Environmental Sustainability of Railway Corridors: Case Studies of Italian High Speed Rail

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Abstract. The increase of carbon footprint and the climate change scenario are central themes of the current technical and political debate. An important contribution is provided by the transport of passengers and goods. Over long national distances the problem becomes even more crucial. In a nutshell, the carbon footprint of High-Speed Rail (HSR) is on average, lower than other modes of transport, such as private cars or airplanes, for the operating phases. The reduction of carbon emissions with the use of HSR for passengers' trips at national scale would make it possible to pursue the Sustainable Development Goals (SDGs) included in the 2030 Agenda, with specific reference to Goal 13: "Climate change". It is necessary to carry out an analysis of the current scientific literature on this topic, considering the levels of environmental impacts in relation to the operative phases of the HSR, through an analysis and comparison of the values of the indicators. The purpose of the paper is to give a synthetic answer to the problem: how sustainable are the HSR systems in terms of carbon footprint?

The results will be twofold. On the one hand, parametric values can be defined which can synthetically represent the environmental advantage provided by the implementation of the HSR for passengers' trips; on the other hand, the fields of unknowledge in which it is useful to carry out research can be delimited. The reference result is given by applying the synthetic parametric approach to a case study: the relationship Rome-Milan (Italy). The link is presented in relation to the current airline connections and passengers flow, and considering several scenarios connected with the implementation of the HSR line. The conclusions allow decision-makers and planners to be supported in the design and construction of new HSR lines with a broader point of view, which considers environmental CO_2 emissions.

Keywords: CO2 emissions · environmental impact · Italian case studies · Transport System Model · High Speed Rail

1 Introduction

High-Speed Rail (HSR) mode-service results to be the most innovative terrestrial passenger transport system designed and built in the last decades. HSR has experienced rapid growth both in supply, in terms of services and infrastructures, and demand sides, in

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terms of passengers transported. There are 64,698 km of HSR lines in operation, 19,927 km under construction and 53,201 km planned [1]. Specifically, China results to have the largest HSR network with about 45,390 km, whereas the whole Europe continent results to have 12,454 km of lines, the Middle East 1,681 km, the North America 735 km and the Africa content 186 km [1].

It is stated that Italy is one of the first countries which have planned, designed and built a HSR infrastructure. The preparation of the NextGenerationEU financial program specified as Piano Nazionale di Ripresa e Resilienza (PNRR) in Italy [2], has given a significant boost to the development of transport planning on a national scale. Taking into account the impact of carbon footprint, in terms of GreenHouse Gas (GHG), it is well known that HSR in the operating phases is, on average, lower than other transport modes, such as private cars or airplanes. In the year 2021, according to [3], the global emissions of the transport sector results to be about 30%, with China as the main contributor to this statistic, and then the USA and Europe. The impact due to the transport sector depends on the structure of supply and demand, in particular with regard to supply, the main papers are identified which are [4–19] on the other hand, the reference papers of supply are [20–40].

A significant contribution is represented by the evaluation of travel demand [41, 42], with regard to the modes of transport utilized for travels on national scale (e.g., rail, bus, car, air), hence in the users' choices [43]. For these travels it is important to evaluate the environmental impact, in order to provide mitigation solutions [44]. The evaluation is crucial in order to know the alternatives with less environmental impact.

The latter theme plays a crucial role in the actual political and technical discussions at global level, in particular considering its global mitigation and reduction. The 17 Sustainable Development Goals specified in the 2030 Agenda regard the travel guidelines on national scale that have less economic impact, generally chosen by users which deals with the environmental economic and social development. Specifically, it involves Goal 9, which concerns sustainable infrastructures and transportation, as well as Goal 13 about climate change [45–48].

A crucial contribution to this issue is provided by LARG approach [44–47]. The theme defined is to identify an approach that allows to support the choices to be made in the programming phase, and therefore which solution to adopt between several alternatives of railways, among others HSR, contributing to the achievement of the SDGs. It is useful to refer to a paradigm (one or more) that in its various articulations has been built over time. The approach was first developed in the automotive industrial sector and was then extended to other industrial sectors.

Within the paradigm LARG, four main components exist specified by the industry sector: *Lean***,** removal of the redundant elements; *Agile***,** ability to react to demand; *Resilience*, ability to respond to the risks; and *Green,* ability to concur positively in the environment.

This paper takes into account the component Green [44] it is possible to deepen the effects of the environmental impacts due to modal share, in terms of emission of greenhouse gases (GHG), especially regarding carbon dioxide equivalent (CO_{2eq}). The emissions assessment framework consists of distinct phases that categorize environmental impacts based on the energy life cycle, that are: Well-to-Tank (WTT), comprising energy

extraction, refining, and distribution; Tank-to-Wheels (TTW), involving the energy consumption and direct exhaust emissions during vehicle movement; and the broader Life Cycle Assessment (LCA) [49], which accounts for the manufacturing, maintenance, and disposal of both vehicles and infrastructure.

This study is focused on the Well-to-Tank (WTT) cycle as it regards the operational phases of the transport modes. This phase of analysis concerns the energy consumed for traction and the associated GHG emissions, enabling a direct comparison between the mode-service of HSR and aircraft.

The paper analyzes several scenarios of impacts caused by the choices of travelers' behavior, thus observed demand flows provided by Telco data, thus a current scenario. In addition, the impacts of modal share due to simulated scenarios are presented, obtained with a sensitivity analysis, hence on one hand from hypothesized improvements on the railway line and implementations of the services offered, therefore a share of demand diverted from the air mode. On the other hand, it is considered a decreasing of demand flows (from rail) towards air mode, hypothesized due to decreasing in the supply of service and/or infrastructural failures, which cause a share of demand regarding air mode. The results show that the air mode impacts with a quantity of GHG more 2.5 times than rail mode of transport.

The paper is organized as follows. Section 1 contains an analysis of the basic state of the art regarding the research topic of the paper itself. Section 2 concerns the specification of the methodology for GHG emission estimation from different transport modes in terms of CO_{2eq} emissions, by means of the indicator provided by the Agenda 2030, as reported in Goal 13, by using the EcoPassenger software provided by UIC [50]. Section 3 deals with the application of the methodology specified within Sect. 2. Therefore, the context of application was specified, namely the Italian Rome-Milan relationship, chosen because it results to be the national reference link in terms of flows and supplied services. The quantity of GHG emitted on the relationship has been calculated for different scenarios, firstly the actual scenario with Telco data. A sensitivity analysis is performed in order to estimate possible different future scenarios of the transport system among this relationship. The last section contains some final considerations.

This work is aimed at supporting transport planners and decision-makers in the evaluation of future investment in HSR lines and services, by means of methodological and modelling tools to assess the potential GHG saving and possible future investments in HSR infrastructure and services.

2 Methods to Estimate the Emissions

The chapter contains the specification of the methodology for calculating GHG emissions from different transport modes in terms of CO_{2eq} emissions, in addition it is included the method for calculating GHG emission parameters.

2.1 Model Specification

The methodology aimed at the calculation of total emissions of GHG and thus the consequent total emission saved due to the modal diversion of passengers from air to HSR mode, is presented in this section.

The data concerning the observed demand flows, for both modes of transport, for the actual scenario is Telco data. It is worth noting that the different scenarios are obtained with sensitivity analysis, reproducing possible variations in the infrastructural or services systems.

The procedure of calculation is carried out through the following equations. The demand flows, for each mode of transport (rail and air), are provided by Telco data (d_m), extracted from big data. The Eq. (1) in the paper is not specified and applied, because is applied the pivoting ±10%. Therefore, the analysis was executed considering 3 different scenarios:

1. Current scenario, C: in which the emission of CO2 (Eq. 2) is related to the demand flows observed;
2. Scenario rail, R: in which there is the hypothesis of diversion of 10% demand from air, towards rail (Eq. 2);
3. Scenario air, A: in which there is the hypothesis of diversion of 10% demand from rail, towards air (Eq. 2).

The calculation of the difference between rail and air transport modes, in terms of emitted CO_2, is estimated with the Eq. (3), thus is the difference between CO2 emitted by the scenario 1 or 2 and the actual scenario.

$$d_{m,w} = f(\mathbf{x}; b) \tag{1}$$

$$CO_{2\,m,w} = f\left(d_{m,w}; \mathbf{x}\right) \tag{2}$$

$$DCO_2 = f\left(CO_{2\,m,C};\ CO_{2\,m,w}\right) \tag{3}$$

With:

$d_{m,w}$ = demand flows referred to the mode *m* and the defined scenario w;
$\mathbf{x}$ = vector of attributes;
$CO_{2\,m,w}$ = carbon dioxide emissions of the mode *m* referred to the scenarios R and A;
$w \in \{C, R, A\}$, defined scenario.

2.2 Parameter Calculation Specification

All the components of greenhouse gas (GHG) produce a particular global warming effect.

Among the seventeen Sustainable Development Goals (SDGs) defined, HSR generates direct and indirect impacts on the following ones.

There exist direct impacts and indirect impacts generated by the transportation sector. On one hand, the direct impacts are related to the Goals 9 “Industry, Innovation and Infrastructure” and Goal 11 “Sustainable Cities and Communities”. On the other hand, the indirect impacts are related to Goals 7 “Affordable and Clean Energy”, Goal 8 “Decent work and Economic Growth”, Goal 10 “Reduce Inequalities” and 13 “Climate Action”.

This paper deepens Goal 13 “Climate Action”, which is a call for urgent action to cope with climate changes and its impacts. It pursues on the strengthening of resilience,

improving climate awareness, as well as integrating climate measures into national policies. Particularly, it is considered the Target 2 "Integrate climate change measures into national policies, strategies and planning", as wells as in particular the estimation of the Indicator 2 "Total greenhouse gas emissions per year". The latter indicator measures the total greenhouse gas emissions (GHG) per year of the actors which participates at the United Nations Framework Convention on Climate Change (UNFCCC) [51].

The total GHG emission, according to the document of United Nations Agenda 2030 [52, 53] is calculated by taking into account the emissions of direct GHGs:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Perfluorocarbons (PFC_x)
- Hydrofluorocarbons (HFC_x)
- Sulphur hexafluoride (SF_6)
- Nitrogen trifluoride (NF_3)

It is important to underline that carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are characterized by a high global warming potential.

The calculation of total GHG emissions is composed of two main steps (equations), established in the IPCC document: the mass of each component that emitted gas, and subsequently, a weighted summation using the respective GWPs is applied to meet the requirements of Indicator 13.2.2 Eq. 3.

$$E = \Sigma (G_i * GWP_i) \tag{4}$$

with:

E = GHG total emission;
G_i = Gas $mass_i$, total physical quantity emitted (in tonnes or megatonnes) of the *i* greenhouse gas (GHG) over a year, calculated by individual country for the various economical sectors (energy, transport, agriculture, waste, etc.);
GWP_i, Global Warming Potential specific to gas i, parametrated on the carbonical anhydride molecule. The UN specifies that this factor is useful to convert the impact of any gas into the same unit of measurement.

Indicator 13.2.2 of Agenda 2030 requires the calculation of total greenhouse gas (GHG) emissions by converting the different gases through their respective global warming potential (GWP), in full compliance with UNFCCC guidelines [51]. In this study, the same methodological principle was applied to quantify the carbon footprint of passenger mobility: the EcoPassenger model already aggregates within itself the different climate-altering factors associated with electricity production and fossil combustion. The unit parameters expressed in g/pkm and extracted from the model already include this conversion to equivalent CO_2 making the dynamic calculation based on Telco data fully consistent with the integrated approach required by Goal 13.

$$\text{Emissions} = \text{Activity Data (x)} * \text{Other Factor } (\beta) \tag{5}$$

With: Activity Data (x): quantitative attribute about activity, for instance tons of fuel burned, kilowatt-hours of electricity used, or kilograms of material consumed; Emission parameter (β): a parameter that converts activity data in quantity of total GHG emitted (e.g., per GJ of energy).

In order to pursue the calculation of the indicator specified by Agenda 2030, thus the indicator 13.2.2, it is used the tool provided by UIC and specified in the Methodology Report, available on the EcoPassenger website, for both components of the Eq. (4). The latter is a software aimed at the calculation of the GHG emitted in a specific context, to be specified.

2.3 Activity Data (X)

Passenger transportation in Europe is provided by different transport modes and services. Within the EcoPassenger software the most important modes of transport using ordinary vehicle types and propulsion systems are taken into account.

As elaborated in the EcoPassenger methodology (Chapter 1.2 [52]), the specified framework focuses uniquely on the emissions related to the operational phases (Well-to-Wheel), thus results to be the Activity data component of Eq. (2). It has been chosen to not include the environmental contributions of the manufacturing, maintenance, and disposal phases of vehicles, hence the construction and maintenance of transport infrastructures. Therefore, the framework does not consider the raw material extraction parameters included in the indicator calculation of Goal 13.

EcoPassenger does not consider other emission or resource consumption parameters because it is a model focused exclusively on operational energy and direct and indirect atmospheric emissions from travel, deliberately excluding the construction of means and infrastructure to ensure homogeneity and immediate data compatibility between the different modes. It considers CO_2 (and equivalent greenhouse effect), nitrogen oxides (NO_x), particulate matter (PM), and non-methane hydrocarbons (NMHC) because the latter are the direct products of combustion or mechanical wear (brakes/wheels) related to the travel itself (Table 1).

However, the methodology proposed by UIC software does not include each of the chemical elements specified in the UN report of Agenda 2030, Goal 13.2.2. The following table shows the elements included in the calculation of GHG by UIC software.

2.4 Other Factors (β)

The Emission parameter is provided by the EcoPassenger Methodology report, specified as “Radiative Forcing Index” - RFI factor, which takes into account the climate effects of the GHG emission component not included in the methodology (in particular nitrogen oxides, ozone, water, soot, sulphur), especially for emissions in high altitudes and dependent to the distance in km), and are specified in the following table. The result, including this parameter, allows to calculate the quantity of CO_2 which would have to be emitted and causing the identical global warming effect, as averaged globally, as the several pollutants collectively.

Considering the component of GHG emission, according to the document of United Nations Agenda 2030, in the following the elements not considered are described.

Table 1. GHG component included in EcoPasssenger (elaboration from: [50]).

GHG component	Description	Motivation for inclusion
CO_2	Carbon dioxide emissions	main indicator for GHG effect
NO_x	Nitrogen oxide emissions	Acidification, eutrophication, eco-toxicity, human toxicity, summer smog
PEC*	Primary energy consumption	Main indicator for resource consumption
NMHC	Non-methane hydro carbons	Human toxicity, summer smog
PM	Exhaust particulate matter from vehicles (combustion), mainly $PM_{2.5}$ and from energy production and provision. Composition: all particle sizes, about 80% $PM_{2.5}$ and PM_{10} (by mass)	Human toxicity, summer smog

PEC*: Well-to-Wheels energy consumption, displayed as "liter petrol equivalent" (1 L = 32.309 MJ.

Table 2. RFI factor individuation

Distance range (km)	RFI factor (average)
500	1.27
625	1.47
750	1.60
1,000	1.87
>1,000	2.50

Therefore, environmental components, for instance land use, noise pollution, and stratospheric ozone depletion were excluded from the framework of this work. Regarding electrified rail transit, the model did not include the radiological risks and waste management challenges associated with nuclear power generation. Furthermore, the current iteration does not take into account non-CO_2 GHG, specifically methane (CH_4) and nitrous oxide (N_2O), as CO_2 represents the main part of GHG emissions within the transport sector. While $CO_{2,eq}$ emissions considered in CH_4 and N_2O are just about 1% higher than pure CO_2 emissions for conventional fuels, this variance increases to a range of 2% to 10% for biofuels and electricity generation, Finally, particulate matter (PM) quantitative determination is rigorously confined to tailpipe and combustion emission exhaust, thus excluding non-exhaust emissions obtained from mechanical abrasion and suspension.

2.5 Query Set up in EcoPassenger for GHG Estimation

In the following it is specified the query to be set up in order to estimate the EF component (Eq. 2).
Step 1. Starting and arrival point: city, railway station, airport; date of departure or arrival.
Step 2. Car, Rail, Flight specifications
2.1. Car Specifications: Vehicle class (middle class/upper class); Engine: Gasoline/Diesel Euro 1–6, Diesel conventional, GPL Euro 1–6, Electric Vehicle. no. of passengers in the car: 1–5, European average utilization (1.5 passengers). The fuel consumption is specified in "Tab. 2–5" of the UIC report about EcoPassenger methodology.

2.2. Rail/Flight Specifications: Utilization per train and flight (Average load factor, Maximum load factor), global warming extra charge of flight (CO_2-emissions with climate factor, CO2-emissions without climate factor).

Concerning the typologies of trains, are considered the following in relation to the route, thus the service: electric and/or diesel for intercity and regional/urban services, electric for high speed services. The fuel and energy consumption is specified in "Tab. 2–7" of the UIC report about EcoPassenger methodology [50] On the other hand, for the flights (short and medium distances in Europe) are considered, by the software, the following typologies of airplanes: B737 family and A319/321 family, and takes into account the different phases of the flight. The latter element is crucial for shorter distances because the greatest consumption occurs in the take-off and landing operations of the flight. However, there are not considered the movements between airports for reasons of repositioning airplanes for following services. The fuel (kerosene) consumption is specified in Tab. 2–9 of the UIC report about EcoPassenger methodology [50].
Step 3. Feeder
3.1. Feeder to and from the airport (car only, train only, taxi);

3.2. Electricity Mix of Railways (national production mix, railway mix including Green Certificates).
Results. Calculated parameters:

- Carbon dioxide CO_2 (greenhouse-gas, global warming), which includes emissions associated with the production of electricity/fuel;
- Energy resource consumption PEC (resource consumption/primary energy), which includes emissions associated with the production and distribution of electricity/fuel;
- Particulate matter PM (human toxicity), related to the combustion (fuel), including production of fuel or electricity power;
- Nitrogen oxides NO_x (acidification, nutrification, summer smog/ozone), including production of fuel or electricity power;
- Nonmethane hydrocarbons NMHC (summer smog/ozone), including production of fuel or electricity power (Fig. 1).

It is important to underline that each of the other specification, concerning the Eco-Passenger GHG estimation, not reported in this work are clearly explained in Report of UIC about the methodology [50].

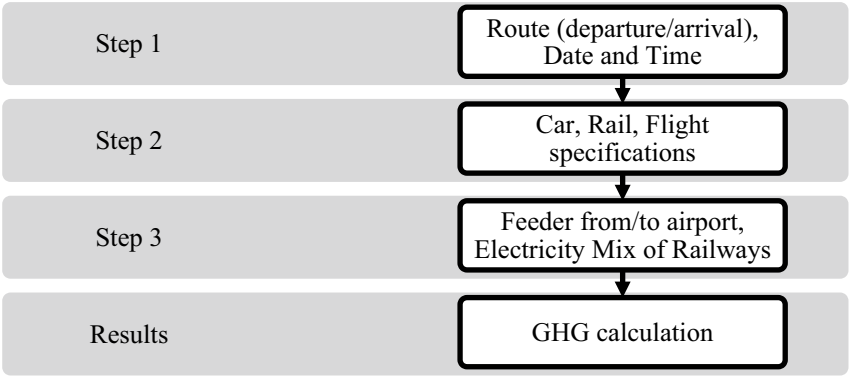

Fig. 1. Description of the specification phase in EcoPassenger

3 Case Study: Italian High Speed Rail

3.1 Experimental Test Site

The HSR line between Rome and Milan (Italy) was selected as it is the main Italian relationship in terms of volume of passengers and of services. The relationship includes the alternative of air services; however, this work does not investigate the mode choice level (Fig. 2).

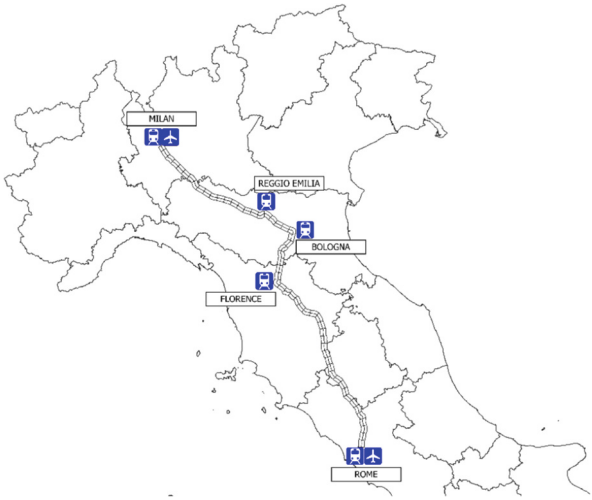

Fig. 2. Experimental test site: Rome-Milan link (Italy)

The case study concerns the Rome-Milan relationship (Italy). On one hand, on the railway side, has been opened in 2009. Consequently, it triggered both intra-modal and inter-modal competition, leading to a significant diversion of travel demand from air

and conventional rail services. Furthermore, induced travel demand emerged as a result of several factors, most notably the increased level of service offered by HSR (e.g., the reduction of in-vehicle travel time). Traffic data observed before and after the HSR opening reveals that passenger flows in 2008 were approximately 2.4 million/year for the air mode and 1.0 million/year for the conventional rail mode. By 2018, passenger flows shifted to 1.2 million/year by air and 3.6 million/year by HSR. Currently, two HSR companies operate along this corridor: Trenitalia, which supplies HSR services alongside conventional and local rail services, and Italo Nuovo Trasporto Viaggiatori (Italo NTV), which exclusively supplies HSR services. These two companies compete with each other at service and run choice levels, while jointly competing at the mode choice level with airline companies. As of 2024, the HSR services stands at approximately 45 runs/day (per direction) for Trenitalia and 32 runs/day for NTV. These scheduled runs are characterized by various operational elements, such as the typology of service (e.g., non-stop or shuttle runs with intermediate stops), in-vehicle travel time, and dynamic fare structures offered to travelers. Conversely, concerning the air mode, approximately 23 flights/day are operated by airline companies between the airports of Milan Linate and Rome Fiumicino.

3.2 Activity Data Estimation

The section contains the calculation of the emission parameters, by means of the EcoPassenger software, provided by UIC [50] (Table 3).

Table 3. Calculation of the emission parameters

Emission parameter	[UoM]	Train (HSR)	Car	Air
Carbon dioxide	[kg]	10.3	63.1	141.7
Energy resource consumption	[l.g.e.]	6.1	28.0	49.0
Particulate matter	[g]	2.2	2.0	10.5
Nitrogen oxides	[g]	25.8	345.8	565.4
Nonmethane hydrocarbons	[g]	1.4	20.5	48.9

With: UoM = unity of measure, kg = kilograms, g = grams l.g.e. = liter gasoline equivalent.

3.3 RFI Factor Individuation

As reported in Table 2 it indicates the RFI factor in relation to the distance of the experimental test site specified in Sect. 3.1, thus Rome-Milan relationship, and results to be 567 km for the railway as well as 472 km for the air link. Consequently, for both modal alternatives the RFI factor results to be 1.27.

3.4 Scenarios: Emission Estimation

The scenarios of the case study are calculated considering a sensitivity analysis with respect to the actual scenario, for both rail and air modes of transportation.

The actual scenario in terms of demand flows is provided by the results of an analysis for obtaining Telco data in the specified relationship, thus is 593.567 passengers for rail mode and 109.500 passengers for air mode. Table 4 contains the results of the GHG emissions estimation. Concerning the rail mode results to be 7.764,4 tons, whereas the GHG emissions for the air mode are 19.705,5 tons. The total GHG emissions for the actual scenario are 27.470,0 tons.

Regarding the scenarios are conducted by means of a sensitivity analysis, as specified in Sect. 2.

The scenario 1 is obtained by hypothesizing the diversion of the demand flows of about 10% from air towards rail, and results 604.517 passengers for rail mode and 98.550 passengers for air mode. Table 4 contains the results of the GHG emissions estimation. Concerning the rail mode results to be 7.907,7 tons, whereas the GHG emissions for the air mode are 17.735,0 tons. The total GHG emissions for scenario 1 are 25.642,6 tons.

The scenario 2 is obtained by hypothesizing the diversion of the demand flows of about 10% from rail towards air, and results 534.210 passengers for rail mode and 168.857 passengers for air mode. Table 4 contains the results of the GHG emissions estimation. Concerning the rail mode results to be 6.988,0 tons, whereas the GHG emissions for the air mode are 30.387,3 tons. The total GHG emissions for scenario 2 are 37.375,3 tons.

Table 4. GHG estimation for the different scenarios

Scenarios	Mode	Activity data	RFI factor	Demand flows	GHG emission	GHG emission
Actual		[kg]		[pax]	[kg]	[tons]
	Train	10,3	1,27	593.567	7.764.449,9	7.764,4
	Air	141,7	1,27	109.500	19.705.510,5	19.705,5
			Total	(actual)	27.469.960,4	27.470,0
1 (+10%)	Train	10,3	1,27	604.517	7.907.686,9	7.907,7
	Air	141,7	1,27	98.550	17.734.959,5	17.735,0
			Total	(1)	25.642.646,3	25.642,6
2 (-10%)	Train	10,3	1,27	534.210	6.988.004,9	6.988,0
	Air	141,7	1,27	168.857	30.387.282,9	30.387,3
			Total	(1)	37.375.287,8	37.375,3

4 Discussion and Conclusions

The paper presents an analysis of GHG production of two transport modes, such as air and rail, and a comparison between the actual and the simulated scenarios of GHG emissions in a case study of passenger mobility along the relationship Rome-Milan (Italy). The analysis' results show the relevant variations of the externalities under consideration

according to the specific sensitivity cases. In particular, the impact of the actual scenario, compared to the simulated ones, demonstrates the massive carbon footprint of the air mode despite its lower passenger flows, producing 19,705.5 tons of GHG against the 7,764.4 tons produced by the rail mode. Moreover, Scenario 1, which hypothesizes a 10% increase in passenger demand of Rail mode of transport due to service improvements, would lead to an overall emissions decreasing, reaching 17.735,0 tons for air and 7.907,7 tons for train. It is observed that scenario 1 is the best in terms of GHG saving and less emissions, whereas scenario 2 shows that the air mode impacts 4.4 times the rail mode of transport, in terms of GHG emissions.

It is clear that the diversion of passengers towards the HSR mode allows a relevant quantity of GHG savings compared to air mode, underling the environmental sustainability of rail transport mode. A crucial role is played by the travel demand; hence, it is important to correctly evaluate the HSR travel demand, because it supports the achievement of UN Sustainable Development Goal 13.

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