Towards sustainable freight transportation: an LCA review

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Abstract: Freight transportation impacts significantly on the environment. A tougher competition for efficiency and sustainability among transportation mode is foreseen in the coming years. However, there is still a gap in the literature concerning the impact assessment of freight transportation, considering all the phases of the life cycle, including infrastructure building, production of vehicles, and end-of-life. This paper aims at reviewing the literature to compare different transport modes, based on a life cycle approach. The results would be pivotal for decision-makers to take informed decisions on which transport modes to incentivize to reduce the environmental impacts while ensuring adequate goods movement internationally.

1. Introduction

The freight transportation (FT) sector is posing several challenges with serious consequences from an environmental perspective (Sims et al., 2018): i) FT relies on longer routes compared to the past, with international transportation becoming increasingly common (Shankar et al., 2019); ii) supply chains are becoming particularly complex, while consumers' preferences and manufacturing requirements are constantly changing (OECD, 2016); iii) FT is projected to triple in 2050 compared to 2015 (International Transport Forum, 2019); iv), the FT sector has changed dramatically: shipments are smaller, more frequent and cover longer routes, which requires fast, energy-intensive transport (OECD, 2016).

The environmental impact of FT is substantial, with greenhouse gas (GHG) emissions doubled compared to 1970 (Sims et al., 2018) and constantly increasing (Our World in Data, 2021), and FT alone accounts for 40% of the global transport energy consumption (Muratori et al., 2017). The environmental impact can be reduced selecting adequate vehicles and transportation modes (Ren et al., 2020), and a strong effort is required to policy-makers in terms of interventions limiting the overall environmental impact.

The Life Cycle Assessment (LCA) methodology could be the proper tool for comparing different solutions and select the least impactful one. The LCA allows quantifying the environmental impacts of a product or system, along its entire life cycle (Finkbeiner et al., 2006). For a holistic evaluation of the impacts of freight transport, several elements should be addressed besides fuel use (Facanha and Horvath, 2007), i.e. manufacturing, use phase, maintenance, end-of-life, durability, land use, behaviour of users (Saxe and Kasraian, 2020).

This paper performs a literature review on the application of the LCA to the FT sector, to facilitate a holistic assessment of each transport mode. The results would allow policymakers to

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take informed decisions on which transport modes to incentivize to reduce the environmental impacts while ensuring adequate goods movement internationally.

2. Literature review: challenges in LCA of freight transport

The FT sector still relies largely on liquid fossil fuels, especially in the use phase of vehicles (Fridell et al., 2019). Emissions are typically related to CO_2, nitrogen oxides, sulfur oxides, particulate matter, elevate ozone concentrations, resulting in poor air quality and connected health issues, eutrophication, acidification, lower crop yields. The extant applications of the LCA in the FT sector is nonetheless mainly focuses on end-of-pipe emissions, without properly assessing vehicles production, end-of-life and infrastructure building (Browne et al., 2005; Facanha and Horvath, 2007). Several challenges emerge when applying the LCA to FT, and in particular considering the infrastructure, as summarized in Table 1 (Saxe and Kasraian, 2020).

Table 1: challenges of applying the LCA methodology to FT (Saxe and Kadraian, 2020)

Demolition and disposal phase	Occur at the beginning rather than at the end of the useful life since the land will need to be cleared to make space for the infrastructure.
Construction phase	Additional emissions (up to the 33% of the total) are generated because of traffic disruption.
Use phase	Should include the users' travel behaviors and the influence of the new infrastructure on the available options.
Induced demand	Must be included, although difficult to estimate. Building additional infrastructure increasing traffic and inducing new travel.
Maintenance	Required at regular intervals, in the long-term may account for a considerable share of the impact.
End-of-life	Difficult to estimate, and virtually there is no such thing for infrastructure transportation (many examples of infrastructure lasting for centuries).
Land use	To be considered not only where the infrastructure is built but also in the adjacent and regional areas.
Spatial spillover	Difficult to quantify. For example, a new highway may induce residential development.

However, vehicles production, end-of-life and infrastructure building may account for a considerable share of the total impact (Saxe and Kasraian, 2020). Properly set system's boundaries should therefore include infrastructure, vehicle and fuel life-cycles (Fridell et al., 2019). The present study will thus focus on the three of them, to achieve a holistic assessment of FT's impact and fill some of the gaps found in the extant literature. The literature has been searched to retrieve information on four typical transport modes (road, rail, air, and sea transport), analyzed considering all the phases of the life cycle and seeking ways to improve their environmental impact. Keywords from the freight transport literature have been used, coupled with keywords such as "impact", "assessment", "environmental". The international database Scopus has been used. Table 2 summarizes the results from the literature review performed.

2.1. Road

Road transportation is used for short to medium hauls trips (Facanha and Horvath, 2007). In the European Union, trucks are only 3% of the total vehicle fleet, but are responsible for over 25% of the total emissions of the transport sector, with an increase in domestic truck traffic (Osorio-Tejada et al., 2018).

Road transportation relies largely on diesel trucks, which have substantial environmental impact (Hannach et al., 2019): toxic and polluting exhausts, causing for instance acid rains, and very fine particle emissions, causing severe health repercussions. During the operation phase, the impact is related more to fuel consumption rather than production (Osorio-Tejada et al., 2018). The conditions of motorways and infrastructures also impact on the fuel consumption, with well-maintained, flat motorways having a lower impact (Osorio-Tejada et al., 2018). Motorways and highways, however, have a high environmental impact in terms of habitat loss and connectivity, land quality, invasive species introduction, degradation of natural areas. Additionally, building new highways may lead to an increase in GHG emissions due to induced traffic and land-use change (Saxe and Kasraian, 2020).

End-of-pipe solutions to improve truck efficiency, as post-exhaustion particulate filters, have proven ineffective and insufficient, considering the urgency of reducing emissions to tackle climate change (Osorio-Tejada et al., 2018). Currently, electric vehicles are expected to help reduce the environmental burden of the transport sector, especially in terms of end-of-pipe emissions (Ren et al., 2020). Recent LCA studies show that electric vehicles may halve the CO_2 equivalent emissions compared to conventional vehicles. The major share of impact for electric vehicles is concentrated in the electricity production phase (Messagie, 2017), and much of the environmental advantages depend on the energy mix used (Hawkins et al., 2013). However, even with a coal-based energy mix, electric vehicles prove 25% less impactful than conventional diesel vehicles (Messagie, 2017). This is an important result that should drive policy interventions.

Electrifying trucks that need to travel long distances may require large batteries, which in turn contain several scarce materials and rare earth and considerably increase costs (Schulte and Ny, 2018). In their study, Hannach et al. (2019) evaluate the life cycle impact of substituting diesel with hydrogen, as it reduces the overall energy used in the life cycle of vehicles, and its exhaust from combustion does not contain toxic or polluting substances. Besides, hydrogen is very abundant on earth and can be easily produced from water. Considering the conversion to dual-fuel trucks, the authors show that even a 30% substitution of diesel with hydrogen brings substantial environmental benefits, that increase as the percentage of substitution raises. The conversion cost from diesel to dual-fuel trucks is limited compared to the cost of the entire vehicle, as only the fuel injection system will have to be modified. After a 50% substitution of diesel with hydrogen, a complete engine substitution could be required.

2.2. Rail

Rail transportation can be carried out using diesel or electric trains (Merchan et al., 2020). During the operation phase, trains' direct impact relates to exhaustion from diesel vehicles; for electric vehicles, emissions of Sulphur hexafluoride (SF_6) – an insulating gas used in the transformers of traction substations – and the direct emissions to soil because of the wear between brakes and wheels, or wheel and rail interfaces. Indirectly, both types of vehicles require primary energy extraction, and then refinement or electricity generation. Diesel vehicles have the highest impact during operation in case conventional diesel is used; as biodiesel brings benefits to the operation phase impact, the burden may be shifted towards agricultural activities. For electric trains, electricity production is the highest impact stage, especially if coal or natural gas is used. The energy mix is thus crucial for proper assessment of different rail vehicles: for instance, using the energy mix of Poland – almost 50% of electricity generated from coal – electric trains have twice the environmental impact of diesel trains in Belgium. Several authors point out that the FT sector relies almost entirely on fossil fuels (Muratori et al., 2017): having a cleaner, low carbon energy mix becomes therefore crucial to lowering the impact of the transportation sector (Jones et al., 2017).

The infrastructure building is the main contributor to freshwater eutrophication, due to the production of primary materials such as copper and steel. Based on data from Belgium, Merchan et al. (2020) conclude that electric trains have a better environmental impact than diesel trains, because of avoided local emissions, lower contribution on different impact categories and an overall higher energy efficiency. Rail infrastructure is critical for rail transport efficiency, yet its environmental impact is not often considered (Pons et al., 2020). The use and maintenance of rail infrastructure have a significant impact on the environment in the case of diesel trains (Hegedić et al., 2018).

2.3. Air

Air transport is used mainly for international shipping (Facanha and Horvath, 2007), especially for highly perishable, high-value products (Si-Log Network, 2019). Aviation is responsible for almost 12% of global transport-related CO_2 emissions, and the share is forecasted to grow 3-5% per year (Cox et al., 2018). Cox et al. (2018) perform a rather complete LCA of air transportation, including aircraft production, use, maintenance, end-of-life; fuel production and consumption; airport construction, maintenance, use, end-of-life. Overall, the authors demonstrate that airport construction, aircraft production and fuel production are the least impactful phases. Direct emissions from aircraft during use make up to 60% of the potential global warming impact. For short flights, NOx has a considerable impact. Besides, the impact per ton-kilometer tends to lower as the size of aircraft and the distance travelled increase. However, Barke et al. (2020) highlight that non-tailpipe emissions (i.e. emissions from aircraft, kerosene use, and infrastructure production) are considerable and may be as high as 16-21%.

To achieve the environmental targets set by the international community, alternative technologies to conventional propulsion are being studied, as fuel efficiency alone will not be sufficient to meet such goals (Melo et al., 2020). Melo et al. (2020) review the most promising technologies to replace conventional fuel propulsion: they identify electric propulsion, biofuels based on vegetable feedstock, e-fuels as hydrogen. In particular, the authors note that the viability of hydrogen as an alternative fuel has been widely discussed in the literature, due to its high energy content, zero CO_2 emissions during use, and the relative easiness of production via water electrolysis. The reduction of environmental cost can be up to 60% compared to conventional kerosene. On the contrary, there is scant literature on the use of electric aircraft.

2.4. Sea

Sea transportation is mainly used for international shipping (Facanha and Horvath, 2007) and it is the most common form of transport, accounting for almost 90% of goods transported yearly (Si-

Log Network, 2019). It is usually used to cover large distances, and it is suitable for non-perishable products (Si-Log Network, 2019). Given the dimension of the tankers, a significant amount of energy is required for sea transportation, which is usually provided in the form of high polluting diesel or residual fuel oils (Bicer and Dincer, 2018).

It is common opinion that that the highest impact of shipbuilding relates to the raw materials, as steel (Shama, 2005). However, it is during operations that the greatest environmental impact of sea transportation is experienced (Chatzinikolaou and Ventikos, 2015). CO_2 emissions are considerable and may account for up to 96% of the total emissions during operations. The building phase, instead, is dominated by CH_4 emissions, mainly due to steel production (Chatzinikolaou and Ventikos, 2015). Lastly, hydrogen may represent a viable solution for an alternative and greener source of fuel (Bicer and Dincer, 2018).

2.5. Intermodal transportation

Besides technological innovation, multi-modal transportation is indicated as an adequate tool to reduce FT's environmental impact. It refers to the use of at least two different transportation modes (Ingrao et al., 2020). Despite a lower environmental impact, it is not widely used in Europe (Hrušovský et al., 2021).

Ingrao et al. (2020) perform an LCA study on different intermodal transportations (ship and trucks; ship and rail; ship, rail and truck) comparing them to the transport by trucks only. The multimodal scenario, when all three means of transport are used, emerges as the most environmentally sound, although posing management issues. Using only trucks for long distances is confirmed to have a substantially higher environmental impact compared to the other scenarios. The results are supported by Pizzol (2019). Additionally, a shift to intermodal transportation may halve the impacts on human and ecosystem health, and non-renewable energy demand (Fries and Hellweg, 2014).

Table 2: A literature review on different transportation modes.

Author, year	Life cycle stage included in the analysis			Transportation modes analyzed			
	Infrastructure	Vehicle	Fuel life	Road	Rail	Air	Sea
Saxe and Kasraian, 2020	✓			✓	✓		
Facanha and Horvath, 2007	✓	✓	✓	✓	✓	✓	
Merchan et al., 2020	✓	✓	✓		✓		
Hannach et al., 2019			✓	✓			
Osorio-Tejada et al., 2018			✓	✓			
Schulte and Ny, 2018			✓	✓			
Hawkins et al., 2012		✓	✓	✓			
Messagie et al., 2017		✓	✓	✓			
Pons et al., 2020	✓				✓		
Hegedić et al., 2018	✓				✓		

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Table 2: (continued from previous page)

Author, year	Life cycle stage included in the analysis			Transportation modes analyzed			
	Infrastructure	Vehicle	Fuel life	Road	Rail	Air	Sea
Jones et al., 2017	✓	✓	✓		✓		
Cox et al., 2018	✓	✓	✓			✓	
Barke et al., 2020	✓	✓	✓			✓	
Melo et al., 2020		✓	✓			✓	
Bicer and Dincer, 2018			✓				✓
Shama, 2005		✓					✓
Chatzinikolaou and Ventikos, 2015		✓					✓
Ingrao et al., 2020	✓	✓	✓	✓	✓		✓
Pizzol, 2019		✓	✓	✓			✓
Fridell et al., 2019	✓			✓	✓	✓	✓
Fries and Hellweg, 2014		✓	✓	✓	✓		

3. Conclusions

The paper analyzed the impacts along the life cycle of four freight transport modes. It emerges the urgency of reducing the environmental impact of FT by selecting adequate transport modes. As it is possible to appreciate from Table 2, most of the papers analyzed consider the fuel life cycle, and to some extent the vehicle life cycle. The inclusion of the infrastructure is rarer, for the above-mentioned reasons. Concerning the transport modes, there is a nourished body of literature analyzing trucks, while sea and air transport are less studied. There are still very few LCA studies on intermodal transportation.

A combination of solutions seems capable to bring the most benefits: technological innovation, fuel efficiency, intermodal transportation. Renewable fuels should be adopted to reduce the emissions of ships, aircraft, and in those situations where the electrification of vehicles poses particular challenges, such as large, long-haul trucks. The use of biofuels should be avoided, especially oil fuels, for the considerable impacts on deforestation and agriculture disruption. Instead, green hydrogen could represent a viable solution. The electricity mix should be greened, going towards complete decarbonization. Finally, intermodal transportation should be adopted to reduce the overall impact of FT.

Future research should develop more holistic analyses on infrastructure, vehicle, and fuel life cycle, allowing a complete overview of FT's environmental impacts. In particular, if the ultimate aim is to get to net zero emissions from the FT sector, more knowledge should be built on how to optimize intermodal transportation and innovative fuels, where several literature gaps are still present. Furthermore, ways to facilitate the transition towards net zero emissions FT should be proposed and evaluated.

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