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Environmental balance of the high speed rail network in Spain: A Life Cycle Assessment approach

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ABSTRACT

Spain has the world's second longest network of high speed rail lines built and in service. High-Speed Rail (HSR) is usually presented as a sustainable means of transport with huge potential to reduce greenhouse gas (GHG) emissions and energy consumption. The majority of studies carried out on this mode of transport have focused on analysing and estimating these savings in terms of network operation, but sometimes ignore the burdens associated with the construction of the infrastructure.

Based on the application of the Life Cycle Assessment (LCA) methodology, this work integrates into the analysis the construction and maintenance phases of the HSR lines in operation in Spain in 2016 together with their operation during that year, and verifies whether construction is justified in terms of reducing environmental impacts and energy consumption.

This article concludes that the construction of the Levante and Northern corridors is not justified in terms of energy savings and emission reductions due to the low demand and therefore the decision to build new HSR sections should be based on an analysis of demand so that only corridors with high transport demand are built. Furthermore, policymakers should consider other measures related to transport that would lead to considerable and rapid reductions in environmental impacts without the burden of building new infrastructures: e.g. reducing the demand for transport, increasing the occupation of private vehicles, promoting electric traction and the use of electricity from renewable sources.

1. Introduction

Spain has the world's second longest network of HSR lines (see Fig. 1), built and in service, surpassed only by China (European Court of Auditors, 2018). In relative terms, Spain is the world leader (Albalate & Bel, 2016). Popularly known as AVE (Alta Velocidad Española), Spanish High-Speed trains can travel at speeds of 250–300 km/h on international gauge lines of 1435 mm, electrified at 25 kV and 50 Hz, on long distance routes (Ferropedia, 2016). Currently, these high-speed services are provided under different commercial brands besides the AVE, such as ALVIA, AVANT and AV-City. In 2005, the state company RENFE was divided into two companies, Renfe Operadora and Adif. The former is currently the only transport operator of passengers and merchandise in the Spanish railway sector, and is responsible for the maintenance and construction of trains. The latter, on the other hand, is the public company in charge of the exploitation of the railway infrastructure, and therefore it is in charge of the construction and maintenance of the HSR lines.

The first HSR line of the AVE between Madrid and Seville was inaugurated on April 21, 1992; since then, the network has spread throughout the country. Currently, four main corridors connect the capital city of Spain, Madrid, with other peripheral regions: Madrid-Catalonia, Madrid-León (Northern corridor), Madrid-Levante and Madrid-Andalusia. In total, 2583 km[1] were already in service in 2016, and several more sections are currently under construction or projected. The majority of the AVE network is new construction with international gauge (1435 mm), in order to solve the barrier effect historically created by the fact that conventional trains in Spain circulate on Iberian gauge

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[1] 3402 km were already in operation at the end of 2019 (ADIF, 2020).

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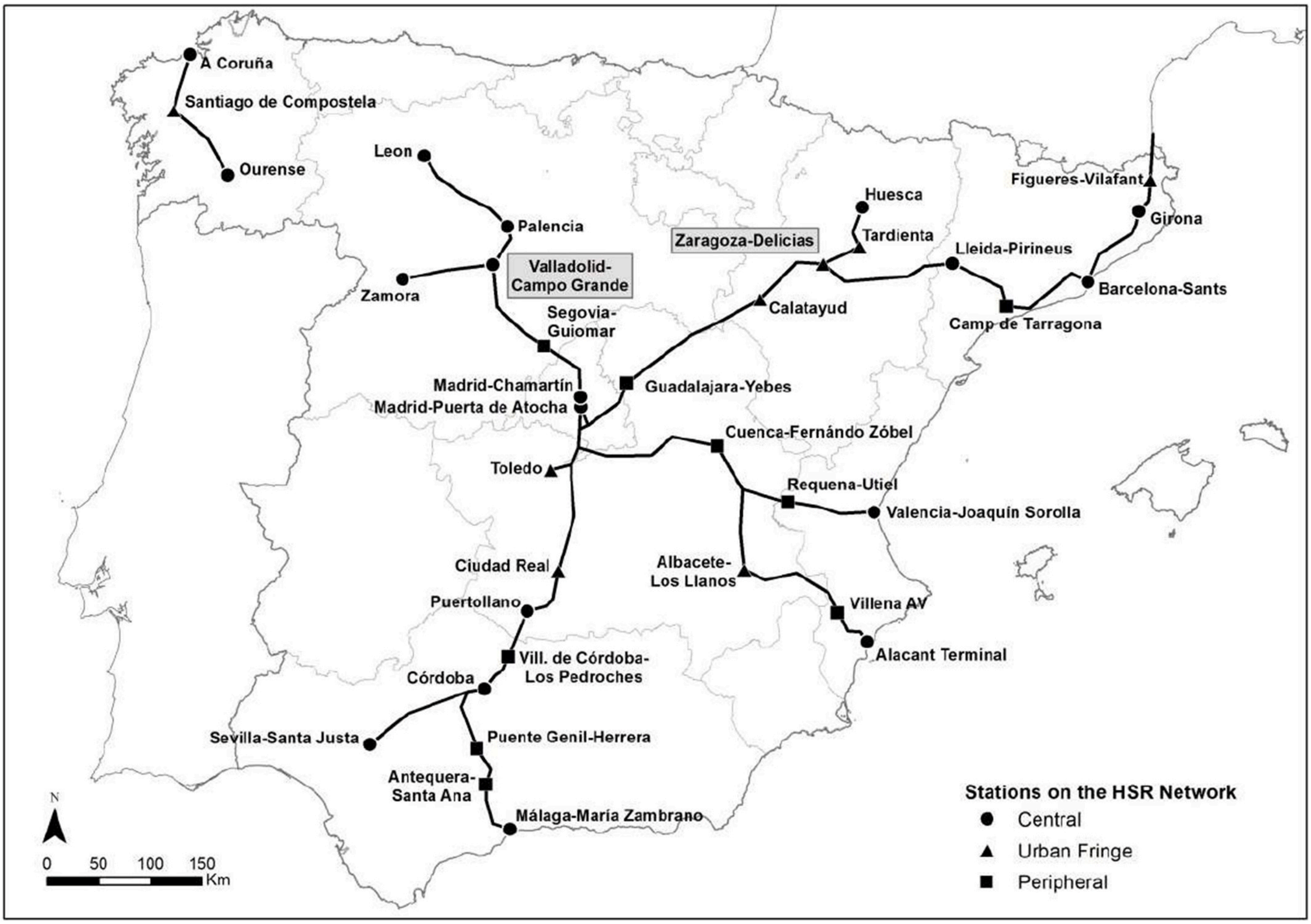

Fig. 1. Spanish HSR network map (2016). Source: Bellet Sanfeliu & Santos Ganges, 2016.

(1668 mm); variable-gauge trains that can travel on both networks are also used (Zembri & Libourel, 2017). There were twenty gauge changers in Spain in January 2017 (European Court of Auditors, 2018).

In general, investment in HSR can respond to several objectives, such as reducing the congestion of conventional networks, modernising the country, reducing oil dependency, improving interconnection with Europe, reducing travel times, or boosting territorial unity. These motivations directly affect the design of the network, its functionality and the effects caused on the environment (Albalate & Bel, 2016). The growing importance of environmental issues in public decision-making, especially in the transport sector, has forced the European Commission to insist on the need to apply a series of measures to limit the contribution of transport activity on climate change, calling for the strengthening of environmental assessments of any political initiative with major environmental impacts (European Commission, 2013).

In this context, HSR is usually presented as a sustainable means of transport with huge potential to achieve significant reductions of greenhouse gas (GHG) emissions and energy savings (California High-Speed Rail Authority, 2016; Jehanno et al., 2011). However, the alleged savings have been questioned by some authors arguing that some of these environmental assessments focus on analysing and estimating these savings in terms of network operation, and fail to account for the burdens associated with the construction, maintenance and dismantling of the infrastructure (Bueno et al., 2017; Chester & Horvath, 2010; Jones et al., 2016).

Given that any HSR project significantly alters the environment, a rigorous analysis of its environmental impacts and benefits becomes essential. In addition to the significant financial resources required, the construction of infrastructure megaprojects also require enormous amounts of natural resources such as concrete and steel, as well as terrain movements, resulting in a considerable consumption of energy and emission of pollutants into the atmosphere. Therefore, project evaluation requires a rigorous cost-benefit analysis to ensure social profitability (Flyvbjerg et al., 2013) and, from an environmental perspective, to account for environmental impacts from cradle to grave, i.e. including the construction phase of the infrastructure and of the rolling stock (Baron et al., 2011; Cour des Comptes, 2014).

The main objective of this article is to analyse the role of the Spanish HSR network in mitigating climate change and reducing energy consumption. Then, this work analyses the most significant environmental impacts and energy consumption associated with the construction, maintenance and operation of the Spanish HSR network under a 60-year lifetime horizon. This comprehensive analysis of the most important environmental burdens generated in the entire life cycle of the HSR network in Spain, are presented under the inventory of the following flows: CO_2eq (related to Global Warming); Cumulative Energy Demand;

Table 1
LCA studies about HSR projects.

Project	Country	Reference	km	Included in the study
California HSR (CAHSR)	USA	Chester and Horvath (2010)	1100	Infrastructure construction; operation
San Francisco-Anaheim (CAHSR)	USA	Chang and Kendall (2011)	725	Infrastructure construction
California HSR (CAHSR)	USA	Barnes E. (2014)	1100	Design/Construction phase; Use phase
Beijing-Shanghai	China	Yue et al. (2015)	1318	Vehicle manufacture, maintenance and disposal; infrastructure construction; operation
Turkish HSR	Turkey	Banar and Özdemir (2015)	888	Construction, maintenance and operation of railway infrastructure; production, maintenance and operation of train vehicles
Europabanan line	Sweden	Akerman J. (2011)	740	Construction, maintenance and operation of infrastructure; manufacturing and maintenance of vehicles
UK HS2	United Kingdom	Cornet et al. (2017)	556	Infrastructure construction; operation
Lisbon and Porto	Portugal	Jones et al. (2016)	297	Construction, maintenance, operation and disposal of railway infrastructure; production, maintenance, operation and disposal of train vehicles
Madrid-Barcelona	Spain	García Álvarez A. (2010)	621	Operation of the train
Y Basque	Spain	Bueno et al. (2017)	180	Infrastructure construction; operation

PM_{10} (related to Human toxicity); SO_2 (Acidification, Human toxicity, Photochemical oxidation); NO_X (Acidification, Eutrophication, Human toxicity) and NMVOC (Ecotoxicity, Human toxicity, Photochemical oxidation, Ozone layer depletion).[2] The geographic scope of the study is the entire network[3] in operation in 2016, which extends over 2500 km along four main corridors.

After a brief introduction and description of the background of the project in section 1, section 2 presents the methodological basis for the study of the LCA of the HSR network in Spain. In section 3 the case study is presented: (1) the data and information necessary for the study is detailed (section 3.1); (2) the modelling approach for the environmental analysis is presented (section 3.2); (3) the characteristics and properties of the baseline scenario and sensitivity analysis are described (section 3.3). Section 4 and 5 presents and discusses the results, respectively. Finally, section 6 contains the conclusions drawn from this work.

2. Methodology

The analysis carried out in this work is based on the Life Cycle Assessment (LCA) methodology. This methodological tool is used to assess environmental impacts associated with all the stages of the life-cycle of a product or service, from raw material extraction to the processing of materials, infrastructure construction, use, maintenance and end-of-life treatments, based on a "cradle-to-grave" approach. LCA relies on the collection and analysis of all inputs (energy and materials consumption) and outputs (emissions, waste and by-products) of the system under study. The LCA of a product or service is often based on the use of exhaustive databases that compile the inventory of the life cycle of other products and processes already analysed.

Several studies have performed the LCA of HSR projects (Table 1). Chester and Horvath (2010) conducted a study on the California high speed line (CAHSR, 1100 km), currently under construction, estimating that between six to eight years would be needed in order to balance the carbon footprint of the construction of the infrastructure, as long as the occupancy rate of the HSR remained higher than the rest of the modes of transportation. Chang and Kendall (2011) raised similar conclusions in their analysis of the San Francisco-Anaheim line (CAHSR, 725 km), considering that it would take six years to amortise GHG emissions, although more than 20 years might be needed if occupancy rates were lower than expected. Barnes (2014) also discussed the California line and showed that replacing some of the cement with fly ash in the production of concrete and the use of renewable energy for the HSR are the most feasible options for the CAHSR to be more efficient in the fight against climate change. Yue et al. (2015) performed the LCA on China's Beijing-Shanghai HSR, concluding that the operation phase of the HSR has a more significant contribution on the environment than the construction phase of its infrastructure, and that overall impacts can be substantially reduced if the consumption of coal to provide power is limited, the use of trains is optimised, fly ash is used, or if the construction of bridges and tunnels is limited. Banar and Özdemir (2015) performed the LCA of the Turkish HSR network determining that, of all the environmental burdens, 58% correspond to the construction phase and 42% to the operation phase.

Different works have carried out the LCA of HSR lines in Europe. Akerman (2011) studied the Swedish Europabanan line from an LCA perspective, determining that total emissions could be reduced by 0.55 million tonnes of CO_2 equivalent per year. Cornet et al. (2017) analysed the carbon footprint of the largest transport infrastructure project of the century in the United Kingdom, the HSR that will link London with different cities in the north (HS2), and argued that it will not contribute to a net reduction of CO_2 emissions.

Jones et al. (2016) analysed the total environmental impacts of the future Portuguese HSR line between Lisbon and Porto, finding that the operation of the HSR is the largest contributor to the total atmospheric emissions of the project (69% of CO_2, 76% of SO_2, 82% of PM_{10}), while the rest would correspond to burdens associated with the construction, maintenance and end-of-life treatment of the infrastructure.

In regards to the AVE network in Spain, to our knowledge no study has been conducted considering all the environmental burdens associated with the network's complete life-cycle. García Álvarez (2010) concluded that each passenger on the Madrid-Barcelona HSR line could contribute to an emissions reduction of 30 kg of CO_2, however failing to account for the infrastructure's construction burdens. Bueno et al. (2017), on the other hand, performed a limited environmental LCA of a new HSR line in the Basque Country, to be connected to the AVE network, that included the construction and maintenance phase of the infrastructure. They concluded that CO_2 emissions linked to infrastructure construction and maintenance would never be compensated, and that it would take 55 years of operation before net energy savings started.

Cuenot (2016) carried out for the UIC (International Union of

[2] This analysis focuses on six main environmental indicators, namely GHG emissions, energy consumption, PM_{10}, SO_2, NO_X and NMVOC; however the reader should bear in mind that other environmental dimensions are also affected by the HSR construction and operation such as: habitat fragmentation, impacts on flora and fauna (affecting biodiversity), occupation of fertile land, landscape and visual impact, noise and vibrations, etc. In fact, impacts are generally similar along road and railways (Cour des Comptes, 2014; Dorsey et al. (2015); Jehanno et al., 2011). See Data in Brief.

[3] The section in Galicia is left out of this study because it does not meet the conditions of high speed when operating on Iberian gauge (Leboeuf M., 2018).

Railways) a synthesis of the works on the main methodologies for the calculation of the carbon footprint of different railway lines, concluding that the most precise, transparent work, and with the best guarantees of offering the most reliable results, is that performed by Tuchschmid et al. (2011). This is the main reason why in this paper we follow the approach employed by Tuchschmid et al. (2011) for the calculations of the construction burdens of the Spanish HSR network. The environmental impact coefficients obtained in this study are collected in the Data in Brief.

3. Case study

3.1. Data

Based on the application of the Life Cycle Assessment (LCA) methodology, this work integrates into the analysis the construction and maintenance phases of the HSR lines in operation in Spain in 2016 together with their operation during that year, and verifies whether construction is justified in terms of reducing environmental impacts and energy consumption.

The analysis of the environmental burdens associated with the construction of railway infrastructure requires, on the one hand, a precise description of the network (including a detailed inventory of all the materials used) and, on the other, information on the transport service provided by the infrastructure –measured in terms of passengers-km – and the modal shifts involved.

The functional unit for our analysis is the passenger transport service provided by the entire HSR network in one year of operation. For simplicity, the scenarios we examine assume that transport conditions remain unchanged during the infrastructure lifetime: annual passenger transport on the network, passengers shifted from other modes of transport, and the environmental impacts associated with both the operation of the HSR and the operation of other modes of transport (car, bus, conventional train and airplane). Freight transport is not included in this analysis, since the Spanish HSR network was designed exclusively for the transport of passengers (Bel, 2010).[4]

3.1.1. Layout of the AVE network

A detailed diagram of each branch of the Spanish HSR network is essential for the calculation of the environmental burdens of its construction and maintenance. This includes maps, routes, infrastructures, measurements, characteristics, etc. Most of the information publicly available consists of partial diagrams that do not allow an adequate characterisation. To remedy this, we conducted an exhaustive review of the routes through satellite and aerial images using Google Earth application, making it possible to characterise the infrastructure in detail[5] (Summary in Table 2).

The first line of the Spanish AVE network between Madrid and Seville was inaugurated on 21 April 1992; since then, the network has spread throughout the country following a radial design around Madrid (Bel, 2010). Currently, there are four main corridors that connect different regions with the state capital (see Fig. 1). These four corridors are: Madrid-Catalonia, Madrid-León (Northern corridor), Madrid-Levante and Madrid-Andalusia. In total, 2583 km were in service in the year 2016.

3.1.2. Passenger transport demand

An important problem that had to be addressed in this work was the absence of detailed quantitative data of HSR passengers and their corresponding travelling distances, essential to adequately assess the operation phase of the infrastructure.

Renfe Operadora, the only passenger operator in the Spanish railway sector, does not provide annual transport data –measured in pkm– on the Spanish HSR corridors, and only data for some specific connections are available (see Table 3) (Fundación de los ferrocarriles españoles, 2017). Every year, conventional long-distance passenger statistics are published without any reference to travelled distances, and with no specific reference to HSR passenger data. The only HSR passenger information available was provided by Galán et al. (2017), presenting data for passenger arrivals and departures for every HSR station in 2015. Similar information for the year 2016 was provided by García (2017). These sources, however, lack crucial information about the distances travelled. This information, however, allows the density of transport to be delimited throughout the infrastructure. For this purpose, a Python algorithm was programmed, which calculated a series of randomly generated matrices of passenger movements between stations compatible with the information provided by Galán et al. (2017) and García (2017), also considering the data provided for some specific connections by Fundación de los ferrocarriles españoles (2017).

For any HSR line with n stations, characterised by its distance matrix (an $n \times n$ matrix with the distances between the n stations) and a vector with the annual travellers arriving/departing from each station, the algorithm allowed the random generation of an $n \times n$ matrix of movements among stations complying with the boundary conditions. Multiple executions (10^5) of the algorithm provided probabilities for passenger transport on the line under review that could be statistically treated.

Table 4 contains the estimation of transport for each of the four corridors of the Spanish HSR in 2016. For the Catalonia corridor, for example, while 11.01 million passenger journeys were recorded in 2016, 10^5 possible distributions of those movements compatible with the available record of passengers in stations provide a transport estimation with a mean value of 5083 million passenger-km, and a standard deviation of 85.7 million passenger-km. This estimation is equivalent to a density of transport of 5.76 million passengers annually over the complete infrastructure, and implies that the average journey on the corridor is 462 km. For the whole Spanish network (2583 km), the average journey is 391 km and density of transport is equivalent to 4.17 million passengers on the complete network. Figures of the Data in Brief show the histograms for the transport calculation of 10^5 runs of the algorithm for each corridor.

3.2. Modelling approach

The net Environmental Impact (EI) balance of a new HSR infrastructure is provided by the comparison of the environmental impacts of all modes of transport in two alternative scenarios, one without the HSR, and the other with the HSR in service. Therefore, the net EI of constructing and operating a new HSR for a specific environmental parameter, such as CO_2eq or NO_x emissions, is mathematically represented as:

$$NetEI(t) = EI_{withHSR} - EI_{withoutHSR} \quad [1]$$

Nevertheless, the calculation of the net EI does not require the explicit calculation of both transport scenarios, with and without the HSR line in operation, but just the differences between them: i.e. the impacts linked to the HSR transport of passengers in the scenario with HSR, and the impacts linked to the transport of passengers in other modes without the HSR that are shifted to the HSR when it is operative.

$$NetEI = EI_{transport\ in\ HSR} - EI_{shifted\ transport\ from\ other\ modes\ to\ HSR} \quad [2]$$

The modal shift of passengers from other more polluting modes of transport to the HSR is an environmental benefit of a HSR line. However,

[4] It can be argued that the construction of a HSR network for passengers may release space for freight on the conventional network and that this effect should be taken into account. However, we find this unnecessary given the conventional network's current idle capacity.

[5] The detailed description of the complete AVE network layout is available in the files attached to the Data in Brief document.

Table 2
Details of the Spanish HSR network in 2016.

Corridor	km	Tunnels (A)	%	Bridges & viaducts (B)	%	Total (A + B)	Total % (A + B)
Andalusia	646.8	46.5	7.2%	46.5	7.2%	93.0	14.4%
Northern	445.2	46.7	10.5%	20.9	4.7%	67.6	15.2%
Catalonia	883.0	95.3	10.8%	66.3	7.5%	161.6	18.3%
Levante	607.9	59.2	9.7%	36.9	6.1%	96.1	15.8%
Total	2582.9	247.8	9.6%	170.5	6.6%	418.4	16.2%

Table 3
Passenger traffic in specific connections of the Spanish HSR network in 2016, provided by Fundación de los ferrocarriles españoles (2017).

Corridor	Connection	Annual passengers, published (in thousands)	Annual passengers, adjusted by Python algorithm (in thousands)
Andalusia	Madrid-Córdoba	880	884
	Madrid-Sevilla	2545	2556
	Madrid-Málaga	1745	1751
Northern corridor	Madrid-Valladolid	390	391
	Madrid-León, -Ourense, -Oviedo	939	940
Catalonia	Madrid-Zaragoza	1373	1384
	Madrid-Lleida	280	282
	Madrid-Tarragona	335	338
	Madrid-Barcelona	3875	3905
	Zaragoza-Barcelona	787	793
Levante	Madrid-Albacete	328	313
	Madrid-Alicante	1394	1330
	Madrid-Valencia	2336	2227

it needs to be balanced with the environmental impacts associated with its construction and to consider the induced transport. So, we calculate the net environmental impacts of any HSR line considering the phases of construction, maintenance and operation, and subtracting from it the environmental burdens linked to the transportation of passengers in other modes of transport that are shifted to the HSR. Mathematically, this can be expressed as:

$$NetEI = \sum EI^{HSR}_{Construction \wedge Maintenance} + \sum EI^{HSR}_{Operation} - \sum_i EI^{i}_{i \to HSR} \quad [3]$$

Where, i denotes the alternative passenger modes of transport to the HSR, i.e. aeroplane, conventional train, bus and private car. As the functional unit for the LCA is the transport service provided by the infrastructure of the HSR in a year of operation, in this calculation the environmental burdens associated with construction and maintenance of the infrastructure are evenly distributed along the considered lifetime horizon (60 years) in order to provide impact indicators in a yearly basis (Table 5).

According to equation [3], any HSR project will provide a net environmental benefit in a particular category if the annual environmental burdens associated to its construction, maintenance and operation are lower than the avoided burdens that transport shifted from other modes to the HSR would produce in a scenario without the HSR in operation (i.e. Net EI < 0). Consequently, net environmental benefits from any HSR line in a given category critically depend on the ability to attract substantial amounts of traffic from other modes of transport with higher emissions and energy intensity levels. In the following subsections, we examine the environmental burdens associated with the construction, maintenance and operation phases of the infrastructure (section 3.2.1) and the environmental savings produced by shifting passengers from other more polluting modes of transport to the HSR (section 3.2.2).

3.2.1. Environmental loads of the construction, maintenance and operation of the HSR

Environmental impacts linked to the construction, maintenance and operation of the HSR infrastructure were calculated as:

$$EI_{HSR} = \sum EI^{HSR}_{Construction \wedge Maintenance} + \sum EI^{HSR}_{Operation} \quad [4]$$

The Spanish HSR network had a total length of 2583 km for the four corridors built and in operation in 2016. Out of the total railway network, 170 km (6.6%) correspond to viaducts and bridges, and 248 km (9.6%) correspond to tunnels, with the independent tunnels of Guadarrama standing out, with a length of 28 km each.

The environmental impacts associated with the construction and maintenance of the HSR network were calculated applying to each item

Table 4
Estimation of annual transport and density of transport for each corridor in 2016.

Corridor	Length (km)	Passenger displacements (million)	Transport (million pkm, mean)	Transport (million pkm, standard deviation)	Length of average displacement (km)	Equivalent passengers over the complete infrastructure (million, mean)	Equivalent passengers over the complete infrastructure (million, standard deviation)
Andalusia	647	9.32	3467	75.05	355	5.36	0.116
Northern	445	3.01	583	1.3	194	1.31	0.048
Catalonia	883	11.01	5083	85.7	462	5.76	0.097
Levante	608	4.23	1650	1.8	390	2.71	0.003
Total	2583	27.57	10 783		391	4.17	

Table 5
Annual environmental impact linked to construction and maintenance of the four corridors of the Spanish HSR network.

	CO_2	CED	PM_{10}	SO_2	NO_X	NMVOC
	$t \cdot km^{-1} \cdot y^{-1}$	$TJ \cdot km^{-1} \cdot y^{-1}$	$t \cdot km^{-1} \cdot y^{-1}$	$t \cdot km^{-1} \cdot y^{-1}$	$t \cdot km^{-1} \cdot y^{-1}$	$t \cdot km^{-1} \cdot y^{-1}$
Andalusia corridor (647 km)	64.846	0.885	0.102	0.164	0.254	0.041
Northern corridor (445 km)	77.775	0.971	0.106	0.171	0.263	0.042
Catalonia corridor (883 km)	83.593	1.051	0.117	0.183	0.289	0.047
Levante corridor (608 km)	76.212	0.993	0.112	0.178	0.279	0.045

of the infrastructure (bridge, tunnel, etc.) the corresponding impact coefficient following Tuchschmid et al. (2011). All the coefficients for each infrastructure's element and impact category are contained in the Data in Brief. As some infrastructure elements, such as rail for tracks and sleepers, have a 30 years lifespan, some construction burdens will occur after half the lifetime of the infrastructure has elapsed. Most maintenance burdens occur throughout the infrastructure lifespan, but our calculation considers them together with all construction burdens and assumes that they occur in the construction phase, for simplification. This deviation from real behaviour implies an overestimation of the years of operation needed for compensation (Tables 9 and 10). This error, however, is very limited, as total maintenance burdens are only 1% of construction burdens (Tuchschmid et al., 2011).

Table 5 provides the total environmental impact in each parameter linked to the construction and maintenance of the Spanish HSR network, subdivided by the corridors. These impacts are quantified in terms of annual tonnes or terajoules per kilometre of network.

The environmental impacts are similar for all the corridors when measured in relative terms. Although the Catalonia corridor presents higher relative impacts and the Andalusia corridor lower relative impacts, deviations from the average for each corridor are below 15% in CO_2 emissions, 10% for CED, and below 7% for PM_{10}, NO_X and NMVOC emissions. The average for CO_2 emissions (75.85 t $km^{-1}\cdot y^{-1}$) is slightly higher than the range provided by Tuchschmid et al. (2011) for conventional networks in some countries (from 38.8 to 71 t $km^{-1}\cdot y^{-1}$), but slightly lower than the range provided by Baron et al. (2011) for some HSR networks (from 79 to 270 t $km^{-1}\cdot y^{-1}$).

The environmental loads associated with the operation of the HSR were obtained from the Ecoinvent database, version 3.7, processed with the open LCA software (see Table 6). As the Ecoinvent database includes the environmental burdens linked to the construction and maintenance of the transport infrastructures and vehicles (roads and railways, cars, bus, conventional trains, aeroplanes, etc.), the construction and maintenance burdens of the HSR were previously removed from Ecoinvent results in order to avoid double counting.

The same environmental parameters proposed by Tuchschmid et al. (2011) were obtained from the Ecoinvent v3.7: Cumulative Energy Demand (CED), as an indicator of primary energy consumption; Carbon dioxide equivalent emissions (CO_2eq), as an indicator of global warming; and Particulate matter (PM_{10}), Sulphur dioxide (SO_2), Non-methane volatile organic compounds (NMVOC) and Nitrogen oxides (NO_X) emissions as indicators of potentially severe consequences to human health and ecosystems.

3.2.2. Environmental loads associated with shifted transport to the HSR

Avoided environmental impacts linked to all the transport shifted from other modes to the HSR, were calculated as:

$$EI_{Avoided} = \sum_i EI^i_{i \rightarrow HSR} \quad [5]$$

The net environmental balance of any HSR infrastructure benefits from any environmental saving that may arise from its implementation, mainly due to the passengers shifted from other more polluting modes of transport. Betancor and Llobet (2015) estimated the origin of the passengers travelling through each of the HSR line sections, specifying percentages of shifted (and induced) traffic. This information is contained in Table 7.

For any specific category, the avoided environmental impact linked to transport shifted from any mode in a section of the corridor to the HSR, is calculated by multiplying the corresponding transport density in the corridor (Table 4, measured in pkm$\cdot y^{-1}$) by the percentage for the shifted transport for that mode (Table 7) and by the corresponding impact category coefficient (Table 6; e.g. 159.37 $gCO_2eq\cdot p^{-1}\cdot km^{-1}$ for avoided CO_2eq emissions due to shifted air transport).

3.3. Description of scenarios

All the scenarios examined in this paper (see Table 8) consider a fixed technological and socioeconomic context during the entire infrastructure's life cycle. This implies that important variables, such as transport demand, diverted traffic, vehicle occupation rates, energy intensities or electricity mix were considered invariable. The calculation period is established in 60 years, as it is the expected useful lifetime of most of the components of a railway network (Stripple & Uppenberg, 2010).

The Baseline Scenario that serves as a reference for this LCA departs from the following assumptions: 56% of the private vehicles in Spain are diesel cars, and 44% are petrol cars[6]; shifted transport from other modes to HSR follows Betancor and Llobet (2015); passenger transport in each corridor of the HSR infrastructure in every year of the lifetime according to section 3.2.2 (Table 4); electricity mix for Spain in 2017 (Ecoinvent v3.7) and, occupancy rate in private vehicles is 1.68 passengers per vehicle following the survey carried out by the S.G de Explotación in 2014 (Ministerio de Transportes, Movilidad y Agenda Urbana, 2018).

In order to respond to the uncertainty of some of the variables considered, five sensitivity scenarios were examined (S1, S2, S3, S4, S5). In each case, one of the variables assumed in the Baseline Scenario was modified in order to analyse its influence on the results. These scenarios do not have any influence on the construction and maintenance burdens, but they may have an impact on the burdens associated with the shifted transport from other modes and the operation of the HSR.

The first two scenarios analyse the influence of an increment of the vehicle occupancy rate. The S1 scenario assumes an occupancy rate of 2.52 passengers per vehicle, as estimated for Spain in 2020 by Adra et al. (2010). The second scenario (S2) analyses the influence of new mobility policies that institutions may promote in terms of vehicle sharing, specifically if the average occupancy rate of private vehicles were to double, 3.36 passengers per vehicle. The third scenario (S3) examines the influence of transport demand assuming that current demand doubles on all corridors. The fourth scenario (S4) explores the influence of transport electrification assuming that all private cars are electric. Finally, the fifth scenario (S5) considers an all-electric car scenario with an average occupancy rate of 3.36 passengers per vehicle, and cars, conventional trains and HSR powered with a 100% renewable electricity mix.

4. Results

This section presents the results obtained with the modelling carried out for the Baseline Scenario, as well as for each of the five alternative scenarios proposed for sensitivity analysis.

4.1. Baseline scenario

Detailed information about the environmental balance of each corridor of the AVE network is contained in the Data in Brief. Table 9 summarises the main results in the Baseline Scenario for the Catalonia corridor, which supports 47% of total transport on the network (see Table 4). Table 10 summarises the main results in the Baseline Scenario for the whole Spanish HSR network.

A negative result in the net impact balance corresponds to a benefit in environmental terms. According to equation [3], a negative result implies that environmental burdens associated with the construction, maintenance and the operation of the HSR network are counterbalanced by the burdens avoided which are linked to the transport of those passengers that are shifted from other modes of transport to HSR.

As most of the impacts linked to the construction and maintenance of the infrastructure occur before the line is put into operation, any new

[6] Statistical data of the DGT (DGT, 2018) about the park of vehicles of Spain in 2018.

Table 6
Impact category coefficients for modes of transport. Own elaboration based on Ecoinvent v3.7 (S1, S2, S3, S4, S5 refer to sensitivity analysis scenarios).

TRANSPORT MODE	Global Warming $gCO_2eq \cdot pkm^{-1}$	CED $MJ \cdot pkm^{-1}$	PM_{10} $g \cdot pkm^{-1}$	SO_2 $g \cdot pkm^{-1}$	NO_X $g \cdot pkm^{-1}$	NMVOC $g \cdot pkm^{-1}$
passenger aircraft, very short haul	159.37	2.41	0.04	0.22	0.72	0.10
passenger coach	49.44	0.82	0.03	0.05	0.47	0.05
passenger car mix (56% diesel, 44% petrol, 1,68 p/v)	187.39	2.86	0.11	0.31	0.46	0.17
passenger car mix (56% diesel, 44% petrol, 2,52 p/v) (S1)	124.92	1.91	0.07	0.21	0.31	0.11
passenger car mix (56% diesel, 44% petrol, 3,36 p/v) (S2)	93.69	1.43	0.05	0.16	0.23	0.08
electric passenger car, Spanish electricity mix, 1,68 p/v (S4)	92.74	1.99	0.12	0.36	0.29	0.07
electric passenger car, 100% renewable electricity mix, 3,36 p/v (S5)	28.15	0.70	0.05	0.09	0.09	0.03
passenger train, Spanish electricity mix	54.65	1.18	0.05	0.19	0.31	0.03
passenger train, 100% renewable electricity mix (S5)	27.12	0.73	0.04	0.05	0.22	0.03
passenger train, high-speed, Spanish electricity mix, (HSR infrastructure excluded)	32.91	0.86	0.03	0.15	0.10	0.01
passenger train, high-speed, 100% renewable electricity mix (HSR infrastructure excluded) (S5)	6.42	0.43	0.02	0.02	0.02	0.00

Table 7
Shifted transport from other modes of transport to the HSR. Own elaboration based on Betancor and Llobet (2015).

	LINE SECTION					
	Madrid-Barcelona	Madrid-Zaragoza Zaragoza-Barcelona	Rest of Catalonia corridor	Andalusia corridor	Levante corridor	Northern corridor
From airplane	43%	2.67%	0%	45%	45%	0%
From bus	3.25%	1.33%	0%	2%	2%	5%
From car	16.07%	20%	45%	12%	15%	30%
From train	27.29%	49.33%	45%	26%	30%	35%
New demand	10.39%	26.67%	10%	15%	8%	30%

Table 8
Description of the scenarios.

	Passenger car occupancy rate (persons per vehicle)	HSR demand	Passenger car	Electricity mix
Baseline Scenario	1.68	Baseline Scenario	56% diesel car, 44% petrol car	Spain 2017
S1	2.52	Baseline Scenario	56% diesel car, 44% petrol car	Spain 2017
S2	3.36	Baseline Scenario	56% diesel car, 44% petrol car	Spain 2017
S3	1.68	100% higher	56% diesel car, 44% petrol car	Spain 2017
S4	1.68	Baseline Scenario	Electric car	Spain 2017
S5	3.36	Baseline Scenario	Electric car	100% renewable

HSR network will start with an environmental deficit that will be compensated after a number of years of operation, if the operation impacts are less than the impacts avoided in other modes of transport. The number of years of operation needed to compensate that initial deficit will vary for each impact category. The exact moment in which these compensations begin is crucial information, especially regarding national objectives related to energy savings and emissions reduction deadlines. The years needed to provide such compensation in each impact category are provided in the last rows of Tables 9 and 10.

As can be observed in Table 10, the net environmental balance for the entire AVE network is negative in all impact categories, except for PM_{10} and SO_2 emissions. CO_2eq, CED, NO_X and NMVOC impact categories need between 9 and 16 years to reach compensation, while SO_2 emissions need 62 years, and PM_{10} emissions (87 years) will not be compensated during the useful life of the infrastructure.

However, these global results vary significantly from corridor to corridor (See Data in Brief). All the corridors connect the periphery of the peninsula with Madrid in a radial design, but with very different conditions regarding transport density and the avoided transport mode mix. Then, it is essential to study the introduction of the HSR in a case-by-case analysis, taking a deeper look into the environmental performance of each of the corridors. By doing so, this work has detected elements that may go unnoticed in other more analytical and methodological studies (D'Alfonso et al., 2015). This is the case of the burdens associated with the construction of the infrastructure. D'Alfonso et al. (2016) assume, based on other studies, that the construction of the HSR infrastructure adds an extra 5 g CO_2 per passenger-kilometre of transport served in the network. This value, however, depends absolutely on the amount of transport served by the network, which in the case of the Spanish HSR is much lower than that of other networks in the world (see Table 15). The data collected in Tables 4 and 5 allow for the calculation of the GHG footprint associated with the construction and maintenance of each of the corridors and for the whole network,

Table 9
Environmental impact balance for the Catalonia corridor in the Baseline Scenario.

Catalonia corridor	Global Warming $kt \cdot CO_2eq \cdot y^{-1}$	CED $TJ \cdot y^{-1}$	PM_{10} $t \cdot y^{-1}$	SO_2 $t \cdot y^{-1}$	NO_X $t \cdot y^{-1}$	NMVOC $t \cdot y^{-1}$
Infrastructure Construction& Maintenance	73.81	927.77	103.72	161.62	254.79	41.69
Operation (5.76 million passengers)	167.27	4370.85	172.39	779.85	524.49	32.17
Shifted transport in other modes	543.71	8900.62	288.55	1017.30	2101.56	393.85
Net Impact	−302.64	−3602.00	−12.44	−75.83	−1322.29	−319.99
Years required for compensation	11.76	12.29	53.57	40.84	9.69	6.92

Table 10
Environmental impact balance for the AVE network (four corridors) in the Baseline Scenario. (N.C: No Compensation in 100 years).

Spanish HSR Network	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
	$kt\cdot CO_2eq\cdot y^{-1}$	$TJ\cdot y^{-1}$	$t\cdot y^{-1}$	$t\cdot y^{-1}$	$t\cdot y^{-1}$	$t\cdot y^{-1}$
Infrastructure Construction& Maintenance	196.69	2535.83	285.02	452.22	705.31	114.96
Operation (4.17 million passengers)	354.82	9271.65	365.68	1654.25	1112.56	68.24
Shifted transport in other modes	1161.63	18838.51	562.48	2088.87	4696.56	809.87
Net Impact	−610.13	−7031.03	88.22	17.60	−2878.69	−626.67
Years required for compensation						
Four corridors (4.17 million passengers)	15	16	87	62	12	9
Andalusia corridor (5.36 million passengers)	9	11	96	57	8	7
Northern corridor (1.31 million passengers)	79	98	N.C	N.C	73	34
Catalonia corridor (5.76 million passengers)	12	12	54	41	10	7
Levante corridor (2.71 million passengers)	20	21	N.C	80	16	14

Table 11
Results of the net balance in the Andalusia corridor for the sensitivity analysis. (N.C: No Compensation in 100 years).

	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
Years required for compensation (Baseline, years)	9	11	96	57	8	7
Years required for compensation (S1, years)	11	13	N.C	94	8	8
Years required for compensation (S2, years)	11	14	N.C	N.C	8	8
Years required for compensation (S3, years)	5	6	48	29	4	4
Years required for compensation (S4, years)	11	13	85	49	8	8
Years required for compensation (S5, years)	9	10	65	18	7	9

taking into account the annual transport in each corridor (See Data in Brief). The average footprint is 18.24 gCO_2eq/pkm for the whole network (3.6 times the value assumed by D'Alfonso et al. (2016)), but with large differences between corridors: 12.1 g in Andalusia, 14.5 g in Catalonia, 28.1 in Levante and 59.3 in the Northern corridor.

The Catalonia corridor (Madrid-Barcelona-France) supports the highest transport volume on the network and a high proportion of transport shifted from aeroplane, which provides similar results to the Andalusia corridor. CO_2eq, CED, NO_X and NMVOC impacts need between 7 and 12 years to be compensated; SO_2 needs 41 years, and PM_{10} is compensated in 54 years. Clearly, this corridor stands as the main contributor to the global warming emissions reduction of the entire Spanish network, as it is responsible for 44% of the total reduction of CO_2eq emissions. This corridor also stands as the main contributor to the reduction of energy consumption (51%) of the network.

The Andalusia corridor (Madrid-Sevilla-Málaga) requires between 7 and 11 years to compensate CO_2eq, CED, NO_X and NMVOC impacts. Around 57 years are needed to compensate SO_2, and no compensation (96 years) is achieved regarding PM_{10}, mainly due to the high proportion of transport shifted from aeroplane (45%). But the annual GHG emissions avoided by air transport (249 kt CO_2 annually) amount to 65% of the total emissions avoided, and are even much higher than the emissions linked to the transport induced in the HSR (15% of the total transport, 17.1 kt CO_2 annually).

Results worsen in the other two corridors, mainly due to the very low density of transport. In the Levante corridor (Madrid-Valencia-Alicante) CO_2eq, CED, NO_X and NMVOC impacts need between 14 and 21 years to be compensated; SO_2 (80 years) and, PM_{10} (143 years) emissions would not be compensated during the lifetime of the infrastructure.

The Northern corridor (Madrid-León-Zamora) offers the poorest results. A transport density of just 1.3 million passengers over the complete infrastructure gives rise to no compensation in the lifetime of the infrastructure in all of the impact categories analysed except for NMVOC, which would need 34 years.

4.2. *Sensitivity analysis*

A sensitivity analysis was carried out in order to check the influence

Table 12
Results of the net balance in the Northern corridor for the sensitivity analysis. (N.C: No Compensation in 100 years).

	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
Years required for compensation (Baseline, years)	79	98	N.C	N.C	73	34
Years required for compensation (S1, years)	N.C	N.C	N.C	N.C	N.C	48
Years required for compensation (S2, years)	N.C	N.C	N.C	N.C	N.C	61
Years required for compensation (S3, years)	40	49	N.C	N.C	36	17
Years required for compensation (S4, years)	N.C	N.C	N.C	N.C	N.C	67
Years required for compensation (S5, years)	N.C	N.C	N.C	N.C	N.C	N.C

Table 13
Results of the net balance in the Catalonia corridor for the sensitivity analysis. (N.C: No Compensation in 100 years).

	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
Years required for compensation (Baseline, years)	12	12	54	41	10	7
Years required for compensation (S1, years)	15	17	88	92	11	9
Years required for compensation (S2, years)	17	20	N.C	N.C	12	10
Years required for compensation (S3, years)	6	6	27	20	5	3
Years required for compensation (S4, years)	17	16	47	33	11	10
Years required for compensation (S5, years)	17	17	64	24	11	12

Table 14
Results of the net balance in the Levante corridor for the sensitivity analysis. (N.C: No Compensation in 100 years).

	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
Years required for compensation (Baseline, years)	20	21	N.C	80	16	14
Years required for compensation (S1, years)	22	25	N.C	N.C	17	16
Years required for compensation (S2, years)	24	27	N.C	N.C	17	17
Years required for compensation (S3, years)	10	11	72	40	8	7
Years required for compensation (S4, years)	24	25	N.C	71	17	17
Years required for compensation (S5, years)	21	22	N.C	36	16	19

of changes in certain variables over the total net environmental balance of the Spanish HSR infrastructure. Five alternative scenarios were analysed (see section 3.3 for a detailed description). The results are presented in Tables 11–14, in terms of years needed for compensation of environmental burdens linked to construction and maintenance of the infrastructure, for each of the four corridors in the AVE network.

It can be seen that the results are somewhat sensitive to the occupancy rate of private vehicles. Impact compensation requires a few more years when the occupancy rate of private vehicles is higher (S1 and S2). Average occupancy rate could increase during the lifetime of the infrastructure, since there are currently several institutional initiatives aimed at promoting vehicle sharing in society, such VAO road lanes exclusively for high occupancy vehicles in Madrid. If that rate is doubled, 3.36 people per vehicle (S2), keeping the number of HSR travellers constant, every environmental indicator worsens with respect to the Baseline Scenario. This is due to the fact that the greater the occupation of private vehicles, the lower the environmental impact per person and kilometre of this mode of private transport. Thus, under S1 and S2 circumstances, attracting passengers to the HSR from private vehicles provides less beneficial effects on the net environmental impact of the HSR project.

Section 3.1.2 described the estimation of the HSR transport demand for each corridor in the year 2016 for the Baseline Scenario. The network considered in this study includes all the HSR corridors in operation at the end of 2016. Under the assumption that passenger transport demand may increase in the future, the S3 scenario considers that the annual transport demand in each corridor doubles, with the rest of the parameters remaining equal. From an environmental point of view, a rise in demand has two opposite impacts: a positive impact, when it relates to a modal shift from more polluting modes of transport, such as air or road; and a negative impact, when it is due to induced (new) demand.

As shown in Tables 11–14, doubling passenger demand improves the environmental performance of all the corridors, reducing the compensation period by more than half, given that the previously mentioned positive effect is greater than the negative effect. However, it is important to denote that these results are highly sensitive to the magnitude of the induced demand: (1) induced demand should not be higher than 70% of the new demand in the corridor of Andalusia, in order to achieve an improvement in CO_2eq emissions; (2) in the Catalonia corridor all new demand could be induced demand; (3) it should not exceed 63% in the case of the Levante corridor; and (4) it should stay below 44% and 34% in the Northern corridor in order to obtain an improvement in terms of CO_2eq and CED, respectively.

The S4 scenario explores a situation in which private vehicles are electric. It is reasonable to consider a progressive penetration of electric motion in the automotive sector, which will reduce future environmental impacts in road transport. The influence of this variable on the annual results of the AVE is noteworthy. In this scenario the burdens associated with the construction, maintenance and operation of the Spanish HSR four corridors do not vary with respect to the Baseline Scenario, but the loads associated with shifted transport are now reduced. All the indicators worsen their balance with respect to the Baseline Scenario, except for PM_{10} and SO_2 that improve, although the former is almost residual. When electrifying road transport, the environmental burdens significantly reduce in this mode, so the benefits from diverting traffic from road to rail are lower. These environmental benefits are even lower if electric vehicles are powered with electricity from renewable sources. This context is explored in the fifth and last scenario (S5), where an occupancy rate of 3.36 passengers per vehicle is considered, together with the assumption that all private vehicles are powered with electricity from renewable sources. Compensation years for this scenario are similar to those provided by the previous one, S4, as a worsening derived from doubling vehicle occupancy tends to compensate with the benefit derived from the fact that the HSR would also operate on 100% renewable electricity.

5. Discussion

The main factor behind the net environmental balance of the Spanish HSR network is clearly the density of total demand as long as it is capable of diverting traffic from more polluting modes of transport (air or road) rather than inducing new demand. Vehicle occupancy rates, electrification of road transport and electricity mix have also been found to have a significant impact on the environmental balance of the network.

In line with the findings of many economic analyses (e.g. Albalate & Bel, 2011; Betancor & Llobet, 2015; De Rus, 2011), the performance of the Spanish HSR network is clearly hampered by its low passenger demand. In 2016 the Spanish HSR network transported the equivalent of just 4.17 million passengers over the complete infrastructure; significantly lower than the transport density supported by other networks in

Table 15
Passenger transport density in national HSR networks in 2016. Own elaboration based on UIC Railway Statistics (2016).

National network	Year	Network length, maximum speed between 160 and 250 km/h	Network length, maximum speed greater than 250 km/h	Transport	Average density of transport (passengers over complete infrastructure)
		(km)	(km)	(Mpkm)	(Mp)
Spanish AVE	2016	669	2503	15059	4.75
France	2015	0	2043	49980	24.46
Germany	2016	1511	994	27213	10.86
Italy	2012	2767	653	12794	3.74
China	2017	12276	20305	577635	17.73
Japan (CJRC)	2017	0	553	54756	99.02
Japan (EJR)	2017	0	1194	23371	19.57
Japan (WJRC)	2017	0	813	21023	25.87
Taiwan (THSRC)	2016	0	350	10488	29.97

Table 16
Comparison of the environmental impact balances for the Catalonia corridor in the Baseline Scenario and a motorway corridor of the same length with scenarios of occupancy doubling (HW1), vehicle electrification (HW2), and occupancy doubling and renewable electricity vehicles (HW3).

Net Impact balance	Global Warming	CED	PM_{10}	SO_2	NO_X	NMVOC
	kt.CO_2eq·y^{-1}	TJ·y^{-1}	t·y^{-1}	t·y^{-1}	t·y^{-1}	t·y^{-1}
Catalonia corridor (Baseline Scenario)	−303	−3602	−12	−76	−1322	−320
HW1 –toll highway of same length, 883 km (6 million v·y^{-1}, double occupancy)	−858	−12924	−601	−1586	−2132	−752
HW2 - toll highway of same length, 883 km (6 million v·y^{-1}, electric vehicles, renewable elec.)	−1218	−13336	−177	−426	−2709	−871
HW3 - toll highway of same length, 883 km (6 Mv·y^{-1}, double occupancy, ren. elect. vehicles)	−1431	−19350	−684	−1718	−4287	−1114

the world, as can be observed in Table 15.

The Spanish HSR network is also hampered by the fact that it allows only for passenger transport, which prevents attracting potentially more polluting traffic from road freight transport. As argued by Akerman (2011, p. 208), "HSR investments may not be justified for the passenger markets alone."

The LCA of Spanish HSR is quite robust in showing that the launch of the Catalonia and Andalusia corridors of the Spanish HSR network has led to a net environmental benefit in CO_2eq after nine-twelve years of operation. However, it also shows that results worsen as the network expands to corridors with lower demand (Levante or Northern corridors). This also coincides with transport economics literature (see e.g. Albalate & Bel, 2011).

However, two questions also need to be addressed in order to evaluate the environmental performance in absolute terms: firstly, is there a significant annual reduction in CO_2eq emissions and energy consumption provided by the Spanish HSR operation? And secondly, how does this reduction compare with other alternative strategies for managing transport passenger demand?

Overall environmental impact reductions derived from the HSR operation in Spain are very limited, if not negligible. Spain's transport sector had a total volume of direct emissions of 85.9 Mt CO_2eq in 2016 (European Environment Agency, 2016). The HSR network presents in the Baseline Scenario an annual net balance of −610.13 kt CO_2eq (Table 10), or less than 1% of emissions linked to transport. Regarding energy consumption, the net balance of −7031.03 TJ (0.17 million toe) in cumulative energy demand is less than 0.5% of the energy consumed by the transport sector in Spain in 2016 (International Energy Agency, 2017). In other words, the Spanish HSR network's capacity to mitigate climate change and reduce oil dependency is clearly insufficient in the current context of the global environmental crisis, which requires a drastic reduction in GHG emissions. In cost-efficiency terms, it is important to consider that the total investment in AVE over the last 25 years has exceeded 50 000 million euros.

From a sustainable mobility perspective, it is important to bear in mind the existence of other alternatives that could further reduce environmental impacts in the transport sector without the need to build new infrastructures (Hoyos, 2009). To illustrate this, Table 16 collects the environmental impact balance of the Catalonia corridor of the AVE network in comparison with three other scenarios applied to a motorway corridor of the same length (883 km). According to traffic statistics from the Ministry of Public Works and Transport (Ministerio de Fomento, 2017), the average daily flow on motorway toll roads in Spain (2550 km) was 16 471 vehicles (heavy vehicles excluded) in 2017, which is equivalent to an annual transport density of 6.01 million light vehicles annually. While the Catalonia corridor gives rise annually to a reduction of emissions of 303 kt CO_2eq, the doubling of light vehicle occupancy on a motorway toll road with the same length (883 km) and under average Spanish traffic conditions would provide an annual reduction of 858 kt CO_2eq (HW1 in Table 16). If those light vehicles were electrified, the reduction would increase to 1218 kt CO_2eq (HW2); and up to 1431 kt CO_2eq if vehicles were also powered with electricity from renewable sources, and with double the average occupancy (HW3).

6. Conclusions

Climate change and oil scarcity have received increasing attention in transport policy. In this context, HSR has often been presented as a sustainable mode of transport, having a leading role in the European Commission's environmental goal of net-zero GHG emissions by 2050, due to its potential contribution to energy savings and GHG emissions reductions. In this paper, it is assessed the environmental performance of the Spanish HSR network by means of LCA under 2016 traffic conditions. Results show that the construction loads of the Spanish network are not disproportionate, as they remain within the lower limit of the range of construction burdens found with other HSR lines. Although these construction loads are not excessive, the net environmental balance of the entire network in the Baseline Scenario, without being detrimental in almost all indicators, is modest: an annual emission reduction of 610 kt CO_2eq, of 7031 TJ of CED, of 2879 t NO_X and of 627 t NMVOC, together with an annual increase of 88 t PM_{10}, of 17 t SO_2. This modest balance means that the infrastructure requires a minimum number of years of operation to offset the initial loads associated with the construction: between 9 and 16 years in all the environmental categories studied except for SO_2 (62 years) and PM_{10} with 87 years. In absolute terms, it means a reduction in CO_2eq emissions equivalent to less than 1% of the annual transport emissions in Spain in the base year (2016), together with a reduction in primary energy demand which is less than the equivalent of 0.5% of annual energy consumption in the transport sector.

The environmental balance varies according to the network corridor considered. The corridors of Catalonia (5.76 Mp) and Andalusia (5.36 Mp) present a slightly better balance than the total average, managing to compensate the initial construction loads in less than 7–12 years in all the analysed categories except for PM_{10} and SO_2. The Northern corridor (1.31 Mp) would not be able to compensate the initial loads in the whole time of operation, and the Levante corridor (2.71 Mp) would need around 14–21 years (except for SO_2 with 80 years and PM_{10} which would not be compensated). According to these results, the construction of the Levante and Northern corridors is not justified in terms of energy savings and emission reductions. Thus, in line with the findings on cost-benefit analysis, the decision to build new HSR sections should be based on the analysis of demand in order to build only those sections that ensure a high demand, that is, to build only those corridors that connect centres with high demographic density (De Rus, 2011).

The sensitivity analysis confirms that the main factor that conditions the net environmental balance is the density of the transport. The density of transport served by the network in 2016, measured in terms of equivalent passengers over the entire network layout (4.17 million passengers) is much lower than the transport served by the French network (24 Mp), the Japanese networks (between 20 and 99 Mp), China (18 Mp) and Taiwan (30 Mp) (Tables 4 and 15). Initially, every HSR project starts operation with an environmental deficit that can be compensated only if transport demand is sufficiently high and it comes, sufficiently, from other modes of transport, minimising new induced demand.

Doubling the quantity of passengers, which is not very likely in the medium term, shows that the results improve in all the corridors, even in the Northern corridor, and the amortisation of several indicators will be given within the term of the infrastructure's useful life. But the nature of this increase in transport demand is a relevant aspect that conditions the results in a crucial way. It is essential that this increase in total demand for HSR is not new induced demand in its entirety; otherwise, the adverse consequences on the environment will increase. In other words, the environmental performance of HSR improves if traffic is diverted from more polluting modes of transport and induced transport remains low. According to results, induced demand should not exceed 44–70% of total demand (except for Catalonia corridor) if positive effects are to be found in terms of CO_2eq emissions. Similar results are found regarding other pollutants and energy consumption. So, from a sustainability perspective, our findings suggest that public institutions should focus on increasing the current levels of passenger demand in the AVE network, prioritising the diversion of existing demand from planes and private cars.

Finally, the United Nations has recently declared a climate emergency under the latest scientific evidence on the consequences of climate change, emphasising the urgent need to be carbon neutral in 2050 and to achieve a 45% reduction in emissions by 2030 in order to keep the rise of temperature below 1.5 °C by the end of the century (UNFCCC, 2019). In this context, policymakers should also consider other measures related to transport that, in application of the transport hierarchy (Hoyos et al., 2016), would provide considerable and rapid reductions in environmental impacts without the burden of building new infrastructures: e.g. reducing the demand for transport, increasing the occupation of private vehicles, promoting electric traction and the use of electricity from renewable sources.

Credit author statement

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