Art. 14 - 20 t	20 000	12 634	6 317	7 581	10 739	13 683	14 946	18 105
Art. 20 - 28 t	28 000	17 077	8 538	10 246	14 515	19 462	21 169	25 439
Art. 28 - 34 t	34 000	21 519	10 759	12 911	18 291	23 241	25 392	30 772
Art. 34 - 40 t	40 000	25 326	12 663	15 196	21 527	27 337	29 869	36 201

[1]Source: Papadimitriou et al., 2013

Table 5.19 shows the direct emissions of particles of road freight transport from road, tyre and brake wear calculated using Equation (11).

Table 5.19. Particle emissions (kg/tkm) of road freight transport resulting from road, tyre and brake wear

Heavy Duty Lorry	Brake wear emissions (kg/tkm)			Tyre wear emissions (kg/tkm)			Road wear emissions (kg/tkm)		
	LF 50%	LF 60%	LF 85%	LF 50%	LF 60%	LF 85%	LF 50%	LF 60%	LF 85%
Rigid <7.5 t	5.22×10^{-5}	4.49×10^{-5}	3.41×10^{-5}	5.18×10^{-4}	4.45×10^{-4}	3.38×10^{-4}	4.50×10^{-5}	3.87×10^{-5}	2.93×10^{-5}
Rigid 7.5 - 12 t	3.07×10^{-5}	2.69×10^{-5}	2.14×10^{-5}	3.04×10^{-4}	2.67×10^{-4}	2.12×10^{-4}	2.64×10^{-5}	2.32×10^{-5}	1.84×10^{-5}
Rigid 12 - 14 t	2.43×10^{-5}	2.16×10^{-5}	1.76×10^{-5}	2.40×10^{-4}	2.14×10^{-4}	1.75×10^{-4}	2.09×10^{-5}	1.86×10^{-5}	1.52×10^{-5}
Rigid 14 - 20 t	2.54×10^{-5}	2.25×10^{-5}	1.83×10^{-5}	2.52×10^{-4}	2.23×10^{-4}	1.81×10^{-4}	2.19×10^{-5}	1.94×10^{-5}	1.57×10^{-5}
Rigid 20 - 26 t	2.27×10^{-5}	2.03×10^{-5}	1.67×10^{-5}	2.25×10^{-4}	2.01×10^{-4}	1.66×10^{-4}	1.96×10^{-5}	1.73×10^{-5}	1.44×10^{-5}
Rigid 26 - 28 t	1.97×10^{-5}	1.77×10^{-5}	1.49×10^{-5}	1.95×10^{-4}	1.76×10^{-4}	1.48×10^{-4}	1.69×10^{-5}	1.53×10^{-5}	1.28×10^{-5}
Rigid 28 - 32 t	2.02×10^{-5}	1.82×10^{-5}	1.52×10^{-5}	2.00×10^{-4}	1.80×10^{-4}	1.51×10^{-4}	1.74×10^{-5}	1.56×10^{-5}	1.31×10^{-5}
Rigid >32 t	1.93×10^{-5}	1.74×10^{-5}	1.47×10^{-5}	1.91×10^{-4}	1.72×10^{-4}	1.45×10^{-4}	1.66×10^{-5}	1.50×10^{-5}	1.26×10^{-5}
Art. 14 - 20 t	1.76×10^{-5}	1.60×10^{-5}	1.37×10^{-5}	1.74×10^{-4}	1.59×10^{-4}	1.36×10^{-4}	1.52×10^{-5}	1.38×10^{-5}	1.18×10^{-5}
Art. 20 - 28 t	1.85×10^{-5}	1.68×10^{-5}	1.42×10^{-5}	1.84×10^{-4}	1.66×10^{-4}	1.41×10^{-4}	1.60×10^{-5}	1.45×10^{-5}	1.23×10^{-5}
Art. 28 - 34 t	1.76×10^{-5}	1.60×10^{-5}	1.37×10^{-5}	1.74×10^{-4}	1.58×10^{-4}	1.36×10^{-4}	1.51×10^{-5}	1.38×10^{-5}	1.18×10^{-5}
Art. 34 - 40 t	1.76×10^{-5}	1.60×10^{-5}	1.37×10^{-5}	1.74×10^{-4}	1.58×10^{-4}	1.35×10^{-4}	1.51×10^{-5}	1.38×10^{-5}	1.18×10^{-5}

By comparing with the values on non-exhaust emissions used in Ecoinvent v3 database (see Appendix C, Tables C.1 and C.2), our results present the same order of magnitude. However, it should be noted that the values from Ecoinvent v3 represent European averages, whereas our results represent a Belgian average.

In order to determine an average particle emission from road, tyre and brake wear for every year, following the same methodology as for energy consumption, the tonne-kilometres moved by each lorry GVW category and emission engine technology have been used to calculate a weighted arithmetic mean (see Table 5.20).

Table 5.20. Particle emissions (kg/tkm) of road freight transport resulting from road, tyre and brake wear

		2006	2007	2008	2009	2010	2011	2012
Brake wear emissions (kg/tkm)	**LF 50%**	1.88×10^{-5}	1.88×10^{-5}	1.87×10^{-5}	1.88×10^{-5}	1.88×10^{-5}	1.88×10^{-5}	1.88×10^{-5}
	LF 60%	1.70×10^{-5}	1.70×10^{-5}	1.70×10^{-5}	1.70×10^{-5}	1.70×10^{-5}	1.70×10^{-5}	1.70×10^{-5}
	LF 85%	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}
Tyre wear emissions (kg/tkm)	**LF 50%**	1.86×10^{-4}	1.86×10^{-4}	1.86×10^{-4}	1.86×10^{-4}	1.86×10^{-4}	1.86×10^{-4}	1.86×10^{-4}
	LF 60%	1.69×10^{-4}	1.69×10^{-4}	1.68×10^{-4}	1.68×10^{-4}	1.68×10^{-4}	1.68×10^{-4}	1.68×10^{-4}
	LF 85%	1.43×10^{-4}	1.43×10^{-4}	1.42×10^{-4}	1.43×10^{-4}	1.43×10^{-4}	1.43×10^{-4}	1.43×10^{-4}
Road wear emissions (kg/tkm)	**LF 50%**	1.62×10^{-5}	1.62×10^{-5}	1.61×10^{-5}	1.62×10^{-5}	1.62×10^{-5}	1.62×10^{-5}	1.62×10^{-5}
	LF 60%	1.47×10^{-5}	1.46×10^{-5}	1.46×10^{-5}	1.46×10^{-5}	1.46×10^{-5}	1.46×10^{-5}	1.46×10^{-5}
	LF 85%	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}

5.3.Lorry

For the manufacturing, maintenance and disposal of lorries, it has been used the Ecoinvent v3 database instead of collecting new data specific to Belgium since this is outside the scope of this study. The lorry demand has been calculated as the inverse of the lifetime transport performance (tkm/lorry) of the vehicles. The lifetime transport performance has been determined using the lifetime kilometric performance (km/vehicle) and the actual payload (t/vehicle) using the load factors of 50%, 60% and 85%. The values on lifetime kilometric performance of road freight transport in Belgium considering the lorry GVW category and the emission engine technology used in our research are in Appendix C (see Table C.5).

The average lorry demand for every year has been determined following the same methodology as for energy consumption, the tkm moved by each lorry GVW category and emission engine technology have been used to calculate a weighted arithmetic mean (see Table 5.21).

Table 5.21. Lorry demand (unit/tkm) for road freight transport in Belgium

		2006	2007	2008	2009	2010	2011	2012
Average road transport (unit/tkm)	**LF 50%**	3.26×10^{-7}	3.28×10^{-7}	3.08×10^{-7}	3.13×10^{-7}	2.78×10^{-7}	2.79×10^{-7}	2.34×10^{-7}
	LF 60%	2.72×10^{-7}	2.73×10^{-7}	2.57×10^{-7}	2.61×10^{-7}	2.32×10^{-7}	2.33×10^{-7}	1.95×10^{-7}
	LF 85%	1.92×10^{-7}	1.93×10^{-7}	1.81×10^{-7}	1.84×10^{-7}	1.64×10^{-7}	1.64×10^{-7}	1.38×10^{-7}
Art. lorry of 34 -40 t (unit/tkm)	**LF 50%**	1.37×10^{-7}	1.33×10^{-7}	1.24×10^{-7}	1.21×10^{-7}	1.14×10^{-7}	1.06×10^{-7}	8.79×10^{-8}
	LF 60%	1.14×10^{-7}	1.11×10^{-7}	1.03×10^{-7}	1.01×10^{-7}	9.50×10^{-8}	8.83×10^{-8}	7.33×10^{-8}
	LF 85%	8.07×10^{-8}	7.80×10^{-8}	7.29×10^{-8}	7.13×10^{-8}	6.71×10^{-8}	6.24×10^{-8}	5.17×10^{-8}

Note that all the environmental interventions are referred to one vehicle (unit). Ecoinvent uses a lorry demand of 1.88×10^{-6} unit/tkm for a lorry 3.5 – 7.5 t, 5.63×10^{-7} unit/tkm for a lorry 7.5 – 16 t, 3.20×10^{-7} unit/tkm for a lorry 16- 32 t and 9.66×10^{-8} unit/tkm for a lorry >32 t (see Appendix C, Tables C.1 and C.2). Therefore, our results present the same order of magnitude than the values from Ecoinvent v3 for the categories lorry 16- 32 t and lorry >32 t.

5.4.Road infrastructure

Similarly to the lorry demand, it has been used the Ecoinvent v3 database instead of collecting new data specific to Belgium for the construction, maintenance and disposal of the road infrastructure since this is outside the scope of this study. Since the road infrastructure is shared between passenger and freight transport, an allocation of the environmental impacts related to the construction, maintenance and disposal of infrastructure has to be performed.

As shown in Equation (13), the allocation factors for the Belgian road infrastructure have been calculated in three steps. Firstly, the length of the Belgian road network has been divided by the total road operating performance (Gtkm) of freight and passenger transport. Secondly, the ratio Gtkm/tkm for freight transport has been obtained. Thirdly, the values determined in the first and second step have been multiplied to obtain the road infrastructure demand per tkm referred to one meter and year (m×a) for road freight transport ((m×a)/tkm). Therefore, the allocation principle for road infrastructure is the vehicle weigh.

$$Infrastructure\ construction\ \left(\frac{m\times a}{tkm}\right) = \frac{Length\ road\ (m)}{Total\ Gtkm\ (freight + passenger)} \times \frac{Gtkm\ freight}{tkm\ freight} \qquad (13)$$

Table 5.22 presents the length of the Belgian road network. For the years 2011 and 2012, the value of the year 2010 has been used.

Table 5.22. Length of road infrastructure in Belgium. Source: Eurostat statistics, 2017

	2005	2006	2007	2008	2009	2010
Length of road (km)	149 625	150 493	151 325	151 832	152 109	153 447

The annual operating performance (Gtkm) of road freight transport has been calculated using the Equation (14). For this, the actual payload has been calculated using Equation (8), the annual transport performance has been determined using Equation (9) and the actual GVW has been calculated using Equation (12).

$$Gtkm = \frac{Actual\ GVW\ (t)}{Actual\ payload\ (t)} \times tkm \qquad (14)$$

The annual operating performance (Gtkm) of road passenger transport has been calculated in four steps. First, the actual payload of passenger vehicles has been calculated using Equation (15).

$$Actual\ payload\ (t) = Weight\ per\ passenger\ \left(\frac{t}{passenger}\right) \times Occupancy\ ratio\ \left(\frac{passenger}{vehicle}\right) \qquad (15)$$

An average weight per passenger of 100 kg has been considered (Loo, 2018) and the occupancy ratio from TRACCS database (Papadimitriou et al., 2013) for Belgium has been taken (see Table 5.23).

Table 5.23. Occupancy ratio (passenger/vehicle) of road passenger transport in Belgium. Source: Papadimitriou et al., 2013

Sector	2006	2007	2008	2009	2010
Mopeds and motorcycles	1.043		1.056		
Passenger cars	1.522		1.510		
Buses	30.737		32.855		

Second, the actual GVW of passenger vehicles has been calculated using the Equation (16).

$$Actual\ GVW\ (t) = Net\ vehicle\ weight\ (t) + Actual\ payload\ (t) \quad (16)$$

An average net vehicle weight per vehicle of 0.14 t for motorbikes, 1.24 t for cars and 11 t for buses (Spielmann et al., 2007) have been considered, respectively. Table 5.24 presents the actual payload and actual GVW of road passenger transport in Belgium. For the years 2011 and 2012, the actual payload and GVW of the period from 2008 to 2010 have been used.

Table 5.24. Actual payload and actual GVW of road passenger transport in Belgium

	Sector	2006	2007	2008	2009	2010
Actual payload (t)	**Mopeds and motorcycles**	0.104		0.106		
	Passenger cars	0.152		0.151		
	Buses	3.074		3.285		
Actual GVW (t)	**Mopeds and motorcycles**	0.244		0.246		
	Passenger cars	1.392		1.391		
	Buses	14.074		14.285		

Third, the annual road passenger transport performance (tkm) has been calculated multiplying the vehicle-kilometres by the actual payload of each passenger vehicle sector (i.e. motorbikes, cars and buses). The annual vehicle-kilometres have been determined using the population of passenger vehicles and the mileage (km/a) of road passenger transport in Belgium of each passenger vehicle sector and emission engine technology (see Equations (9) and (10)). The values of population of passenger vehicles and the mileage (km/a) of road passenger transport in Belgium considering the passenger vehicle sector and emission engine technology used in our research are in Appendix C (see Tables C.6 and C.7).

Fourth, the Gtkm of passenger transport has been calculated using the Equation (14). Table 5.25 presents the transport performance (million tkm) and operating performance (Gtkm) for road passenger transport in Belgium.

Table 5.25. Transport performance (million tkm) and operating performance (Gtkm) for road passenger transport in Belgium

	2006	2007	2008	2009	2010	2011	2012
Transport performance (million tkm)	14 452	14 548	15 884	15 970	16 255	16 344	15 068
Operating performance (million Gtkm)	118 648	119 800	130 092	130 905	133 418	134 571	124 232

The average road infrastructure demand for every year has been determined following the same methodology as for energy consumption, the tkm moved by each lorry GVW category and emission standard have been used to calculate a weighted arithmetic mean (see Table 5.26).

Table 5.26. Road infrastructure demand for road freight transport in Belgium

		2006	2007	2008	2009	2010	2011	2012
Average road transport ((m×a)/tkm)	**LF 50%**	1.09×10^{-3}	1.10×10^{-3}	9.80×10^{-4}	1.01×10^{-3}	1.01×10^{-3}	1.03×10^{-3}	1.11×10^{-3}
	LF 60%	9.39×10^{-4}	9.41×10^{-4}	8.42×10^{-4}	8.64×10^{-4}	8.66×10^{-4}	8.85×10^{-4}	9.53×10^{-4}
	LF 85%	7.04×10^{-4}	7.06×10^{-4}	6.30×10^{-4}	6.48×10^{-4}	6.50×10^{-4}	6.65×10^{-4}	7.17×10^{-4}
Art. lorry of 34 -40 t ((m×a)/tkm)	**LF 50%**	1.02×10^{-3}	1.02×10^{-3}	9.18×10^{-4}	9.40×10^{-4}	9.43×10^{-4}	9.62×10^{-4}	1.04×10^{-3}
	LF 60%	8.81×10^{-4}	8.84×10^{-4}	7.92×10^{-4}	8.12×10^{-4}	8.15×10^{-4}	8.32×10^{-4}	8.96×10^{-4}
	LF 85%	6.68×10^{-4}	6.70×10^{-4}	5.99×10^{-4}	6.15×10^{-4}	6.18×10^{-4}	6.32×10^{-4}	6.81×10^{-4}

Ecoinvent v3 uses a road infrastructure demand of 1.95×10^{-3} (m×a)/tkm for a lorry 3.5 - 7.5 t, 1.09×10^{-3} (m×a)/tkm for a lorry 7.5 - 16 t and a lorry >32 t, and 1.05×10^{-3} (m×a)/tkm for a lorry 16 - 32 t (see Appendix C, Tables C.1 and C.2). Overall, our results present lower values than the values from Ecoinvent v3, but in the same order of magnitude.

5.5. Life Cycle Impact Assessment of road transport in Belgium

The four stages of a LCA study described in Chapter 2 are applied to road freight transport. We restate them hereunder for completeness. First, the goal and scope definition, which in this chapter is to determine the environmental impacts of road freight transport in Belgium. The functional unit chosen is "one tonne-kilometre of freight transported by lorry". The second stage of a LCA is the Life Cycle Inventory (LCI) analysis. We have used the Ecoinvent v3 database and we have collected information specific to Belgium from several literature sources. The third stage is the Life Cycle Impact Assessment (LCIA). All calculations were made with the SimaPro 8.0.5 software using the LCIA method "ILCD 2011 Midpoint+" (version V1.06 / EU27 2010), which is the method recommended by the European Commission (European Commission, 2010). As mentioned above, "ILCD 2011 Midpoint+" is a midpoint method including 16 environmental impact indicators. However, in this analysis it has been used only the indicators with a level of quality "I" (climate change, ozone depletion and particulate matter), and "II" (ionizing radiation – human health, photochemical ozone formation, acidification, terrestrial and freshwater eutrophication and mineral, fossil and renewable resource depletion). Finally, the fourth stage is the assessment of the results obtained in the previous stages.

5.5.1. Life Cycle Impact Assessment of average road freight transport

Figure 5.8 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by lorry with a 50% of load factor in Belgium in the year 2012. Therefore, to calculate the LCIA of one tonne-kilometre of road freight transport with a 50% of load factor in 2012 it is necessary to consider a lorry demand of 2.34×10^{-7} unit/tkm, a road infrastructure demand of 1.11×10^{-3} (m×a)/tkm, a diesel consumption of 0.0232 kg/tkm (994 kJ/tkm), the exhaust emissions produced during the combustion of the fuel and the particle emission from road, tyre and brake wear in the transport operation.

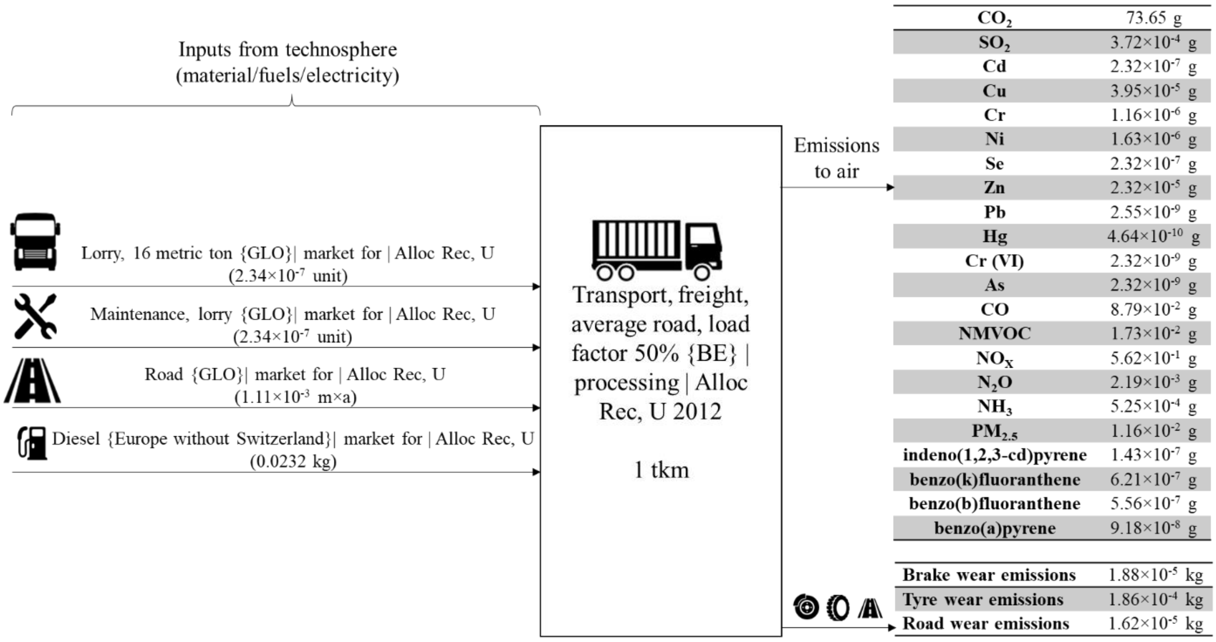


Figure 5.8. Inputs and outputs of 1 tkm transported by lorry with a 50% of load factor in Belgium in 2012

Table 5.27 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 50% in Belgium from 2006 to 2012, the average LCIA of Belgium taking as reference the period from 2006 to 2012 and the reference values of the process from Ecoinvent v3 “Transport, freight, lorry, unspecified {RER}| size-specific lorry transport to generic market for lorry transport | Alloc Rec, U”. This process from Ecoinvent v3 for the year 2014 is a mix of the following four road transport processes considering an emission standard Euro III (see Appendix C, Tables C.1 and C.2): lorry 3.5 – 7.5 t (4%), lorry 7.5 – 16 t (3%), lorry 16 - 32 t (34%) and lorry >32 t (59%).

Table 5.27. LCIA of 1 tkm transported by road freight transport with a load factor of 50% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012	Belgian average	Ecoinvent v3[1]
Climate change	**kg CO_2 eq**	1.17×10^{-1}	1.17×10^{-1}	1.14×10^{-1}	1.15×10^{-1}	1.13×10^{-1}	1.14×10^{-1}	1.13×10^{-1}	1.15×10^{-1}	1.36×10^{-1}
Ozone depletion	**kg CFC-11 eq**	2.12×10^{-8}	2.12×10^{-8}	2.07×10^{-8}	2.08×10^{-8}	2.07×10^{-8}	2.08×10^{-8}	2.09×10^{-8}	2.09×10^{-8}	2.50×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	9.12×10^{-5}	8.86×10^{-5}	8.36×10^{-5}	8.25×10^{-5}	7.95×10^{-5}	7.78×10^{-5}	7.58×10^{-5}	8.27×10^{-5}	9.18×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.02×10^{-2}	1.02×10^{-2}	9.81×10^{-3}	9.92×10^{-3}	9.77×10^{-3}	9.82×10^{-3}	9.82×10^{-3}	9.93×10^{-3}	1.13×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	1.14×10^{-3}	1.09×10^{-3}	1.02×10^{-3}	9.85×10^{-4}	9.38×10^{-4}	8.88×10^{-4}	8.62×10^{-4}	9.90×10^{-4}	1.06×10^{-3}
Acidification	**molc H+ eq**	9.93×10^{-4}	9.59×10^{-4}	9.06×10^{-4}	8.81×10^{-4}	8.41×10^{-4}	8.07×10^{-4}	7.82×10^{-4}	8.81×10^{-4}	9.55×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.17×10^{-3}	3.98×10^{-3}	3.74×10^{-3}	3.58×10^{-3}	3.40×10^{-3}	3.19×10^{-3}	3.08×10^{-3}	3.59×10^{-3}	3.82×10^{-3}
Freshwater eutrophication	**kg P eq**	1.13×10^{-5}	1.14×10^{-5}	1.07×10^{-5}	1.09×10^{-5}	1.01×10^{-5}	1.02×10^{-5}	9.54×10^{-6}	1.06×10^{-5}	1.03×10^{-5}
Resource depletion	**kg Sb eq**	1.39×10^{-5}	1.40×10^{-5}	1.31×10^{-5}	1.33×10^{-5}	1.19×10^{-5}	1.20×10^{-5}	1.02×10^{-5}	1.26×10^{-5}	1.12×10^{-5}

[1]Source: Weidema et al., 2013

Figure 5.9 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by lorry with a load factor of 50% in Belgium (from Table 5.27). Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the year with less impact and the highest value represents the maximum impact.

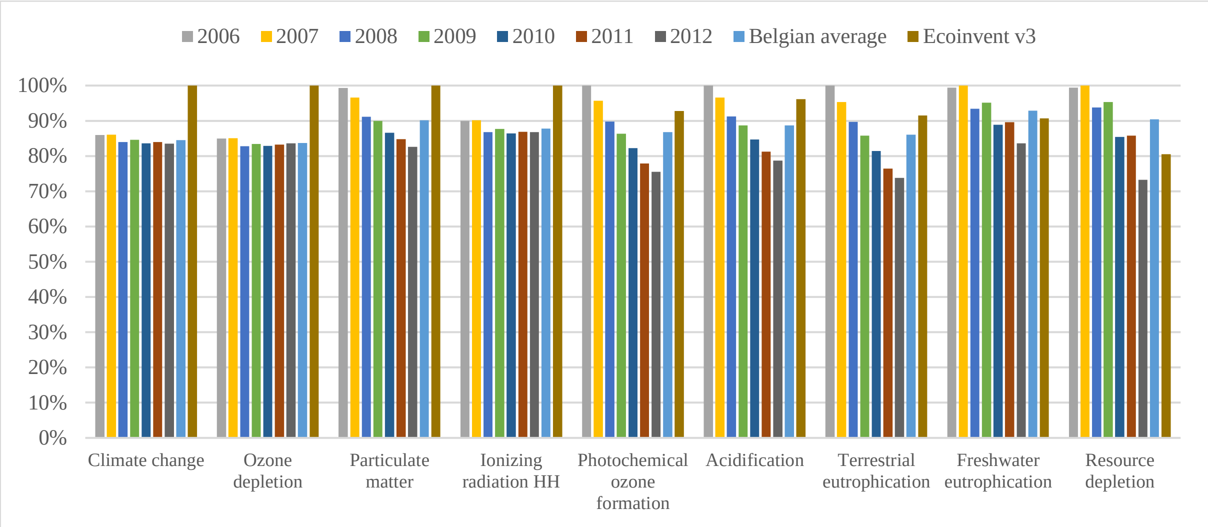


Figure 5.9. LCIA of 1 tkm transported by road freight transport with a load factor of 50% in Belgium and the reference values of the process from Ecoinvent v3 "Transport, freight, lorry, unspecified {RER}| size-specific lorry transport to generic market for lorry transport | Alloc Rec, U"

The year 2006 presents the maximum impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication due to the higher exhaust emissions on NO_X produced because of this year presents the least environmental performance share of emission standards (see Figure 5.4). Moreover, the higher sulphur content of the diesel used in the year 2006 (24 ppm) compared to the other years (9 ppm in 2007 and 8 ppm from 2008 to 2012) generates large emissions of SO_2 as exhaust emissions. The year 2007 presents the maximum impact in the indicators freshwater eutrophication and resource depletion (but showing similar values than the year 2006) due to the higher lorry and road infrastructure demand. There are no significant differences in terms of impact in the processes from our study for Belgium in the indicators climate change, ozone depletion and ionizing radiation (damage to human health).

The process from Ecoinvent v3 presents the maximum impact in the indicators climate change, ozone depletion, particulate matter and ionizing radiation (damage to human health) because of this process uses a highest energy consumption (the mix of the four road transport processes results in 1 238 kJ/tkm) than those calculated in our research.

By comparing the environmental impacts of the average road freight transport (from 2006 to 2012) with the values from Ecoinvent v3, our results for Belgium show a lower impact in all the indicators except the indicators freshwater eutrophication and resource depletion.

In addition to the analysis of the environmental impact of road freight transport with a load factor of 50%, it has been studied the environmental impact of transport by lorry with a 60% and 85% of load factor. Table 5.28 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 60% in Belgium.

Table 5.28. LCIA of 1 tkm transported by road freight transport with a load factor of 60% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	1.01×10^{-1}	1.01×10^{-1}	9.82×10^{-2}	9.89×10^{-2}	9.79×10^{-2}	9.82×10^{-2}	9.77×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.83×10^{-8}	1.83×10^{-8}	1.79×10^{-8}	1.80×10^{-8}	1.79×10^{-8}	1.80×10^{-8}	1.81×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	7.85×10^{-5}	7.62×10^{-5}	7.21×10^{-5}	7.11×10^{-5}	6.86×10^{-5}	6.72×10^{-5}	6.56×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	8.77×10^{-3}	8.77×10^{-3}	8.46×10^{-3}	8.54×10^{-3}	8.42×10^{-3}	8.47×10^{-3}	8.46×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	9.58×10^{-4}	9.16×10^{-4}	8.60×10^{-4}	8.27×10^{-4}	7.88×10^{-4}	7.47×10^{-4}	7.25×10^{-4}
Acidification	**molc H+ eq**	8.37×10^{-4}	8.08×10^{-4}	7.64×10^{-4}	7.43×10^{-4}	7.10×10^{-4}	6.82×10^{-4}	6.61×10^{-4}
Terrestrial eutrophication	**molc N eq**	3.49×10^{-3}	3.33×10^{-3}	3.13×10^{-3}	3.00×10^{-3}	2.85×10^{-3}	2.67×10^{-3}	2.58×10^{-3}
Freshwater eutrophication	**kg P eq**	9.61×10^{-6}	9.63×10^{-6}	9.02×10^{-6}	9.17×10^{-6}	8.59×10^{-6}	8.66×10^{-6}	8.09×10^{-6}
Resource depletion	**kg Sb eq**	1.16×10^{-5}	1.16×10^{-5}	1.09×10^{-5}	1.11×10^{-5}	9.97×10^{-6}	1.00×10^{-5}	8.54×10^{-6}

Figure 5.10 presents a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by lorry with a load factor of 60% in Belgium (from Table 5.28). The year 2006 presents the maximum impact in six indicators and the year 2007 presents the maximum impact in three indicators. However, these two years show similar values in all the indicators but the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication due to the difference in the share of emission standards. Since the year 2007 presents a higher share of Euro IV emissions engine technology (see Figure 5.4), the exhaust emissions of $PM_{2.5}$, NO_X or NMVOC are lower. Therefore, as the new emission standards are implemented in the heavy duty market, the environmental impact decreases in these indicators.

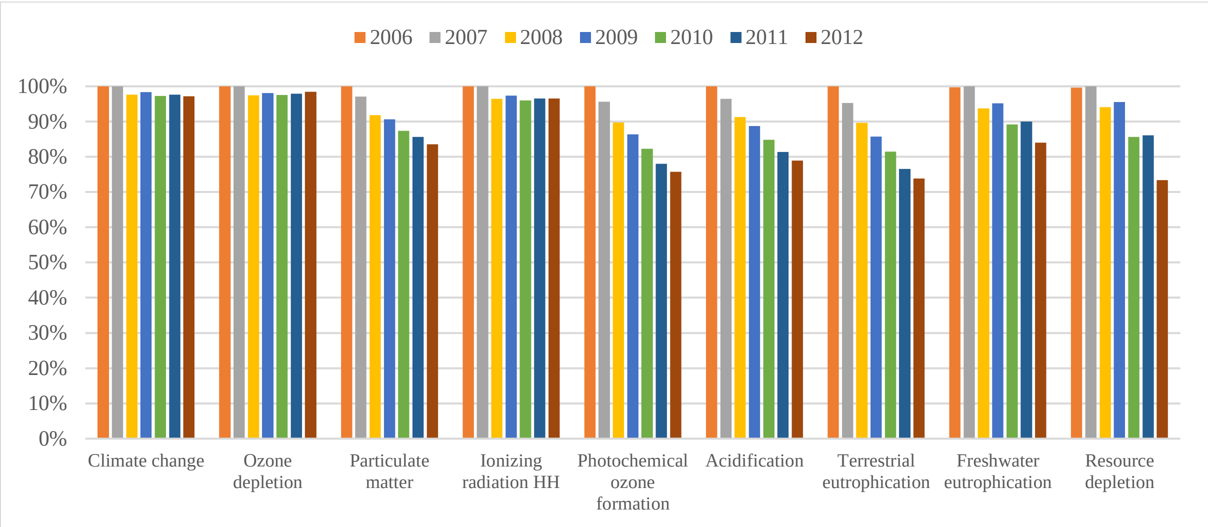


Figure 5.10. LCIA of 1 tkm transported by road freight transport with a load factor of 60% in Belgium

Table 5.29 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 85% in Belgium.

Table 5.29. LCIA of 1 tkm transported by road freight transport with a load factor of 85% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	7.70×10^{-2}	7.70×10^{-2}	7.52×10^{-2}	7.58×10^{-2}	7.50×10^{-2}	7.53×10^{-2}	7.50×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.41×10^{-8}	1.41×10^{-8}	1.37×10^{-8}	1.38×10^{-8}	1.37×10^{-8}	1.38×10^{-8}	1.39×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	5.97×10^{-5}	5.81×10^{-5}	5.51×10^{-5}	5.45×10^{-5}	5.27×10^{-5}	5.17×10^{-5}	5.06×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	6.67×10^{-3}	6.68×10^{-3}	6.44×10^{-3}	6.50×10^{-3}	6.42×10^{-3}	6.46×10^{-3}	6.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	6.87×10^{-4}	6.58×10^{-4}	6.17×10^{-4}	5.94×10^{-4}	5.67×10^{-4}	5.38×10^{-4}	5.24×10^{-4}
Acidification	**molc H+ eq**	6.06×10^{-4}	5.85×10^{-4}	5.53×10^{-4}	5.39×10^{-4}	5.16×10^{-4}	4.96×10^{-4}	4.82×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.49×10^{-3}	2.38×10^{-3}	2.24×10^{-3}	2.14×10^{-3}	2.03×10^{-3}	1.91×10^{-3}	1.85×10^{-3}
Freshwater eutrophication	**kg P eq**	7.00×10^{-6}	7.03×10^{-6}	6.57×10^{-6}	6.68×10^{-6}	6.28×10^{-6}	6.32×10^{-6}	5.95×10^{-6}
Resource depletion	**kg Sb eq**	8.23×10^{-6}	8.27×10^{-6}	7.75×10^{-6}	7.88×10^{-6}	7.08×10^{-6}	7.09×10^{-6}	6.09×10^{-6}

Figure 5.11 presents a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by lorry with a load factor of 85% in Belgium (from Table 5.29). The distribution between years of the different indicators is similar to the case of transport by lorry with a 60% of load factor (Figure 5.10). Therefore, the year 2006 presents the maximum impact in six indicators and the year 2007 presents the maximum impact in three indicators.

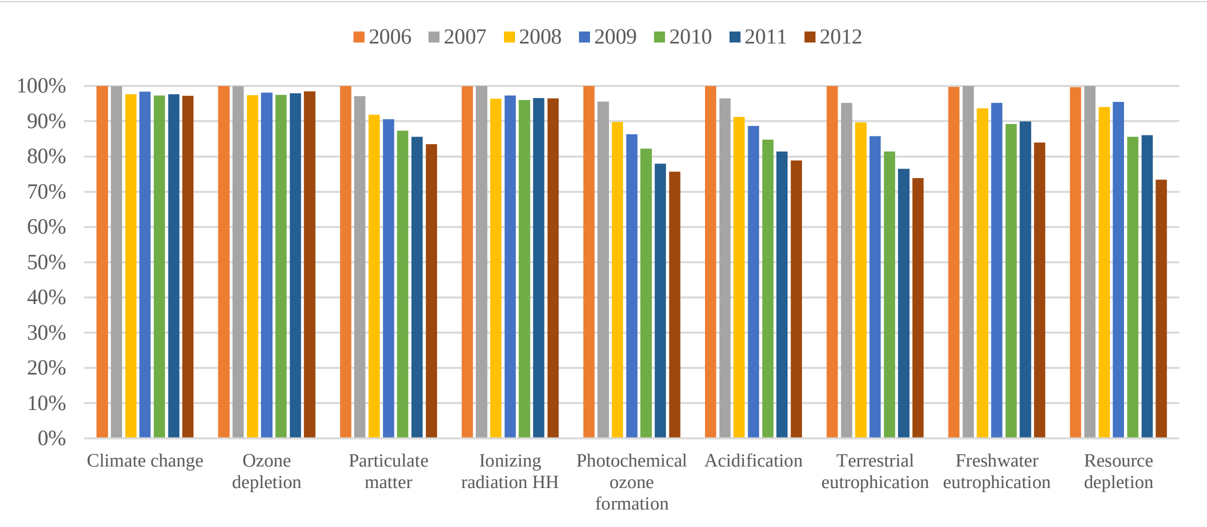


Figure 5.11. LCIA of 1 tkm transported by road freight transport with a load factor of 85% in Belgium

It has been studied the environmental impact of road freight transport performed by an articulated lorry of 34-40 t with the load factors of 50%, 60% and 85%. However, the distribution of the environmental impacts between the different indicators is similar to the case of transport by an average road transport. Therefore, the same conclusions can be drawn. The results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with the load factors of 50%, 60% and 85% in Belgium are in Appendix D.

5.5.2. Life Cycle Impact Assessment of road freight transport using different load factors

A comparison of the environmental performance of one tonne-kilometre of freight transported by an average lorry and an articulated lorry of 34-40 t with a load factor of 50%, 60% and 85% in Belgium in the year 2012 is showed in Figure 5.12. Moreover, the reference values of the process from Ecoinvent v3 "Transport, freight, lorry, unspecified {RER}| size-specific lorry transport to generic market for lorry transport | Alloc Rec, U" for 2014 are presented as well.

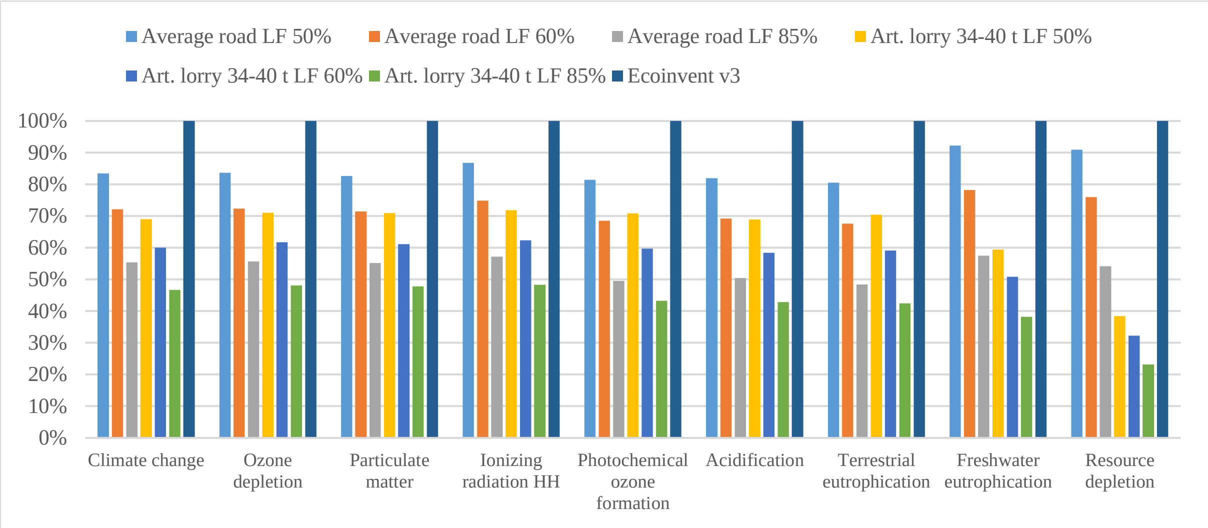


Figure 5.12. LCIA of 1 tkm transported by average road freight transport and an articulated lorry of 34-40 t with a load factor (LF) of 50%, 60% and 85% in Belgium in 2012. Moreover, the reference values of the process from Ecoinvent v3 "Transport, freight, lorry, unspecified {RER}| size-specific lorry transport to generic market for lorry transport | Alloc Rec, U"

The reference process from Ecoinvent v3 shows the highest impact in all the indicators because of this process uses a highest energy consumption (1 238 kJ/tkm) than the calculated in our research (994 kJ/tkm, 863 kJ/tkm and 670 kJ/tkm for average road freight transport with a load factor of 50%, 60% and 85%, respectively). Moreover, the transport process from Ecoinvent uses an emission standard Euro III, whereas the lorries with a conventional emission engine technology represented the 4% of the Belgian heavy duty market in 2012, the Euro I a 7%, the Euro II a 19%, the Euro III a 26%, the Euro IV a 21% and the Euro V a 22%. Therefore, the environmental performance of the processes of our research is higher.

Within the average road freight transport processes of our research, the average lorry with a load factor of 50% presents the highest environmental impact in all the indicators, then the road freight transport with a load factor of 60% and the road freight transport with a load factor of 85% has the lowest environmental impact. Similarly, within the lorry GVW category articulated lorry 34-40 t, the process with a load factor of 50% presents the highest environmental impact in all the indicators, then the process with a load factor of 60% and the lowest environmental impact is presented by the articulated lorry of 34-40 t with a load factor of 85%. These results highlight the importance of improving the load factors of road freight transport in order to enhance its environmental performance. Hence, the load factor is shown as a determining factor in the environmental impact of road freight transport.

5.5.3. Life Cycle Impact Assessment of an articulated lorry of 34-40 t using different emission engine technologies

The emission engine technology plays a major role in the environmental impact of road freight transport, especially in the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication.

The environmental impact of an articulated lorry of 34-40 t has been analysed using the different types of engine standards: conventional (cnv.), Euro I, Euro II, Euro III, Euro IV, Euro V and Euro VI. Even if the Euro VI emission engine technology has not been included in our study because of it appears in the year 2014 in the Belgian heavy duty vehicle market, it would be interesting to compare an articulated lorry of 34-40 t with an emission engine technology Euro VI with the other emissions engine technologies. The articulated lorry of 34-40 t Euro VI has been developed using all the parameters of an articulated lorry of 34-40 t in the year 2012 but using the emission factors for an engine technology Euro VI for the pollutant emissions dependent on the engine emission technology (e.g. CO, NMVOC, NO_X, N_2O, NH_3 and $PM_{2.5}$).

As mentioned in Section 5.2.2, the emission factors from EMEP/EEA represent European averages for different parameters such as driving speed, ambient temperatures, driving conditions (e.g. urban, rural or highway) or trip length for example (Ntziachristos and Samaras, 2014). Thus, these emission factors may vary depending on the conditions considered. It should be noted that the EMEP/EEA air pollutant emission inventory guidebook 2013 (Ntziachristos and Samaras, 2014) proposes a methodology to conduct a more detailed study of the emissions. However, this methodology has not been carried out because it is outside the scope of this study.

Table 5.30 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium using different emission standards in the year 2012.

Table 5.30. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium using different emission standards in 2012

Impact category	Unit	Cnv.	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI
Climate change	**kg CO_2 eq**	9.36×10^{-2}	9.32×10^{-2}	9.32×10^{-2}	9.31×10^{-2}	9.34×10^{-2}	9.42×10^{-2}	9.41×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.77×10^{-8}	1.77×10^{-8}	1.77×10^{-8}	1.77×10^{-8}	1.77×10^{-8}	1.77×10^{-8}	1.77×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	9.58×10^{-5}	8.32×10^{-5}	7.04×10^{-5}	6.59×10^{-5}	5.44×10^{-5}	5.34×10^{-5}	5.01×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	8.13×10^{-3}	8.13×10^{-3}	8.13×10^{-3}	8.13×10^{-3}	8.13×10^{-3}	8.13×10^{-3}	8.13×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	1.29×10^{-3}	9.90×10^{-4}	1.00×10^{-3}	8.47×10^{-4}	6.00×10^{-4}	4.44×10^{-4}	2.76×10^{-4}
Acidification	**molc H+ eq**	1.04×10^{-3}	8.17×10^{-4}	8.35×10^{-4}	7.23×10^{-4}	5.58×10^{-4}	4.44×10^{-4}	3.20×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.86×10^{-3}	3.60×10^{-3}	3.71×10^{-3}	3.06×10^{-3}	2.11×10^{-3}	1.46×10^{-3}	7.41×10^{-4}
Freshwater eutrophication	**kg P eq**	6.15×10^{-6}	6.15×10^{-6}	6.15×10^{-6}	6.15×10^{-6}	6.15×10^{-6}	6.15×10^{-6}	6.15×10^{-6}
Resource depletion	**kg Sb eq**	4.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}

Figure 5.13 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium using different emission standards in the year 2012 (from Table 5.30). Moreover, the average articulated lorry of 34-40 t with a load factor of 50% in Belgium in the year 2012 (see Table 5.30) has been included.

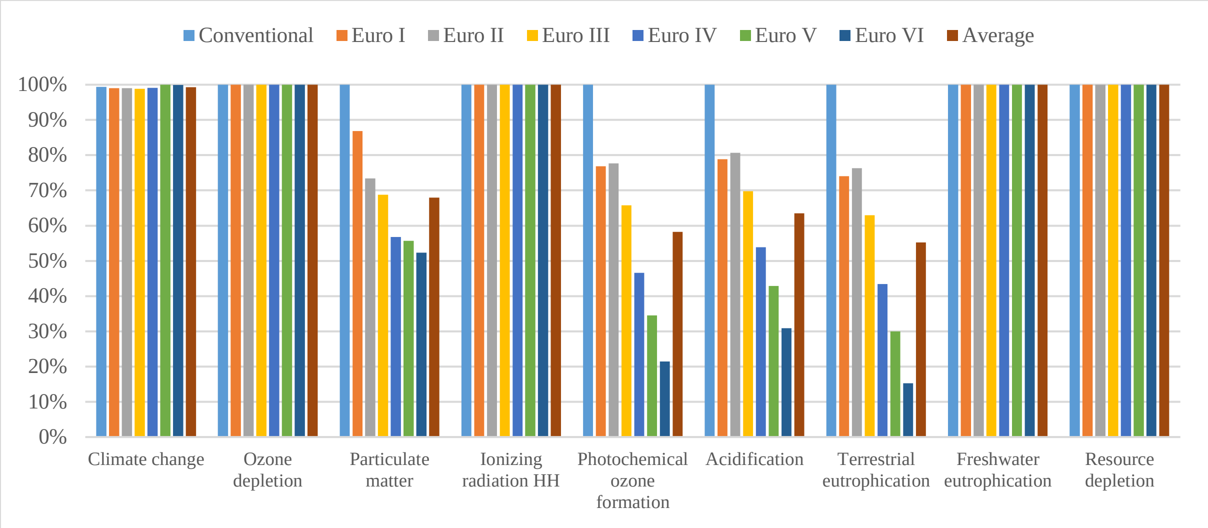


Figure 5.13. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium using different emission standards in 2012

As mentioned above, the change of emission standards has a strong influence in the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. Thereby, each new generation of emission standards reduces the impact on these indicators. However, a slight increase in the impact between the Euro I and Euro II emission standards in the indicators photochemical zone formation, acidification and terrestrial eutrophication can be observed. This is due to the higher NO_X emissions of the Euro II (9.36 g/km) compared to the Euro I (9.04 g/km) of a lorry >32 t (see Table 5.11).

In the indicator climate change, the emission standard Euro V presents the maximum impact (but slightly higher than the rest of emission standards) due to this emission engine technology present the highest emission factor of N_2O (see Table 5.11). Moreover, the impact is higher in the Euro VI standard than in older emission engine technologies due to the higher N_2O exhaust emissions. It should be noted that the differences are not significant.

All the transport processes show the same impact in the indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. Thus, the emission standards do not affect these indicators.

Furthermore, the average articulated lorry of 34-40 t shows values between an articulated lorry of 34-40 t Euro III and Euro IV (which represent the 22% and 20%, respectively (see Figure 5.5)) in the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication.

Table 5.31 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium using different emission standards in the year 2012. The distribution between emission standards of the different indicators is similar to the case of transport by an articulated lorry of 34-40 t with a 50% of load factor (Figure 5.13). Therefore, the same conclusion can be drawn.

Table 5.31. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium using different emission standards in 2012

Impact category	Unit	Cnv.	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI
Climate change	**kg CO_2 eq**	8.14×10^{-2}	8.11×10^{-2}	8.11×10^{-2}	8.10×10^{-2}	8.12×10^{-2}	8.19×10^{-2}	8.18×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.54×10^{-8}	1.54×10^{-8}	1.54×10^{-8}	1.54×10^{-8}	1.54×10^{-8}	1.54×10^{-8}	1.54×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	8.23×10^{-5}	7.18×10^{-5}	6.11×10^{-5}	5.74×10^{-5}	4.78×10^{-5}	4.69×10^{-5}	4.42×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	7.05×10^{-3}	7.05×10^{-3}	7.05×10^{-3}	7.05×10^{-3}	7.05×10^{-3}	7.05×10^{-3}	7.05×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	1.08×10^{-3}	8.32×10^{-4}	8.41×10^{-4}	7.13×10^{-4}	5.07×10^{-4}	3.77×10^{-4}	2.37×10^{-4}
Acidification	**molc H+ eq**	8.73×10^{-4}	6.90×10^{-4}	7.05×10^{-4}	6.11×10^{-4}	4.74×10^{-4}	3.79×10^{-4}	2.76×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.07×10^{-3}	3.02×10^{-3}	3.11×10^{-3}	2.57×10^{-3}	1.78×10^{-3}	1.23×10^{-3}	6.34×10^{-4}
Freshwater eutrophication	**kg P eq**	5.26×10^{-6}	5.26×10^{-6}	5.26×10^{-6}	5.26×10^{-6}	5.26×10^{-6}	5.26×10^{-6}	5.26×10^{-6}
Resource depletion	**kg Sb eq**	3.63×10^{-6}	3.63×10^{-6}	3.63×10^{-6}	3.63×10^{-6}	3.63×10^{-6}	3.63×10^{-6}	3.63×10^{-6}

Table 5.32 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium using different emission standards in the year 2012. The distribution between emission standards of the different indicators is similar to the case of transport by an articulated lorry of 34-40 t with a 50% of load factor (Figure 5.13). Therefore, the same conclusion can be drawn.

Table 5.32. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium using different emission standards in 2012

Impact category	Unit	Cnv.	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI
Climate change	**kg CO_2 eq**	6.34×10^{-2}	6.31×10^{-2}	6.31×10^{-2}	6.31×10^{-2}	6.32×10^{-2}	6.37×10^{-2}	6.36×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}	1.20×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	6.24×10^{-5}	5.49×10^{-5}	4.74×10^{-5}	4.48×10^{-5}	3.81×10^{-5}	3.74×10^{-5}	3.55×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	5.47×10^{-3}	5.47×10^{-3}	5.47×10^{-3}	5.47×10^{-3}	5.47×10^{-3}	5.47×10^{-3}	5.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	7.75×10^{-4}	5.99×10^{-4}	6.06×10^{-4}	5.15×10^{-4}	3.70×10^{-4}	2.78×10^{-4}	1.80×10^{-4}
Acidification	**molc H+ eq**	6.32×10^{-4}	5.02×10^{-4}	5.13×10^{-4}	4.47×10^{-4}	3.50×10^{-4}	2.83×10^{-4}	2.10×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.91×10^{-3}	2.16×10^{-3}	2.22×10^{-3}	1.84×10^{-3}	1.28×10^{-3}	8.95×10^{-4}	4.76×10^{-4}
Freshwater eutrophication	**kg P eq**	3.95×10^{-6}	3.95×10^{-6}	3.95×10^{-6}	3.95×10^{-6}	3.95×10^{-6}	3.95×10^{-6}	3.95×10^{-6}
Resource depletion	**kg Sb eq**	2.60×10^{-6}	2.60×10^{-6}	2.60×10^{-6}	2.60×10^{-6}	2.60×10^{-6}	2.60×10^{-6}	2.60×10^{-6}

5.5.4. Contribution of the sub-systems road transport operation, lorry and road infrastructure to the environmental impact of road freight transport

For the LCIA of the Belgian road freight transport, all life cycle phases of road freight transport operation, lorry demand and road infrastructure are taken into account. The first part of this section presents the results obtained in the LCIA of one tonne-kilometre of freight transported by different load factors (i.e. 50%, 60% and 85%) of an average road freight transport in Belgium in 2012. Moreover, an articulated lorry of 34-40 t with a load factor of 50% using both an average emission standard and an emission standard Euro V have been studied. The second part of this section presents the discussion of the results (see Figure 5.14).

Table 5.33 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by road freight transport with a load factor of 50% in Belgium in 2012.

Table 5.33. LCIA of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012

Impact category	Unit	Transport operation	Lorry maint.	Lorry mfg.	Road	Diesel production	Total
Climate change	**kg CO_2 eq**	7.43×10^{-2}	3.74×10^{-3}	5.50×10^{-3}	1.51×10^{-2}	1.45×10^{-2}	1.13×10^{-1}
Ozone depletion	**kg CFC-11 eq**	1.23×10^{-12}	4.73×10^{-10}	4.24×10^{-10}	3.81×10^{-9}	1.62×10^{-8}	2.09×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	3.85×10^{-5}	4.29×10^{-6}	5.44×10^{-6}	1.44×10^{-5}	1.32×10^{-5}	7.58×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	6.83×10^{-7}	4.57×10^{-4}	5.18×10^{-4}	2.49×10^{-3}	6.36×10^{-3}	9.82×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	5.79×10^{-4}	1.48×10^{-5}	2.46×10^{-5}	1.55×10^{-4}	8.86×10^{-5}	8.62×10^{-4}
Acidification	**molc H+ eq**	4.19×10^{-4}	3.03×10^{-5}	4.16×10^{-5}	1.29×10^{-4}	1.62×10^{-4}	7.82×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.40×10^{-3}	3.85×10^{-5}	6.54×10^{-5}	3.66×10^{-4}	2.06×10^{-4}	3.08×10^{-3}
Freshwater eutrophication	**kg P eq**	7.96×10^{-10}	1.22×10^{-6}	3.51×10^{-6}	3.11×10^{-6}	1.71×10^{-6}	9.54×10^{-6}
Resource depletion	**kg Sb eq**	4.76×10^{-10}	6.11×10^{-6}	3.21×10^{-6}	6.02×10^{-7}	3.02×10^{-7}	1.02×10^{-5}

Table 5.34 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by road freight transport with a load factor of 60% in Belgium in 2012.

Table 5.34. LCIA of 1 tkm transported by road freight transport with a load factor of 60% in Belgium in 2012

Impact category	Unit	Transport operation	Lorry maint.	Lorry mfg.	Road	Diesel production	Total
Climate change	**kg CO_2 eq**	6.45×10^{-2}	3.12×10^{-3}	4.58×10^{-3}	1.30×10^{-2}	1.26×10^{-2}	9.77×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.11×10^{-12}	3.94×10^{-10}	3.53×10^{-10}	3.27×10^{-9}	1.40×10^{-8}	1.81×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	3.36×10^{-5}	3.58×10^{-6}	4.53×10^{-6}	1.24×10^{-5}	1.14×10^{-5}	6.56×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	6.17×10^{-7}	3.81×10^{-4}	4.31×10^{-4}	2.13×10^{-3}	5.52×10^{-3}	8.46×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	4.83×10^{-4}	1.23×10^{-5}	2.05×10^{-5}	1.33×10^{-4}	7.70×10^{-5}	7.25×10^{-4}
Acidification	**molc H+ eq**	3.49×10^{-4}	2.52×10^{-5}	3.47×10^{-5}	1.11×10^{-4}	1.41×10^{-4}	6.61×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.00×10^{-3}	3.21×10^{-5}	5.45×10^{-5}	3.14×10^{-4}	1.79×10^{-4}	2.58×10^{-3}
Freshwater eutrophication	**kg P eq**	7.19×10^{-10}	1.01×10^{-6}	2.92×10^{-6}	2.67×10^{-6}	1.49×10^{-6}	8.09×10^{-6}
Resource depletion	**kg Sb eq**	4.30×10^{-10}	5.09×10^{-6}	2.67×10^{-6}	5.17×10^{-7}	2.62×10^{-7}	8.54×10^{-6}

Table 5.35 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by road freight transport with a load factor of 85% in Belgium in 2012.

Table 5.35. LCIA of 1 tkm transported by road freight transport with a load factor of 85% in Belgium in 2012

Impact category	Unit	Transport operation	Lorry maint.	Lorry mfg.	Road	Diesel production	Total
Climate change	**kg CO_2 eq**	5.00×10^{-2}	2.21×10^{-3}	3.24×10^{-3}	9.77×10^{-3}	9.77×10^{-3}	7.50×10^{-2}
Ozone depletion	**kg CFC-11 eq**	9.44×10^{-13}	2.79×10^{-10}	2.50×10^{-10}	2.46×10^{-9}	1.09×10^{-8}	1.39×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	2.67×10^{-5}	2.53×10^{-6}	3.21×10^{-6}	9.32×10^{-6}	8.87×10^{-6}	5.06×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	5.25×10^{-7}	2.70×10^{-4}	3.05×10^{-4}	1.61×10^{-3}	4.29×10^{-3}	6.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	3.41×10^{-4}	8.70×10^{-6}	1.45×10^{-5}	9.98×10^{-5}	5.98×10^{-5}	5.24×10^{-4}
Acidification	**molc H+ eq**	2.47×10^{-4}	1.78×10^{-5}	2.45×10^{-5}	8.33×10^{-5}	1.09×10^{-4}	4.82×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.41×10^{-3}	2.27×10^{-5}	3.86×10^{-5}	2.36×10^{-4}	1.39×10^{-4}	1.85×10^{-3}
Freshwater eutrophication	**kg P eq**	6.12×10^{-10}	7.17×10^{-7}	2.07×10^{-6}	2.01×10^{-6}	1.16×10^{-6}	5.95×10^{-6}
Resource depletion	**kg Sb eq**	3.66×10^{-10}	3.60×10^{-6}	1.89×10^{-6}	3.89×10^{-7}	2.04×10^{-7}	6.09×10^{-6}

In addition to comparing average road freight transport, the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium in 2012 have been included (see Table 5.36).

Table 5.36. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium in 2012

Impact category	Unit	Transport operation	Lorry maint.	Lorry mfg.	Road	Diesel production	Total
Climate change	**kg CO_2 eq**	6.35×10^{-2}	1.41×10^{-3}	2.07×10^{-3}	1.42×10^{-2}	1.24×10^{-2}	9.35×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.15×10^{-12}	1.77×10^{-10}	1.59×10^{-10}	3.57×10^{-9}	1.38×10^{-8}	1.77×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	3.67×10^{-5}	1.61×10^{-6}	2.04×10^{-6}	1.35×10^{-5}	1.12×10^{-5}	6.51×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	6.39×10^{-7}	1.72×10^{-4}	1.94×10^{-4}	2.33×10^{-3}	5.43×10^{-3}	8.13×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	5.14×10^{-4}	5.54×10^{-6}	9.23×10^{-6}	1.45×10^{-4}	7.57×10^{-5}	7.50×10^{-4}
Acidification	**molc H+ eq**	3.72×10^{-4}	1.14×10^{-5}	1.56×10^{-5}	1.21×10^{-4}	1.39×10^{-4}	6.58×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.13×10^{-3}	1.45×10^{-5}	2.46×10^{-5}	3.43×10^{-4}	1.76×10^{-4}	2.69×10^{-3}
Freshwater eutrophication	**kg P eq**	7.45×10^{-10}	4.56×10^{-7}	1.32×10^{-6}	2.91×10^{-6}	1.46×10^{-6}	6.15×10^{-6}
Resource depletion	**kg Sb eq**	4.45×10^{-10}	2.29×10^{-6}	1.21×10^{-6}	5.64×10^{-7}	2.58×10^{-7}	4.32×10^{-6}

Moreover, it has been taken into account the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t using an emission engine technology Euro V with a load factor of 50% in Belgium in 2012 (see Table 5.37). It should be noted that the transport process articulated lorry of 34-40 t with a load factor of 50% (see Table 5.36) and this process, which uses an emission standard Euro V, show differences in the LCIA results in the indicators climate change, particulate matter, photochemical zone formation, acidification and terrestrial eutrophication. This is due to changes in the exhaust emissions during the road transport operation. Thereby, the others life cycle phases (i.e. lorry demand and road infrastructure) present the same environmental impact. Furthermore, they have the same impact in the indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. Therefore, as mentioned above, the emission standards do not affect these indicators.

Table 5.37. LCIA of 1 tkm transported by an articulated lorry of 34-40 t using an emission engine technology Euro V with a load factor of 50% in Belgium in 2012

Impact category	Unit	Transport operation	Lorry maint.	Lorry mfg.	Road	Diesel production	Total
Climate change	**kg CO_2 eq**	6.42×10^{-2}	1.41×10^{-3}	2.07×10^{-3}	1.42×10^{-2}	1.24×10^{-2}	9.42×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.15×10^{-12}	1.77×10^{-10}	1.59×10^{-10}	3.57×10^{-9}	1.38×10^{-8}	1.77×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	2.49×10^{-5}	1.61×10^{-6}	2.04×10^{-6}	1.35×10^{-5}	1.12×10^{-5}	5.34×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	6.39×10^{-7}	1.72×10^{-4}	1.94×10^{-4}	2.33×10^{-3}	5.43×10^{-3}	8.13×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	2.09×10^{-4}	5.54×10^{-6}	9.23×10^{-6}	1.45×10^{-4}	7.57×10^{-5}	4.44×10^{-4}
Acidification	**molc H+ eq**	1.58×10^{-4}	1.14×10^{-5}	1.56×10^{-5}	1.21×10^{-4}	1.39×10^{-4}	4.44×10^{-4}
Terrestrial eutrophication	**molc N eq**	8.98×10^{-4}	1.45×10^{-5}	2.46×10^{-5}	3.43×10^{-4}	1.76×10^{-4}	1.46×10^{-3}
Freshwater eutrophication	**kg P eq**	7.45×10^{-10}	4.56×10^{-7}	1.32×10^{-6}	2.91×10^{-6}	1.46×10^{-6}	6.15×10^{-6}
Resource depletion	**kg Sb eq**	4.45×10^{-10}	2.29×10^{-6}	1.21×10^{-6}	5.64×10^{-7}	2.58×10^{-7}	4.32×10^{-6}

Figure 5.14 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported by different load factors (i.e. 50%, 60% and 85%) of an average road freight transport (see Tables 5.33, 5.34 and 5.35) in Belgium in 2012. Moreover, it includes an average articulated lorry of 34-40 t with a load factor of 50% (see Table 5.36) and an articulated lorry of 34-40 t using an emission engine technology Euro V with a load factor of 50% in Belgium in 2012 (see Table 5.37).

Figure 5.14. LCIA of 1 tkm transported by average road freight transport with a load factor (LF) of 50%, 60% and 85% and an articulated lorry of 34-40 t with a LF of 50% and an emission standard Euro V in Belgium in 2012

For road freight transport, the transport operation stage is the main source of impact in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication.

For the indicator climate change, the exhaust emissions from lorries of GHG during the transport operation is a major source of impact. Road infrastructure represents from 13% to 15% of the total impact on the different road transport processes as a result of the combustion of diesel in the road construction and the production of gravel, bitumen and concrete. Moreover, the GHG emissions during the petroleum refinery operation constitute a 13 % of the total impact in climate change for road freight transport.

For the indicator particulate matter, the particle emissions from tyre, break and road wear during the road transport activity are the main source of impact. The exhaust emissions of $PM_{2.5}$ and NO_X during the transport operation have an important influence in the result of this indicator. Moreover, the impact generated by the road infrastructure is a major source of impact in this indicator due to the emissions of particles and SO_2 during the combustion of diesel in the road construction and the production of materials used in the road infrastructure as gravel and bitumen. Furthermore, the particle and SO_2 emissions during the petroleum refinery operation constitute from 17% to 21% of the total impact in particle matter for road freight transport. It must be borne in mind that particulate matter can be emitted directly (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as SO_X, NO_X, NH_3 or VOC.

For the indicator photochemical ozone formation, the exhaust emissions of mainly NO_X and NMVOC and to a lesser degree SO_2 are the main contributor in this indicator. Moreover, the NMVOC emissions from paving works as a result of the use of bitumen in road construction is an important source of impact in this indicator. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC by photochemical reaction under the influence of solar radiation.

For the indicator acidification, the exhaust emissions of NO_X and SO_2 are a major source of impact. Moreover, the SO_2 emissions during the petroleum refinery operation constitute from 21% to 42% of the total impact in acidification for road freight transport. For the indicator terrestrial eutrophication, the main source of impact are the exhaust emissions of NO_X.

For the indicator ozone depletion, the main contributor of the impact is the emissions of bromotrifluoromethane ($CBrF_3$ or halon 1 301) to air during the petroleum refinery operation. This gas contributes to the depletion of the stratospheric ozone layer, which filters ultraviolet radiation from the sun. The impact generated by the road infrastructure (from 18% to 20% of the total impact) in this indicator comes mostly from the bitumen production. For the indicator ionizing radiation (damage to human health), the main impact is produced by the low-level radioactive wastes generated during oil production.

For the indicator freshwater eutrophication, the electricity generation in the manufacturing countries of materials (mainly gravel and steel) used in the road infrastructure is the source of the main impact due to the hard coal and lignite mining. Moreover, the production of steel, copper and other metals used in the lorry manufacturing is an important source of impact in this indicator. For the indicator resource depletion, the lead used in the lorry batteries is the main source of impact.

Chapter 6. Comparison of the environmental impacts of the inland freight transport modes

6.1. Introduction

The purpose of this chapter is to compare the energy consumption (Tank-to-Wheel) and environmental performance of the different inland freight transport modes in Belgium. The results obtained for rail freight transport (Chapter 3), IWW transport (Chapter 4) and road freight transport (Chapter 5) have been compared.

6.2. Comparison of energy consumption (Tank-To-Wheel) during the transport operation

A comparison of the energy consumptions obtained for the inland freight transport modes studied from the period 2006 to 2012 in Belgium and the reference values from EcoTransIT (2008) and Ecoinvent v3 (years 2005 and 2014 respectively) has been carried out. As shown in Table 6.1, the values of energy consumption for rail freight transport (Belgian traction mix), electric trains and diesel trains have included in the comparison. For IWW transport, the values for IWW in canal, upstream and downstream have been considered. Within road freight transport, three scenarios with different load factors of 50%, 60% and 85% have been taken into account. As mentioned in Chapter 5, these load factors have been used due to the load factor of an average cargo in road transport including empty trips is 50% (EcoTransIT, 2008) and for intermodal road transport is 85% for the main haulage and 60% for the post-haulage (Janic, 2008). Moreover, since the lorry category articulated lorry of 34-40 t represents approximately 75% of the road freight transport performance (i.e. tonne-kilometres) every year in Belgium, it has been used to compare the different inland freight transport modes because it is representative.

The values on energy consumption for the year 2005 from EcoTransIT (2008) represent European averages and comprise the energy consumption of both transport operation and fuels and electricity production, i.e. WTW energy consumption (EcoTransIT, 2008). For rail freight transport, it uses the values of 456 kJ/tkm for electric trains and 530 kJ/tkm for diesel trains. For IWW transport, the energy consumptions of 727 kJ/tkm for IWW upstream and 438 kJ/tkm for IWW downstream are considered. Note the great difference in energy consumption between the values of EcoTransIT (2008) on IWW transport and our results for Belgium. This is primarily due to the higher specific energy consumptions used by EcoTransIT (2008) compared to those used in our study, especially for IWW transport upstream, and the inclusion of the primary energy consumption from fuel production. For road freight transport, it estimates 1 082 kJ/tkm for an articulated lorry of 34-40 t and emission engine technology Euro III.

In the case of the Ecoinvent v3 database (Weidema et al., 2013), the values on energy consumption for the year 2014 represent the final energy consumption during transport operation (similar to our study). The values represent European averages except for rail freight transport, which is a Belgian average. For rail freight transport (Belgian traction mix), Ecoinvent v3 presents a consumption of 417 kJ/tkm (including 260 kJ of electricity and 157 kJ of diesel). For IWW transport, an energy consumption of 402 kJ/tkm is considered. For road freight transport, the energy consumption for a lorry of >32 t is approximately 727 kJ/tkm.

Table 6.1. Energy consumption (kJ/tkm) of the different inland freight transport modes in Belgium

Energy consumption (kJ/tkm)	2006	2007	2008	2009	2010	2011	2012	Ecoinvent v3[1] (2014)	EcoTransIT[2] (2005)
Rail transport (Belgian traction mix)	585	565	592	590	491	479	457	417	-
Electric trains	541	527	549	547	438	454	427	-	456[3]
Diesel trains	725	685	746	804	760	608	650	-	530[3]
IWW canal	319	312	304	299	293	290	288	402	-
IWW upstream	241	236	231	228	224	221	219	-	727[3]
IWW downstream	206	201	197	193	189	187	184	-	438[3]
Road transport (LF 50%)	997	995	990	993	993	993	994	-	-
Road transport (LF 60%)	865	864	860	862	862	862	863	-	-
Road transport (LF 85%)	672	671	668	670	669	670	670	-	-
Art. lorry of 34-40 t (LF 50%)	849							-	1 082[3]
Art. lorry of 34-40 t (LF 60%)	741							727	-
Art. lorry of 34-40 t (LF 85%)	582							-	-

[1]Source: Weidema et al., 2013; [2]Source: EcoTransIT (2008); [3]WTW energy consumption

Figure 6.1 shows a comparison of the energy consumption (kJ/tkm) obtained for the transport of one tonne-kilometre of freight transported by train, barge and lorry in Belgium (from Table 6.1). Moreover, the reference values from EcoTransIT (2008) for the year 2005 and Ecoinvent v3 for the year 2014 have been included.

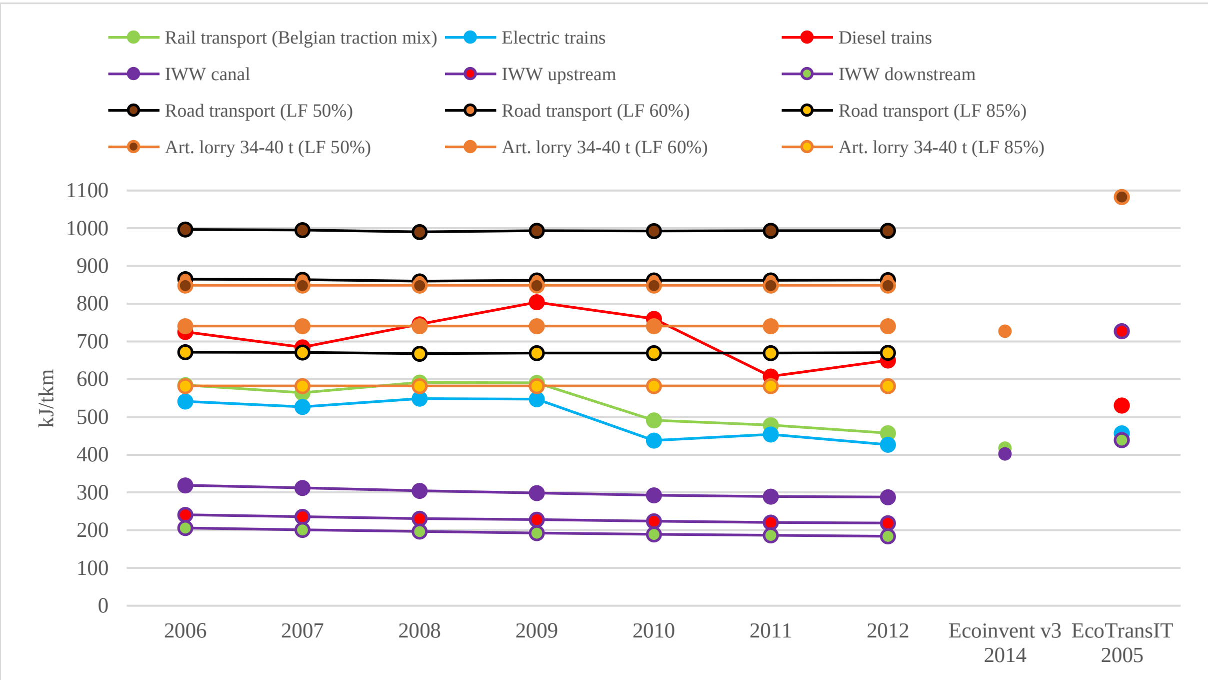


Figure 6.1. Comparison of the energy consumption (kJ/tkm) of the different inland freight transport modes in Belgium

IWW transport is the most energy-efficient mode of inland freight transport. It represents the least energy consuming mode of transport in our study, but also in both the Ecoinvent v3 database and EcoTransIT (2008) for IWW downstream. However, our results for Belgium present lower values than the reference values.

Within rail freight transport, electric traction has the lowest energy consumption, while diesel traction has the highest. The Belgian traction mix, which includes a combination of electric and diesel traction, achieves an intermediate consumption, but closer at the energy consumption of the electric traction due to its greatest share of the Belgian traction mix.

Focusing on road transport, road freight transport with a load factor of 50% presents the highest energy consumption among the different transport modes, followed by road freight transport with a load factor of 60%. However, with a load factor of 85%, it achieves a lower energy consumption than diesel trains until the year 2010, when a drop in the energy consumption of diesel trains occurs as a result of an improved energy efficiency. In the case of an articulated lorry of 34-40 t with a load factor of 50%, it presents an energy consumption slightly lower than an average road freight transport with a 60% of load factor. However, with a load factor of 60%, it achieves a lower energy consumption than diesel trains for several years. Moreover, it shows a similar energy consumption than Ecoinvent v3 database for a lorry of >32 t. An articulated lorry of 34-40 t with an 85% of load factor presents lower energy consumption than diesel trains. Furthermore, it presents a slightly lower energy consumption than freight trains (Belgian traction mix) for several years.

6.3. Life Cycle Impact Assessment of the inland freight transport modes in Belgium

The Life Cycle Impact Assessment (LCIA) of the different inland freight transport modes have been performed using the LCIA method “ILCD 2011 Midpoint+” (version V1.06 / EU27 2010) and the LCIA method “ReCiPe 2008” (hierarchist, version V1.12 / Europe). All calculations were made with the SimaPro 8.0.5 software.

6.3.1. Life Cycle Impact Assessment using the method ILCD 2011 Midpoint+

Table 6.2 presents the results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in the year 2012 by rail freight transport considering the Belgian traction mix of 2012 (i.e. 86.3% of electric trains and 13.7% of diesel trains), diesel trains (including shunting activity), electric trains, IWW transport in canal and road freight transport using the load factors of 50%, 60% and 85%.

Table 6.2. LCIA of 1 tkm transported by inland freight transport in Belgium in 2012

Impact category	Unit	Rail freight transport			IWW canal	Road freight transport		
		Belgian traction mix	Diesel trains	Electric trains		LF 50%	LF 60%	LF 85%
Climate change	**kg CO_2 eq**	6.42×10^{-2}	8.32×10^{-2}	6.12×10^{-2}	7.47×10^{-2}	1.13×10^{-1}	9.77×10^{-2}	7.50×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.19×10^{-8}	1.38×10^{-8}	1.16×10^{-8}	7.81×10^{-9}	2.09×10^{-8}	1.81×10^{-8}	1.39×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	3.55×10^{-5}	5.89×10^{-5}	3.17×10^{-5}	4.74×10^{-5}	7.58×10^{-5}	6.56×10^{-5}	5.06×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	5.85×10^{-2}	7.27×10^{-3}	6.67×10^{-2}	1.26×10^{-2}	9.82×10^{-3}	8.46×10^{-3}	6.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	3.03×10^{-4}	1.09×10^{-3}	1.78×10^{-4}	5.29×10^{-4}	8.62×10^{-4}	7.25×10^{-4}	5.24×10^{-4}
Acidification	**molc H+ eq**	3.64×10^{-4}	9.25×10^{-4}	2.74×10^{-4}	6.23×10^{-4}	7.82×10^{-4}	6.61×10^{-4}	4.82×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.04×10^{-3}	4.07×10^{-3}	5.62×10^{-4}	1.98×10^{-3}	3.08×10^{-3}	2.58×10^{-3}	1.85×10^{-3}
Freshwater eutrophication	**kg P eq**	1.96×10^{-5}	1.69×10^{-5}	2.00×10^{-5}	1.94×10^{-5}	9.54×10^{-6}	8.09×10^{-6}	5.95×10^{-6}
Resource depletion	**kg Sb eq**	2.34×10^{-6}	2.45×10^{-6}	2.32×10^{-6}	6.62×10^{-7}	1.02×10^{-5}	8.54×10^{-6}	6.09×10^{-6}

Figure 6.2 shows a comparison of the results (from Table 6.2) obtained in the LCIA of different modes of inland freight transport in Belgium in 2012. Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the transport mode with less impact and the highest value represents the maximum impact.

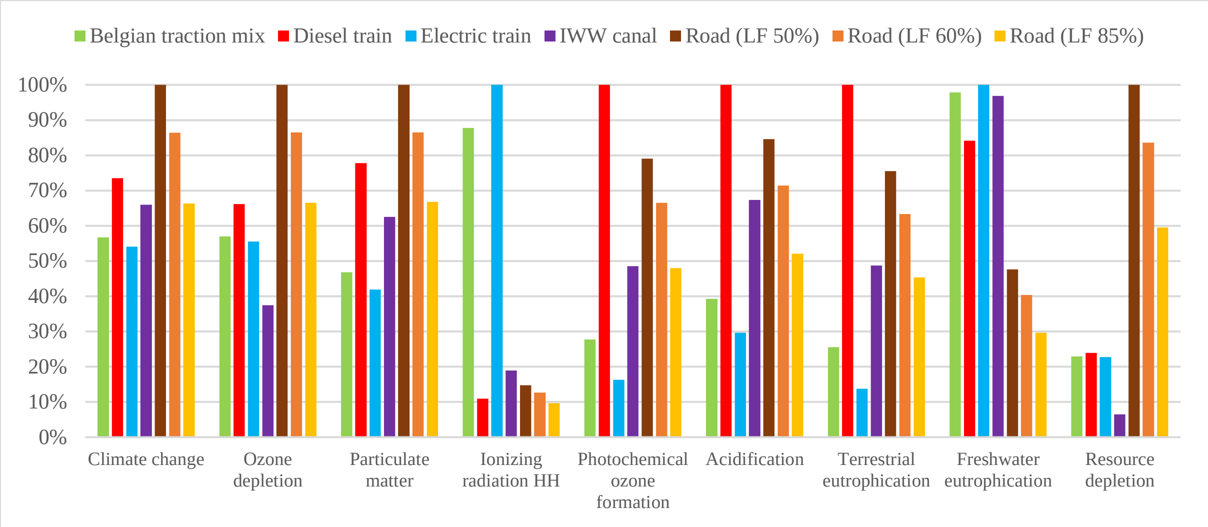


Figure 6.2. LCIA of 1 tkm transported by inland freight transport in Belgium in 2012 using the LCIA method ILCD 2011

Due to uncertainties regarding the LCIA results, a discussion of the most significant differences between transport modes has been performed. Road freight transport with a load factor of 50% present the maximum impact in the indicators climate change, ozone depletion, particulate matter and resource depletion.

For the indicator climate change, the GHG exhaust emissions during the road transport activity are the main contributor to this indicator. However, road freight transport with a load factor of 85% presents nearly the same environmental impact on climate change than IWW, having both a lower impact than diesel trains. Electric trains emits SF_6 (a powerful GHG) during electricity conversion at traction substations, but the main GHG emissions are produced in the electricity generation, especially in the natural gas power plants. For IWW transport, the infrastructure (especially the port facilities demand) is the main source of impact in this indicator.

For the indicator ozone depletion, the main contributor of the impact in diesel trains, IWW and road freight transport is the emissions of bromotrifluoromethane ($CBrF_3$ or halon 1 301) to air during the petroleum refinery operation. This gas contributes to the depletion of the stratospheric ozone layer, which filters ultraviolet radiation from the sun. For electric trains and rail freight transport (Belgian traction mix), nuclear power is the main contributor to this indicator due to the use of refrigerant gases in the uranium enrichment.

For the indicator particulate matter, the main source of impact for road freight transport are the particle emissions from tyre, break and road wear during the road transport activity. The exhaust emissions of $PM_{2.5}$, NO_X and SO_2 during the transport operation have an important influence in the result of this indicator, being the main source of impact for diesel trains. Furthermore, the impact generated by the railway infrastructure is important for rail freight transport in this indicator. For IWW transport, the impact generated by the transport infrastructure (mostly from port facilities demand) is a major source of impact in this indicator. It must be borne in mind that particulate matter can be emitted directly (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as SO_X, NO_X, NH_3 or VOC.

Diesel trains present the maximum impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication due to the exhaust emissions produced in the diesel locomotives. For the indicator photochemical ozone formation, the exhaust emissions of mainly NO_X and NMVOC are the main contributors in this indicator. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC by photochemical reaction under the influence of solar radiation. For the indicator acidification, the exhaust emissions of NO_X and SO_2 are a major source of impact and for the indicator terrestrial eutrophication, the main source of impact are the exhaust emissions of NO_X. Furthermore, the transport operation is the most important source of impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions for IWW and road transport.

Electric trains present the maximum impact in the indicator ionizing radiation (damage to human health) due to the use of nuclear power in the electricity production in Belgium (41.88% of the electricity supply mix in the year 2012). Moreover, electric trains show the maximum impact in the indicator freshwater eutrophication due to the railway infrastructure. The electricity generation is also an important contributor in this indicator due to the hard coal and lignite mining. Furthermore, IWW shows a similar value in this indicator than electric trains as a result of the infrastructure (especially the port facilities demand).

For the indicator resource depletion, road freight transport presents the maximum impact as a result of the lead used in the lorry batteries. Rail freight transport including the Belgian traction mix, diesel trains and electric trains show a similar impact in this indicator due to the similar demand of railway infrastructure and rail equipment.

Concerning road freight transport, the improvement of the emission standards would reduce on the one hand the impact in the indicators particulate matter, photochemical zone formation, acidification and terrestrial eutrophication. On the other hand, the emission standards do not affect the indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. For the indicator climate change, since the emission standards Euro V and Euro VI presents higher N_2O emissions than the rest of emission standards a slightly higher impact would be achieved but without significant differences. Furthermore, the load factor is shown as a determining factor in the environmental impact of road freight transport. Thereby, road freight transport with a load factor of 85% can achieve a similar impact (even slightly lower) than diesel trains in the indicators climate change, ozone depletion and particulate matter.

6.3.1.1. External normalisation of the LCIA results using ILCD 2011 Midpoint+

As mentioned in Chapter 2 (section 2.3.3.4), normalisation is an optional stage of the LCIA allowing the identification of the most relevant environmental impact categories by comparing the LCIA results with references values. The normalisation can be internal or external depending on whether the references are from the same study or from outside the study, respectively. Chapters 3, 4 and 5 were concerned with internal normalisation. In this section, the external normalisation of the LCIA results obtained for the different inland freight transport modes in Belgium is performed. To do this, the normalisation factors used by the LCIA method ILCD 2011 Midpoint +, which are based on Benini et al. (2014) have been used. These normalisation factors represent the environmental impact of one EU-27 inhabitant in the year 2010 adopting a production-based approach. Table 6.3 present the results from the external normalisation of the LCIA results obtained for the different modes of inland freight transport in Belgium in 2012 (see Table 6.2), applying the normalisation factors from ILCD 2011.

Table 6.3. External normalisation of the LCIA of 1 tkm transported by inland freight transport in Belgium in 2012

Impact category	Unit	Rail freight transport			IWW canal	Road freight transport		
		Belgian traction mix	Diesel trains	Electric trains		LF 50%	LF 60%	LF 85%
Climate change	**kg CO_2 eq**	7.06×10^{-6}	9.15×10^{-6}	6.73×10^{-6}	8.22×10^{-6}	1.24×10^{-5}	1.08×10^{-5}	8.25×10^{-6}
Ozone depletion	**kg CFC-11 eq**	5.51×10^{-7}	6.39×10^{-7}	5.37×10^{-7}	3.62×10^{-7}	9.66×10^{-7}	8.36×10^{-7}	6.43×10^{-7}
Particulate matter	**kg $PM_{2.5}$ eq**	9.33×10^{-6}	1.55×10^{-5}	8.35×10^{-6}	1.25×10^{-5}	1.99×10^{-5}	1.72×10^{-5}	1.33×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	5.18×10^{-5}	6.43×10^{-6}	5.90×10^{-5}	1.12×10^{-5}	8.69×10^{-6}	7.49×10^{-6}	5.72×10^{-6}
Photochemical ozone formation	**kg NMVOC eq**	9.54×10^{-6}	3.43×10^{-5}	5.60×10^{-6}	1.67×10^{-5}	2.71×10^{-5}	2.28×10^{-5}	1.65×10^{-5}
Acidification	**molc H+ eq**	7.67×10^{-6}	1.95×10^{-5}	5.79×10^{-6}	1.31×10^{-5}	1.65×10^{-5}	1.39×10^{-5}	1.02×10^{-5}
Terrestrial eutrophication	**molc N eq**	5.92×10^{-6}	2.31×10^{-5}	3.19×10^{-6}	1.13×10^{-5}	1.75×10^{-5}	1.47×10^{-5}	1.05×10^{-5}
Freshwater eutrophication	**kg P eq**	1.33×10^{-5}	1.14×10^{-5}	1.36×10^{-5}	1.31×10^{-5}	6.45×10^{-6}	5.47×10^{-6}	4.02×10^{-6}
Resource depletion	**kg Sb eq**	2.31×10^{-5}	2.42×10^{-5}	2.30×10^{-5}	6.55×10^{-6}	1.01×10^{-4}	8.46×10^{-5}	6.03×10^{-5}

Figure 6.3 shows a comparison of the results (from Table 6.3) obtained in the external normalisation of the LCIA of different modes of inland freight transport in Belgium in 2012.

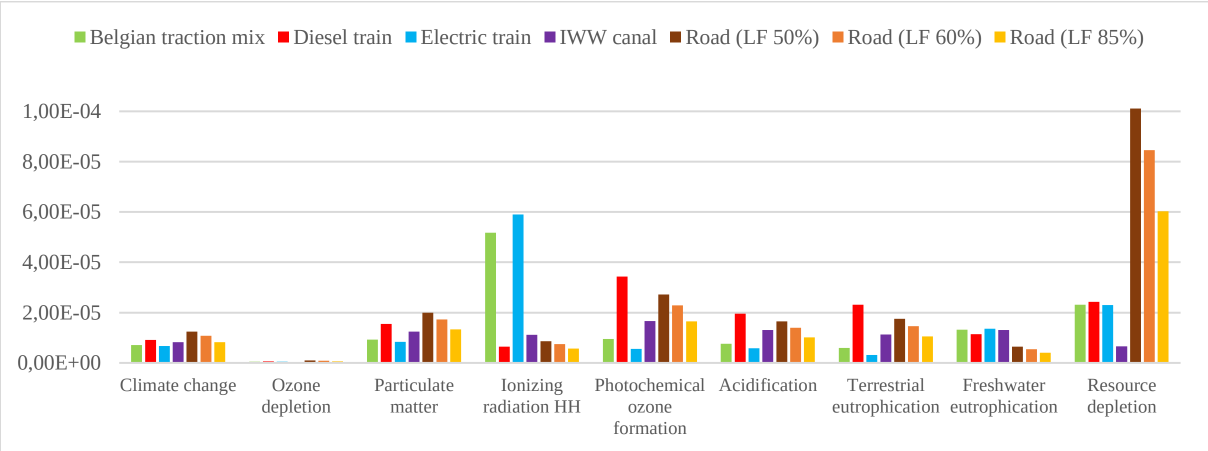


Figure 6.3. Normalisation of the LCIA of 1 tkm transported by inland freight transport in Belgium in 2012 using the LCIA method ILCD 2011

According to the normalisation analysis, the most relevant impact category is resource depletion and the least relevant one is ozone depletion. Among the other impact categories, the impact of electric trains (and the Belgian traction mix because of the 86.3% of electric traction in it) in the indicator ionizing radiation (damage to human health) stands out compared to the other modes of transport. The rest of the impact categories present values in the same range of magnitude, with the exception of diesel trains, which stand out in the indicators photochemical ozone radiation, acidification and terrestrial eutrophication.

6.3.1.2. *Contribution of the sub-systems transport operation, vehicle and infrastructure to the environmental impact of inland freight transport*

For the LCIA of the Belgian rail freight transport, all life cycle phases of rail freight transport operation, electricity generation for electric trains (i.e. the calculated electricity supply mix in Belgium of the year 2012), diesel production for diesel trains, railway infrastructure and rail equipment (i.e. locomotive and wagons) are taken into account. Similarly, for the LCIA of IWW transport, all life cycle phases of IWW transport operation, fuel production, IWW infrastructure (including canals and port facilities), and barge are included. For the LCIA of road transport, all life cycle phases of road transport operation, diesel production, lorry and road infrastructure are included.

Table 6.4 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by rail in Belgium using the Belgian traction mix of the year 2012 (i.e. 86.3% of electric traction and 13.7% of diesel traction). The process infrastructure includes the values of rail infrastructure construction and maintenance. Moreover, the values of rail equipment maintenance and manufacturing have been grouped in the process vehicles.

Table 6.4. LCIA of 1 tkm transported by rail freight transport in Belgium in 2012

Impact category	Unit	Transport operation	Electricity	Fuel	Infrastructure	Vehicles	Total
Climate change	**kg CO_2 eq**	6.72×10^{-3}	3.21×10^{-2}	1.20×10^{-3}	1.61×10^{-2}	8.01×10^{-3}	6.42×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	7.27×10^{-9}	1.44×10^{-9}	2.76×10^{-9}	4.29×10^{-10}	1.19×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	3.51×10^{-6}	8.06×10^{-6}	1.09×10^{-6}	1.36×10^{-5}	9.22×10^{-6}	3.55×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	5.49×10^{-2}	5.54×10^{-4}	2.43×10^{-3}	6.00×10^{-4}	5.85×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	1.25×10^{-4}	5.63×10^{-5}	7.49×10^{-6}	8.65×10^{-5}	2.73×10^{-5}	3.03×10^{-4}
Acidification	**molc H+ eq**	8.49×10^{-5}	8.20×10^{-5}	1.38×10^{-5}	1.22×10^{-4}	6.11×10^{-5}	3.64×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.88×10^{-4}	1.74×10^{-4}	1.69×10^{-5}	2.81×10^{-4}	8.31×10^{-5}	1.04×10^{-3}
Freshwater eutrophication	**kg P eq**	0	6.00×10^{-6}	1.27×10^{-7}	9.46×10^{-6}	4.03×10^{-6}	1.96×10^{-5}
Resource depletion	**kg Sb eq**	0	3.60×10^{-7}	1.73×10^{-8}	1.51×10^{-6}	4.48×10^{-7}	2.34×10^{-6}

Table 6.5 shows the results obtained in the LCIA of one tonne-kilometre of freight transported by diesel trains (including shunting activity) in Belgium in 2012.

Table 6.5. LCIA of 1 tkm transported by diesel trains in Belgium in 2012

Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Climate change	**kg CO_2 eq**	4.83×10^{-2}	8.76×10^{-3}	1.61×10^{-2}	9.97×10^{-3}	8.32×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	1.05×10^{-8}	2.76×10^{-9}	5.44×10^{-10}	1.38×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	2.56×10^{-5}	7.98×10^{-6}	1.36×10^{-5}	1.18×10^{-5}	5.89×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	4.04×10^{-3}	2.43×10^{-3}	7.93×10^{-4}	7.27×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	9.14×10^{-4}	5.47×10^{-5}	8.65×10^{-5}	3.50×10^{-5}	1.09×10^{-3}
Acidification	**molc H+ eq**	6.20×10^{-4}	1.01×10^{-4}	1.22×10^{-4}	8.29×10^{-5}	9.25×10^{-4}
Terrestrial eutrophication	**molc N eq**	3.56×10^{-3}	1.23×10^{-4}	2.81×10^{-4}	1.07×10^{-4}	4.07×10^{-3}
Freshwater eutrophication	**kg P eq**	0	9.27×10^{-7}	9.46×10^{-6}	6.48×10^{-6}	1.69×10^{-5}
Resource depletion	**kg Sb eq**	0	1.26×10^{-7}	1.51×10^{-6}	8.08×10^{-7}	2.45×10^{-6}

Table 6.6 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by electric trains in Belgium in 2012.

Table 6.6. LCIA of 1 tkm transported by electric trains in Belgium in 2012

Impact category	Unit	Transport operation	Electricity	Infrastructure	Vehicles	Total
Climate change	**kg CO_2 eq**	1.19×10^{-4}	3.72×10^{-2}	1.61×10^{-2}	7.70×10^{-3}	6.12×10^{-2}
Ozone depletion	**kg CFC-11 eq**	0	8.43×10^{-9}	2.76×10^{-9}	4.10×10^{-10}	1.16×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	0	9.35×10^{-6}	1.36×10^{-5}	8.82×10^{-6}	3.17×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	0	6.37×10^{-2}	2.43×10^{-3}	5.69×10^{-4}	6.67×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	0	6.53×10^{-5}	8.65×10^{-5}	2.60×10^{-5}	1.78×10^{-4}
Acidification	**molc H+ eq**	0	9.50×10^{-5}	1.22×10^{-4}	5.76×10^{-5}	2.74×10^{-4}
Terrestrial eutrophication	**molc N eq**	0	2.02×10^{-4}	2.81×10^{-4}	7.93×10^{-5}	5.62×10^{-4}
Freshwater eutrophication	**kg P eq**	0	6.95×10^{-6}	9.46×10^{-6}	3.64×10^{-6}	2.00×10^{-5}
Resource depletion	**kg Sb eq**	0	4.17×10^{-7}	1.51×10^{-6}	3.90×10^{-7}	2.32×10^{-6}

Table 6.7 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canal in Belgium in 2012. The values of transport operation and bilge oil have been clustered in the process transport operation. Moreover, the values of vessel maintenance and manufacturing have been grouped in the process vehicles.

Table 6.7. LCIA of 1 tkm transported by barge in canal in Belgium in 2012

Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Climate change	**kg CO_2 eq**	2.16×10^{-2}	3.88×10^{-3}	4.78×10^{-2}	1.41×10^{-3}	7.47×10^{-2}
Ozone depletion	**kg CFC-11 eq**	3.07×10^{-12}	4.65×10^{-9}	3.07×10^{-9}	9.12×10^{-11}	7.81×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	4.75×10^{-6}	3.53×10^{-6}	3.76×10^{-5}	1.48×10^{-6}	4.74×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.81×10^{-6}	1.79×10^{-3}	1.07×10^{-2}	9.63×10^{-5}	1.26×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	3.43×10^{-4}	2.42×10^{-5}	1.39×10^{-4}	2.27×10^{-5}	5.29×10^{-4}
Acidification	**molc H+ eq**	2.51×10^{-4}	4.45×10^{-5}	3.17×10^{-4}	1.04×10^{-5}	6.23×10^{-4}
Terrestrial eutrophication	**molc N eq**	1.44×10^{-3}	5.45×10^{-5}	4.78×10^{-4}	1.51×10^{-5}	1.98×10^{-3}
Freshwater eutrophication	**kg P eq**	4.15×10^{-8}	4.11×10^{-7}	1.82×10^{-5}	7.57×10^{-7}	1.94×10^{-5}
Resource depletion	**kg Sb eq**	2.36×10^{-10}	5.59×10^{-8}	4.74×10^{-7}	1.31×10^{-7}	6.62×10^{-7}

Table 6.8 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by road freight transport with a load factor of 50% in Belgium in 2012. The process vehicle includes the values of lorry manufacturing and maintenance.

Table 6.8. LCIA of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012

Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Climate change	kg CO_2 eq	7.43×10^{-2}	1.45×10^{-2}	1.51×10^{-2}	9.25×10^{-3}	1.13×10^{-1}
Ozone depletion	kg CFC-11 eq	1.23×10^{-12}	1.62×10^{-8}	3.81×10^{-9}	8.97×10^{-10}	2.09×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	3.85×10^{-5}	1.32×10^{-5}	1.44×10^{-5}	9.73×10^{-6}	7.58×10^{-5}
Ionizing radiation HH	kBq U235 eq	6.83×10^{-7}	6.36×10^{-3}	2.49×10^{-3}	9.75×10^{-4}	9.82×10^{-3}
Photochemical ozone formation	kg NMVOC eq	5.79×10^{-4}	8.86×10^{-5}	1.55×10^{-4}	3.93×10^{-5}	8.62×10^{-4}
Acidification	molc H+ eq	4.19×10^{-4}	1.62×10^{-4}	1.29×10^{-4}	7.19×10^{-5}	7.82×10^{-4}
Terrestrial eutrophication	molc N eq	2.40×10^{-3}	2.06×10^{-4}	3.66×10^{-4}	1.04×10^{-4}	3.08×10^{-3}
Freshwater eutrophication	kg P eq	7.96×10^{-10}	1.71×10^{-6}	3.11×10^{-6}	4.72×10^{-6}	9.54×10^{-6}
Resource depletion	kg Sb eq	4.76×10^{-10}	3.02×10^{-7}	6.02×10^{-7}	9.31×10^{-6}	1.02×10^{-5}

Figure 6.4 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in the year 2012 by rail freight transport considering the Belgian traction mix of 2012 (see Table 6.4) diesel trains (see Table 6.5), electric trains (see Table 6.6), IWW in canal (see Table 6.7) and road freight transport using a 50% of load factor (see Table 6.8).

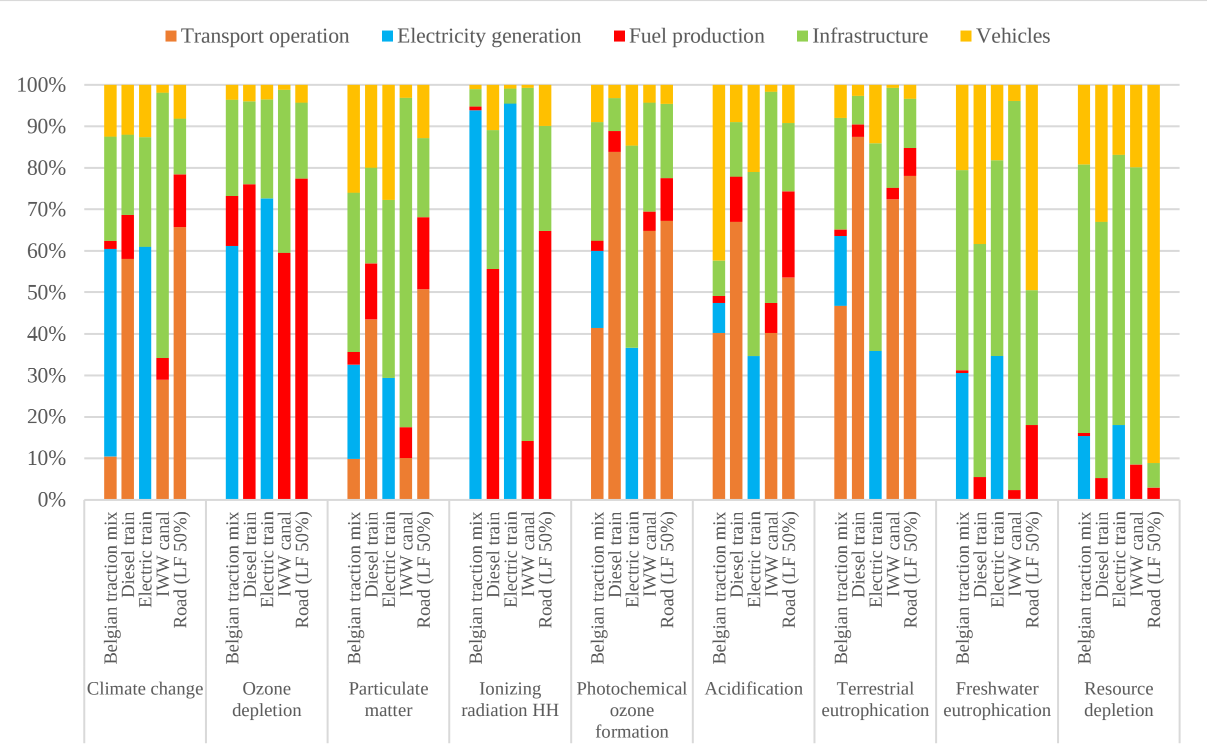


Figure 6.4. LCIA of 1 tkm of freight transport using rail, IWW and road in Belgium in 2012 using the LCIA method ILCD 2011

Within rail freight transport, on the one hand the transport operation is the main source of impact for diesel trains in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions of diesel locomotives. On the other hand, the electricity generation is the main source of impact for electric trains in the indicators climate change, ozone depletion and ionizing radiation (damage to human health). Furthermore, the railway infrastructure construction is the main contributor for rail freight transport, including the Belgian traction mix, diesel trains and electric trains, in both indicators freshwater eutrophication and resource depletion

In the case of IWW transport, the infrastructure sub-system (especially the port facilities demand) is the main source of impact in the indicators climate change, particulate matter, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. For road freight transport, the transport operation stage is the main source of impact in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication.

6.3.2. Life Cycle Impact Assessment using the method ReCiPe 2008[2]

As mentioned in Chapter 2, ReCiPe 2008 is a LCIA method including 18 midpoint impact categories with their respective characterisation models and factors and midpoint impact category indicators. Moreover, most of these midpoint impact indicators can be multiplied by damage factors and aggregated into three endpoint impact categories. Therefore, through the application of ReCiPe 2008, the resources consumed and contribution of the pollutants emitted by freight transport and determined in the Life Cycle Inventory can be analysed using midpoint impact categories such as climate change, photochemical oxidant formation or particulate matter formation. Then, the influence of most of these midpoint impact categories can be evaluated (i.e. all except marine eutrophication and water depletion due to methodological limitations in ReCiPe 2008) in terms of endpoint impact categories such as damage to human health, damage to ecosystem diversity and damage to resource availability (Goedkoop et al., 2013). Figure 6.5 represents the relations between the Life Cycle Inventory, the 18 midpoint impact categories and the three endpoint impact categories of the LCIA method ReCiPe 2008.

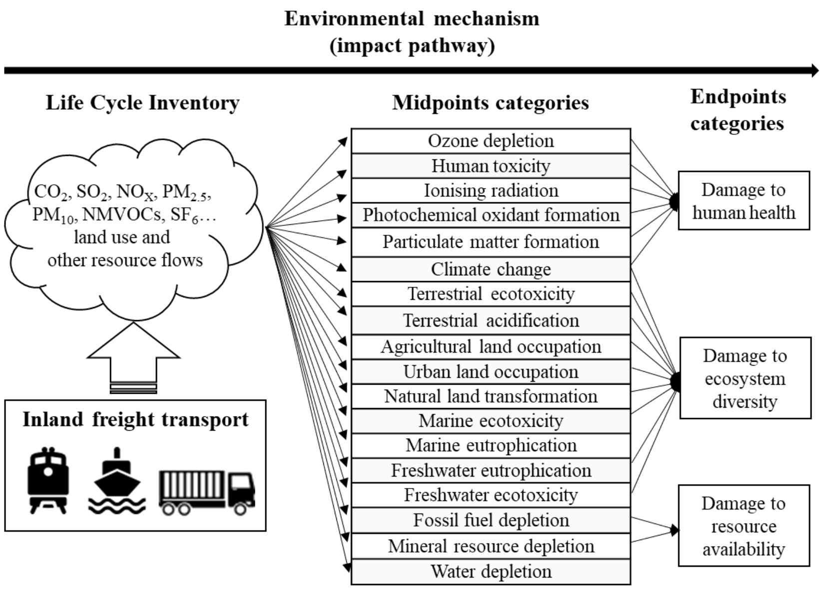


Figure 6.5. Simplified diagram of the Life Cycle Impact Assessment method ReCiPe 2008 applied on inland freight transport. Source: Adapted from Goedkoop et al., 2013

[2] The results presented in this section have been published in Merchan et al. (2019)

LCA studies applied to transport mainly focused on air emissions, especially CO_2, CO, NO_X, SO_2, NMVOC and particulate matter (Spielmann and Scholz, 2005; Facanha and Horvath, 2006, 2007; Chester and Horvath, 2009, 2010; Van Lier and Macharis, 2014; Jones et al., 2017). Therefore, it has been considered that the following midpoint environmental impact categories are relevant for our study on freight transport: climate change (kg CO_2 eq.), photochemical oxidant formation (kg NMVOC eq.) and particulate matter formation (kg PM_{10} eq.).

Moreover, ReCiPe 2008 allows us the study of the environmental impacts of freight transport at the endpoint level. ReCiPe 2008 assesses damage to human health using the indicator disability-adjusted loss of life years (DALY), which encompass the number of years of life lost and the number of years of life disabled. The damage to ecosystem diversity is assessed using the indicator loss of species in a certain area during a year (species × year). The damage to resource availability is assessed using the indicator increased cost, which is expressed in a monetary unit ($) and it is based on the surplus costs of future resource production in the future (Goedkoop et al., 2013). Please note that comparing endpoint categories leads to a greater uncertainty than comparing midpoint categories, due to a more complete modelling of impact pathways (Kägi et al., 2016). Therefore, these results on endpoint damages should be interpreted with caution because of the uncertainty related to the methodology.

Table 6.9 presents the results obtained in the LCIA (using ReCiPe 2008) of one tonne-kilometre of freight transported in Belgium in the year 2012 by rail freight transport considering the Belgian traction mix of 2012 (86.3% of electric trains and 13.7% of diesel trains), diesel trains (including shunting activity), electric trains, IWW in canal and road freight transport using the load factors of 50%, 60% and 85%. Furthermore, the life-cycle inventory of NO_X emissions to air have been included in our study due to its importance as precursor for tropospheric ozone formation and particulate matter.

Table 6.9. Environmental impact assessment of 1 tkm transported by inland freight transport in Belgium in 2012 using the LCIA method ReCiPe 2008

		Unit	Rail freight transport			IWW canal	Road freight transport		
			Belgian traction mix	Diesel trains	Electric trains		LF 50%	LF 60%	LF 85%
Midpoint category	Climate change	kg CO_2 eq	6.42×10^{-2}	8.32×10^{-2}	6.12×10^{-2}	7.47×10^{-2}	1.13×10^{-1}	9.77×10^{-2}	7.50×10^{-2}
	Photochemical oxidant formation	kg NMVOC eq	3.13×10^{-4}	1.11×10^{-3}	1.86×10^{-4}	5.34×10^{-4}	8.72×10^{-4}	7.34×10^{-4}	5.30×10^{-4}
	Particulate matter formation	kg PM_{10} eq	1.33×10^{-4}	3.10×10^{-4}	1.05×10^{-4}	1.92×10^{-4}	3.09×10^{-4}	2.63×10^{-4}	1.96×10^{-4}
Endpoint category	Damage to human health	DALY	1.45×10^{-7}	2.16×10^{-7}	1.33×10^{-7}	1.66×10^{-7}	2.65×10^{-7}	2.28×10^{-7}	1.75×10^{-7}
	Damage to ecosystem diversity	species × year	6.64×10^{-10}	8.04×10^{-10}	6.42×10^{-10}	7.89×10^{-10}	1.20×10^{-9}	1.04×10^{-9}	7.93×10^{-10}
	Damage to resource availability	$	4.04×10^{-3}	5.39×10^{-3}	3.82×10^{-3}	3.65×10^{-3}	7.26×10^{-3}	6.27×10^{-3}	4.79×10^{-3}
Inventory	Nitrogen oxides emissions to air	kg NO_X	2.38×10^{-4}	9.50×10^{-4}	1.25×10^{-4}	4.61×10^{-4}	7.17×10^{-4}	6.01×10^{-4}	4.31×10^{-4}

Figure 6.6 shows a comparison of the results (from Table 6.9) obtained in the LCIA of different modes of inland freight transport in Belgium in 2012. Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact

of the indicator. Therefore, the lowest value represents the transport mode with less impact and the highest value represents the maximum impact.

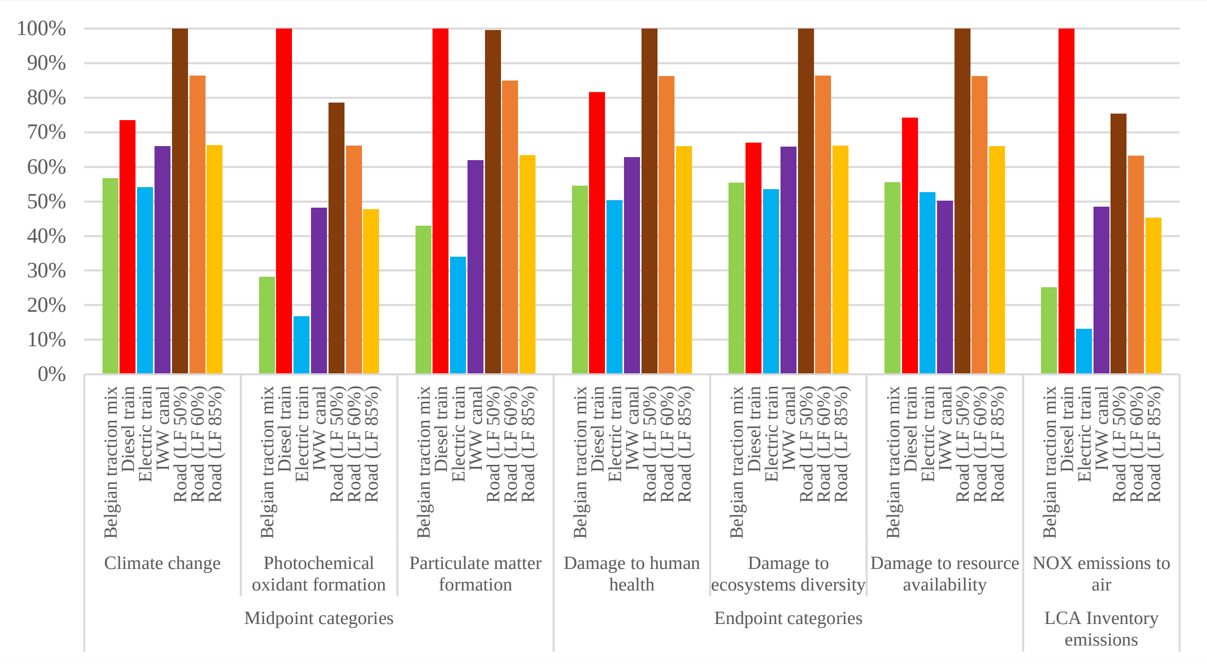


Figure 6.6. Environmental impact assessment of 1 tkm transported by inland freight transport in Belgium in 2012 using the LCIA method ReCiPe 2008

Within the midpoint categories, both LCIA methods ILCD 2011 and ReCiPe 2008 (hierarchist version) show similar results for the indicator climate change. This is because both LCIA methods use the Global Warming Potential for a time horizon of 100 years as impact category indicator. Therefore, road freight transport with a load factor of 50% present the maximum impact in this indicator as a result of the GHG exhaust emissions during the road transport operation. For electric trains, the GHG emitted by the natural power plant for the electricity generation is the main source of impact. In the case of IWW transport the main source of impact for climate change is the infrastructure construction (especially the port facilities).

For the category photochemical ozone formation, the results obtained by ReCiPe 2008 present slightly higher values (without being a significant difference) than the results obtained by ILCD 2011. However, both LCIA methods present a similar distribution of the impacts between modes of transport (see Figure 6.2). Thereby, diesel trains show the maximum impact in this indicator due to the exhaust emissions of mainly NO_X and NMVOC produced in the diesel locomotives.

For the category particulate matter formation, the results obtained in both LCIA methods are different. It should be noted that the indicators used for this impact category in both LCIA methods are different. Thereby, the indicator used by ILCD 2011 uses kg $PM_{2.5}$ eq. as unit and the indicator used by ReCiPe 2008 uses kg PM_{10} eq. In the case of the analysis of particulate matter formation using ReCiPe 2008, diesel trains present the maximum impact but with a similar value than road freight transport with a 50% of load factor. This is because the characterisation model used by ReCiPe 2008 for the indicator particulate matter formation assigns a higher characterisation factor to NO_X emissions to air than the characterisation model used by ILCD 2011. ReCiPe 2008 considers a characterisation factor for NO_X emissions to air of 0.22 kg PM_{10}/kg NO_X while ILCD 2011 applies a characterisation factor of 0.00728 kg $PM_{2.5}$/kg NO_X. Therefore the higher exhaust emission on NO_X of diesel trains (0.836 g/tkm) compared to IWW in canal (0.336 g/tkm) and road freight transport with a load factor of 50% (0.562 g/tkm) is the main reason of the increase of impact of diesel trains in ReCiPe 2008.

As shown in Figure 6.7, the transport operation stage acquires additional relevance for the indicator particulate matter formation used by ReCiPe 2008 compared to the indicator used by ILCD 2011. In the case of diesel trains, the transport operation represents 43% of the environmental impact on particulate matter formation for ILCD 2011 while for ReCiPe 2008 the transport operation constitutes the 68 % of the total impact in this indicator. As explained before, this is mainly the result of the higher characterisation factor for NO_X emission to air used by ReCiPe 2008. Furthermore, the 6.67×10^{-6} kg/tkm of particulate matter between 2.5 µm and 10 µm ($PM_{10} > PM > PM_{2.5}$) emitted to air from abrasion of brake linings, wheels and rails during the transport operation of electric trains (see Table 3.7) are considered by the characterisation model of ReCiPe 2008, representing 6% of the total impact for electric trains in the indicator particulate matter formation.

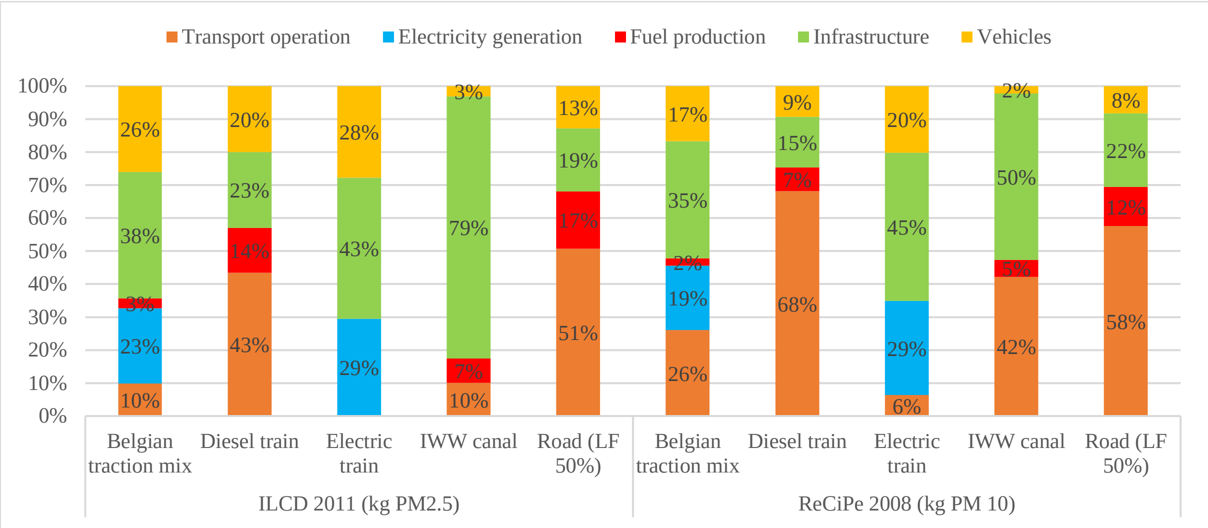


Figure 6.7. Comparison of the indicator particulate matter formation using the LCIA methods ILCD 2011 Midpoint+ and ReCiPe 2008

Within the endpoint categories, road freight transport with a load factor of 50% presents the maximum impact in all the endpoint indicators (see Figure 6.6). In the indicators damage to human health and ecosystems diversity as a result of the exhaust emissions of lorries and for the endpoint indicator damage to resource availability the main source of impact is the diesel production.

Concerning the inventory of NO_X emissions to air, diesel trains present the highest emissions. As discussed above, these high NOx emissions to air cause diesel trains to have the maximum impact on the indicators photochemical oxidant formation and particulate matter formation. As mentioned in Chapter 3, the high exhaust emissions (specially on NO_X) of diesel locomotives as a result of the low rate of replacement of locomotives due to their longer life span is shown as a determining factor in the environmental performance of diesel trains. Therefore, the implementation of new engines with better emission technologies in diesel locomotives appears as an opportunity to improve the environmental impact of rail freight transport by diesel train.

6.3.2.1. Contribution of the sub-systems transport operation, vehicle and infrastructure to the environmental impact of inland freight transport

Similarly to the Section 6.3.1.2, all life cycle phases of rail freight transport, IWW transport and road freight transport have been analysed but using the LCIA method ReCiPe 2008.

Table 6.10 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by rail in Belgium using the Belgian traction mix of the year 2012 (i.e. 86.3% of electric traction and 13.7% of diesel traction). The process infrastructure includes the values of rail infrastructure construction and maintenance. Moreover, the values of rail equipment maintenance and manufacturing have been grouped in the process vehicles.

Table 6.10. LCIA of 1 tkm transported by rail freight transport in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Transport operation	Electricity	Fuel	Infrastructure	Vehicles	Total
Midpoint category	Climate change	kg CO_2 eq	6.72×10^{-3}	3.21×10^{-2}	1.20×10^{-3}	1.61×10^{-2}	8.01×10^{-3}	6.42×10^{-2}
	Photochemical oxidant formation	kg NMVOC eq	1.27×10^{-4}	5.78×10^{-5}	7.58×10^{-6}	9.12×10^{-5}	2.95×10^{-5}	3.13×10^{-4}
	Particulate matter formation	kg PM_{10} eq	3.48×10^{-5}	2.60×10^{-5}	3.05×10^{-6}	4.73×10^{-5}	2.23×10^{-5}	1.33×10^{-4}
Endpoint category	Damage to human health	DALY	1.85×10^{-8}	5.70×10^{-8}	2.61×10^{-9}	4.51×10^{-8}	2.13×10^{-8}	1.45×10^{-7}
	Damage to ecosystem diversity	species × year	5.37×10^{-11}	3.05×10^{-10}	1.49×10^{-11}	2.10×10^{-10}	8.08×10^{-11}	6.64×10^{-10}
	Damage to resource availability	$	0	1.69×10^{-3}	4.49×10^{-4}	1.28×10^{-3}	6.26×10^{-4}	4.04×10^{-3}

Table 6.11 shows the results obtained in the LCIA of one tonne-kilometre of freight transported by diesel trains (including shunting activity) in Belgium in 2012.

Table 6.11. LCIA of 1 tkm transported by diesel trains in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Midpoint category	Climate change	kg CO_2 eq	4.83×10^{-2}	8.76×10^{-3}	1.61×10^{-2}	9.97×10^{-3}	8.32×10^{-2}
	Photochemical oxidant formation	kg NMVOC eq	9.25×10^{-4}	5.53×10^{-5}	9.12×10^{-5}	3.77×10^{-5}	1.11×10^{-3}
	Particulate matter formation	kg PM_{10} eq	2.12×10^{-4}	2.23×10^{-5}	4.73×10^{-5}	2.91×10^{-5}	3.10×10^{-4}
Endpoint category	Damage to human health	DALY	1.23×10^{-7}	1.91×10^{-8}	4.51×10^{-8}	2.91×10^{-8}	2.16×10^{-7}
	Damage to ecosystem diversity	species × year	3.86×10^{-10}	1.09×10^{-10}	2.10×10^{-10}	9.97×10^{-11}	8.04×10^{-10}
	Damage to resource availability	$	0	3.28×10^{-3}	1.28×10^{-3}	8.39×10^{-4}	5.39×10^{-3}

Table 6.12 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by electric trains in Belgium in 2012.

Table 6.12. LCIA of 1 tkm transported by electric trains in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Transport operation	Electricity	Infrastructure	Vehicles	Total
Midpoint category	Climate change	kg CO_2 eq	1.19×10^{-4}	3.72×10^{-2}	1.61×10^{-2}	7.70×10^{-3}	6.12×10^{-2}
	Photochemical oxidant formation	kg NMVOC eq	0	6.69×10^{-5}	9.12×10^{-5}	2.81×10^{-5}	1.86×10^{-4}
	Particulate matter formation	kg PM_{10} eq	6.67×10^{-6}	3.01×10^{-5}	4.73×10^{-5}	2.12×10^{-5}	1.05×10^{-4}
Endpoint category	Damage to human health	DALY	1.90×10^{-9}	6.61×10^{-8}	4.51×10^{-8}	2.01×10^{-8}	1.33×10^{-7}
	Damage to ecosystem diversity	species × year	9.44×10^{-13}	3.53×10^{-10}	2.10×10^{-10}	7.78×10^{-11}	6.42×10^{-10}
	Damage to resource availability	$	0	1.95×10^{-3}	1.28×10^{-3}	5.92×10^{-4}	3.82×10^{-3}

Table 6.13 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by barge in canal in Belgium in 2012. The values of transport operation and bilge oil have been clustered in the process transport operation. Moreover, the values of vessel maintenance and manufacturing have been grouped in the process vehicles.

Table 6.13. LCIA of 1 tkm transported by barge in canal in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Midpoint category	Climate change	kg CO_2 eq	2.16×10^{-2}	3.88×10^{-3}	4.78×10^{-2}	1.41×10^{-3}	7.47×10^{-2}
	Photochemical oxidant formation	kg NMVOC eq	3.44×10^{-4}	2.45×10^{-5}	1.42×10^{-4}	2.33×10^{-5}	5.34×10^{-4}
	Particulate matter formation	kg PM_{10} eq	8.10×10^{-5}	9.86×10^{-6}	9.69×10^{-5}	4.21×10^{-6}	1.92×10^{-4}
Endpoint category	Damage to human health	DALY	5.13×10^{-8}	8.45×10^{-9}	1.03×10^{-7}	3.87×10^{-9}	1.66×10^{-7}
	Damage to ecosystem diversity	species × year	1.73×10^{-10}	4.81×10^{-11}	5.52×10^{-10}	1.62×10^{-11}	7.89×10^{-10}
	Damage to resource availability	$	4.17×10^{-6}	1.45×10^{-3}	2.08×10^{-3}	1.13×10^{-4}	3.65×10^{-3}

Table 6.14 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by road freight transport with a load factor of 50% in Belgium in 2012. The process vehicle includes the values of lorry manufacturing and maintenance

Table 6.14. LCIA of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Transport operation	Fuel	Infrastructure	Vehicles	Total
Midpoint category	Climate change	kg CO_2 eq	7.43×10^{-2}	1.45×10^{-2}	1.51×10^{-2}	9.25×10^{-3}	1.13×10^{-1}
	Photochemical oxidant formation	kg NMVOC eq	5.83×10^{-4}	8.98×10^{-5}	1.57×10^{-4}	4.20×10^{-5}	8.72×10^{-4}
	Particulate matter formation	kg PM_{10} eq	1.78×10^{-4}	3.66×10^{-5}	6.89×10^{-5}	2.55×10^{-5}	3.09×10^{-4}
Endpoint category	Damage to human health	DALY	1.66×10^{-7}	3.16×10^{-8}	4.20×10^{-8}	2.48×10^{-8}	2.65×10^{-7}
	Damage to ecosystem diversity	species × year	6.00×10^{-10}	1.78×10^{-10}	3.35×10^{-10}	8.68×10^{-11}	1.20×10^{-9}
	Damage to resource availability	$	4.47×10^{-7}	5.07×10^{-3}	1.44×10^{-3}	7.55×10^{-4}	7.26×10^{-3}

Figure 6.8 shows a comparison of the results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in the year 2012 by rail freight transport considering the Belgian traction mix of 2012 (see Table 6.10) diesel trains (see Table 6.11), electric trains (see Table

6.12), IWW in canal (see Table 6.13) and road freight transport using a 50% of load factor (see Table 6.14).

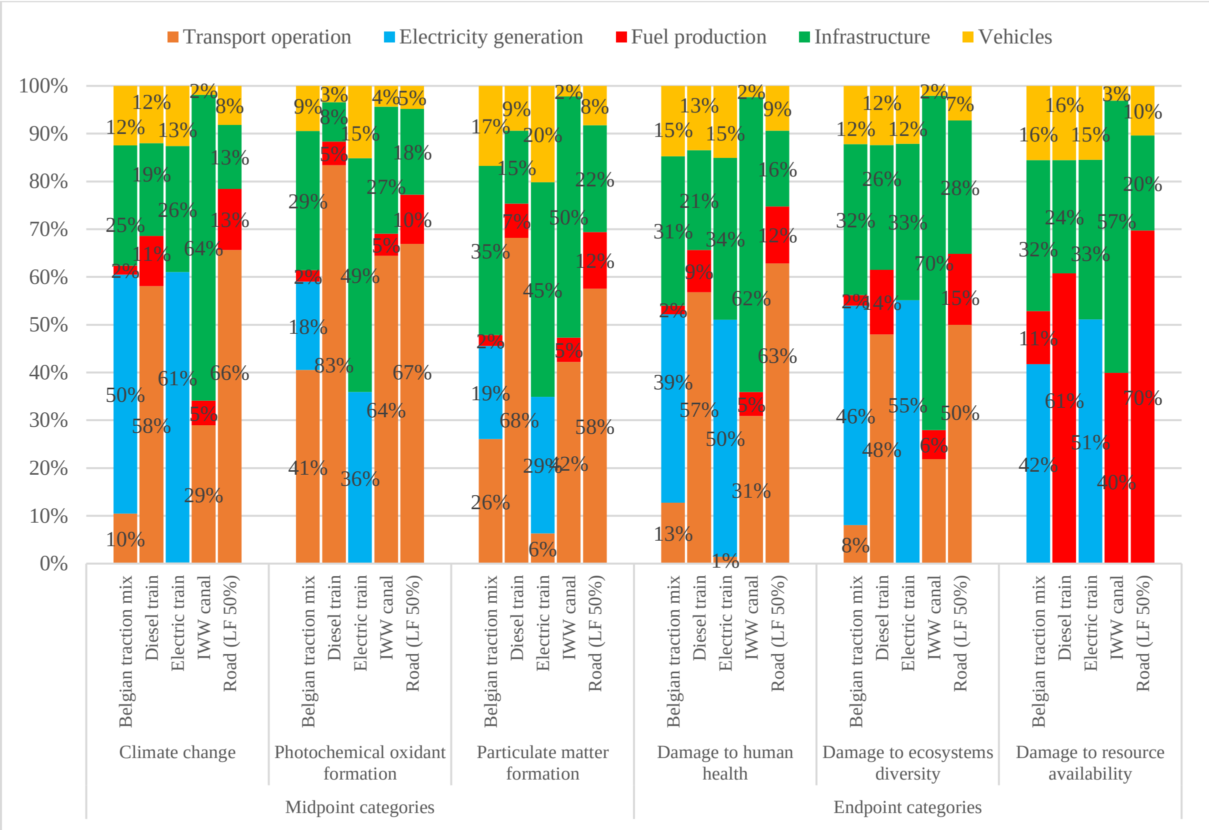


Figure 6.8. LCIA of 1 tkm transported by inland freight transport in Belgium in 2012 using the LCIA method ReCiPe 2008

For the indicator at midpoint level climate change, the generation of the electricity used by electric trains is the main source of impact for the Belgian rail freight transport. It should be noted that the 86.3% of rail freight transport was produced by electric traction in Belgium in 2012. Thereby, the GHG emitted by the natural gas and coal power plants represent the 19% and 9% of the total impact of freight trains in this indicator, respectively. In Belgium, the natural gas power plants contributed 22.18% of the total electricity supply mix and the coal power plants were responsible for 4.99% in the year 2012. Additionally, diesel trains constituted the 13.7% of the total freight trains in Belgium in 2012, representing the GHG emitted as direct emissions from diesel trains the 10% of the total impact in the indicator climate change. Diesel trains are also responsible for 2% of indirect GHG emissions from the production of diesel used in transport. Focusing on the contribution of railway infrastructure to the indicator climate change, the production of steel, concrete and gravel are the main sources of GHG emissions. The production of the steel used in the manufacturing of the rolling stock is the main contributor to climate change for the vehicle stage. For IWW transport, the main source of impact for this indicator is related to the production of materials such as concrete and steel used in canals and port facilities. In the case of road transport, the main source of impact in the indicator climate change is the GHG emissions emitted as exhaust emission by the lorries in the transport activity. Moreover, the petroleum refining to obtain the diesel is a major source of impact.

For the indicator photochemical oxidant formation, the exhaust emissions during transport operation of NO_X and NMVOC from diesel trains, barge and lorries are the main contributor in this indicator. The tropospheric ozone is formed from other precursor pollutants such as NO_X and NMVOC by photochemical reaction under the influence of solar radiation.

For the indicator particulate matter formation, the exhaust emissions of NO_X and $PM_{2.5}$ from diesel trains, lorries and barges are a major source of impact in this indicator. The impact generated by the transport infrastructure is important in this indicator due to the emissions of SO_2 and particles during the production of materials used in the transport infrastructure such as steel, gravel and concrete. Moreover, the production of electricity used by electric trains from fossil fuels such as coal and natural gas power plants is a main source of impact for freight trains. The production of diesel is a main source of impact in road transport for the indicator particulate matter. Particulate matter can be emitted directly from vehicles (primary particulate matter) or be formed in the atmosphere from precursor pollutants such as SO_X, NO_X, NH_3 or VOC.

The electricity generation is the main contributor for rail freight transport in the indicators at endpoint level damage to human health, ecosystems diversity and resource availability. This finding corroborates the recommendation of Banar and Özdemir (2015) to better improve the LCA results of rail freight transport by shifting the electricity mix to cleaner energy sources. For IWW transport, the main source of impact for the endpoint indicators is the infrastructure demand. In the case of road transport, the transport operation stage is the main source of impact in the indicators damage to human health and ecosystems diversity as a result of the exhaust emissions of lorries and the diesel production is the main source of impact for the endpoint indicator damage to resource availability.

6.4. Uncertainty analysis

An uncertainty analysis performed with the Monte Carlo method has been carried out to study the robustness of the LCIA results obtained using both LCIA methods: ILCD 2011 Midpoint+ (version V1.06 / EU27 2010) and ReCiPe 2008 (hierarchist, version V1.12 / Europe).

The Monte Carlo analysis is the most common uncertainty propagation method used to analyse uncertainties in LCA (Igos et al., 2018). The accuracy of Monte Carlo analysis increases as the number of iterations grows, but it is difficult to predict how many iterations are sufficient (Rosenbaum et al., 2018b). Therefore, it has been decided to set at 10 000 the number of iterations in all the analyses. This number of iterations is considered sufficient to achieve a representative analysis and is widely used in other LCA studies (Igos et al., 2018).

All calculations of this uncertainty analysis have been performed with the Monte Carlo implementation of SimaPro 8.0.5 software (Pré, 2013). For each transport process (i.e. rail freight transport considering the Belgian traction mix of 2012, diesel trains, electric trains, IWW transport in canal and road freight transport using the load factors of 50%, 60% and 85%), the uncertainty analysis includes a table showing the uncertainty distribution using the mean, median value, standard deviation (SD), coefficient of variability (CV) and standard error of mean (SEM) using a 95% confidence interval. Moreover, a bar chart with the uncertainty ranges per impact category considering a 95% confidence interval (i.e. 95% of the results obtained in the Monte Carlo simulation are within the range) is included as well.

6.4.1. Uncertainty analysis of the Life Cycle Impact Assessment using the method ILCD 2011 Midpoint+

Table 6.15 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in 2012 by rail freight transport considering the Belgian traction mix of 2012 (i.e. 86.3% of electric trains and 13.7% of diesel trains).

Table 6.15. Uncertainty analysis of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	kg CO_2 eq	6.42×10^{-2}	6.39×10^{-2}	5.08×10^{-3}	7.92	5.50×10^{-2}	7.53×10^{-2}	5.08×10^{-5}
Ozone depletion	kg CFC-11 eq	1.18×10^{-8}	1.15×10^{-8}	2.59×10^{-9}	21.88	7.97×10^{-9}	1.78×10^{-8}	2.59×10^{-11}
Particulate matter	kg $PM_{2.5}$ eq	3.55×10^{-5}	3.47×10^{-5}	5.80×10^{-6}	16.35	2.65×10^{-5}	4.88×10^{-5}	5.80×10^{-8}
Ionizing radiation HH	kBq U235 eq	5.89×10^{-2}	3.54×10^{-2}	8.65×10^{-2}	146.83	1.35×10^{-2}	2.50×10^{-1}	8.65×10^{-4}
Photochemical ozone formation	kg NMVOC eq	3.02×10^{-4}	2.99×10^{-4}	3.62×10^{-5}	11.96	2.40×10^{-4}	3.81×10^{-4}	3.62×10^{-7}
Acidification	molc H+ eq	3.63×10^{-4}	3.61×10^{-4}	3.62×10^{-5}	9.97	3.00×10^{-4}	4.42×10^{-4}	3.62×10^{-7}
Terrestrial eutrophication	molc N eq	1.04×10^{-3}	1.03×10^{-3}	1.31×10^{-4}	12.53	8.16×10^{-4}	1.33×10^{-3}	1.31×10^{-6}
Freshwater eutrophication	kg P eq	1.95×10^{-5}	1.76×10^{-5}	8.40×10^{-6}	43.12	1.00×10^{-5}	3.99×10^{-5}	8.40×10^{-8}
Resource depletion	kg Sb eq	2.34×10^{-6}	2.22×10^{-6}	6.38×10^{-7}	27.27	1.50×10^{-6}	3.90×10^{-6}	6.38×10^{-9}

Figure 6.9 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by rail using the Belgian traction mix of 2012 considering a 95% confidence interval. On the one hand, the indicator climate change shows the lowest uncertainty. On the other hand, the indicator ionizing radiation (damage to human health) presents the highest uncertainty. Moreover, the indicators freshwater eutrophication, resource depletion and ozone depletion show a high uncertainty.

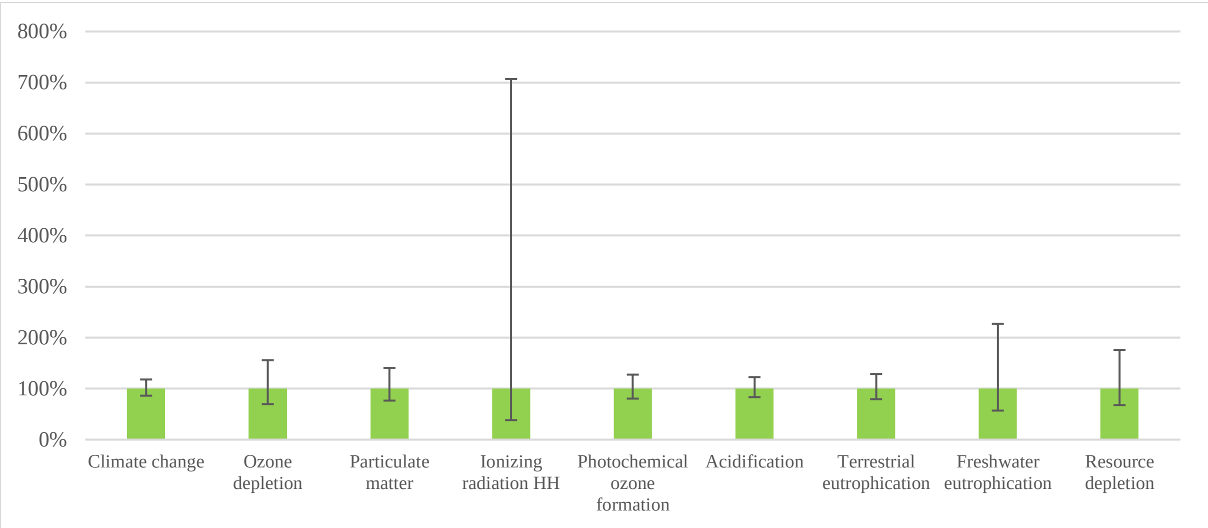


Figure 6.9. Uncertainty analysis of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.16 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by diesel train in Belgium in 2012.

Table 6.16. Uncertainty analysis of 1 tkm transported by diesel train in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	**kg CO_2 eq**	8.32×10^{-2}	8.29×10^{-2}	4.83×10^{-3}	5.81	7.45×10^{-2}	9.35×10^{-2}	4.83×10^{-5}
Ozone depletion	**kg CFC-11 eq**	1.38×10^{-8}	1.23×10^{-8}	6.29×10^{-9}	45.63	6.57×10^{-9}	2.93×10^{-8}	6.29×10^{-11}
Particulate matter	**kg $PM_{2.5}$ eq**	5.92×10^{-5}	5.67×10^{-5}	1.34×10^{-5}	22.57	4.07×10^{-5}	9.14×10^{-5}	1.34×10^{-7}
Ionizing radiation HH	**kBq U235 eq**	7.30×10^{-3}	6.18×10^{-3}	4.86×10^{-3}	66.51	2.66×10^{-3}	1.86×10^{-2}	4.86×10^{-5}
Photochemical ozone formation	**kg NMVOC eq**	1.09×10^{-3}	1.07×10^{-3}	1.77×10^{-4}	16.22	7.94×10^{-4}	1.48×10^{-3}	1.77×10^{-6}
Acidification	**molc H+ eq**	9.24×10^{-4}	9.10×10^{-4}	1.39×10^{-4}	15.02	6.89×10^{-4}	1.23×10^{-3}	1.39×10^{-6}
Terrestrial eutrophication	**molc N eq**	4.07×10^{-3}	4.00×10^{-3}	7.45×10^{-4}	18.30	2.82×10^{-3}	5.73×10^{-3}	7.45×10^{-6}
Freshwater eutrophication	**kg P eq**	1.69×10^{-5}	1.50×10^{-5}	8.41×10^{-6}	49.64	9.13×10^{-6}	3.64×10^{-5}	8.41×10^{-8}
Resource depletion	**kg Sb eq**	2.44×10^{-6}	2.31×10^{-6}	7.18×10^{-7}	29.37	1.55×10^{-6}	4.09×10^{-6}	7.18×10^{-9}

Figure 6.10 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by diesel train considering a 95% confidence interval. The indicator climate change shows the lowest uncertainty. The indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion present a high uncertainty.

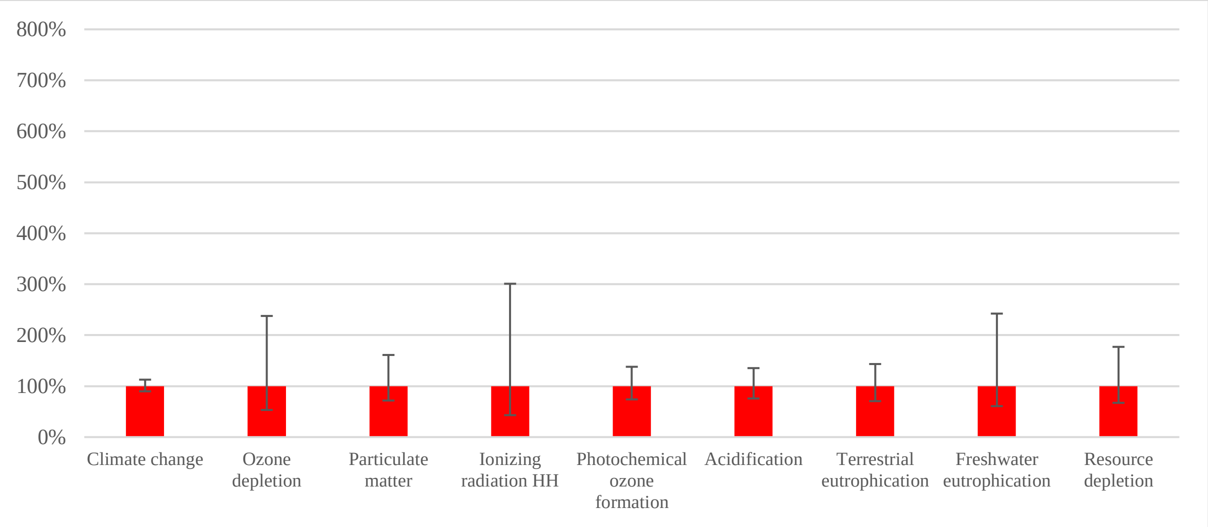


Figure 6.10. Uncertainty analysis of 1 tkm transported by diesel train in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.17 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by electric train in Belgium in 2012.

Table 6.17. Uncertainty analysis of 1 tkm transported by electric train in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	kg CO_2 eq	6.11×10^{-2}	6.08×10-^{2}	5.42×10^{-3}	8.86	5.14×10^{-2}	7.25×10^{-2}	5.42×10^{-5}
Ozone depletion	kg CFC-11 eq	1.16×10^{-8}	1.12×10^{-8}	2.49×10^{-9}	21.49	7.78×10^{-9}	1.75×10^{-8}	2.49×10^{-11}
Particulate matter	kg $PM_{2.5}$ eq	3.18×10^{-5}	3.09×10^{-5}	5.66×10^{-6}	17.83	2.35×10^{-5}	4.52×10^{-5}	5.66×10^{-8}
Ionizing radiation HH	kBq U235 eq	6.43×10^{-2}	3.99×10^{-2}	8.18×10^{-2}	127.24	1.49×10^{-2}	2.70×10^{-1}	8.18×10^{-4}
Photochemical ozone formation	kg NMVOC eq	1.78×10^{-4}	1.74×10^{-4}	2.77×10^{-5}	15.58	1.34×10^{-4}	2.42×10^{-4}	2.77×10^{-7}
Acidification	molc H+ eq	2.75×10^{-4}	2.72×10^{-4}	3.05×10^{-5}	11.12	2.24×10^{-4}	3.41×10^{-4}	3.05×10^{-7}
Terrestrial eutrophication	molc N eq	5.62×10^{-4}	5.52×10^{-4}	8.28×10^{-5}	14.73	4.29×10^{-4}	7.51×10^{-4}	8.28×10^{-7}
Freshwater eutrophication	kg P eq	2.01×10^{-5}	1.82×10^{-5}	9.84×10^{-6}	48.87	1.01×10^{-5}	4.17×10^{-5}	9.84×10^{-8}
Resource depletion	kg Sb eq	2.32×10^{-6}	2.20×10^{-6}	6.60×10^{-7}	28.39	1.48×10^{-6}	3.95×10^{-6}	6.60×10^{-9}

Figure 6.11 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by electric train considering a 95% confidence interval. On the one hand, the indicator climate change shows the lowest uncertainty. On the other hand, the indicator ionizing radiation (damage to human health) presents the highest uncertainty. Moreover, the indicators freshwater eutrophication, resource depletion and ozone depletion show a high uncertainty.

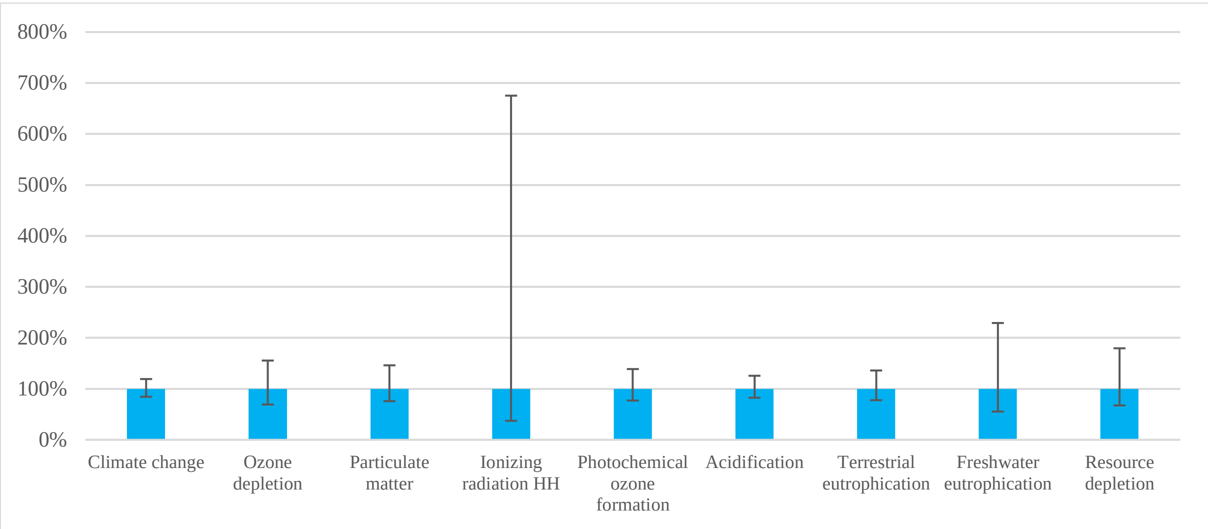


Figure 6.11. Uncertainty analysis of 1 tkm transported by electric train in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.18 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by IWW transport in canal in Belgium in 2012.

Table 6.18. Uncertainty analysis of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	kg CO_2 eq	7.48×10^{-2}	7.32×10^{-2}	1.36×10^{-2}	18.12	5.27×10^{-2}	1.05×10^{-1}	1.36×10^{-4}
Ozone depletion	kg CFC-11 eq	7.83×10^{-9}	7.07×10^{-9}	3.36×10^{-9}	42.91	3.79×10^{-9}	1.63×10^{-8}	3.36×10^{-11}
Particulate matter	kg $PM_{2.5}$ eq	4.77×10^{-5}	4.43×10^{-5}	1.62×10^{-5}	33.85	2.75×10^{-5}	8.84×10^{-5}	1.62×10^{-7}
Ionizing radiation HH	kBq U235 eq	1.28×10^{-2}	8.87×10^{-3}	1.71×10^{-2}	133.26	3.71×10^{-3}	4.62×10^{-2}	1.71×10^{-4}
Photochemical ozone formation	kg NMVOC eq	5.28×10^{-4}	5.16×10^{-4}	1.06×10^{-4}	20.12	3.57×10^{-4}	7.66×10^{-4}	1.06×10^{-6}
Acidification	molc H+ eq	6.23×10^{-4}	6.09×10^{-4}	1.23×10^{-4}	19.66	4.23×10^{-4}	9.00×10^{-4}	1.23×10^{-6}
Terrestrial eutrophication	molc N eq	1.98×10^{-3}	1.93×10^{-3}	4.40×10^{-4}	22.21	1.27×10^{-3}	2.98×10^{-3}	4.40×10^{-6}
Freshwater eutrophication	kg P eq	1.93×10^{-5}	1.66×10^{-5}	1.10×10^{-5}	57.11	6.59×10^{-6}	4.73×10^{-5}	1.10×10^{-7}
Resource depletion	kg Sb eq	6.58×10^{-7}	6.21×10^{-7}	2.08×10^{-7}	31.68	3.75×10^{-7}	1.16×10^{-6}	2.08×10^{-9}

Figure 6.12 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by IWW transport in canal considering a 95% confidence interval. The indicator ionizing radiation (damage to human health) presents the highest uncertainty. Moreover, the indicators freshwater eutrophication, resource depletion and ozone depletion show a high uncertainty.

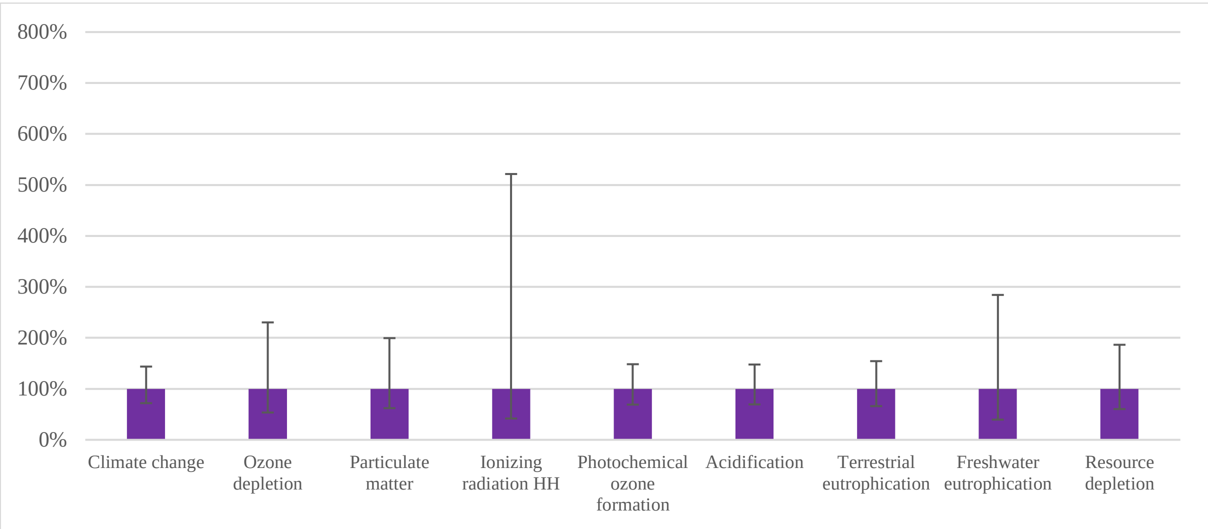


Figure 6.12. Uncertainty analysis of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.19 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 50% in Belgium in 2012.

Table 6.19. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	**kg CO_2 eq**	1.13×10^{-1}	1.11×10^{-1}	1.12×10^{-2}	9.89	9.61×10^{-2}	1.40×10^{-1}	1.12×10^{-4}
Ozone depletion	**kg CFC-11 eq**	2.07×10^{-8}	1.83×10^{-8}	1.06×10^{-8}	51.30	8.29×10^{-9}	4.71×10^{-8}	1.06×10^{-10}
Particulate matter	**kg $PM_{2.5}$ eq**	7.57×10^{-5}	7.35×10^{-5}	1.19×10^{-5}	15.69	5.94×10^{-5}	1.05×10^{-4}	1.19×10^{-7}
Ionizing radiation HH	**kBq U235 eq**	9.80×10^{-3}	8.50×10^{-3}	5.51×10^{-3}	56.23	3.48×10^{-3}	2.42×10^{-2}	5.51×10^{-5}
Photochemical ozone formation	**kg NMVOC eq**	8.61×10^{-4}	8.41×10^{-4}	1.07×10^{-4}	12.48	7.12×10^{-4}	1.12×10^{-3}	1.07×10^{-6}
Acidification	**molc H+ eq**	7.80×10^{-4}	7.63×10^{-4}	1.14×10^{-4}	14.67	6.18×10^{-4}	1.05×10^{-3}	1.14×10^{-6}
Terrestrial eutrophication	**molc N eq**	3.07×10^{-3}	3.04×10^{-3}	2.93×10^{-4}	9.53	2.63×10^{-3}	3.77×10^{-3}	2.93×10^{-6}
Freshwater eutrophication	**kg P eq**	9.48×10^{-6}	8.22×10^{-6}	5.40×10^{-6}	56.98	3.47×10^{-6}	2.26×10^{-5}	5.40×10^{-8}
Resource depletion	**kg Sb eq**	1.02×10^{-5}	8.70×10^{-6}	6.04×10^{-6}	59.29	3.44×10^{-6}	2.63×10^{-5}	6.04×10^{-8}

Figure 6.13 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 50% considering a 95% confidence interval. The indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion show a high uncertainty. It should be noted that the three road transport processes have similar uncertainty ranges per impact category.

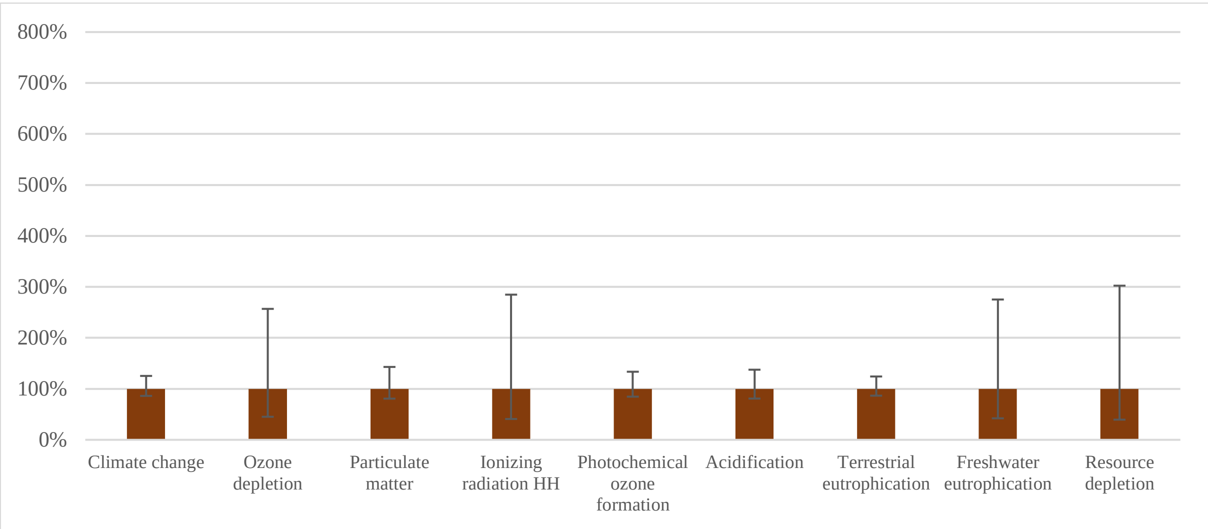


Figure 6.13. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.20 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 60% in Belgium in 2012.

Table 6.20. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 60% in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	**kg CO_2 eq**	9.77×10^{-2}	9.63×10^{-2}	9.71×10^{-3}	9.94	8.29×10^{-2}	1.20×10^{-1}	9.71×10^{-5}
Ozone depletion	**kg CFC-11 eq**	1.80×10^{-8}	1.59×10^{-8}	9.05×10^{-9}	50.33	7.41×10^{-9}	4.09×10^{-8}	9.05×10^{-11}
Particulate matter	**kg $PM_{2.5}$ eq**	6.56×10^{-5}	6.36×10^{-5}	1.04×10^{-5}	15.87	5.17×10^{-5}	9.13×10^{-5}	1.04×10^{-7}
Ionizing radiation HH	**kBq U235 eq**	8.56×10^{-3}	7.37×10^{-3}	4.96×10^{-3}	57.94	2.99×10^{-3}	2.10×10^{-2}	4.96×10^{-5}
Photochemical ozone formation	**kg NMVOC eq**	7.25×10^{-4}	7.08×10^{-4}	9.38×10^{-5}	12.95	5.96×10^{-4}	9.57×10^{-4}	9.38×10^{-7}
Acidification	**molc H+ eq**	6.60×10^{-4}	6.43×10^{-4}	1.01×10^{-4}	15.24	5.21×10^{-4}	9.00×10^{-4}	1.01×10^{-6}
Terrestrial eutrophication	**molc N eq**	2.58×10^{-3}	2.54×10^{-3}	2.56×10^{-4}	9.91	2.20×10^{-3}	3.19×10^{-3}	2.56×10^{-6}
Freshwater eutrophication	**kg P eq**	8.04×10^{-6}	6.95×10^{-6}	4.54×10^{-6}	56.51	2.98×10^{-6}	1.95×10^{-5}	4.54×10^{-8}
Resource depletion	**kg Sb eq**	8.42×10^{-6}	7.24×10^{-6}	4.84×10^{-6}	57.50	2.78×10^{-6}	2.11×10^{-5}	4.84×10^{-8}

Figure 6.14 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 60% considering a 95% confidence interval. The indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion show a high uncertainty. As mentioned above, the three road transport processes have similar uncertainty ranges per impact category.

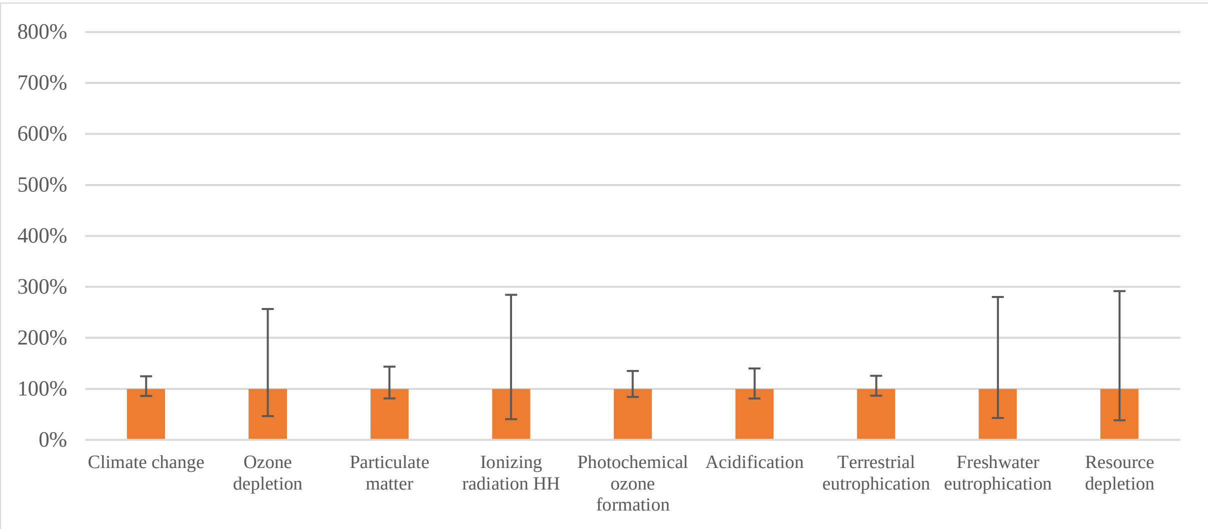


Figure 6.14. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 60% in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

Table 6.21 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 85% in Belgium in 2012.

Table 6.21. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 85% in Belgium in 2012 using the LCIA method ILCD 2011

Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
						2.5%	97.5%	
Climate change	kg CO_2 eq	7.50×10^{-2}	7.40×10^{-2}	7.14×10^{-3}	9.52	6.39×10^{-2}	9.20×10^{-2}	7.14×10^{-5}
Ozone depletion	kg CFC-11 eq	1.39×10^{-8}	1.22×10^{-8}	7.21×10^{-9}	51.78	5.60×10^{-9}	3.25×10^{-8}	7.21×10^{-11}
Particulate matter	kg $PM_{2.5}$ eq	5.06×10^{-5}	4.92×10^{-5}	7.64×10^{-6}	15.12	4.01×10^{-5}	6.92×10^{-5}	7.64×10^{-8}
Ionizing radiation HH	kBq U235 eq	6.49×10^{-3}	5.65×10^{-3}	3.78×10^{-3}	58.25	2.31×10^{-3}	1.57×10^{-2}	3.78×10^{-5}
Photochemical ozone formation	kg NMVOC eq	5.23×10^{-4}	5.10×10^{-4}	6.81×10^{-5}	13.02	4.29×10^{-4}	6.95×10^{-4}	6.81×10^{-7}
Acidification	molc H+ eq	4.82×10^{-4}	4.69×10^{-4}	7.80×10^{-5}	16.19	3.77×10^{-4}	6.61×10^{-4}	7.80×10^{-7}
Terrestrial eutrophication	molc N eq	1.85×10^{-3}	1.82×10^{-3}	1.86×10^{-4}	10.07	1.58×10^{-3}	2.30×10^{-3}	1.86×10^{-6}
Freshwater eutrophication	kg P eq	5.95×10^{-6}	5.15×10^{-6}	3.36×10^{-6}	56.40	2.22×10^{-6}	1.45×10^{-5}	3.36×10^{-8}
Resource depletion	kg Sb eq	6.04×10^{-6}	5.25×10^{-6}	3.42×10^{-6}	56.64	2.04×10^{-6}	1.45×10^{-5}	3.42×10^{-8}

Figure 6.15 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 85% considering a 95% confidence interval. The indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion show a high uncertainty. As mentioned above, the three road transport processes have similar uncertainty ranges per impact category.

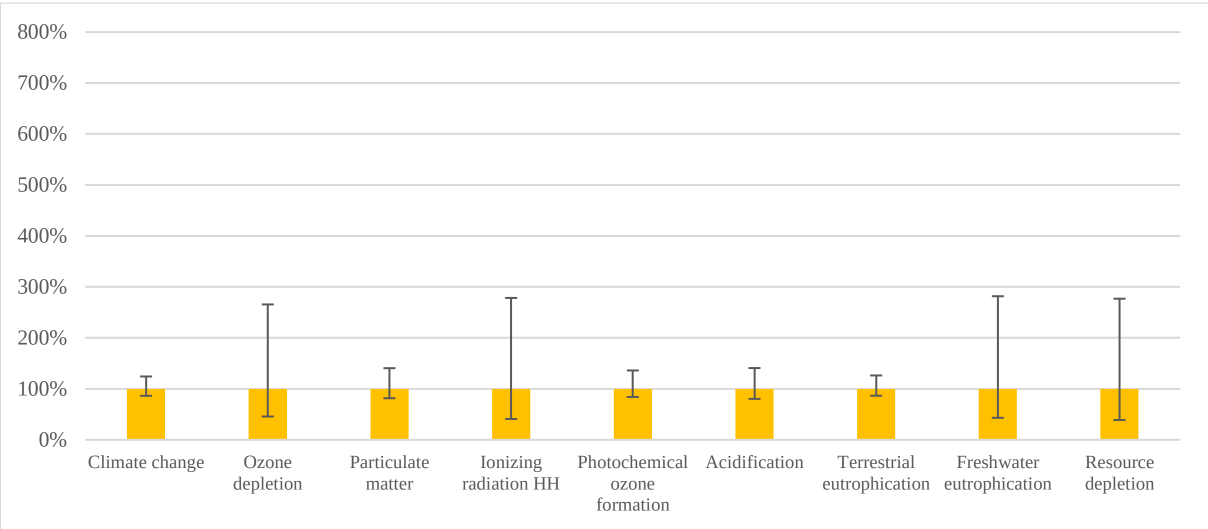


Figure 6.15. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 85% in Belgium in 2012 using the LCIA method ILCD 2011 and considering a 95% confidence interval

6.4.2. Uncertainty analysis of the Life Cycle Impact Assessment using the method ReCiPe 2008

Table 6.22 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in 2012 by rail freight transport considering the Belgian traction mix of 2012 (i.e. 86.3% of electric trains and 13.7% of diesel trains).

Table 6.22. Uncertainty analysis of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	6.41×10^{-2}	6.38×10^{-2}	5.05×10^{-3}	7.88	5.52×10^{-2}	7.49×10^{-2}	5.05×10^{-5}
	Photochemical oxidant formation	kg NMVOC eq	3.12×10^{-4}	3.09×10^{-4}	3.69×10^{-5}	11.83	2.50×10^{-4}	3.96×10^{-4}	3.69×10^{-7}
	Particulate matter formation	kg PM_{10} eq	1.33×10^{-4}	1.32×10^{-4}	1.43×10^{-5}	10.76	1.09×10^{-4}	1.65×10^{-4}	1.43×10^{-7}
Endpoint category	Damage to human health	DALY	1.45×10^{-7}	1.43×10^{-7}	1.58×10^{-08}	10.92	1.22×10^{-7}	1.77×10^{-7}	1.58×10^{-10}
	Damage to ecosystem diversity	species × year	6.64×10^{-10}	6.61×10^{-10}	6.79×10^{-11}	10.22	5.40×10^{-10}	8.07×10^{-10}	6.79×10^{-13}
	Damage to resource availability	$	4.04×10^{-3}	4.01×10^{-3}	4.30×10^{-4}	10.63	3.29×10^{-3}	4.97×10^{-3}	4.30×10^{-6}

Figure 6.16 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by rail using the Belgian traction mix of 2012 considering a 95% confidence interval. The midpoint indicator climate change shows the lowest uncertainty. The other indicators present similar uncertainty ranges.

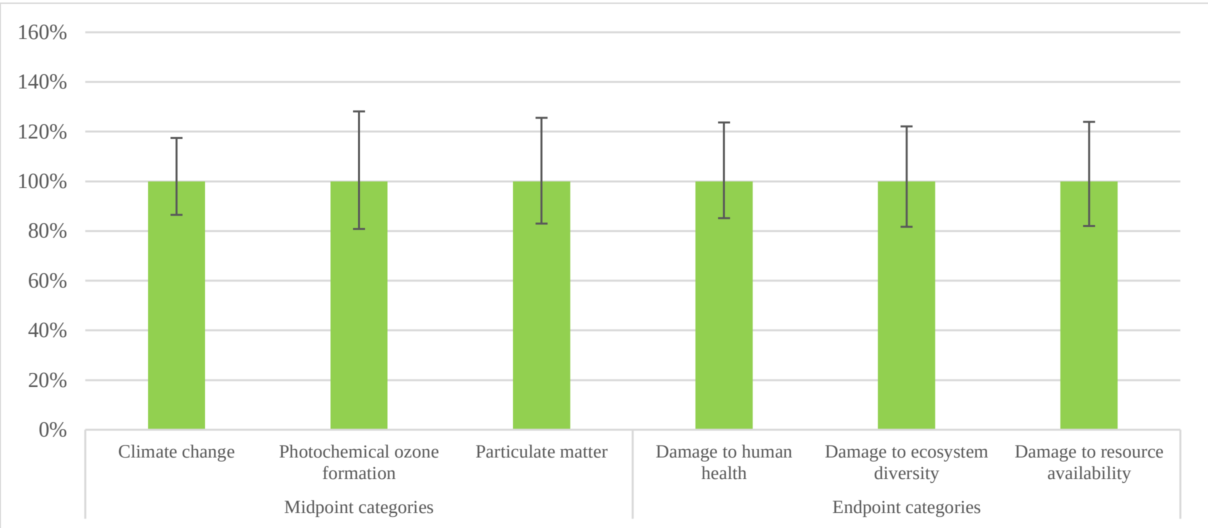


Figure 6.16. Uncertainty analysis of 1 tkm transported by rail freight transport (Belgian traction mix) in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.24 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by diesel train in Belgium in 2012.

Table 6.23. Uncertainty analysis of 1 tkm transported by diesel train in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	8.32×10^{-2}	8.30×10^{-2}	4.82×10^{-3}	5.80	7.45×10^{-2}	9.34×10^{-2}	4.82×10^{-5}
	Photochemical oxidant formation	kg NMVOC eq	1.11×10^{-3}	1.09×10^{-3}	1.80×10^{-4}	16.27	8.06×10^{-4}	1.51×10^{-3}	1.80×10^{-6}
	Particulate matter formation	kg PM_{10} eq	3.10×10^{-4}	3.07×10^{-4}	4.35×10^{-5}	14.01	2.35×10^{-4}	4.07×10^{-4}	4.35×10^{-7}
Endpoint category	Damage to human health	DALY	2.16×10^{-7}	2.14×10^{-7}	1.84×10^{-08}	8.53	1.86×10^{-7}	2.54×10^{-7}	1.84×10^{-10}
	Damage to ecosystem diversity	species × year	8.03×10^{-10}	7.99×10^{-10}	6.04×10^{-11}	7.51	6.98×10^{-10}	9.34×10^{-10}	6.04×10^{-13}
	Damage to resource availability	$	5.39×10^{-3}	5.32×10^{-3}	7.94×10^{-4}	14.75	4.04×10^{-3}	7.14×10^{-3}	7.94×10^{-6}

Figure 6.17 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by diesel train considering a 95% confidence interval. The midpoint indicators photochemical oxidant formation and particulate matter formation and the endpoint indicator damage to resource availability present the higher uncertainty.

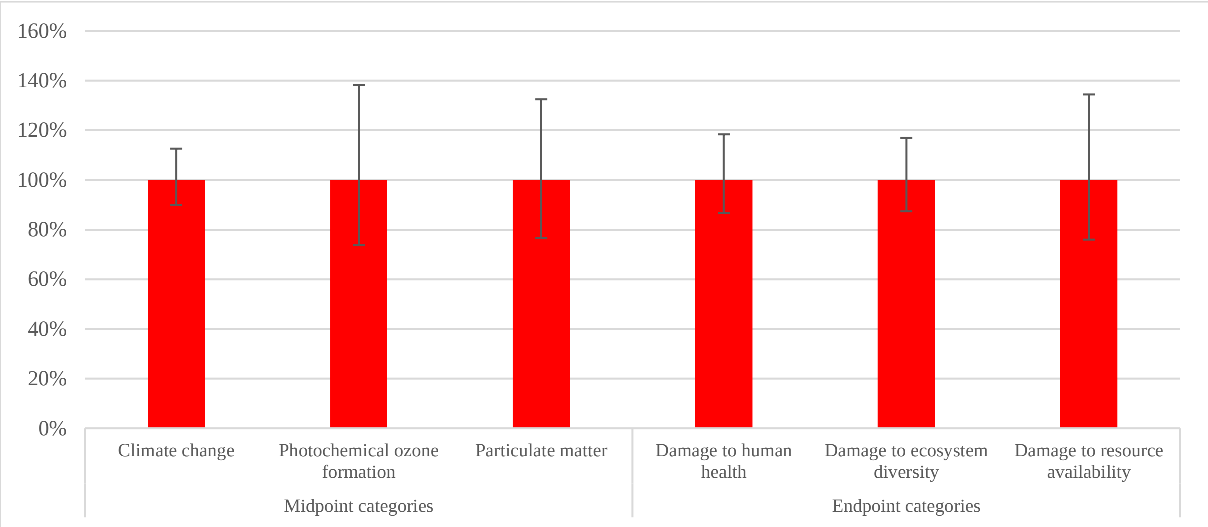


Figure 6.17. Uncertainty analysis of 1 tkm transported by diesel train in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.24 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by electric train in Belgium in 2012.

Table 6.24. Uncertainty analysis of 1 tkm transported by electric train in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	6.11×10^{-2}	6.07×10^{-2}	5.40×10^{-3}	8.84	5.13×10^{-2}	7.25×10^{-2}	5.40×10^{-5}
	Photochemical oxidant formation	kg NMVOC eq	1.86×10^{-4}	1.83×10^{-4}	2.88×10^{-5}	15.50	1.41×10^{-4}	2.52×10^{-4}	2.88×10^{-7}
	Particulate matter formation	kg PM_{10} eq	1.05×10^{-4}	1.04×10^{-4}	1.33×10^{-5}	12.65	8.33×10^{-5}	1.34×10^{-4}	1.33×10^{-7}
Endpoint category	Damage to human health	DALY	1.33×10^{-7}	1.32×10^{-7}	1.45×10^{-8}	10.86	1.10×10^{-7}	1.65×10^{-7}	1.45×10^{-10}
	Damage to ecosystem diversity	species × year	6.43×10^{-10}	6.40×10^{-10}	7.33×10^{-11}	11.41	5.06×10^{-10}	7.97×10^{-10}	7.33×10^{-13}
	Damage to resource availability	$	3.82×10^{-3}	3.80×10^{-3}	4.45×10^{-4}	11.64	3.06×10^{-3}	4.80×10^{-3}	4.45×10^{-6}

Figure 6.18 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by electric train considering a 95% confidence interval. The midpoint indicator climate change shows the lowest uncertainty and the indicator photochemical oxidant formation presents the highest uncertainty. The three endpoints categories have similar uncertainty ranges.

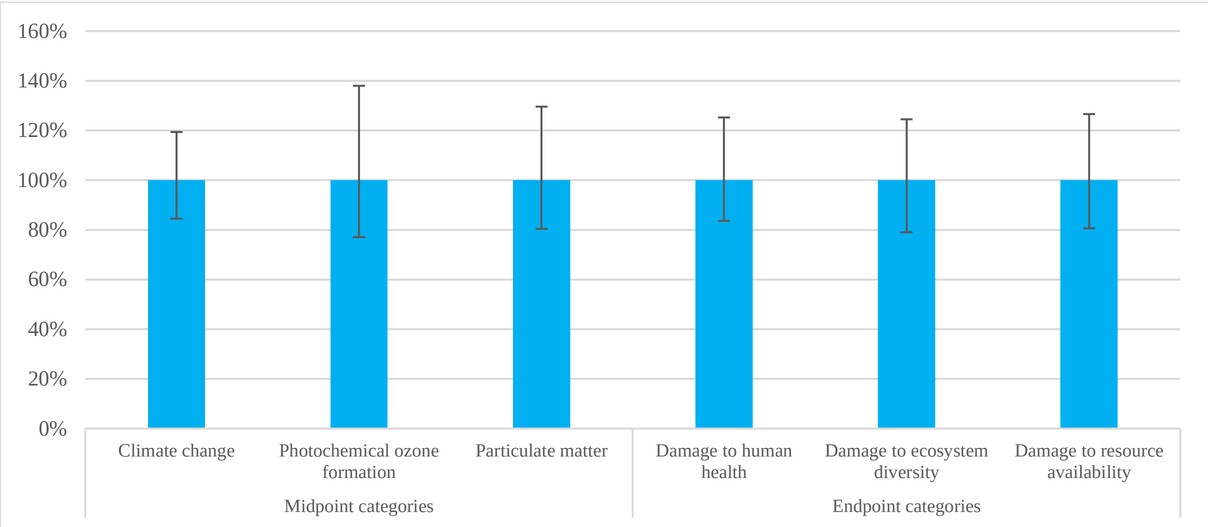


Figure 6.18. Uncertainty analysis of 1 tkm transported by electric train in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.25 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by IWW transport in canal in Belgium in 2012.

Table 6.25. Uncertainty analysis of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	7.48×10^{-2}	7.32×10^{-2}	1.35×10^{-2}	18.00	5.27×10^{-2}	1.06×10^{-1}	1.35×10^{-4}
	Photochemical oxidant formation	kg NMVOC eq	5.33×10^{-4}	5.20×10^{-4}	1.06×10^{-4}	19.84	3.62×10^{-4}	7.70×10^{-4}	1.06×10^{-6}
	Particulate matter formation	kg PM_{10} eq	1.92×10^{-4}	1.89×10^{-4}	3.51×10^{-5}	18.30	1.33×10^{-4}	2.72×10^{-4}	3.51×10^{-7}
Endpoint category	Damage to human health	DALY	1.66×10^{-7}	1.62×10^{-7}	3.00×10^{-8}	18.05	1.19×10^{-7}	2.35×10^{-7}	3.00×10^{-10}
	Damage to ecosystem diversity	species × year	7.88×10^{-10}	7.71×10^{-10}	1.48×10^{-10}	18.82	5.49×10^{-10}	1.12×10^{-9}	1.48×10^{-12}
	Damage to resource availability	$	3.64×10^{-3}	3.57×10^{-3}	7.35×10^{-4}	20.21	2.42×10^{-3}	5.26×10^{-3}	7.35×10^{-6}

Figure 6.19 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by IWW transport in canal considering a 95% confidence interval. All the indicators present similar uncertainty ranges. The midpoint indicators have higher uncertainty ranges compared to the rest of the transport processes.

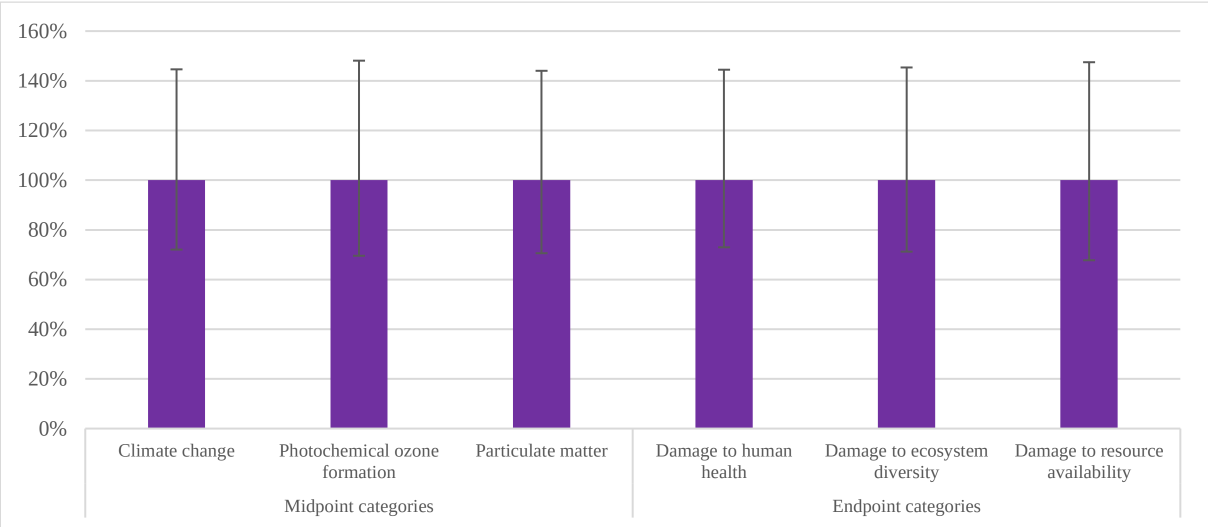


Figure 6.19. Uncertainty analysis of 1 tkm transported by IWW transport in canal in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.26 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 50% in Belgium in 2012.

Table 6.26. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	1.13×10^{-1}	1.11×10^{-1}	1.11×10^{-2}	9.80	9.61×10^{-2}	1.39×10^{-1}	1.11×10^{-4}
	Photochemical oxidant formation	kg NMVOC eq	8.71×10^{-4}	8.51×10^{-4}	1.06×10^{-4}	12.23	7.21×10^{-4}	1.14×10^{-3}	1.06×10^{-6}
	Particulate matter formation	kg PM_{10} eq	3.09×10^{-4}	2.99×10^{-4}	4.70×10^{-5}	15.23	2.45×10^{-4}	4.30×10^{-4}	4.70×10^{-7}
Endpoint category	Damage to human health	DALY	2.65×10^{-7}	2.60×10^{-7}	3.04×10^{-8}	11.49	2.23×10^{-7}	3.38×10^{-7}	3.04×10^{-10}
	Damage to ecosystem diversity	species × year	1.20×10^{-9}	1.15×10^{-9}	2.30×10^{-10}	19.13	9.07×10^{-10}	1.79×10^{-9}	2.30×10^{-12}
	Damage to resource availability	$	7.27×10^{-3}	7.09×10^{-3}	1.52×10^{-3}	20.86	4.89×10^{-3}	1.07×10^{-2}	1.52×10^{-5}

Figure 6.20 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 50% considering a 95% confidence interval. The midpoint indicator climate change shows the lowest uncertainty. The endpoint indicators damage to ecosystem diversity and damage to resource availability present the higher uncertainty. As in the case of the LCIA method ILCD 2011 Midpoint+, the three road transport processes have similar uncertainty ranges per impact category.

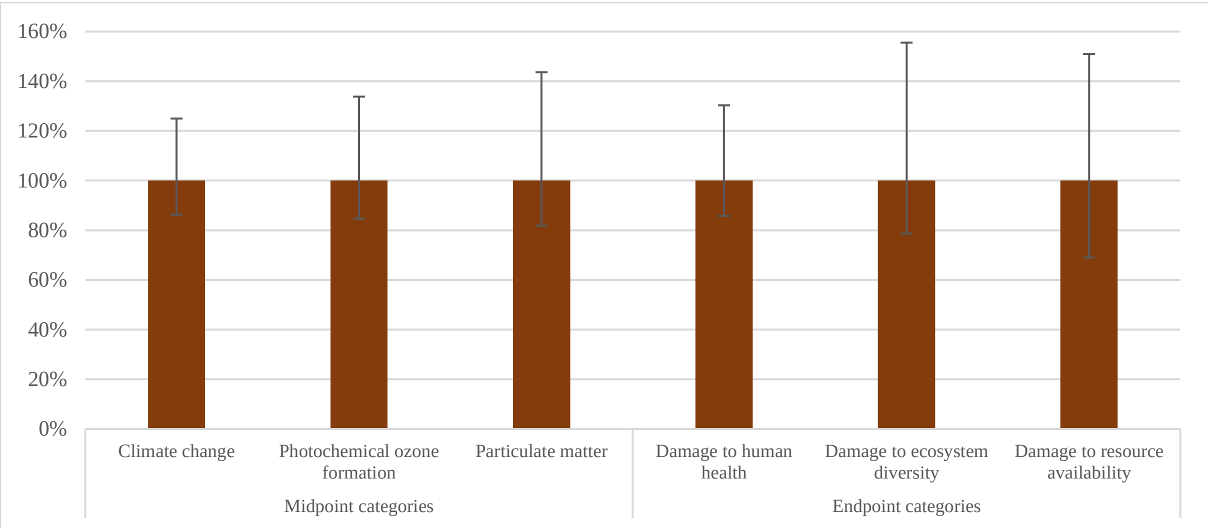


Figure 6.20. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 50% in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.27 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 60% in Belgium in 2012.

Table 6.27. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 60% in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	9.78×10^{-2}	9.65×10^{-2}	9.49×10^{-3}	9.71	8.32×10^{-2}	1.20×10^{-1}	9.49×10^{-5}
	Photochemical oxidant formation	kg NMVOC eq	7.33×10^{-4}	7.18×10^{-4}	9.16×10^{-5}	12.50	6.05×10^{-4}	9.59×10^{-4}	9.16×10^{-7}
	Particulate matter formation	kg PM_{10} eq	2.63×10^{-4}	2.55×10^{-4}	4.10×10^{-5}	15.56	2.10×10^{-4}	3.65×10^{-4}	4.10×10^{-7}
Endpoint category	Damage to human health	DALY	2.28×10^{-7}	2.24×10^{-7}	2.61×10^{-8}	11.42	1.93×10^{-7}	2.92×10^{-7}	2.61×10^{-10}
	Damage to ecosystem diversity	species × year	1.04×10^{-9}	9.94×10^{-10}	1.97×10^{-10}	19.04	7.88×10^{-10}	1.54×10^{-9}	1.97×10^{-12}
	Damage to resource availability	$	6.29×10^{-3}	6.14×10^{-3}	1.30×10^{-3}	20.73	4.21×10^{-3}	9.19×10^{-3}	1.30×10^{-5}

Figure 6.21 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 60% considering a 95% confidence interval. The midpoint indicator climate change shows the lowest uncertainty. The endpoint indicators damage to ecosystem diversity and damage to resource availability present the higher uncertainty. As mentioned above, the three road transport processes have similar uncertainty ranges per impact category.

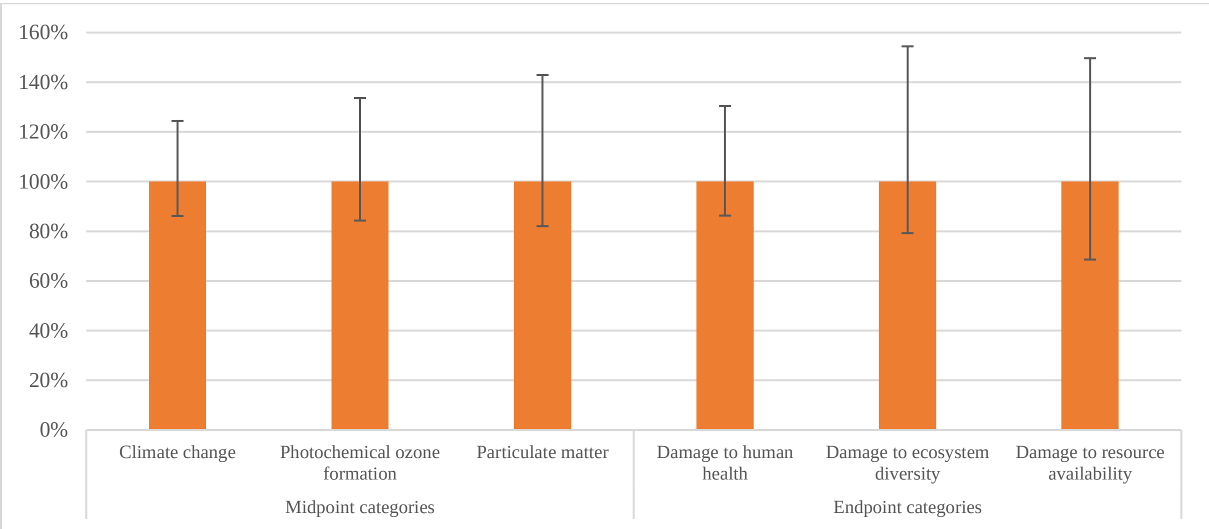


Figure 6.21. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 60% in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Table 6.28 presents the uncertainty analysis results obtained in the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 85% in Belgium in 2012.

Table 6.28. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 85% in Belgium in 2012 using the LCIA method ReCiPe 2008

	Impact category	Unit	Mean	Median	SD	CV (%)	Confidence interval 95%		SEM
							2.5%	97.5%	
Midpoint category	Climate change	kg CO_2 eq	7.51×10^{-2}	7.40×10^{-2}	7.11×10^{-3}	9.47	6.41×10^{-2}	9.19×10^{-2}	7.11×10^{-5}
	Photochemical oxidant formation	kg NMVOC eq	5.30×10^{-4}	5.17×10^{-4}	6.93×10^{-5}	13.09	4.34×10^{-4}	7.02×10^{-4}	6.93×10^{-7}
	Particulate matter formation	kg PM_{10} eq	1.96×10^{-4}	1.90×10^{-4}	3.01×10^{-5}	15.34	1.56×10^{-4}	2.72×10^{-4}	3.01×10^{-7}
Endpoint category	Damage to human health	DALY	1.75×10^{-7}	1.71×10^{-7}	1.93×10^{-8}	11.03	1.48×10^{-7}	2.22×10^{-7}	1.93×10^{-10}
	Damage to ecosystem diversity	species × year	7.95×10^{-10}	7.62×10^{-10}	1.50×10^{-10}	18.84	6.07×10^{-10}	1.17×10^{-9}	1.50×10^{-12}
	Damage to resource availability	$	4.80×10^{-3}	4.67×10^{-3}	9.96×10^{-4}	20.75	3.21×10^{-3}	7.07×10^{-3}	9.96×10^{-6}

Figure 6.22 shows the uncertainty analysis for the LCIA of one tonne-kilometre of freight transported by lorry with a load factor of 85% considering a 95% confidence interval. The midpoint indicator climate change shows the lowest uncertainty. The endpoint indicators damage to ecosystem diversity and damage to resource availability present the higher uncertainty. As mentioned above, the three road transport processes have similar uncertainty ranges per impact category.

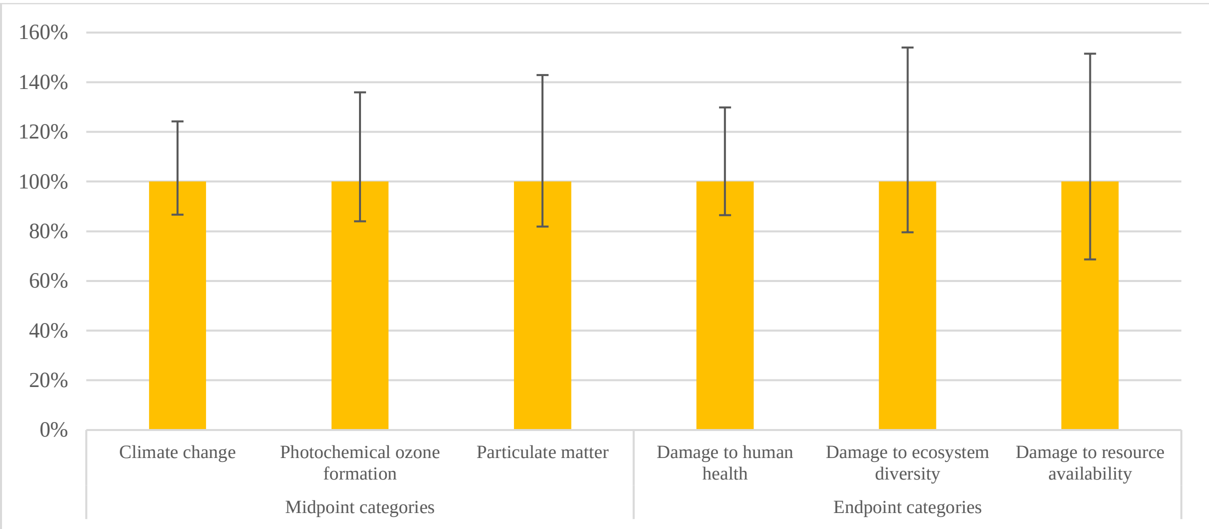
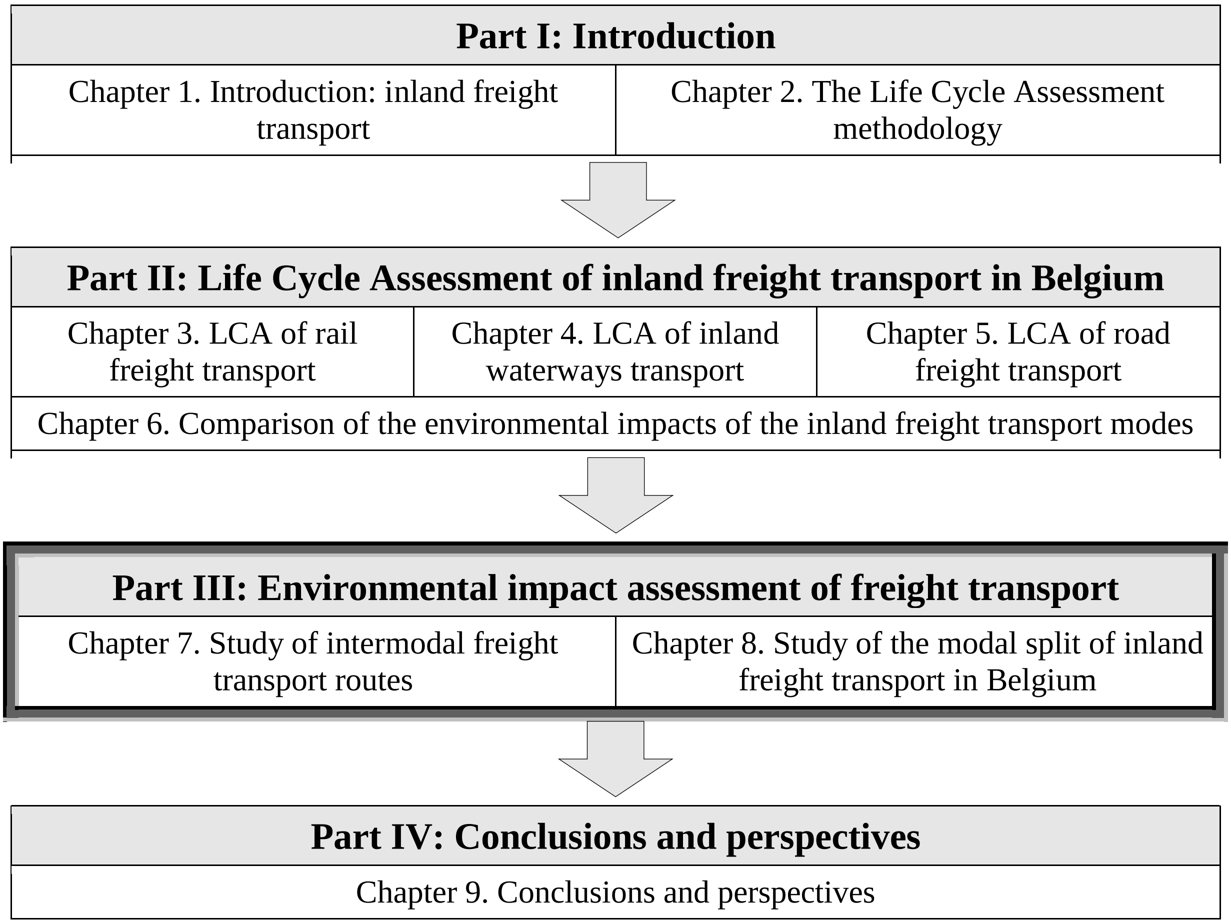


Figure 6.22. Uncertainty analysis of 1 tkm transported by road freight transport with a load factor of 85% in Belgium in 2012 using the LCIA method ReCiPe 2008 and considering a 95% confidence interval

Part III: Environmental impact assessment of freight transport



Chapter 7. Study of intermodal freight transport routes

7.1. Introduction

After conducting the LCA of the three modes of inland freight transport (rail freight transport in Chapter 3, IWW transport in Chapter 4 and road freight transport in Chapter 5), the study of intermodal freight transport has been carried out.

As mentioned in Chapter 1, the intermodal freight transport is the transport of goods by at least two different modes of transport and using the same Intermodal Transport Unit (ITU) without handling the goods themselves when changing modes (ITF, Eurostat, UNECE, 2009). During the major part of the journey or main haulage, the ITU (e.g. container, swap body or road vehicle) is transported by rail, IWW or sea. Road transport is used for the shortest possible initial (pre-haulage) and final (post-haulage) parts of the transport chain (Tawfik and Limbourg, 2018). At the intermodal terminal, the ITUs are transferred between modes of transport. Therefore, the intermodal terminal acts as a point of collection, sorting, transhipment and distribution of goods. A twenty-foot equivalent unit (TEU) is the most common unit used in intermodal transport to describe the capacity of container ships or terminals. This unit is based on an intermodal container of twenty foot length (i.e. 6.1 m). Therefore, a standard forty-foot container is two TEU (ITF, Eurostat, UNECE, 2009).

In order to analyse the environmental impacts related to intermodal freight transport, two consolidated intermodal rail-road routes in Belgium from the Port of Antwerp have been studied. Since the Port of Antwerp is the largest port in Belgium and the second in Europe in both total maritime freight volume and total tonnage and TEU of containers, this case is considered as representative for Belgium. Moreover, a study of the international intermodal route from the Port of Antwerp to Ludwigshafen (Germany), which is an important international route of B-Logistics (LINEAS) has been carried out. Finally, the environmental impact of international intermodal transport routes within the three Trans-European Transport Network (TEN-T) core network corridors crossing Belgium has been analysed: Rhine-Alpine, North Sea-Mediterranean and North Sea-Baltic.

The purpose of this chapter is to analyse the results obtained from the study of the Belgian and European intermodal routes using a LCA approach. Thereby, the environmental impacts of these intermodal routes depending on the freight transport mode chosen for the major part of the intermodal route can be compared: rail freight transport, IWW transport or road transport.

7.2. Methodology used to analyse the intermodal freight transport routes

The aim is to compare the environmental impacts of the three inland freight transport modes for these intermodal routes carrying the same number of containers with the same load. Thereby, it has been considered the transport of 78 TEU, which is the maximum payload of an average conventional intermodal freight train consisting of 26 wagons and a capacity of 3 TEU per wagon (Janic, 2008). An average gross weight of 14.3 t/TEU has been taken into account, which includes 2.3 t of the container weight and a load per container of 12 t (Janic, 2008), resulting in 1 115.4 t for the 78 TEU transported.

For the intermodal freight trains, a train load factor of 75% has been considered (Janic, 2008) and this, together with 78 TEU per train of maximum payload, results in an actual payload of 58.5 TEU per train. Therefore, 1.3 trains are needed to transport the 78 TEU studied.

For the main haulage by IWW, a container vessel with a capacity of 200 TEU has been considered (EcoTransIT, 2016). A load factor of the containers transported by vessel of 60% has been used (EcoTransIT, 2016), resulting in an actual payload of 120 TEU per vessel. Thus, 0.65 vessels are required to transport the 78 TEU considered.

For road transport, it has been used an articulated lorry 34-40 t, which represents approximately 75% of the road freight transport performance (i.e. tonne-kilometres) every year in Belgium. A capacity of 2 TEU per lorry has been considered but three scenarios with different load factors of 50%, 60% and 85% have been studied. The choice of these load factors is because the load factor of an average cargo in road transport including empty trips is 50% (EcoTransIT, 2008). Moreover, the load factors of intermodal road transport are 85% for the main haulage and 60% for the post-haulage (Janic, 2008). Therefore, the vehicle demands for the load factors of 50%, 60% and 85% are 78 lorries, 65 lorries and 45.9 lorries, respectively.

In order to transfer the TEU between modes of transport, cargo handling equipment such as gantry cranes or reach stackers are used in intermodal terminals. For the transhipment in the Port of Antwerp and the final destination intermodal terminal (except for the Terminal Container Athus), it has been considered an energy consumption in the transhipment processes of 16 560 kJ per TEU (Messagie et al., 2014a). EcoTransIT (2008) estimates an energy consumption in the transhipment processes of 15 840 kJ per TEU, but it has been decided to use the most conservative value. Therefore, an energy consumption of 1 291 680 kJ has been estimated for the transhipment of 78 TEU either in the Port of Antwerp or the final destination intermodal terminal.

7.3. Environmental impact assessment of Belgian intermodal routes

Two consolidated intermodal rail-road routes in Belgium from the Port of Antwerp have been analysed. The first is the intermodal connection between seaports from the Port of Antwerp to the Port of Zeebrugge. A second intermodal route from the Port of Antwerp to the Terminal Container Athus has been analysed. In collaboration with Terminal Container Athus, detailed information has been collected on energy consumption for the handling of containers in the intermodal terminal of Terminal Container Athus.

Table 7.1 presents the results obtained in the LCIA of one tonne-kilometre of freight transported in Belgium in the year 2012 by diesel trains (including shunting activity), electric trains, an average articulated lorry of 34-40 t with the load factors of 50%, 60% and 85% and an articulated lorry of 34-40 t Euro V with the same load factors. These transport modes have been chosen for the main haulage in the study of the Belgian intermodal routes.

Table 7.1. LCIA of 1 tkm transported by inland freight transport in Belgium in 2012

Impact category	Unit	Rail transport		Articulated lorry of 34-40 t					
		Diesel trains	Electric trains	LF 50% Euro V	LF 50% Average	LF 60% Euro V	LF 60% Average	LF 85% Euro V	LF 85% Average
Climate change	**kg CO_2 eq**	8.32×10^{-2}	6.12×10^{-2}	9.42×10^{-2}	9.35×10^{-2}	8.19×10^{-2}	8.13×10^{-2}	6.37×10^{-2}	6.33×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.38×10^{-8}	1.16×10^{-8}	1.77×10^{-8}	1.77×10^{-8}	1.54×10^{-8}	1.54×10^{-8}	1.20×10^{-8}	1.20×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	5.89×10^{-5}	3.17×10^{-5}	5.34×10^{-5}	6.51×10^{-5}	4.69×10^{-5}	5.61×10^{-5}	3.74×10^{-5}	4.39×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	7.27×10^{-3}	6.67×10^{-2}	8.13×10^{-3}	8.13×10^{-3}	7.05×10^{-3}	7.05×10^{-3}	5.47×10^{-3}	5.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	1.09×10^{-3}	1.78×10^{-4}	4.44×10^{-4}	7.50×10^{-4}	3.77×10^{-4}	6.32×10^{-4}	2.78×10^{-4}	4.58×10^{-4}
Acidification	**molc H+ eq**	9.25×10^{-4}	2.74×10^{-4}	4.44×10^{-4}	6.58×10^{-4}	3.79×10^{-4}	5.57×10^{-4}	2.83×10^{-4}	4.09×10^{-4}
Terrestrial eutrophication	**molc N eq**	4.07×10^{-3}	5.62×10^{-4}	1.46×10^{-3}	2.69×10^{-3}	1.23×10^{-3}	2.26×10^{-3}	8.95×10^{-4}	1.62×10^{-3}
Freshwater eutrophication	**kg P eq**	1.69×10^{-5}	2.00×10^{-5}	6.15×10^{-6}	6.15×10^{-6}	5.26×10^{-6}	5.26×10^{-6}	3.95×10^{-6}	3.95×10^{-6}
Resource depletion	**kg Sb eq**	2.45×10^{-6}	2.32×10^{-6}	4.32×10^{-6}	4.32×10^{-6}	3.63×10^{-6}	3.63×10^{-6}	2.60×10^{-6}	2.60×10^{-6}

Figure 7.1 shows a comparison of the results (from Table 7.1) obtained in the LCIA of the different modes of inland freight transport in Belgium in 2012 used for the analysis of the Belgian intermodal routes. Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the transport mode with less impact and the highest value represents the maximum impact.

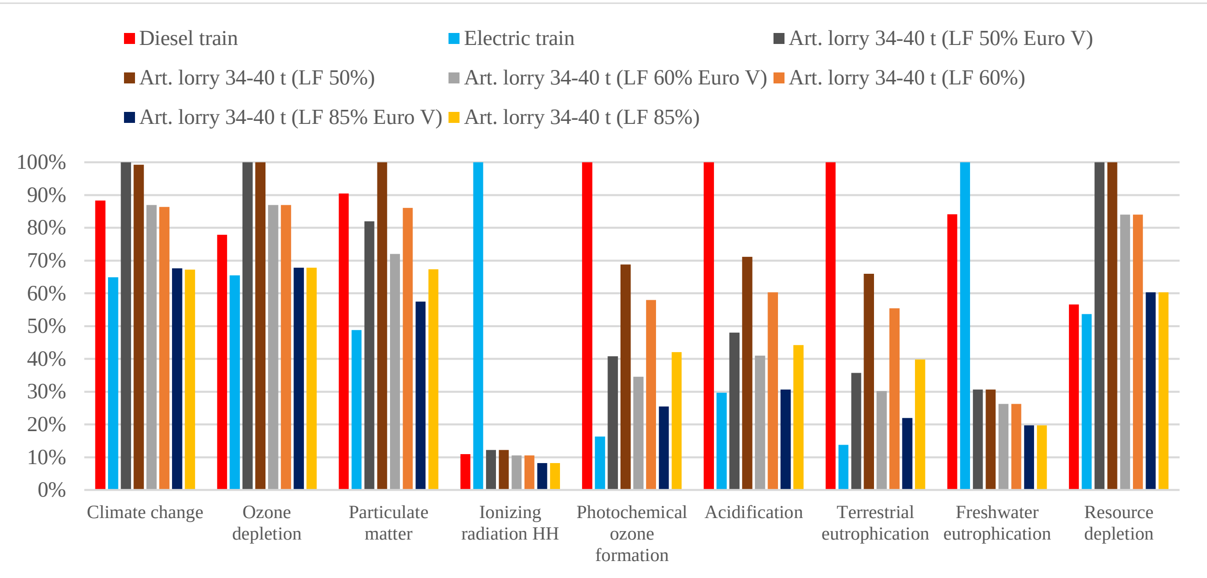


Figure 7.1. LCIA of 1 tkm transported by inland freight transport in Belgium in 2012

The articulated lorry of 34-40 t with a load factor of 50% presents the maximum impact in the indicators climate change, ozone depletion, particulate matter and resource depletion. The transport process with an average emission standard shows the maximum impact in the indicator particulate matter. For climate change, there are no significant differences between the process with an average emission standard and the process with an emission standard Euro V. Moreover, the emission standards do not affect the indicators ozone depletion or resource depletion.

For road transport, the exhaust emissions during the road transport activity of GHG for climate change and $PM_{2.5}$, NO_X and SO_2 (including particle emissions from tyre, break and road wear) for particulate matter are the main sources of impact to these indicators. Moreover, road transport with a load factor of 50% and 60% (regardless of the emission standard) shows the maximum impact in the indicator ozone depletion due to the higher diesel consumption. For this indicator, the main contributor of the impact is the emissions of bromotrifluoromethane ($CBrF_3$ or halon 1 301) to air during the petroleum refinery operation. Furthermore, the lead used in the lorry batteries is the main contributor in the indicator resource depletion.

Diesel trains present the maximum impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions during the transport operation. Thereby, the NO_X and NMVOC exhaust emissions are the main contributor for the indicator photochemical ozone formation, NO_X and SO_2 for acidification and NO_X for terrestrial eutrophication.

Electric trains present the highest impact in the indicator ionizing radiation (damage to human health) due to the use of a 41.88% of nuclear power in the electricity supply mix in Belgium in the year 2012. Moreover, freight trains show a higher impact than road transport in the indicator freshwater eutrophication due to the railway infrastructure, but electric trains presents the maximum impact as a result of the hard coal and lignite mining in the electricity generation.

As mentioned above, the purpose of the study is to compare the environmental impacts of the intermodal routes using different transport modes but carrying the same number of containers with the same load. Therefore, as cargo is equal, the main factor that determines the final impact of the intermodal route for each transport mode is the distance travelled. Since the road network is greater than the railway network, road transport is usually the shortest possible route.

Considering all the above, one question arises: what is the minimum distance difference needed between road and rail transport to achieve an equal impact on the different environmental impact categories? And for example, more specifically, what is the minimum distance difference needed between an articulated lorry of 34-40 t with a load factor of 50% and a diesel or electric train to achieve an equal impact on climate change? Considering the environmental impacts of the transport modes showed in Figure 7.1, an articulated lorry of 34-40 t with a load factor of 50% needs at least 11% or more difference in distance to match or improve the environmental performance of diesel trains in the indicator climate change. In order to improve the environmental performance on climate change compared to an electric train (using the Belgian electricity supply mix), an articulated lorry of 34-40 t with a 50% of load factor needs at least 34% or more difference in distance.

Focusing on the indicator particulate matter, a diesel train needs at least 18% or more difference in distance to match or improve the environmental performance of a lorry of 34-40 t with a load factor of 60% Euro V. However, this lorry needs at least 23% or more difference in distance to match or improve the environmental performance of electric trains (using the Belgian electricity supply mix) in this indicator. Similarly for the indictor photochemical ozone formation, a diesel train needs at least 74% or more difference in distance to match or improve the environmental performance of a lorry of 34-40 t with a load factor of 85% Euro V. However, this lorry needs at least 9% or more difference in distance to match or improve the environmental performance of electric trains (using the Belgian electricity supply mix) in this indicator.

7.3.1. Intermodal route from the Port of Antwerp to the Port of Zeebrugge

As shown in Figure 7.2, the intermodal connection between seaports from Port of Antwerp to Port of Zeebrugge includes the processes of transhipment in the Port of Antwerp, the main haulage by rail or road and the transhipment in the Port of Zeebrugge.

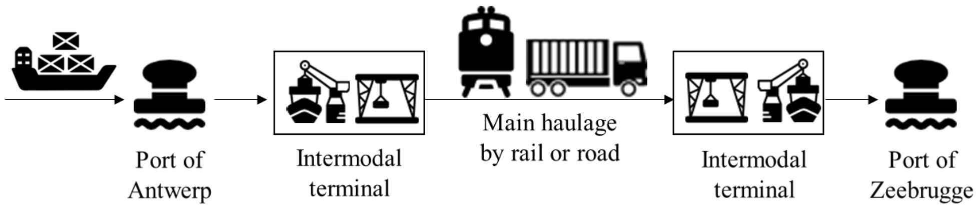


Figure 7.2. Intermodal route from the Port of Antwerp to the Port of Zeebrugge

The distances between the ports of Antwerp and Zeebrugge have been calculated using EcoTransIT World (2017), resulting in 139.5 km by rail and 96.44 km by road (see Figure 7.3).

Figure 7.3. Intermodal route from the Port of Antwerp to the Port of Zeebrugge by train (left) and by road (right). Source: EcoTransIT World, 2017

Table 7.2 shows the main characteristics of the intermodal route from the Port of Antwerp to the Port of Zeebrugge using as mode of transport for the main haulage rail and road transport. Considering a handle volume of 1 115.4 t for the 78 TEU transported, the transport performance calculated is 155 598 tkm for rail transport and 107 569 tkm for road transport.

Table 7.2. Main characteristics of the intermodal route from the Port of Antwerp to the Port of Zeebrugge

		Main haulage by	
		Train	**Lorry**
Average gross weight TEU		14.3 t/TEU	
1. Transhipment in the Port of Antwerp		16 560 kJ/TEU	
2. Main haulage	**Maximum payload (TEU/vehicle)**	78	2
	Load factor	75%	50% - 60% 85%
	Actual payload (TEU/vehicle)	58.5	1 – 1.2 – 1.7
	Vehicle demand	1.3	78 – 65 – 45.9
	Handled volume	1 115.4 t	
	Distance (km)	139.5	96.44
	Transport performance (tkm)	155 598	107 569
3. Transhipment in the Port of Zeebrugge		16 560 kJ/TEU	

Figure 7.4 shows a comparison of the results obtained from the LCIA of the intermodal route from the Port of Antwerp to the Port of Zeebrugge using the main characteristics shown in Table 7.2. Thereby, seven types of transport modes in Belgium for the year 2012 have been chosen for the main haulage: diesel train, electric train, an average articulated lorry of 34-40 t with the load factors of 50%, 60% and 85% and an articulated lorry of 34-40 t Euro V with the same load factors. For the transhipment processes, it has been used the electricity supply mix of Belgium for the year 2012.

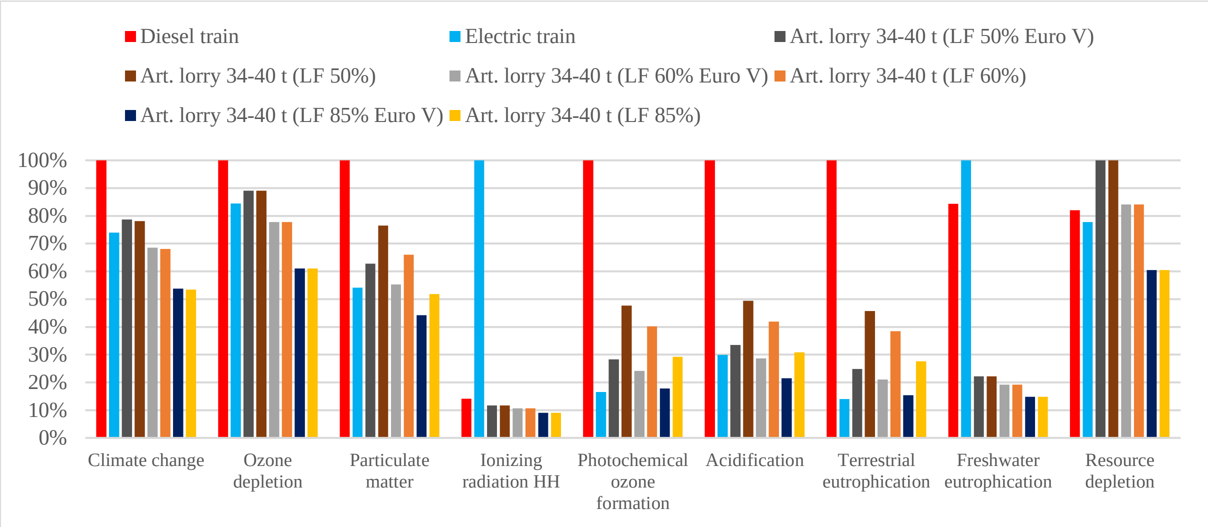


Figure 7.4. LCIA of the intermodal route from the Port of Antwerp to the Port of Zeebrugge

Diesel trains present the maximum impact in six environmental impact indicators. Regarding the indicators climate change, ozone depletion and particulate matter, it is the result of the route by road being 31% shorter than the rail route. Moreover, electric trains present the highest impact in the indicators ionizing radiation (damage to human health) and freshwater eutrophication.

Road transport with a load factor of 50% (regardless of the emission standard) shows the maximum impact in the indicator resource depletion. It should be noted that the use of an emission standard Euro V reduces the impact of road freight transport on the indicators particulate matter (from 8% to 14%), photochemical zone formation (from 11% to 19%), acidification (from 9% to 16%) and terrestrial eutrophication (from 12% to 21%).

7.3.2. Intermodal route from the Port of Antwerp to the Terminal Container Athus

Figure 7.5 shows the consolidated intermodal rail-road route in Belgium from the Port of Antwerp to the Terminal Container Athus. This intermodal route includes the processes of transhipment in the Port of Antwerp, the main haulage by rail or road and the transhipment in the intermodal terminal of Terminal Container Athus.

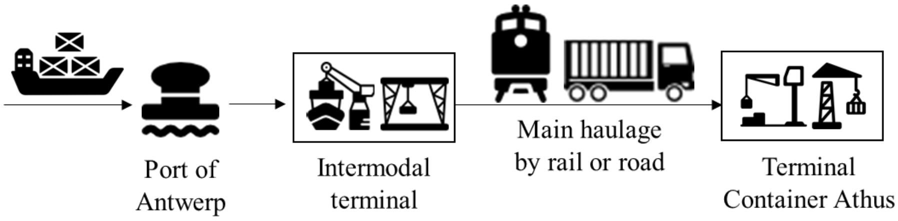


Figure 7.5. Intermodal route from the Port of Antwerp to the Terminal Container Athus

Figure 7.6 presents the route between the Port of Antwerp and the intermodal terminal of Terminal Container Athus by train (307 km) and by road (245 km).

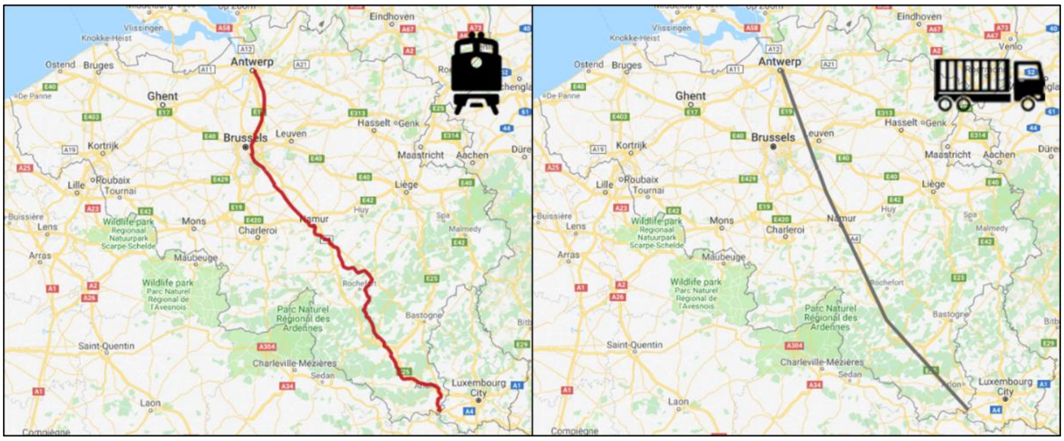


Figure 7.6. Intermodal route from the Port of Antwerp to the Terminal Container Athus by train (left) and by road (right). Source: EcoTransIT World, 2017

Data on this intermodal route have been collected in collaboration with Terminal Container Athus. Table 7.3 presents the characteristics of this intermodal route using as mode of transport rail freight transport. An average of 903.8 trains per year with an average of 70.3 TEU per train and a load factor of 90.2% perform this intermodal route. Considering the average handled volume (70.3 TEU/train) and the average load factor (90.2%), a train with a maximum payload of 78 TEU/train is obtained.

Table 7.3. Characteristics of the intermodal route from the Port of Antwerp to the Terminal Container Athus by train

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Number of journeys (train/year)	953	953	964	949	932	966	954	867	847	820	814	826
Handled volume (TEU/train)	61.3	66.1	72.3	66	67.6	71.6	67.4	67.6	68.4	76.4	79.5	79.3
Load factor (%)	81.7	88.2	96.4	88	90.2	95.5	89.8	90.2	89.2	95.5	89.6	87.5

Furthermore, as shown in Table 7.4, detailed information on electricity and diesel consumption for the handling of containers in the Terminal Container Athus has been collected as well.

Table 7.4. Energy consumption in the Terminal Container Athus

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Electricity consumed (kWh/a)	281 400	281 833	333 312	340 055	324 645	293 010	290 410	279 550	354 350	285 550	296 050	296 605
Diesel consumed (L/a)	275 569	269 685	344 320	337 104	244 526	249 529	245 522	244 109	235 914	237 252	247 642	284 412
Total handled volume (TEU)	221 527	213 261	257 302	261 328	199 031	213 820	218 210	209 267	198 296	195 855	181 281	183 826
Handled volume by train (TEU)	84 118	81 079	99 431	103 140	75 794	81 611	81 313	76 732	72 973	69 355	64 537	65 981
Handled volume by lorry (TEU)	137 408	132 183	157 871	158 189	123 237	132 209	136 897	132 534	125 323	126 500	116 744	117 745
Electricity consumed (kJ/TEU)	4 573	4 758	4 663	4 685	5 872	4 933	4 791	4 809	6 433	5 249	5 879	5 809
Diesel consumed (kJ/TEU)[1]	44 723	45 464	48 111	46 377	44 170	41 956	40 452	41 938	42 772	43 551	49 113	55 624
Total energy consumed (kJ/TEU)	49 296	50 222	52 774	51 061	50 042	46 889	45 243	46 747	49 205	48 800	54 992	61 433

[1]Considering that the density of diesel is 0.84 kg/L and the diesel net calories are 42.8 MJ/kg

Table 7.5 shows the main characteristics of the intermodal route from the Port of Antwerp to the Terminal Container Athus using as mode of transport for the main haulage rail and road transport. An average gross weight of 14.3 t/TEU has been considered, which includes 2.3 t of the container weight and a load per container of 12 t (Janic, 2008), resulting in 1 005.2 t for the average 70.3 TEU per train transported in this intermodal route.

Table 7.5. Main characteristics of the intermodal route from the Port of Antwerp to the Terminal Container Athus

		Main haulage by	
		Train	**Lorry**
Average gross weight TEU		14.3 t/TEU	
1. Transhipment in the Port of Antwerp		16 560 kJ/TEU	
2. Main haulage	**Maximum payload (TEU/vehicle)**	78	2
	Load factor	90.2%	50% - 60% 85%
	Actual payload (TEU/vehicle)	70.3	1 – 1.2 – 1.7
	Vehicle demand	1	70.3 – 58.6 – 41.4
	Handled volume	1 005.2 t	
	Distance (km)	307	245
	Transport performance (tkm)	308 587	246 267
3. Transhipment in the Terminal Container Athus	**Electricity**	5 204 kJ/TEU	
	Diesel	45 354 kJ/TEU	

For the transhipment processes in the Port of Antwerp, an energy consumption of 16 560 kJ per TEU from Messagie et al. (2014a) has been considered. Thus, the energy consumption estimated for the transhipment in the Port of Antwerp of 70.3 TEU is 1 164 030 kJ.

For the intermodal freight trains, an average train load factor of 90.2% has been considered and this, together with 78 TEU per train of maximum payload, results in an actual payload of 70.3 TEU per train. For road transport, a capacity of 2 TEU per lorry has been considered but three different load factors have been used to transport the same 70.3 TEU of a train. Thereby, the vehicle demands for the load factors of 50%, 60% and 85% are 70.3 lorries, 58.6 lorries and 41.4 lorries, respectively. The distances between the Port of Antwerp and the Terminal Container Athus by train and by road are 307 km and 245 km, respectively. Therefore, considering a handle volume of 1 005.2 t for the 70.3 TEU transported, the transport performance calculated is 308 587 tkm for rail transport and 246 267 tkm for road transport.

For the transhipment of the containers in the Terminal Container Athus, an average of 5 204 kJ of electricity and 45 354 kJ of diesel per TEU have been calculated, resulting in an average total of 50 559 kJ of energy per TEU (see Table 7.4). Thus, an energy consumption of 365 831 kJ of electricity and 3 188 023 kJ of diesel have been obtained for the transhipment of 70.3 TEU. Note the great difference in energy consumption in the transhipment processes between the value from Messagie et al. (2014a) (16 560 kJ/TEU) and our result for the Terminal Container Athus (50 559 kJ/TEU). This could be due to the increased use of diesel-powered cargo handling equipment in the Terminal Container Athus.

In order to determine the different environmental impacts produced depending on the choice of mode of transport for the intermodal route from the Port of Antwerp to the Terminal Container Athus, an analysis considering the main characteristics showed in Table 7.5 has been performed. As shown in Figure 7.7, seven types of transport modes in Belgium for the year 2012 have been chosen for the main haulage: diesel train, electric train, an average articulated lorry of 34-40 t with the load factors of 50%, 60% and 85% and an articulated lorry of 34-40 t Euro V with the same load factors. For the transhipment processes, it has been used the electricity supply mix of Belgium for the year 2012.

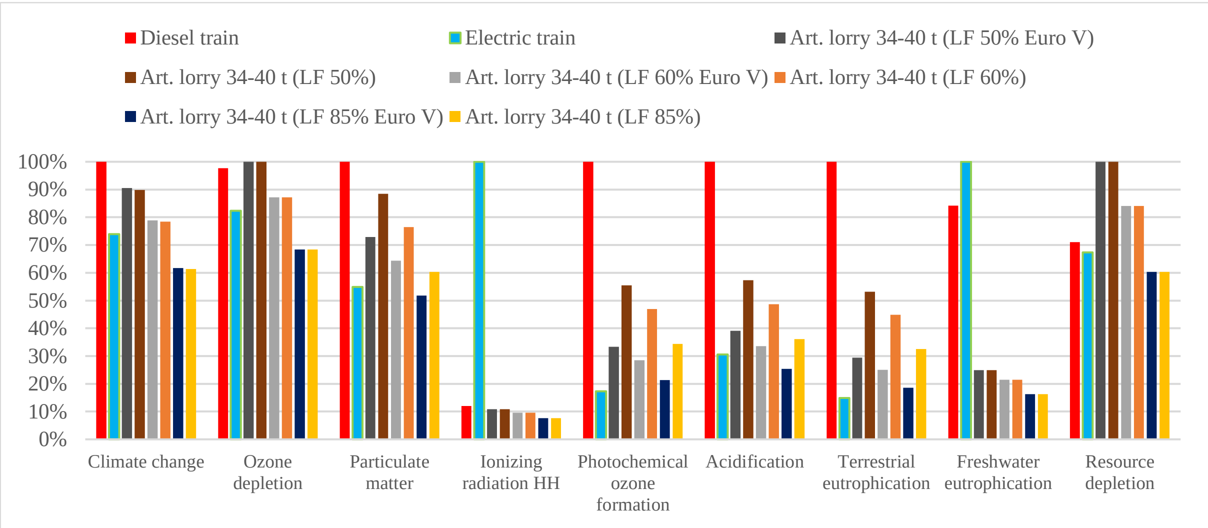


Figure 7.7. LCIA of the intermodal route from the Port of Antwerp to the Terminal Container Athus

By comparing the results obtained in the LCIA of the intermodal routes from the Port of Antwerp to the Port of Zeebrugge (see Figure 7.4) and to the Terminal Container Athus (see Figure 7.7), the difference between the environmental impacts of diesel trains and road transport is lower in the latter intermodal route. This is because the route by road is a 31% shorter than the rail route in the intermodal route to the Port of Zeebrugge and in the case of the intermodal route to the Terminal Container Athus, the route by road is a 20% shorter than the rail route.

Diesel trains present the maximum impact in five environmental impact indicators. Regarding the indicators climate change and particulate matter, it is the result of the route by road being 20% shorter than the rail route. Moreover, electric trains present the highest impact in the indicators ionizing radiation (damage to human health) and freshwater eutrophication. It should be noted that a lorry needs at least an 85% of load factor in order to have a lower impact on climate change than an electric train in this intermodal route.

Road transport with a load factor of 50% (regardless of the emission standard) shows the maximum impact in the indicators ozone depletion and resource depletion. It would need at least a route with at least 22% less distance to have a lower impact than diesel trains for the indicator ozone depletion. In the case of the indicator resource depletion, 43% less distance would be needed. For road transport, the use of an emission standard Euro V reduces the impact of road freight transport on the indicators particulate matter (from 9% to 16%), photochemical zone formation (from 13% to 22%), acidification (from 11% to 18%) and terrestrial eutrophication (from 14% to 24%).

7.4. Environmental impact assessment of the intermodal route from the Port of Antwerp to Ludwigshafen (Germany)

A study of the international intermodal route from the Port of Antwerp to Ludwigshafen (Germany) has been carried out. This is an important international route of LINEAS, which is the main rail freight operator in Belgium. As shown in Figure 7.8, this major intermodal route includes the processes of transhipment in the Port of Antwerp, the main haulage by train, barge or lorry and the transhipment in an intermodal terminal in Ludwigshafen.

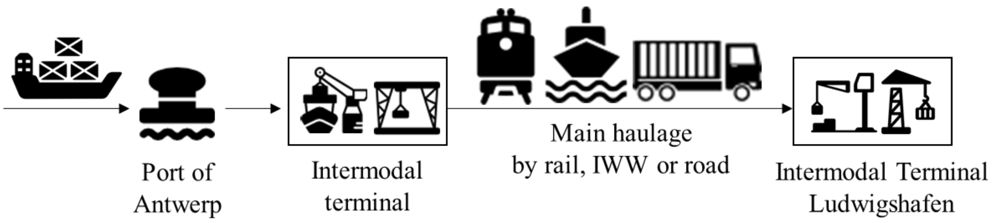


Figure 7.8. Intermodal route from the Port of Antwerp to Ludwigshafen

The distances between the Port of Antwerp and Ludwigshafen have been calculated using EcoTransIT World (2017), resulting in 488 km by train, 621 km by IWW and 407 km by road (see Figure 7.9).

Figure 7.9. Intermodal route from the Port of Antwerp to Ludwigshafen by train (left), IWW (centre) and road (right). Source: EcoTransIT World, 2017

Table 7.6 shows the main characteristics of the intermodal route from the Port of Antwerp to Ludwigshafen using as mode of transport for the main haulage rail, IWW and road transport. Considering a handle volume of 1 115.4 t for the 78 TEU transported, the transport performance calculated is 544 315 tkm for rail transport, 692 663 tkm for IWW transport and 453 968 tkm for road transport.

Table 7.6. Main characteristics of the intermodal route from the Port of Antwerp (Belgium) to Ludwigshafen (Germany)

		Main haulage by		
		Train	Barge	Lorry
Average gross weight TEU		14.3 t/TEU		
1. Transhipment in the Port of Antwerp		16 560 kJ/TEU		
2. Main haulage	**Maximum payload (TEU/vehicle)**	78	200	2
	Load factor	75%	60%	50% - 60% 85%
	Actual payload (TEU/vehicle)	58.5	120	1 – 1.2 – 1.7
	Vehicle demand	1.3	0.65	78 – 65 – 45.9
	Handled volume	1 115.4 t		
	Distance (km)	488	621	407
	Transport performance (tkm)	544 315	692 663	453 968
3. Transhipment in Ludwigshafen		16 560 kJ/TEU		

As mentioned above, the electricity supply mix used for electric trains plays an important role in determining the environmental impacts. Hence, depending on the energy split of the country (i.e. the share of nuclear or natural gas power for example), the environmental impacts of the electric rail freight transport varies. Therefore, since the intermodal transport route studied runs through two countries, our study uses the electricity supply mix of Belgium and Germany corresponding to the year 2012 (see Table 3.40) for the part of the intermodal route that passes in that country. Thereby, 158 km takes place in Belgium and 330 km in Germany, resulting in 176 233 tkm in Belgium and 368 082 tkm in Germany. Furthermore, the railway infrastructure process and demand used in our study are different in Belgium and Germany. Thereby, while for the Belgian railway infrastructure a complete inventory has been carried out, for the German railway infrastructure the railway infrastructure process and demand from the Ecoinvent v3 database (Weidema et al., 2013) has been used.

The processes related to the rail equipment and rail transport operation (except for electricity supply mix) such as energy consumption or direct emissions remains the same, since the train does not change throughout the route. In the cases of IWW and road transport, since the Ecoinvent v3 database has been used in the inventory of the Belgian infrastructure, no distinction has been made between the infrastructures of the different countries and therefore of the transport processes. However, for IWW transport the port demand has been modified according to the distance between the Port of Antwerp and Ludwigshafen by IWW (621 km), resulting in 8.75×10^{-14} unit/tkm.

Table 7.7 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by the transport modes chosen for the main haulage in the intermodal route from the Port of Antwerp to Ludwigshafen. These transport modes for the year 2012 are the followings: diesel and electric train in Belgium and Germany, IWW using the port demand specific for this route and an average articulated lorry of 34-40 t Euro V with the load factors of 50%, 60% and 85%.

Table 7.7. LCIA of 1 tkm transported by inland freight transport in Belgium {BE} and Germany {DE} in 2012

Impact category	Unit	Rail transport {BE}		Rail transport {DE}		IWW in canal	Articulated lorry of 34-40 t		
		Diesel trains	Electric trains	Diesel trains	Electric trains		LF 50% Euro V	LF 60% Euro V	LF 85% Euro V
Climate change	kg CO_2 eq	8.32×10^{-2}	6.12×10^{-2}	7.86×10^{-2}	9.90×10^{-2}	5.37×10^{-2}	9.42×10^{-2}	8.19×10^{-2}	6.37×10^{-2}
Ozone depletion	kg CFC-11 eq	1.38×10^{-8}	1.16×10^{-8}	1.20×10^{-8}	6.13×10^{-9}	6.38×10^{-9}	1.77×10^{-8}	1.54×10^{-8}	1.20×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	5.89×10^{-5}	3.17×10^{-5}	5.51×10^{-5}	2.76×10^{-5}	2.87×10^{-5}	5.34×10^{-5}	4.69×10^{-5}	3.74×10^{-5}
Ionizing radiation HH	kBq U235 eq	7.27×10^{-3}	6.67×10^{-2}	6.35×10^{-3}	2.53×10^{-2}	6.59×10^{-3}	8.13×10^{-3}	7.05×10^{-3}	5.47×10^{-3}
Photochemical ozone formation	kg NMVOC eq	1.09×10^{-3}	1.78×10^{-4}	1.05×10^{-3}	1.55×10^{-4}	4.70×10^{-4}	4.44×10^{-4}	3.77×10^{-4}	2.78×10^{-4}
Acidification	molc H+ eq	9.25×10^{-4}	2.74×10^{-4}	8.83×10^{-4}	2.66×10^{-4}	4.66×10^{-4}	4.44×10^{-4}	3.79×10^{-4}	2.83×10^{-4}
Terrestrial eutrophication	molc N eq	4.07×10^{-3}	5.62×10^{-4}	3.97×10^{-3}	5.28×10^{-4}	1.78×10^{-3}	1.46×10^{-3}	1.23×10^{-3}	8.95×10^{-4}
Freshwater eutrophication	kg P eq	1.69×10^{-5}	2.00×10^{-5}	1.16×10^{-5}	9.92×10^{-5}	1.01×10^{-5}	6.15×10^{-6}	5.26×10^{-6}	3.95×10^{-6}
Resource depletion	kg Sb eq	2.45×10^{-6}	2.32×10^{-6}	1.62×10^{-6}	1.35×10^{-6}	5.69×10^{-7}	4.32×10^{-6}	3.63×10^{-6}	2.60×10^{-6}

Figure 7.10 shows a comparison of the results (from Table 7.7) obtained in the LCIA of the different modes of inland freight transport in Belgium and Germany in 2012.

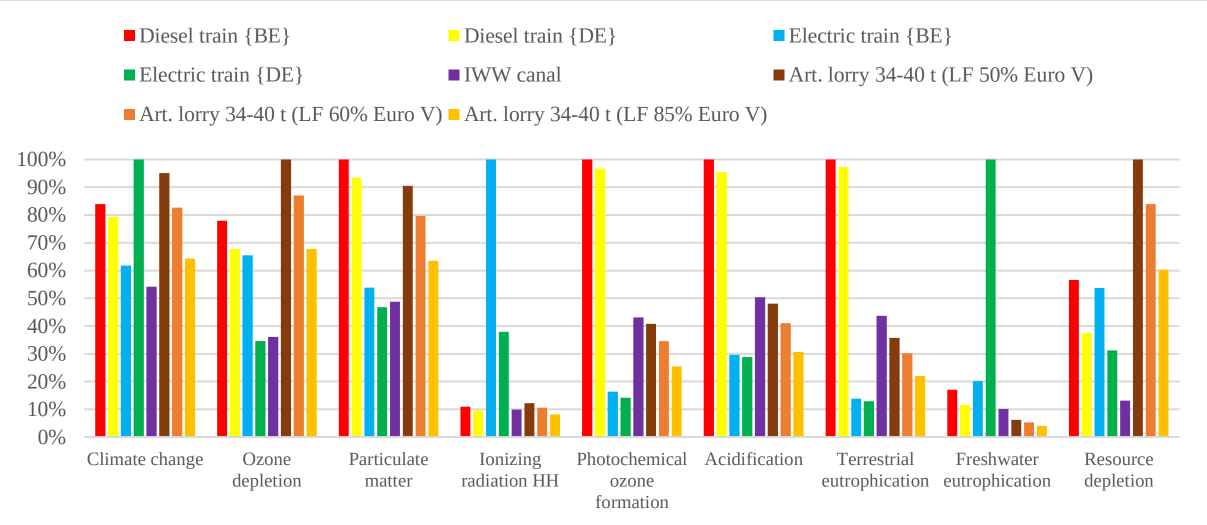


Figure 7.10. LCIA of 1 tkm transported by inland freight transport in Belgium {BE} and Germany {DE} in 2012

The articulated lorry of 34-40 t Euro V with a load factor of 50% presents the maximum impact in the indicators ozone depletion due to the higher diesel consumption and resource depletion as a results of the lead used in the lorry batteries.

Diesel trains present the maximum impact in the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions during the transport operation. Thereby, the $PM_{2.5}$, NO_X and SO_2 exhaust emissions are the main contributor for the indicator particulate matter, the NO_X and NMVOC for photochemical ozone formation, NO_X and SO_2 for acidification and NO_X for terrestrial eutrophication.

Comparing diesel trains in both countries, in Germany they present a lower impact in every indicator due to the lower infrastructure demand. As mentioned above, while in the case of Belgium a detailed study has been performed, for Germany it has been used the inventory and infrastructure demand from Ecoinvent v3 database. This implies a higher material demand for the Belgian railway infrastructure due to the greater completeness of our study and therefore a higher environmental impact.

Focusing on electric trains, in Germany they present the maximum impact in the indicators climate change and freshwater eutrophication due to the use of a 42% of coal and lignite in the electricity supply mix of Germany. Therefore, when an electric train crosses the border between Belgium and Germany, it presents a higher impact than an articulated lorry of 34-40 t Euro V with a load factor of 50% on climate change. This highlights the fundamental role that the electricity supply mix plays in the environmental impact of electric trains. Electric trains in Belgium have a higher impact on ozone depletion and ionizing radiation (damage to human health) than electric trains in Germany to the use of a 41.88% of nuclear power in the electricity supply mix in Belgium in the year 2012. Furthermore, electric trains show a higher impact in Belgium than in Germany in the indicators particulate matter, photochemical ozone formation, acidification, terrestrial eutrophication and resource depletion due to the greater completeness in our study of the Belgian railway infrastructure.

Figure 7.11 compares the LCIA of the transhipment of 78 TEU in the Port of Antwerp and the intermodal terminal in Ludwigshafen using the electricity supply mix of Belgium and Germany, respectively. This results can be used to understand how the electricity supply mix of Germany has a great influence in the environmental impacts of electric trains explained above. Thereby, the indicators climate change and freshwater eutrophication present a greater impact for the German electricity than for the Belgian one as a result of the use of a 42% of coal and lignite. For resource depletion, the uranium used in nuclear power plants leads to the electricity supply mix of Belgium (41.88% of nuclear power) to have a greater impact on this indicator.

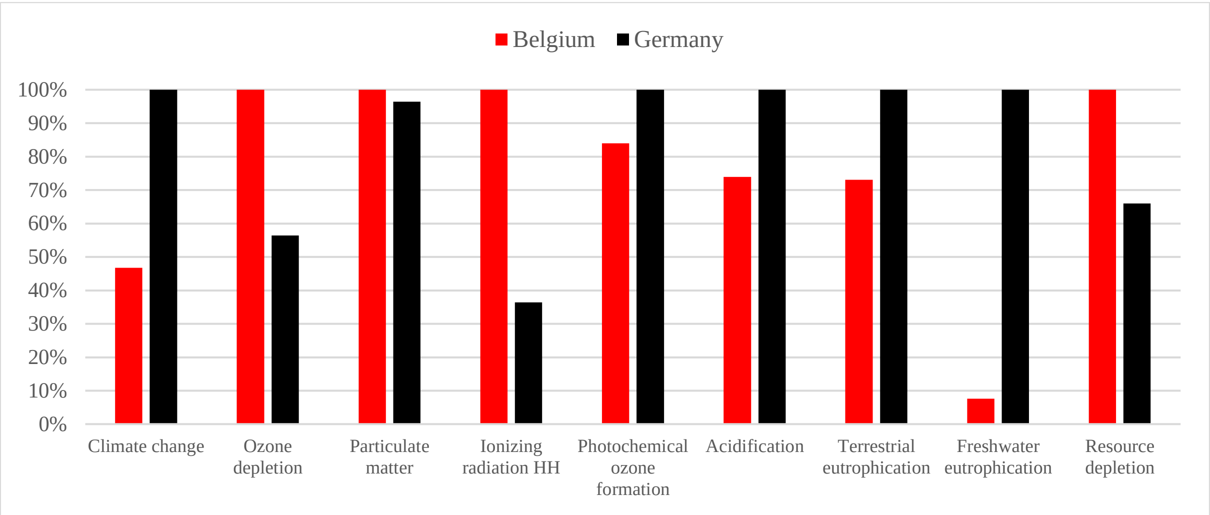


Figure 7.11. LCIA of the transhipment of 78 TEU using electricity from Belgium and Germany in the year 2012

Figure 7.12 shows a comparison of the results obtained from the LCIA of the intermodal route from the Port of Antwerp to Ludwigshafen using the main characteristics shown in Table 7.6. Thereby, six types of modes of transport have been chosen for the main haulage: diesel train, electric train, IWW and an articulated lorry of 34-40 t Euro V with the load factors of 50%, 60% and 85%. For the transhipment processes, it has been used the electricity supply mix of Belgium and Germany for the year 2012.

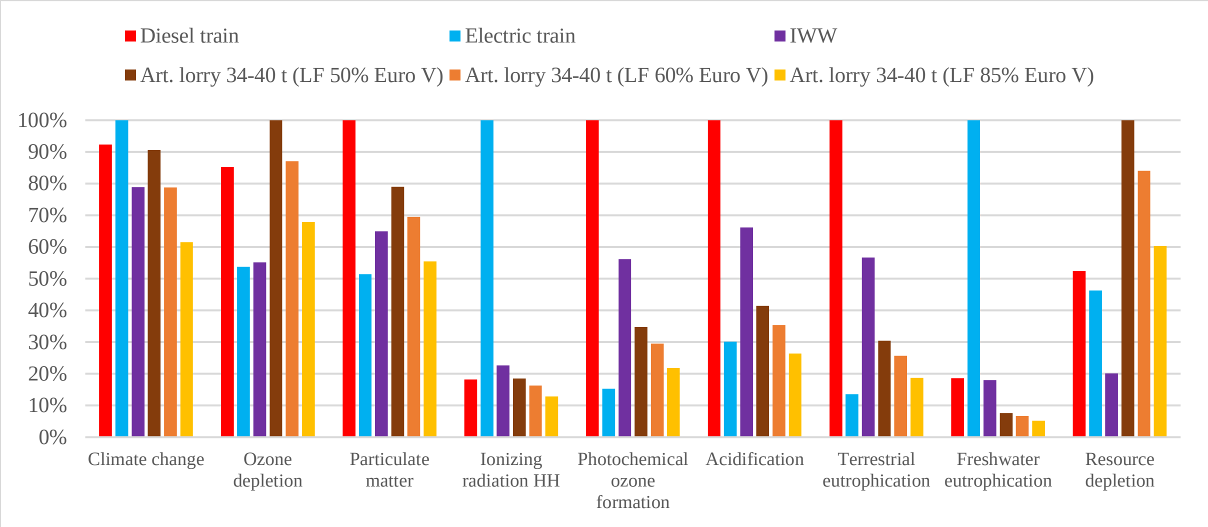


Figure 7.12. LCIA of the intermodal route from the Port of Antwerp to Ludwigshafen by different freight transport modes

Diesel trains have the maximum impact in four indicators, electric trains in three indicators and the articulated lorry of 34-40 t Euro V with a load factor of 50% presents the maximum impact in two environmental impact indicators. It should be noted that the same lorry with an 85% of load factor shows the lowest impact in four indicators, including climate change.

It must be emphasised that electric trains present the maximum impact on climate change due to the high indirect emissions of GHG in the electricity generation in Germany. The hard coal and lignite power plants were responsible for 42% of the total electricity supply mix in Germany in the year 2012, which explains the high GHG indirect emissions.

On the basis of the results obtained in the study of the three routes, the distance of the intermodal route is shown as determining factor in the environmental impacts of the transport mode chosen. Thereby, IWW transport experiences a high increase of its environmental impacts compared to rail and road transport due to the greatest distance that the barge has to travel (i.e., the 621 km compared to 488 km by rail and 407 km by road). Thus, IWW transport shows a higher impact than electric trains and road transport (presenting a significant difference) in the intermodal route in the indicators photochemical ozone formation, acidification and terrestrial eutrophication. However, it should be noted that this intermodal route is not conducive to IWW since the distance by barge is 53% greater than the distance by road.

7.5. Environmental impact assessment of the European Corridors crossing Belgium

The environmental impact of international intermodal transport routes within the three Trans-European Transport Network (TEN-T) core network corridors crossing Belgium have been analysed. As shown in Figure 7.13, these corridors are part of the nine TEN-T core network corridors that cover Europe: Rhine-Alpine (in orange), North Sea-Mediterranean (in purple) and North Sea-Baltic (in red).

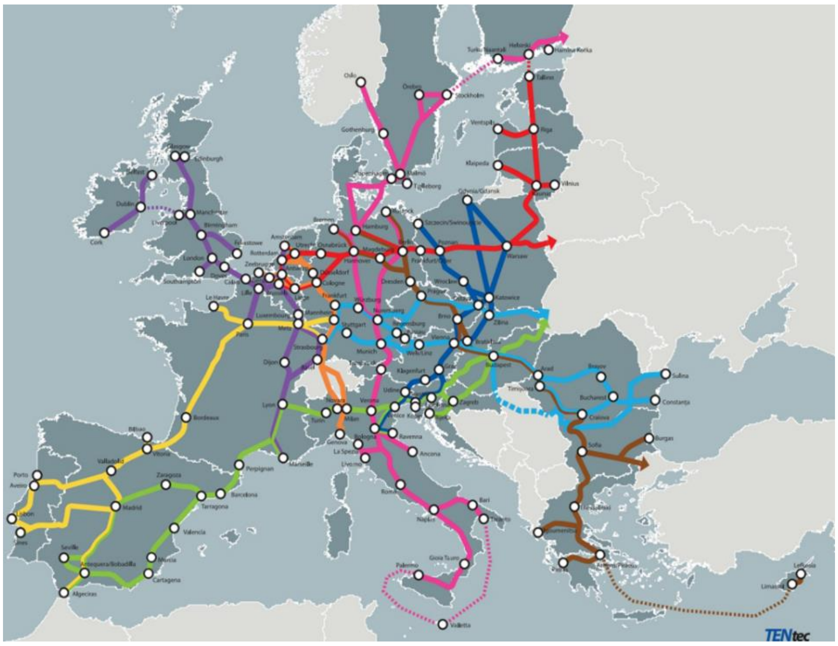


Figure 7.13. TEN-T core network corridors. Source: European Commission, 2018

Figure 7.14 shows the processes included in the study of the intermodal transport routes within the three TEN-T core network corridors. This intermodal routes includes the processes of transhipment in the Port of Antwerp the main haulage by train, barge or lorry and the transhipment in the final destination intermodal terminal.

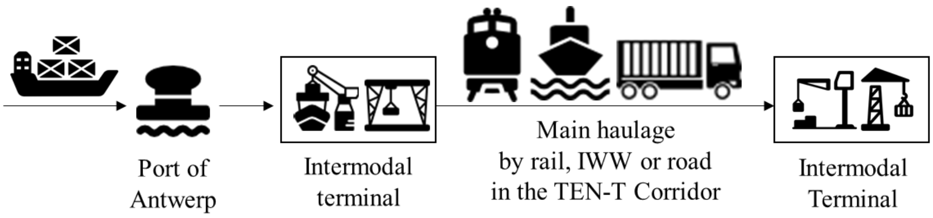


Figure 7.14. Example of intermodal route in the TEN-T corridors

For rail freight transport, since it is assumed that the train is the same throughout the entire intermodal route, the processes related to the rail equipment and rail transport operation (except for electricity supply mix) such as energy consumption remain the same. The kilometres travelled through every country for rail freight transport have been taken into account. Therefore, it was possible to consider the environmental impact related to the electricity supply mix of the corresponding country used for electric trains. Moreover, the railway infrastructure processes and demands used in our study are different in every country. In the cases of IWW and road transport, since the Ecoinvent v3 database has been used in the inventory of the Belgian infrastructure, no distinction has been made between the infrastructures of the different countries and therefore of the transport processes. For IWW transport, the port demand has been modified according to the distance between the Port of Antwerp and the final destination.

Table 7.8 shows the main characteristics of the intermodal routes within the three TEN-T core network corridors using as mode of transport for the main haulage rail, IWW and road transport. Hence, six types of modes of transport have been chosen for the main haulage: diesel train, electric train, IWW and an articulated lorry of 34-40 t Euro V with the load factors of 50%, 60% and 85%. For the transhipment processes, the electricity supply mix of the corresponding country for the year 2012 have been used.

Table 7.8. Main characteristics of the intermodal route in the TEN-T corridors

		Main haulage by		
		Train	**Barge**	**Lorry**
Average gross weight TEU		14.3 t/TEU		
1. Transhipment in the Port of Antwerp		16 560 kJ/TEU		
2. Main haulage	**Maximum payload (TEU/vehicle)**	78	200	2
	Load factor	75%	60%	50% - 60% 85%
	Actual payload (TEU/vehicle)	58.5	120	1 – 1.2 – 1.7
	Vehicle demand	1.3	0.65	78 – 65 – 45.9
	Handled volume	1 115.4 t		
3. Transhipment in the intermodal terminal		16 560 kJ/TEU		

In order to study the evolution of the environmental impacts throughout the intermodal route, the following midpoint environmental impact categories have been considered as the most relevant environmental problems on freight transport: climate change (kg CO_2 eq.), particulate matter formation (kg $PM_{2.5}$ eq.) and photochemical ozone formation (kg NMVOC eq.).

7.5.1. Rhine-Alpine corridor

Within the TEN-T corridor Rhine-Alpine, some relevant line services from the Port of Antwerp have been selected considering the best distance and time and when possible using the same terminal rail/IWW (Port of Antwerp, 2018). Moreover, only main cities on the corridor have been considered, excluding the cities with sea connections. Thus, the line services from the Port of Antwerp to Cologne (Germany), Frankfurt (Germany), Mannheim (Germany), Karlsruhe (Germany), Strasbourg (France), Basel (Switzerland) and Milan (Italy) have been studied.

The distances between the Port of Antwerp and the final destination have been calculated using EcoTransIT World (2017). Table 7.9 presents the distances travelled by rail, IWW and road freight transport. As mentioned above, the kilometres travelled through every country for rail freight transport have been taken into account. Our study uses the electricity supply mix of Belgium, Germany, Luxembourg, France and Italy corresponding to the year 2012 (see Table 3.41). For Switzerland, the electricity supply mix from Ecoinvent v3 database (Weidema et al., 2013) has been used. For example, in the intermodal transport route from the Port of Antwerp to Milan (Italy), for rail freight transport, a distance of 251 km in Belgium, 34 km in Luxembourg, 337 km in France, 315 km in Switzerland and 55 km in Italy has been considered.

Table 7.9. Distances by mode of transport between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine

		Distance from the Port of Antwerp to						
		Cologne (Germany)	Frankfurt (Germany)	Mannheim (Germany)	Karlsruhe (Germany)	Strasbourg (France)	Basel (Switzerland)	Milan (Italy)
Railway distance in country (km)	Belgium	163	163	163	163	251	251	251
	Germany	82	262	330	396	-	-	-
	Luxembourg	-	-	-	-	34	34	34
	France	-	-	-	-	211	334	337
	Switzerland	-	-	-	-	-	12	315
	Italy	-	-	-	-	-	-	55
Total railway (km)		245	425	493	559	496	631	992
IWW (km)		366	597	627	691	762	883	-
Road (km)		210	396	417	476	483	581	923

The main characteristics shown in Table 7.8 and Table 7.9 have been used to create the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine. Figure 7.15 shows a comparison of the LCIA results obtained on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine. In order to facilitate the interpretation of the results, all the scores of the different transport modes used in an intermodal route (e.g. from the Port of Antwerp to Cologne) have been divided by the highest score of the intermodal route, which represents the transport mode with the maximum impact in the intermodal route. Therefore, the lowest value represents the transport mode with reduced impact and the highest value represents the transport mode with the maximum impact.

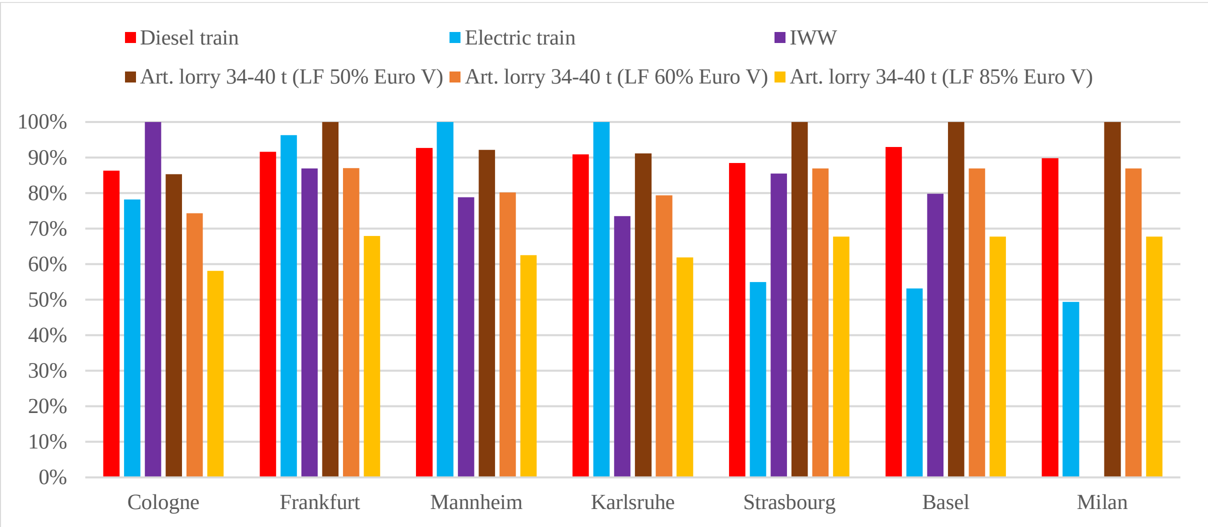


Figure 7.15. Comparison of the environmental impact on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine

In view of the results obtained on climate change, the difference in the distance travelled along the intermodal route compared to the other transport modes becomes an important factor. Hence, the impact of IWW decreases from Cologne to Karlsruhe compared to rail and road freight transport as the difference in the distance is reduced. The route by IWW is a 49% longer than the rail route in Cologne, but a 24% longer in Karlsruhe. Furthermore, it should be noted that the methodology developed by Spielmann et al. (2007) to calculate the port demand uses the transport distance. Thus, the higher the distance travelled by the barge, the lower the port demand, and therefore the total impact of IWW transport is reduced.

Electric trains increase their impact on climate change compared to road freight transport from Cologne to Karlsruhe as the share of the German railway grows, becoming greater than road freight transport with a load factor of 50% in Mannheim and Karlsruhe. This is because the share of the electricity supply mix of Germany, which presents a 42% of hard coal and lignite power in the year 2012, increases as the distance travelled in Germany is longer. Moreover, the environmental impact of electric trains decreases in Strasbourg, Basel and Milan as a result of the greater use of French and Swiss electricity. The electricity supply mix of France presents a 75% of nuclear power and the Swiss electricity a 35% of nuclear power and a 25% of hydropower.

Figure 7.16 presents a comparison of the LCIA results obtained on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine. By comparing rail and road freight transport, diesel trains presents a higher impact than road transport (using an emission standard Euro V) due to the greater exhaust emissions on $PM_{2.5}$ and NO_X of diesel locomotives. However, electric trains show a lower impact than road transport in all the intermodal routes.

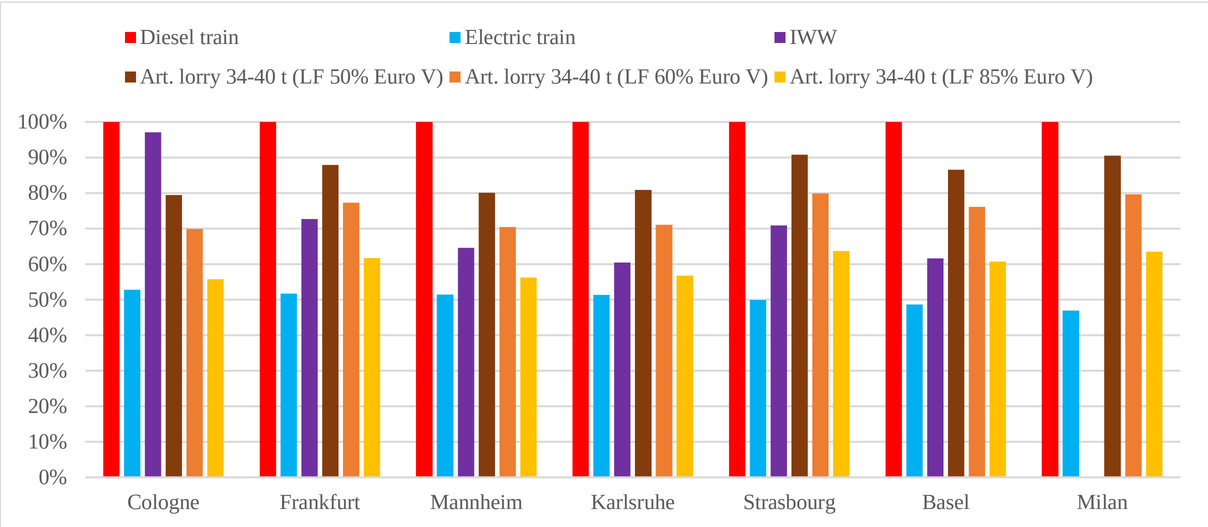


Figure 7.16. Comparison of the environmental impact on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine

Figure 7.17 presents a comparison of the LCIA results obtained on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine. Diesel trains show the maximum impact as a result of the greater exhaust emissions on NO_X and NMVOC of diesel locomotives during the transport operation. It should be noted that electric trains present the lowest impact in all the intermodal routes. Furthermore, IWW transport shows a significant difference compared road freight transport due to the longer route.

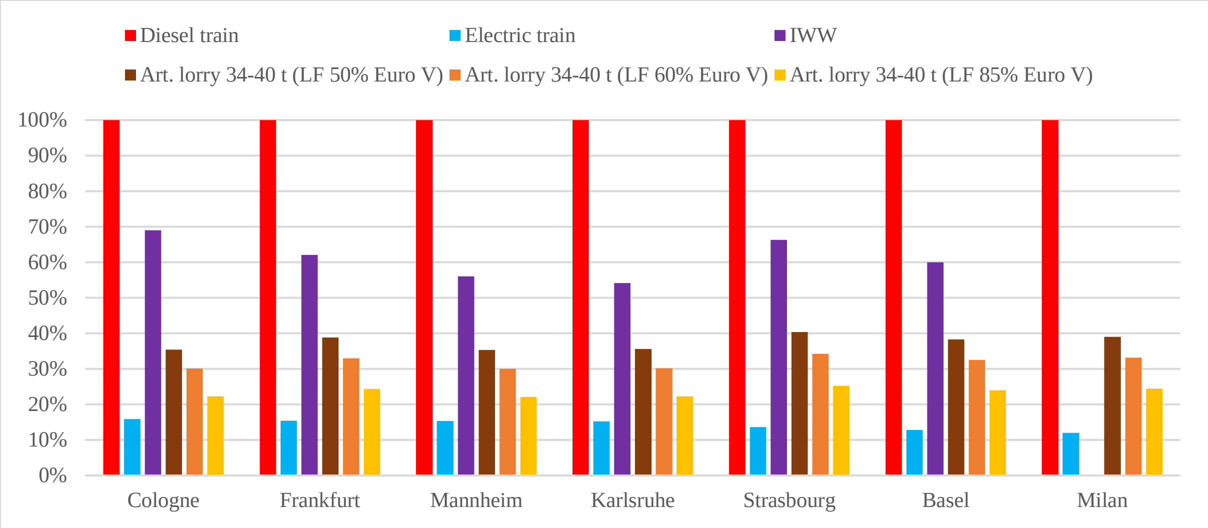


Figure 7.17. Comparison of the environmental impact on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor Rhine-Alpine

7.5.2. North Sea-Mediterranean corridor

Within the TEN-T corridor North Sea - Mediterranean, some relevant line services from the Port of Antwerp have been selected considering only main cities, the best distance and time and when possible using the same terminal rail/IWW (Port of Antwerp, 2018). Therefore, the line services from the Port of Antwerp to Bettembourg (Luxembourg), Metz (France), Strasbourg (France), Basel (Switzerland), Dijon (France), Lyon (France) and Marseille (France) have been studied. The distances between the Port of Antwerp and the final destination have been calculated using EcoTransIT World (2017). Table 7.10 presents the distances travelled by rail, IWW and road freight transport. As mentioned above, the kilometres travelled through every country for rail freight transport have been taken into account. Our study uses the electricity supply mix of Belgium, Luxembourg and France corresponding to the year 2012 (see Table 3.41). For Switzerland, the electricity supply mix from Ecoinvent v3 database (Weidema et al., 2013) has been used. For example, in the intermodal transport route from the Port of Antwerp to Basel (Switzerland), it has been considered for rail freight transport, a distance of 251 km in Belgium, 34 km in Luxembourg, 334 km in France and 12 km in Switzerland.

Table 7.10. Distances by mode of transport between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean

		Distance from the Port of Antwerp to						
		Bettembourg (Luxembourg)	**Metz (France)**	**Strasbourg (France)**	**Basel (Switzerland)**	**Dijon (France)**	**Lyon (France)**	**Marseille (France)**
Railway distance in country (km)	**Belgium**	251	251	251	251	251	251	140
	Luxembourg	30	34	34	34	34	34	-
	France	-	44	211	334	317	502	968
	Switzerland	-	-	-	12	-	-	-
Total railway (km)		281	329	496	631	602	787	1108
IWW (km)		-	-	762	883	-	-	-
Road (km)		269	315	483	581	594	777	1075

The main characteristics shown in Table 7.8 and Table 7.10 have been used to create the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean. Figure 7.18 shows a comparison of the LCIA results obtained on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea – Mediterranean.

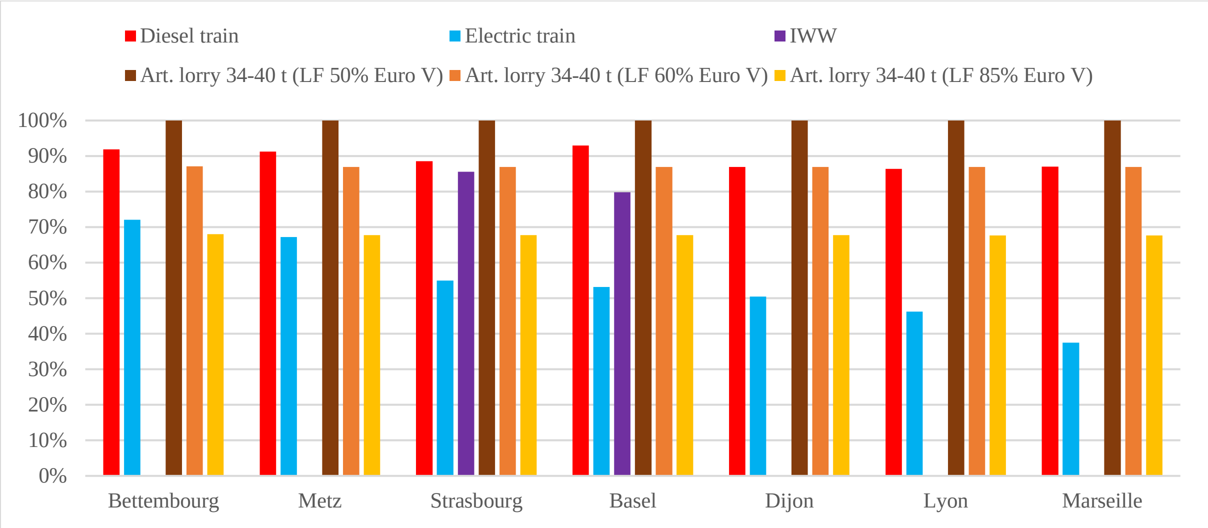


Figure 7.18. Comparison of the environmental impact on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean

The difference on the distance between the rail and road route is small in this intermodal route. Hence, the greatest difference is in Basel where the route by road is an 8% shorter than the rail route and the smallest difference is at Dijon and Lyon where the route by road is only a 1% shorter than the rail route. Therefore, the articulated lorry of 34-40 t with a load factor of 50% presents the maximum impact in all the intermodal routes.

Electric trains decrease their impact on climate change compared to road freight transport as the share of the French railway grows. This is because the share of the electricity supply mix of France, which presents a 75% of nuclear power in the year 2012, increases as the distance travelled in France is longer. Furthermore, diesel trains present an environmental impact similar to an articulated lorry of 34-40 t with a load factor of 60%.

Figure 7.19 presents a comparison of the LCIA results obtained on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean. Diesel trains present the highest impact in all the intermodal routes as a result of the greater exhaust emissions during the transport operation on $PM_{2.5}$ and NO_X than road transport (using an emission standard Euro V). It should be noted that electric trains show the lowest impact in all the intermodal routes.

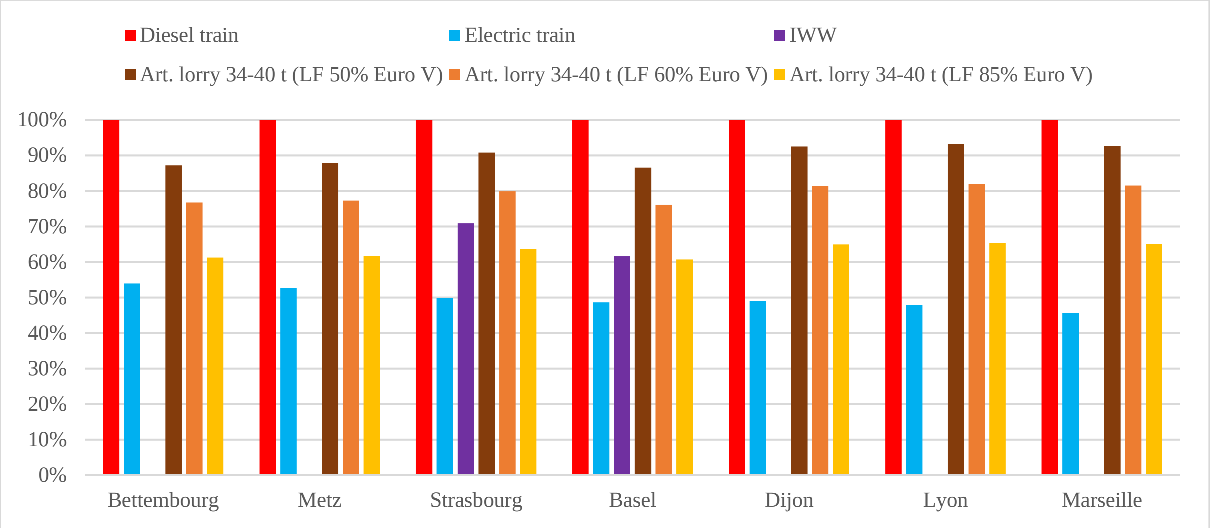


Figure 7.19. Comparison of the environmental impact on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean

Figure 7.20 shows a comparison of the LCIA results obtained on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean. Diesel trains show the maximum impact as a result of the greater exhaust emissions on NO_X and NMVOC of diesel locomotives during the transport operation. However, electric trains present the lowest impact in all the intermodal routes.

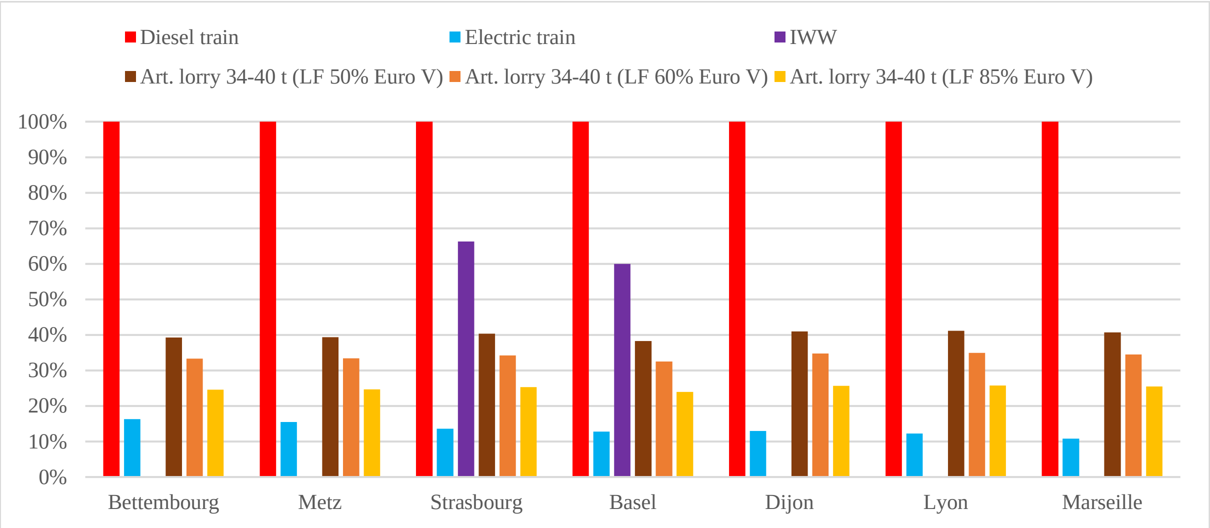


Figure 7.20. Comparison of the environmental impact on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Mediterranean

7.5.3. North Sea-Baltic corridor

Within the TEN-T corridor North Sea - Baltic, some relevant line services from the Port of Antwerp have been selected considering only main cities, the best distance and time and when possible using the same terminal rail/IWW (Port of Antwerp, 2018). Therefore, the line services from the Port of Antwerp to Rotterdam (The Netherlands), Cologne (Germany), Hanover (Germany), Bremen (Germany), Hamburg (Germany), Berlin (Germany), Poznan (Poland) and Warsaw (Poland) have been studied.

The distances between the Port of Antwerp and the final destination have been calculated using EcoTransIT World (2017). Table 7.11 presents the distances travelled by rail, IWW and road freight transport. As mentioned above, the kilometres travelled through every country for rail freight transport have been taken into account. Our study uses the electricity supply mix of Belgium, The Netherlands, Germany and Poland corresponding to the year 2012 (see Table 3.41). For example, in the intermodal transport route from the Port of Antwerp to Warsaw (Poland), it has been considered for rail freight transport, a distance of 31 km in Belgium, 144 km in The Netherlands, 664 km in Germany and 469 km in Poland.

Table 7.11. Distances by mode of transport between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic

		Distance from the Port of Antwerp to							
		Rotterdam (The Netherlands)	Cologne (Germany)	Hanover (Germany)	Bremen (Germany)	Hamburg (Germany)	Berlin (Germany)	Poznan (Poland)	Warsaw (Poland)
Railway distance in country (km)	Belgium	31	163	31	31	31	31	31	31
	The Netherlands	64	-	144	248	248	144	144	144
	Germany	-	82	313	208	303	574	664	664
	Poland	-	-	-	-	-	-	183	469
Total railway (km)		95	245	488	487	582	749	1 022	1 308
IWW (km)		120	366	-	-	-	-	-	-
Road (km)		97	210	432	439	544	717	961	1 240

The main characteristics shown in Table 7.8 and Table 7.11 have been used to create the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic. Figure 7.21 shows a comparison of the LCIA results obtained on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic.

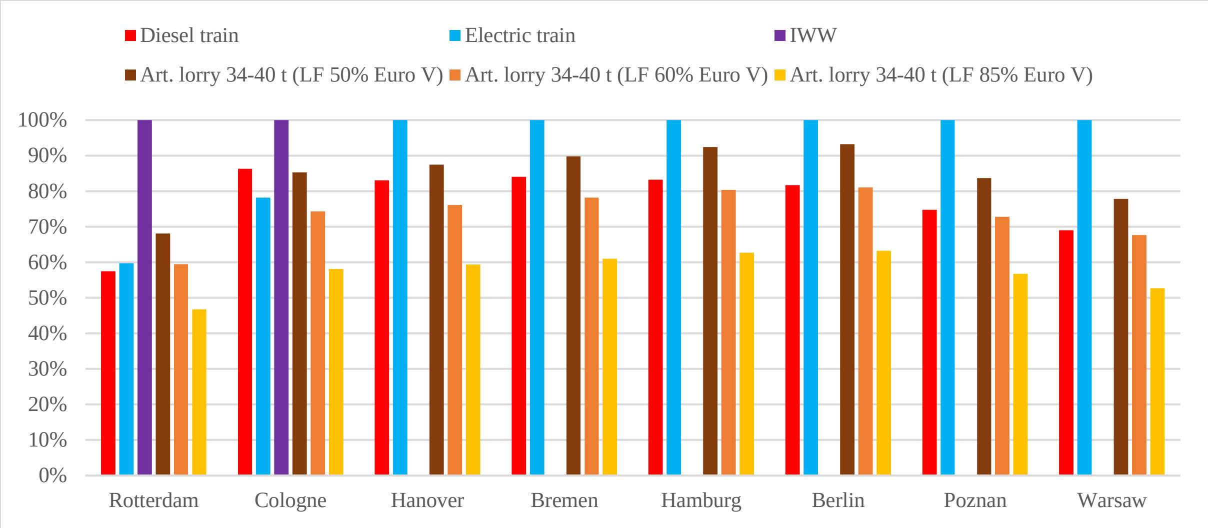


Figure 7.21. Comparison of the environmental impact on climate change of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea – Baltic

For the intermodal connection between seaports from the Port of Antwerp to the Port of Rotterdam, IWW presents the maximum impact due to highest port demand calculated as a result of the small distance (120 km). This highlight the problem of the methodology developed by Spielmann et al. (2007) to calculate the port demand using the transport distance. Hence, the smaller the distance travelled by the barge, the greater the port demand, and therefore the higher the total impact of IWW transport.

Electric trains show the maximum impact from Hanover to Warsaw as a results of the use of German and Polish electricity. The electricity supply mix of Germany and Poland present a 42% and 81% of hard coal and lignite power in the year 2012, respectively. Hence, the difference of the impact between electric trains and the other transport modes increases in Poznan and Warsaw. Furthermore, the articulated lorry of 34-40 t with a load factor of 85% presents the lowest impact in all the intermodal routes.

Figure 7.22 presents a comparison of the LCIA results obtained on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic. Diesel trains have the highest impact in all the intermodal routes (excluding Rotterdam) due to the greater exhaust emissions on $PM_{2.5}$ and NO_X of diesel locomotives compared to road transport (using an emission standard Euro V). It should be noted the increase of the impact on particulate matter formation of electric trains in Poznan and Warsaw as the distance travelled in Poland is longer due to the electricity supply mix of Poland.

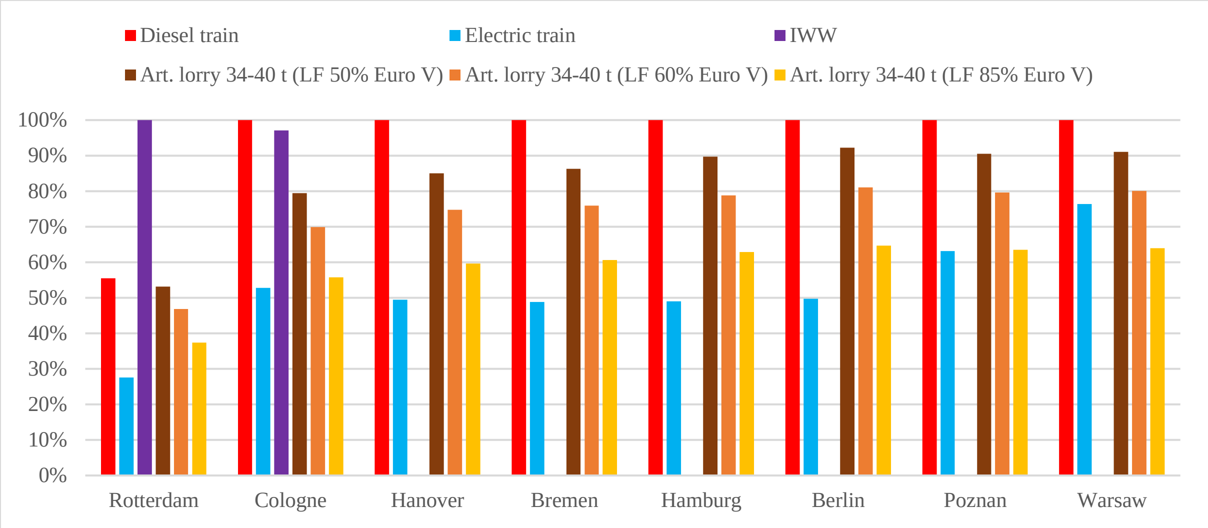


Figure 7.22. Comparison of the environmental impact on particulate matter formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic

Figure 7.23 shows a comparison of the LCIA results obtained on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea - Baltic. Diesel trains show the maximum impact as a result of the greater exhaust emissions on NO_X and NMVOC of diesel locomotives during the transport operation. It should be noted that electric trains present the lowest impact in all the intermodal routes.

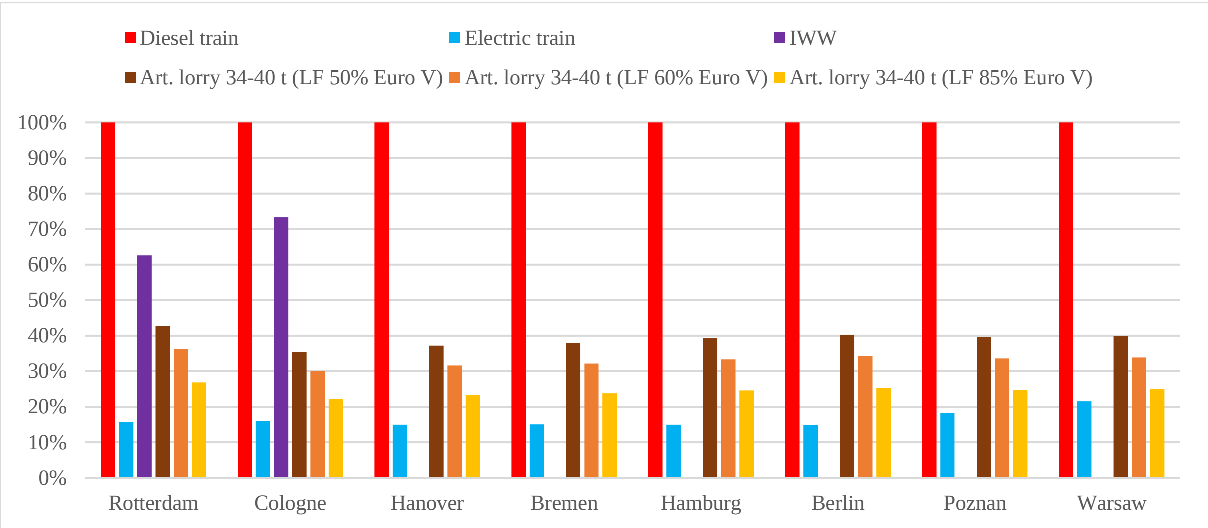


Figure 7.23. Comparison of the environmental impact on photochemical ozone formation of the intermodal routes between the Port of Antwerp and the final destination within the TEN-T corridor North Sea – Baltic

7.6. Conclusions of the study of intermodal freight transport routes

The environmental impact of different intermodal routes in Belgium and Europe have been studied using different inland freight transport modes for the major part of the intermodal route. The three modes of transport chosen for the intermodal routes carried the same number of containers with the same load. This allows to study the influence of the distance travelled by each transport mode on the environmental impact of freight transport. Hence, from an environmental point of view, road transport benefits because the road network is greater than the railway and IWW network. Therefore, road transport is usually the shortest possible route. IWW transport is the most affected by distance due to the strong limitations imposed by geography in this transport mode.

The minimum distance difference needed to achieve an equal environmental impact depends on the transport mode chosen and the environmental impact category considered. For example, for the Belgian intermodal routes an articulated lorry of 34-40 t with a load factor of 50% (regardless of the emission standard) needs at least 11% or 34% or more difference in distance to match or improve the environmental performance on climate change of diesel trains or electric trains (using the Belgian electricity supply mix), respectively.

For the European intermodal routes, the environmental impact of electric trains varies depending on the electricity supply mix of the different countries. Thereby, on the one hand, electric trains increase their impact on climate change compared to the other transport modes as the share of the electricity from Germany or Poland grows (42% and 81% of hard coal and lignite power in the energy split, respectively), becoming even greater than diesel trains and road transport. On the other hand, the impact on climate change of electric trains decreases as the distance travelled in France (75% of nuclear power in the energy split) or Switzerland (35% of nuclear power and 25% of hydropower in the energy split) is longer.

Moreover, electric trains present the lowest impact in all the European intermodal routes on particulate matter and photochemical ozone formation. Diesel trains show the maximum impact on particulate matter in all the intermodal routes (except in the case of the connection between seaports from the Port of Antwerp to the Port of Rotterdam) due to the greater exhaust emissions on $PM_{2.5}$ and NO_X of diesel locomotives during the transport operation. Similarly, diesel trains present the maximum impact on photochemical ozone formation in all the European intermodal routes as a result of the greater exhaust emissions on NO_X and NMVOC of diesel locomotives.

Furthermore, the environmental impact of IWW transport is strongly influenced by the transport distance in the calculation of port demand due to the methodology developed by Spielmann et al. (2007). Hence, the higher the distance travelled by the barge, the lower the port demand, and therefore the total impact of IWW transport is reduced.

Overall, there are no single solutions for all intermodal routes. Hence, multiple factors such as the distance travelled by each transport mode or the energy split of the country through which electric trains pass are decisive. Furthermore, the environmental performance of a transport mode changes depending on the environmental impact category considered.

Chapter 8. Study of the modal split of inland freight transport in Belgium

8.1. Introduction

The purpose of this chapter is to analyse how the increase of rail freight transport in the modal split as a result of the possible development of the intermodal rail freight transport could affect the environmental impacts of inland freight transport in Belgium. Hence the environmental impacts of the modal splits of inland freight transport in Belgium have been studied for several scenarios such as the increase of rail freight transport or the optimization of the operational costs and environmental factors.

8.2. Environmental impact assessment of three scenarios in the year 2030 considering an increase of rail demand of 133%, 64% and 10%

In 2011, the European Commission's White Paper on transport set ten strategic goals with the objective of increasing the rail market share in Europe. The third strategic goal states that "30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050, facilitated by efficient and green freight corridors" (European Commission, 2011).

Three plausible scenarios directly linked to the third strategic goal of the European Commission's White Paper on transport (2011) have been built for further analysis. As a result, a best, a worst and a medium case scenarios have been developed.

For the best-case scenario, an increase of rail demand by 133% has been estimated considering as reference year 2012. This implies a growth from the 7 279 million tkm of rail freight transport to approximately 17 000 million tkm of goods transported by rail in the year 2030. A total inland freight transport of 85 000 million tkm in the year 2030 has been estimated by Troch et al. (2015) and this, together with the 17 000 million tkm of rail freight transport considered, results in a modal split share of 20% for rail freight transport in the year 2030. Therefore, the estimated growth of rail freight transport ranges from 14.6% in the year 2012 to 20% in 2030. This growth in rail freight transport could be achieved as a result of increased standardization and interoperability between countries, development of railway infrastructure to increase transport capacity and an expansion of the railway market considering the opportunities in the Eastern European countries (Troch et al., 2015).

A study by the European Parliament proposes that as a realistic medium-term objective, rail freight transport should have a modal split share of 20% measured in tonne-kilometres, which is in line with our best-case scenario. Furthermore, it states that the 30% shift of road freight over 300 km to rail or waterborne transport by 2030 would imply a transfer of approximately the 3.5% of the total transport of the European Union (Gleave et al., 2015).

For the medium-case scenario, an increase of rail demand by 64% has been estimated considering as reference year 2012. This implies a growth from the 7 279 million tkm of rail freight transport to approximately 12 000 million tkm of goods transported by rail in the year 2030. A total inland freight transport of 71 500 million tkm in the year 2030 has been estimated by Troch et al. (2015) and this, together with the 12 000 million tkm of rail freight transport considered, results in a modal split share of 16.8% for rail freight transport in the year 2030. Therefore, the estimated growth of rail freight transport ranges from 14.6% in the year 2012 to 16.8% in 2030 (Troch et al., 2015).

For the worst-case scenario, an increase of rail demand by 10% has been estimated considering as reference year 2012. This implies a growth from the 7 279 million tkm of rail freight transport to approximately 8 000 million tkm of goods transported by rail in the year 2030. A total inland freight transport of 57 000 million tkm in the year 2030 has been estimated by Troch et al. (2015) and this, together with the 8 000 million tkm of rail freight transport considered, results in a modal split share of 14% for rail freight transport in the year 2030. Therefore, rail freight transport will experience a growth in absolute terms but a slight decline in relative terms in the year 2030 (Troch et al., 2015).

In order to analyse how the shift from road transport to rail freight transport affects the environmental impacts of inland freight transport, the modal split share of IWW has remained at the value of the year 2012 (i.e. 20.9%). Once the values of rail freight transport and IWW have been calculated, the road freight transport and its modal split for the three scenarios has been determined. Table 8.1 shows the modal split and inland freight transport estimated for the three scenario in the year 2030.

Table 8.1. Modal split and inland freight transport in Belgium for the three scenarios considering increase of rail demand of 133%, 64% and 10%

		Year 2012	Scenarios in the year 2030		
			Best-case	Medium-case	Worst-case
Modal split (%)	Rail	14.6	20	16.8	14
	IWW	20.9	20.9	20.9	20.9
	Road	64.5	59.1	62.3	65
Freight transport (million tkm)	Rail	7 279	17 000	12 000	8 000
	IWW	10 420	17 784	14 959	11 926
	Road	32 105	50 216	44 541	37 074
	Total	49 804	85 000	71 500	57 000

Islam et al. (2013) estimated a shift from road to rail of 4.86% for a “white paper high scenario" (equivalent to our best-case scenario) and 1.13 % for a "white paper low scenario" (equivalent to our medium-case scenario). In our study, there has been a shift from road to rail of 5.4% for the best-case scenario and 2.2% for medium-case scenario. Furthermore, it should be noted a shift from rail to road of 0.6% in the worst-case scenario.

8.2.1. Life Cycle Impact Assessment of the transport processes used in the scenarios

The environmental impacts of the inland freight transport in the year 2012 have been determined using the following three processes: rail freight transport considering the Belgian traction mix of the year 2012 (i.e. 86% of electric trains and 14% of diesel trains), IWW transport of the year 2012 and average road transport with a load factor of 50% of the year 2012.

In order to estimate the environmental impacts of the three scenarios in the year 2030, the process IWW transport has been considered to remain the same than 2012. For rail freight transport, since the use of diesel trains is decreasing over the years in Belgium (see Table 1.6), it has been considered that the rail freight transport will be performed mostly by electric traction in Belgium in the year 2030.

As mentioned above, the electricity supply mix used for electric trains plays an important role in determining the environmental impact. Therefore, to determine the environmental impacts related to the electricity production in the year 2030, the energy mix of Belgium for this year has been estimated. Table 8.2 presents the energy mix considered for the year 2030 in Belgium. These values have been extracted from a study of Léonard and Belboom (2016) on electricity supply mix in Belgium. For the year 2030, it has been considered a scenario in which all the all targets for CO_2 emission reduction have been achieved and nuclear power is no longer used. It should be noted that this scenario is extreme and could be considered unrealistic. Electricity imports from other countries are not considered, thus only the domestic production mix of Belgium has been used.

Table 8.2. Domestic production mix considered for the electricity production in Belgium in the year 2030. Source: Léonard and Belboom, 2016

Energy source	Year 2030
Nuclear	0%
Coal	0%
Oil	0%
Natural gas	11.65%
Natural gas, co-generation	24.07%
Wind, offshore	22.13%
Wind, onshore	12.97%
Biogas	5.75%
Biomass	7.47%
Hydro	0.70%
Waste	2.69%
Photovoltaic	10.56%
Geothermal	2.01%

For road transport in the year 2030, it has been assumed that the share of the population of lorries classified by gross vehicle weight remains stable (see Figure 5.3) but the load factor has improved from an average of 50% of load factor in the year 2012 to an average of 60% in the year 2030. Moreover, it has been considered that the emission engine technology Euro VI (which has been introduced in the year 2014) will be the main engine technology in the Belgian heavy duty vehicle market.

Table 8.3 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by the different transport processes used in the modal split of the scenarios, i.e. reference year 2012 and the best, medium and worst case scenarios for the year 2030. These transport processes are as follows: rail freight transport considering the Belgian traction mix of 2012 (i.e. 86% of electric trains and 14% of diesel trains), IWW transport of the year 2012, average road transport with a load factor of 50% of the year 2012, rail freight transport of the year 2030 (considering only electric traction and the domestic production mix of Belgium in the year 2030) and average road transport with a load factor of 60% and Euro VI emission standard for the year 2030.

Table 8.3. LCIA results of 1 tkm of freight transported by the transport processes used in the scenarios

Impact category	Unit	Year 2012			Year 2030	
		Rail transport (Belgian traction mix)	IWW	Road transport (LF 50%)	Electric trains	Road transport (LF 60% Euro VI)
Climate change	kg CO_2 eq	6.42×10^{-2}	7.47×10^{-2}	1.13×10^{-1}	5.36×10^{-2}	9.83×10^{-2}
Ozone depletion	kg CFC-11 eq	1.19×10^{-8}	7.81×10^{-9}	2.09×10^{-8}	6.13×10^{-9}	1.81×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	3.55×10^{-5}	4.74×10^{-5}	7.58×10^{-5}	2.78×10^{-5}	5.29×10^{-5}
Ionizing radiation HH	kBq U235 eq	5.85×10^{-2}	1.26×10^{-2}	9.82×10^{-3}	4.54×10^{-3}	8.46×10^{-3}
Photochemical ozone formation	kg NMVOC eq	3.03×10^{-4}	5.29×10^{-4}	8.62×10^{-4}	1.60×10^{-4}	2.82×10^{-4}
Acidification	molc H+ eq	3.64×10^{-4}	6.23×10^{-4}	7.82×10^{-4}	2.35×10^{-4}	3.44×10^{-4}
Terrestrial eutrophication	molc N eq	1.04×10^{-3}	1.98×10^{-3}	3.08×10^{-3}	5.70×10^{-4}	7.57×10^{-4}
Freshwater eutrophication	kg P eq	1.96×10^{-5}	1.94×10^{-5}	9.54×10^{-6}	1.44×10^{-5}	8.09×10^{-6}
Resource depletion	kg Sb eq	2.34×10^{-6}	6.62×10^{-7}	1.02×10^{-5}	2.41×10^{-6}	8.54×10^{-6}

Figure 8.1 shows a comparison of the results (from Table 8.3) obtained in the LCIA of one tonne-kilometre of freight transported by the inland freight transport modes used in the modal split of the different scenarios. As mentioned above, since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the transport mode with less impact and the highest value represents the maximum impact.

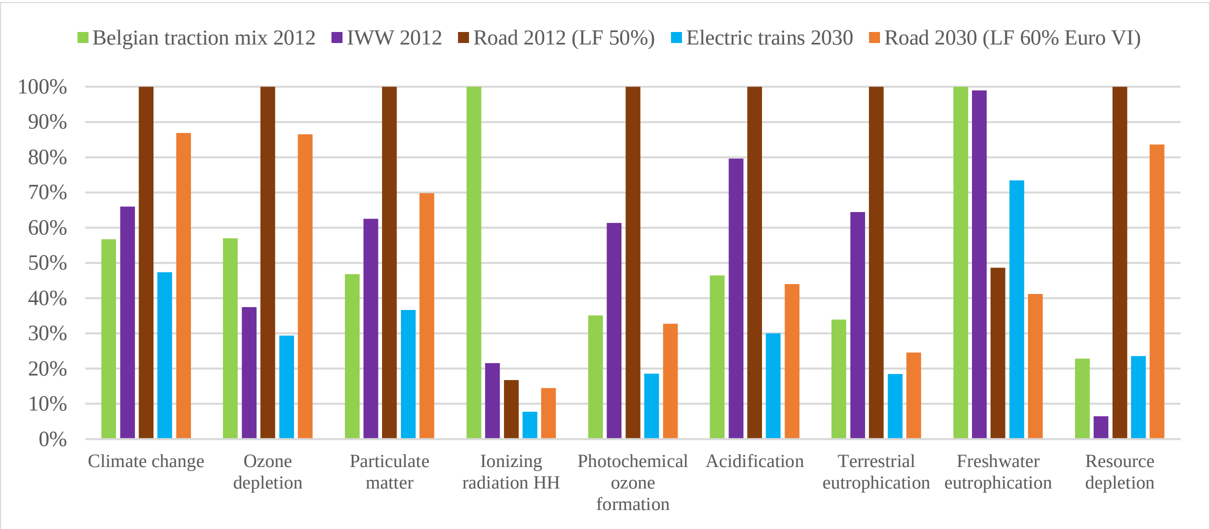


Figure 8.1. LCIA of 1 tkm of freight transported by the transport processes used in the scenarios

The average road transport with a load factor of 50% of the year 2012 presents the maximum impact in seven environmental impact indicators. The average road transport used in the three scenarios of the year 2030 has a load factor of 60% and this, together with the Euro VI emission engine technology, results in a lower environmental impact in all the indicators of the road transport process of the year 2030. The Euro VI emission engine technology influences on the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication due to the lower exhaust emissions in comparison with the other engine technologies on $PM_{2.5}$, NMVOC and NO_X.

The process rail freight transport considering the Belgian traction mix of 2012 (i.e. 86% of electric trains and 14% of diesel trains) presents the maximum impact in the indicator ionizing radiation (damage to human health) due to the use of a 41.88% of nuclear power in the electricity production in Belgium in 2012. Since it has been considered that the nuclear power will be not used in the domestic production mix of electricity in the year 2030 (see Table 8.2), the environmental impact on this indicators of the transport process electric train in the year 2030 are the lowest. Moreover, rail freight transport shows the maximum impact in the indicator freshwater eutrophication due to the railway infrastructure and the use of hard coal in the electricity generation. Electric trains in the year 2030 have a lower impact than the Belgian traction mix of 2012 due to the domestic production mix of electricity in the year 2030 does not present hard coal power anymore.

8.2.2. Life Cycle Impact Assessment of the scenarios

The LCIA of the different scenarios has been performed using the values of modal split presented in Table 8.1 and the transport processes shown in Table 8.3. Hence, it has been analysed how the change of the modal split share of rail freight affects the environmental impacts of inland freight transport in Belgium. Table 8.4 presents the results obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the reference year 2012 and the best, medium and worst case scenarios for the year 2030.

Table 8.4. LCIA results of 1 tkm of freight transported considering the modal split of the scenarios

Impact category	Unit	Modal split 2012	Scenarios in the year 2030		
			Best-case	Medium-case	Worst-case
Climate change	**kg CO_2 eq**	9.80×10^{-2}	8.44×10^{-2}	8.58×10^{-2}	8.71×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.68×10^{-8}	1.35×10^{-8}	1.39×10^{-8}	1.42×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	6.40×10^{-5}	4.67×10^{-5}	4.75×10^{-5}	4.82×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.75×10^{-2}	8.55×10^{-3}	8.68×10^{-3}	8.78×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	7.11×10^{-4}	3.09×10^{-4}	3.13×10^{-4}	3.17×10^{-4}
Acidification	**molc H+ eq**	6.88×10^{-4}	3.81×10^{-4}	3.84×10^{-4}	3.87×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.55×10^{-3}	9.76×10^{-4}	9.82×10^{-4}	9.88×10^{-4}
Freshwater eutrophication	**kg P eq**	1.31×10^{-5}	1.17×10^{-5}	1.15×10^{-5}	1.13×10^{-5}
Resource depletion	**kg Sb eq**	7.07×10^{-6}	5.67×10^{-6}	5.86×10^{-6}	6.03×10^{-6}

The results obtained from the LCIA of the different scenarios showing the contribution of every transport mode to the total environmental impact are showed in Figure 8.2. Road transport is the main contributor in all the scenarios to the total impact on all the environmental impact indicators. The only exception to this is in indicator ionizing radiation in the reference scenario of the year 2012, where rail freight transport represents 49% of the total impact due to the use of electricity produced partially with nuclear power by the electric trains.

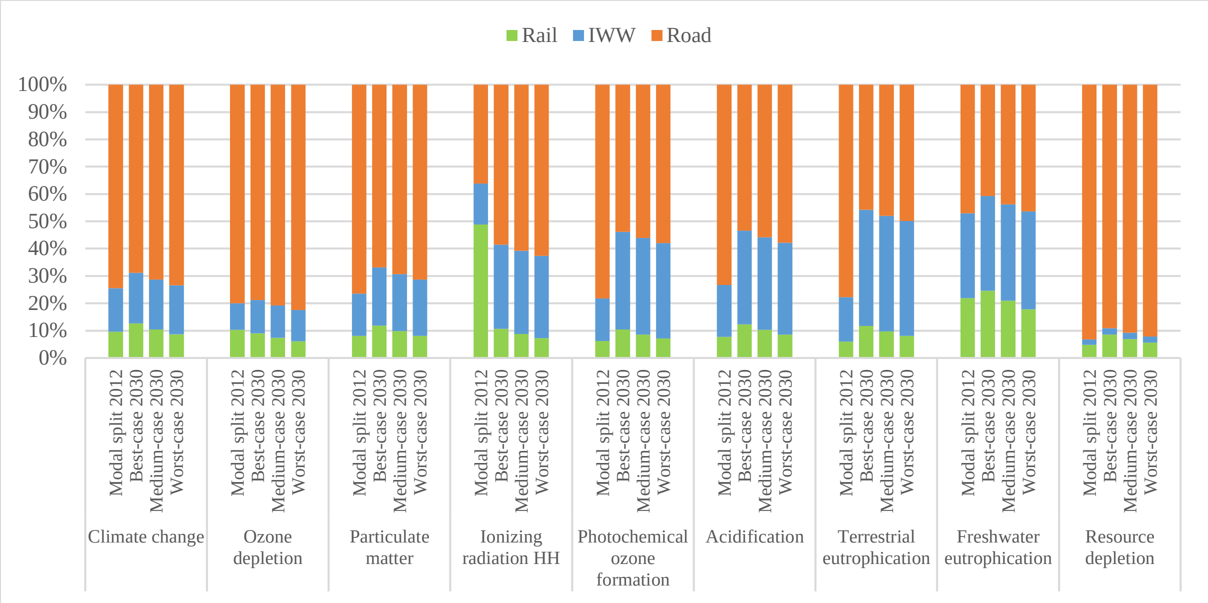


Figure 8.2. LCIA results of 1 tkm of freight transported considering the modal split of the year 2012 and the best, medium and worst case scenarios for the year 2030

Figure 8.3 presents a comparison of the results (from Table 8.4) obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the different scenarios.

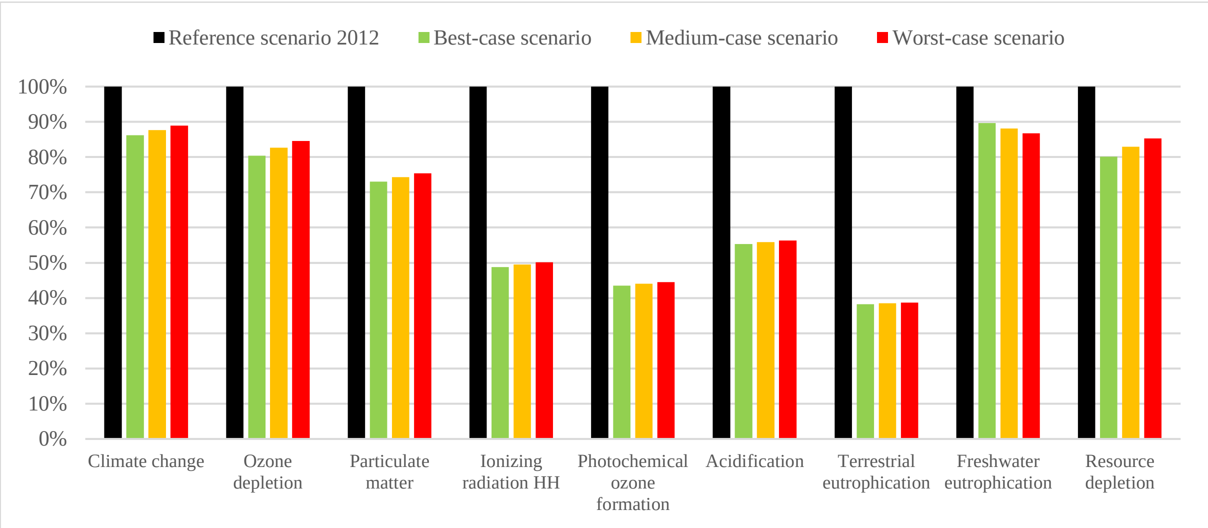


Figure 8.3. LCIA of 1 tkm of freight transported considering the modal split of the different scenarios

The reference scenario of the year 2012 shows the maximum impact in all the environmental impact indicators due to the great influence of the average road transport process with a load factor of 50%. As explained above, this process has the highest energy consumption and exhaust emissions of the transport processes considered in the study. Thereby, even the worst-case scenario, which has a slightly higher road transport share in the modal split (65% compared to the 64.5% of road transport in the modal split of 2012), has a lower impact in all the scenarios than the reference scenario due to the use of the average road transport process with a load factor of 60% and the Euro VI emission engine technology. The Euro VI emission standard used in the road transport process of 2030 reduces the impact on the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. Moreover, the non-use of nuclear power in the domestic production mix of electricity in the year 2030 (used by electric trains) influences on the indicator ionizing radiation (damage to human health).

Focusing on the three scenarios developed for the year 2030, the higher the share of road transport (and therefore lower the rail freight transport modal split share), the greater the environmental impact. It must be borne in mind that the differences between scenarios are not significant.

8.3. Environmental impact assessment of the scenarios obtained for the optimization of operational costs

The intermodal allocation model developed by Mostert et al. (2017a, 2018) has been used to obtain the flow distribution between rail, IWW and road freight transport for the economic optimization (optimization of operational costs). This model considers the existing intermodal terminals in Belgium and determine the resulting optimal flow distribution for the optimization of operational costs (Mostert et al., 2017b). Table 8.5 shows the modal split of Belgium in the year 2012 and the values calculated for the optimization of operational costs in a reference scenario and a best, medium and worst case scenarios in the year 2030.

Table 8.5. Modal split (%) in Belgium for the scenarios obtained for the optimization of operational costs

	Year 2012	Optimization of operational costs			
		Reference scenario	Best-case in 2030	Medium-case in 2030	Worst-case in 2030
Rail	14.6	23	30	23	13
IWW	20.9	4	6	4	1
Road	64.5	73	64	73	86

The purpose of this section is to analyse how the change of the modal split and the improvement of the technology used by the different transport modes affects the environmental impacts of inland freight transport in Belgium. The environmental impacts of the modal splits of the year 2012 (used as reference year), a reference scenario and the three scenarios of the year 2030 have been analysed considering the values shown in Table 8.5.

Two approaches have been used to create the transport processes of the year 2030. On the one hand, the transport processes from Section 8.2.1 have been considered. Therefore, this method takes into account the same transport processes in the three scenarios of the year 2030, focusing on the influence of the change of modal split. On the other hand, transport processes with different direct emissions to air and energy consumptions have been considered in the three scenarios of the year 2030. This method allows the study of the influence of the change of technology.

8.3.1. Analysis of the three scenarios of the year 2030 using the same transport processes

In this section, the values of modal split for the optimization of operational costs presented in Table 8.5 and the transport processes from Section 8.2.1 (see Table 8.3 and Figure 8.1) have been used. Thereby, it has been analysed how the change of modal split affects the environmental impacts of inland freight transport in Belgium.

In order to determine the environmental impacts of the modal splits of the year 2012 and the reference scenario for the optimization of operational costs, the following three processes have been used: rail freight transport considering the Belgian traction mix of 2012 (i.e. 86% of electric trains and 14% of diesel trains), IWW transport of the year 2012 and average road transport with a load factor of 50% of the year 2012. Hence, the only difference between both scenarios is the modal split.

For the analysis of the three scenarios in the year 2030, the following three processes have been considered: rail freight transport of the year 2030 (considering only electric traction and the domestic production mix of Belgium in the year 2030), IWW transport of the year 2012 and average road transport with a load factor of 60% and Euro VI emission engine technology for the year 2030.

Table 8.6 presents the results obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the reference year 2012, the reference scenario for the optimization of operational cost and the best, medium and worst case scenarios for the year 2030.

Table 8.6. LCIA results of 1 tkm of freight transported considering the modal split of the scenarios for the optimization of operational costs

Impact category	Unit	Modal split 2012	Optimization of operational costs			
			Reference scenario	Best-case in 2030	Medium-case in 2030	Worst-case in 2030
Climate change	**kg CO_2 eq**	9.80×10^{-2}	1.00×10^{-1}	8.35×10^{-2}	8.71×10^{-2}	9.23×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.68×10^{-8}	1.83×10^{-8}	1.39×10^{-8}	1.49×10^{-8}	1.64×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	6.40×10^{-5}	6.54×10^{-5}	4.50×10^{-5}	4.69×10^{-5}	4.96×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.75×10^{-2}	2.11×10^{-2}	7.54×10^{-3}	7.73×10^{-3}	8.00×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	7.11×10^{-4}	7.20×10^{-4}	2.60×10^{-4}	2.64×10^{-4}	2.69×10^{-4}
Acidification	**molc H+ eq**	6.88×10^{-4}	6.79×10^{-4}	3.28×10^{-4}	3.30×10^{-4}	3.33×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.55×10^{-3}	2.57×10^{-3}	7.75×10^{-4}	7.63×10^{-4}	7.45×10^{-4}
Freshwater eutrophication	**kg P eq**	1.31×10^{-5}	1.23×10^{-5}	1.07×10^{-5}	1.00×10^{-5}	9.02×10^{-6}
Resource depletion	**kg Sb eq**	7.07×10^{-6}	8.02×10^{-6}	6.23×10^{-6}	6.82×10^{-6}	7.67×10^{-6}

The results obtained from the LCIA of the different scenarios showing the contribution of every transport mode to the total environmental impact are shown in Figure 8.4. Road transport is the main contributor in all the scenarios to the total impact on all the environmental impact indicators. The only exception to this is in indicator ionizing radiation in the modal split and the reference scenario for the optimization of operational costs of the year 2012, where rail freight transport represents 49% and 64% of the total impact, respectively. This is due to the use of electricity produced partially with nuclear power by the electric trains.

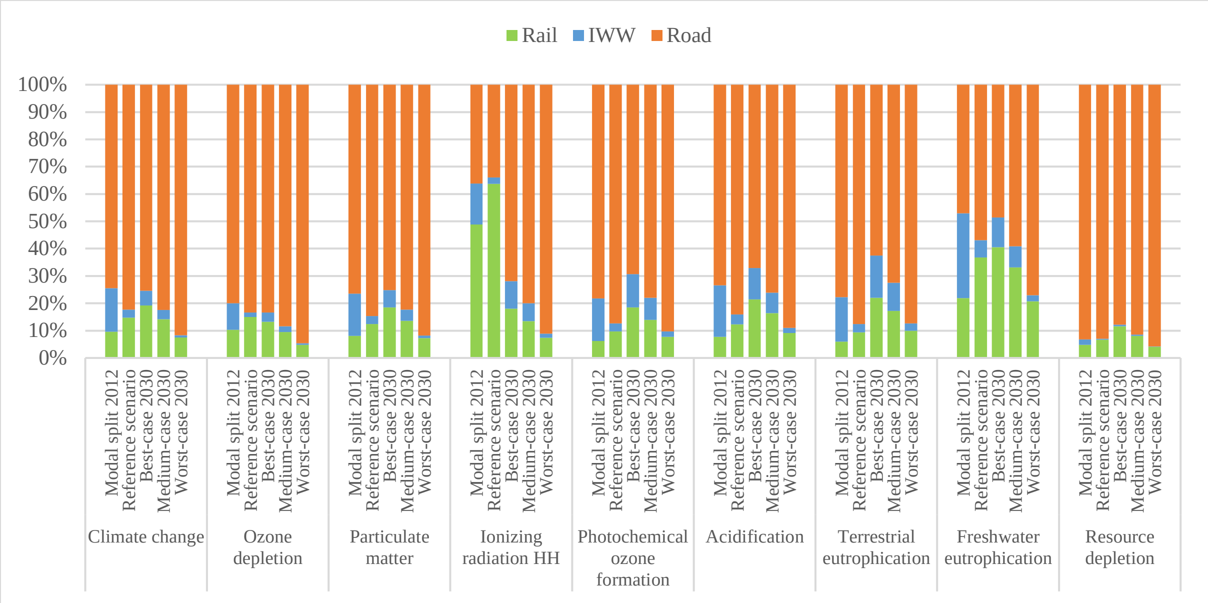


Figure 8.4. LCIA results of 1 tkm of freight transported considering the modal split of the year 2012 and the reference, best, medium and worst case scenarios for the optimization of operational costs

Figure 8.5 shows a comparison of the results (from Table 8.6) obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the different scenarios for the optimization of operational costs.

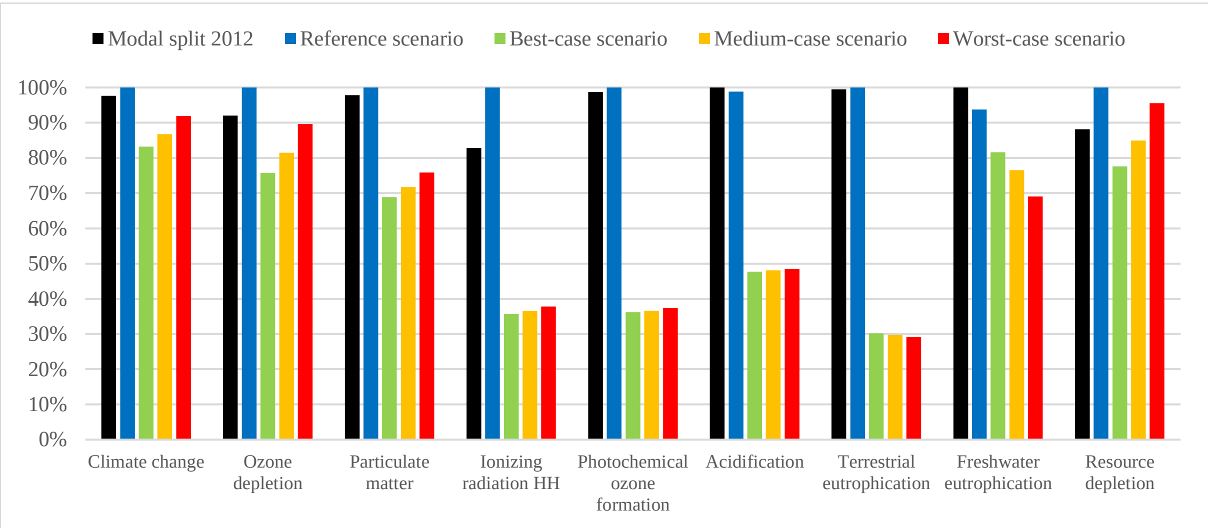


Figure 8.5. LCIA of 1 tkm of freight transported considering the modal split of the scenarios for the optimization of operational costs

As mentioned above, the transport processes used in the modal split of 2012 and the reference scenario for the optimization of operational costs are the same, being the only difference the modal split. It should be noted that even if rail freight transport increases with the optimization of operational costs (from 14.6% to 23%, resulting in a higher impact in the indicator ionizing radiation), IWW transport presents a drop in the modal split share (from 17.6% to 4%) and road transport increases (from 67.9% to 73%), causing the reference scenario to have a higher environmental impact than the modal split of 2012 in almost every indicator. However, the differences between these two scenarios are not significant.

The reference scenario has the same modal split than the medium-case scenario. However, the medium-case scenario presents lower scores in all the indicators because of the use of electric trains (using the electricity supply mix of 2030) and road transport with improved load factor (from 50% to 60%) and an engine with Euro VI emission technology. It should be noted the influence of the Euro VI emission standard used in the road transport process of 2030 on the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. Moreover, the non-use of nuclear power in the domestic production mix of electricity in the year 2030 (used by electric trains) influences on the indicator ionizing radiation (damage to human health).

Since the best-case scenario has the lowest share of road transport (64%), it presents the lowest environmental impact in almost every indicator. Within the scenarios of 2030, this scenario shows the higher score in the indicators related with the eutrophication due to the highest presence of rail transport (30%) and IWW (6%). However, the difference between the scenarios of 2030 are not significant.

8.3.2. Analysis of the three scenarios of the year 2030 using different transport processes

In this section, the values of modal split for the optimization of operational costs presented in Table 8.5 have been used. Moreover, new transport processes have been created with different direct emissions to air and energy consumptions in the three scenarios of the year 2030. Hence, it has been analysed how the improvement of the environmental performance of the different modes of transport affects the environmental impacts of inland freight transport in Belgium.

Table 8.7 presents the rates of reduction that have been applied to the direct emissions to air and energy consumptions for the best, medium and worst case scenarios in the year 2030. These reduction factors are based on technological advances in terms of energy efficiency and reduction of exhaust emissions. Since the year 2012 has been used as reference year, the rates of reduction have been applied to the direct emissions to air and energy consumptions of the following three transport processes: rail freight transport considering the Belgian traction mix of the year 2012 (i.e. 86% of electric trains and 14% of diesel trains), IWW transport of the year 2012 and average road transport with a load factor of 50% of the year 2012. Unlike in the first method (see Section 8.3.1), in this case it has been considered that in the year 2030 there will be the same traction mix for rail freight transport than in the year 2012, thus there will be an 86% of electric trains and 14% of diesel trains.

Table 8.7. Rates of reduction used for scenario creation

			Scenarios in the year 2030		
			Best	Medium	Worst
Direct emissions to air	Fuel dependent emissions (CO_2 and heavy metals)	Road	-10%	-15%	-30%
		Diesel trains	-20%		-10%
		IWW			
	Other emissions (SO_2, NO_X, NMVOC, particles, etc.)	Road	-20%	-20%	-40%
		Diesel trains	-40%		-10%
		IWW			
Energy consumption		Road	-10%	-15%	-30%
		Electric trains	-20%		-10%
		Diesel trains			
		IWW			

The rates of reduction of transport emissions have been applied only to the direct emissions to air produced during the transport operation. As mentioned above, these pollutants as direct emissions do not yet represent environmental impact categories such as climate change or photochemical ozone formation. These direct emissions during transport operation are part of the inventory analysis and this, together with the energy consumption during transport operation and the emissions, energy and material consumptions from the energy generation and the vehicle and infrastructure stages, constitute the required elements to model the freight transport system. It is necessary to consider all the elements from the inventory analysis to evaluate the contribution of the freight transport to environmental impact categories.

For the fuel dependent emissions such as CO_2 and heavy metals, the rates of reduction are the same than for energy consumption. The other direct emissions to air such as NO_X, SO_2, NMVOC or particulate matter have the same rates of reduction in the three scenarios of the year 2030. For IWW transport, the same rates of reduction of energy consumption and direct emissions to air than diesel trains have been considered in every scenario.

The only direct emissions to air considered for electric trains are the SF_6 emissions from the electricity conversion at traction substations. Thus, the rates of reduction of direct emissions to air for electric trains have been applied only for this pollutant emission. Furthermore, the electricity supply mix of the year 2030 (see Table 8.2) has been used for rail freight transport in the three scenarios.

The values of direct emissions to air and energy consumptions obtained for rail (see Table E.1), IWW (see Table E.2) and road freight transport (see Table E.3) in the best, medium and worst case scenarios of the year 2030 are in Appendix E.

As in the first method, the environmental impacts of the modal splits of the year 2012 and the reference scenario for the optimization of operational costs have been determined using the following three processes: rail freight transport considering the Belgian traction mix of 2012 (i.e. 86% of electric trains and 14% of diesel trains), IWW transport of the year 2012 and average road transport with a load factor of 50% of the year 2012. Therefore, the only difference between both scenarios is the modal split.

The LCIA of the different scenarios has been performed using the values of modal split presented in Table 8.5 and the transport processes obtained using the rates of reduction from Table 8.7. Table 8.8 presents the results obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the reference year 2012, the reference scenario and the best, medium and worst case scenarios for 2030.

Table 8.8. LCIA results of 1 tkm of freight transported considering the modal split of the scenarios for the optimization of operational costs

Impact category	Unit	Modal split 2012	Optimization of operational costs			
			Reference scenario	Best-case in 2030	Medium-case in 2030	Worst-case in 2030
Climate change	**kg CO_2 eq**	9.80×10^{-2}	1.00×10^{-1}	8.62×10^{-2}	8.78×10^{-2}	8.21×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.68×10^{-8}	1.83×10^{-8}	1.47×10^{-8}	1.53×10^{-8}	1.47×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	6.40×10^{-5}	6.54×10^{-5}	5.72×10^{-5}	6.04×10^{-5}	6.09×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.75×10^{-2}	2.11×10^{-2}	7.97×10^{-3}	8.03×10^{-3}	7.54×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	7.11×10^{-4}	7.20×10^{-4}	5.63×10^{-4}	6.12×10^{-4}	5.59×10^{-4}
Acidification	**molc H+ eq**	6.88×10^{-4}	6.79×10^{-4}	5.52×10^{-4}	5.84×10^{-4}	5.34×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.55×10^{-3}	2.57×10^{-3}	1.98×10^{-3}	2.15×10^{-3}	1.91×10^{-3}
Freshwater eutrophication	**kg P eq**	1.31×10^{-5}	1.23×10^{-5}	1.15×10^{-5}	1.09×10^{-5}	9.86×10^{-6}
Resource depletion	**kg Sb eq**	7.07×10^{-6}	8.02×10^{-6}	7.26×10^{-6}	7.99×10^{-6}	9.03×10^{-6}

The results obtained from the LCIA of the different scenarios showing the contribution of every transport mode to the total environmental impact are shown in Figure 8.6. Road transport is the main contributor in all the scenarios to the total impact on all the environmental impact indicators. The only exception to this is in indicator ionizing radiation in the modal split and the reference scenario for the optimization of operational costs of the year 2012, where rail freight transport represents 49% and 64% of the total impact, respectively. This is due to the use of electricity produced partially with nuclear power by the electric trains.

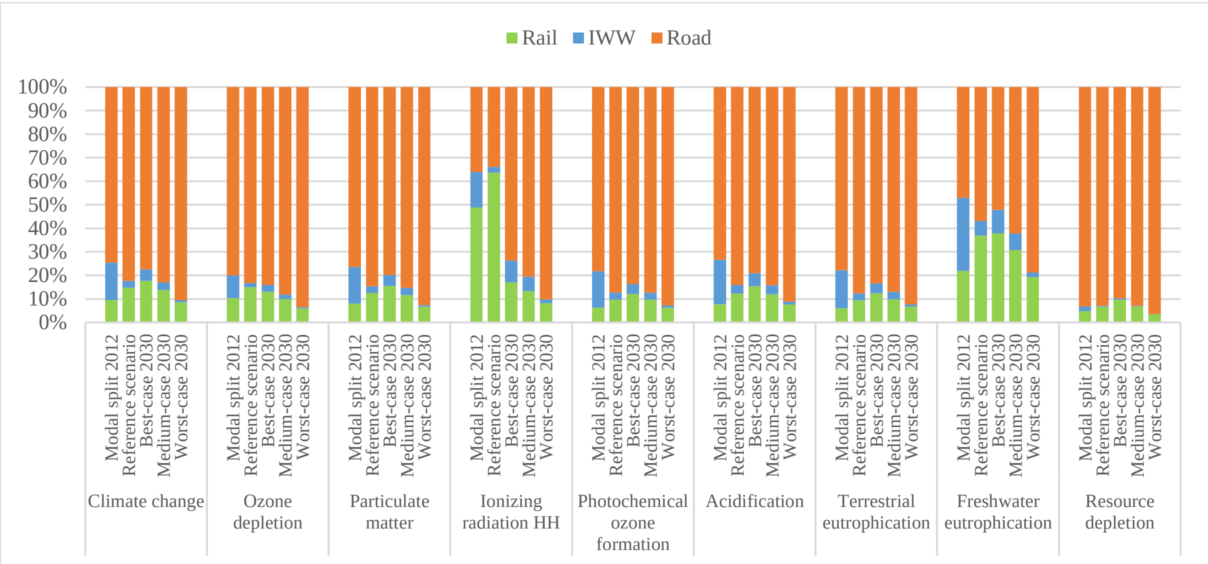


Figure 8.6. LCIA results of 1 tkm of freight transported considering the modal split of the year 2012 and the reference, best, medium and worst case scenarios for the optimization of operational costs

Figure 8.7 shows a comparison of the results (from Table 8.8) obtained in the LCIA of one tonne-kilometre of freight transported considering the modal split of the different scenarios for the optimization of operational costs. The modal split of 2012 and the reference scenario for the optimization of operational costs are the same than in the first approach. Therefore, the same conclusions as in the first method can be drawn.

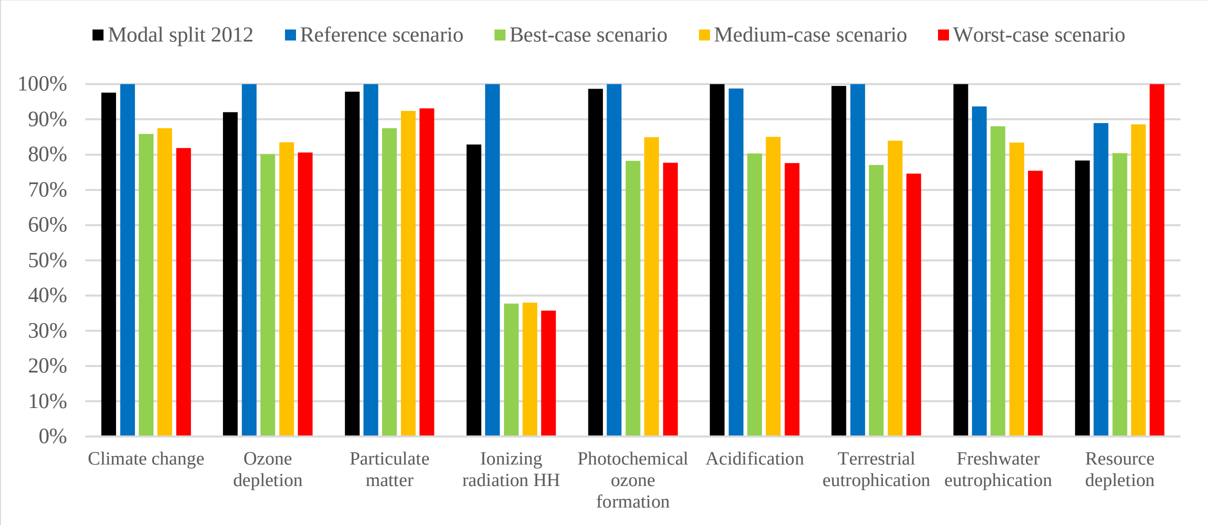


Figure 8.7. LCIA of 1 tkm of freight transported considering the modal split of the scenarios for the optimization of operational costs

The reference scenario has the same modal split than the medium-case scenario. However, the medium-case scenario presents lower scores in all the indicators because of a decrease of 15% in the energy consumption and fuel dependent emissions (i.e. CO_2 and heavy metals) and a decrease of 20% in the others direct emissions to air in all the transport modes. Moreover, the non-use of nuclear power in the domestic production mix of electricity in the year 2030 (used by electric trains) influences on the indicator ionizing radiation.

The worst-case scenario shows the higher score in the indicator resource depletion due to the highest presence of road transport (86%). It should be noted that the road transport process used in this method with a load factor of 50% has a higher environmental impact than the road transport process used in the first method, which uses a load factor of 60% and a Euro VI emission engine technology.

The reference scenario presents the highest environmental impact in the indicators climate change, particulate matter emissions and photochemical ozone formation because of the presence of a 73% of road transport with a load factor of 50% in the modal split. The three scenarios of the year 2030 show lowest values for these indicators because the reduction in all the transport processes of the energy consumption and GHG direct emissions to air in the case of the indicator climate change, the reduction of the particulate direct emissions to air in the case of the indicator particulate matter emissions and the reduction of the NO_X and NMVOC direct emissions to air in the case of the indicator photochemical ozone formation. Moreover, the use of the electricity supply mix of 2030 in the electric trains influences the reduction of the environmental impact in the indicator climate change.

Focusing in the three scenarios of 2030, the worst-case scenario has the lowest impact in the indicator climate change even though it presents the highest share of road transport (86%), since the road transport process used has been calculated considering a reduction of 30% of diesel consumption and CO_2 direct emissions to air, and a 40% of N_2O direct emissions. Otherwise, the worst-case scenario has the highest impact in the indicator particulate matter emissions (but with similar values than the medium-case scenario) because this scenario presents the highest share of road transport (86%), even though the road transport process has a reduction of 40% of particulate matter direct emissions to air. It should be noted the strong influence in the result of this indicator of the direct emissions to soil of tire, break and road wear during the road transport activity.

For the indicator photochemical ozone formation, the medium-case scenario has the highest impact because the presence of a 73% of road transport in the modal split and a reduction of only 20% of NO_X and NMVOC direct emissions to air in all the transport modes, while there is a reduction of 40% of NO_X and NMVOC direct emissions to air in the worst-case scenario for road transport and in the best-case scenario for diesel trains and IWW.

8.3.3. Conclusions of the environmental impact assessment of the scenarios obtained for the optimization of operational costs

Two methods have been used to analyse the environmental impacts of the modal splits obtained for the optimization of operational cost in Belgium. Thereby, it has been analysed how the change of the modal split and the improvement of the technology used by the different modes of transport influences the environmental impacts of inland freight transport in Belgium.

The modal split of 2012 and the reference scenario for the optimization of operational costs are the same in both methods. Moreover, the transport processes used in the modal split of 2012 and the reference scenario are the same, being the only difference the modal split. Even if the reference scenario has a higher environmental impacts than the modal split of 2012 in almost every indicator because its higher share of road transport (from 64.5% to 73%), the differences between these two scenarios are not significant.

When comparing these two scenarios with those of the year 2030, even if there is an increase of the road transport share (from 64.5% in the year 2012 to 73% and 86% in the medium and worst case scenarios, respectively), the environmental impacts are generally lower in the year 2030 for both methods. Furthermore, for some indicators there is a high difference in the environmental impacts between the scenarios of the year 2012 and those of the year 2030. Otherwise, within the scenarios of the year 2030, even with a difference of 22% in the share of road transport (from the 64% of the best-case scenario to the 86% of the worst case scenario) the differences between scenarios are not significant in both methods.

The load factor and emission engine technology are shown as determining factors in the environmental impacts of road transport process of the first method. Therefore, these factors have a strong influence in the environmental impact of the total inland freight transport due to the prominent position of road transport in Belgium. Moreover, the electricity supply mix plays a fundamental role in the environmental impacts of rail freight transport when using electric traction in both methods. Thus, as the use of electric trains increases in the future and have a higher share of the total inland freight transport, the energy split for the electricity generation will be more important in the environmental impacts of goods transport.

Considering all the above, the following question arises: which one of the following two measures would have a greater influence in the environmental impacts of inland freight transport, reducing the share of road transport in the modal split or improving the technology thus achieving a reduction of the energy consumption and direct emissions from road transport? In view of the foregoing, a better environmental performance could be achieved by improving the characteristics of the transports modes such as load factor, emission engine technology or the electricity supply mix, rather than by reducing the modal share of road transport.

However, decreasing the share of road transport in favour of more environmentally friendly and energy-efficient modes of transport such as IWW and rail is still a significant measure to apply, which in the case of rail transport becomes especially interesting when electric trains are powered by sustainable electricity. Hence, in order to reduce the environmental impacts of inland freight transport the change of modal split has to be accompanied by the improvement of technology in the transport modes.

Part IV: Conclusion and perspectives

Part I: Introduction

Chapter 1. Introduction: inland freight transport	Chapter 2. The Life Cycle Assessment methodology

Part II: Life Cycle Assessment of inland freight transport in Belgium

Chapter 3. LCA of rail freight transport	Chapter 4. LCA of inland waterways transport	Chapter 5. LCA of road freight transport

Chapter 6. Comparison of the environmental impacts of the inland freight transport modes

Part III: Environmental impact assessment of freight transport

Chapter 7. Study of intermodal freight transport routes	Chapter 8. Study of the modal split of inland freight transport in Belgium

Part IV: Conclusions and perspectives

Chapter 9. Conclusions and perspectives

Chapter 9. Conclusions and perspectives

9.1. Conclusions

This thesis is concerned with a study of the environmental impacts of rail freight intermodality using a life cycle approach. Intermodal freight transport is essentially the shifting of road freight transport in long distances to others modes of transport with improved environmental performance such as rail freight transport and IWW transport. Therefore, a study of the environmental impacts of the different inland freight transport modes in Belgium has been carried out, while focusing on rail freight transport. Moreover, several consolidated intermodal freight transport routes in Belgium and Europe have been analysed, allowing the comparison of the environmental impacts of these intermodal routes depending on the freight transport mode chosen. Finally, it has been analysed how the increase of rail freight transport as a result of the possible development of the intermodal rail freight transport affects the environmental impacts of the modal split of inland freight transport in Belgium.

There exists a current trend towards a better understanding of the environmental aspects of transport from a life cycle perspective. In the last decade, there has been an increasing number of studies using the LCA approach to study the environmental impacts of transport. This interest has increased as the LCA methodology has established itself as an effective tool to assess the environmental impacts of transport, and most importantly, to find clues about how to improve its environmental performance. The system perspective of the LCA methodology implies the need to analyse not only the direct processes related to the transport activity such as energy consumption and exhaust emissions, but also the processes connected with the energy production (including electricity and fossil fuels), vehicles and infrastructure. Moreover, the LCA methodology allows the quantification of all relevant environmental and health impacts and resource depletion issues that are associated with transport. Furthermore, as a result of the LCA perspective, the connections between the energy and the transport sector have been analysed. Hence, it has been studied how the production of electricity is a major hotspot to improve the environmental performance of electric trains.

In Chapter 3, the environmental impacts of rail freight transport in Belgium has been analysed, including diesel trains, electric trains using the electricity supply mix in Belgium and other European countries and rail freight transport considering the Belgian traction mix. On the basis of the results obtained in the LCIA of rail freight transport in the year 2012, electric trains in Belgium show a better environmental performance than diesel trains. On the one hand, the use of electric trains rather than diesel trains represents a reduction of 26% of environmental impact on climate change, 16% on ozone depletion, 46% on particulate matter, 84% on photochemical ozone formation, 70% on acidification, 86% on terrestrial eutrophication and 5% on resource depletion. On the other hand, the use of electric trains represents an increase of 89% of impact on the indicator ionizing radiation (damage to human health) and 16% on freshwater eutrophication with regard to diesel trains.

The environmental impacts of the electric trains varies widely depending of the electricity source used. Hence, the electricity supply mix of several European countries have been used to study how the electricity supply mix affects the environmental impacts of electric trains when they run through different countries in Europe. For instance, an electric train using the electricity supply mix of Poland has a higher impact on climate change, particulate matter and acidification than a diesel train in Belgium. However, it must be borne in mind that the use of electric trains leads to a reduction in local air pollution. Hence, electric trains avoid the population exposure to air pollutants such as NO_X or particles, which are emitted at ground level by diesel trains.

Focusing on the sub-systems of rail freight transport (i.e. transport operation, rail equipment and rail infrastructure), on the one hand the transport operation is the main source of impact for diesel trains in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions of diesel locomotives. On the other hand, the electricity generation is the main source of impact for electric trains in the indicators climate change, ozone depletion and ionizing radiation (damage to human health). Furthermore, the railway infrastructure is the main contributor for rail freight transport in both indicators freshwater eutrophication and resource depletion.

Chapter 4 focused in the study of the environmental impacts of IWW transport in Belgium. For IWW transport, the infrastructure sub-system (especially the port facilities demand) is the main source of impact due to the production of materials such as concrete and steel used in canals and port facilities in the indicators climate change, particulate matter, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. The transport operation sub-system is the most important source of impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication as a result of the exhaust emissions of barges.

In Chapter 5, the environmental impacts of road freight transport in Belgium have been analysed. The influence of load factor and emission engine technology in the environmental performance of road transport has been studied for an average road transport in Belgium and for an articulated lorry 34-40 tonnes. The load factor is a key factor in the environmental impact of road freight transport. Hence, the higher the load factor implies a better environmental performance. The improvement of the emission engine technology reduces the impact in the indicators particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. Therefore, each new generation of emission standards reduces the impact on these indicators. However, the emission standards do not affect the indicators ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. The road transport operation stage is the main source of impact in the indicators climate change, particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication due to the exhaust emissions. For the indicator resource depletion, the lead used in the lorry batteries is the main source of impact.

Chapter 6 compared the environmental performance of the different inland freight transport modes in Belgium. By comparing the environmental impacts at midpoint level (using the LCIA method ILCD 2011) of the different inland freight transport modes, road freight transport with a load factor of 50% presents the maximum impact in the indicators climate change, ozone depletion, particulate matter and resource depletion. Diesel trains present the maximum impact in the indicators photochemical ozone formation, acidification and terrestrial eutrophication due to the exhaust emissions produced in the diesel locomotives. It should be noted that road freight transport with a load factor of 85% can achieve a similar impact (even slightly lower) than diesel trains in the indicators climate change, ozone depletion and particulate matter. Electric trains present the maximum impact in the indicator ionizing radiation (damage to human health) due to the use of nuclear power in the electricity production in Belgium.

Focusing on the endpoint categories from the LCIA method ReCiPe 2008, road transport with a load factor of 50% presents the maximum impact in all the endpoint indicators. In the indicators at endpoint level damage to human health and ecosystems diversity because of the exhaust emissions of lorries during the transport operation and for the indicator damage to resource availability the main source of impact is the diesel production as a result of the high fuel consumption. For rail freight transport, the electricity generation is the main contributor in all the endpoint indicators. For IWW transport, the main source of impact for the endpoint indicators is the infrastructure construction.

Chapter 7 focused on the environmental impacts of different intermodal routes in Belgium and Europe depending on the transport mode chosen but carrying the same number of containers with the same load. Therefore, as cargo is equal, the main factor that determines the final impact for each transport mode is the distance travelled along the intermodal route. Since the road network is greater than the railway and IWW network, road transport is usually the shortest possible route. For the European intermodal routes, the environmental impact of electric trains varies depending of the electricity supply mix of the different countries. Electric trains present the lowest impact in all the intermodal routes on particulate matter and photochemical ozone formation. Diesel trains show the maximum impact on particulate matter due to the higher exhaust emissions on $PM_{2.5}$ and NO_X of diesel locomotives during the transport operation. Similarly, diesel trains present the maximum impact on photochemical ozone formation as a result of the greater exhaust emissions on NO_X and NMVOC of diesel locomotives during the transport operation

In Chapter 8, the environmental impact of the modal splits of inland freight transport in Belgium has been analysed for several scenarios such as the increase of rail freight transport or the optimization of the operational costs and environmental factors. It has been analysed how the change of the modal split and the improvement of the technology used by the different transport modes influences the environmental impacts of inland freight transport in Belgium. On the one hand, the improvement of the technology of the different modes of transport with the aim of reducing direct emissions and energy consumption are decisive regarding the reduction of the environmental impacts of transport. Moreover, the electricity supply mix is shown as a determining factor in the environmental impacts of electric trains. On the other hand, decreasing the share of road transport in the modal split produces modest results but is still shown to be an effective measure to reduce the environmental impact of transport. Therefore, in order to reduce the environmental impacts of inland freight transport the change of modal split has to be accompanied by the improvement of technology in the transport modes.

Overall, electric trains in Belgium presents a lower environmental impact compared to road transport. However, the environmental performance of electric trains is highly dependent on the electricity source. Hence, the same electric train can have a different environmental impact depending on the country in which it is located. Diesel trains show a greater environmental impact than road transport in the impact categories where the exhaust emissions are decisive due to the high exhaust emissions of diesel locomotives. When road transport is performed with high load factors and vehicles with new standard emissions, it can achieve a better environmental performance than rail or IWW transport. Furthermore, road transport has a more extended road network, allowing the reduction of transport distances in most cases compared to rail and IWW transport (which is itself strongly limited by geographical conditions). This shorter distances allows road transport to have a lower environmental impact on certain routes.

9.2.Recommendations

In view of the results obtained in our study, a better environmental performance of intermodal freight transport could be achieved by improving the characteristics of the inland freight transports modes such as energy efficiency, load factor, emission technology, use of alternative fuels and the electricity used in electric trains. Some recommendations based on this research have been formulated to improve the environmental impacts of intermodal freight transport.

9.2.1. Increase of the share of electric trains in the Belgian traction mix

In view of the results obtained in our study, electric trains show a better life-cycle environmental performance than diesel trains. Thereby, electric trains are more energy-efficient than diesel trains and the use of electric locomotives rather than diesel locomotives enables to transport heavier loads. It should be noted that even though the use of diesel is present in rail freight transport in Belgium, the use of electric traction is much greater. Moreover, the use of diesel traction is decreasing in Belgium, which means that only a small part of the rail freight produces exhaust emissions. Therefore, the increased use of electric trains in intermodal transport represents an opportunity to attain a more environmentally and health-friendly, and energy-efficient transport system.

9.2.2. Enhancement of the electricity supply mix used by electric trains

The electricity supply mix is a decisive factor in the environmental performance of rail freight transport when using electric traction. Thus, as the use of electric trains increases in the future and have a higher share of the total inland freight transport, the energy mix for the electricity generation will be more important in the environmental impacts of goods transport. Since the use of electric trains becomes especially interesting when they are powered by sustainable electricity, the liberalization of the energy supplier market for the rail freight transport companies could be seen as an opportunity to improve the electric supply mix of electric trains. Rail freight transport operators could commit to clean electricity as a competitive factor. However, this could also have a negative effect, since companies could opt for cheaper energies such as nuclear energy or coal. It must be borne in mind that nuclear fission does not produce direct air emissions such as GHG for example, but instead nuclear wastes with a high potential impact on human health and ecosystems are produced.

9.2.3. Increase of the energy efficiency of freight transport

The transport is the sector with the highest energy consumption in the EU-28 and the second in Belgium. Therefore, the search for a more energy-efficient transport system becomes necessary. Within rail freight transport, electric traction has the lowest energy consumption, while diesel traction has the highest. IWW transport is the most energy-efficient mode of inland freight transport. Focusing on road transport, our study shows that the energy consumption is highly dependent of the load factor. Thereby, an average road freight transport with a load factor of 50% presents the highest energy consumption among the different transport modes. However, an articulated lorry of 34-40 t with an 85% of load factor presents lower energy consumption than diesel trains.

9.2.4. Increase of load factors in freight transport

The increase of load factors reduces the energy consumption on transport. Higher load factors in freight transport can be achieved through the shifting of road freight transport in long distances to rail freight transport. Thereby, the higher payload capacity of trains promotes their shared use by several companies, which would improve the load factor and a reduction of the transport intensity. Moreover, the higher operating costs of rail freight transport entail the optimization of the load factor to make it profitable. Furthermore, rail freight transport improves its energy-efficiency through the use of longer and heavier trains.

9.2.5. Improvement of the emission technology of the vehicles used in freight transport

Road transport is the main source of NOx emissions in the EU-28 and Belgium. Moreover, transport is a major source of air pollutants such as particles ($PM_{2.5}$ and PM_{10}) and NMVOC. The emission technology of a vehicle as a diesel locomotive, barge or lorry is a determining factor in the environmental impacts of freight transport. The air pollutant emissions from road transport have decreased over the years as a result of the implementation of the Euro emission standards, which have promoted enhancements of the emission control technologies.

In view of the results obtained in our study, diesel trains present the highest emissions of NO_X emissions to air, which is determinant in the environmental performance of diesel trains. The high exhaust emissions (including NO_X) of diesel locomotives could be reduced through the implementation of new engines with better emission technologies. However, the long life span of the locomotives (around 40 years) causes a low rate of replacement and therefore a slow implementation of new engines with better emission technologies. This compares with the higher rate of renewal of the lorry fleet causing a faster improvement in road transport emissions.

9.2.6. Use of alternatives fuels

The use of alternative fuels can lead to the reduction of environmental impacts. For instance, the use of biodiesel produces advantages in terms of CO_2 emissions. However, if we consider the complete life cycle of biodiesel, the advantages in terms of impact on climate change may be compromised by the greater impact in other environmental impacts during the production of biodiesel. Hence, the pollution can be transferred from air when combusting to soil and water during crop production. Therefore, the environmental advantages of the use of biodiesel depend on the specific type and source of the biodiesel. Furthermore, other pollutants emitted during the transport activity as exhaust emissions such as NO_X or particles may not be reduced by the use of biodiesel. Hence, the photochemical ozone and particulate matter formation in cities would therefore not be affected.

The use of low-sulphur fuels has proven to be effective in ensuring a reduction of the direct SO_2 emissions of freight transport. This is because the exhaust emissions of SO_2 are dependent on the sulphur content in fuels. Therefore, the higher the sulphur content in the fuel, the greater the SO_2 emissions. The fuel quality legislation has been shown as an effective measure to reduce the exhaust SO_2 emissions. In Belgium, the amount of sulphur by mass permissible for diesel used by diesel locomotives and lorries is 10 ppm from 2009. However, diesel in Belgium has an average sulphur content of 8 ppm since 2008. Similarly, the gas-oil used in barges has a limit of sulphur content of 10 ppm from 2011.

Another example of alternative fuels is the hydrogen in rail freight transport. The use of hydrogen fuel-cell locomotives is especially interesting for shunting activity, since it avoids the exhaust emissions of pollutants as NO_X or particles from diesel locomotives in surrounding areas, which are usually populated. However, the production of hydrogen should be considered regarding the environmental performance from a life cycle perspective.

9.3.Perspectives

Several interesting perspectives arise from the results of this thesis. They are categorized into three groups: perspectives related to an update and improvement of the considered data, enhancement of the LCA methodology and extensions of some parts of this thesis.

Considering the improvement of the collected data, a key limiting factor in this thesis has been the lack of available data regarding Belgian freight transport. Moreover, the data collection has been even more difficult due to the existence of several freight operators and the regionalization of information in Belgium. In order to address this lack of information, two approaches have been used: the extrapolation of data from past years and the use of European averages extracted from commercial databases. Therefore, the collection of more specific data on transport in Belgium would improve this research. This could be achieved by establishing further partnerships with the most representative actors in the transport sector, which would allow conducting interviews or even collecting data on the field.

Due to a lack of available data for recent years, the environmental impacts of inland freight transport has been analysed in the period from 2006 to 2012. However, this implies that this study does not account for recent changes in transport, such as variations in the modal split, rail freight traction share, electricity mix used by electric trains or use of new engine emission technologies. Among these, the introduction of the emission standard Euro VI in the Belgian heavy duty market in the year 2014 has to be highlighted. It is believed that these changes could potentially affect the environmental impacts of the different modes of transport, and thus an extension to more recent years should be performed.

This research has presented some limitations related to the LCA methodology as well. For example, the environmental impact indicators required to determine accidents damage, noise impact and land use need to be improved from a methodological point of view. Thereby, these environmental impacts have not been considered in this thesis, even though they would be of great interest in our context. Other environmental impact indicators such as those related to human toxicity and ecotoxicity are not fully mature because some substances are not fully considered in the characterisation models and therefore their contribution to the impact indicator results is not reflected. However, these and other indicators are currently being developed and improved, and it would be interesting to consider them in our study when they are completely operational.

Finally, some aspects of this thesis should be further investigated. A natural extension would be to develop a similar study for other countries. Most of the methodology and tools developed for this thesis could be directly reused for the case of other countries, possibly by making only some specific adaptations. Another extension would be the study of other intermodal routes, which could be compared with the ones considered in this thesis and which could also complement the application of the methodology on other countries. Further research activities could include the environmental impact assessment of intermodal terminals and ports, including a deeper analysis of the cargo handling equipment such as gantry cranes or reach stackers used in intermodal terminal. This would be interesting because intermodal terminals and ports are a key element in intermodal transport due to their connecting role in the transport routes. Moreover, to the best of our knowledge this area has not been thoroughly studied in the literature.

Appendix A

The author of this thesis is most thankful to all interviewees and respondents, and their home organizations, for providing valuable information to carry out this research. We especially thank Infrabel for all the information received on railway infrastructure. Likewise, we would like to thank LINEAS, ITB (Instituut voor het Transport langs de Binnenwateren / Institut pour le Transport par Batellerie) and Terminal Container Athus for assistance with data collection (see Table A.1).

Table A.1. List of resource persons

<table>
<tr><th>Company</th><th>Contact</th><th>Contact type</th><th>Data provided</th></tr>
<tr><td rowspan="5">Infrabel</td><td>Guy Hendrix
Els Houtman</td><td>Meeting</td><td>Information on Infrabel</td></tr>
<tr><td>Stéphane Floss</td><td>Meeting</td><td>Information on Infrabel</td></tr>
<tr><td>Marie-Bernadette Gennotte</td><td>Questionnaire</td><td>Data on railway infrastructure</td></tr>
<tr><td>Jürgen Sohier
Arnaud Fougère
Michaël Cowez</td><td>Questionnaire</td><td>Data on overhead contact line systems</td></tr>
<tr><td>Stéphanie Dufour</td><td>Questionnaire</td><td>Data on railway infrastructure</td></tr>
<tr><td rowspan="2">LINEAS</td><td>Frédéric Buyse</td><td>Meeting</td><td>Information on intermodal transport</td></tr>
<tr><td>Niels Muys</td><td>Meeting</td><td>Rail equipment used by LINEAS</td></tr>
<tr><td>ITB</td><td>Frédéric Swiderski</td><td>Questionnaire</td><td>Data on IWW transport</td></tr>
<tr><td>Terminal Container Athus</td><td>Benoît Collet</td><td>Questionnaire</td><td>Data on the intermodal terminal processes</td></tr>
<tr><td>Logistics in Wallonia</td><td>Bernad Piette</td><td>Meeting</td><td>Information on intermodal transport in Belgium</td></tr>
</table>

Appendix B

As stated in Section 4.2.1, the energy consumption calculated for IWW transport can change significantly depending on the chosen literature source. In this appendix, the average energy consumption during the IWW transport operation has been calculated using the class specific fuel consumption of barges from Spielmann et al. (2007) shown in Table 4.1. The methodology followed in this appendix is the same as used in Section 4.2.1.

Table B.1 shows the average fuel consumption of IWW transport calculated from the period 2006 to 2012 using the specific fuel consumptions from Spielmann et al. (2007). By comparing the values obtained in our study for Belgium (see Table 4.5) with the values obtained in this appendix, these values are higher than the results obtained for Belgium using the class specific fuel consumption of barges in Wallonia from Service Public de Wallonie (2014). Furthermore, the values from Table B.1 are lower than the energy consumption for IWW transport used in the Ecoinvent v3 database (402 kJ/tkm). As mentioned in Section 4.2.1, the value of the Ecoinvent v3 database for the year 2014 is calculated by Spielmann et al. (2007) using the same specific energy consumption than those used in this appendix.

Table B.1. Average fuel consumption of IWW transport of dry bulk using the class specific fuel consumption of barges from Spielmann et al. (2007)

Unit	2006	2007	2008	2009	2010	2011	2012
g/tkm	9.36	9.26	9.19	9.13	9.07	9.02	8.98
kJ/tkm[1]	400	396	393	391	388	386	384

[1]Considering that diesel net calories are 42.8 MJ/kg

In order to determine the direct emissions during the IWW transport operation for every year, following the same methodology described in Section 4.2.2, the emission factors from Spielmann et al. (2007) and the calculated fuel consumptions have been used. Table B.2 presents the direct emissions of barges in Belgium using the fuel consumption from Table B.1.

Table B.2. Direct emissions (g/tkm) of IWW transport calculated using the values on energy consumption from by Spielmann et al. (2007)

IWW transport (g/tkm)	2006	2007	2008	2009	2010	2011	2012
CO_2	29.68	29.37	29.14	28.97	28.77	28.61	28.48
SO_2	3.74×10^{-2}	3.70×10^{-2}	1.84×10^{-2}	1.83×10^{-2}	1.81×10^{-2}	1.80×10^{-4}	1.80×10^{-4}
Cd	9.36×10^{-8}	9.26×10^{-8}	9.19×10^{-8}	9.13×10^{-8}	9.07×10^{-8}	9.02×10^{-8}	8.98×10^{-8}
Cu	1.59×10^{-5}	1.57×10^{-5}	1.56×10^{-5}	1.55×10^{-5}	1.54×10^{-5}	1.53×10^{-5}	1.53×10^{-5}
Cr	4.68×10^{-7}	4.63×10^{-7}	4.59×10^{-7}	4.57×10^{-7}	4.54×10^{-7}	4.51×10^{-7}	4.49×10^{-7}
Ni	6.55×10^{-7}	6.48×10^{-7}	6.43×10^{-7}	6.39×10^{-7}	6.35×10^{-7}	6.31×10^{-7}	6.28×10^{-7}
Se	9.36×10^{-8}	9.26×10^{-8}	9.19×10^{-8}	9.13×10^{-8}	9.07×10^{-8}	9.02×10^{-8}	8.98×10^{-8}
Zn	9.36×10^{-6}	9.26×10^{-6}	9.19×10^{-6}	9.13×10^{-6}	9.07×10^{-6}	9.02×10^{-6}	8.98×10^{-6}
Pb	1.03×10^{-9}	1.02×10^{-9}	1.01×10^{-9}	1.00×10^{-9}	9.98×10^{-10}	9.92×10^{-10}	9.87×10^{-10}
Hg	1.87×10^{-10}	1.85×10^{-10}	1.84×10^{-10}	1.83×10^{-10}	1.81×10^{-10}	1.80×10^{-10}	1.80×10^{-10}
CO	2.53×10^{-2}	2.50×10^{-2}	2.48×10^{-2}	2.47×10^{-2}	2.45×10^{-2}	2.44×10^{-2}	2.42×10^{-2}
NO_X	4.68×10^{-1}	4.63×10^{-1}	4.59×10^{-1}	4.57×10^{-1}	4.54×10^{-1}	4.51×10^{-1}	4.49×10^{-1}
$PM_{2.5}$	8.64×10^{-3}	8.55×10^{-3}	8.48×10^{-3}	8.43×10^{-3}	8.37×10^{-3}	8.32×10^{-3}	8.29×10^{-3}
PM_{10}	3.65×10^{-4}	3.61×10^{-4}	3.58×10^{-4}	3.56×10^{-4}	3.54×10^{-4}	3.52×10^{-4}	3.50×10^{-4}
$PM_{10} > PM > PM_{2.5}$	7.20×10^{-4}	7.13×10^{-4}	7.07×10^{-4}	7.03×10^{-4}	6.98×10^{-4}	6.94×10^{-4}	6.91×10^{-4}
Methane	2.25×10^{-4}	2.22×10^{-4}	2.21×10^{-4}	2.19×10^{-4}	2.18×10^{-4}	2.16×10^{-4}	2.15×10^{-4}
Toluene	7.49×10^{-5}	7.41×10^{-5}	7.35×10^{-5}	7.31×10^{-5}	7.26×10^{-5}	7.22×10^{-5}	7.18×10^{-5}
Benzene	1.78×10^{-4}	1.76×10^{-4}	1.75×10^{-4}	1.74×10^{-4}	1.72×10^{-4}	1.71×10^{-4}	1.71×10^{-4}
Xylene	7.49×10^{-5}	7.41×10^{-5}	7.35×10^{-5}	7.31×10^{-5}	7.26×10^{-5}	7.22×10^{-5}	7.18×10^{-5}
NMVOC	9.36×10^{-3}	9.26×10^{-3}	9.19×10^{-3}	9.13×10^{-3}	9.07×10^{-3}	9.02×10^{-3}	8.98×10^{-3}
NH_3	4.85×10^{-4}	4.80×10^{-4}	4.77×10^{-4}	4.74×10^{-4}	4.70×10^{-4}	4.68×10^{-4}	4.66×10^{-4}
N_2O	7.49×10^{-4}	7.41×10^{-4}	7.35×10^{-4}	7.31×10^{-4}	7.26×10^{-4}	7.22×10^{-4}	7.18×10^{-4}
Benzo(a)pyrene	7.20×10^{-8}	7.13×10^{-8}	7.07×10^{-8}	7.03×10^{-8}	6.98×10^{-8}	6.94×10^{-8}	6.91×10^{-8}
HCl	9.92×10^{-6}	9.82×10^{-6}	9.74×10^{-6}	9.68×10^{-6}	9.61×10^{-6}	9.56×10^{-6}	9.52×10^{-6}

Table B.3 presents the results obtained in the Life Cycle Impact Assessment (LCIA) of one tonne-kilometre of freight transported by barge in Belgium from 2006 to 2012. The vessel, canal and port demands remain the same than the used in the environmental impact of IWW transport in canal, upstream or downstream in Belgium.

Table B.3. LCIA of 1 tkm transported by IWW transport in Belgium using the values on energy consumption from by Spielmann et al. (2007)

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	9.04×10^{-2}	8.69×10^{-2}	8.57×10^{-2}	9.57×10^{-2}	8.66×10^{-2}	8.45×10^{-2}	8.32×10^{-2}
Ozone depletion	**kg CFC-11 eq**	9.99×10^{-9}	9.71×10^{-9}	9.59×10^{-9}	1.02×10^{-8}	9.61×10^{-9}	9.45×10^{-9}	9.37×10^{-9}
Particulate matter	**kg $PM_{2.5}$ eq**	5.71×10^{-5}	5.43×10^{-5}	5.21×10^{-5}	5.96×10^{-5}	5.32×10^{-5}	5.06×10^{-5}	5.01×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	1.45×10^{-2}	1.35×10^{-2}	1.31×10^{-2}	1.52×10^{-2}	1.37×10^{-2}	1.32×10^{-2}	1.32×10^{-2}
Photochemical ozone formation	**kg NMVOC eq**	6.93×10^{-4}	6.82×10^{-4}	6.73×10^{-4}	6.98×10^{-4}	6.65×10^{-4}	6.58×10^{-4}	6.52×10^{-4}
Acidification	**molc H+ eq**	8.23×10^{-4}	7.95×10^{-4}	7.59×10^{-4}	8.22×10^{-4}	7.66×10^{-4}	7.27×10^{-4}	7.22×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.63×10^{-3}	2.58×10^{-3}	2.55×10^{-3}	2.64×10^{-3}	2.54×10^{-3}	2.51×10^{-3}	2.49×10^{-3}
Freshwater eutrophication	**kg P eq**	2.16×10^{-5}	2.03×10^{-5}	1.97×10^{-5}	2.34×10^{-5}	2.04×10^{-5}	1.97×10^{-5}	1.95×10^{-5}
Resource depletion	**kg Sb eq**	7.54×10^{-7}	7.59×10^{-7}	7.61×10^{-7}	8.59×10^{-7}	7.13×10^{-7}	7.20×10^{-7}	6.80×10^{-7}

Figure B.1 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by barge in Belgium (from Table B.3). The year 2009 presents the maximum impact in almost all the indicators mainly due to this year presents the highest demand of canals and port facilities. However, there are no significant differences among the years, especially between the years 2006 and 2009.

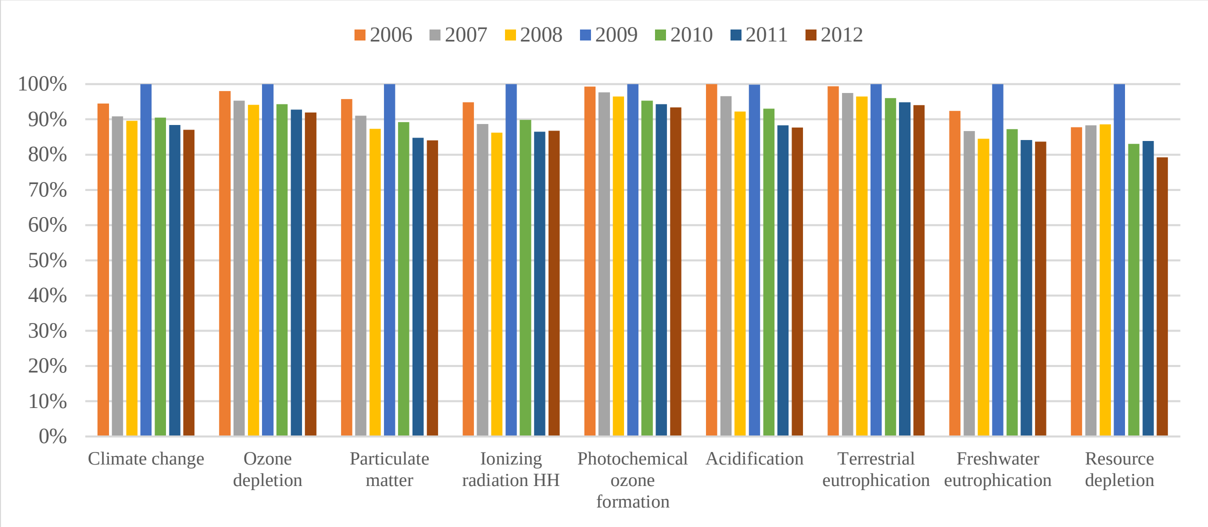


Figure B.1. LCIA of 1 tkm transported by IWW transport in Belgium using the values on energy consumption from by Spielmann et al. (2007)

Appendix C

Tables C.1 and C.2 show the values used in the road transport processes of Ecoinvent v3 database. These values from Ecoinvent v3 represent European averages.

Table C.1. Inputs and outputs of 1 tkm transported by the lorries 3.5 - 7.5 t and 7.5 - 16 t used in the road transport processes of Ecoinvent v3 database (European average). Source: Weidema et al., 2013

	Lorry 3.5 - 7.5 t				Lorry 7.5 - 16 t			
	Euro III	**Euro IV**	**Euro V**	**Euro VI**	**Euro III**	**Euro IV**	**Euro V**	**Euro VI**
Fuel consumption (g/tkm)	111.17	109.56	109.30	109.60	48.08	47.33	47.30	47.21
Exhaust emissions (g/tkm)								
CO_2	353.08	347.90	347.07	348.04	151.96	149.72	149.62	149.11
SO_2	1.78×10^{-3}	1.75×10^{-3}	1.74×10^{-3}	1.75×10^{-3}	7.55×10^{-4}	7.41×10^{-4}	7.40×10^{-4}	7.40×10^{-4}
Cd	9.67×10^{-7}	9.53×10^{-7}	9.51×10^{-7}	9.54×10^{-7}	4.18×10^{-7}	4.12×10^{-7}	4.12×10^{-7}	4.11×10^{-7}
Cu	2.36×10^{-6}	2.32×10^{-6}	2.32×10^{-6}	2.32×10^{-6}	1.02×10^{-6}	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}
Cr	3.34×10^{-6}	3.29×10^{-6}	3.28×10^{-6}	3.29×10^{-6}	1.44×10^{-6}	1.42×10^{-6}	1.42×10^{-6}	1.42×10^{-6}
Ni	9.78×10^{-7}	9.64×10^{-7}	9.62×10^{-7}	9.64×10^{-7}	4.23×10^{-7}	4.17×10^{-7}	4.16×10^{-7}	4.15×10^{-7}
Se	1.11×10^{-8}	1.10×10^{-8}	1.09×10^{-8}	1.10×10^{-8}	4.81×10^{-9}	4.73×10^{-9}	4.73×10^{-9}	4.72×10^{-9}
Zn	1.93×10^{-4}	1.90×10^{-4}	1.90×10^{-4}	1.90×10^{-4}	8.36×10^{-5}	8.23×10^{-5}	8.22×10^{-5}	8.20×10^{-5}
Pb	5.79×10^{-6}	5.71×10^{-6}	5.69×10^{-6}	5.71×10^{-6}	2.50×10^{-6}	2.47×10^{-6}	2.46×10^{-6}	2.46×10^{-6}
Hg	5.89×10^{-7}	5.81×10^{-7}	5.79×10^{-7}	5.81×10^{-7}	2.55×10^{-7}	2.51×10^{-7}	2.51×10^{-7}	2.50×10^{-7}
Cr (VI)	6.67×10^{-9}	6.57×10^{-9}	6.56×10^{-9}	6.58×10^{-9}	2.88×10^{-9}	2.84×10^{-9}	2.84×10^{-9}	2.83×10^{-9}
As	1.11×10^{-8}	1.10×10^{-8}	1.09×10^{-8}	1.10×10^{-8}	4.81×10^{-9}	4.73×10^{-9}	4.73×10^{-9}	4.72×10^{-9}
CO	5.11×10^{-1}	4.87×10^{-1}	4.90×10^{-1}	2.72×10^{-1}	2.32×10^{-1}	2.21×10^{-1}	2.22×10^{-1}	1.27×10^{-1}
NO_X	2.51	1.43	8.29×10^{-1}	1.27×10^{-1}	1.14	6.47×10^{-1}	3.98×10^{-1}	6.38×10^{-2}
$PM_{2.5}$	4.76×10^{-2}	8.37×10^{-3}	8.43×10^{-3}	1.36×10^{-3}	2.29×10^{-2}	4.09×10^{-3}	4.13×10^{-3}	5.99×10^{-4}
Methane	2.29×10^{-3}	2.62×10^{-4}	2.63×10^{-4}	2.05×10^{-4}	1.07×10^{-3}	1.22×10^{-4}	1.22×10^{-4}	9.42×10^{-5}
Ethane	2.79×10^{-5}	3.20×10^{-6}	3.21×10^{-6}	2.50×10^{-6}	1.34×10^{-5}	1.48×10^{-6}	1.49×10^{-6}	1.15×10^{-6}
Propane	9.31×10^{-5}	1.07×10^{-5}	1.07×10^{-5}	8.33×10^{-6}	4.46×10^{-5}	4.95×10^{-6}	4.97×10^{-6}	3.83×10^{-6}
Butane	1.40×10^{-4}	1.60×10^{-5}	1.61×10^{-5}	1.25×10^{-5}	6.70×10^{-5}	7.42×10^{-6}	7.46×10^{-6}	5.75×10^{-6}
Pentane	5.59×10^{-5}	6.40×10^{-6}	6.42×10^{-6}	5.00×10^{-6}	2.68×10^{-5}	2.97×10^{-6}	2.98×10^{-6}	2.30×10^{-6}
Heptane	2.79×10^{-4}	3.20×10^{-5}	3.21×10^{-5}	2.50×10^{-5}	1.34×10^{-4}	1.48×10^{-5}	1.49×10^{-5}	1.15×10^{-5}
Acrolein	1.65×10^{-3}	1.89×10^{-4}	1.89×10^{-4}	1.47×10^{-4}	7.90×10^{-4}	8.75×10^{-5}	8.80×10^{-5}	6.78×10^{-5}
Styrene	5.21×10^{-4}	5.98×10^{-5}	5.99×10^{-5}	4.66×10^{-5}	2.50×10^{-4}	2.77×10^{-5}	2.78×10^{-5}	2.15×10^{-5}
Benzaldehyde	1.28×10^{-3}	1.46×10^{-4}	1.47×10^{-4}	1.14×10^{-4}	6.12×10^{-4}	6.78×10^{-5}	6.81×10^{-5}	5.25×10^{-5}
Toluene	9.31×10^{-6}	1.07×10^{-6}	1.07×10^{-6}	8.33×10^{-7}	4.46×10^{-6}	4.95×10^{-7}	4.97×10^{-7}	3.83×10^{-7}
Benzene	6.52×10^{-5}	7.47×10^{-6}	7.49×10^{-6}	5.83×10^{-6}	3.12×10^{-5}	3.46×10^{-6}	3.48×10^{-6}	2.68×10^{-6}
m-Xylene	9.13×10^{-4}	1.05×10^{-4}	1.05×10^{-4}	8.16×10^{-5}	4.37×10^{-4}	4.85×10^{-5}	4.87×10^{-5}	3.75×10^{-5}
o-Xylene	3.72×10^{-4}	4.27×10^{-5}	4.28×10^{-5}	3.33×10^{-5}	1.79×10^{-4}	1.98×10^{-5}	1.99×10^{-5}	1.53×10^{-5}
Formaldehyde	7.82×10^{-3}	8.97×10^{-4}	8.99×10^{-4}	7.00×10^{-4}	3.75×10^{-3}	4.15×10^{-4}	4.18×10^{-4}	3.22×10^{-4}
Acetaldehyde	4.26×10^{-3}	488×10^{-4}	4.89×10^{-4}	3.81×10^{-4}	2.04×10^{-3}	2.26×10^{-4}	2.27×10^{-4}	1.75×10^{-4}
NMVOC	7.56×10^{-2}	8.67×10^{-3}	8.70×10^{-3}	6.77×10^{-3}	3.63×10^{-2}	4.02×10^{-3}	4.04×10^{-3}	3.11×10^{-3}
NH_3	3.05×10^{-3}	3.05×10^{-3}	3.05×10^{-3}	3.05×10^{-3}	9.13×10^{-4}	9.13×10^{-4}	9.13×10^{-4}	9.13×10^{-4}
N_2O	2.23×10^{-3}	6.19×10^{-3}	1.78×10^{-2}	1.60×10^{-2}	1.07×10^{-3}	3.12×10^{-3}	9.23×10^{-3}	7.85×10^{-3}
PAH	8.69×10^{-6}	8.57×10^{-6}	8.55×10^{-6}	8.57×10^{-6}	3.76×10^{-6}	3.70×10^{-6}	3.70×10^{-6}	3.69×10^{-6}

Non-exhaust emissions (kg/tkm)		
Brake wear emissions	4.13×10^{-5}	1.30×10^{-5}
Tyre wear emissions	4.10×10^{-4}	1.29×10^{-4}
Road wear emissions	3.56×10^{-5}	1.12×10^{-5}
Lorry demand (unit/tkm)	1.88×10^{-6}	5.63×10^{-7}
Road demand ((m×a)/tkm)	1.95×10^{-3}	1.09×10^{-3}

Table C.2. Inputs and outputs of 1 tkm transported by the lorries 16 - 32 t and >32 t used in the road transport processes of Ecoinvent v3 database (European average). Source: Weidema et al., 2013

	Lorry 16 - 32 t				Lorry >32 t			
	Euro III	Euro IV	Euro V	Euro VI	Euro III	Euro IV	Euro V	Euro VI
Fuel consumption (g/tkm)	37.85	37.44	37.47	36.65	17.27	16.97	16.98	16.98
Exhaust emissions (g/tkm)								
CO_2	118.69	117.30	117.37	114.80	55.09	54.14	54.19	50.50
SO_2	5.86×10^{-4}	5.76×10^{-4}	5.76×10^{-4}	5.67×10^{-4}	2.82×10^{-4}	2.77×10^{-4}	2.77×10^{-4}	2.77×10^{-4}
Cd	3.29×10^{-7}	3.26×10^{-7}	3.26×10^{-7}	3.19×10^{-7}	1.50×10^{-7}	1.48×10^{-7}	1.48×10^{-7}	1.48×10^{-7}
Cu	8.02×10^{-7}	7.94×10^{-7}	7.94×10^{-7}	7.77×10^{-7}	3.66×10^{-7}	3.60×10^{-7}	3.60×10^{-7}	3.60×10^{-7}
Cr	1.14×10^{-6}	1.12×10^{-6}	1.12×10^{-6}	1.10×10^{-6}	5.18×10^{-7}	5.09×10^{-7}	5.09×10^{-7}	5.09×10^{-7}
Ni	3.33×10^{-7}	3.30×10^{-7}	3.30×10^{-7}	3.22×10^{-7}	1.52×10^{-7}	1.49×10^{-7}	1.49×10^{-7}	1.49×10^{-7}
Se	3.78×10^{-9}	3.74×10^{-9}	3.75×10^{-9}	3.66×10^{-9}	1.73×10^{-9}	1.70×10^{-9}	1.70×10^{-9}	1.70×10^{-9}
Zn	6.58×10^{-5}	6.51×10^{-5}	6.51×10^{-5}	6.37×10^{-5}	3.00×10^{-5}	2.95×10^{-5}	2.95×10^{-5}	2.95×10^{-5}
Pb	1.97×10^{-6}	1.95×10^{-6}	1.95×10^{-6}	1.91×10^{-6}	9.00×10^{-7}	8.84×10^{-7}	8.85×10^{-7}	8.85×10^{-7}
Hg	2.01×10^{-7}	1.98×10^{-7}	1.99×10^{-7}	1.94×10^{-7}	9.15×10^{-8}	8.99×10^{-8}	9.00×10^{-8}	9.00×10^{-8}
Cr (VI)	2.27×10^{-9}	2.25×10^{-9}	2.25×10^{-9}	2.20×10^{-9}	1.04×10^{-9}	1.02×10^{-9}	1.02×10^{-9}	1.02×10^{-9}
As	3.78×10^{-9}	3.74×10^{-9}	3.75×10^{-9}	3.66×10^{-9}	1.73×10^{-9}	1.70×10^{-9}	1.70×10^{-9}	1.70×10^{-9}
CO	1.92×10^{-1}	1.86×10^{-1}	1.87×10^{-1}	1.13×10^{-1}	8.24×10^{-2}	7.76×10^{-2}	7.77×10^{-2}	4.44×10^{-2}
NO_X	9.46×10^{-1}	5.48×10^{-1}	3.31×10^{-1}	5.22×10^{-2}	4.46×10^{-1}	2.32×10^{-1}	1.38×10^{-1}	2.22×10^{-2}
$PM_{2.5}$	2.20×10^{-2}	3.57×10^{-3}	3.60×10^{-3}	4.94×10^{-4}	8.96×10^{-3}	1.50×10^{-3}	1.52×10^{-3}	2.03×10^{-4}
Methane	9.89×10^{-4}	1.02×10^{-4}	1.03×10^{-4}	8.11×10^{-5}	3.82×10^{-4}	4.26×10^{-5}	4.30×10^{-5}	3.50×10^{-5}
Ethane	1.21×10^{-5}	1.24×10^{-6}	1.25×10^{-6}	9.89×10^{-7}	4.67×10^{-6}	5.20×10^{-7}	5.24×10^{-7}	4.27×10^{-7}
Propane	4.02×10^{-5}	4.15×10^{-6}	4.17×10^{-6}	3.30×10^{-6}	1.56×10^{-5}	1.73×10^{-6}	1.75×10^{-6}	1.42×10^{-6}
Butane	6.03×10^{-5}	6.22×10^{-6}	6.26×10^{-6}	4.94×10^{-6}	2.33×10^{-5}	2.60×10^{-6}	2.62×10^{-6}	2.14×10^{-6}
Pentane	2.41×10^{-5}	2.49×10^{-6}	2.50×10^{-6}	1.98×10^{-6}	9.33×10^{-6}	1.04×10^{-6}	1.05×10^{-6}	8.54×10^{-7}
Heptane	1.21×10^{-4}	1.24×10^{-5}	1.25×10^{-5}	9.89×10^{-6}	4.67×10^{-5}	5.20×10^{-6}	5.24×10^{-6}	4.27×10^{-6}
Acrolein	7.12×10^{-4}	7.34×10^{-5}	7.39×10^{-5}	5.83×10^{-5}	2.75×10^{-4}	3.07×10^{-5}	3.09×10^{-5}	2.52×10^{-5}
Styrene	2.25×10^{-4}	2.32×10^{-5}	2.34×10^{-5}	1.85×10^{-5}	8.71×10^{-5}	9.71×10^{-6}	9.79×10^{-6}	7.97×10^{-6}
Benzaldehyde	5.51×10^{-4}	5.68×10^{-5}	5.72×10^{-5}	4.52×10^{-5}	2.13×10^{-4}	2.38×10^{-5}	2.39×10^{-5}	1.95×10^{-5}
Toluene	4.02×10^{-6}	4.15×10^{-7}	4.17×10^{-7}	3.30×10^{-7}	1.56×10^{-6}	1.73×10^{-7}	1.75×10^{-7}	1.42×10^{-7}
Benzene	2.82×10^{-5}	2.90×10^{-6}	2.92×10^{-6}	2.31×10^{-6}	1.09×10^{-5}	1.21×10^{-6}	1.22×10^{-6}	9.97×10^{-7}
m-Xylene	3.94×10^{-4}	4.06×10^{-5}	4.09×10^{-5}	3.23×10^{-5}	1.52×10^{-4}	1.70×10^{-5}	1.71×10^{-5}	1.40×10^{-5}
o-Xylene	1.61×10^{-4}	1.66×10^{-5}	1.67×10^{-5}	1.32×10^{-5}	6.22×10^{-5}	6.94×10^{-6}	6.99×10^{-6}	5.70×10^{-6}
Formaldehyde	3.38×10^{-3}	3.48×10^{-4}	3.50×10^{-4}	2.77×10^{-4}	1.31×10^{-3}	1.46×10^{-4}	1.47×10^{-4}	1.20×10^{-4}
Acetaldehyde	1.84×10^{-3}	1.89×10^{-4}	1.91×10^{-4}	1.51×10^{-4}	7.11×10^{-4}	7.92×10^{-5}	7.99×10^{-5}	6.51×10^{-5}
NMVOC	3.27×10^{-2}	3.37×10^{-3}	3.39×10^{-3}	2.68×10^{-3}	1.26×10^{-2}	1.41×10^{-3}	1.42×10^{-3}	1.16×10^{-3}
NH_3	5.18×10^{-4}	5.18×10^{-4}	5.18×10^{-4}	5.18×10^{-4}	1.56×10^{-4}	1.56×10^{-4}	1.56×10^{-4}	1.56×10^{-4}
N_2O	8.32×10^{-4}	2.30×10^{-3}	6.76×10^{-3}	6.14×10^{-3}	3.71×10^{-4}	1.01×10^{-3}	2.93×10^{-3}	2.60×10^{-3}
PAH	2.96×10^{-6}	2.93×10^{-6}	2.93×10^{-6}	2.87×10^{-6}	1.35×10^{-6}	1.33×10^{-6}	1.33×10^{-6}	1.33×10^{-6}
Non-exhaust emissions (kg/tkm)								
Brake wear emissions	3.90×10^{-5}				1.41×10^{-5}			
Tyre wear emissions	3.86×10^{-4}				1.39×10^{-4}			
Road wear emissions	3.36×10^{-5}				1.21×10^{-5}			
Lorry demand (unit/tkm)	3.20×10^{-7}				9.65×10^{-8}			
Road demand ((m×a)/tkm)	1.05×10^{-3}				1.09×10^{-3}			

Table C.3 presents the population of heavy duty lorries in Belgium considering the lorry GVW category and the emission engine technology.

Table C.3. Population of heavy duty lorries in Belgium. Source: COPERT

Heavy Duty Lorry	Technology	2006	2007	2008	2009	2010	2011	2012
Rigid <7.5 t	Conventional	3 279	2 206	1 626	944	499	315	120
	Euro I	3 333	3 013	3 105	2 641	2 158	2 397	1 831
	Euro II	7 966	7 535	8 340	7 910	7 597	6 233	6 202
	Euro III	7 843	7 471	8 368	8 091	8 015	7 826	7 816
	Euro IV	1 625	3 451	6 120	5 922	5 876	5 952	5 939
	Euro V	0	0	0	1 513	2 467	4 581	6 088
	Euro VI	0	0	0	0	0	0	0
Rigid 7.5 - 12 t	Conventional	3 398	2 346	1 501	890	477	390	134
	Euro I	3 456	3 203	2 869	2 495	2 069	2 030	1 531
	Euro II	8 261	8 014	7 714	7 468	7 286	5 509	5 427
	Euro III	8 136	7 946	7 739	7 642	7 688	7 543	7 534
	Euro IV	1 684	3 671	5 657	5 594	5 637	6 083	6 070
	Euro V	0	0	0	1 428	2 366	4 630	6 154
	Euro VI	0	0	0	0	0	0	0
Rigid 12 - 14 t	Conventional	604	385	232	127	64	273	86
	Euro I	614	526	443	355	276	396	363
	Euro II	1 467	1 315	1 191	1 062	973	595	610
	Euro III	1 445	1 304	1 195	1 087	1 027	663	664
	Euro IV	299	602	873	796	753	724	724
	Euro V	0	0	0	203	316	848	1 140
	Euro VI	0	0	0	0	0	0	0
Rigid 14 - 20 t	Conventional	3 064	2 087	1 327	775	412	321	104
	Euro I	3 115	2 851	2 534	2 169	1 782	1 582	1 170
	Euro II	7 445	7 129	6 809	6 496	6 279	4 408	4 236
	Euro III	7 331	7 068	6 832	6 644	6 624	6 530	6 523
	Euro IV	1 518	3 265	4 995	4 863	4 857	5 499	5 487
	Euro V	0	0	0	1 242	2 039	4 224	5 616
	Euro VI	0	0	0	0	0	0	0
Rigid 20 - 26 t	Conventional	2 534	1 768	1 152	697	377	307	115
	Euro I	2 578	2 417	2 202	1 944	1 635	1 926	1 498
	Euro II	6 159	6 042	5 921	5 825	5 755	4 729	4 767
	Euro III	6 063	5 989	5 941	5 961	6 072	5 800	5 792
	Euro IV	1 257	2 767	4 344	4 362	4 451	4 508	4 499
	Euro V	0	0	0	1 115	1 870	3 413	4 536
	Euro VI	0	0	0	0	0	0	0
Rigid 26 - 28 t	Conventional	46	54	4	2	1	1	0
	Euro I	47	74	8	6	6	5	3
	Euro II	113	185	22	18	22	13	11
	Euro III	111	183	22	18	23	25	24
	Euro IV	23	85	16	13	17	14	14
	Euro V	0	0	0	3	7	22	29

	Euro VI	0	0	0	0	0	0	0
Rigid 28 - 32 t	**Conventional**	367	264	169	105	58	462	384
	Euro I	373	361	322	294	253	403	401
	Euro II	892	903	866	880	889	608	614
	Euro III	878	895	869	901	938	682	682
	Euro IV	182	414	635	659	687	564	563
	Euro V	0	0	0	168	289	474	632
	Euro VI	0	0	0	0	0	0	0
Rigid >32 t	**Conventional**	1 089	739	514	296	158	71	26
	Euro I	1 108	1 009	983	829	683	651	486
	Euro II	2 646	2 524	2 640	2 483	2 406	1 889	1 827
	Euro III	2 606	2 503	2 649	2 540	2 538	2 537	2 533
	Euro IV	540	1 156	1 937	1 859	1 861	1 991	1 988
	Euro V	0	0	0	475	782	1 509	2 007
	Euro VI	0	0	0	0	0	0	0
Articulated 14 - 20 t	**Conventional**	104	86	85	74	65	10	10
	Euro I	42	36	36	33	30	26	26
	Euro II	90	77	78	71	65	50	50
	Euro III	111	94	96	87	79	101	95
	Euro IV	26	50	82	74	68	95	88
	Euro V	0	0	0	21	42	76	99
	Euro VI	0	0	0	0	0	0	0
Articulated 20 - 28 t	**Conventional**	84	67	72	61	52	3	3
	Euro I	34	28	31	27	24	17	17
	Euro II	73	60	66	58	52	40	39
	Euro III	89	74	81	71	63	84	79
	Euro IV	21	39	69	61	54	78	73
	Euro V	0	0	0	17	34	64	82
	Euro VI	0	0	0	0	0	0	0
Articulated 28 - 34 t	**Conventional**	97	77	85	72	124	7	7
	Euro I	39	32	36	32	57	57	55
	Euro II	84	69	78	68	123	129	126
	Euro III	103	84	96	84	151	217	213
	Euro IV	24	45	82	72	130	177	174
	Euro V	0	0	0	20	80	96	125
	Euro VI	0	0	0	0	0	0	0
Articulated 34 - 40 t	**Conventional**	10 595	9 710	9 608	8 527	7 655	6 202	5 741
	Euro I	4 291	4 036	4 104	3 783	3 530	4 064	3 990
	Euro II	9 211	8 668	8 811	8 119	7 576	6 223	6 173
	Euro III	11 293	10 627	10 803	9 956	9 289	9 877	9 628
	Euro IV	2 620	5 639	9 287	8 558	7 984	8 697	8 438
	Euro V	0	0	0	2 359	4 931	6 966	9 123
	Euro VI	0	0	0	0	0	0	0
	TOTAL	144 525	145 317	154 372	152 111	151 574	155 514	159 453

Table C.4 presents the mileage (km/a) of road freight transport in Belgium considering the lorry GVW category and the emission engine technology.

Table C.4. Mileage (km/a) of road freight transport in Belgium. Source: COPERT

Heavy Duty Lorries	Technology	2006	2007	2008	2009	2010	2011	2012
Rigid <7.5 t	Conventional	16 630	15 916	16 219	15 575	15 195	13 799	12 291
	Euro I	19 002	18 187	18 533	17 796	17 362	15 767	14 044
	Euro II	21 720	20 787	21 183	20 341	19 845	18 021	16 053
	Euro III	24 841	23 774	24 227	23 264	22 696	20 611	18 359
	Euro IV	28 413	27 193	27 711	26 610	25 960	23 575	20 999
	Euro V	0	0	0	30 453	29 709	26 979	24 032
	Euro VI	0	0	0	0	0	0	0
Rigid 7.5 - 12 t	Conventional	19 729	18 882	19 242	18 477	18 026	16 370	14 581
	Euro I	22 543	21 575	21 986	21 112	20 597	18 704	16 661
	Euro II	25 767	24 661	25 130	24 131	23 542	21 379	19 044
	Euro III	29 469	28 204	28 741	27 599	26 925	24 451	21 780
	Euro IV	33 707	32 260	32 874	31 568	30 797	27 967	24 912
	Euro V	0	0	0	36 127	35 244	32 006	28 510
	Euro VI	0	0	0	0	0	0	0
Rigid 12 - 14 t	Conventional	13 532	12 951	13 197	12 673	12 364	11 228	10 001
	Euro I	15 462	14 798	15 080	14 481	14 127	12 829	11 428
	Euro II	17 673	16 914	17 236	16 551	16 147	14 664	13 062
	Euro III	20 212	19 345	19 713	18 930	18 467	16 771	14 939
	Euro IV	23 119	22 126	22 548	21 652	21 123	19 182	17 087
	Euro V	0	0	0	24 778	24 173	21 952	19 554
	Euro VI	0	0	0	0	0	0	0
Rigid 14 - 20 t	Conventional	20 762	19 871	20 249	19 444	18 969	17 227	15 345
	Euro I	23 723	22 705	23 137	22 218	21 675	19 684	17 533
	Euro II	27 116	25 952	26 446	25 395	24 775	22 498	20 041
	Euro III	31 012	29 681	30 246	29 044	28 335	25 731	22 920
	Euro IV	35 471	33 949	34 595	33 220	32 409	29 431	26 216
	Euro V	0	0	0	38 018	37 090	33 682	30 002
	Euro VI	0	0	0	0	0	0	0
Rigid 20 - 26 t	Conventional	24 893	23 825	24 278	23 314	22 744	20 655	18 398
	Euro I	28 444	27 223	27 741	26 639	25 988	23 601	21 022
	Euro II	32 512	31 116	31 708	30 448	29 705	26 976	24 029
	Euro III	37 183	35 587	36 264	34 823	33 973	30 852	27 481
	Euro IV	42 530	40 704	41 479	39 831	38 858	35 288	31 433
	Euro V	0	0	0	45 583	44 470	40 384	35 973
	Euro VI	0	0	0	0	0	0	0
Rigid 26 - 28 t	Conventional	28 095	26 889	27 401	26 312	25 670	23 311	0
	Euro I	32 103	30 725	31 309	30 065	29 331	26 636	23 726
	Euro II	36 693	35 118	35 787	34 365	33 526	30 445	27 119
	Euro III	41 966	40 164	40 929	39 303	38 343	34 820	31 016
	Euro IV	48 001	45 940	46 815	44 954	43 857	39 827	35 476
	Euro V	0	0	0	51 446	50 190	45 579	40 600

	Euro VI	0	0	0	0	0	0	0
Rigid 28 - 32 t	**Conventional**	31 091	29 756	30 322	29 118	28 407	25 797	22 979
	Euro I	35 525	34 000	34 647	33 271	32 458	29 476	26 256
	Euro II	40 605	38 862	39 602	38 028	37 100	33 691	30 011
	Euro III	46 440	44 446	45 292	43 493	42 431	38 532	34 323
	Euro IV	53 118	50 838	51 806	49 747	48 532	44 073	39 259
	Euro V	0	0	0	56 931	55 541	50 438	44 928
	Euro VI	0	0	0	0	0	0	0
Rigid >32 t	**Conventional**	95 646	91 540	93 282	89 576	87 388	79 359	70 690
	Euro I	109 288	104 596	106 587	102 352	99 853	90 678	80 772
	Euro II	124 916	119 554	121 829	116 988	114 132	103 646	92 323
	Euro III	142 865	136 733	139 335	133 799	130 531	118 539	105 589
	Euro IV	163 410	156 395	159 372	153 039	149 302	135 585	120 773
	Euro V	0	0	0	175 140	170 864	155 165	138 214
	Euro VI	0	0	0	0	0	0	0
Articulated 14 - 20 t	**Conventional**	81 922	78 405	79 897	76 723	74 849	67 972	60 547
	Euro I	93 606	89 588	91 293	87 666	85 525	77 667	69 183
	Euro II	106 992	102 399	104 348	100 202	97 755	88 774	79 076
	Euro III	122 366	117 113	119 343	114 600	111 802	101 530	90 438
	Euro IV	139 963	133 954	136 504	131 080	127 879	116 130	103 444
	Euro V	0	0	0	150 010	146 347	132 901	118 382
	Euro VI	0	0	0	0	0	0	0
Articulated 20 - 28 t	**Conventional**	56 128	53 718	54 741	52 566	51 282	46 570	41 483
	Euro I	64 133	61 380	62 549	60 063	58 596	53 213	47 400
	Euro II	73 304	70 158	71 493	68 652	66 976	60 822	54 178
	Euro III	83 838	80 239	81 766	78 517	76 600	69 562	61 963
	Euro IV	95 894	91 777	93 524	89 808	87 615	79 565	70 873
	Euro V	0	0	0	102 777	100 268	91 055	81 108
	Euro VI	0	0	0	0	0	0	0
Articulated 28 - 34 t	**Conventional**	45 582	43 625	44 456	42 689	41 647	37 820	33 689
	Euro I	52 083	49 848	50 796	48 778	47 587	43 215	38 494
	Euro II	59 531	56 976	58 060	55 753	54 392	49 395	43 999
	Euro III	68 086	65 163	66 403	63 765	62 208	56 492	50 321
	Euro IV	77 876	74 533	75 952	72 934	71 153	64 616	57 557
	Euro V	0	0	0	83 467	81 429	73 947	65 869
	Euro VI	0	0	0	0	0	0	0
Articulated 34 - 40 t	**Conventional**	104 838	100 338	102 248	98 185	95 787	86 987	77 484
	Euro I	119 792	114 649	116 831	112 189	109 450	99 394	88 536
	Euro II	136 922	131 044	133 539	128 232	125 101	113 607	101 196
	Euro III	156 596	149 874	152 727	146 658	143 077	129 932	115 737
	Euro IV	179 115	171 426	174 689	167 748	163 652	148 616	132 381
	Euro V	0	0	0	191 973	187 285	170 078	151 498
	Euro VI	0	0	0	0	0	0	0

Table C.5 presents the lifetime kilometric performance (km) of road freight transport in Belgium considering the lorry GVW category and the emission engine technology.

Table C.5. Mean fleet mileage (km) of road freight transport in Belgium. Source: COPERT

Heavy Duty Lorries	Technology	2006	2007	2008	2009	2010	2011	2012
Rigid <7.5 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	99 896	123 521	145 675	167 387	187 647	198 514	216 797
	Euro IV	28 413	40 695	53 445	80 028	105 370	119 564	138 889
	Euro V	0	0	0	30 453	48 393	63 555	95 166
	Euro VI	0	0	0	0	0	0	0
Rigid 7.5 - 12 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	118 509	146 536	172 818	198 576	222 610	235 502	257 192
	Euro IV	33 707	48 277	63 403	94 939	125 003	141 842	164 768
	Euro V	0	0	0	36 127	57 409	75 396	112 898
	Euro VI	0	0	0	0	0	0	0
Rigid 12 - 14 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	81 283	100 506	118 532	136 199	152 684	161 526	176 403
	Euro IV	23 119	33 113	43 487	65 117	85 737	97 287	113 011
	Euro V	0	0	0	24 778	39 376	51 713	77 434
	Euro VI	0	0	0	0	0	0	0
Rigid 14 - 20 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	124 714	154 208	181 866	208 972	234 265	247 831	270 656
	Euro IV	35 471	50 805	66 723	99 910	131 547	149 268	173 394
	Euro V	0	0	0	38 018	60 415	79 344	118 808
	Euro VI	0	0	0	0	0	0	0
Rigid 20 - 26 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	149 531	184 894	218 056	250 556	280 882	297 148	324 516
	Euro IV	42 530	60 915	80 000	119 791	157 724	178 972	207 898
	Euro V	0	0	0	45 583	72 437	95 133	142 450
	Euro VI	0	0	0	0	0	0	0
Rigid 26 - 28 t	Conventional	808 491	822 217	834 767	851 553	866 922	879 148	0
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	168 765	208 676	246 103	282 784	317 011	335 369	366 257
	Euro IV	48 001	68 750	90 290	135 200	178 012	201 992	234 639

	Euro V	0	0	0	51 446	81 754	107 369	160 773
	Euro VI	0	0	0	0	0	0	0
Rigid 28 - 32 t	**Conventional**	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	186 757	230 924	272 341	312 932	350 808	371 124	405 305
	Euro IV	53 118	76 080	99 917	149 614	196 990	223 527	259 655
	Euro V	0	0	0	56 931	90 470	118 816	177 914
	Euro VI	0	0	0	0	0	0	0
Rigid >32 t	**Conventional**	808 491	822 217	834 767	851 553	866 922	879 148	893 189
	Euro I	695 222	726 897	754 837	784 040	809 248	862 177	897 764
	Euro II	519 585	564 055	604 482	644 990	681 259	744 185	791 369
	Euro III	574 529	710 401	837 816	962 687	1 079 207	1 141 706	1 246 857
	Euro IV	163 410	234 047	307 378	460 263	606 009	687 646	798 788
	Euro V	0	0	0	175 140	278 318	365 520	547 324
	Euro VI	0	0	0	0	0	0	0
Articulated 14 - 20 t	**Conventional**	1 287 830	1 299 561	1 306 526	1 317 565	1 323 860	1 385 113	1 409 714
	Euro I	889 553	954 480	1 015 971	1 080 035	1 138 301	1 210 641	1 275 709
	Euro II	588 447	656 959	724 341	795 388	864 674	919 825	985 271
	Euro III	513 026	652 597	791 441	935 165	1 078 219	1 108 021	1 214 323
	Euro IV	139 963	201 411	264 471	406 751	549 496	619 741	722 181
	Euro V	0	0	0	150 010	217 727	285 895	439 700
	Euro VI	0	0	0	0	0	0	0
Articulated 20 - 28 t	**Conventional**	1 287 830	1 299 561	1 306 526	1 317 565	1 323 860	1 385 113	1 409 714
	Euro I	889 553	954 480	1 015 971	1 080 035	1 138 301	1 210 641	1 275 709
	Euro II	588 447	656 959	724 341	795 388	864 674	919 825	985 271
	Euro III	351 494	447 119	542 246	640 716	738 729	759 146	831 978
	Euro IV	95 894	137 995	181 199	278 680	376 481	424 608	494 794
	Euro V	0	0	0	102 777	149 173	195 878	301 255
	Euro VI	0	0	0	0	0	0	0
Articulated 28 - 34 t	**Conventional**	1 287 830	1 299 561	1 306 526	1 317 565	1 323 860	1 385 113	1 409 714
	Euro I	889 553	954 480	1 015 971	1 080 035	1 138 301	1 210 641	1 275 709
	Euro II	588 447	656 959	724 341	795 388	864 674	919 825	985 271
	Euro III	285 452	363 111	440 365	520 334	599 931	616 512	675 660
	Euro IV	77 876	112 067	147 154	226 320	305 745	344 829	401 828
	Euro V	0	0	0	83 467	121 145	159 075	244 653
	Euro VI	0	0	0	0	0	0	0
Articulated 34 - 40 t	**Conventional**	1 287 830	1 299 561	1 306 526	1 317 565	1 323 860	1 385 113	1 409 714
	Euro I	889 553	954 480	1 015 971	1 080 035	1 138 301	1 210 641	1 275 709
	Euro II	588 447	656 959	724 341	795 388	864 674	919 825	985 271
	Euro III	656 538	835 152	1 012 835	1 196 764	1 379 836	1 417 974	1 554 013
	Euro IV	179 115	257 754	338 454	520 534	703 210	793 105	924 202
	Euro V	0	0	0	191 973	278 633	365 871	562 701
	Euro VI	0	0	0	0	0	0	0

Table C.6 presents the population of passenger vehicles in Belgium considering the vehicle passenger sector and the emission engine technology.

Table C.6. Population of passenger vehicles in Belgium. Source: COPERT

Sector	Subsector	Technology	2006	2007	2008	2009	2010	2011	2012
Mopeds	2-stroke <50 cm³	Conventional	494 480	411 032	350 490	299 772	251 112	556 574	556 857
		Mop - Euro II	94 393	187 071	274 192	334 616	393 189	97 742	97 594
		Mop - Euro III	0	0	0	0	0	0	10 386
Motor-cycles	2-stroke >50 cm³	Conventional	32 958	36 152	42 318	44 984	46 973	53 992	51 027
		Mot - Euro I	5 245	6 072	7 506	8 448	9 358	9 148	9 861
		Mot - Euro II	2 403	2 789	3 451	3 895	4 345	4 901	5 498
		Mot - Euro III	2 939	5 317	8 614	11 871	17 694	11 521	14 455
	4-stroke <250 cm³	Conventional	11 281	9 768	8 560	6 970	5 808	11 607	9 666
		Mot - Euro I	6 302	5 972	5 698	4 988	4 374	4 476	4 616
		Mot - Euro II	2 828	2 750	2 725	2 519	2 383	1 195	1 202
		Mot - Euro III	5 809	10 624	15 375	19 130	20 823	16 435	18 772
	4-stroke 250 - 750 cm³	Conventional	95 832	84 714	78 047	71 035	67 098	62 536	54 273
		Mot - Euro I	13 714	12 620	12 100	11 462	11 286	10 563	10 930
		Mot - Euro II	6 048	5 567	5 338	5 060	4 987	4 835	4 866
		Mot - Euro III	18 484	33 390	46 764	58 675	62 954	69 813	80 054
	4-stroke >750 cm³	Conventional	51 973	44 625	38 740	32 239	25 544	39 826	31 768
		Mot - Euro I	35 259	34 857	35 256	34 488	32 257	16 961	17 554
		Mot - Euro II	14 923	15 003	15 611	15 985	16 053	9 686	9 744
		Mot - Euro III	18 187	28 890	39 742	50 333	64 233	72 957	82 606
Passenger Cars	Gasoline 0.8 – 1.4 L	ECE 15/03	0	0	0	0	0	14	4
		ECE 15/04	37	7	0	0	0	1 360	346
		Improved Conventional	440 858	385 751	329 297	261 423	179 421	351 059	331 900
		PC Euro 1	43 267	22 836	10 405	3 815	1 013	57 264	34 874
		PC Euro 2	198 062	161 090	126 028	91 016	56 786	159 709	142 625
		PC Euro 3	402 739	391 732	383 117	363 065	313 133	307 480	306 258
		PC Euro 4	189 559	297 697	420 359	534 797	526 082	210 189	209 745
		PC Euro 5	0	0	0	0	172 737	97 380	139 371
	Gasoline 1.4 – 2.0 L	ECE 15/03	3	2	2	2	1	105	26
		ECE 15/04	140 094	124 136	111 223	100 502	86 931	1 876	815
		Improved Conventional	158 515	140 459	125 849	113 718	98 363	4 491	2 229
		PC Euro 1	155 716	137 979	123 626	111 710	96 625	46 524	32 490
		PC Euro 2	157 537	139 593	125 073	113 017	97 756	133 340	111 498
		PC Euro 3	181 716	161 017	144 269	130 362	112 759	166 239	150 733
		PC Euro 4	58 103	85 084	108 591	125 332	108 408	166 663	162 613
		PC Euro 5	0	0	0	0	60 309	112 361	160 885
	Gasoline >2.0 L	ECE 15/03	1 189	1 106	1 053	1 000	893	1 464	850
		ECE 15/04	29 056	27 026	25 718	24 439	21 811	4 711	3 820
		PC Euro 1	42 237	39 286	37 385	35 525	31 705	19 784	16 568
		PC Euro 2	28 863	26 846	25 547	24 276	21 666	16 704	14 348
		PC Euro 3	42 917	39 918	37 986	36 096	32 215	19 159	16 909

		PC Euro 4	7 804	12 061	16 336	19 781	17 654	43 581	40 038
		PC Euro 5	0	0	0	0	12 359	27 247	37 952
	Diesel 1.4 – 2.0 L	**Conventional**	119 772	93 657	72 266	56 478	47 561	143 936	120 498
		PC Euro 1	148 279	120 056	95 864	77 513	67 609	215 477	186 877
		PC Euro 2	185 372	154 806	127 432	106 173	95 380	198 878	177 995
		PC Euro 3	954 020	828 076	707 882	612 037	570 206	530 499	475 899
		PC Euro 4	798 052	1 152 532	1 482 798	1 755 643	1 715 404	1 235 446	1 134 443
		PC Euro 5	0	0	0	0	263 749	790 509	1 088 504
	Diesel >2.0 L	**Conventional**	42 391	39 191	36 285	33 521	27 974	2 682	2 976
		PC Euro 1	55 498	53 166	51 012	48 922	42 760	14 707	14 860
		PC Euro 2	121 103	118 571	116 189	113 731	101 399	54 644	52 524
		PC Euro 3	151 455	152 089	152 662	152 910	139 377	103 305	95 815
		PC Euro 4	40 400	67 345	96 519	124 227	117 343	224 972	209 794
		PC Euro 5	0	0	0	0	56 706	88 237	123 315
	LPG	**Conventional**	7 894	6 185	4 797	3 489	2 367	752	421
		PC Euro 1	18 762	16 438	14 778	12 959	11 046	10 900	9 721
		PC Euro 2	14 796	12 993	11 725	10 344	8 900	10 698	10 070
		PC Euro 3	10 024	8 805	7 951	7 023	6 055	8 649	8 472
		PC Euro 4	2 970	4 596	5 974	6 692	5 773	2 167	2 154
		PC Euro 5	0	0	0	0	1 713	634	908
	E85	**PC Euro 4**	0	0	0	0	0	333	323
		PC Euro 5	0	0	0	0	0	395	591
	CNG	**PC Euro 4**	0	0	0	0	0	594	662
		PC Euro 5	0	0	0	0	0	29	71
	Hybrid Gasoline <1.4 L	**PC Euro 4**	123	238	351	846	1 303	8 241	8 707
	Hybrid Gasoline 1.4 – 2.0 L	**PC Euro 4**	1 182	1 776	3 024	3 921	5 650	35 736	37 756
	Hybrid Gasoline >2.0 L	**PC Euro 4**	452	802	1 121	1 363	1 741	11 012	11 634
Buses	**Urban Buses Midi <15 t**	**Conventional**	136	119	110	92	77	38	33
		HD Euro I	58	54	53	47	42	38	34
		HD Euro II	118	112	111	101	92	88	83
		HD Euro III	148	159	180	167	156	130	127
		HD Euro IV	18	37	60	71	83	110	108
		HD Euro V	0	0	0	17	40	89	111
		HD Euro VI	0	0	0	0	0	0	0
	Urban Buses Standard 15 - 18 t	**Conventional**	1 479	1 302	1 167	1 008	854	431	386
		HD Euro I	578	533	500	452	404	396	369
		HD Euro II	1 256	1 181	1 128	1 039	947	900	857
		HD Euro III	1 660	1 988	2 378	2 256	2 118	1 332	1 281
		HD Euro IV	0	0	0	343	700	1 106	1 083
		HD Euro V	0	0	0	0	0	894	1 117
		HD Euro VI	0	0	0	0	0	0	0
	Urban Buses Articulated >18 t	**Conventional**	214	197	200	175	172	84	75
		HD Euro I	84	81	86	78	81	79	74
		HD Euro II	182	179	194	180	191	181	172
		HD Euro III	240	301	408	391	426	268	258

		HD Euro IV	0	0	0	60	141	224	220
		HD Euro V	0	0	0	0	0	181	226
		HD Euro VI	0	0	0	0	0	0	0
	Coaches Standard <18 t	Conventional	1 019	736	591	471	366	110	98
		HD Euro I	466	361	310	266	222	241	224
		HD Euro II	900	711	625	547	466	552	524
		HD Euro III	1 071	868	782	701	612	690	667
		HD Euro IV	238	405	578	532	476	511	504
		HD Euro V	0	0	0	155	353	408	512
		HD Euro VI	0	0	0	0	0	0	0
	Coaches Articulated >18 t	Conventional	1 506	1 401	1 287	1 185	1 021	311	278
		HD Euro I	689	686	675	669	620	675	629
		HD Euro II	1 331	1 353	1 360	1 376	1 301	1 539	1 461
		HD Euro III	1 584	1 652	1 702	1 764	1 710	1 925	1 859
		HD Euro IV	351	771	1 259	1 338	1 331	1 427	1 408
		HD Euro V	0	0	0	390	986	1 140	1 429
		HD Euro VI	0	0	0	0	0	0	0

Table C.7 presents the mileage (km/a) of road passenger transport in Belgium considering the vehicle passenger sector and the emission engine technology.

Table C.7. Mileage (km/a) of road passenger transport in Belgium. Source: COPERT

Sector	Subsector	Technology	2006	2007	2008	2009	2010	2011	2012
Mopeds	2-stroke <50 cm³	Conventional	581	554	568	542	471	496	434
		Mop - Euro II	760	725	743	709	616	649	568
		Mop - Euro III	0	0	0	0	0	0	629
Motor-cycles	2-stroke >50 cm³	Conventional	4 427	4 226	4 329	4 129	3 590	3 781	3 312
		Mot - Euro I	5 064	4 834	4 952	4 723	4 106	4 325	3 788
		Mot - Euro II	5 795	5 532	5 667	5 405	4 699	4 950	4 335
		Mot - Euro III	6 407	6 116	6 266	5 976	5 195	5 472	4 793
	4-stroke <250 cm³	Conventional	4 458	4 256	4 360	4 158	3 615	3 808	3 335
		Mot - Euro I	5 100	4 868	4 987	4 756	4 135	4 356	3 815
		Mot - Euro II	5 836	5 571	5 707	5 443	4 732	4 985	4 365
		Mot - Euro III	6 452	6 159	6 310	6 018	5 231	5 511	4 826
	4-stroke 250 - 750 cm³	Conventional	4 490	4 286	4 391	4 188	3 640	3 835	3 359
		Mot - Euro I	5 136	4 902	5 022	4 790	4 164	4 386	3 841
		Mot - Euro II	5 877	5 610	5 747	5 482	4 765	5 020	4 396
		Mot - Euro III	6 498	6 202	6 354	6 060	5 268	5 550	4 860
	4-stroke >750 cm³	Conventional	4 521	4 316	4 421	4 217	3 666	3 862	3 382
		Mot - Euro I	5 171	4 936	5 057	4 824	4 193	4 417	3 868
		Mot - Euro II	5 918	5 649	5 788	5 520	4 799	5 055	4 427
		Mot - Euro III	6 543	6 246	6 399	6 103	5 305	5 589	4 894
Passenger Cars	Gasoline 0.8 – 1.4 L	ECE 15/03	0	0	0	0	0	4 359	3 817
		ECE 15/04	6 017	5 743	0	0	0	5 139	4 501
		Improved Conventional	6 874	6 561	6 722	6 411	5 573	5 871	5 142

		PC Euro 1	8 973	8 564	8 774	8 369	7 275	7 664	6 712
		PC Euro 2	10 256	9 789	10 029	9 566	8 315	8 760	7 671
		PC Euro 3	11 729	11 196	11 470	10 940	9 510	10 018	8 774
		PC Euro 4	13 416	12 806	13 120	12 513	10 878	11 459	10 035
		PC Euro 5	0	0	0	0	12 448	13 114	11 485
	Gasoline 1.4 – 2.0 L	**ECE 15/03**	4 473	4 270	4 374	4 172	3 627	3 820	3 346
		ECE 15/04	5 274	5 034	5 158	4 920	4 276	4 505	3 945
		Improved Conventional	6 025	5 751	5 892	5 620	4 885	5 146	4 507
		PC Euro 1	7 865	7 507	7 691	7 336	6 377	6 718	5 883
		PC Euro 2	8 990	8 581	8 791	8 385	7 289	7 678	6 724
		PC Euro 3	10 281	9 814	10 054	9 590	8 336	8 782	7 691
		PC Euro 4	11 760	11 225	11 500	10 969	9 535	10 044	8 797
		PC Euro 5	0	0	0	0	10 912	11 495	10 067
	Gasoline >2.0 L	**ECE 15/03**	5 177	4 941	5 062	4 828	4 197	4 421	3 872
		ECE 15/04	5 914	5 645	5 783	5 516	4 795	5 051	4 424
		PC Euro 1	6 757	6 450	6 608	6 303	5 479	5 772	5 055
		PC Euro 2	7 724	7 372	7 553	7 204	6 262	6 597	5 777
		PC Euro 3	8 834	8 432	8 638	8 239	7 162	7 545	6 608
		PC Euro 4	10 104	9 644	9 881	9 424	8 192	8 630	7 558
		PC Euro 5	0	0	0	0	9 375	9 876	8 649
	Diesel 1.4 – 2.0 L	**Conventional**	13 967	13 367	13 621	13 080	12 761	11 588	10 322
		PC Euro 1	15 959	15 274	15 564	14 946	14 581	13 241	11 795
		PC Euro 2	18 241	17 458	17 790	17 083	16 666	15 135	13 481
		PC Euro 3	20 862	19 966	20 346	19 538	19 061	17 310	15 419
		PC Euro 4	23 862	22 837	23 272	22 347	21 802	19 799	17 636
		PC Euro 5	0	0	0	0	24 950	22 658	20 183
	Diesel >2.0 L	**Conventional**	13 532	12 951	13 197	12 673	12 364	11 228	10 001
		PC Euro 1	15 462	14 798	15 080	14 481	14 127	12 829	11 428
		PC Euro 2	17 673	16 914	17 236	16 551	16 147	14 664	13 062
		PC Euro 3	20 212	19 345	19 713	18 930	18 467	16 771	14 939
		PC Euro 4	23 119	22 126	22 548	21 652	21 123	19 182	17 087
		PC Euro 5	0	0	0	0	24 173	21 952	19 554
	LPG	**Conventional**	21 101	16 317	16 994	19 046	18 063	21 642	24 152
		PC Euro 1	24 111	18 644	19 418	21 763	20 640	24 729	27 597
		PC Euro 2	27 559	21 310	22 194	24 875	23 591	28 265	31 543
		PC Euro 3	31 519	24 372	25 384	28 450	26 981	32 327	36 075
		PC Euro 4	36 051	27 877	29 034	32 541	30 861	36 976	41 263
		PC Euro 5	0	0	0	0	35 318	42 315	47 222
	E85	**PC Euro 4**	0	0	0	0	0	11 516	10 086
		PC Euro 5	0	0	0	0	0	13 179	11 542
	CNG	**PC Euro 4**	0	0	0	0	0	1 386	1 910
		PC Euro 5	0	0	0	0	0	1 586	2 186
	Hybrid Gasoline <1.4 L	**PC Euro 4**	13 215	12 614	12 923	12 326	10 714	11 287	9 885
	Hybrid Gasoline 1.4 – 2.0 L	**PC Euro 4**	11 583	11 057	11 328	10 804	9 392	9 894	8 665
	Hybrid Gasoline >2.0 L	**PC Euro 4**	9 952	9 500	9 732	9 283	8 069	8 500	7 444

Buses	**Urban Buses Midi <15 t**	**Conventional**	46 771	44 763	45 615	43 802	42 733	38 807	34 567
		HD Euro I	53 442	51 147	52 121	50 050	48 828	44 342	39 498
		HD Euro II	61 084	58 462	59 574	57 207	55 810	50 683	45 146
		HD Euro III	69 861	66 862	68 135	65 427	63 830	57 965	51 633
		HD Euro IV	79 907	76 477	77 933	74 836	73 009	66 301	59 058
		HD Euro V	0	0	0	85 643	83 552	75 876	67 587
		HD Euro VI	0	0	0	0	0	0	0
	Urban Buses Standard 15 - 18 t	**Conventional**	47 100	45 078	45 936	44 111	43 034	39 080	34 811
		HD Euro I	53 818	51 508	52 488	50 403	49 172	44 654	39 776
		HD Euro II	61 514	58 874	59 994	57 610	56 204	51 040	45 464
		HD Euro III	70 354	67 333	68 615	65 889	64 280	58 374	51 997
		HD Euro IV	0	0	0	75 363	73 523	66 768	59 474
		HD Euro V	0	0	0	0	0	76 410	68 063
		HD Euro VI	0	0	0	0	0	0	0
	Urban Buses Articulated >18 t	**Conventional**	47 430	45 394	46 258	44 420	43 335	39 354	35 055
		HD Euro I	54 195	51 869	52 856	50 756	49 516	44 967	40 055
		HD Euro II	61 945	59 286	60 414	58 014	56 597	51 397	45 782
		HD Euro III	70 846	67 805	69 095	66 350	64 730	58 783	52 361
		HD Euro IV	0	0	0	75 891	74 038	67 235	59 890
		HD Euro V	0	0	0	0	0	76 945	68 540
		HD Euro VI	0	0	0	0	0	0	0
	Coaches Standard <18 t	**Conventional**	42 155	40 346	41 114	39 480	38 516	34 977	31 156
		HD Euro I	48 168	46 100	46 978	45 111	44 009	39 966	35 600
		HD Euro II	55 056	52 692	53 696	51 562	50 303	45 681	40 691
		HD Euro III	62 967	60 264	61 411	58 971	57 531	52 245	46 538
		HD Euro IV	72 022	68 930	70 242	67 451	65 804	59 758	53 230
		HD Euro V	0	0	0	77 192	75 307	68 388	60 917
		HD Euro VI	0	0	0	0	0	0	0
	Coaches Articulated >18 t	**Conventional**	42 452	40 630	41 403	39 758	38 787	35 224	31 376
		HD Euro I	48 507	46 425	47 309	45 429	44 320	40 248	35 851
		HD Euro II	55 444	53 064	54 074	51 925	50 657	46 003	40 978
		HD Euro III	63 411	60 689	61 844	59 387	57 936	52 613	46 866
		HD Euro IV	72 529	69 416	70 737	67 926	66 268	60 179	53 605
		HD Euro V	0	0	0	77 736	75 838	68 870	61 347
		HD Euro VI	0	0	0	0	0	0	0

Appendix D

It has been studied the environmental impact of road freight transport performed by an articulated lorry of 34-40 t with the load factors of 50%, 60% and 85% (see Section 5.5). The lorry GVW category articulated lorry of 34-40 t represents approximately 75% of the road freight transport performance (i.e. tonne-kilometres) every year in Belgium (see Table 5.5). Therefore, this lorry GVW category has been used to compare the different inland freight transport modes and to study intermodal transport routes because it is representative and it presents the usual capacity for containers.

Figure D.1 presents the values of the inventory flows calculated in the LCI stage to model one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a 50% of load factor in Belgium in the year 2012. Therefore, to calculate the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a 50% of load factor in 2012 it is necessary to consider a lorry demand of 8.79×10^{-8} unit/tkm, a road infrastructure demand of 1.04×10^{-3} (m×a)/tkm, a diesel consumption of 0.0198 kg/tkm (849 kJ/tkm), the exhaust emissions produced during the combustion of the fuel and the particle emission from road, tyre and brake wear in the transport operation.

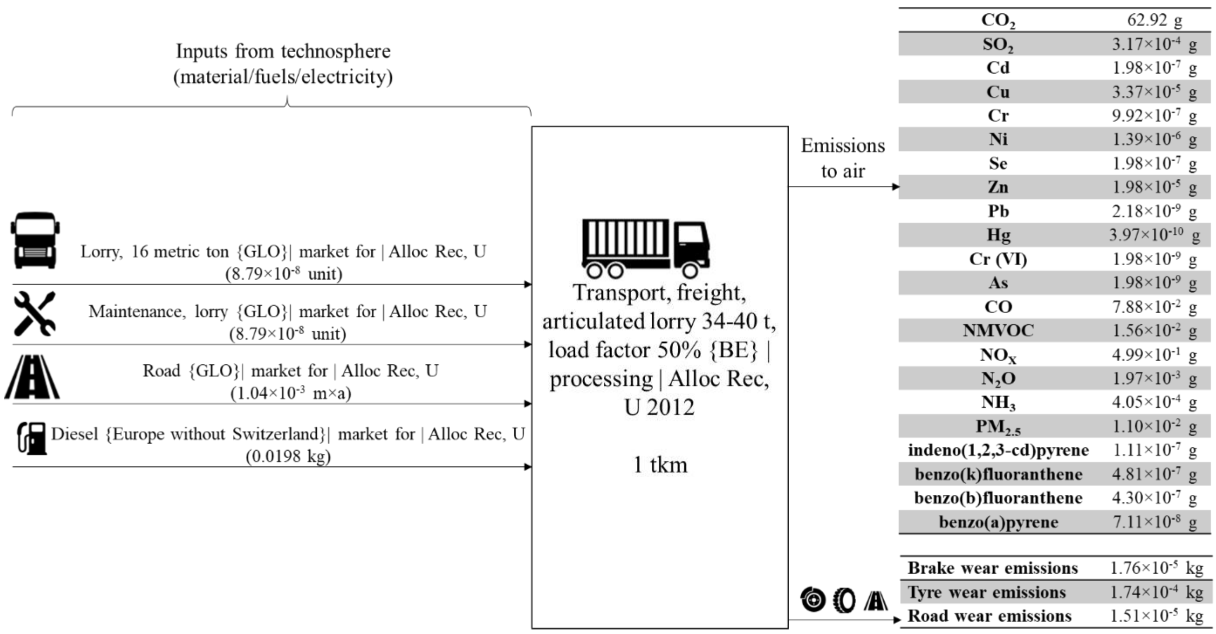


Figure D.1. Inputs and outputs of 1 tkm transported by an articulated lorry of 34-40 t with a 50% of load factor in Belgium in 2012

Table D.1 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium.

Table D.1. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	9.49×10^{-2}	9.48×10^{-2}	9.31×10^{-2}	9.33×10^{-2}	9.31×10^{-2}	9.31×10^{-2}	9.35×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.78×10^{-8}	1.78×10^{-8}	1.74×10^{-8}	1.75×10^{-8}	1.75×10^{-8}	1.75×10^{-8}	1.77×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	7.60×10^{-5}	7.36×10^{-5}	6.99×10^{-5}	6.86×10^{-5}	6.69×10^{-5}	6.50×10^{-5}	6.51×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	8.28×10^{-3}	8.27×10^{-3}	8.00×10^{-3}	8.04×10^{-3}	8.02×10^{-3}	8.03×10^{-3}	8.13×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	9.78×10^{-4}	9.36×10^{-4}	8.84×10^{-4}	8.48×10^{-4}	8.08×10^{-4}	7.67×10^{-4}	7.50×10^{-4}
Acidification	**molc H+ eq**	8.26×10^{-4}	7.96×10^{-4}	7.57×10^{-4}	7.31×10^{-4}	7.02×10^{-4}	6.72×10^{-4}	6.58×10^{-4}
Terrestrial eutrophication	**molc N eq**	360×10^{-3}	3.43×10^{-3}	3.25×10^{-3}	3.10×10^{-3}	2.94×10^{-3}	2.77×10^{-3}	2.69×10^{-3}
Freshwater eutrophication	**kg P eq**	7.08×10^{-6}	7.00×10^{-6}	6.53×10^{-6}	6.54×10^{-6}	6.40×10^{-6}	6.29×10^{-6}	6.15×10^{-6}
Resource depletion	**kg Sb eq**	6.27×10^{-6}	6.11×10^{-6}	5.69×10^{-6}	5.59×10^{-6}	5.31×10^{-6}	5.00×10^{-6}	4.32×10^{-6}

Figure D.2 shows a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium (from Table D.1). Since each indicator is expressed in different units, and to facilitate the interpretation of the results, all the scores of an indicator have been divided by the highest score of the indicator, which represents the maximum impact of the indicator. Therefore, the lowest value represents the year with less impact and the highest value represents the maximum impact.

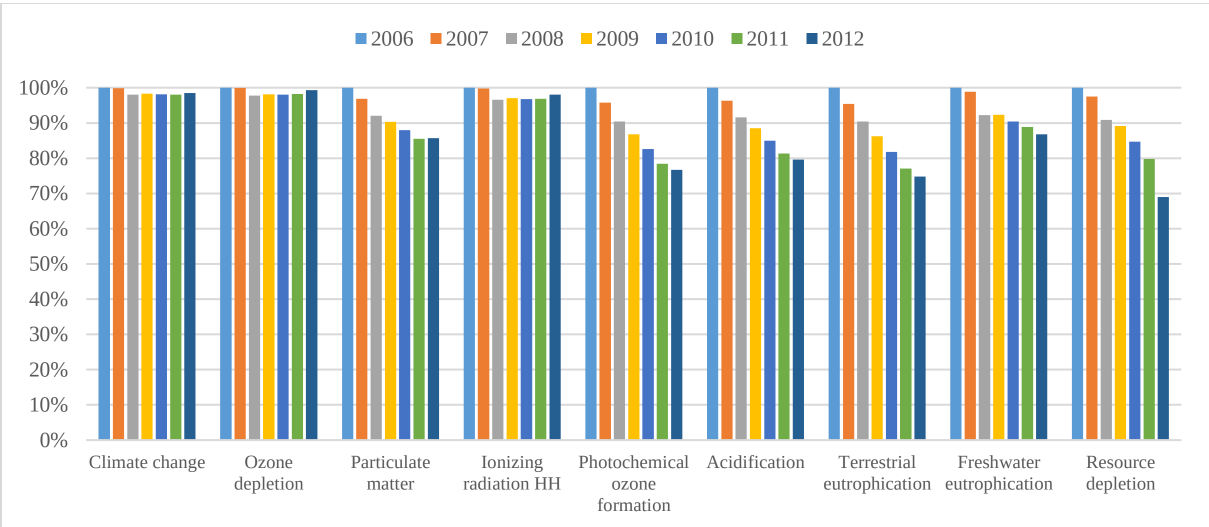


Figure D.2. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 50% in Belgium

The year 2006 presents the maximum impact in all the indicators due to this year has the highest lorry demand and the least environmental performance share of emission standards (see Figure 5.5). However, the difference between the years 2006 and 2007 is not significant in the indicators climate change, ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion.

Table D.2 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium.

Table D.2. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	8.24×10^{-2}	8.24×10^{-2}	8.08×10^{-2}	8.11×10^{-2}	8.10×10^{-2}	8.10×10^{-2}	8.13×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.55×10^{-8}	1.55×10^{-8}	1.52×10^{-8}	1.52×10^{-8}	1.52×10^{-8}	1.52×10^{-8}	1.54×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	6.56×10^{-5}	6.38×10^{-5}	6.06×10^{-5}	5.96×10^{-5}	5.81×10^{-5}	5.66×10^{-5}	5.61×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	7.17×10^{-3}	7.18×10^{-3}	6.93×10^{-3}	6.97×10^{-3}	6.96×10^{-3}	6.97×10^{-3}	7.05×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	8.21×10^{-4}	7.87×10^{-4}	7.43×10^{-4}	7.13×10^{-4}	6.80×10^{-4}	6.46×10^{-4}	6.32×10^{-4}
Acidification	**molc H+ eq**	6.97×10^{-4}	6.73×10^{-4}	6.38×10^{-4}	6.18×10^{-4}	5.94×10^{-4}	5.69×10^{-4}	5.57×10^{-4}
Terrestrial eutrophication	**molc N eq**	3.01×10^{-3}	2.88×10^{-3}	2.72×10^{-3}	2.60×10^{-3}	2.47×10^{-3}	2.33×10^{-3}	2.26×10^{-3}
Freshwater eutrophication	**kg P eq**	5.96×10^{-6}	5.97×10^{-6}	5.51×10^{-6}	5.57×10^{-6}	5.47×10^{-6}	5.39×10^{-6}	5.26×10^{-6}
Resource depletion	**kg Sb eq**	5.08×10^{-6}	5.08×10^{-6}	4.64×10^{-6}	4.65×10^{-6}	4.45×10^{-6}	4.19×10^{-6}	3.63×10^{-6}

Figure D.3 presents a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium (from Table D.2).

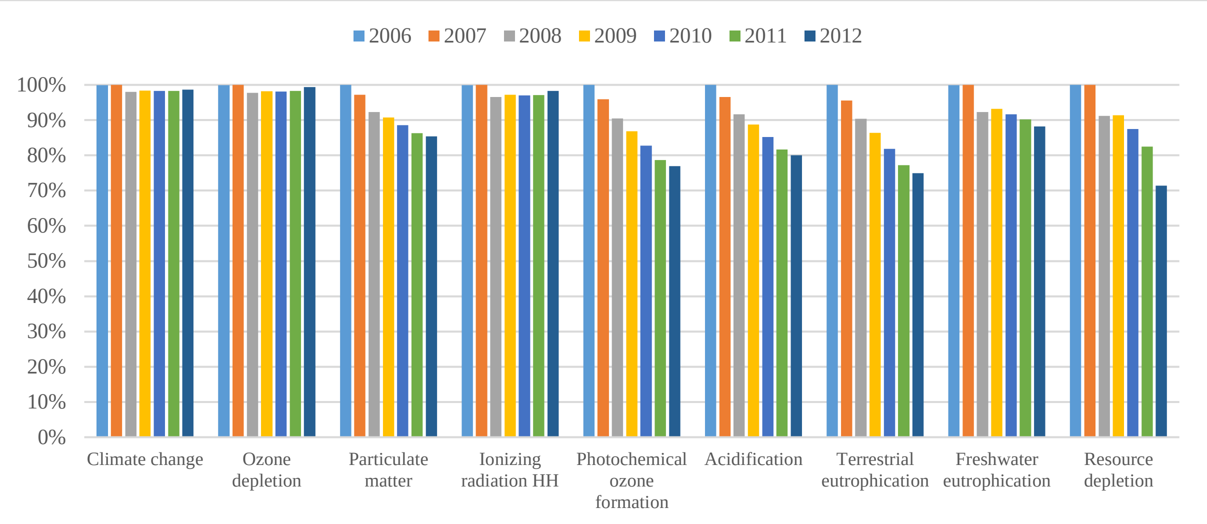


Figure D.3. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 60% in Belgium

On the one hand, the year 2006 presents the maximum impact in the indicators where the emission standards have a greater influence such as particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. On the other hand, the year 2007 presents the maximum impact in the other indicators: climate change, ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion.

As mentioned in the case of an articulated lorry of 34-40 t using a load factor of 50%, the difference between the years 2006 and 2007 is not significant in the indicators climate change, ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion. Therefore, depending on the load factor the difference between these years may vary slightly, making one or the other year have the maximum impact in those indicators.

Table D.3 presents the results obtained in the LCIA of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium.

Table D.3. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium

Impact category	Unit	2006	2007	2008	2009	2010	2011	2012
Climate change	**kg CO_2 eq**	6.41×10^{-2}	6.41×10^{-2}	6.28×10^{-2}	6.30×10^{-2}	6.31×10^{-2}	6.30×10^{-2}	6.33×10^{-2}
Ozone depletion	**kg CFC-11 eq**	1.21×10^{-8}	1.21×10^{-8}	1.18×10^{-8}	1.19×10^{-8}	1.19×10^{-8}	1.19×10^{-8}	1.20×10^{-8}
Particulate matter	**kg $PM_{2.5}$ eq**	5.07×10^{-5}	4.94×10^{-5}	4.69×10^{-5}	4.63×10^{-5}	4.54×10^{-5}	4.42×10^{-5}	4.39×10^{-5}
Ionizing radiation HH	**kBq U235 eq**	5.55×10^{-3}	5.56×10^{-3}	5.36×10^{-3}	5.39×10^{-3}	5.40×10^{-3}	5.40×10^{-3}	5.47×10^{-3}
Photochemical ozone formation	**kg NMVOC eq**	5.92×10^{-4}	5.68×10^{-4}	5.35×10^{-4}	5.15×10^{-4}	4.92×10^{-4}	4.68×10^{-4}	4.58×10^{-4}
Acidification	**molc H+ eq**	5.08×10^{-4}	4.91×10^{-4}	4.65×10^{-4}	4.51×10^{-4}	4.35×10^{-4}	4.17×10^{-4}	4.09×10^{-4}
Terrestrial eutrophication	**molc N eq**	2.15×10^{-3}	2.06×10^{-3}	1.95×10^{-3}	1.86×10^{-3}	1.77×10^{-3}	1.67×10^{-3}	1.62×10^{-3}
Freshwater eutrophication	**kg P eq**	4.49×10^{-6}	4.49×10^{-6}	4.09×10^{-6}	4.14×10^{-6}	4.15×10^{-6}	4.03×10^{-6}	3.95×10^{-6}
Resource depletion	**kg Sb eq**	3.72×10^{-6}	3.73×10^{-6}	3.29×10^{-6}	3.30×10^{-6}	3.30×10^{-6}	3.00×10^{-6}	2.60×10^{-6}

Figure D.4 presents a comparison of the results obtained in the environmental impact assessment of one tonne-kilometre of freight transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium (from Table D.3).

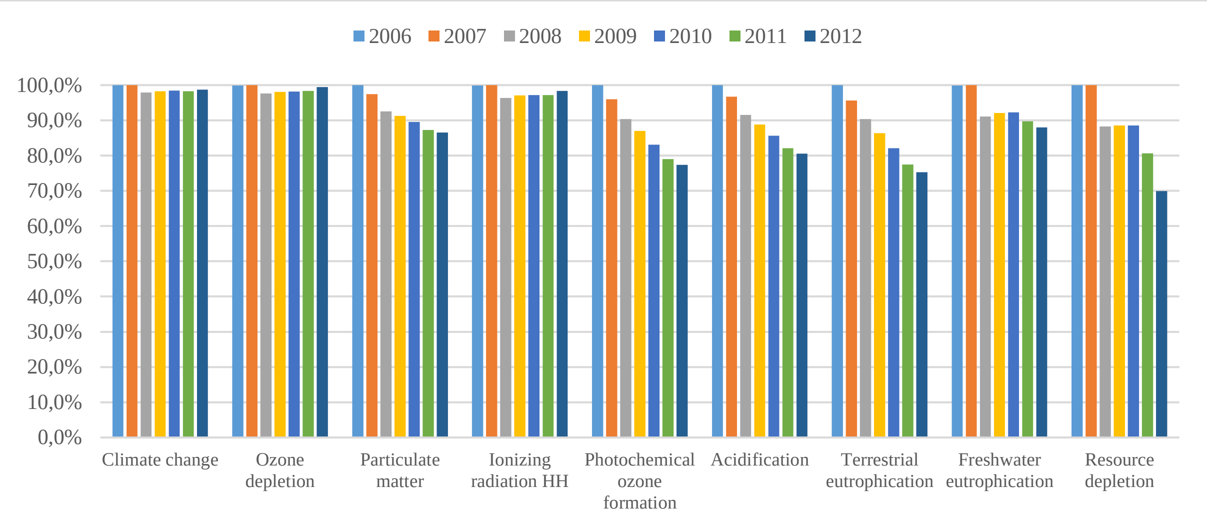


Figure D.4. LCIA of 1 tkm transported by an articulated lorry of 34-40 t with a load factor of 85% in Belgium

On the one hand, the year 2006 presents the maximum impact in the indicators where the emission standards have a greater influence such as particulate matter, photochemical ozone formation, acidification and terrestrial eutrophication. On the other hand, the year 2007 presents the maximum impact in the other indicators: climate change, ozone depletion, ionizing radiation (damage to human health), freshwater eutrophication and resource depletion.

Appendix E

In order to analyse how the improvement of the environmental performance of the different modes of transport affects the environmental impacts of inland freight transport in Belgium, new transport processes with different direct emissions to air and energy consumptions for three scenarios in the year 2030 (see Section 8.3.2) have been created.

Table E.1 presents the direct emissions to air and energy consumptions obtained for rail freight transport in a best, medium and worst case scenarios of the year 2030. The rail freight transport process of the year 2012 has been used as reference year. The reduction factors are based on technological advances in terms of energy efficiency and reduction of exhaust emissions.

Table E.1. Direct emissions to air and energy consumptions used in the rail freight transport process for the three scenarios of 2030

	Values in 2012	Rates of reduction			Values in the year 2030		
		Best	Medium	Worst	Best	Medium	Worst
Electricity consumption (kJ/tkm)	368	20%	15%	10%	295	313	331
Diesel consumption (kJ/tkm)	89				71	76	80
Direct emissions to air (g/tkm)							
CO_2	6.55	20%	15%	10%	5.24	5.57	5.89
SO_2	3.33×10^{-5}	40%	20%		2.00×10^{-5}	2.66×10^{-5}	3.00×10^{-5}
Cd	2.08×10^{-8}	20%	15%		1.67×10^{-8}	1.77×10^{-8}	1.87×10^{-8}
Cu	3.54×10^{-6}				2.83×10^{-6}	3.01×10^{-6}	3.18×10^{-6}
Cr	1.04×10^{-7}				8.33×10^{-8}	8.85×10^{-8}	9.37×10^{-8}
Ni	1.46×10^{-7}				1.17×10^{-7}	1.24×10^{-7}	1.31×10^{-7}
Se	2.08×10^{-8}				1.67×10^{-8}	1.77×10^{-8}	1.87×10^{-8}
Zn	2.08×10^{-6}				1.67×10^{-6}	1.77×10^{-6}	1.87×10^{-6}
Pb	2.29×10^{-10}				1.83×10^{-10}	1.95×10^{-10}	2.06×10^{-10}
Hg	4.16×10^{-11}				3.33×10^{-11}	3.54×10^{-11}	3.75×10^{-11}
CO	3.29×10^{-2}	40%	20%		1.97×10^{-2}	2.63×10^{-2}	2.96×10^{-2}
NO_X	1.14×10^{-1}				6.87×10^{-2}	9.16×10^{-2}	1.03×10^{-1}
$PM_{2.5}$	2.66×10^{-3}				1.60×10^{-3}	2.13×10^{-3}	2.40×10^{-3}
PM_{10}	1.56×10^{-2}				9.39×10^{-3}	1.25×10^{-2}	1.41×10^{-2}
PM_{10} > PM > $PM_{2.5}$	6.90×10^{-3}				4.14×10^{-3}	5.52×10^{-3}	6.21×10^{-3}
Methane	2.71×10^{-4}				1.62×10^{-4}	2.16×10^{-4}	2.44×10^{-4}
Toluene	8.33×10^{-5}				5.00×10^{-5}	6.66×10^{-5}	7.49×10^{-5}
Benzene	2..08×10^-4				1.25×10^{-4}	1.67×10^{-4}	1.87×10^{-4}
Xylene	8.33×10^{-5}				5.00×10^{-5}	6.66×10^{-5}	7.49×10^{-5}
NMVOC	1.06×10^{-2}				6.33×10^{-3}	8.44×10^{-3}	9.50×10^{-3}
NH_3	4.16×10^{-5}				2.50×10^{-5}	3.33×10^{-5}	3.75×10^{-5}
N_2O	2.08×10^{-4}				1.25×10^{-4}	1.67×10^{-4}	1.87×10^{-4}
SF_6 from electricity	4.50×10^{-6}				2.70×10^{-6}	3.60×10^{-6}	4.05×10^{-6}

Table E.2 presents the direct emissions to air and energy consumptions obtained for IWW in a best, medium and worst case scenarios of the year 2030. The IWW process of the year 2012 has been used as reference year. The reduction factors are based on technological advances in terms of energy efficiency and reduction of exhaust emissions.

Table E.2. Direct emissions to air and energy consumptions used in the IWW process for the three scenarios of 2030

	Values in 2012	Rates of reduction			Values in the year 2030		
		Best	Medium	Worst	Best	Medium	Worst
Fuel consumption (kJ/tkm)	288	20%	15%	10%	230	245	259
Direct emissions to air (g/tkm)							
CO_2	21.34	20%	15%	10%	17.07	18.14	19.21
SO_2	$1.35×10^{-4}$	40%	20%		$8.07×10^{-5}$	$1.08×10^{-4}$	$1.21×10^{-4}$
Cd	$6.73×10^{-8}$	20%	15%		$5.38×10^{-8}$	$5.72×10^{-8}$	$6.06×10^{-8}$
Cu	$1.14×10^{-5}$				$9.15×10^{-6}$	$9.72×10^{-6}$	$1.03×10^{-5}$
Cr	$3.36×10^{-7}$				$2.69×10^{-7}$	$2.86×10^{-7}$	$3.03×10^{-7}$
Ni	$4.71×10^{-7}$				$3.77×10^{-7}$	$4.00×10^{-7}$	$4.24×10^{-7}$
Se	$6.73×10^{-8}$				$5.38×10^{-8}$	$5.72×10^{-8}$	$6.06×10^{-8}$
Zn	$6.73×10^{-6}$				$5.38×10^{-6}$	$5.72×10^{-6}$	$6.06×10^{-6}$
Pb	$7.40×10^{-10}$				$5.92×10^{-10}$	$6.29×10^{-10}$	$6.66×10^{-10}$
Hg	$1.35×10^{-10}$				$1.08×10^{-10}$	$1.14×10^{-10}$	$1.21×10^{-10}$
CO	$1.82×10^{-2}$	40%	20%		$1.09×10^{-2}$	$1.45×10^{-2}$	$1.63×10^{-2}$
NO_X	$3.36×10^{-1}$				$2.02×10^{-1}$	$2.69×10^{-1}$	$3.03×10^{-1}$
$PM_{2.5}$	$6.21×10^{-3}$				$3.73×10^{-3}$	$4.97×10^{-3}$	$5.59×10^{-3}$
PM_{10}	$2.62×10^{-4}$				$1.57×10^{-4}$	$2.10×10^{-4}$	$2.36×10^{-4}$
PM_{10} > PM > $PM_{2.5}$	$5.18×10^{-4}$				$3.11×10^{-4}$	$4.14×10^{-4}$	$4.66×10^{-4}$
Methane	$1.61×10^{-4}$				$9.69×10^{-5}$	$1.29×10^{-4}$	$1.45×10^{-4}$
Toluene	$5.38×10^{-5}$				$3.23×10^{-5}$	$4.31×10^{-5}$	$4.84×10^{-5}$
Benzene	$1.28×10^{-4}$				$7.67×10^{-5}$	$1.02×10^{-4}$	$1.15×10^{-4}$
Xylene	$5.38×10^{-5}$				$3.23×10^{-5}$	$4.31×10^{-5}$	$4.84×10^{-5}$
NMVOC	$6.73×10^{-3}$				$4.04×10^{-3}$	$5.38×10^{-3}$	$6.06×10^{-3}$
NH_3	$3.49×10^{-4}$				$2.09×10^{-4}$	$2.79×10^{-4}$	$3.14×10^{-4}$
N_2O	$5.38×10^{-4}$				$3.23×10^{-4}$	$4.31×10^{-4}$	$4.84×10^{-4}$
Benzo(a)pyrene	$5.18×10^{-8}$				$3.11×10^{-8}$	$4.14×10^{-8}$	$4.66×10^{-8}$
HCl	$7.13×10^{-6}$				$4.28×10^{-6}$	$5.71×10^{-6}$	$6.42×10^{-6}$

Table E.3 presents the direct emissions to air and energy consumptions obtained for road freight transport in a best, medium and worst case scenarios of the year 2030. The average road transport process with a load factor of 50% of the year 2012 has been used as reference year. The reduction factors are based on technological advances in terms of energy efficiency and reduction of exhaust emissions.

Table E.3. Direct emissions to air and energy consumptions used in the road freight transport process for the three scenarios of 2030

	Values in 2012	Rates of reduction			Values in the year 2030		
		Best	Medium	Worst	Best	Medium	Worst
Diesel consumption (kJ/tkm)	988	10%	15%	30%	889	840	691
Direct emissions to air (g/tkm)							
CO_2	73.21	10%	15%	30%	65.89	62.22	51.24
SO_2	3.69×10^{-4}	20%	20%	40%	2.95×10^{-4}	2.95×10^{-4}	2.22×10^{-4}
Cd	2.31×10^{-7}	10%	15%	30%	2.08×10^{-7}	1.96×10^{-7}	1.62×10^{-7}
Cu	3.92×10^{-5}				3.53×10^{-5}	3.33×10^{-5}	2.75×10^{-5}
Cr	1.15×10^{-6}				1.04×10^{-6}	9.81×10^{-7}	8.08×10^{-7}
Ni	1.62×10^{-6}				1.45×10^{-6}	1.37×10^{-6}	1.13×10^{-6}
Se	2.31×10^{-7}				2.08×10^{-7}	1.96×10^{-7}	1.62×10^{-7}
Zn	2.31×10^{-5}				2.08×10^{-5}	1.96×10^{-5}	1.62×10^{-5}
Pb	2.54×10^{-9}				2.28×10^{-9}	2.16×10^{-9}	1.78×10^{-9}
Hg	4.62×10^{-10}				4.15×10^{-10}	3.92×10^{-10}	3.23×10^{-10}
Cr (VI)	2.31×10^{-9}				2.08×10^{-9}	1.96×10^{-9}	1.62×10^{-9}
As	2.31×10^{-9}				2.08×10^{-9}	1.96×10^{-9}	1.62×10^{-9}
CO	1.06×10^{-1}	20%	20%	40%	8.49×10^{-2}	8.49×10^{-2}	6.37×10^{-2}
NO_X	6.40×10^{-1}				5.12×10^{-1}	5.12×10^{-1}	3.84×10^{-1}
$PM_{2.5}$	1.42×10^{-2}				1.14×10^{-2}	1.14×10^{-2}	8.51×10^{-3}
NMVOC	2.14×10^{-2}				1.72×10^{-2}	1.72×10^{-2}	1.29×10^{-2}
NH_3	4.17×10^{-4}				3.33×10^{-4}	3.33×10^{-4}	2.50×10^{-4}
N_2O	1.77×10^{-3}				1.42×10^{-3}	1.42×10^{-3}	1.06×10^{-3}
indeno(1,2,3-cd)pyrene	1.43×10^{-7}				1.14×10^{-7}	1.14×10^{-7}	8.56×10^{-8}
benzo(k)fluoranthene	6.20×10^{-7}				4.96×10^{-7}	4.96×10^{-7}	3.72×10^{-7}
benzo(b)fluoranthene	5.55×10^{-7}				4.44×10^{-7}	4.44×10^{-7}	3.33×10^{-7}
benzo(a)pyrene	9.17×10^{-8}				7.33×10^{-8}	7.33×10^{-8}	5.50×10^{-8}

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Units, abbreviations and acronyms

A	Annum (year)
Al	Aluminium
Art.	Articulated
As	Arsenic
ASIF	Activity Structure Intensity Fuel
$CBrF_3$	Bromotrifluoromethane
Cd	Cadmium
CEMT	Conférence Européenne des Ministres de Transport
CFC-11	Trichlorofluoromethane
CH_4	Methane
Cnv.	Conventional
CO	Carbon monoxide
CO_2	Carbon dioxide
COPERT	Computer programme to calculate emissions from road transport
Cr	Chromium
Cr (VI)	Hexavalent chromium
CTU	Comparative Toxic Unit
Cu	Copper
CV	Coefficient of variability
DALY	Disability-adjusted loss of life years
EC	Energy consumption
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EPD	Environmental Product Declaration
Eq	Equivalent
Equip.	Equipment
EU-27	European Union (27 countries)
EU-28	European Union (28 countries)
Fe	Iron
GHG	Greenhouse gas
Gtkm	Gross tonne-kilometre
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
H+	Hydron
Hg	Mercury
HH	Human Health
HSL	High Speed Lines
IEA	International Energy Agency
ILCD	International Life Cycle Data
IO-LCA	Input-output LCA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITB	Institute pour le Transport par Batellerie
ITF	International Transport Forum
ITU	Intermodal Transport Unit
IWW	Inland waterways
kBq	Kilobecquerel
LCA	Life Cycle Assessment
LCC	Life Cycle Cost

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Assessment
LF	Load factor
LULUCF	Land use, land use change and forestry
Maint.	Maintenance
Mfg.	Manufacturing
Mn	Manganese
Molc	Mol of charge
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
Ni	Nickel
NMVOC	Non-Methane Volatile Organic Compound
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
O_3	Ozone
O-LCA	Organizational LCA
OEF	Organisation Environmental Footprint
PAH	Polycyclic Aromatic Hydrocarbon
P	Phosphorus
Pb	Lead
PEF	Product Environmental Footprint
PM	Particulate matter
PM_{10}	Particles measuring 10 µm or less
$PM_{2.5}$	Particles measuring 2.5 µm or less
RER	Europe
RoW	Rest-of-the-World
Sb	Antimony
SD	Standard Deviation
Se	Selenium
SEM	Standard error of mean
SETAC	Society of Environmental Toxicology and Chemistry
SF_6	Sulphur hexafluoride
SLCA	Social LCA
Sn	Tin
SNCB	National Railway Company of Belgium
SO_2	Sulphur dioxide
SO_X	Sulphur oxides
VOC	Volatile Organic Compound
TEN-T	Trans-European Transport Network
TEU	Twenty-foot equivalent unit
T	Tonne
Tkm	Tonne-kilometre
TRACCS	Transport data collection supporting the quantitative analysis of measures relating to transport and climate change
TTW	Tank-To-Well
U235	Uranium-235
UIC	International union of railways

UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
Vkm	Vehicle-kilometre
VMM	Vlaamse Milieumaatschappij
WMO	World Meteorological Organization
WTT	Well-To-Tank
WTW	Well-To-Wheel

List of Tables

List of Figures