Study of an international intermodal freight route based on an Environmental Life Cycle Assessment perspective

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***Abstract*—This paper analyses the results obtained from the study of the environmental impacts of the consolidated intermodal freight route from the Port of Antwerp (Belgium) to Ludwigshafen (Germany) using the Life Cycle Assessment (LCA) methodology. In the framework of our research, we have performed the LCA of rail freight transport (distinguishing between electric and diesel traction), inland waterways transport and road freight transport in Belgium independently. Then, we have used the results obtained previously to carry out a study of the environmental impacts related to the intermodal freight transport. The purpose of this analysis is to compare the environmental impacts of this intermodal route depending of the freight transport mode chosen.**

Keywords*—*intermodal transport; Life Cycle Assessment; electricity supply mix

I. INTRODUCTION

The transport sector was responsible for 24.1% 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) in the year 2010. A 71.8% of the GHG transport emissions were caused by road transport, including passenger and freight transport. Furthermore, transport represents an important source of air pollution. In the EU-28, road transport was the main source of nitrogen oxides (NO_X) emissions in 2010, representing 39.3% of the total emissions. Moreover, transport was a major source of Non-Methane Volatile Organic Compounds (NMVOC) with 13.5% of the total emissions, sulphur oxides (SO_X) with 2.2% of the total emissions, primary particulate matter of a diameter of 2.5 µm or less ($PM_{2.5}$) with 15.3% of the total emissions and particles with a diameter of 10 µm or less (PM_{10}) with 14% of the total emissions [1]. The mentioned pollutants are produced by fuel combustion during transport operation, but other non-exhaust emissions of particulate matter, including PM_{10} and $PM_{2.5}$, 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. Additionally, the transport sector was the main consumer of energy in the EU-28 with a 31.3% of the final energy consumption in the year 2010 [1].

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 [2] [3] especially when electrified railway is used [4]. Although inland waterways 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 [5].

A study of the international intermodal route from the Port of Antwerp (Belgium) to Ludwigshafen (Germany) has been carried out to analyse the environmental impacts related to intermodal transport. This is an important international route of B-Logistics (rebranded to Lineas, April 2017), which is the main rail freight operator in Belgium with a market share of 86.62% of tkm in 2012 [6]. The purpose of this analysis is to compare the environmental impacts of this intermodal route depending on the freight transport mode chosen for the major part of the intermodal route: rail freight transport, inland waterways transport or road transport. As shown in Fig. 1, 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.

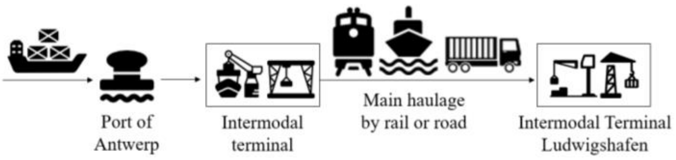

Fig. 1. Intermodal route from Port of Antwerp (Belgium) to Ludwigshafen (Germany).

II. METHODOLOGY

The Life Cycle Assessment (LCA) methodology has been chosen to analyse the environmental impact of intermodal freight transport, because it provides a system perspective analysis that allows assessing environmental impacts through all the stages of the intermodal freight transport system (transport operation, vehicle and infrastructure), from raw material extraction, through materials use, and finally disposal. Furthermore, the LCA methodology allows modelling in a quantitative and multi-criteria way the environmental impacts of all relevant pollutant emissions and energy and material consumptions in numerous environmental impact categories, such as climate change, particulate matter emissions or photochemical ozone formation for example [7].

Furthermore, the LCA approach allows us to analyse the overall life cycle of the energy carrier. Thereby, we consider the environmental impacts related to the use of energy (e.g. diesel or electricity) starting from the raw materials extraction (e.g. oil or uranium), continuing with energy generation (e.g. diesel refining or electricity production) and ending with the energy distribution to the traction unit (locomotive, barge or lorry). Besides the assessment of the environmental impacts related to the energy consumption during the transport operation, the LCA methodology includes the emissions and energy and raw material consumptions from the construction and maintenance of transport infrastructure and the manufacturing and maintenance of transport vehicles [8].

A. Rail freight transport

We have carried out a detailed study of the rail freight transport system in Belgium, collecting data in collaboration with Infrabel (the Belgian railway infrastructure manager) and B-Logistics. As shown in Fig. 2, the rail freight transport system has been divided in three sub-systems: rail transport operation, rail infrastructure and rail equipment (locomotives and wagons).

The subsystem 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 refining. 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 the electricity production. 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. It should be noted that the specific energy consumption of electric and diesel trains has been determined separately, resulting in 438 kJ/tkm for electric trains and 760 kJ/tkm for diesel trains in the year 2010 [9].

For electric trains, to adjust as closely as possible the environmental impacts related to the electricity consumption, and since the intermodal transport route studied runs through two countries, our study uses the electricity supply mix in Belgium and Germany corresponding to the year 2010 according to Eurostat data [1].

Table 1 presents the electricity supply mix used in our study for electric trains and transhipment processes.

TABLE I. ELECTRICITY SUPPLY MIX OF BELGIUM AND GERMANY IN THE YEAR 2010. SOURCES: [1], [10]

Energy source	Belgium (%)	Germany (%)
Nuclear, pressure water	44.78	17.8
Nuclear, boiling water	-	4.82
Natural gas	25.88	12.00
Hard coal	5.82	17.78
Lignite	-	21.95
Oil	0.43	1.31
Treatment blast furnace gas	1.70	1.05
Treatment of coal gas	0.08	0.30
Hydro, pumped storage	1.32	1.07
Hydro, reservoir, non-alpine region	-	0.74
Hydro, run-of-river	1.61	3.78
Wind, <1 MW turbine	0.04	1.04
Wind, >3 MW turbine	0.12	0.56
Wind, 1-3 MW turbine	1.05	4.78
Wind, 1-3 MW turbine, offshore	0.04	0.01
Co-generation, biogas	0.50	1.55
Co-generation, wood chips	2.61	1.28
Imports from France	3.58	2.88
Imports from Luxembourg	2.09	-
Imports from The Netherlands	8.36	0.60
Imports from Austria	-	1.52
Imports from Czech Republic	-	1.77
Imports from Denmark	-	0.57
Imports from Poland	-	0.03
Imports from Switzerland	-	0.61
Imports from Sweden	-	0.21

The subsystem rail infrastructure takes into account the processes that are connected with the construction, maintenance and disposal of railway tracks. For the Belgian railway infrastructure, our inventory includes very specific characteristics such as railway track materials or maintenance processes. For the German railway infrastructure, we have used the railway infrastructure process and demand from the Ecoinvent v3 database [10]. Finally, the subsystem rail equipment includes the processes of manufacturing, maintenance and disposal of locomotives and wagons.

B. Inland waterways transport

Analogously to the rail transport system, the inland waterways system consist of three subsystems (see Fig. 3). The Directive 1999/32/EC established a sulphur content of gas-oil used by barges of 1000 ppm in the year 2010.

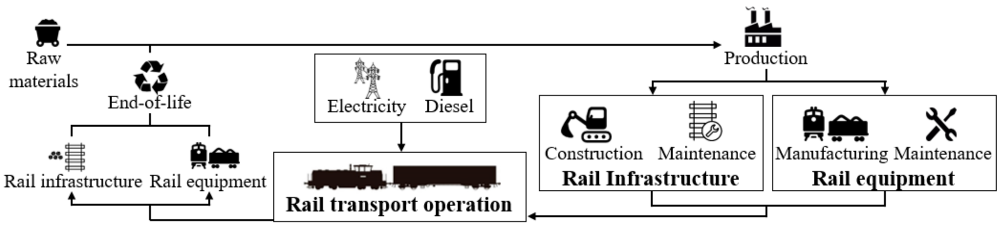

Fig. 2. Life cycle rail transport system boundaries

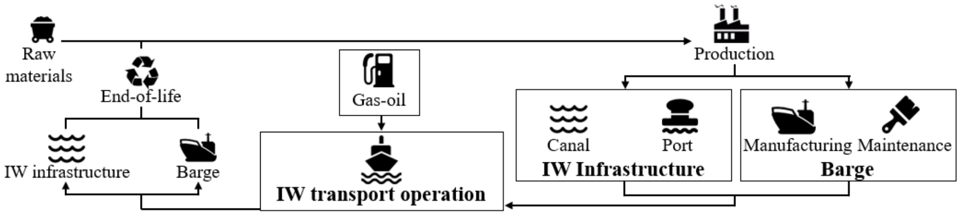

Fig. 3. Life cycle inland waterways transport system boundaries

For the inland waterway infrastructure, the Port of Antwerp and the Belgian inland waterways have been used as references. The average fuel consumption of inland waterways transport calculated was 293 kJ/tkm in the year 2010 [9].

C. Road freight transport

In the same way, the road transport system comprises the subsystems road transport operation, road infrastructure and lorry (see Fig. 4). For this study, 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. The average diesel consumption calculated for an articulated lorry 34-40 t in the year 2010 with a load factor of 50%, 60% and 85% was 849 kJ/tkm, 708 kJ/tkm and 500 kJ/tkm, respectively [9]. The choice of these load factors is because the load factor of an average cargo in road transport including empty trips is 50% [11]. Moreover, the load factors of intermodal road transport are 85% for the main haulage and 60% for the post-haulage [12].

Moreover, a Euro V emission engine technology has been chosen to calculate the exhaust emissions of the road transport operation. Within the articulated lorries of 34-40 t in Belgium in the year 2010, the lorries with an emission engine technology conventional represented the 13% of the Belgian market, the Euro I a 7%, the Euro II a 17%, the Euro III a 24%, the Euro IV a 23% and the Euro V a 16%.

III. RESULTS

After conducting the LCA of the three modes of inland freight transport shown above, we have carried out the study of the intermodal freight route from the Port of Antwerp (Belgium) to Ludwigshafen (Germany). The aim is to compare the environmental impacts of the three transport modes for this international intermodal route carrying the same number of containers with the same load. Thereby, it has been considered the transport of 78 TEU (Twenty-foot Equivalent Unit), which is the maximum payload of an average conventional intermodal freight train consisting of 26 wagons and a capacity of 3 TEU per wagon [12].

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 [12], resulting in 1115.4 t for the 78 TEU transported.

For the intermodal freight trains, a train load factor of 75% has been considered [12] and this, together with 78 TEU per train of maximum payload, results in an actual payload of 58.5 TEU per train. Thus, 1.3 trains are needed to transport the 78 TEU studied.

For the main haulage by inland waterways transport, we have considered a container vessel with a capacity of 200 TEU [13]. A load factor of the containers transported by vessel of 60% has been used [13], resulting in an actual payload of 120 TEU per vessel. Thus, only a 65% of this vessel is used to transport the 78 TEU considered.

For road transport, we have considered a capacity of 2 TEU per lorry but three different load factors have been used to transport the 78 TEU. Therefore, the vehicle demands for the load factors of 50%, 60% and 85% are 78 lorries, 65 lorries and 45.9 lorries, respectively.

For the transhipment in the Port of Antwerp and the intermodal terminal in Ludwigshafen, it has been considered an energy consumption in the transhipment processes of 16,560 kJ per TEU [14] (other literature source estimates an energy consumption in the transhipment processes of 15,840 kJ per TEU [11], but we have decided to use the most conservative value). Therefore, the energy consumption estimated for the transhipment of 78 TEU either in the Port of Antwerp or the intermodal terminal in Ludwigshafen is 1,291,680 kJ.

The distances between the Port of Antwerp and Ludwigshafen have been calculated using EcoTransIT World [15], resulting in 488 km by train, 621 km by inland waterways and 407 km by road. Therefore, considering a handle volume of 1115.4 t for the 78 TEU transported, the transport performance calculated is 544,315 tkm for rail transport, 692,663 tkm for inland waterways transport and 453,968 tkm for road transport.

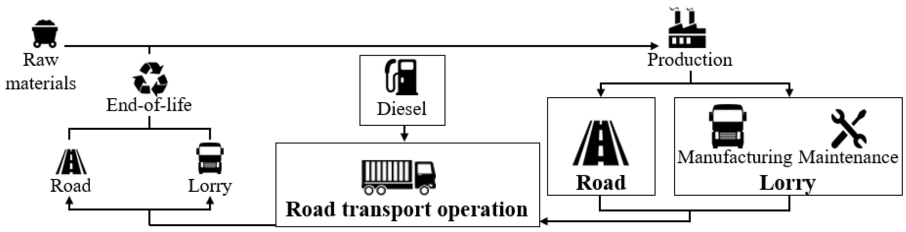

Fig. 4. Life cycle road transport system boundaries

Table 2 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 transport, inland waterways transport and road transport.

TABLE II. MAIN CHARACTERISTICS OF THE INTERMODAL ROUTE

		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 - 2.2 - 1.7
	Vehicle demand	1.3	0.65	78 - 65 - 45.9
	Handled volume	1115.4 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. Thereby, 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, the electricity supply mix of Belgium and Germany have been used for the part of the intermodal route that passes in that country (see Table 1). 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 we have carried out a complete inventory, for the German railway infrastructure we have used the Ecoinvent v3 database [10].

It should be noted that 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 inland waterways 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.

A. Life Cycle Impact Assessment of the modes of tranport

Fig. 5 shows a comparison of the results obtained in the Life Cycle Impact Assessment (LCIA) of one tonne-kilometre of freight transported in Belgium in the year 2010 by diesel train, electric train, inland waterways transport and an articulated lorry of 34-40 t Euro V with the load factors of 50%, 60% and 85%. All calculations were made with the SimaPro 8.0.5 software using the Life Cycle Impact Assessment (LCIA) method "ILCD 2011 Midpoint+" (version V1.06 / EU27 2010), which is the method recommended by the European Commission [7]. Since each environmental impact indicator is expressed in different units, and to facilitate the interpretation of the LCIA 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 mode of transport with less impact and the highest value represents the maximum impact.

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. Moreover, diesel trains show the maximum impact in the indicator "Human toxicity, cancer effects", but with a similar value than electric trains due to the similar steel demand in the railway infrastructure. Electric trains present the maximum impact in the two indicators related with the radiation due to the use of nuclear power in the electricity production in Belgium. Inland waterways transport presents the maximum impact in the indicator freshwater eutrophication due to the infrastructure demand of canals and port facilities.

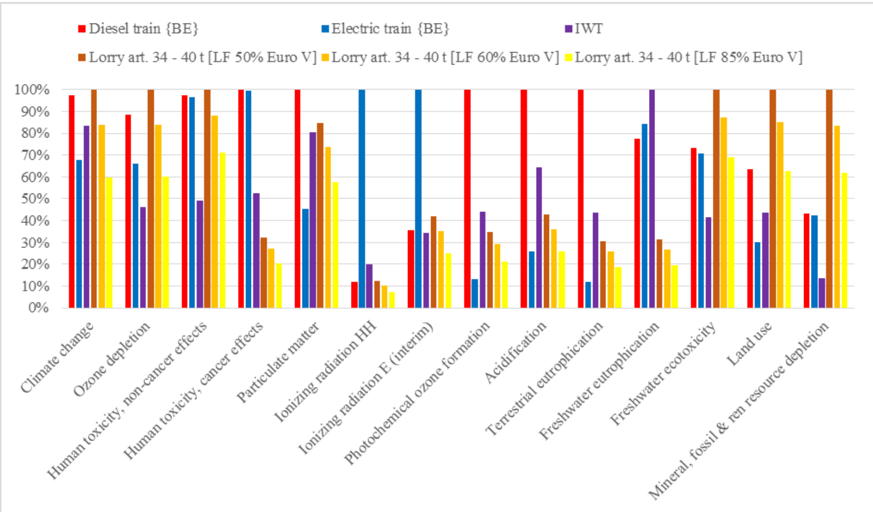

Fig. 5. LCIA of 1 tkm of freight transported by different freight transport modes in Belgium in the year 2010

For the indicator climate change, the articulated lorry of 34-40 t with a load factor of 50% presents the maximum impact due to the exhaust emissions during the transport activity. However, diesel trains show a very similar value in this indicator. It should be noted that an articulated lorry of 34-40 t with a load factor of 60% presents nearly the same environmental impact on climate change than inland waterways transport. Although, with a load factor of 85% have the lowest score for this indicator. Electric trains emits SF_6 during electricity conversion at traction substations, but the main greenhouse gas emissions are produced in the electricity generation, especially in the natural gas power plants.

B. Life Cycle Impact Assessment of the intermodal route

Fig. 6 shows a comparison of the results obtained from the Life Cycle Impact Assessment (LCIA) of the intermodal route from Port of Antwerp to Ludwigshafen considering the main characteristics shown in table 2. Thereby, six types of modes of transport have been chosen for the main haulage: diesel train, electric train, inland waterways transport and an articulated lorry of 34-40 t Euro V with the load factors of 50%, 60% and 85%.

Diesel trains have the maximum impact in the environmental impact indicators photochemical ozone formation, acidification and terrestrial eutrophication due to the exhaust emissions produced in the diesel locomotives. It should be noted that the articulated lorries of 34-40 t Euro V have a lower impact than diesel trains for the indicator photochemical ozone formation due to the lower exhaust emissions on NO_X and NMVOC of the Euro V emission engine technology. Similarly, for the indicators acidification and terrestrial eutrophication, the articulated lorries of 34-40 t Euro V has a lower impact than diesel trains due to the lower exhaust emissions on NO_X of the lorries Euro V. Electric trains show the maximum impact in five environmental impact indicators, being two of them related with the radiations due to the use of nuclear power in the electricity generation.

Moreover, electric trains show the maximum impact in the indicator "Human toxicity, non-cancer effects" and "Human toxicity, cancer effects" due to the indirect emissions during the electricity production in Germany. Furthermore, the high steel demand of the railway infrastructure constitutes an important part in the indicator "Human toxicity, cancer effects" in both rail freight transport modes. The articulated lorry of 34-40 t Euro V with a load factor of 50% presents the maximum impact in three environmental impact indicators. For the indicator particulate matter, besides the exhaust emissions from the diesel combustion in the engine, the direct emissions in the road transport activity of tire wear, break wear and road wear have a strong influence in the result. The inland waterways transport shows the maximum impact in the indicators climate change and particulate matter as a result of 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).

For the indicator climate change, inland waterways transport presents the maximum impact due to the exhaust emissions of greenhouse gases (GHG) during the transport activity. It must be emphasised that electric trains present a higher impact on climate change than the articulated lorries of 34-40 t Euro V due to the high indirect emissions of GHG in the electricity generation in Germany. The hard coal and lignite power plants were responsible for 39.73% of the total electricity supply mix in Germany in the year 2010, which explains the high GHG indirect emissions.

Fig. 7 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 those related with human toxicity and freshwater present a greater impact for the German electricity than for the Belgian one.

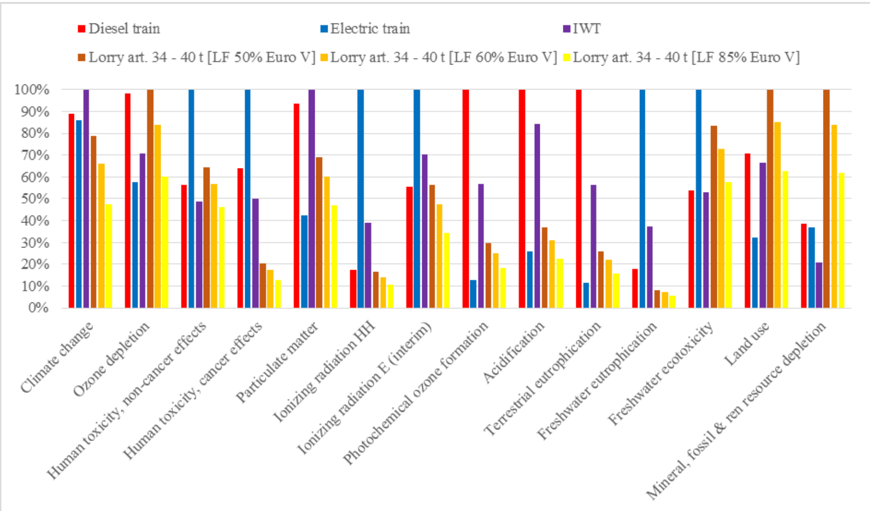

Fig. 6. LCIA of the intermodal route from the Port of Antwerp to Ludwigshafen by different freight transport modes

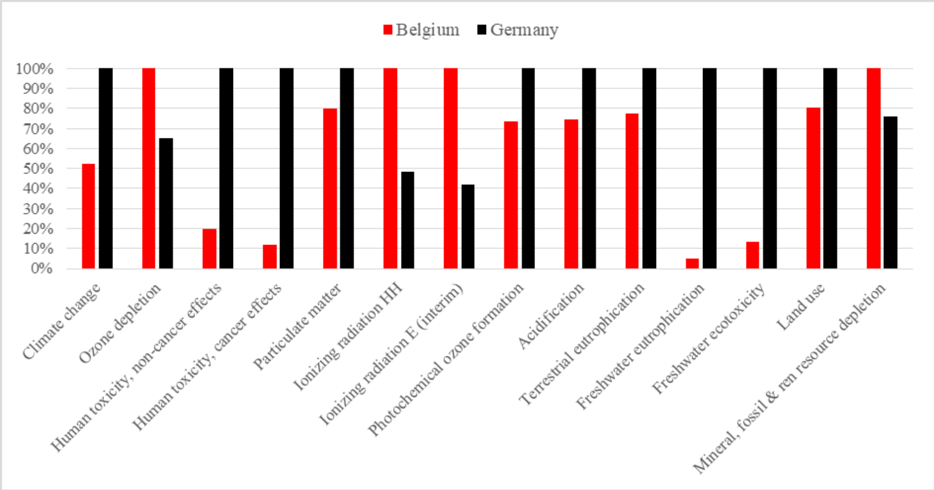

Fig. 7. LCIA of the transhipment of 78 TEU using electricity from Belgium and Germany in the year 2010

Considering all the above, one question arises: how does the electricity supply mix affect the environmental impact of electric trains when they cross the border between Belgium and Germany?

Fig. 8 shows the LCIA of 1 tkm moved in Belgium and Germany by diesel and electric trains. 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 we have performed a detailed study, 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 a higher impact on indicators such as climate change and those related to human toxicity and freshwater due to the electricity supply mix of Germany (as already seen in Fig. 7).

In addition, electric trains in Germany present a higher impact on climate change than diesel trains in both Belgium and Germany. In Belgium, the electric trains have the highest impact in the indicators related with the radiation due to the use of a 44.78% of nuclear power in the electricity production in the year 2010.

CONCLUSION

In view of the results obtained in the study of the different transport modes, 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. Furthermore, the fundamental role that the electricity supply mix plays in the environmental impact of electric trains has been highlighted. Thereby, electrics trains powered by German electricity (approximately half of which was generated from fossil fuels in the year 2010) present a higher environmental impact than diesel trains on indicators such as climate change and those related to human toxicity and freshwater. Therefore, as the use of electric trains increases in the future, the energy split for the electricity generation will be more important in the environmental impacts of goods transport.

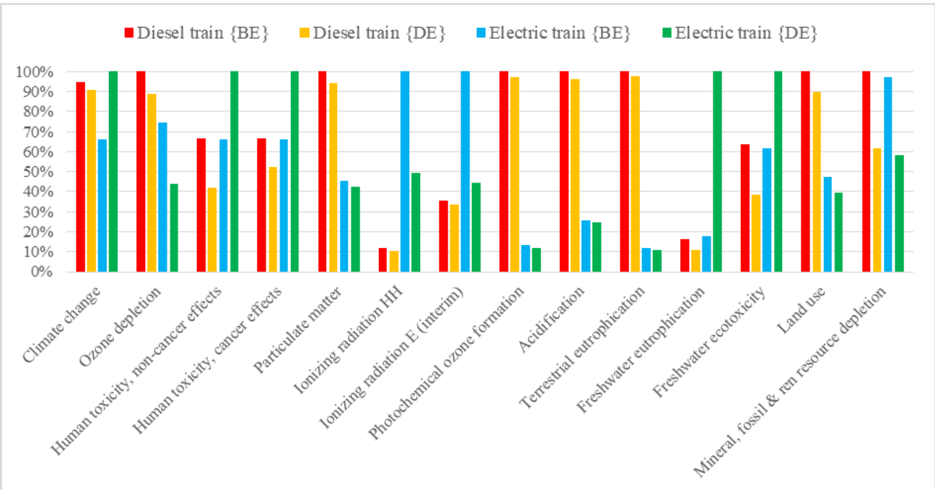

Fig. 8. LCIA of 1 tonne-kilometre (tkm) of rail freight transport in Belgium and Germany in the year 2010

The results show intermodal transport by barge or electric train as an opportunity from an environmental point of view. Thereby, when comparing one tonne-kilometre of freight transported in Belgium by rail or inland waterways transport instead of road transport with a 50% of load factor, the environmental impact on climate change decrease by 32% using an electric train, 16% by barge and only a 3% by diesel train. However, the load factor is shown as determining factor in the environmental impacts of road transport. Thereby, an articulated lorry of 34-40 t with a load factor of 60% presents nearly the same environmental impact on climate change than inland waterways transport and with a load factor of 85% have the lowest impact.

Other important environmental impact indicators in transport that should be highlighted are particulate matter emissions and photochemical ozone formation. The use of an electric train represents a reduction of 12% and 8% of environmental impact compared to a lorry 34-40 t Euro V with a load factor of 85% on the indicators particulate matter and photochemical ozone formation, respectively. However, the use of diesel trains produces a higher impact in both indicators than road transport with a Euro V emission engine technology due to the higher exhaust emissions on particulate matter, NO_X and NMVOC of diesel locomotives. This highlight the importance of upgrading the emission engine technology of diesel locomotives. However, on the one hand the lower rate of replacement of the locomotives due to their longer life span causes a slow implementation of new engines with better emission technologies. On the other hand, the higher rate of renewal of the lorry fleet produces a faster improvement in road transport emissions. It should be noted that the use of lorries with a Euro VI emission engine technology (which appeared in the year 2014 in the European heavy duty vehicle market) would have improved the environmental performance of road transport in the indicators particulate matter, photochemical ozone formation, terrestrial eutrophication and acidification. This is because the lower emissions on $PM_{2.5}$, NO_X and N_2O of a Euro VI engine compared to a Euro V.

On the basis of the results obtained in the study of the three routes (i.e. rail, inland waterways and road), the distance of the intermodal route is shown as determining factor in the environmental impacts of the transport mode chosen. Thereby, inland waterways transport experiences a high increase of its environmental impacts compared to rail and road transport due to the greater distance that the barge has to travel. Thereby, inland waterways transport shows the higher impact in the intermodal route in the indicators climate change and particulate matter. However, it should be noted that this intermodal route is not conducive to inland waterways transport since the distance by barge is 53% greater than the distance by road.

However, shifting road freight transport in long distances in favour of electric trains and inland waterways transport is still a significant measure to apply, which in the case of electric trains becomes especially interesting when they are powered by sustainable electricity. In view of the foregoing, a better environmental performance of intermodal transport could be achieved by improving the characteristics of the transports modes such as load factor, emission engine technology or the electricity supply mix.

ACKNOWLEDGMENT

The researches underlying these results have been financed by the Belgian Science Policy under Contract No. [BR/132/A4/BRAIN-TRAINS].

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