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# Environmental assessment of road freight transport services beyond the tank-to-wheels analysis based on LCA

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## Abstract

Reducing environmental impacts in transport motivates many studies to offer more sustainable freight services. However, most methodologies focus on impacts from fuel consumption, and approaches trying to integrate other transport components have not facilitated its application to actual and specific transport services. In this study, we present a harmonized approach to address the transport services with a holistic way to increase the knowledge about hotspots of the transport sector based on the life cycle assessment methodology. In this framework, vehicle manufacturing, fuel production, and infrastructure construction are the key transport components around the traffic process. Besides fuel usage, the operation and maintenance of vehicles and infrastructures are also included. We developed a tool to create the life cycle inventories for each transport component to be applied to specific transport services in any location with a comprehensive view and low uncertainty in the results. This approach was applied to road-freight services in Colombia, Malaysia, and Spain. The main results showed the nature and origin of the environmental impacts, which are highly influenced by the emissions control technologies, road characteristics, and traffic volume. The contribution of atmospheric pollutants per tonne-km can decrease by a quarter when Euro VI trucks on highways instead of conventional trucks on single-lane roads are used. However, these contributions are highly affected by fuel production due to the origin of biofuels. The proposed methodology provides relevant information to estimate transport impacts in the life cycle assessment of products with superior precision and identify strategies for systemically improving sustainability.

**Keywords** Sustainability · Life cycle analysis · Environmental accounting · Carbon footprint · Biofuels

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# 1 Introduction

The vital role of freight transport in economic growth has hampered the implantation of strategies to reduce energy consumption and emissions in this sector in recent years. Energy consumption in the transport sector is closely linked to the economic situation, showing reductions during economic recessions, and increasing after economic recovery despite the efforts to mitigate transport emissions (IEA, 2020). Given this correlation between energy consumption and trading volume, a significant increase in greenhouse gases (GHG) emissions at global levels due to the rapid growth in emerging economies is expected.

In the short and medium term, strategies for promoting sustainability in road transport should be raised by implementing technological developments in vehicles, improving roads, providing logistics platforms, promoting intermodality, and using alternative energy (European Commission 2013). Nonetheless, any strategy should be evaluated from several perspectives by public administration and companies to ensure economic, environmental, and social sustainability in response to the demand of all stakeholders (Osorio-Tejada et al., 2020).

Awareness of the environmental impacts of road freight transport is relatively recent, and hitherto the main priority of the sector has been given to cost optimization. A turning point has been including vehicle operation on policy packages for transport climate policy. Almost simultaneously, customers of transport companies have begun to demand services that add the lowest possible carbon footprint to their products, and companies have started to calculate it based on fuel consumption.

The increased number of tools to estimate carbon emissions per tonne of product transported per km (tkm) has been related to the need of manufacturers and freight companies to include the impacts of transport on the carbon footprint. However, available tools are developed for the driving conditions in industrialized countries. In these countries, roads are constructed to provide the most efficient and safe driving by avoiding mountainous terrains with tunnels and bridges and providing roads with two or more lanes to allow smooth and constant traffic for most of the vehicle journey. In this sense, using these tools for transport services carried out in developing countries with mountainous terrains would underestimate fuel consumption and emissions. Additionally, most of the tools and methodologies focus on diesel trucks and GHG emissions, forgetting that more and more new propulsion technologies are gaining ground, such as electric mobility. New technologies reduce dependence on fossil fuels and require less maintenance, decreasing GHG emissions, but increasing impacts related to water and human toxicity due to the disposal of batteries (Engerer & Horn, 2010). In this sense, analyses of strategies to reduce carbon emission should be evaluated from a more comprehensive perspective through life cycle assessments (LCA). Life cycle inventories databases, such as Ecoinvent (ETH, 2022), include not only the impacts of fuel consumption but also the impacts of other transport components, such as manufacturing and maintenance of trucks and roads. However, the data are mainly based on the characteristics of Switzerland transport, which increases the uncertainty in the results when these inventories are used for LCA of products mobilized in other latitudes.

For these reasons, developing methodologies and tools adapted to the peculiarities of the freight service and location that provide a comprehensive environmental assessment would be helpful for decision-making by all stakeholders (Osorio-Tejada et al., 2018; Scarpellini et al., 2013).

Suppose the focus on fuels is complemented with these integrated analyses. In that case, companies could document the environmental sustainability of the services offered, and public administrations could track the achievement of policy goals. Finally, consumers would have access to information to select the most sustainable services. Furthermore, in a virtuous circle, freight companies might ask for vehicles, fuels, and more environment-friendly infrastructures from knowing their impacts. In addition, any analysis from a life cycle perspective provides comprehensive information about the global implications of changes in technologies, management, and behaviour that are proposed as a solution, being integrated approaches among the best ways to achieve sustainable alternatives (Aydin et al., 2021).

With these premises, this study presents a methodological approach to logically define boundaries and activities included in the transport system and describe how to specific model the life cycle inventories for each transport component, considering the characteristics of cargo, vehicle, fuel, route, and driving conditions. This approach is applied to three case studies in very different scenarios from the technological and geographical points of view.

The remainder of this article is structured as follows. In Sect. 2, previous LCA studies conducted in the transport sector are classified according to their scope to identify the activities included in their analyses and the approaches' limitations, solved by applying the harmonized approach proposed in this work. In Sect. 3, the methodological approach, the developed tool for life cycle inventories creation, and the selected case studies are described. In Sect. 4, the results obtained through applying the methodology in the different case studies in Colombia, Spain, and Malaysia are discussed. Results representativeness and the implications of the methodology for future practices and policies are drawn in the conclusions.

## 2 Background

This section provides a review of various LCA published to date to assess individual transport components (fuels, vehicles, and infrastructure) and several approaches to integrating several components. The objective is to determine what sources of information and what evaluation methods were used to identify limitations in the state-of-the-art environmental assessment of transport services. This theoretical approach sets the basis for developing a specific methodology for integrating road freight services in any geographical location.

Although most of the LCAs for the road freight transport sector have focused on the calculation of GHG emissions, following the guidelines of the standard EN 16, 258 "Methodology for calculation and declaration on energy consumptions and GHG Emissions in transport services (goods and passengers transport)" (Auvinen et al., 2014), this standard limits the assessment to the well-to-wheels (WTW) or fuel life cycle analysis. That is, it considers only the emissions from the fuel usage (tank-to-wheels (TTW) analysis) plus the emissions from the fuel production and distribution (well-to-tank (WTT) analysis). For this reason, there are extensive LCA studies about fuels and their use in different vehicles and fewer studies about the life cycle of the other components of the transport systems.

A general picture of transport systems was defined by NTM (2015), identifying five components. Based on this definition, Fig. 1 serves as the basis to conduct the literature review about LCA studies of each of these components. It must be considered that the impacts of the end-of-life activities are usually incorporated in the LCA of the
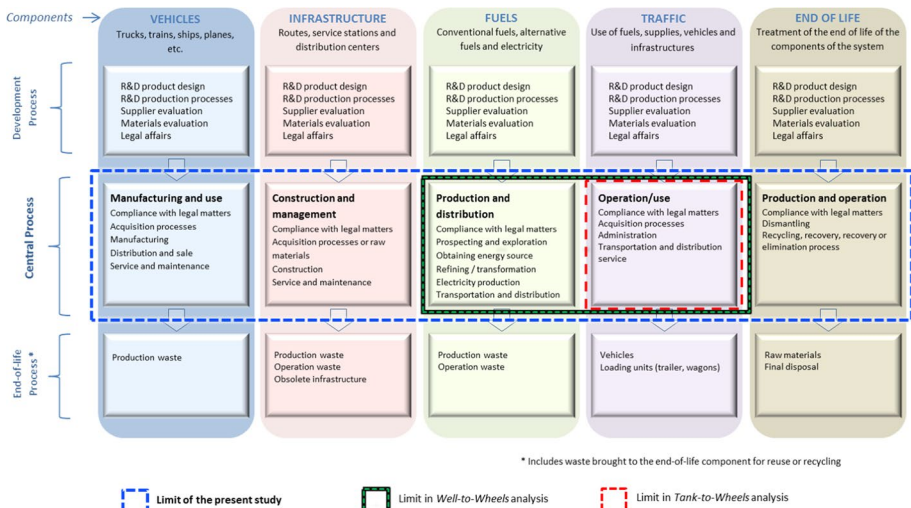
**Fig. 1** Components of the transport system Source: Own elaboration from (NTM, 2015)

infrastructures or vehicles. For this reason, it is not common to find an LCA designed explicitly for specific waste recovery plants such as that published by Ciacci et al. (2010).

## 2.1 LCA on fuels

Most LCAs for the transport sector have focused on fuels, almost exclusively in the GHG (the so-called carbon footprint) (Shonnard et al., 2015). In the light of these studies, different methodologies, tools such as Excel spreadsheets or software and web-based tools and emission factors databases have been developed (Lewis et al., 2014).

The standard EN 16, 258 (Auvinen et al., 2014) is the first international standard that harmonizes and normalizes the procedures for calculating and reporting emissions and energy consumption for the transport sector, and European companies fully accept it. This standard provides one possible basis for future international normalization initiatives because it considers specific aspects of freight transport, such as the need to define a vehicle operating system (VOS) as a basis for calculating emissions. It also considers the allocation principles for $CO_2$ emissions to the load and sets the tkm as the functional unit. Finally, EN 16, 258 establishes that emissions at the product level or shipment must be calculated as a percentage of the total amount of tkm performed in the VOS according to the proportion of the product in the total mass transported (Davydenko et al., 2014). However, there are still some issues to be resolved. First, the standard leaves the user free to choose the VOS. This ambiguity could trigger mean values of the annual activity of a fleet without discriminating the route or the geographical location of a specific service. Second, the principle that the emissions should be assigned to the causing entity, the base tkm, is insufficient. It produces the arbitrary allocation of emissions to individual loads, especially for combined shipments of light (and bulky) and heavy products, resulting in emissions mainly assigned to heavier products. The third issue that is still unsolved is related to the fact that the standard is concerned with the providers of transport services and not customer oriented. The standard should incorporate a reporting mechanism that allows the responsible party to add shipping emissions in the transport chain. This means that compliance with

the standard should include not only the ability to calculate emissions in transport activity, but also a mandatory reporting to the shipping applicant.

Concerning the considered emissions, it has to be taken into account that some emissions such as $CO_2$ and $SO_2$ are directly related to the amount of fuel consumed, but other pollutants such as CO, NOx, $CH_4$, $N_2O$, $NH_3$ and volatile particles also depend on the load factor of the vehicle and the emission control measures.

WTT emission factors for conventional fuels are virtually identical in most LCA studies and databases because the fuel production processes have been unchanged for decades. Slight differences are due to the distances in transporting crude to the refinery plant and the final product to service stations. Regarding the TTW phase, current databases contain factors for the specific use of diesel and gasoline in road transport. The EMEP/EEA air pollutant emission inventory guidebook (EEA 2019) includes biodiesel and natural gas but advises that these factors lack accuracy for trucks because there are not enough experiences to ensure their reliability statistically.

The interest in finding more environmentally friendly fuels reflects the numerous studies comparing the environmental performance of alternative energy sources and fossil fuels. It could be envisaged to generalize the results and even use them as a data source. However, after analysing recent studies, emission factors vary widely due to having been obtained under different boundaries and approximations. For example, in Fig. 2, considering studies for palm oil biodiesel, it can be concluded that variability of emissions is related to the location, dramatically increasing when the palm is cropped in tropical forests. For microalgae biodiesel, emissions are largely related to the production process.

For ethanol, Fig. 3, as the gasoline alternative, it also appeared that emission factors (from 25 to 65 $gCO_{2eq}/MJ$) vary depending on the type of biomass from which ethanol is produced and not on the conversion process that is invariably fermentation.
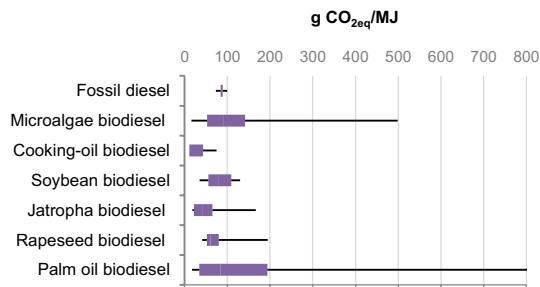


**Fig. 2** Life cycle GHG Emissions for diesel alternatives *Sources*: Fossil diesel (AEA group, 2014; ANL-Argonne National Laboratory, 2021; Beer et al., 2007; Bio Intelligence Service, 2011; European Commission, 2009; Hou et al., 2011; Lee Chang et al., 2015; Mata et al., 2011; Styles et al., 2015; Tokunaga & Konan, 2014); Algae biodiesel (Adesanya et al., 2014; Azadi et al., 2014; Collet et al., 2014; Hou et al., 2011; Lee Chang et al., 2015; Mata et al., 2011; Passell et al., 2013; Soratana et al., 2013; Tu et al., 2018; Wu et al., 2018; Yuan et al., 2015); Cooking oil biodiesel (Beer et al., 2007; Bhonsle et al., 2022; Bobadilla et al., 2021; European Commission, 2009; Ou et al., 2009; Whitaker et al., 2010); Soybean biodiesel (European Commission, 2009; Hou et al., 2011; Mata et al., 2011; Ou et al., 2009; Panichelli et al., 2009; Tokunaga & Konan, 2014; Zhang et al., 2022); Jatropha biodiesel (Chatterjee et al., 2014; Hagman et al., 2013; Hou et al., 2011; Ou et al., 2009; Tokunaga & Konan, 2014); Rapeseed biodiesel (Beer et al., 2007; Chatterjee et al., 2014; Elsayed et al., 2003; European Commission, 2009; Malça et al., 2014; Mata et al., 2011; Styles et al., 2015; Whitaker et al., 2010); Palm oil biodiesel (Achten et al., 2010; Anyaoha & Zhang, 2022; Arpornpong et al., 2015; Beer et al., 2007; Chatterjee et al., 2014; Choo et al., 2011; European Commission, 2009; Hassan et al., 2011; Mata et al., 2011; Permpool & Gheewala, 2017; Tokunaga & Konan, 2014; Wicke et al., 2008; Yung et al., 2021)

**g CO$_{2eq}$/MJ**
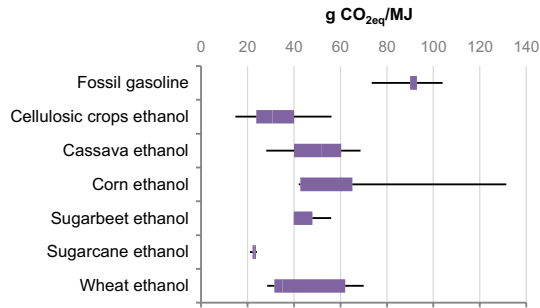


**Fig. 3** Life cycle GHG Emissions for gasoline alternatives Sources: Fossil gasoline (ANL-Argonne National Laboratory, 2021; Bio Intelligence Service, 2011; Daystar et al., 2015; Ou et al., 2009; Styles et al., 2015); Cellulosic crops ethanol (Cai et al., 2013; Daystar et al., 2015; Jeswani et al., 2015; Murphy & Kendall, 2015; Olofsson et al., 2017; Shuai et al., 2016; Sun et al., 2021); Cassava ethanol (Jiao et al., 2019; Nguyen et al., 2007; Ou et al., 2009); Corn ethanol (European Commission, 2009; Kauffman et al., 2011; Liska et al., 2009; Ou et al., 2009; Xu et al., 2022); Sugarbeet ethanol (Elsayed et al., 2003; European Commission, 2009; Whitaker et al., 2010); Sugarcane ethanol (European Commission, 2009; Hiloidhari et al., 2021; Simone P. Souza & Seabra, 2014; Simone Pereira Souza et al., 2012); Wheat ethanol (Bernesson et al., 2006; Elsayed et al., 2003; European Commission, 2009; Styles et al., 2015; Whitaker et al., 2010)

## 2.2 LCA on vehicles

The first LCA focused on vehicles manufacturing, use, and final disposal were made by truck manufacturers in the 90 s to identify the primary sources of energy waste and take measures to achieve savings and reduce the environmental impact (Finkbeiner et al., 2000; Volvo AB 2001). Some truck manufacturers, such as Daimler AG, have been using LCA for more than 20 years, performing more than 100 individual LCA both for vehicle parts and complete trucks (Finkbeiner et al., 2000). DAF Trucks developed an internal tool for LCA analysis of new parts and began to apply it to trucks in 2006 (DAF, 2006). Scania AB has also adopted a strategy of optimizing the life cycle, designing for reuse, and recyclability as the relevant areas in its sustainability policy (Scania AB 2014). Before 2006, when Scania began to implement LCA, some Environmental Product Declarations (EPD) for trucks had been made, but it is unclear whether these were based on LCA (Nordhall, 2007). Recently, Hanesch et al. (2022) presented a LCA for the comparison of an standard Scania articulated truck R450 and an overhead line hybrid truck, which would emit 100.7 and 82 g CO$_{2eq}$/tkm, respectively. In this comparison, the authors concluded that the manufacturing of the standard truck, diesel production, and diesel usage contribute to the 5%, 14.4%, and 80.6%, respectively, while for the hybrid truck, its manufacturing (including recharge infrastructure), energy production, and energy usage contribute to the 31.1%, 17.6%, and 51.2%, respectively.

Volvo AB has reported that 94% of GHG emissions from a Renault tractor Euro VI are generated in the use phase since most vehicle materials can be recycled (Volvo AB 2013).

IVECO started using LCA methodologies in 2008. Although initially it was applied to identify ecological alternatives to refrigerants in the air-conditioning systems, their use has been spread to the whole manufacturing process (Fiat group, 2009). According to their reports, 85% of CO$_2$ emissions correspond to the use phase.

MAN SE concluded that more than 90% of GHG emissions come from trucks' use phase, taking into account the life cycle assessment of fuel. In 2013, the company launched the project LCA based on ISO 14064 (Davydenko et al., 2014). In 2015, impact categories

such as acidification, photochemical ozone creation potential, eutrophication, and ozone depletion (MAN SE, 2014) began to be included.

Besides manufacturers publishing results on GHG emissions without detailing the inventories of materials and energy for trucks manufacturing, they also generally include the component of traffic in the LCAs, which dwarfs the relative environmental impacts of truck manufacturing in the life cycle in this kind of freight vehicle.

## 2.3 LCA on infrastructure

The infrastructure needed for road freight transport consists of roads, service stations and logistics centres such as warehouses, intermodal terminals, and parking lots (Bhatt et al., 2019). Of these infrastructures, the impact of roads has been the most widely studied due to the interest that their construction arouses for society in general since it affects freight and passenger transport users and communities and ecosystems in their area of influence. As summarized in Table 1, the published studies are very variable from which life cycle phases are considered.

The LCAs also differ in the objective. There are studies focused on the environmental impact caused by the use of recycled materials (Fernández-Sánchez et al., 2015; Mroueh et al., 2000) in the construction phase, on those generated by additives and textures to the (Birgisdóttir et al., 2006; Milachowski et al., 2011; Santero et al., 2013), on maintenance activities (Huang et al., 2009a, 2009b) or specific issues such as deforestation (Barandica et al., 2013; Melanta et al., 2012; Mroueh et al., 2000).

Although the initial phase of excavations and soil movements is not considered in many studies, Barandica et al. (2013) concluded that this initial phase contributes between 60 and 85% of total GHG emissions. It is important to note that the mentioned study did not analyse the impact of traffic or the end-of-life phase.

Based on the analysis of several LCAs conducted for roads, Muench, 2010 concluded that, on average, the energy used during the construction of the road equals that used by the vehicles in 1 or 2 years of circulation. These values translate into a range of between 125 and 375 kg of $CO_2$ equivalent for each metre of lane built.

Muench (2010), Loijos (2011), and Hoxha et al. (2021) highlighted the complex comparability of the results. Mainly reasons are the different criteria adopted to select the functional units, system boundaries, the availability and quality of the data and the particularities of the roads in terms of geotechnical conditions, traffic intensity and climate. These same reasons prevent extrapolating the results obtained to other cases.

## 2.4 LCA on several components

Previous works that considered the joint analysis of several components are scarce and generally aim to compare different transport systems. Among these studies, Marheineke et al. (1998) included the life cycle of trucks and roads for a case study in Germany and Stodolsky et al. (1998) compared the $CO_2$ emissions of rail and road transport in the USA. In this latter study, the authors concluded that trains generate three times fewer emissions than trucks by tkm transported, considering the manufacture of vehicles, fuel production, and its consumption during the use phase and excluding the infrastructure construction and use. On the contrary, Dimoula (2015) included the infrastructure in a comparative study for the case of Greece and concluded that railways construction emits twice as many GHG emissions as road

**Table 1** Case studies on life cycle assessment of roads

| References | Life cycle phase | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | Extraction and production of materials | Construction | | Maintenance | Traffic / usage | End of Life |
| | | Soil movement | Paving | | | |
| Häkkinen and Mäkele (1996) | x | | x | x | x | x |
| Horvath and Hendrickson (1998) | x | | x | | | x |
| Mroueh et al. (2000) | x | x | x | x | x | |
| Stripple (2001) | x | x | x | x | x | |
| Chappat and Bilal (2003) | x | | x | x | x | |
| Park et al. (2003) | x | x | x | x | | x |
| Peuportier (2003) | x | | x | x | x | x |
| Treloar et al. (2004) | x | | x | x | x | |
| Hoang et al. (2005) | x | | x | x | | |
| Zapata and Gambatese (2005) | x | | x | x | | x |
| Athena Institute (2006) | x | | x | x | | |
| Birgisdóttir et al. (2006) | x | x | x | x | | |
| SUSCON (2006) | x | x | x | x | | |
| Garrain and Vidal (2008) | x | | x | | x | |
| Huang et al. (2009b) | x | | x | x | | |
| Sayagh et al. (2010) | x | | x | x | | |
| ECRPD (2010) | x | | x | x | x | |
| Milachowski et al. (2011) | x | x | x | x | x | |
| Loijos (2011) | x | | x | x | x | x |
| Cass and Mukherjee (2011) | x | x | x | | | |
| Huang et al. (2012) | x | x | x | x | | |
| Melanta et al. (2012) | x | x | x | | | |
| Butt et al. (2012) | x | | x | x | | x |
| Vidal et al. (2013) | x | x | x | x | x | x |

**Table 1** (continued)

| References | Life cycle phase | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | Extraction and production of materials | Construction | | Maintenance | Traffic / usage | End of Life |
| | | Soil movement | Paving | | | |
| Barandica et al. (2013) | x | x | x | x | | |
| Santero et al. (2013) | x | | x | x | x | x |
| Araujo et al. (2014) | x | x | x | x | x | x |
| Celauro et al. (2015) | x | x | x | x | | |
| Fernández-Sánchez et al. (2015) | x | x | x | x | | |
| Mladenovic et al. (2015) | x | | x | x | | |
| Giani et al. (2015) | x | | x | x | | x |
| Anthonissen et al. (2015) | x | | x | x | | x |
| Yang et al. (2015) | x | | | | x | |
| Anastasiou et al. (2015) | x | x | x | x | | x |
| Schlegel et al. (2016) | x | | x | x | | x |
| Mao et al. (2017) | x | | x | x | | x |
| Celauro et al. (2017) | x | | x | x | | |
| Santos et al. (2018) | x | | x | x | x | x |
| Garraín and Lechón (2019) | x | x | x | x | | x |
| Alzard et al. (2019) | x | x | x | x | x | x |
| Vandewalle et al. (2020) | x | | x | x | | |
| Wang et al. (2020) | x | | x | x | x | |
| Inti and Tandon (2021) | x | | x | x | x | |
| Siverio Lima et al. (2021) | x | | x | x | x | x |
| Patel and Ruparathna (2021) | x | | x | x | | |
| Tefa et al. (2022) | x | | x | | | |

**Table 1** (continued)

| References | Life cycle phase | | | | | | |
|---|---|---|---|---|---|---|---|
| | Extraction and production of materials | Construction | | Maintenance | Traffic / usage | End of Life |
| | | Soil movement | Paving | | | |
| Liu et al. (2022) | x | | x | x | x | x |

construction. However, road transport emits 22 times more GHG per transported tkm than rail transport during the traffic phase.

Hanesch et al. (2022) included the energy production and usage, the truck manufacturing, and the additional infrastructure for electricity recharging for overhead line hybrid trucks, which would emit 22.8% more carbon emission than a conventional diesel truck. However, roads construction, neither maintenance nor end-of-life of the systems, were included in this LCA study.

Other works have developed more comprehensive analyses for freight services. In order to make a comparison of the Swiss and European freight transport sectors, Spielmann and Scholz (2005) analysed the three main components (fuel, infrastructure, and vehicles) for road, rail and river modes, whose results and scope were adopted by the Ecoinvent database (Spielmann et al. 2007).

Facanha and Horvath (2007) conducted a comparative study of road, rail, and air freight transport in the USA, evaluating $CO_2$, NOx, $PM_{10}$, CO and $SO_2$ emissions. In this study, the impacts of fuel production and fuel usage were contemplated separately. The study concluded that the impacts are underestimated if only fuel usage is considered. For example, the TTW phase is responsible for 76% of all $CO_2$ emissions and 92% of NOx emissions for road transport. However, almost 75% of $PM_{10}$ emissions come from the construction and maintenance of roads, while the manufacture and maintenance of vehicles are mainly responsible for CO emissions. The authors discussed the sensitivity of the amount of polluting substances emitted by tkm with the type of vehicle, the geography, and the vehicle load.

Nahlik et al. (2016) analysed the vehicle operation, the manufacturing and maintenance of vehicles, the construction and maintenance of infrastructure, and the fuel production as separate components to estimate the emissions generated by different means of freight transport in California. Unlike the Facanha and Horvath (2007) study, $PM_{10}$ emissions came mostly from vehicle operation and not from infrastructure for road transport. Although CO emissions are generated during vehicle manufacturing, the operation phase continues to be the most relevant. The authors explained the low contribution of the infrastructure in the impacts by tkm because the volume of goods transported through these North American roads is very high, mainly with long distance services and large tonnage.

Analysing integrated LCA for transport services to date has shown no consensus on how to set the boundaries for the considered components and which activities should be included in the evaluation. In addition, most of the published studies lack specific descriptions of how calculations were made and data sources, being difficult to replicate the studies in other scenarios. The approach followed in the Ecoinvent database described the data sources and assumptions. However, the use of this database in LCA software does not allow to modify the specific characteristics of the freight service such as load factor, speed, road gradients, vehicle lifespan, annually mileage, frequency of maintenance, or traffic flow to adequately allocate the impacts of manufacturing and maintenance of vehicle and roads to each tkm. This difficulty increases the uncertainty in the results for services outside Europe since most of the assumptions were based on data from Switzerland or European averages for traffic and road conditions and from Germany for truck manufacturing.

# 3 Materials and methods

For the analysis of strategies aimed to reduce the transport carbon footprint, such as introducing an alternative fuel, its application can occasionally shift the effects to another environmental impact category, another phase of the fuel life cycle, or another system component. In this sense, the core analysis of the proposed methodological approach was based on the ISO 14040 standard (ISO 2006) for LCA studies, detailed below.

## 3.1 Goal and scope definition

The most crucial step for the integrated LCA analysis of transport services is the system definition. For this purpose, the components of the system (Fig. 1) were reorganized around a central and transversal traffic process (Fig. 4), considering that activities such as maintenance and end-of-life activities for vehicles and infrastructures can mainly
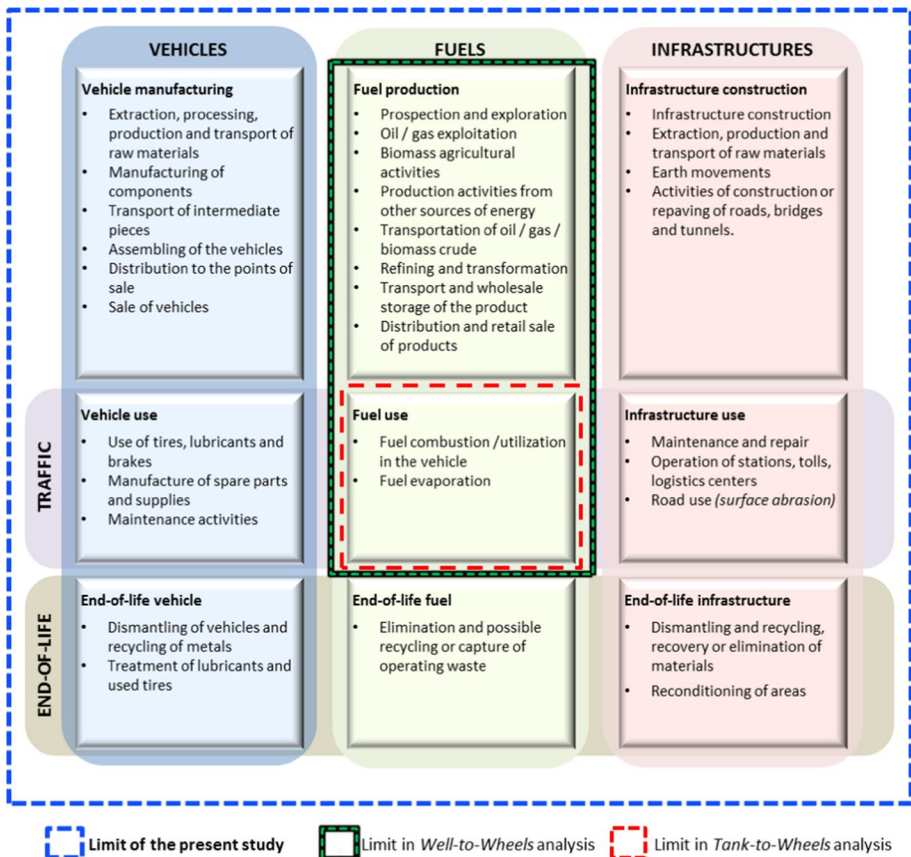


**Fig. 4** Transport system transversal traffic process Source: Own elaboration

occur if there are traffic operations. This traffic process consists of the emissions from vehicle operation such as fuel combustion, lube oil and urea consumption and brakes, tires, and road surface abrasion, plus the emissions due to the maintenance of roads and vehicles.

This approach solves several limitations in analysing transport systems with components in parallel. First, the VOS is perfectly defined, allowing to identify and assign to the transport service only the impacts that occur when this takes place and not those of a fleet. Second, it sets the system's limits under analysis which, on the one hand, avoids double accounting and, on the other hand, makes it possible to compare results. Third, assigning the direct impacts to each tkm allows establishing the effect of the vehicle and load efficiency with more reliability.

In short, this new proposed system is more interesting for management and decision making on the environmental impacts of transport. For example, the carbon footprint of a road freight service could be calculated as the sum of the direct $CO_{2eq}$ emissions caused by the traffic process (fuel consumed plus the use and maintenance of vehicles and infrastructure) and three indirect footprints on those that the transport company can influence by selecting the vehicle, the fuel, and the route.

The goal of each case study was to draw up the environmental profiles of specific road freight services to find out the activities that generate the most relevant impacts in each transport system. A comparative analysis of the studies can also ascertain the influence of vehicle technology, load factor and road characteristics. The system functions included freight services of a certain amount of merchandise from one point to another in a specific type of vehicle and given geographical conditions. The functional unit is the tkm.

Three different services were selected from the technological and geographical point of view to analyse the effect of traffic conditions, road topology, and technological and normative variables on environmental impacts. In this sense, a freight service using a non-regulated rigid truck in a mountainous road in Colombia, a Euro I rigid truck on a flat road with heavy traffic in Malaysia, and a Euro VI articulated truck in rolling roads with low traffic in Spain. The main data are collected in Table 2.

Regarding the impacts assessment method, ReCiPe (Goedkoop et al., 2009) was selected since it brings together the most relevant aspects for the transport sector in a set of 18 impact categories and three damage areas (human health, ecosystems, and resources). The impacts assessment was modelled using the SimaPro 8.5.0 tool (PRé Consultants, 2018), considering mass allocation under the cut-off approach and the hierarchical (100 years) perspective, excluding long-term emissions.

### 3.2 Inventory analysis

The life cycle inventories analysis initiates by defining a set of data related to the flow of materials, energy, and emissions in each of the components of the system. The detailed procedures for elaborating inventories and allocation factors are summarized in Fig. 5.

According to the procedures detailed in the diagram in Fig. 5, we have developed a helpful tool to estimate the emissions from each transport component by considering the specific characteristics of the assessed transport services. This procedure would reduce the uncertainty in the results, especially when the vehicle, roads, and driving conditions differ significantly from the average European characteristics. For this complex inventory analysis, the Excel-based calculator is in the supplementary information SI-1. For the main activity of vehicle operation, specific information for the service and the route such

**Table 2** Summary data of the study cases

| Variable | Colombia | Malaysia | Spain |
|---|---|---|---|
| Route | Pereira-Quibdo (one-way trip) | Kuala Lumpur- Kulim (round trip) | Zaragoza- Almussafes (round trip) |
| Distance travelled | 260.5 km | 774 km | 694 km |
| Vehicle | Ford F600 (1958) readapted in 2010 | Nissan PKD211 (2002) | Scania AB (2016) |
| Emission control technology | Pre-euro | Euro I | Euro VI |
| Gross vehicle weight (GVW) | 16 t | 16 t | 40 t |
| Loading capacity | 10 t | 10 t | 25 t |
| Weight of the transported goods | 10 t | Outward 2 + 0.5t return 0.5 t (racks) | Outward 10 + 5t return 5 t (racks) |
| Load factor | 100% | 25% | 60% |
| Distance travelled empty | 0 km | 387 km | 347 km |
| Journey time | 8.66 h (+ 0.66 h rest) | 6.66 h (+ 0.25 h rest) | 4.5 h (+ 0.5 h rest) |
| Average speed | 30 km/h | 58 km/h | 77 km/h |
| Fuel type | diesel B10 | diesel B7 | diesel B5 |
| Fuel consumption | Model (Tier 3): 116 L 44.7 L/100 km | Model (Tier 3): 167 L 21.6 L/100 km | Model (Tier 3): 216 L 31.2 L/100 km |
| Type of infrastructure (Slope of the terrain) | Rugged roads (average gradient: 3.2% -3.3% maximum gradient: 21.2% −30.7%) | Freeways in slightly uneven terrains (Average gradient: 0.8%–0.8% Maximum gradient: 11.5%–12.7%) | Freeways in rolling terrain (Average gradient: 1.1%–1.4% maximum gradient: 6.5%–5.6%) |
| tkm | 10 t×260.5 km = 2605 tkm | 2 t×774 km /2 = 774 tkm | 10 t×694 km/2 = 3470 tkm |

| ACTIVITY | | INVENTORY | METHOD | ALLOCATION |
|---|---|---|---|---|
| Traffic process | Vehicle operation | Emissions from fuel combustion, oil and urea usage, and parts abrasion | Tier 3 by sections - equations and factors EMEP/EEA | Total emission/ tkm service |
| | Vehicle maintenance | Materials and energy used annually | Specific inventory according to frequency of parts change | Inventory year / tkm transported per year |
| | Road operation and maintenance | Materials, energy, and emissions per meter-year (m-y) | Data according to the km of bridges, tunnels, and type of roads in the country | (m roads/vkm total fleet year) * vkm/tkm service |
| Vehicle manufacturing | | Materials, energy, and emissions per unit | Adjust generic data for source of materials and energy for the country of | Total inventory / tkm transported useful life |
| Fuel production | | Materials, energy, and emissions per kg of fuel | Specific inventory for the biofuel and fossil fuel production | kg of fuel service/ tkm service |
| Road construction | | Materials, energy, and emissions per meter-year | Data according to the km of bridges, tunnels, and type of roads in the country | (m roads/Gtkm total fleet year) * Gtkm/tkm service |
| End-of-life activities | | Materials, energy, and emissions per vehicle and m-y of road | Adjust generic data for distances and materials that would not be recycled | Same as for vehicle and roads |

**Fig. 5** Transport system inventory analysis procedures

as load factor, size and axles number of the vehicle, emissions control technology, speed, and road gradients was considered. The EMEP/EEA 1.A.3.b.i-iv Road transport hot EFs Annex (EEA, 2019) coefficients are applied for estimating CO, NOx, VOC, and PM emissions. These coefficients are estimated by considering the specific emission control technology (conventional, Euro I–VI), load factor (0%, 50% and 100%) and the road gradient $(0\%, \pm 2\%, \pm 4\%$ and $\pm 6\%)$ to obtain the results based on the vehicle speed. For the specific load factor (LF), emissions factors (EF) were obtained for 0% and 100% LF and then, calculated to the partial load $(EF_{LF} = EF_{empty} + (EF_{full} - EF_{empty}) \times LF)$. For the other fuel combustion emissions ($CO_2$, $CH_4$, $N_2O$, $NH_3$, PAHs, alkanes, alkenes cycloalkanes, aldehydes, and aromatics) and tire and brake abrasion particles, Tier 2 and Tier 1 factors were applied (EEA, 2019). This approach was applied for different sections of the route, which was split at the points where considerable changes in road gradient, speed, or driving zone (urban or interurban) took place. Otherwise, taking an average gradient and speed for the complete route would omit road sections with rough conditions, underestimating the results. The routes were divided into 33, 33, and 29 sections for the assessed services in Colombia, Malaysia, and Spain.

Regarding fuel production, specific data for the origin of fossil sources and biofuels were considered to create the inventories for the fuel mixture used in each case. For trucks manufacturing and road construction, as well as for maintenance activities, based on generic inventories from Ecoinvent (Spielmann et al. 2007), specific inventories were developed by considering country statistics for each case study such as the length and proportion of highways, primary, secondary, and tertiary roads, and quantity of tunnels and bridges per km for each kind of road.

Given that vehicles are used for different transport services in their useful life, and the infrastructure is shared for other purposes such as passenger transport, a key aspect was

how to allocate the resulting impacts for the different system components to the evaluated road freight service. In this sense, the road construction impacts were distributed among the gross tonnes per km (Gtkm) mobilized annually in the country, considering the average load factors of the different freight and passenger vehicles and total km travelled by each kind of vehicle in the country. The impacts allocation of the road maintenance activities was made based on the vehicle-kilometres (vkm) travelled annually. The impacts allocation of the manufacturing and maintenance of the vehicle was based on the total tkm transported in its useful life. The created inventory data for each case study are presented in the supplementary information SI-2.

## 4 Results and discussion

### 4.1 Impacts assessment and interpretation

Based on these findings from the inventory analyses, the life cycle impacts assessment results for each case are presented in Table 3. The contribution of each component of the proposed system is shown in Fig. 6 for the different case studies.

In general, the assessed service in Malaysia had the highest impacts per tkm mainly because of the low load factor of this freight service, being the total impacts allocated in fewer transported tonnes.

According to Fig. 6, in Colombia and Malaysia, the prevalent responsible in most of the impact categories was the traffic process, while in Spain, it was mainly the production of fuel.

**Table 3** LCA midpoint results for the total system per tkm

| Impact category | Units | Colombia | Malaysia | Spain |
|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | 1.67E-01 | 8.01E-01 | 2.31E-01 |
| Ozone depletion | kg CFC11 eq | 3.45E-08 | 4.10E-08 | 3.60E-08 |
| Ionizing radiation | kBq U235 eq | 1.43E-03 | 5.49E-02 | 1.19E-02 |
| Formation of particulate matter | $PM_{10}$ kg eq | 6.56E-04 | 2.34E-03 | 2.11E-04 |
| Formation of photochemical oxidants | kg NMVOC | 2.61E-03 | 8.29E-03 | 5.16E-04 |
| Terrestrial acidification | kg $SO_2$ eq | 1.47E-03 | 5.05E-03 | 4.38E-04 |
| Fresh water eutrophication | kg P eq | 1.04E-05 | 4.32E-05 | 1.74E-05 |
| Marine eutrophication | kg N eq | 1.03E-04 | 5.22E-04 | 9.16E-05 |
| Terrestrial ecotoxicity | kg 1,4-DCB eq | 1.43E-04 | 2.30E-03 | 1.54E-03 |
| Fresh water ecotoxicity | kg 1,4-DCB eq | 4.15E-04 | 2.26E-03 | 1.10E-03 |
| Marine ecotoxicity | kg 1,4-DCB eq | 4.41E-04 | 2.96E-03 | 8.73E-04 |
| Human toxicity | kg 1,4-DCB eq | 2.94E-02 | 1.12E-01 | 2.62E-02 |
| Agricultural land occupation | $m^2$. yr | 1.06E-02 | 2.76E-02 | 9.71E-03 |
| Urban land occupation | $m^2$. yr | 4.26E-03 | 5.04E-03 | 8.01E-03 |
| Natural land transformation | $m^2$ | -2.44E-04 | 4.37E-04 | 1.71E-04 |
| Mineral resource depletion | kg Fe eq | 4.30E-03 | 2.12E-02 | 1.01E-02 |
| Fossil fuel depletion | kg oil eq | 5.68E-02 | 2.52E-01 | 7.12E-02 |
| Water consumption | $m^3$ | 4.26E-04 | 2.24E-03 | 8.21E-04 |
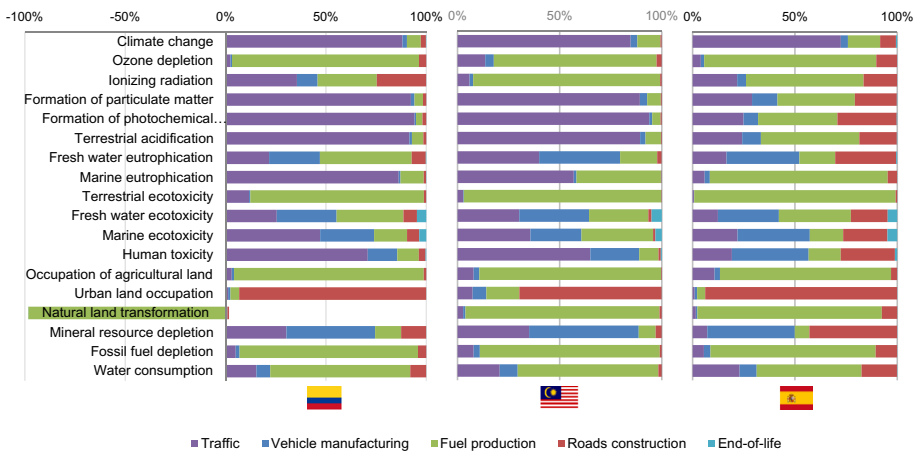
**Fig. 6** Contribution of the system components in midpoints

In general terms, the traffic process generated the highest contributions to global warming (from 72 to 86%) and terrestrial ecotoxicity (from 66 to 88%). It is followed by the fuels production component with a high contribution to marine eutrophication (from 88 to 96%), fossil fuel depletion (from 81 to 89%), and land use in Malaysia and Spain.

The contribution of vehicle manufacturing was moderate in Colombia and Malaysia, with the most significant impacts in the categories of mineral resources depletion (from 41 to 47%) and human carcinogenic toxicity (from 36 to 50%). Nevertheless, in the Spanish case, the environmental impacts of this input were present in many more categories.

Road construction had the highest contribution in the urban land occupation category, with significant differences for the other impacts among the three countries. In Malaysia, the low contribution road construction in the assessed service was due to the significant traffic volume along the roads; hence, the allocation of road construction to the specific service was minimal. On the contrary, a high proportion of the assessed roads in Spain corresponded to highways, which present relatively low traffic volumes. Here, the assignment of the impacts associated with the construction of highways to each transported tkm was considerable, which explains its high contribution to most of the impact categories. In addition, the traffic process in the Spanish case had lower contributions than in the other cases because a Euro VI truck was used, emitting low pollutant emissions. Consequently, the lower the impact of the traffic process, the more significant the contribution of the other components in the related categories.

One of the main results to be analysed was the positive impact on the natural land transformation category in the Colombian case study due to the fuel production component, Fig. 6. In this sense, the midpoint characterization results for the production and distribution of B10 diesel (90% fossil diesel + 10% palm oil biodiesel) in the Colombian case are shown in Fig. 7.

This positive environmental impact in Fig. 7 was due to palm oil biodiesel production, positively impacting climate change. However, this positive accounting is debatable. Firstly, the natural land transformation was considered positive in the ReCiPe method because most palm oil has been planted on former grasslands or annual crops (ETH 2022) in Colombia, which is considered reforestation. However, considering monocultures as forests is debatable mainly due to biodiversity issues (Fonseca 2003) and
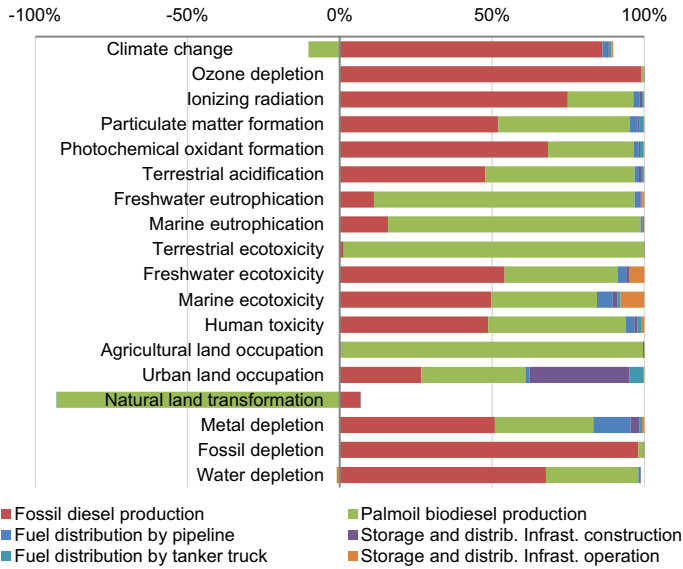
**Fig. 7** WTT analysis of 1 kg of B10 at Pereira station

the effect on native forests and carbon stocks from indirect land use changes (EFE 2015; Grainger 2013; Vijay et al. 2016). Secondly, ReCiPe considered the absorption of $CO_2$ during palm growing positively, but this is not correct when this biomass is for combustion, where $CO_2$ is re-released. The additional carbon stock in the soil is released when the land is prepared for another crop. In the updated method ReCiPe 2016, these positive accountings were removed, consequently increasing the climate change results from 232 to 320 g $CO_{2eq}$ per kg of B10 diesel at a fuel station.
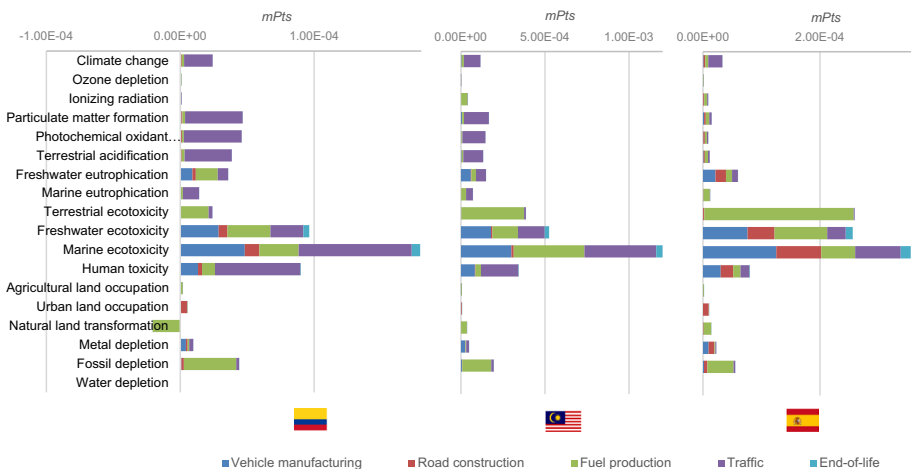


**Fig. 8** Normalized characterization results per tkm

In addition to analysing which components of the transport systems had greater or lesser relevance in each impact category, it is important to analyse the normalized results to identify the magnitude of impacts on the global environmental problem, as shown in Fig. 8.

It could be concluded that the results of the LCA for the cases of Colombia and Malaysia agreed with similar studies for Europe (Spielmann et al. 2007) and North America (Facanha & Horvath, 2007; Nahlik et al., 2016), where the traffic process is responsible for most of the emissions related to climate change and air quality, such as $CO_2$, CO, NOx, PM and NMVOC. However, when the normalized results are isolated for the traffic process, as shown in Fig. 9 for the Colombian case, emissions from fuel combustion are not the only primary source of pollution. Vehicle maintenance and brake abrasion also generate toxic pollutants such as copper and other metal particles released into the air and water. Specifically, impacts of maintenance activities are due to the use of electricity, which requires the use of cooper in the distribution networks.

In this same line, the analysis of the impact of the fuel production on the different environmental impact categories also yields information of interest Fig. 10.

In the Malaysian (diesel B7) and Spanish (diesel B5) case studies, biodiesel in the fuel mixture had a higher contribution than its proportion in the mixture in categories related to ecosystems toxicity and atmospheric pollution. For example, biodiesel (fatty acid methyl ester, FAME) production was responsible for 36% of the total $CO_{2eq}$ emissions from diesel B5 in Spain. The production of 1 kg of FAME from crude palm oil imported from Indonesia generates 5.12 kg $CO_{2eq}$, while the production of 1 kg of ultra-low sulphur diesel (ULSD) produces 0.46 kg $CO_{2eq}$. Unlike other energy crops that tend to be established in already exploited soils, most palm oil crops in Indonesia were settled in tropical and peat forests, whose preparation for cultivation releases a large amount of $CO_2$.
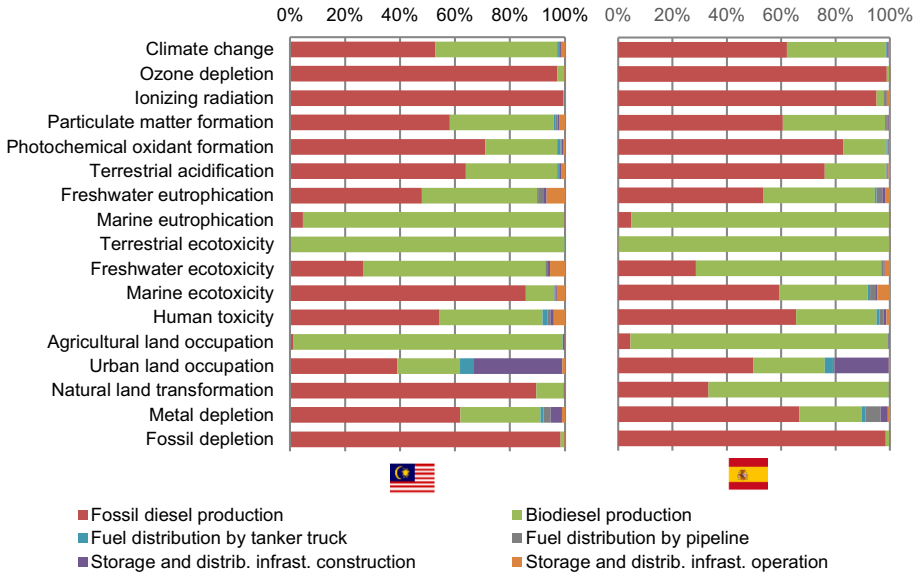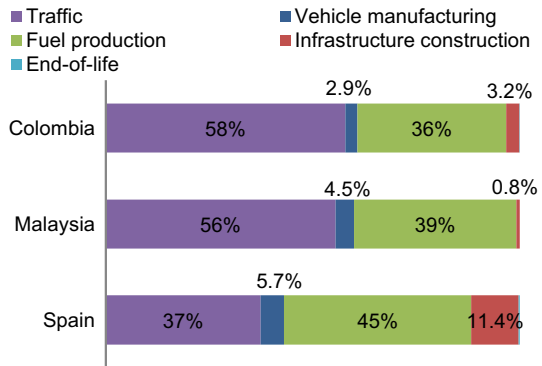


Fig. 9 Normalized results. Traffic process—Colombia
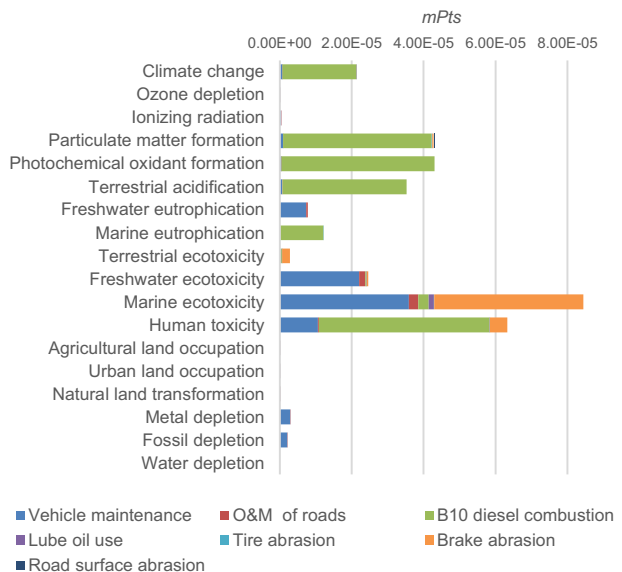
**Fig. 10** Fuel production component. Malaysia and Spain



**Fig. 11** Overall environmental impact shares

Contrary to expectations, the incorporation of biofuels in the case of Spain and Malaysia caused an increase in the impacts on climate change and land uses, which placed a burden on final damages to ecosystems.

In order to compare the global environmental impact of each of the three freight transport services, the contribution of each transport component in the aggregated score is shown in Fig. 11. It can see that the most significant differences are due to the key parameters: vehicle characteristics (technological and regulatory differences), route typology, and service efficiency.

The type of route, mainly a one-lane road in each direction in mountainous terrain and the efficiency of the vehicle, explains the high fuel consumption per km travelled in the case of Colombia. Even though fuel consumption was higher in the Spanish case than in the Malaysian case, emissions control measures in the vehicle make direct

emissions less dominant in the Spanish case. In this sense, the lower the traffic impacts of using a Euro VI vehicle, the higher the contributions of the rest of the components.

In the Colombian case, although the environmental impacts per unit of fuel are low, the high fuel consumption in the route explains the critical contribution of this component in the aggregated score. On the other hand, the low contribution of the vehicle manufacturing is because the truck was usually used with high load factors and a longer vehicle life span than in the other cases.

As for the road construction process, the expenditure of energy and materials for constructing highways was high, but it was compensated by a high volume of traffic per km built. In Malaysia, the traffic volume was double that in Spain, making the environmental impact of road construction very low per each transported tkm.

In brief, addressing the environmental impacts of transport services with a holistic approach has allowed us to identify hotspots in other components than the traffic process and understand the extent to which the kinds of vehicles, fuels, and roads contribute to the total environmental impacts. The significant impacts related to the emissions control technology, the kind of fuel, and road reveal the need for promoting different propulsion technologies and transport modes and their respective infrastructures to enable more fluid and efficient freight services. The results of this study would also suggest the implantation and evaluation of freight services on electric vehicles, following the electrification of processes in the way to the net-zero emissions scenario. However, the observed impacts on toxicity due to the electricity distribution networks might suggest that electric vehicles would be acceptable as long as they use electricity locally produced in a distributed manner on small-scale plants from renewable sources.

## 4.2 Validation of results

The proposed methods for estimating the emissions of vehicle operation have demonstrated to increase the accuracy of the results, especially for transport services in mountainous or steep areas where the fuel consumption ratios and the average emission factors available in the literature are not representative. For example, the averaged fuel consumption for this route informed by the transport company in the case in Colombia was 58 L/100 km. However, if fuel consumption was estimated by using Tier 2 factors, considering only the vehicle's size and emissions control technology, as well as the energy density of diesel B10, the estimate would be 21.6 L/100 km. While using Tier 3 equations for the whole route, considering also a unique average road gradient, the estimate would be 39.2 L/100 km. In contrast, the obtained estimate of 44.7 L/100 km by the proposed Tier 3 by sections was closer than other methods. For example, a well-known web-based free access tool, such as EcoTransIT (IFEU 2022), estimates a consumption of 24 L/100 km for the Pereira-Quibdo transport service. Moreover, the Ecoinvent datasets also use Tier 2 factors, based on the Handbook emission factors for road transport-HBEFA (Keller et al., 2010), with average equivalent consumption of 19 L/100 km of diesel B10 for the 7.5–16 t diesel trucks datasets.

For the cases in Malaysia and Spain, the Tier 3 by sections method also gave the best estimates, even closer to the measured fuel consumptions. Tier 2 and Tier 3 estimates were not too different because the characteristics of the transport services through highways were similar to the average European conditions. That is, using the methods Tier 2, Tier 3, Tier 3 by sections, and the direct measurement of the transport company, the fuel

consumptions rates were 18.5, 19.0, 21.6, and 26 L/100 km in the Malaysian case, and 29.9, 30.5, 31.2, and 31.0 L/100 km in the Spanish case, respectively.

Regarding the impacts of the other components of the transport systems, the allocation of impacts through using specific load factors and vehicle lifespan, as well as the statistics for tkm and vkm travelled by each kind of vehicle in each country, also generated more accurate results than when life cycle inventories databases are utilised. For example, the total tkm transported in a 16-tonne rigid truck in Ecoinvent v2 were 1,582,200 tkm (Spielmann et al. 2007), and in the current Ecoinvent v3 (ETH, 2022) database is 1,776,600 tkm; this given that the average load factors were updated from 2.93 t to 3.29 t for a vehicle lifetime performance of 540,000 km, based on the models EcoTransIT (Knörr et al., 2011) and Tremove (G et al., 2009). On the other hand, a total of 5,565,000 tkm were considered for the Colombian case due to the high average load factor and the 21 year vehicle lifespan. This difference is reflected in the transport components contributions, e.g. in the aggregated endpoints assessment using the Ecoinvent datasets for a 7.5–16 t diesel truck, the vehicle manufacturing impact shared around 7% of the impacts, while in the Colombian case the share was 2.9%. Similarly, given that most of total Gtkm in Colombia are mobilized over single-lane roads, whose construction generates fewer impacts than highways, as well as the high traffic volume on these roads, the allocation of these impacts per tkm was small. This situation resulted in a share of 3.2% of the infrastructure component in the Colombian case, in comparison with the average share of 10% using the Ecoinvent datasets.

The total tkm transported in the vehicle lifespan, as well as the total Gtkm mobilized in the specific roads, were also pointed out as relevant aspects by Nahlik et al. (2016) (following previous works published by Facanha and Horvath (2007)), whose results showed low contributions of the vehicle and infrastructure components on the total emissions per tkm. The authors concluded that these contributions were due to the high volume of freight traffic with large tonnage on the evaluated route. This scenario might be comparable to the analysed transport service in Malaysia. However, given that Nahlik et al. (2016) did not characterized the emissions into impact categories, only the estimated quantity of $CO_{2eq}$ per tkm could be compared to our results for the climate change category. They estimated emission factors of 0.34 and 0.22 kg $CO_{2eq}$ per tkm transported in a medium- and large-size diesel trucks, respectively, which are higher to the European datasets from Ecoinvent with averages of 0.21 and 0.09 kg $CO_{2eq}$ per tkm transported by 7.5–16 t and > 32 t diesel trucks. While, in the case in Malaysia, the freight service in the medium-size vehicle generated an average of 0.80 kg $CO_{2eq}$ per tkm. This large difference in the emission factor was due to the few tkm transported in the service in Malaysia, whose average load factor was only 1.0 t (i.e. 20% loaded in the outward journey and empty return). In contrast, the emission factor in the Colombian case was only 0.17 kg $CO_{2eq}$ per tkm because the vehicle transported 10 t (full loaded), obtaining a lower rate per tkm despite the high fuel consumption per km. Yet, a similarity of the Colombian and Malaysian cases with the Nahlik et al. (2016) study was the low contribution of infrastructure construction given the high traffic volume on the assessed roads. Another similarity with this study was the emission factor for large-size diesel truck for the case in Spain, where the service emitted 0.23 $CO_{2eq}$ per tkm. However, the contribution of infrastructure was near 10% in the Spanish case, mainly due to the relative low traffic volume. Moreover, despite the average load factor in this case was low (5.0 t, i.e. 40% loaded in the outward journey and empty return), the emission factor not high given the high fuel efficiency due to the skilled driver, the modern Euro VI vehicle and, more importantly, the smooth driving conditions related to the low traffic volume.

In short, this benchmark demonstrates that despite different services generate similar emission factors, each service has particularities that can be only analysed by a holistic approach, which unveils the contributions to the total impacts of each transport system component. The respective results can guide to analyse the causes of the impacts and design strategies to improve the environmental performance of transport services, based on well-defined components across the traffic operations.

# 5 Conclusions

Due to the energy transition and the need to improve the sustainability of the transport sector, a specific integrated methodology has been developed to deliver a better understanding of the relevance of transport components for LCA practitioners. This methodological approach presents a novel perspective to define the boundaries and scopes of transport systems to address its evaluation logically and systematically. This integrated approach was applied to three different case studies. An Excel-based calculator to create the life cycle inventories for each transport component was developed, considering the specific characteristics of the transport services in each case study in Colombia, Malaysia, and Spain. Additionally, the obtained results of the studies carried out in different countries and continents can be incorporated into the inventories of the life cycle of diesel and biodiesel production and construction and road maintenance for future studies in these territories.

As a general remark, this study raises awareness of the importance of the specific transport modelling in the environmental assessments, resulting in enormous differences in the contribution of this input in the carbon or ecological footprints of any assessed product. This fact is significant when a product must be transported for long distances, making it necessary to establish strategies to reduce emissions focused on other transport components than fuel combustion.

The results show that in the event of accounting only for exhaust emissions, the total life cycle emissions are underestimated between 15 and 30% in the case of $CO_{2eq}$ and between 10 and 80% for the rest of the atmospheric pollutants. It can also be deduced that mixing biofuels with diesel can exacerbate some of the impacts that are intended to be reduced. This situation raises concerns on the importance of analysing the origin of biofuels, which can cause worse impacts than fossil fuels if they come from burnt forests or displaced crops.

The obtained results also suggest the expansion in the debate and investigation about the critical points of the transport sector. Research on alternatives for road transport has focused on comparing the reduction in emissions by energy use, without giving relevance to the emissions caused by the abrasion of tires and brakes, which have relevant impacts on water and human toxicity. In general terms, it would mean increasing the energy efficiency of transport through both more efficient engines and better roads (in the case of Colombia); finding fuels with lower production impacts and balancing the traffic to the highways (if applicable in the case of Spain, the improvements would be substantial), and optimizing the load of the vehicles (in the case of Malaysia).

Since the overall aggregated scores depend on weighting factors used in the assessment method, they should be taken as an approximation to the real potential impacts and used only as a comparison. However, the results obtained for the three cases under study show a clear correlation with three critical parameters of a freight transport service: vehicle characteristics, route topology, and service efficiency.

Following all the above, one of the main contributions of this study is related to the decision-making process to define the most appropriate strategies and the priorities in each territory to achieve more environmentally sustainable transport services. In addition, the new system that has been defined in this analysis focused on the transversal traffic process also could be applied to other transport services by train or ship and intermodal, both goods and passengers.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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