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figuBanning short-haul flights and investing in high-speed railways for a sustainable future?

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Abstract

Long-distance mobility sustainability, high-speed railways (HSR) decarbonization effect, and bans for short-haul flights are debated in Europe. Yet, holistic environmental assessments on these topics are scarce. A comparative life cycle assessment (LCA) was conducted on the Paris-Bordeaux transportation options in France: HSR, plane, coach, personal car, and carpooling. The overall ranking on four environmental indicators, from best to worst, is as follows: coach, HSR, carpooling, private car, and plane. Scenario analyses showed that increasing train occupancy decreases the environmental impact of the mode (-12%), while decreasing speed does not. Moreover, worldwide carbon footprints of electric HSR modes range 30-120 gCO₂eq per passenger-kilometer traveled. Finally, a consequential LCA highlighted carbon paybacks of the HSR project. Under a business-as-usual trip substitution scenario, the HSR gets net-zero 60 years after construction. With a short-haul flight ban, it occurs after 10 years. This advocates for generalizing short-haul flight bans and investing in HSR infrastructure.

Keywords: Decarbonization investment; Carbon payback; High-speed rail; Short-haul flight ban;

Long-distance mobility; Life Cycle Assessment;

1 Introduction

Exploring the role of high-speed railway (HSR) development to make long-distance mobility more sustainable is not a new topic (Goodenough and Page, 1994; D'Alfonso et al., 2015), but has gained momentum recently. Indeed, HSR transportation can compete with air and road modes, depending on socio-economic determinants (Bergantino and Madio, 2020). In terms of environmental sustainability, a new HSR generates environmental burdens for its construction, maintenance and end-of-life (EoL), but also impacts positively or negatively the environment due to its usage, depending on trip substitutions (Bergantino and Madio, 2020) and potential induced traffic (D'Alfonso et al., 2015). These multiple and variable effects tend to complexify the assessment of the role of HSR in a more sustainable future (D'Alfonso et al., 2015), despite most studies appraising environmental benefits from HSR developments (e.g., Sun et al., 2020; Yang et al., 2019; Chester and Horvath, 2012).

France carried out a major campaign to develop HSR (Zembri and Libourel, 2017), before the national Mobility 21 commission recommended to rather allocate public funds to existing railways and policies relating to commuting (Commission Mobilité 21, 2013). The latest French HSR line started to be operated in 2017, but awareness around the environmental impact of air transportation has revived the idea of expanding the HSR network in France (Girard, 2020). With the “LOM”—the latest Mobility Orientation Law in France (Legifrance, 2019), the French government aims to decrease air transportation, by banning (1) domestic flights for which an alternative train journey shorter than 2.5 hours exists as well as (2) airport extensions and construction. Banishing air transportation advertisement has even been proposed by the French Green deputies (Assemblée Nationale, 2019). Nevertheless, these choices are motivated by fragmentary arguments: mainly the important contribution of air transportation to national greenhouse gas (GHG) emissions (estimated around 5%), and its high carbon footprint—145 gCO₂eq per passenger-kilometer traveled (pkt)—compared to bus and rail—resp. 20 and 3.5 gCO₂eq/pkt according to the French amendment (Assemblée Nationale, 2019).

While comparing the environmental impact of transportation modes is one of the first steps in guiding sustainable public policies, the previous figures are both biased and insufficient. Biased as they are based on the EN 16258 standards (AFNOR, 2013), which only takes into account the GHG emissions linked to the vehicle use stage. However, depending on the mode, major contributions to the environmental performance of transportation modes can come from the rest of the vehicle life cycle (de Bortoli, 2021) or even the infrastructure (de Bortoli et al., 2017), especially for HSR modes (Chester and Horvath, 2012b). The insufficiency of the analysis also relates to the mono-criterion approach, considering only climate change as an environmental priority. Yet, to be reliable, transparent, and anticipate environmental burden-shifting, public policies must be based on a comprehensive environmental assessment of transportation modes, through a multicriteria and integrated modal life cycle assessments (LCA), i.e., considering the vehicle and infrastructure life cycle impacts (de Bortoli and Christoforou, 2020).

Performing an attributional LCA (ALCA) including both vehicles and infrastructure over their entire life cycle has first been performed by Chester, to assess the environmental performance of long-distance modes in the United States (US) (Chester, 2008). His approach was based on a hybrid LCA—i.e., a mix between process-based LCA (standard LCA) and environmentally-extended input-output analysis (EEIO-A), and partially theoretical data. In addition, the geographic relevance of his analysis is restricted to the US and data date back to the 2000s. According to the characterization of data quality used in LCA with the Pedigree matrix (Weidema and Wesnæs, 1996), data older than 15 years is considered to be of the poorest quality, thus potentially generating large uncertainties. Hence, understanding globally long-distance mobility environmental impacts to compare modes requires updated and regionalized LCA models, i.e., a wider geographic and technological coverage.

Second, the environmental comparison of transportation modes is not enough. Indeed, developing HSR requires the construction of new infrastructure, which generates environmental impacts, while other infrastructure already exists, may not have reached their capacity (roads, airports), and could be used instead. It means that, when comparing different modes using ALCA, temporal aspects of the

impacts are not considered, i.e., the fact that certain impacts have already occurred and cannot be avoided in the future—e.g., to produce the infrastructure or vehicles—while other impacts are to come. This leads to a bias in the analysis, as only future impacts matter to drive the ecological transition, which is even more true to reach net-zero. A consequential approach is therefore more appropriate in a nearer term to assess the sustainability impact of the development of HSRs, by comparing the environmental situation with and without the new infrastructure. Such an approach has been used several times in the past, but always on a truncated perimeter. For instance, the International Union of Railways only considered the GHG emissions of the HSR construction and modal shifts (use stage) (UIC, 2016), neglecting the other impacts considered in an integrated modal LCA. A similar restricted perimeter was considered by Wand and Sandberg, but adding the train construction impact, and using EEIO-A (2012).

This paper aims to answer the following questions: should we invest in HSR at a time when it is urgent to make the wisest choices for the planet in terms of both the allocation of public funds and natural resources? Should we ban short-haul flights? What are the best environmental alternatives for long-distance travel? First, the section 2 of this article details the methodology, and how the attributional and consequential LCA models have been developed to answer these questions. Then, section 3 presents and analyzes the results. Last, section 4 discusses (1) the seminal comparative US results in the light of our new models and results, (2) the adequate system boundaries for modal assessments on which to base unbiased environmental transportation recommendations, and (3) the options for sustainable long-distance travels toward net-zero.

2 Method

2.1 Case study

Train is commonly considered as an environmentally-friendly transportation mode and is often subsidized by governments in Europe (Autorité de régulation des transports, 2020). Europe has an important railway network, France having the second-longest network with a total of 28100 km (Autorité de régulation des transports, 2020). From the beginning of rail mobility in France in 1841,

the passenger rail traffic intensity has regularly increased—and doubled these last 40 years—to reach 1238 million travelers and 91.5 billion passenger-kilometers traveled annually in 2018 (SNCF, 2019). The massive HSR deployment plan from the last decades must have contributed to this surge. In 2019, 2600 km of HSR were operated in France (Autorité de régulation des transports, 2020), and the newest 302 km-long HSR route runs between the cities of Tours and Bordeaux since July 2017 (de Bortoli et al., 2020), reducing passenger time between Paris and Bordeaux by 30%. This new service is now in competition with other modes on the Paris-Bordeaux corridor, including short-haul flights and road modes—coach, personal car, and carpooling. The objective of the case study is to compare the environmental impacts of the different modes on the Paris-Bordeaux corridor, to explore the sensitivity of these impacts to different operational parameters, and to assess the environmental impact of the HSR project from a consequential point of view, including carbon payback times.

2.2 Calculation overview

To assess the environmental relevance of the Paris-Bordeaux HSR project—and of HSR in general, we will conduct a multicriteria environmental assessment of the competing modes on the Paris-Bordeaux corridor using the Life-Cycle Assessment (LCA) methodology to compare their impacts. LCA is a standardized method to assess the environmental impact of a system—a service, a product, an organization—on various quantitative dimensions and potentially over the entire life cycle of the system (International Organization for Standardization, 2006a, 2006b). To compare the competing modes, only mono-modal trips will be considered. For instance, the aerial alternative will be considered from airport to airport, neglecting the trips to access and leave the hub. These additional trips can be done using public transportation: by RER train that has a very low environmental impact in Paris (de Bortoli and Christoforou, 2020) and by buses in Bordeaux. Thus, we assume this would not substantially change the comparison. A contribution analysis will be carried out to understand the main drivers of the environmental performance of each mode depending on the indicator considered.

Then, scenario analyses (SAs) will be conducted to highlight key parameters of the four environmental impacts of the transportation modes assessed, and to understand their influence. Technological progress is often put forward as the preeminent means of solving the environmental problems of our time. To test this hypothesis in the case of long-distance journeys, we will calculate the environmental performance of trains, planes, and cars with conventional engines and more advanced engines. Then, we will perform sensitivity analyses focused on the HSR, by testing the impact of the electricity mix (selection of a set of geographical areas with electricity mixes covering in the worldwide carbon footprint range), the train capacity, and the commercial speed.

Finally, consequential LCAs will also be carried out to quantify the net carbon footprint of the HSR project, considering the infrastructure life cycle and the impact of trip substitutions from air to rail under two scenarios: a business-as-usual (BAU) scenario and a scenario where short-haul flights are banned. The new HSR was opened mid-2017. Based on traffic data from the French aviation Directorate (DGAC, 2020, 2019, 2018), we calculated that the annual air traffic of the link decreased by 7.1% in 2017, 17.3% in 2018, and 3% in 2019, showing a clear reduction trend in the number of passengers (see supplementary material). Nevertheless, it is still difficult to draw a precise trajectory on the long-term annual modal shifts due to the new HSR service, especially because of exogenous factors (e.g., national strike in 2019–2020). Moreover, a decrease in the number of passengers does not mean a decrease in the number of flights—and thus of environmental impacts—as it depends on the airline company strategy. Under the BAU scenario, we assumed a steady annual modal shift from air to rail at around 250 000 passengers per year (average between the rail operator and the plane operator figures), i.e., a drop of 4 return flights daily over the 16 operated before the HSR opening (Provenzano, 2019). Considering the respective distances between Paris and Bordeaux by plane (507 km) and by rail (497 km), and the carbon footprint per pkt with or without the infrastructure respectively by air and rail, we will estimate the carbon payback period of the HSR project (see calculation details in the supplementary material). The second scenario—referred to as the “ban scenario”—accounts for 12000 flights avoided per year, i.e. 16 return flights a day based on the daily

average operation of the line in 2021, equal to 1.6 million of passenger-trip traveled (Mptt) avoided annually.

2.3 Scope and functional units

The first part of the study relies on a process-based attributional LCA of transportation modes, considering both the infrastructure and the vehicles, as well as the entire life cycle—from the production to the End-of-Life (EoL). This approach is defined as an “integrated modal LCA” (de Bortoli, 2021). The system boundaries of such a method are presented in Figure 1. Two functional units (FU) will be considered for the comparative ALCAs: “moving one person from Paris to Bordeaux”, i.e., the ptt, and “moving one person over one kilometer”, i.e., the pkt.

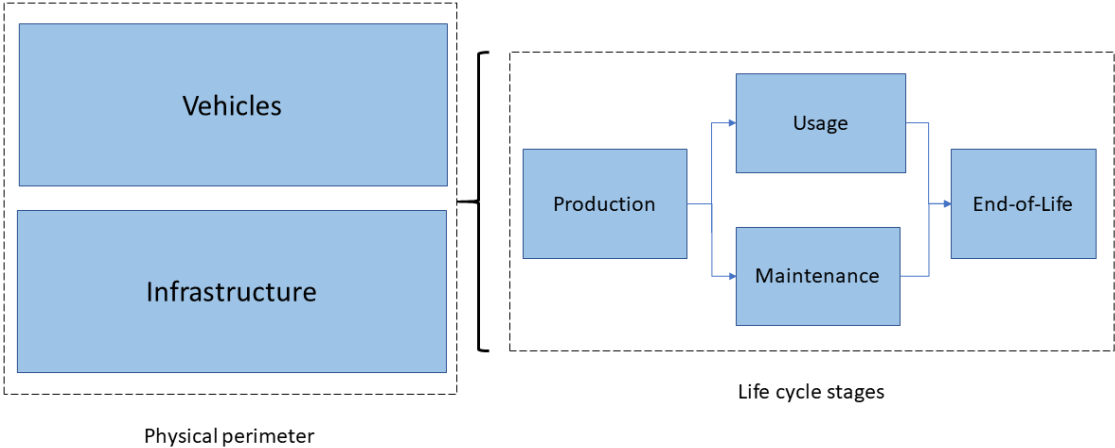


Figure 1 System boundaries of the integrated modal LCA method

The consequential approach will be based on a consequential LCA (see for instance Weidema et al., 2018), and will quantify the net GHG emissions of the HSR project, considering the impact of the traffic on the HSR and the avoided emissions due to traffic displacement from aerial transportation, again based on integrated LCA.

2.4 Integrated modal LCA equation

The LCA software used is OpenLCA 1.9. The formula to calculate the environmental impact of a mode *i* per pkt using integrated modal LCA is presented in Equation (1) (de Bortoli and Christoforou,

2020), with $EF_{veh,i}$ the environmental factor from the vehicle component of the mode i per pkt, $EF_{infra,i}$ the environmental factor from the infrastructure component of the mode i per pkt, $EF_{1veh,i}$ the environmental factor of one average vehicle of the mode i over its life cycle, $PKT_{1veh,i}$ the lifetime mileage of one vehicle, PKT_{ij} the number of pkt on the infrastructure j for the mode i , $a_{i,j}$ the “specific infrastructural demand” (Spielmann et al., 2007) of type j by the mode i (see further explanations below), q_j the number of units of the infrastructure j used by the mode i , $EF_{1u,j}$ the environmental factor of one unit (surface or length) of the infrastructure j , b_{ij} the infrastructural allocation factor of the infrastructure j for the mode i , and VKT_{ij} the number of vehicle-kilometers traveled (vkt) by mode i on the infrastructure j .

$$EF_i = EF_{veh,i} + EF_{infra,i} = \frac{EF_{1veh,i}}{PKT_{1veh,i}} + \sum_j \frac{1}{PKT_{ij}} \cdot a_{ij} \cdot q_j \cdot EF_{1u,j} =$$

$$\frac{EF_{1veh,i}}{PKT_{1veh,i}} + \sum_j \frac{1}{PKT_{ij}} \cdot \frac{b_{ij} \cdot VKT_{ij}}{\sum_i b_{ij} \cdot VKT_{ij}} \cdot q_j \cdot EF_{1u,j} \quad (1)$$

We multiply EF_i by the number of kilometers of the trip to obtain the environmental impact per ppt.

2.5 Characterization methods

Our set of indicators is based on the Cumulative Energy Demand (CED) and the v1.47 IMPACTWorld+ (IW+) characterization methods (Bulle et al., 2019), as well as the IPCC 2013 Global warming potentials. A set of four indicators, encompassing primary energy consumption (addition of the sub-indicators of the CED method), damages to ecosystems and human health (IW+ method), as well as climate change contribution, are selected. We choose the endpoint level of IW+ indicators as the objective of this LCA is to provide a comprehensive snapshot of the environmental sustainability of long-distance travel modes for decision-makers, considering as exhaustively as possible the complexity of environmental issues. Endpoint indicators, sometimes considered as less reliable than midpoint indicators as they are based on more complex calculations, have the advantage of providing a complete environmental assessment in a restricted number of indicators, without using subjective weighting methods. The two midpoint indicators—primary energy consumption and

contribution to climate change—are calculated for comparison purposes as they are the most popular in public policies and scientific publications.

2.6 Main modeling assumptions

The main characteristics of the parameters used in our transportation LCA models are presented in Table 1. They will be detailed further in the article and its supplementary material (text document and Excel spreadsheets). The capacity of the vehicles is expressed in number of passengers (pax).

Table 1 Synthesis of the modeling main parameters

<i>Mode (+ distance)</i>	<i>Infrastructure lifespan (years)</i>	<i>Vehicle type</i>	<i>Weight (t)</i>	<i>Vehicle lifetime mileage (km)</i>	<i>Capacity (pax)</i>	<i>Occupancy rate (%)</i>
Train (497 km)	Rail: 120	Atlantique	445	12 000 000	454	68%
	Stations: 100	Avelia Euroduplex	401	12 000 000	556	68%
		Oceane				
		Ouigo	401	12 000 000	634	76%
Plane (507 km)	Airport: 100	A320-ceo	43	28 871 000	155	86%
		A320-neo	44	28 871 000	165	81%
Road (589 km)	Earthworks: 100	Coach	13	1 000 000	51	69%
	(Sub)base course: 30	Diesel car	1.3	200 000	5	44%
	Wearing course: 13	Petrol car	1.3	200 000	5	44%
		Diesel carpooling	1.3	200 000	5	68%
	Petrol carpooling	1.3	200 000	5	68%	

2.7 Life cycle inventories

Ecoinvent v3.2, with the cut-off allocation system, is used as a background database. Ecoinvent is the most comprehensive Life Cycle Inventories (LCIs) database, containing international industrial data enabling to assess the environmental impact of energies, resource extraction, chemical products, metals, agriculture, waste management services and transportation services (Wernet et al., 2016). The foreground LCIs have been collected from transportation operators, infrastructure construction companies and concessionaires, and completed by data from the literature when needed. They are summarized below by mode, and exhaustively explained in the supplementary material. EoL allocation is a 100:100 approach, considering a credit for avoided virgin production at a rate of 100% (Allacker et al., 2017).

2.7.1 High-speed rail modes

2.7.1.1 *Railways and stations*

LCIs of the railway are adapted from the study of de Bortoli et al. (2020) (see supplementary material). The HSR section only goes from Poitiers to Bordeaux, over 302 km, and the beginning of the line is a standard railway. A theoretical full HSR line has been modeled by scaling up the real HSR section LCI. Because no other data were available to conduct the LCA of the HSR stations, we estimated the type of building and the areas of the four other HSR stations using Google Maps and its different tools (measure a distance, Satellite and Street View). The characteristics of the stations are detailed in the supplementary material.

2.7.1.2 *Trains*

Two kinds of carriages are considered on the HSR corridor: the Atlantique train that is a single-stage train and the Avelia Euroduplex Oceane trains that is a double-stage train (called “Duplex train” in the rest of the article). New LCIs are developed, as the only model in ecoinvent is a German ICE single-stage train. Details on the LCIs can be found in the supplementary material. For the production stage, material quantities were provided by Alstom’s experts, while the rest of the inventories were

compiled from the existing ecoinvent LCI on the production train process, which also includes the EoL (Spielmann et al., 2007). Transportation activities between the diverse manufacturing sites to the final assembling plant in Belfort, France, are detailed in the supplementary material. The locations of the different sites come from declarations from the French Ministry of Transportation (Ville, Rail et Transports, 2019). The average electricity consumption on the HSR section has been measured equal to 22.9 kWh/km for Euroduplex Oceane trains and 27.1 kWh/km for Atlantique trains by the concessionaire of the line, LISEA, for maximum speeds ranging between 300 and 320 km/h. The maintenance has been modeled using the ecoinvent's process "*maintenance, train, passenger, high-speed, DE*", rescaled based on the train's weights (ratio 401 tons for the Euroduplex Oceane train / 640 tons for the German train). Finally, the EoL scenario is based on a report from the French Professional syndicate for recycling companies and includes recycling, landfill, and other disposals (FEDEREC and ADEME, 2017). A distance of 400 km has been considered from the dismantling point to the recycling platform (FEDEREC and ADEME, 2017).

2.7.2 Plane mode

2.7.2.1 Airports

Three airports are used to travel by plane between Paris and Bordeaux: two in the French capital—Paris-Charles de Gaulle (CDG) airport which represents 40% of the Paris-Bordeaux flight departures based on our calculations, and Orly airport, which represents the remaining 60% (DGAC, 2014)—and the one in Bordeaux-Mérignac. Because airports did not share any data to conduct an LCA, the process "Airport Construction—RER" from the ecoinvent database was reused. As the data change significantly from one airport to another depending on the size, the construction techniques, and the electricity mix, the ecoinvent process was adjusted for each of the three French airports considered using a method detailed in the supplementary material.

2.7.2.2 Aircrafts

The air link between Paris and Bordeaux is operated by Air France airline. The fleet comprises planes from the Airbus A320 family. Two A320 models are used: the classical A320ceo ("ceo" standing for

Current Engine Option) and the new model A320neo (“neo” standing for New Engine Option). The construction and EoL LCIs are built on the results of the PAMELA project of Airbus, an LCA conducted on an A330-200 aircraft (de Oliveira Fernandes Lopes, 2010) and adapted to the specific aircraft used on the link Paris-Bordeaux. Three types of components are modeled: the aircraft frame, the seats, and the engines. Details can be found in the supplementary material. The aircraft maintenance is out of the scope, due to a lack of data. The use stage has been modeled particularly carefully as it may carry most of the impact (Chester, 2008). Two use stage cycles were considered: the Landing and Take-Off cycle (LTO) and the climb/cruise/descent (CCD) cycle. The duration of each period of each cycle is set based on Chester and Horvath data (Chester and Horvath, 2008). Kerosene consumption and emissions for the CDD cycle were calculated using the “Master emissions calculator 2016” spreadsheet (EMEP/EEA, 2017a) accompanying the EMEP/EEA air pollutant emission inventory guidebook 2016 (European Environment Agency, 2016). For the LTO cycle, the dedicated LTO emissions calculator was used, specifying the type of aircraft, the type of engine, as well as the specific airport and year considered (EMEP/EEA, 2017b). The EMEP spreadsheet does not allow to specify the type of engine: a 12% improvement in consumption and emissions has been considered, accounting for the LEAP-1A26 engine performance and the extra-weight of the A320neo (Hensey and Magdalina, 2018).

2.7.3 Road modes

Three road transportation modes are studied: average passenger car transportation, using gasoline or diesel, car-sharing, and coach. These vehicles travel on the highway A10, linking Paris and Bordeaux.

2.7.3.1 *Cars and coaches*

Standard vehicle categories are created to build the related LCIs. The average weight of a passenger car in France is 1278 kg (Compte, 2018). The representative coach is set as a Volvo B10M / Berkhof Axial 50, a two-axle bus weighing 13 300 kg with a capacity of 51 passengers (UK government, 2016). The material compositions of the average vehicles come fromecoinvent. The EoL treatment is included in the ecoinvent production process for vehicles. The maintenance of both passenger cars and

coaches are modeled directly using the existingecoinvent processes, namely “*maintenance, passenger car—REK*” and “*market for maintenance, bus—GLO*”. For the use stage, the emission model selected is the European EMEP/EEA guidebook. The “EMEP guidebook” gives emission factors of different types of vehicles for different speeds depending on a set of parameters like the gradient of the road and the occupancy rate of the coach to consider the impact of load on consumption and emissions. Between Paris and Bordeaux, speeds on the highway A10 are limited to 130 km/h for light vehicles and 90 km/h for heavy vehicles, while average speeds for these vehicles are respectively 118 and 88 km/h (73 and 55 mph) (de Bortoli et al., 2022). The coach consumes diesel, while the passenger car can consume either diesel or petrol (=gasoline).

2.7.3.2 Roadways

With 62.9 million trucks traveling over the highway A10 each year, it is a “class TC7” road according to the French catalog of road structures (Corte et al., 1998), with a PF3-class platform (George et al., 2001). We modeled the cross-section and construction materials requirement for construction using the French road catalog (Corte et al., 1998), following the French specifications for highway sub-base and base courses (LCPC-Sétra, 1998). Details can be found in the supplementary material. The maintenance consists of milling and rebuilding a very-thin asphalt concrete layer over 2.5cm after thirteen years, the base after thirty years, and the earthworks after 100 years, based on a French survey on pavement layer lifespans (de Bortoli, 2018).

3 Results and interpretation

3.1 ALCA: modal impacts and comparisons

In this section, we present the environmental impacts and rankings of the different means of transportation on the four selected indicators.

3.1.1 Absolute results

Table 2 gives the environmental impacts of each means of transportation by ptt and pkt. These results will be compared first per ptt in section 3.1.2, and second per pkt in section 3.1.3, to test the importance of the functional unit on the ranking of long-distance transportation modes.

Table 2 Environmental impacts of each means of transportation per functional unit (pkt and ptt)

	<i>FU</i>	<i>Climate change</i> <i>(gCO₂eq)</i>	<i>Ecosystem quality</i> <i>(PDF.m2)</i>	<i>Human health</i> <i>(DALY)</i>	<i>Energy</i> <i>(MJ)</i>
Railway Duplex	pkt	3.79E-02	4.38E-02	3.53E-06	7.45E-01
	ptt	1.91E+01	2.20E+01	1.90E-03	4.00E+02
Railway Atlantique	pkt	3.88E-02	4.47E-02	3.99E-06	8.41E-01
	ptt	1.96E+01	2.25E+01	2.15E-03	4.53E+02
Air CEO	pkt	2.42E-01	2.58E-01	4.19E-06	3.91E+00
	ptt	1.23E+02	1.30E+02	2.12E-03	1.98E+03
Air NEO	pkt	2.13E-01	1.96E-01	3.99E-06	3.43E+00
	ptt	1.08E+02	9.93E+01	2.02E-03	1.74E+03
Car gasoline	pkt	1.23E-01	1.27E-01	2.37E-06	1.87E+00
	ptt	7.27E+01	7.46E+01	1.40E-03	1.10E+03
Car diesel	pkt	1.06E-01	1.09E-01	2.20E-06	1.62E+00
	ptt	6.26E+01	6.42E+01	1.30E-03	9.56E+02
Carpooling	pkt	7.29E-02	7.51E-02	1.47E-06	1.11E+00
	ptt	4.31E+01	4.42E+01	8.66E-04	6.55E+02

Coach	pkt	2.07E-02	2.15E-02	5.43E-07	3.13E-01
	ptt	1.22E+01	1.27E+01	3.20E-04	1.84E+02

3.1.2 Comparison per passenger-trip traveled

As shown in Table 2 and Figure 2, when considering the ptt as a functional unit, the ranking globally indicates that traveling by plane is the most impacting mode on all indicators, followed by traveling by private car, carpooling, high-speed train, and finally coach (the best on primary energy consumption only, and otherwise equally ranked with other modes as the best mode). The results also show the importance of the multicriteria approach as the ranking on damage to human health is different. Indeed, train travels are almost as impacting as plane travels on this indicator. This importance is due to (a) the construction and maintenance of the railway, and more precisely to the water consumed in the electricity mix (around 60% of the total indicator, potentially due to the wrong spatialization of water flows in IW+ for openLCA, or a wrong assessment of the water consumed by hydroelectricity production in IW+, and the importance of hydroelectricity in the French electricity mix), (b) the production of steel (around 40% of the total indicator), but also (c) to the French aggregate production and its impact in terms of particulate matter (around 20% of the total impact), modeled with the LCIs of UNPG (French National Union of Aggregates Producers) (UNPG, 2011a, 2011b).

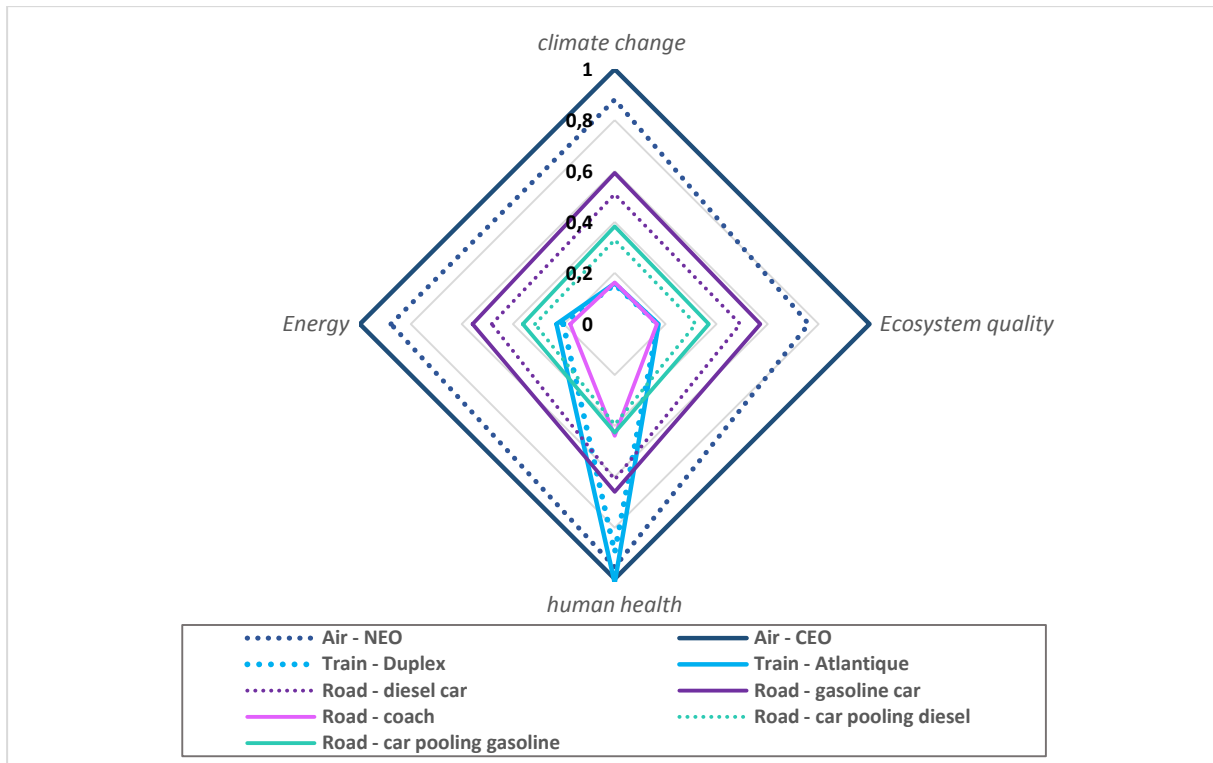


Figure 2 Normalized impacts of the different means of transportation per passenger-trip traveled

3.1.3 Per passenger-kilometer traveled

The standard functional unit to compare the environmental impact of transportation modes is the pkt. However, a trip between two cities presents different distances depending on the mean of transportation used. We want to check if the distance difference changes the environmental ranking of the modes on the Paris-Bordeaux case study. While Figure 2 presented the ranking based on the ptt, Figure 3 provides the ranking of the transportation modes studied per pkt. Although the ranking remains globally stable, the environmental performance of road modes gets better respectively to other modes, and the train performance deteriorates slightly. This is explained by the distances 16% longer by road than by plane, and 19% longer by road than by train. Indeed, Table 1 shows that traveling from Paris to Bordeaux is shorter by train (497 km), followed by plane (507 km) then by coach and car (589 km). Thus, a trip using the roads “consumes” more kilometers than using the railway, explaining the distortion in the two figures.

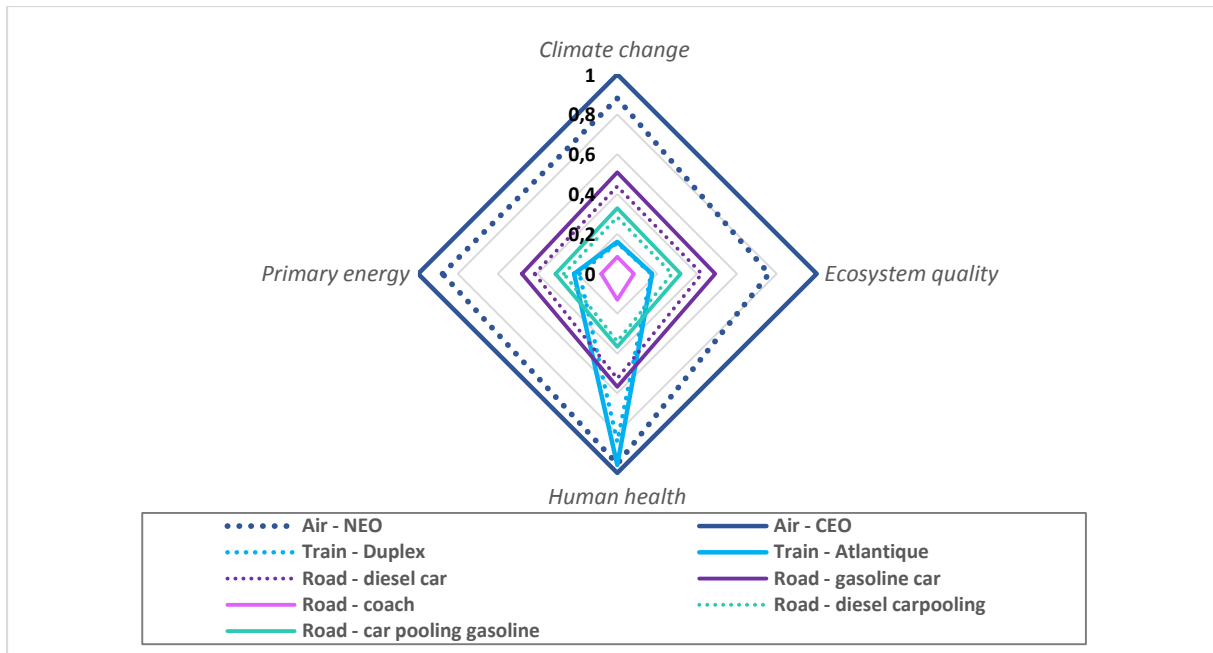


Figure 3 Normalized impacts of the different means of transportation per passenger-kilometer traveled

3.2 ALCA: contribution analyses

Figure 4 to Figure 7 show the distribution of the environment contributions from the different components of the transportation modes. The different contributions presented are the vehicle use stage (tagged as “use”, in blue), the rest of the vehicle life cycle (manufacturing amortization, vehicle maintenance, and EoL, in magenta), and the infrastructure life cycle (raw material extraction, construction, maintenance, EoL, in gray). For plane and road transportation, the use stage globally brings most of the impacts (from 30 to 80% of the total impact for air; from 25 to 80% for car), while for train transportation, the most important contribution is mostly due to the infrastructure (between 25 and 90% from the railway). The contribution of the different components of each transportation mode will be described further below.

In Figure 4, we can see that the railway represents the main contributor to climate change and ecosystem quality for the train mode, while the second contributor is the use stage. For human health and energy, the trends are opposite: the use stage is the main contributor, the railway the second most

important contributor. The vehicle contribution is negligible—between 1 and 3% of the two impacts. Stations also bring tiny contributions, as they represent around 0.06% of each impact.

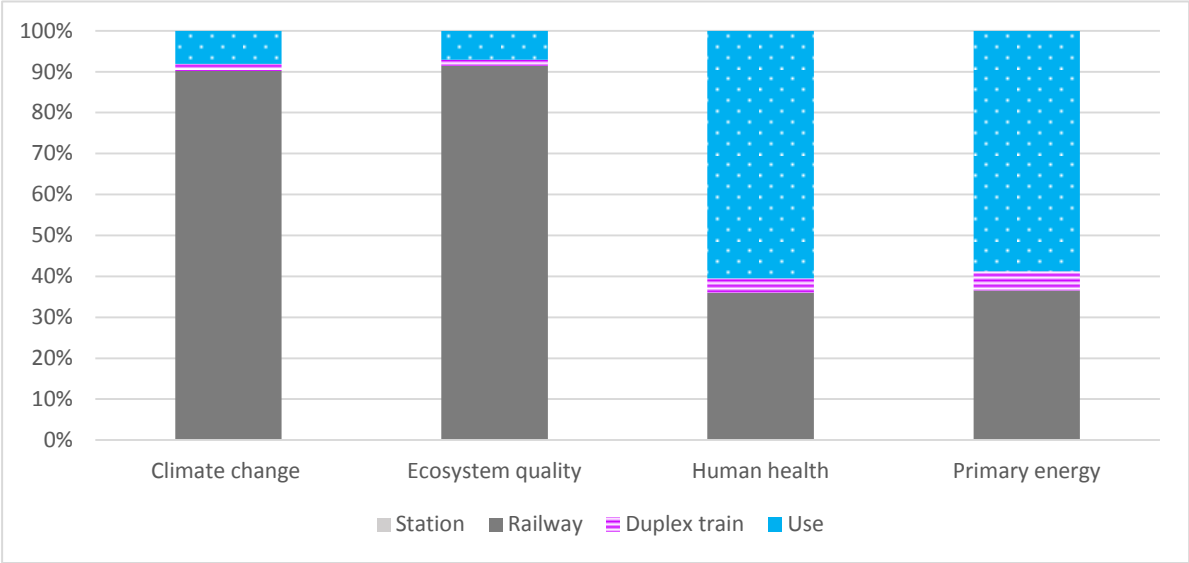


Figure 4 Contribution of the different components to the total impact for a trip by Duplex train

Figure 5 shows that the use stage has the most important impact for air transportation on the four indicators, followed by the airport, except for human health damage where the trends are opposite. The life cycle contribution to the total impacts of the neo aircraft represents between 0.3 and 4.5%.

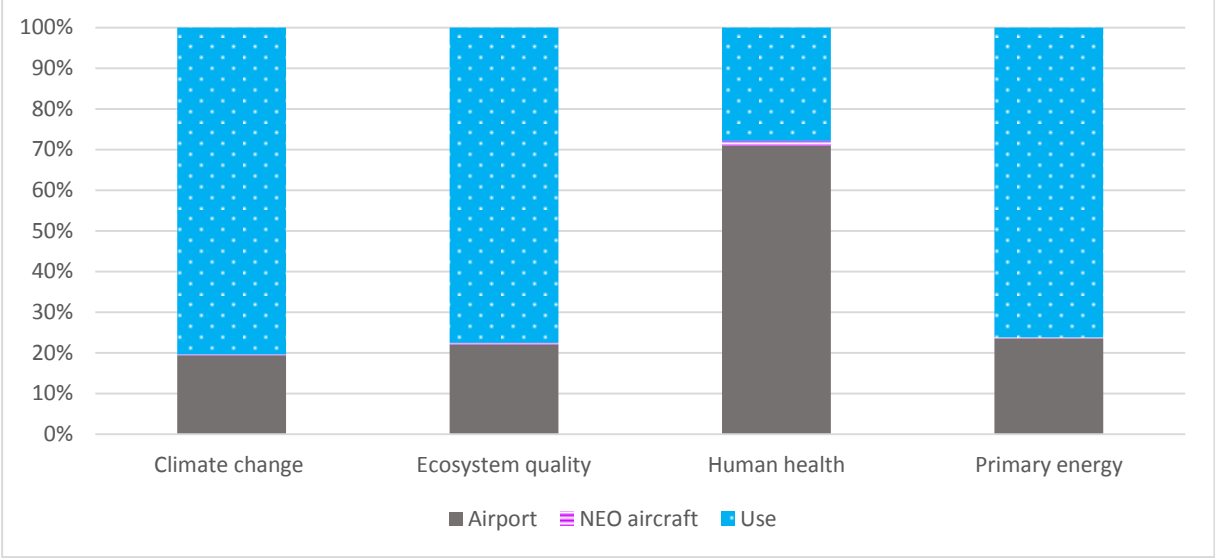


Figure 5 Contribution of the different components to the total impact when traveling by NEO

aircraft

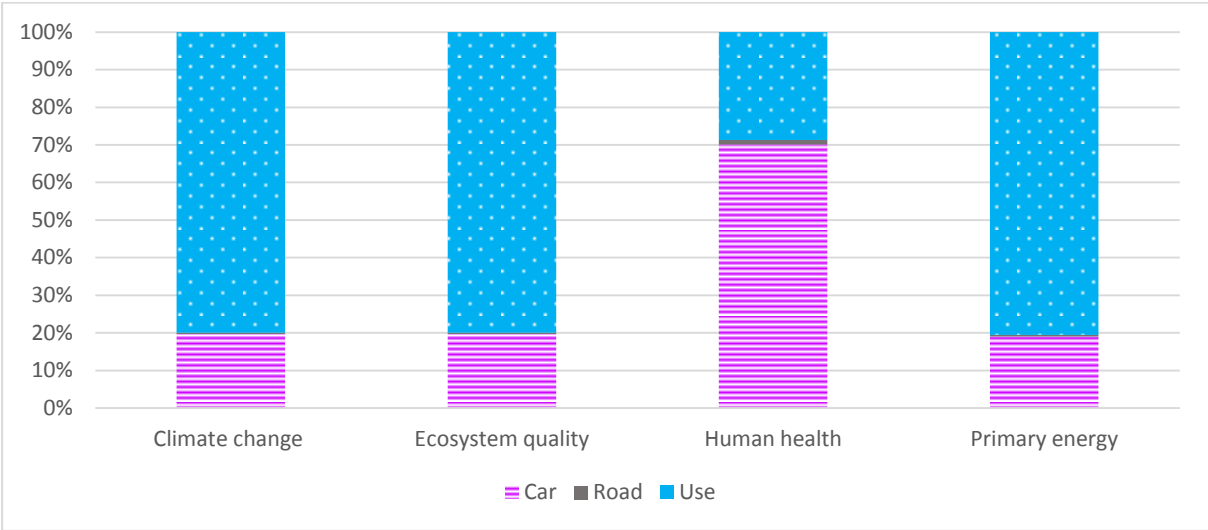


Figure 6 shows that for car modes (personal car and carpooling), the use stage—which includes direct emissions and fuel consumption—is the main contributor for all indicators except for human health again. The vehicle life cycle is the second-biggest contributor, while it is the first contributor for human health due to the use of water. The contribution from pavements is negligible: it represents between 0.1 and 1.5% of each impact.

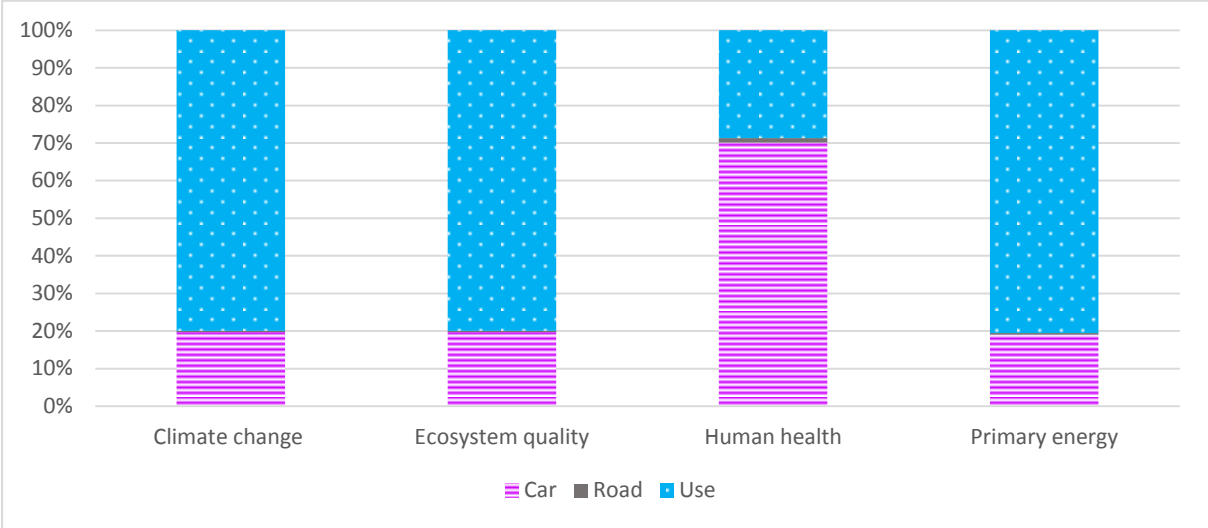


Figure 6 Contribution of the different components to the total impact for a trip by car (61% diesel, 39% gasoline)

For transportation by coach, Figure 7 highlights how the use stage generally represents the main contributor, followed by the road. Damage to human health is the exception, where the road is the

most impacting, followed by the vehicle. This relative importance of the infrastructure environmental impact is due to the fact that the impact of the coach mode per passenger is much lower than in a car, due to (1) the very high occupancy in a coach compared to the occupancy in a car (private or carpooling) and (2) an over consumption of the coach, that does not offset the benefit of carrying more users. The contribution of the pavement, of course, depends on how infrastructure allocation is performed (see discussion by de Bortoli and Christoforou (2020)).

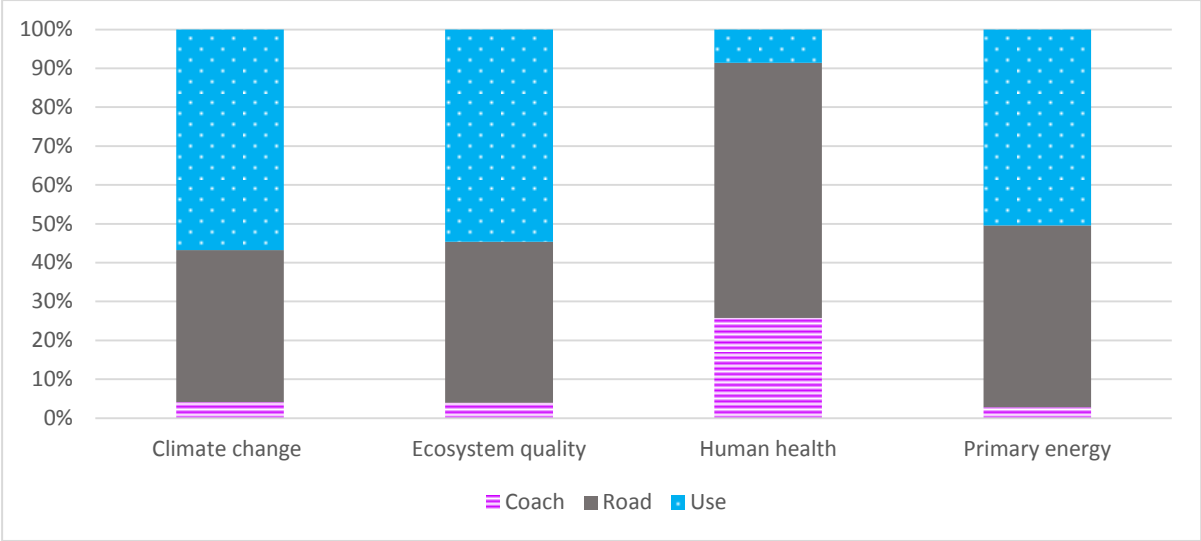


Figure 7 Contribution of the different components to the total impact for a trip by coach

3.3 ALCA: scenario analyses

3.3.1 Intramodal comparisons: impact of vehicle technology improvement

3.3.1.1 Rail: Duplex/Atlantique comparison

Figure 8 presents the comparison of the normalized impacts of train travels (per ptt) using two types of rolling stocks on Paris-Bordeaux: the Atlantique and the Duplex trains. Traveling onboard of a Duplex train presents lower impacts – by 4 to 22% depending on the indicator, and resp. on climate change and human health damage - than traveling onboard of an Atlantique train. This is not explained by the higher energy consumption of the Atlantique rolling stock (27.1 kWh/km compared to 22.9 kWh/km for the Duplex train), but rather by the higher capacity of the Duplex trains (556 versus 454 passengers). Thus, in our case study, the newest rolling stock allows reducing the environmental impact of traveling by train. Nevertheless, the impact in terms of climate change is limited.

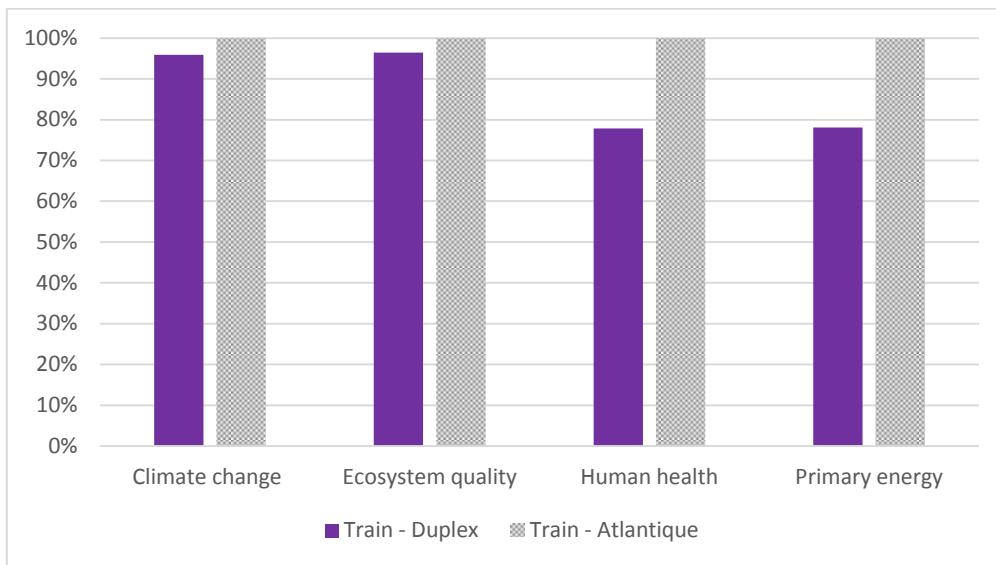


Figure 8 Train transportation: normalized comparison between a Duplex and an Atlantique carriage

3.3.1.2 Aircraft type: neo versus ceo comparison

Figure 9 shows the environmental comparison of a Paris-Bordeaux trip, using an A320neo aircraft versus an A320ceo aircraft. While producing an A320neo aircraft is more impacting than manufacturing a ceo version, a trip by neo aircraft presents a better environmental performance on the life cycle by 4 to 24% depending on the indicator, resp. on damage to human health and damage to ecosystem quality. This is due to the use stage, as the neo aircraft has a higher capacity and a better engine performance, thus a lower kerosene consumption. Again, the new technology performs better environmentally.

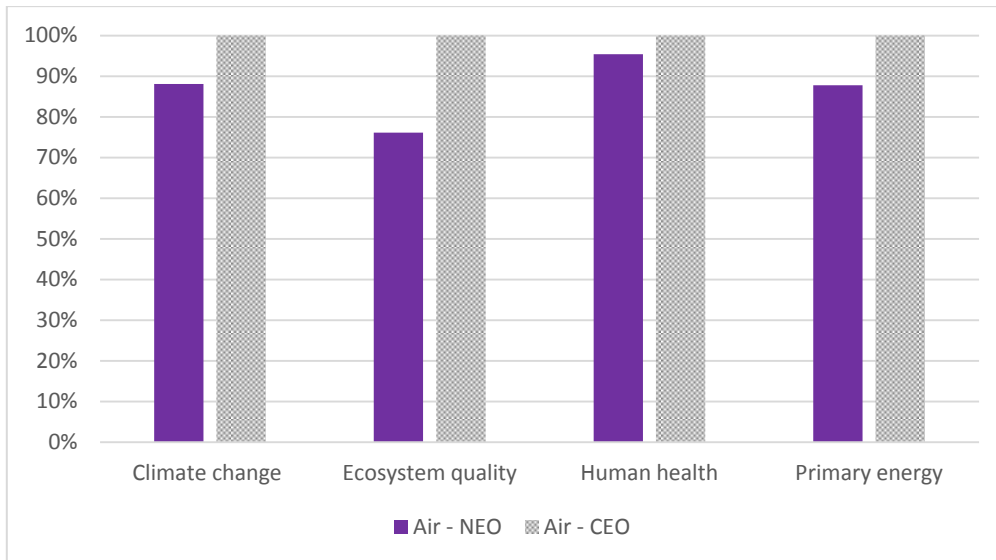


Figure 9 Air transportation: normalized comparison between CEO and NEO technologies

3.3.1.3 Car propulsion: comparison between diesel and gasoline engines

Figure 10 presents the environmental comparison of a Paris-Bordeaux trip using a diesel car versus a gasoline car. The diesel car has lower impacts—from 7 to 14% depending on the indicator. This can be explained by the use stage which has a lower impact on the diesel car (around 8% less). Indeed, diesel engines consume a smaller quantity of fuel compared to gasoline engines, while the volumetric impact of the two fuels are quite similar. These results based on an LCA are consistent to other studies (e.g. Platt et al., 2017) and opposed to the choice of catch-up of the diesel tax on that of gasoline put in place by the French government on the grounds of increased pollution from diesel engines compared to gasoline engines (Patel, 2013).

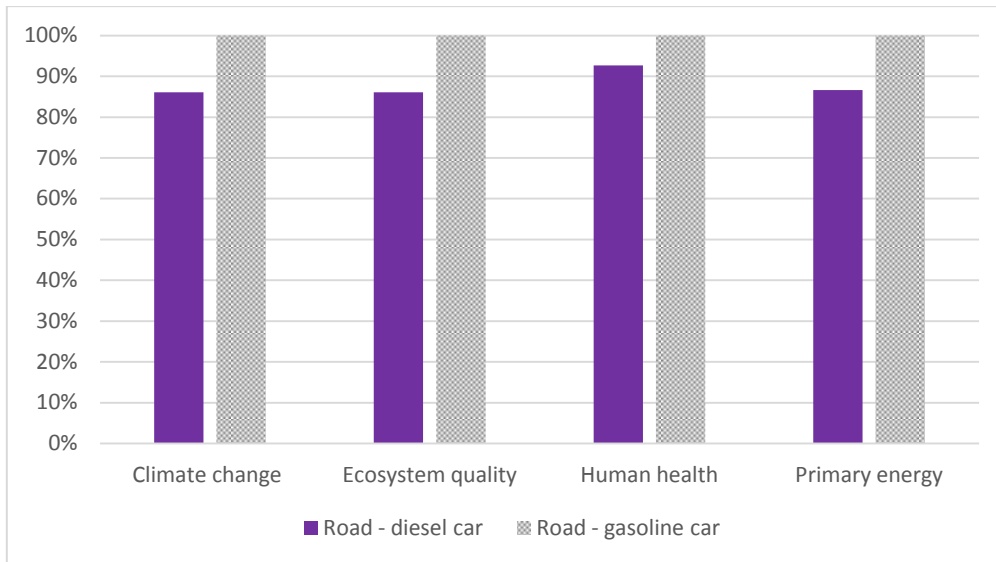


Figure 10 Car transportation: normalized comparison between diesel and gasoline engines

3.3.2 Focus on the HSR mode

3.3.2.1 Electricity mix

Figure 11 shows the climate change contribution of one pkt by train in different countries. As a simplification, the infrastructure and vehicle are considered identical in the different countries, as well as the occupancy rates, but the electricity mix varies. As steel is a major contributor to the infrastructural impacts, and that it represents a global market, this simplification should be acceptable. Results show that the climate change contribution depends highly on the electricity mix. The electricity mix with the lower carbon intensity comes from Norway while in Europe, among our selection, the highest intensity can be found in Germany. In this country, the high-speed train mode almost emits 60 gCO₂eq/pkt, while the same trip in a medium car (61% diesel, 39% gasoline) emits around 120 gCO₂eq/pkt: the HSR is still about 50% less emitting than the average car mode (de Bortoli and Christoforou, 2020). But the mode emits nearly twice more in Germany than in the countries where electricity has the lowest carbon intensity—Switzerland, Norway, and France.

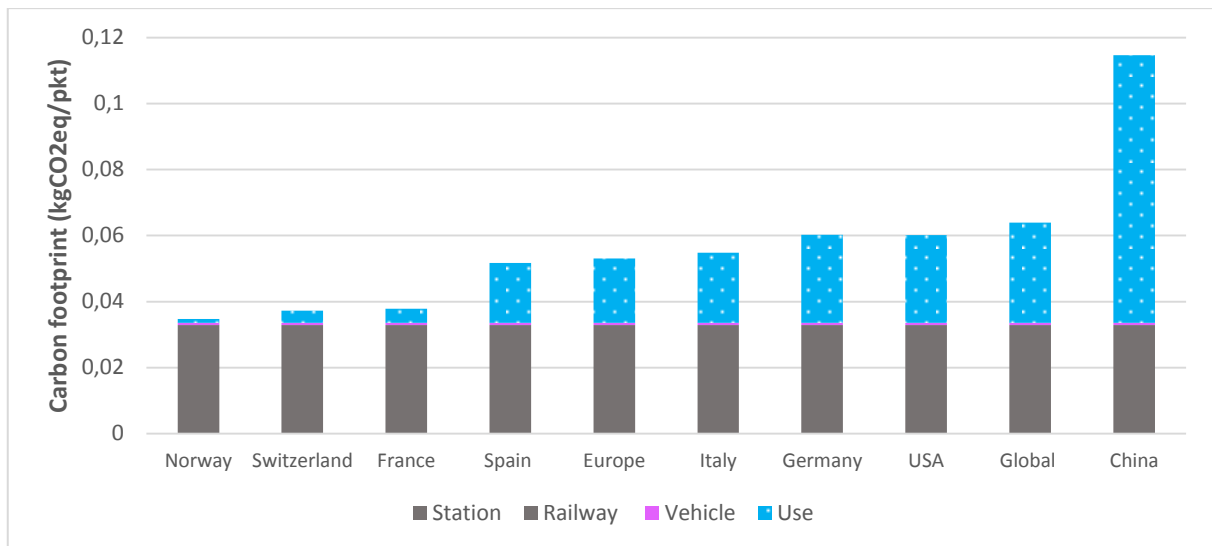


Figure 11 Carbon footprint to travel by duplex HSR in different geographical areas

3.3.2.2 Optimization of capacities: low-cost offer

One-quarter of the HSR trips between Paris and Bordeaux are bought to Ouigo, the low-cost operator (Provenzano, 2019), with a capacity of the trains jumping from 556 passengers per train in a classic Duplex train to 634 passengers for the low-cost Duplex configuration, by removing the dining car. Moreover, lower fares induce higher demands and finally occupancies: on average, Ouigo trains in France showed an 85% occupancy rate in 2017 according to the general director of the operator company “voyages SCNF” (Vérier, 2017). A higher occupancy rate means lower environmental impacts per pkt, *ceteris paribus*. According to the French transportation regulation agency, the Ouigo train occupancy rate was 8% higher than the standard train occupancy in 2018 (Autorité de régulation des transports, 2019). On the Paris-Bordeaux line, the Ouigo occupancy rate would thus be around $68 + 8 = 76\%$ in 2018. Figure 12 shows the climate change contribution of one pkt on standard Duplex and low-cost Duplex trains. With the low-cost mode, 12% of CO₂ equivalent is saved, falling from almost 38 gCO₂eq/pkt to 33 g.

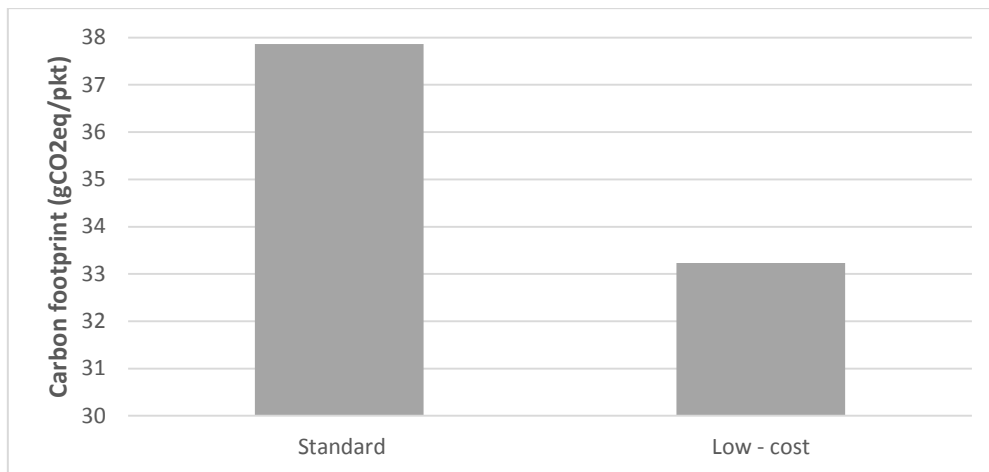


Figure 12 Carbon footprint to travel by HSR per pkt depending on the type of offer: standard Vs low-cost

Nevertheless, the induced trips due to attractive fares would account for 40% (Vérier, 2017). This potentially majors the final environmental impact of the line, by adding passenger trains on the railway, and potentially consuming some railway capacity to the detriment of rail freight, that is more environmentally friendly than trucks. Indeed, in France, only 15% of the national railway capacity is used for freight (Autorité de régulation des transports, 2019). The question of railway allocation to reduce overall environmental impacts of transportation, both from freight and passenger transportation, must be addressed holistically, including modal shifts from road and air. But despite the induced traffic due to this low-cost offer, a low-cost offer is socially beneficial as it allows low-income households to afford traveling.

3.3.2.3 Train's speed

A classic question to plan railway projects is the choice of the commercial speed. If the trend of recent decades has been to increase the travel speed, we can question the environmental cost of this decision. In fact, in the case of rail, infrastructural constraints—and thus the environmental cost of construction—are higher when speed increases. The maintenance requirements are also higher, as well as the impact of the maintenance. Finally, since the energy consumption of a train would vary according to the square of its speed (Kato et al., 2019), a higher commercial speed means higher environmental impacts too. In the absence of infrastructural data to rigorously compare the impact of

two railway projects with different commercial speeds, we will test the sensitivity of the impact to speed based on the operator’s data. According to LISEA, the concessionaire of the Tours-Bordeaux HSR, a "TGV"—i.e., a first-generation high-speed train—travels at 230 km per hour in France and consumes 16.5 kWh per kilometer. On the other hand, the new generation high-speed trains travels at 300 km per hour on average, and consumes 22.9 kWh per kilometer. Figure 13 shows that a higher electricity consumption in the case of the new HSR has a negligible impact, increasing by only 4% the carbon footprint per pkt. Nevertheless, in a country with a higher carbon-intensity electricity mix, a higher speed would be more detrimental. It should be noted that, while HSRs are said to be more impacting in terms of construction and maintenance, the environmental impacts for the respective processes in ecoinvent “*market for railway track, for a high-speed train, GLO*” and “*market for railway track, RoW*” show that the HSR infrastructure would be less impactful, e.g., emitting almost twice as fewer GHG emissions as the standard railway infrastructure over their life cycles. The ecoinvent models might benefit from an update.

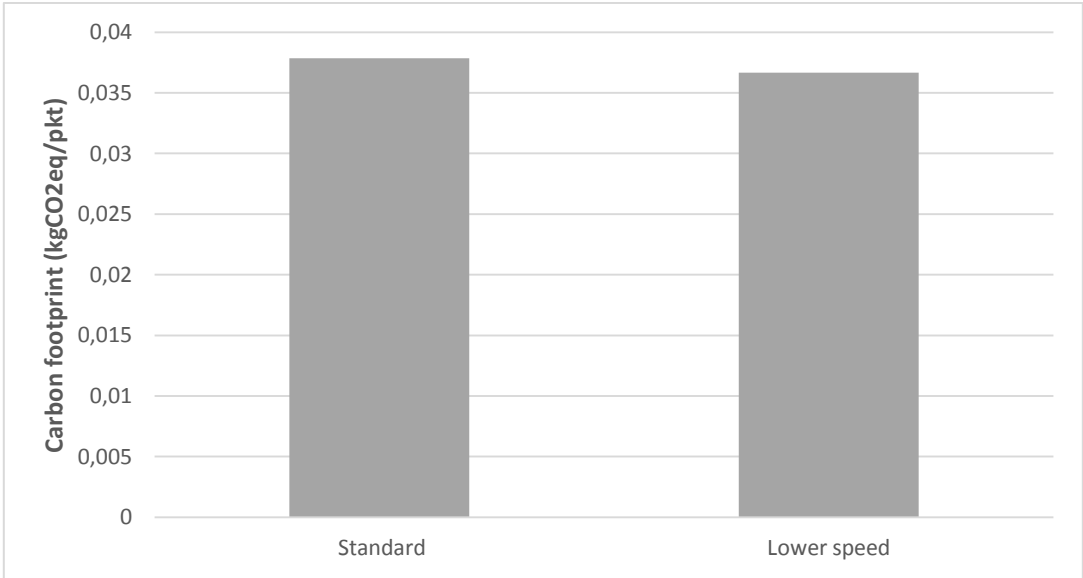


Figure 13 Carbon footprint per pkt depending on the train’s speed: standard (high-speed) vs lower speed.

3.4 CLCA: considering trip substitutions from air to rail

3.4.1 Business-as-usual scenario

Considering a steady annual modal shift, the respective distances between Paris and Bordeaux by plane (507 km) and by rail (497 km), and the carbon footprint per pkt resp. with and without the infrastructure by air and rail, we can estimate the time needed for the HSR project to become GHG neutral, i.e., the carbon payback period of the HSR project. We consider the GHG emitted to build the HSR section ($1.4 \cdot 10^9$ kgCO₂eq), the carbon footprint of the maintenance over 120 years ($1.1 \cdot 10^9$ kgCO₂eq) that we allocate every 30 years except at the EoL, and the benefits from the components' recycling and reuse ($-4.8 \cdot 10^8$ kgCO₂eq) that we allocate every 30 years (de Bortoli et al., 2020). Figure 14 shows how the initial carbon investment is repaid twice at the presumed end of life of the railway section (after 120 years). With the modal shifts observed these last few years, the net-zero target (including avoided emissions) would be reached around 60 years after construction. It should be noted that we slightly underestimate the impact of the infrastructure, since we only consider the high-speed section (340 km), the rest of the 497 km being traveled on a conventional rail network that was already built but still need maintenance. But consideration of the expected future reduction in the carbon footprint of the electricity mix in France could slightly shorten the carbon payback time. Nevertheless, this new HSR is considered to have made the rest of the rail traffic rise (Arraud, 2019). Whether this rise is due to induced trips or modal shifts from more impacting modes is the key question to understand the environmental consequence of this more complex effect.

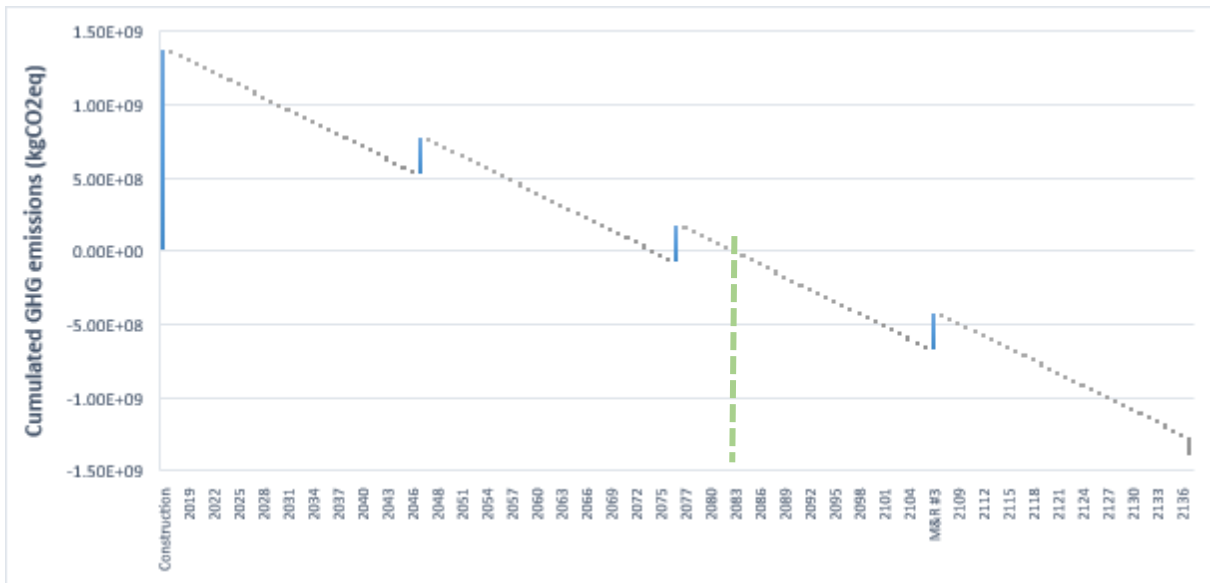


Figure 14 Net carbon footprint of the HSR project over the years, considering a 200 000-passenger modal shift between planes and rail

3.4.2 Short-haul flight ban scenario

France voted and published in its “Climate law” at the end of 2021 an article to ban domestic flights for which direct train trips of less than 2 hours and 30 minutes exist (Légifrance, 2021). This is the case on the Paris-Bordeaux route. Later voted by the European commission, if this short-haul flight ban was actually applied in 2022, the GHG emissions due to the HSR construction would be offset thanks to modal shifts within around 10 years (Figure 15). At the end of the life of the HSR, in 2137, the project would have avoided nearly 20 million tons of CO₂ equivalent, i.e., the annual emissions of 2.2 million French people considering their current lifestyle (Baude, 2022).

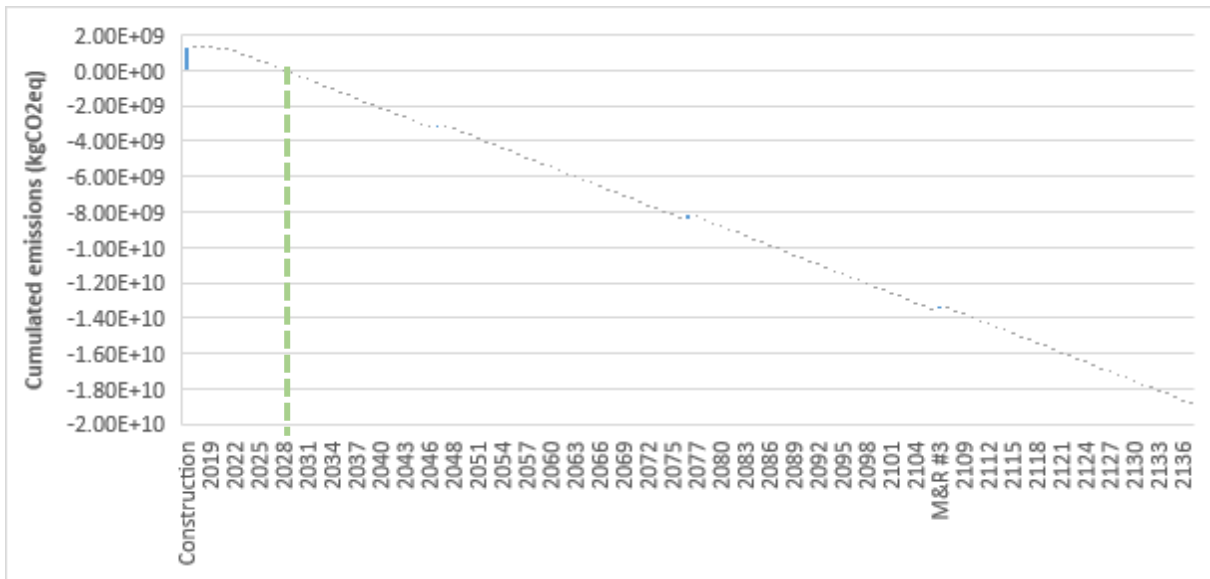


Figure 15 Net carbon footprint of the HSR over the years with a short-haul flight ban

4 Discussion

4.1 A necessary update of long-distance transportation assessments: comparison with former American LCA estimates

In Figure 16, we compare the carbon footprint and energy consumption of HSR, plane, car, and coach modes on the Paris-Bordeaux corridor with the seminal US results in Chester’s work. The HSR performance we consider is an average between “HSR Future WECC-2010 670” and “HSR Future WECC-2010 150” (Chester and Horvath, 2012a) to get approximately the same occupancy rate. The plane considered is the “Bombardier CS-300 ER” with 82 passengers (Chester and Horvath, 2012a) for the same reason. The French gasoline car mode is compared to the US conventional gasoline sedan and the French coach mode with the urban bus on peak for lack of more similar mode (Chester and Horvath, 2009).

In terms of energy consumption, the results are quite similar in France and the US for the HSR modes. Nevertheless, the French HSR mode emits twice as fewer GHG emissions as the US one in 2010. This could have been simply explained by the difference in the electricity mix, but consideration of contributions shows it is more complicated. In the American study, around 50% of the GHG emissions

and energy consumption come from the propulsion electricity. In our study, almost 90% of the GHG emissions come from the railway, while 70% of the energy is consumed due to the use stage and 30% due to the railway. The environmental profiles of the HSR mode in the two studies are thus very different. When comparing air modes, the estimates by Chester and Horvath were far lower than those found for Paris-Bordeaux. First, the impact estimated from the airport is higher in our study (50 gCO₂eq/pkt) than in the American study (8g), which may be explained by (1) high-traffic airports in the US, (2) infrastructural allocation discrepancy, (3) underestimates in the US model due to the use of EEIO-A instead of process-based LCA, and probable non-endogenized capital goods in the EEIO database used, what would not be suitable to assess airport impacts. The gasoline car in France is less impacting than in the American study, due to 30% lighter cars in France (IEA, 2019) and potentially a higher occupancy considered in the French model. Finally, a high-occupancy urban bus in the US consumes and emits more than a high-occupancy coach in France, maybe due to high consumptions and emissions in urban conditions, while a steady speed at 80 km/h is almost optimal in terms of consumption and thus emissions.

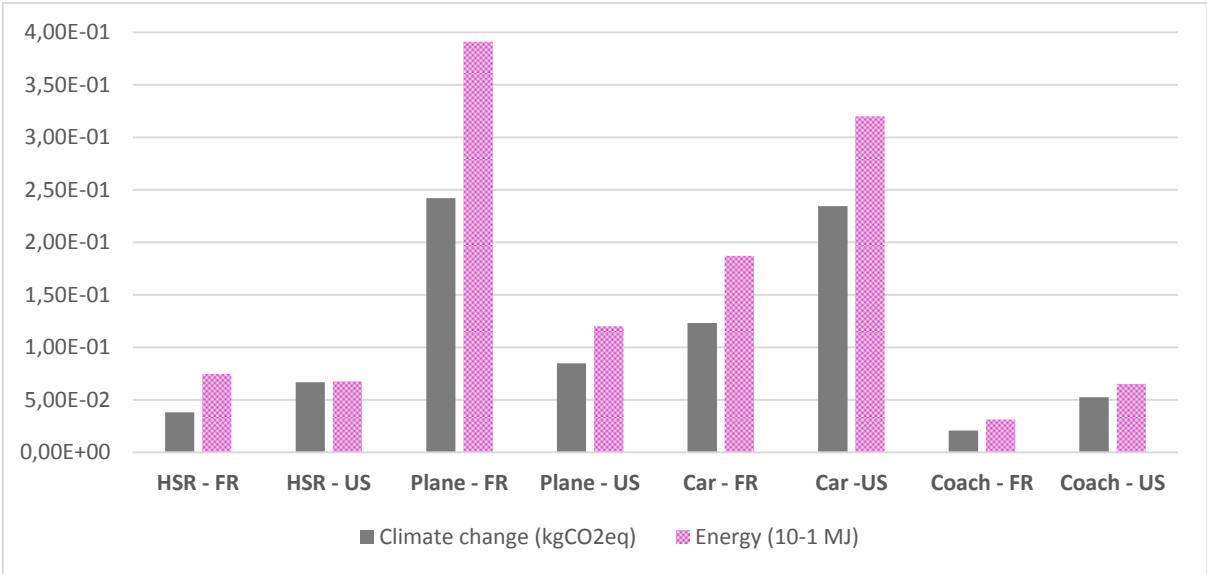


Figure 16 Comparison of the carbon footprint and energy consumption of HSR, plane, car, and coach modes on the Paris-Bordeaux corridor with the seminal US results by Chester

4.2 Considering the use stage is not enough: environmental transportation policy recommendations must rely on complete life cycle assessments

In France, the NF EN 16258 standard requires the calculation of energy consumed and GHG generated by transportation services, these impacts must be indicated on the services sold (train tickets, plane tickets, freight, etc.): it is the “French carbon label” for transportation services. However, according to the standard, these evaluations must be carried out on scopes 1 and 2: they only consider the use stage of the vehicles. Thus, the national operator indicates that the high-speed train’s GHG emissions account for 1.73 gCO₂eq/pkt and those of the Ouigo for 0.73 g. Our study highlighted the major contribution of the infrastructure to the carbon footprint of high-speed rail (90%), and thus, that the carbon footprint of the Paris-Bordeaux HSR is 20 higher than the one indicated on the French carbon label. As a conclusion, the NF EN 16258 standard inordinately favors the train to the detriment of other modes in the case of France. Finally, only an evaluation including scopes 1, 2 and 3 according to the GHG Protocol (WBCSD and WRI, 2011)—i.e., on a complete life cycle including the vehicle and infrastructure—will ensure an unbiased environmental comparison of transportation modes and sound policy recommendations.

4.3 Generalizing short-haul flight bans and investing in HSR infrastructure to reach net-zero?

A transportation mode can have highly variable environmental performances, in particular depending on the technology of the vehicles used, their filling rate, the type of energy they consume, and the impact of the infrastructure they use. Thus, saying that one mode is “bad for the environment” as frequently done in popular newspapers, or that one mode is absolutely worse than another, is wrong. Nevertheless, we can draw some general trends on the performances evaluated in several contexts and with several technologies, as done in this article. At the same occupancy rate, the carbon footprint of ICE cars is relatively stable geographically due to the major impact resulting from direct CO₂ emissions. We have shown that the carbon footprint of traveling by HSR highly varies too: our case study and scenario analyses showed a factor of 4, between a little more than 30 gCO₂eq/pkt (by combining high occupancies of low-cost offers and low carbon intensity of Norway’s electricity mix) and at least 120 gCO₂eq/pkt (with an electricity mix mainly based on coal). Overall, this is much lower

than emissions due to traveling by personal car, but it can compete with carpooling. Besides, we have shown that HSR can also be a decarbonization investment due to the air/rail competition and related modal shifts. An HSR project often generates a spontaneous trip substitution from planes to trains. In this case, the carbon neutrality of the project can be achieved after a relatively long period, such as the 60 years highlighted in our study. On the other hand, with a proactive public policy, the carbon neutrality of a large rail project can be achieved in a few years—less than 10 years in the case of the Tours-Bordeaux rail section with a short-haul flight ban. While the GHG balance will take longer to achieve in countries with high carbon-intensity electricity mixes, rail nevertheless seems to be an investment for a sustainable future to be coupled with adapted transportation policies to reduce the use of fossil fuels and reach net-zero. However, coach services can perform better than HSR if the vehicles reach a high occupancy rate, like on the Paris-Bordeaux corridor. This questions the affordability of fast long-distance travels on our narrow path to net-zero, and maybe the affordability of any long-distance mobility.

5 Conclusions

An integrated transportation LCA model has been developed for the main transportation modes of the Paris-Bordeaux corridor: High-Speed Rail (HSR), plane, and road modes—coach, personal car and carpooling. The model considered the vehicle (manufacturing, maintenance, EoL), its use stage, and the infrastructure for each mean of transportation assessed. ALCA results show that French modes globally rank as follows: coach > HSR > carpooling > private car > plane. Moreover, considering the passenger-trip traveled instead of the standard passenger-kilometer traveled as the functional unit does not substantially change this ranking, is more accurate, and shows comparative lower impacts of the road modes, as road distances are 15 to 19% higher than other modes' distances. The main contributor to the environmental impacts can be either the infrastructure, the use stage, or the vehicle amortization, depending on the mode and the indicator considered. Thus, transportation environmental policies must be based on integrated and multicriteria modal LCAs. Second, several SAs were conducted. They first globally show that technological progress leads to environmental improvements of the transportation

modes, from a few percent to 14% for the technologies studied. Also, the low-cost train offer on the Paris-Bordeaux corridor reduces the carbon footprint of the trips by 12% compared to the standard offer, due to a higher occupancy. But changing the train's commercial speed does not impact notably the environmental impact of the mode in France. Moreover, to give an international perspective, we calculated that electric HSR modes would emit between 33 and 120 gCO₂eq/pkt depending on the electricity mix considered and the occupancy. Third, considering a consequential approach, we calculated the carbon payback of the Paris-Bordeaux HSR project. Under a business-as-usual scenario, it is reached after 60 years thanks to flight trip substitutions. But with a short-haul flight ban, the carbon payback falls under 10 years. This demonstrates the importance of investing in HSR to decarbonize fast long-distance mobility, as high occupancy coaches are less emitting but much slower. Finally, these figures combined to the carbon paybacks calculated on the Paris-Bordeaux case study advocate for generalizing short-haul flight bans and investing in HSR infrastructure, if we decide to maintain long-distance mobility in our possible pathways toward net-zero. Otherwise, developing efficient coach services or even reducing long-distance mobility are better options to decarbonize fast enough our lifestyles to limit dreadful climate change consequences.

Declarations

The authors declare that they have no competing interests.

Availability of data and material

All the models are available on a repository online, and the excel spreadsheets are provided in the supplementary material, as well as complementary information, to ensure full reproducibility of the study.

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