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Air versus terrestrial transport modalities: An energy and environmental comparison

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ABSTRACT

In the last 15 years, worldwide air transportation has grown at an average yearly rate of 4.5%. Forecasts confirm that this could be the average increase rate for the next 20 years, although recent oscillation of oil price translated into a slowing down of such a trend, with several air companies forced out of business. Within this framework, low cost airlines keep increasing their market share, in so making airplane to compete with terrestrial transport modalities, not only for medium and long distance, but also for short trips. This is because air transport is obviously faster than transport by trains and cars, and most often it also is a cheaper option in money terms.

In spite of its apparent success, air transportation is a source of concern for many analysts, because it is considered as the more energy intensive and polluting transport modality. In order to explore the correctness of such an issue, we compared air transportation to high speed trains and other modern terrestrial modalities, by using a "whole-system" approach. The present study applies an LCA-like approach, by taking into account all the energy and materials directly and indirectly required to make and operate infrastructures (i.e. tunnels, railways, highways) and vehicles. Efficiency and environmental loading are assessed by means of Material Flow Accounting, Embodied Energy Analysis and Emergy Synthesis methods. Results point out that the gap among the environmental performances of air, road and railway modalities is significantly narrower than expected. The thermodynamic and environmental costs of road and railway infrastructure cannot be disregarded as negligible. In a selected number of cases these transport modalities perform even worse than the air transportation mode, where infrastructures play a much smaller role.

1. Introduction

A day-by-day increasing share of transportation activities as well as a wide section of the global economy is predicted to rely on air transport both for passengers and freight transportation [1] over the next decades. Such a transportation mode is and will be supported by a massive and increasing use of fossil fuels (mainly kerosene). It is not easy at present to foresee an alternative energy source able to replace to a significant extent the fossil energy used by air transport operation. Such a difficulty depends upon two main aspects: firstly, the world wide production of biofuels is not yet sufficient to the purpose and the recent debate on the competition between food and non-food land use could lead to a further reduction of first generation biofuel production. Second generation biofuels (based on cellulosic substrates) are still far from commercial production. The second point is that airplanes require a high density energy fuel (in terms of MJ/l) in order to minimize the volume of the tank. The use of hydrogen in aviation by, e.g., the so called Cryoplane [2,3] also seems far away in time. As a consequence of its intensive reliance on fossil fuels, and related environmental concerns [4] (among which global warming and contrails [5]), air transport is perceived as the most energy intensive and polluting way to move passengers and commodities followed by road transport [5,6]. On the contrary, the shift towards a more intensive use of electricity powered railway systems is considered by many authors [7] and by the general public as a viable solution to reduce the CO_2 emissions of the

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[1] Mirco Federici passed away in a mountain accident at the age of 34 years while this paper was under review. Mirco, MS in Chemistry in the year 2000, PhD in Environmental Chemistry in the year 2004, dedicated his short but very promising research activity to the thermodynamic, environmental, and social performance of transportation systems, alternative fuels and energy efficiency. His death is a huge loss for his family, for his friends and colleagues, as well as for all the scholars who had the opportunity to appreciate his scientific insight in national and international projects and events.

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whole transport sector. This sort of classification among the different transport modalities is the result of a comparison procedure only based on the direct use of fuel and energy by vehicles, most often disregarding the resource demand and the environmental load related to the construction of infrastructures. Published LCA studies on road [8] and rail [9,10] systems very seldom account for infrastructures in detail, mainly focusing on the construction of vehicles and their fuel use. Since trains cannot run without railroads or cars without roads, infrastructures must be included into the energy and environmental accounting of transport systems. Such a choice strongly affects the final performance of the investigated modalities.

In the present work we focus on resources and energy demand over the whole life cycle of air transport systems and provide performance indicators accordingly. Results are compared to other ones related to road and railroad transportation [11,12], previously published by the Authors, with the aim to identify the less resource-intensive transport modalities for better use of available opportunities. One of the underlying reasons of the present study is the worldwide environmental concern related to the scarcity of fossil fuels and the effects of carbon emissions on climate change. The study does not, instead, deal with environmental impacts that are specific of only one modality (e.g., radiative forcing in the troposphere caused by airplanes) or that are characterized by high uncertainty of available data and impact factors. Other more subjective categories such as comfort, and travel security, are also not accounted for.

In order to carry out a reliable comparison of the different modalities, we referred all costs and impacts to one person or 1 tonne of commodity transported over one km, i.e. to functional units typical of transportation systems. The choice of such a functional unit seems the only one that allows a fair comparison of so different transportation modalities by means of so different evaluation methods. In so doing, the comparison can be drawn independently on the distance, provided such a distance is the same for all the transportation modalities investigated We therefore calculated the average demand for resources and environmental support related to such functional units, identified as p-kms and t-kms. By means of a whole-system approach, we were able to calculate and compare the material and energy depletion required as well as the environmental impact generated per functional unit of each analysed transport system, taking into account all the system's steps and components, not just the specific performance of individual vehicles, out of their operational context.

2. Materials and methods

2.1. The approach

The paper compares the environmental load of the air transport modality with highway and railway modalities, in terms of material and energy depletion as well as of demand for environmental support, per unit of passengers and freight transported. The approach used in the evaluation of the case studies compares and integrates three different evaluation methods, namely Material Flow Accounting (MFA) [13] Embodied Energy Analysis (EEA) [14], and Emergy Synthesis (ES) [15]. These methods, deeply rooted in the principles of Thermodynamics [16], complement the traditional economic evaluations and provide additional insight into the feasibility and viability of transportation policies. Description of theory and inner assumptions of each method can be found in the cited literature, and they are not repeated here in detail. MFA suggests large-scale environmental degradation as a consequence of intensive use of abiotic, biotic and water material flows; EEA accounts for intensive use of fossil fuels and fossil fuel-equivalent energy flows, thus suggesting risk for depletion of worldwide energy storages; and finally, ES accounts for global demand for environmental support in the form of environmental services and natural capital exploited and used up. The latter method also accounts for the past work of the biosphere in order to generate the resource storages, in so taking their turnover time and renewability into proper account.

In short, an LCA-like inventory of mass and energy flows is performed for both construction of infrastructures (each input flow allocated according to life time of assets) and operation of subsystems, to become the basis for a large-scale assessment of indirect material flow (MFA) and embodied energy demand (EEA) as well as to allow for a more comprehensive assessment of the environmental work of past and present ecosystem activities in support to the investigated systems (ES). Local-scale input data are converted into MFA, EEA and ES flows by means of conversion factors available from published databases. These factors are most often referred to as Material, Embodied Energy and Emergy Intensities (the latter also named Transformities), the values of which are listed in the web accessible-Table 1.

Unlike in our previous papers [11,12], exergy analysis is not applied here, because the focus has now shifted from process efficiency to the environmental load of transportation service, accounted on a supply-side and whole-system basis. For the same reasons, downstream matter flows (i.e. airborne, waterborne and solid emissions) are also not addressed in details.

2.2. Evaluation steps

The following steps have been implemented for each transportation modality:

- Construction of infrastructures (airport, road, railway, bridges and tunnels). Each flow was divided by the assumed infrastructure life time.
- Construction of vehicles (airplanes, cars, intercity and high speed trains). Each flow was divided by the assumed infrastructure lifetime.
- Operation phase (annual flows).

Table 1
Annual inventory of main material and energy parameters used for air transport evaluation, Italy 2005 [19].

Rome Leonardo Da Vinci International Airport	
Construction materials (amounts divided by 50 years life time of assets)	
Sand and gravel (kg/year)	1.18E+08
Soil moved (kg/year)	6.66E+07
Asphalt (kg/year)	1.36E+08
Ciampino (Rome) International Airport	
Construction materials (amountsdivided by 50 years life time of assets)	
Sand and gravel (kg/year)	2.18E+07
Soil moved (kg/year)	1.30E+07
Asphalt (kg/year)	2.39E+07
Aircraft (Airbus 320)	
Construction input (flows divided by 30 years life time of assets)	
Composite aramidic fiber (kg/yr)	4.84E+02
Aluminium alloy (kg/yr)	2.61E+02
Steel (kg/yr)	3.72E+02
PU foam (kg/yr)	1.24E+02
Electric Energy (kwh/yr)	5.85E+04
Natural Gas (MJ/yr)	1.01E+04
Oil (Mj/yr)	4.46E+02
Water (kg/yr)	1.74E+05
Aircraft operation data (average value for a 500 km trip)	
Kerosene fuel (kg/km)	5.4

In doing so we are able to assess the annual energy and material resource depletion related to each step of the whole transportation process as well as its relation with the surrounding environment: the sum of direct and indirect flows in support of the three consumption steps investigated represents the total annual resource consumption of each transport modality.

What we ultimately obtain, for each modality, is a set of intensive thermodynamic indicators per unit transported that can be easily used for comparison. Material, energy and emergy intensities are, respectively, expressed as g, J, and seJ per p-km, and t-km. Extensive results of each transport modalities can finally be calculated and compared. How distance affects the final results was also investigated for all modalities, in order to take into proper account the allocation of infrastructural and vehicle cost to the chosen functional unit.

Data for road and railway transport systems are taken from our previous works [11] and [12] in which we provided an assessment of such modalities. In the present paper we present a detailed analysis of the air transportation mode on the same itinerary, in so integrating and completing our previous results and thus allowing a proper evaluation of all available transportation means over a mobility axis that is crucial for the economic life of the country. Concerning highway and train traffic, the investigated itinerary is from Napoli to Milano; concerning air traffic, centered around Roma Airports, calculations were adjusted in order to take into account the main fraction Roma-Milano and the very minor Roma-Napoli. Our highway study accounts for all traffic over the investigated Napoli-Milano road axis, including local use by cars and trucks that travel only over short distances (highway has entrance and exit stations every 30–40 km). IC (intercity) trains connect all main cities over a rail line not purposely designed for high speed (never more than 150 km/h); frequent stops and slow speed make the IC train less attractive for long-distance travellers, but allow easy connections to the large number of minor lines that compose the Italian railway system. HS trains are designed for travelling at speed higher than 250 km/h on a dedicated line and only connect the most important Italian cities (Napoli, Roma, Firenze, Bologna and Milano). Such a dedicated line is almost completely flat, in order to allow the train to travel at the required speed; therefore a large number of galleries and bridges are needed to cross the Appennini mountains in central Italy without up-and-down pathways.

The comparison of different transport modalities over the Milano-Napoli axis (about 800 km) is also projected over a theoretical distance of 4000 km, that is the final length of the European High Speed Train Axis that will link Lisbon (in Portugal) to Kiev (Ukraine). Such a reference is made possible by the Europe wide implementation of the TEN-T project (Trans European Transport Network) supported by the European Union [17] and still in progress. TEN-T encompasses railway, high speed railway, terrestrial and acquatic roadways (but not airways), with a foreseen investment of about 300 billion Euro for a total length of 47,579 km. High speed railway account for 80% of total investment and 30% of total distance covered [18]. The large investment allocated to high speed train modality as well as its huge average cost per km (15.5 M€/km, without including the actual cost of trains and management) call for a careful evaluation of the overall large-scale benefits and costs, with special focus on energy and environmental aspects. Such an evaluation may allow for a comparison with benefits and costs of possible different uses of the same investment, e.g. alternative transportation options, including air transport. We try in the present paper to provide a framework for the analysis and apply it to a national case, in the hope that other similar studies are performed elsewhere for comparison.

For all the transport sub-systems presented in this paper, data related to the construction of galleries were carefully accounted for. Unfortunately, it was not possible to obtain similarly accurate and detailed data about piers used for bridges and viaducts construction because each of them shows different characteristics (mainly dependent on length, height and ground typology) and were constructed by different companies over a considerable range of time. It was impossible to contact all of them to obtain the precise project tenders. Such a lack of data unavoidably may lead to an underestimate of final results, although the relative comparison between road and railway systems should not be significantly affected. In fact, roads and railways in the considered case study lay most often on the same kind of structural support. As a result of the difficulty in contacting all the companies involved in the construction of the infrastructures, some minor items might have been unavoidably neglected.

2.3. Sensitivity analysis

In order to double-check the reliability of results, a sensitivity analysis was also performed (as partially detailed in the Appendix) by implementing a calculation procedure on an Excel platform. We gradually assumed a variation of the main inflows from ±10% to ±20%, and assessed to what extent such a variation affected the final results (i.e. the matter, energy and emergy based performance indicators). The assumed variations were independently and jointly applied – by means of a variable multiplicative cell – to:

(a) the raw amount of each input flow;
(b) the values of matter, energy or emergy intensities;
(c) occupancy factors in the different transportation modalities and/or European countries; and
(d) turnover years assumed in calculations of infrastructures and vehicles.

In doing so, it was possible to account for the uncertainty of estimates, possible differences of intensity factors, as well as oscillations of data across time and countries, with non-linear effects on final results. The procedure was applied to selected individual flows larger than 5% ot total matter, energy and emergy use (electricity, steel, concrete, etc). Results pointed out the importance of flows simultaneously characterized by large amounts and by large intensity values (e.g. electricity, steel, occupancy factors), more likely to affect changes of the related indicators. However, within the range of the assumed uncertainty and oscillations of input data, the final results were not significantly affected (see Appendix for details). A variation of turnover time of infrastructure within the above indicated ranges is only capable to affect the final results of those cases in which infrastructure plays a very important role (e.g.: HS railway) and for those methods that assign a huge importance to material flows (e.g. MFA and ES). Such a finding calls for accurate double-check of input data and turnover assumptions. Sensitivity analysis is specially important for the evaluation carried out in the present study. Although it relies on average Italian data, sensitivity results ensure its applicability also to the European context.

2.4. Allocation procedures

Roads, railways and airports support both passenger and freight transport. A choice about allocation method should involve firstly the relative amount of traffic supported. Although different allocation procedures could have been chosen, we decided to allocate all infrastructural costs linearly according to total weight of vehicles (mass of vehicle + mass of passengers or commodities) that use such infrastructures. Our choice is based on the evidence that, a part from weathering, degradation of infrastructure over time is mainly related to the pressure of use, which we assumed to be linearly proportional to the weight of the vehicles. We applied the same rationale to the degradation of vehicles (including airplains). In order to compare passengers and freight transport and allocate infrastructure and maintenance input accordingly, an average passenger weight of 65 kg was assumed. Based on such an assumption, the final weight of an IC passenger train is about 576 tonnes (out of which only a negligible 6% is passenger weight) versus the average weight of 984 tonnes for a freight transportation train (55% of which is commodities transported, and 45% train mass). On the sub-system level, commodity traffic represents the 96.2% of total weight transported via highway, while it is 78.8% for IC railways and 84.4% for HS trains (planned freight transport when full operativeness is achieved). Under the assumption that highway commodity transport affects highway degradation by 96.2%, non-linearity as a function of truck and car weight should not be considered significant.

The situation – and therefore the allocation procedure – is completely reversed as far as air transport is concerned. In fact, air passenger transport represents respectively 93.7% and 89% of the total weight moved in Leonardo da Vinci and Ciampino Airports, respectively (the two main airports in Roma, Italy).

3. The systems investigated

3.1. The air transport case study

3.1.1. Airport construction

In order to assess and verify the contribution of the infrastructure to the whole environmental performance of air transport systems, two different airports have been investigated: the Leonardo da Vinci International Airport, i.e. the main airport of Rome (Italy), and the Ciampino Airport (Rome, Italy), smaller airport mainly used for domestic and low cost trips and military operations. Data have been kindly supplied by Rome Airports Company [19].

These airports are very different in size, traffic intensity and services supplied to customers; selected characteristics are shown in Table 2. Data show that the yearly consumption of electricity and fuels in Leonardo da Vinci Airport is about 5–9 times higher than for the much smaller Ciampino Airport: this can be mainly ascribed to the different amount of people and freight transportation (Ciampino only 9% of Leonardo da Vinci airport), the different size of the landing and take-off tracks (Ciampino about 18% of Leonardo da Vinci), and to the different size of the shopping mall areas (Ciampino about 5% of Leonardo da Vinci).

A life time of 50 years is assumed for airports buildings, while a 5 years life time is assumed for runways (essentially the duration of asphalt of the track surface). The total amount of material and energy consumption for airport infrastructure is not dependent on the travel distances, while – of course – calculated indicators per functional unit of passenger and freight transported do. Therefore, the yearly amount of material, electricity and fossil fuel used by each airport is divided by the amount of yearly passenger and freight transit in order to ascertain how much the infrastructure cost affects the final performance indicators of air traffic.

Table 2
Rome Airports data [19].

Items	Leonardo da Vinci	Ciampino
Passengers (units/yr)	2.8×10^7	2.5×10^6
Freight (t/yr)	1.32×10^5	2.17×10^4
Track area (m^2)	4.04×10^6	7.46×10^5
Terminal area (m^2)	2.50×10^5	1.03×10^4
Trade area (m^2)	1.9×10^4	1.12×10^3
Electricity consumption (kWh/yr)	1.56×10^8	7.50×10^6
Diesel consumption (l/yr)	2.17×10^6	2.98×10^4
Natural Gas (m^3/yr)	7.60×10^6	3.23×10^5

Yearly traffic data are assumed as constant amounts over the infrastructure lifetime, disregarding forecasts about next annual growth. Such a conservative choice could have been considered inaccurate one year ago, while it seems much more reasonable now, in the presence of decreasing air traffic caused by economic crisis, gradual increase of air fares, and finally recent unexpected competition by high speed trains. In so doing we get at least a rough estimate, for example, of the future electricity requirement and fuel consumption per unit of passenger (or freight) transported, to be used for scenario construction. The sensitivity analysis discussed above and in the Appendix confirms that such a choice is not crucial for the reliability of performance indicators.

3.1.2. Aircraft construction

The Airbus 320 aircraft family (Airbus A319, A320, etc) is the reference vehicle for our study, based on the fact that it is the most commonly used by European air companies. For longer distances within Europe and outside, the Airbus A330 family is used. According to [21] the Airbus and Boeing families show very similar performances (A330/A340 versus Boeing 747, and A320 versus Boeing 737). The A320 aircraft family, the most common in Europe, has an empty weight of 40.6 tonnes, and a maximum payload capacity of 180 people per trip. The A330 aircraft family (A340, etc) has a maximum payload capacity of 330 persons per trip and an empty weight of 122 tonnes.

Data about the material and the energy consumption for industrial construction of airplanes are taken from the Environmental Declaration of the Airbus Company [20]. According to the Company declaration, the aircraft lifetime was assumed as about 30 years. During such a period an average distance of about 43 million of kilometres can be covered.

The material composition of the last aircraft generation is on average:

- 39%, aramidic fibers and epoxy resin;
- 21%, aluminium alloy;
- 30%, steel;
- 10%, PU foam.

The whole aircraft assemblage process requires on average 9.75 MWh consumption of electricity per seat, equivalent to an indirect cumulative consumption of 14.01 MWh of natural gas and 0.62 MWh of oil for electricity production [21].

The material and energy input to make the airplane was then divided by the total number of p-kms and t-kms supported during the whole life cycle, calculated as the product of the number of seats (or tonne, at the assumed payload capacity) times the life time kilometres.

3.1.3. The flying operation

Notwithstanding the large amount of material and energy required to construct the airplane and the airport infrastructures, the fuel economy during the flight emerges as the crucial factor of the whole air transport system.

The flying cycle is composed of several steps: the taxi in, the take-off, the climb, the cruise, the descent, the landing and the taxi out. Usually all the operations occurring below 1000 m (3000 feets) altitude, are grouped as Landing and Take Off cycle (here after, LTO).

The amount of fuel consumed during the LTO cycle is tremendously high: for a short-distance trip (250 km) it represents about the 50% of the whole flight cycle consumption. Clearly such a percentage decreases with increasing distance. Therefore, for distances longer than 2800 km, the LTO fuel consumption decreases to 10% of total fuel use. This is because the LTO consumption can be considered as a constant amount, similarly to the infrastructure related costs, while the cruise fuel consumption clearly depends on the distance covered.

For passenger transport load factor is a crucial factor. It is, of course, itinerary and season specific. The Roma-Milano itinerary is surely the one with the highest load factor in Italy and it can be certainly referred to as a representative parameter for European traffic. However, we assumed two different load factors for our calculation: an optimistic 80% of the maximum payload capacity (144 passenger per trip), and the actual average Italian load factor, equal to 50% of the payload capacity (90 passenger per trip). For cargo aircraft a 100% load factor has been assumed. Such a choice allows for a double comparison with the other modalities, one based on actual Italian load factors, and another one based on expected and still possible increase of passenger traffic in the near future. Data regarding aircraft fuel economy are taken from the CORINAIR report [22].

3.2. The highway case study

The highway chosen is the main Italian road axis; in the year 2001, total traffic was of 1.19×10^{10} v-km (vehicle-km) equal to a total passenger traffic of 2.10×10^{10} p-km; commodity transport was 4.09×10^{9} v-km equal to 3.6×10^{10} t-km [23]. The total length of the investigated highway is 803 km, and the materials required for its construction are shown in Table 3.

Road construction data were mainly available from tenders and design developed by the owner company [23]. Data were integrated, when needed, by means of further information provided by subcontracting companies. A lower road layer was mainly made with compacted gravel and other inert materials, for which an average lifetime of 70 years was assumed on the basis of interviews with engineering personnel of such companies. The lower layer was then covered by upper layers made with bituminous materials to which a 5-years turnover time was assigned. Concrete reinforcement banks were also built when this was required by the slope or the nature of the soil. Such a reinforcement was needed for about 10% of total road length. The machinery used for road construction was also accounted for, and a lifetime of 30 years was assumed.

Lifetime assumed for vehicles that use the highway is 10 years, according to an estimate of the average turnover time of vehicles in Italy performed by the Automobil Club Italia, the Italian Association of Drivers [23,24]. Such an estimate should be considered a conservative one, because in the most recent years incentives were given to drivers in order to replace old vehicles with new ones fulfilling the EU directives for energy saving and lower emissions. As a consequence, recent turnover time of vehicles was shortened.The average load factors used are 1.8 passenger per car, and 11.8 tonnes per truck [23,24]. Fuel economy used for vehicles is shown in Table 4.

Table 3
Materials required for the construction of the terrestrial infrastructures of the Milan-Naples Axis [12].

Items	Highway (kg)	HS Railway (kg)	IC Railway (kg)
Sand and gravel	6.48×10^{10}	2.64×10^{11}	2.78×10^{11}
Top soil moved	6.22×10^{10}	9.78×10^{10}	7.76×10^{10}
Asphalt	7.52×10^{9}	n.a.	n.a.
Concrete	4.48×10^{8}	2.92×10^{10}	2.52×10^{10}
Reinforced concrete	1.34×10^{8}	2.76×10^{9}	2.76×10^{9}
Concrete for traffic divider	7.92×10^{8}	n.a.	n.a.
Steel for guardrail	1.29×10^{8}	n.a.	n.a.
Steel in track	n.a.	1.85×10^{8}	1.87×10^{8}
Steel in electric poles	n.a.	2.6×10^{7}	2.19×10^{6}
Steel in tunnels structures	7.68×10^{8}	2.50×10^{9}	1.81×10^{9}
Copper in electric cables	n.a.	7.72×10^{6}	7.78×10^{6}
Diesel for construction	1.89×10^{6}	2.81×10^{10}	1.84×10^{7}

3.3. Intercity and high speed railways

IC Railway and HS Railways axis chosen for the comparison lay on the same track (Milan-Naples axis) with a total length of about 800 km. A lower layer of gravel and small stones supports a track structure made with steel and cement: a lifetime of 50 years is assumed for the underground layer, while a 10 years lifetime is assumed for the track. Railway construction data were provided by RFI Spa [25], the public Company managing the rail transport in Italy. Railways require a higher amount of material compared to the highway and this is mainly because of the larger number of tunnels. Assumptions for the lifetime of HS infrastructures are the same adopted for the "normal" railway, used by IC trains. The two train sub-systems show some non-negligible differences: HS Railways require higher specific power to move the trains at the required speed (8 MW versus 6 or 4 MW for the IC trains), and are characterized by a lower payload capacity (550 passengers for HS trains versus 700 passengers for IC trains). Moreover, in order to be able to keep the highest possible constant velocity, HS trains cannot run on up-and-down pathways. For this to be possible, many more tunnels and viaducts are needed, to keep the track on a horizontal pattern. Such a technological requirement increases dramatically the material and fuel consumption for infrastructures (on the Milan-Naples axis, 196 km of tunnels are required for the HS railway, that is 40% more than the 141 km needed for the IC railway). Railway data are shown in Table 3.

4. Results

Figs. 1–3 show how the calculated performance indicators change with increasing distance. Before discussing each indicator in detail, it is worth noting that the most important features of our diagrams (decline, increase, intersection of different modalities) occur at distances below 1000 km, that are the most realistic

Table 4
Fuel economy for road vehicles.

Items	km/l
Passenger gasoline car	
<1400 cc	15.3
1400–2000 cc	13.3
>2000 cc	10.6
Passenger diesel car	
<1400 cc	25.0
1400–2000 cc	20.1
>2000 cc	14.2
Gasoline truck	
<3.5 t	5.0
>3.5 t	3.3
Diesel truck	
1.5–3.5 t	6.0
3.5–7.5 t	6.0
7.5–16 t	4.1
16–32 t	3.1
>32 t	2.4

Data about fuel economy of car and truck were estimated by cross-checking information from the Italian National Statistic Institute [15] and Automobil Club Italia [16]. These data were used to define a virtual "weighted average highway vehicle" with average fuel performance, average size and emissions.

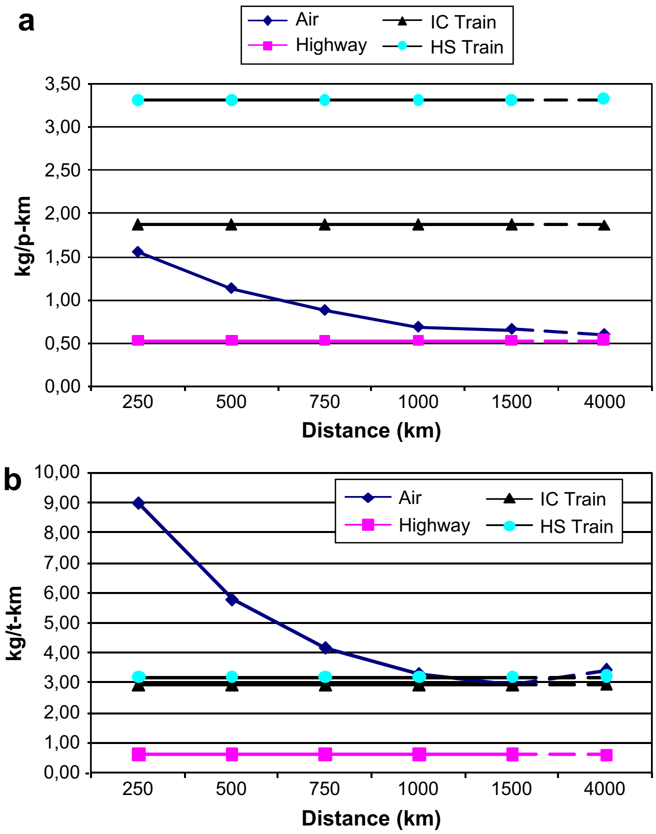

Fig. 1. (a) Comparison of material input per p-km for air, train and highway passenger transport. Air related MI (calculated under the assumption of 50% of maximum payload capacity) declines steadily with distance, due to the declining importance of infrastructure in such a transportation modality. Airplanes are always competitive with HS train and IC trains, concerning material intensity indicators, due to the dominating influence of infrastructure. (b) Comparison of material input per t-km for air, train and highway freight transport. Air related MI declines steadily with distance, due to the declining importance of infrastructure in such a transportation modality. Under the same assumptions used for (a), air transport is never competitive, while highway truck transport is always the less intensive option, as far as material intensity is concerned.

distances for Europe wide travelling. Some non-negligible trends are also shown in the range 1000–1500 km, while instead no new patterns are shown above the 1500 km threshold.

4.1. MFA indicators

The aim of the MFA methodology [26,27] is the assessment of the amount of materials (abiotic, water, air and biotic) directly and indirectly moved, degraded and/or depleted to obtain a unit of the product or service considered: for each transport modality, MFA provides the amount of global Material Input Per Service (MIPS) expressed as kg/p-km for passengers and kg/t-km for freight.

Results of MFA of air transport are shown in Table 5. MIPS values have been calculated for different distances, in the two airports considered, both for passenger and commodity transportations.

Results confirm that increasing distance makes the material requirement per functional unit to decrease proportionally. This is because the final value is affected by the materials directly and indirectly used for:

(a) the construction of the airport,
(b) the construction of the aircraft,
(c) the yearly maintenance,
(d) the fuel consumed during the LTO cycle, and
(e) the fuel consumed during the rest of the flight.

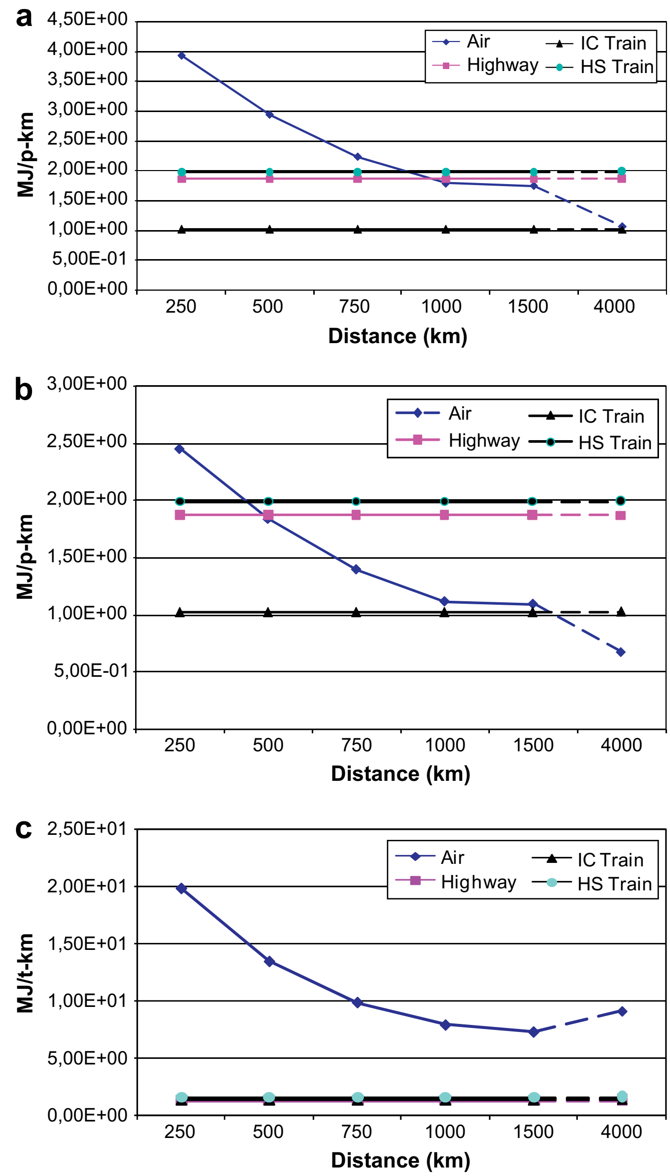

Fig. 2. (a) Comparison of embodied energy input per p-km for air, train and highway passenger transport. A 50% of maximum payload capacity was assumed for air transport. Air transport becomes competitive with High Speed train and highway car transport at a distance of 1000 km, while it is never competitive with intercity train. (b) Comparison of embodied energy input per p-km for air, train and highway passenger transport. An 80% of maximum payload capacity was assumed for air transport. Air transport becomes competitive with high speed train and highway car transport at a distance of 500 km, while it is never competitive with intercity train. (c) Comparison of embodied energy input per p-km for air, train and highway freight transport. Because of their small freight payload capacity, airplane performances are always much worse than all other modalities.

Items from (a) to (d) are substantially independent of the total flight distance (although their influence on the final indicators is not, since total p-kms and t-kms increase with distance), while (e) is directly proportional to the length covered. Therefore, when distance increases the importance of inputs (a)–(d) decreases and MIPS values are only affected by the specific fuel consumption of the aircraft. Results also show that infrastructures affect the final values of performance indicators much more for smaller airports, probably because of the lower traffic intensity. Air transport data from Table 5 are compared with the other modalities in Fig. 1a.

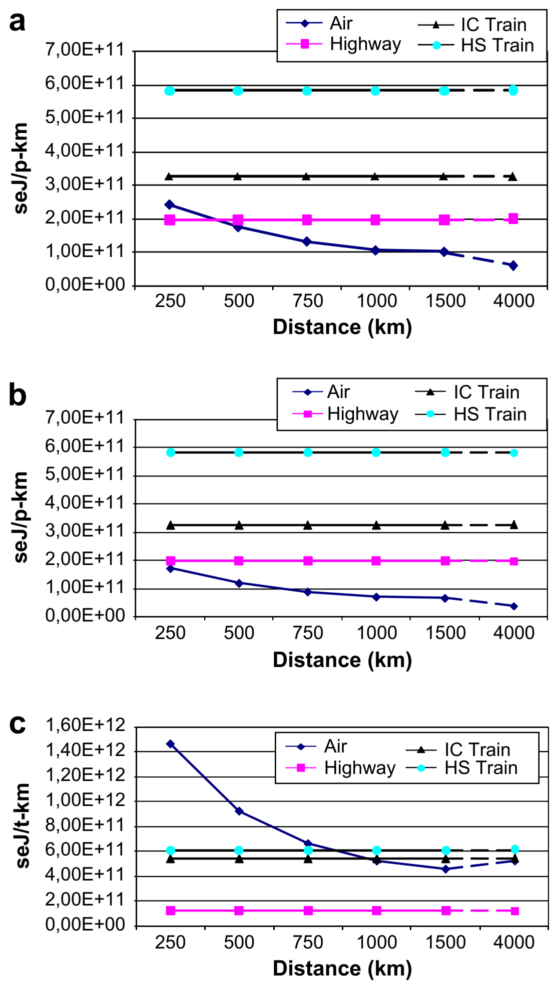

Fig. 3. (a) Comparison of emergy input per p-km for air, train and highway passenger transport. An 80% of maximum payload capacity was assumed for air transport. Because of the marginal role of infrastructures for air transportation modalities and the increased importance of material infrastructures of the other modalities according to the Emergy Synthesis method, air transport is always the most competitive transportation pattern, as far as emergy is concerned. (b) Comparison of emergy input per p-km for air, train and highway passenger transport. A 50% of maximum payload capacity was assumed for air transport. Under such an assumption, air transport becomes competitive with highway car transportation only for distances higher than 400 km. (c) Comparison of emergy input per t-km for air, train and highway freight transport. Under an emergy point of view, the most competitive transportation pattern is the highway truck modality.

Material intensities of terrestrial transport modalities appear independent of the distance covered: this is because materials and energy used for road and railway construction have been allocated to the whole p-km and t-km traffic over the entire life time of the infrastructure [12]. In other words, the material intensities of terrestrial transport systems are expressed "per km" of built infrastructures, and this value is not affected by the distance. Longer car and train trips require longer roads and longer rails, so that the relative importance of infrastructures within the final indicators (mass or energy per p-km) remains constant. Instead, air transport infrastructure and vehicles gradually lose their relative importance when distance increases and only fuel consumption keeps affecting the final MFA indicators to a significant extent.

Notwithstanding the assumed low passenger occupancy, Fig. 1a shows that passenger air transportation is always less material intensive than railway and HS railway systems. This can be easily understood by considering that the construction of 1 km of railway tunnel requires 12,400 tonnes of steel, and that the weight of a 10-coach train is about 550 tonnes. On the contrary the mass of a 180-passenger airplane is in the order of 40 tonnes, and the only infrastructure required is the landing track and the air terminal. According to Fig. 1a, passenger transport by car is less material intensive than by airplane for distances below 1500 km, while for higher distances this gap becomes increasingly narrower.

Freight transport requires further considerations: the payload capacities for cargo aircraft are in general low, typically ranging from 20 to 30 tonnes per trips, so that freight air transport is characterized by higher material and fuel intensity than road and railway systems. The low amount of freight per trip also causes a higher allocation of the airport infrastructure if compared with the passenger air transport. Freight transport comparison is shown in Fig. 1b. As a result of their low payload capacity, airplanes perform worse than the terrestrial systems for distances below 1300 km. From 1300 to 2500 km, airplanes perform better than railway systems. Finally, for distances higher than 2500 km the need for bigger and more powerful airplanes causes the increase of the specific fuel economy, so that differences among MIPS values of airplanes and trains become negligible.

The material intensity for passenger and freight transport by highway is always lower than the other modalities because of the huge road traffic intensity that reduces drastically the material cost of infrastructures per unit transported.

Table 5
MFA results for passenger and freight air transport.

	Distance (km)	MIPS[a]	Infrastructure fraction[b]
Passenger transport			
Rome Ciampino Airport	238	1.54 kg/p-km	20.3%
	460	1.13 kg/p-km	14.5%
	875	0.83 kg/p-km	10.5%
	1400	0.65 kg/p-km	8.6%
	1800	0.66 kg/p-km	6.9%
	4000	0.59 kg/p-km	2.3%
Leonardo da Vinci Airport	238	1.39 kg/p-km	12%
	460	1.05 kg/p-km	8%
	875	0.79 kg/p-km	6%
	1400	0.63 kg/p-km	5%
	1800	0.62 kg/p-km	4%
	4000	0.58 kg/p-km	1%
Freight transport			
Rome Ciampino Airport	238	8.88 kg/t-km	50.1%
	460	5.80 kg/t-km	39.9%
	875	3.87 kg/t-km	31.8%
	1400	2.93 kg/t-km	26.5%
	1800	2.77 kg/t-km	22.0%
	4000	3.28 kg/t-km	5.0%
Leonardo da Vinci Airport	238	6.64 kg/t-km	33.3%
	460	4.64 kg/t-km	24.9%
	875	3.26 kg/t-km	19.0%
	1400	2.55 kg/t-km	15.5%
	1800	2.48 kg/t-km	12.7%
	4000	3.21 kg/t-km	2.9%

[a] MIPS: material input per unit of service. MIPS represents the whole direct and indirect amount of material used up to obtain a unit of considered product or service.
[b] Infrastructure fraction: represents the percentage of contribution of the infrastructure to MIPS.

4.2. EEA

EEA [28] accounts for the direct and indirect energy cost of all the material and energy flows supporting each step of the investigated systems. It provides an estimate of the total "commercial" (i.e. not freely available: fossil fuels, nuclear, etc, in terms of oil equivalent amounts or MJ) energy requirement of the service considered; the final energy intensities are expressed as MJ/p-km and MJ/t-km.

Unlike the previous MFA case, EEA results (Table 6) show that the energy used to build the airport infrastructures and the vehicles is not so significant when compared to the fuel directly consumed during the flight: the weight of energy cost of infrastructures ranges between 2.35% of the total energy requirement, for distance less than 250 km, and 0.43% for distance more than 1800 km. For increasing distance, the energy requirement per unit transported tends to coincide with just the specific fuel economy of the airplanes, as already pointed out for MFA results. Energy results confirm distance as a critical parameter, in order to properly assess the performance of the air transport system, while instead highway and railway systems with constant loading factor and constant average speed show energy per p-km and energy per t-km independent of trip length. Comparison with other transport modalities is shown in Fig. 2a–c, where two payload capacities are assumed for air transport, for the sake of better understanding of options available.

Fig. 2a and b shows at what distance air transport could be considered a better or a worse option compared to the present terrestrial transport to move passengers within the assumptions described in the previous sections. Figures show the comparison of air transport with highway car transport at 1.8 passengers per car, and IC and HS trains at 50% loading factor, corresponding, respectively, to 350 and 250 passengers on board (all average Italian load factors). Comparison is carried out assuming for air traffic both the present average 50% load factor (90 passengers on board, Fig. 2a) and an optimistic 80% load factor (144 passengers on board, Fig. 2b). For a 50% loading factor (that is the actual loading factor in Italy and might decrease further as a consequence of the present crisis of the air transport sector) Fig. 2a shows that the air transport is more energy intensive than the other modalities: airplanes would perform better than cars only for distances higher than 1000 km, and better than HS train for distances higher than 1300 km. In this case the gap between airplanes and IC trains would be much higher.

Under the most optimistic expectations (80% loading factor, Fig. 2b) the air transport would show a global energy intensity per p-km lower than car transport for distances higher than 460 km. Under the same assumptions, the airplane could also be considered an energy saving option respect to the HS trains for distances higher than 350 km. IC trains can be always considered as the less energy intensive way to move people.

Fig. 2c shows the results of freight transport comparison: because of the very low loading capacity (25 tonnes for short-medium distance and 35 tonnes for long distances), the air transport systems always appear as the most energy intensive option.

Table 6
Embodied Energy results for passenger and freight air transport.

	Distance (km)	Energy[a]	Infrastructure fraction[b]
Passenger transport			
Rome Ciampino Airport	238	3.93 MJ/p-km	13.60%
	460	2.94 MJ/p-km	9.16%
	875	2.24 MJ/p-km	8.10%
	1400	1.79 MJ/p-km	7.66%
	1800	1.75 MJ/p-km	5.31%
	4000	1.63 MJ/p-km	2.32%
Leonardo da Vinci Airport	238	3.72 MJ/p-km	8.79%
	460	2.84 MJ/p-km	5.85%
	875	2.17 MJ/p-km	5.18%
	1400	1.74 MJ/p-km	4.91%
	1800	1.72 MJ/p-km	3.40%
	4000	1.62 MJ/p-km	1.54%
Freight transport			
Rome Ciampino Airport	238	19.82 MJ/t-km	38.34%
	460	13.41 MJ/t-km	28.41%
	875	9.82 MJ/t-km	25.99%
	1400	7.83 MJ/t-km	24.46%
	1800	7.27 MJ/t-km	17.82%
	4000	9.11 MJ/t-km	5.56%
Leonardo da Vinci Airport	238	16.92 MJ/t-km	27.53%
	460	12.00 MJ/t-km	19.56%
	875	8.85 MJ/t-km	17.74%
	1400	7.14 MJ/t-km	16.63%
	1800	6.77 MJ/t-km	11.84%
	4000	8.92 MJ/t-km	3.61%

[a] Calculated as the whole direct and indirect amount of energy used up to obtain a unit of considered product or service (MJ/unit transported).
[b] Infrastructure fraction: represents the contribution of the infrastructure to the total energy use.

4.3. ES

ES provides an assessment of environmental sustainability based on the total demand for resources and environmental services on the global scale of the biosphere. Materials, energy sources, free environmental flows (such as rain, wind and solar radiation), and finally human labour and services required directly and indirectly to provide a product flow or storage are expressed in terms of solar equivalent joules, seJ [29]; specific emergy factors (seJ/g; seJ/J; seJ/p-km; seJ/t-km, etc) provide a measure of total environmental resource requirement per unit of product or service. Results of the ES application to passengers transport are listed in Table 7 and their dependence on distance is graphically shown in Fig. 3a and b.

Emergy results are both interesting and somehow surprising. When calculations are performed under an assumption of 50% of the maximum payload capacity (Fig. 3a), highway car transport appears as the less emergy intensive modality for distances below the 400 km. For longer distances air transport shows the lowest emergy intensity. Fig. 3b shows that air transport under an optimistic assumption of 80% loading factorwould always perform better than terrestrial transport modalities, within the uncertainty ranges highlighted in the sensitivity analysis (Appendix). As for the MFA results, this finding can be explained by considering that terrestrial transport modalities require a huge amount of infrastructures for each km of covered distance, while the only infrastructure required by air transportation is a departure and a destination airport. Since ES accounts for direct and indirect environmental support, it includes the past biosphere work to provide resources as well as the present work and environmental services (provided for free by nature) to keep the system running (e.g., wind to disperse pollutants, not only fuel and materials). Such additional input is larger for terrestrial systems than for air transport (although further exploration is needed for better understanding of the actual flight impacts different than just emissions and resource demand).

Air freight transport, shown in Fig. 3c, is very emergy intensive for short distance, showing a value of 1.2×10^{12} seJ/t-km versus 5.47 and 6.13×10^{11} seJ/t-km of IC train and HS train, respectively. Such a gap decreases very fast with increasing distances, so that air freight transport becomes less emergy intensive than rail systems for trips longer than 800 km.

Road freight transport appears always to be the most sustainable option. Its low emergy intensity (1.25×10^{11} seJ/t-km) can be attributed to (a) to the high traffic intensity, that reduces the importance of infrastructure emergy per unit transported, and (b) the low specific fuel consumption of trucks.

Table 7
Emergy results for passenger and freight air transport.

	Distance (km)	Emergy[a]	Infrastructure fraction[b]
Passenger transport			
Rome Ciampino Airport	238	2.43×10^{11} seJ/p-km	22.88%
	460	1.76×10^{11} seJ/p-km	15.90%
	875	1.32×10^{11} seJ/p-km	14.11%
	1400	1.05×10^{11} seJ/p-km	13.34%
	1800	1.01×10^{11} seJ/p-km	9.33%
	4000	9.16×10^{10} seJ/p-km	3.98%
Leonardo da Vinci Airport	238	2.20×10^{11} seJ/p-km	14.53%
	460	1.64×10^{11} seJ/p-km	9.80%
	875	1.24×10^{11} seJ/p-km	8.65%
	1400	9.94×10^{10} seJ/p-km	8.16%
	1800	9.71×10^{10} seJ/p-km	5.63%
	4000	9.01×10^{10} seJ/p-km	2.40%
Freight transport			
Rome Ciampino Airport	238	1.47×10^{12} seJ/t-km	54.03%
	460	9.29×10^{11} seJ/t-km	42.79%
	875	6.68×10^{11} seJ/t-km	39.75%
	1400	5.28×10^{11} seJ/t-km	37.77%
	1800	4.63×10^{11} seJ/t-km	28.79%
	4000	5.26×10^{11} seJ/t-km	9.67%
Leonardo da Vinci Airport	238	1.12×10^{12} seJ/t-km	39.87%
	460	7.55×10^{11} seJ/t-km	29.71%
	875	5.52×10^{11} seJ/t-km	27.18%
	1400	4.42×10^{11} seJ/t-km	25.58%
	1800	4.06×10^{11} seJ/t-km	18.67%
	4000	5.04×10^{11} seJ/t-km	5.79%

[a] Emergy is expressed as seJ/unit transported.
[b] Infrastructure fraction: represents the percentage of the contribution of infrastructure to the total Emergy.

5. Discussion

When different evaluation methods are jointly adopted, their results may not always converge. When this happens, as it is partially the case in the present study, the evaluator faces two alternatives: (a) interpreting a multiplicity of indicators or, (b) assigning a weight to the different indicators in order to unify them into a final aggregate index. We hardly believe that such an aggregate index can be telling and useful for policy, because it necessarily hides too many details. We therefore suggest that a multicriteria approach is adopted, according to Ulgiati et al. (2006) [30]: different answers are acceptable depending on different scales and methods of investigation and require a final compromise among contrasting yet legitimate interests.

The methodologies used to analyze the three transport modalities are based on different paradigms as well as on different spatial and time scales. As a consequence, the final indicators (MIPS, energy and emergy intensities of functional units) show different emphasis on selected aspects. In general, MFA and ES are most sensitive than EEA to the presence of infrastructure and related embodied resources. In addition, ES also focuses on the time embodied in the resources used and provides a measure of sustainability based on their renewability and scarcity. EEA is usually more sensitive to fuels and electricity used by a process (in this case fuels directly used up by vehicles, which make up for the largest fraction of energy used).

Results obtained in this work converge towards identifying the High Speed Train and air transport as the most material and energy intensive transport modalities among the ones investigated, while IC train is always the best option under all the considered points of view: under optimistic, but not impossible, flight occupancy assumptions (80%), airplanes show better performance indicators compared with HS trains over medium distances (>400 km). Results highly depend on the huge amount of steel and concrete required to build up the HS infrastructure and coaches, as well as on the high power (up to 10 MW) required to move the HS trains. Assessing the indirect energy and material consumption sheds light on aspects that are in general disregarded, i.e. the large amounts of resources involved at regional and global spatial and time scales in support to a given transportation process. However, even when the evaluation is restricted to the direct energy consumption, we must be aware that it can be only optimized by increasing the number of passengers (and freight) per trip. Considering that the utilization rate assumed to perform our calculation is already very optimistic (and close to the maximum payload capacity, in the case of HS trains), such improvement can only be expected to play a marginal effect over the final value of indicators. The large impact of HS infrastructures could be also reduced by increasing the number of trains per day, i.e. by using the track more intensively and thus providing a better service. Unfortunately this is also not possible for safety reasons: the high velocity that characterises such a modality imposes a time interval of 15 min between two consecutive trains, and calculation in this work was performed based on the maximum infrastructure capacity consistent with time constraints.

Considering that the construction of HS tunnels requires 12,000 tonne of steel per km, the first question arising from these results is about the real need for HS trains forced to cross the Appennini mountains in Central Italy or the Northern Alps (or mountains in general). The most important outcome of the present investigation is not that below or beyond a specific threshold a given modality performs better than another one, but instead is that modalities claimed to be quite environmentally sound may display much worse performances when all hidden costs are clearly accounted for, or when their dependence on distance is included into the account.

In addition to widely speaking "environmental" issues, concern about the real need for HS Railways is reinforced by socio-economic aspects related to high fares, high maintenance costs and high investments required, which displace competitive projects for railway improvement at local and regional scales: an immediate consequence of HS trains is that local railway becomes a less attractive business and is abandoned on a degradation path.

In Italy and Europe the realization of new HS infrastructures is claimed by EU and national governments as high priority investments (above cited TEN-T project); such a "high speed agenda" is likely to further delay the development of urban and metropolitan railways. Instead, priority on long-distance transport infrastructures should be reconsidered in favor of less resource-intensive metropolitan transport systems, able to replace the daily use of individual cars and – in so doing – capable of generating much more important environmental benefits.

Most often, comparison is drawn only on the basis of direct fuel consumption and ends up with stating that a given modality contributes to fossil energy depletion and global warming much less than another. Such a way of dealing with resource accounting problems is misleading and is most likely to be a shortcut to support further implementation of highly intensive and high-business technological plans, claiming that they are more environmentally sustainable. Our results – based on accounting for hidden resource and environmental costs – highlight the other side of the coin, i.e.

(a) All direct and indirect resource flows, not just direct fuel use, need to be considered when evaluating a transportation pattern.
(b) Proper use of each transport modality (load factor, appropriate range of distances, efficiency) is the key for good environmental performance. Advanced technology in itself is not a step to solution.

6. Conclusion

As already mentioned, this work does not explore the direct contribution to atmospheric pollution and air quality degradation caused by airplane in the troposphere or by terrestrial transportation patterns. We do not wish to state that in general the overall impact of air transport (or other modality) is better or worse than alternative transport modes. We are not even suggesting that airplanes should replace IC train and HS trains, based on their claimed or real better performance under a selected set of points of view. Our issue is that biophysical and environmental indicators point out the (most often hidden) huge costs faced in order to reach high speeds and in order to move people and commodities at very large distances, as dictated by globalized trade and societies.

Results obtained in this work highlight that when cars and trains are not properly used (i.e. they are operated within a range of distances where better options are available, or at a low 50% of their maximum payload capacity) even airplanes might be considered as a relatively "less resources-intensive" option.

The service of necessary mobility (commuting and commodity transport at local scale) does not necessarily imply that high-speed/high-technology/long-distance patterns are favored. As a consequence of the high absolute thermodynamic and environmental costs of such modalities as well as the high relative cost of infrastructures compared to total costs, policies aimed at implementing sustainable transport patterns should favor local products, short-distance/low-speed commuting, and light-infrastructure transportation services.

Finally, thermodynamic and environmental costs only cover a selected set of impacts involved in transportation. Other aspects that may also affect the final choice (travel comfort, time required, fare cost, among others) are not dealt with in the present paper, but their importance should not be disregarded in transportation policy making. It is not a given that a transportation modality is always to be preferred to another at any time, nor that economics should always rely on high-tech transportation patterns for all uses. Proper matching of tools to needs is the likely way to implement a sustainable transportation policy.

Appendix

Sensitivity analysis

While data related to the fuel economy of vehicles are well known, reproducible and tested, data concerning materials, electric energy and fuels used in the construction of infrastructures are obtained from cross-checking of several sources of information, integrated – when necessary – by Authors' calculation and educated guesses. In order to point out the crucial data and uncertainty risks, a sensitivity analysis was therefore performed for all calculated indicators. In the following, only results related to EEA are shown as an example of the procedure used and results obtained.

Air transport

According to Table 6, the contribution of the energy cost of infrastructures to the final energy intensity of passenger transport is very low; this in turn reflects a low sensitivity of the calculated indicators to the uncertainty of infrastructures data (airport + vehicle construction). Natural gas, diesel, electricity and asphalt represent the main energy input flows used for infrastructure (Table 1): the effects caused by variations of 10% of their values can be double-checked individually and altogether. Results (Table A1) clearly show that the uncertainty about input values has a very low influence on the calculated intensity values throughout the increasing distance considered. Instead, a variation of +10% in fuel economy during flight operation linearly affects the final values of energy intensity and leads to expected increments of 9.63–9.93% (Table A2).

Table A2
Effects of 10% variations in fuel economy on final energy intensity values.

Distance (km)	MJ/p-km[a]	Effect of 10% variation
238	2.42	9.63%
460	1.88	9.74%
875	1.44	9.81%
1400	1.15	9.83%
1800	1.16	9.86%
4000	1.10	9.93%

[a] Values from Fig. 2a.

High speed train

The large amount of steel and concrete required to make tunnels and tracks accounts for 35.5% of the whole energy intensity per p-km [12]. Table A3 shows the effects of +10% variations of steel and concrete input on the final values of energy intensity.

Table A3
Effect of +10% variations of the infrastructures input flows on the HS energy intensity.

	Reference value [12]	concrete + 10%	steel +10%	all +10%
MJ/p-km	1.99	2.02	2.02	2.05
Variation	0%	1.6%	1.3%	2.9%

Instead, an increase of 10% of the electricity used to power the trains translates into a 6.4% growth of the final energy intensity value (2.12 MJ/p-km [12]).

Table A1
Effect of +10% variations of the infrastructure input on the final Energy Intensity values.

Distance (km)	MJ/p-km[a]	Electricity + 10%	Asphalt + 10%	Natural gas + 10%	Diesel + 10%	All inputs + 10%
238	2.47	1.06%	0.09%	0.16%	0.06%	1.37%
460	1.85	0.73%	0.06%	0.11%	0.04%	0.95%
875	1.38	0.52%	0.05%	0.08%	0.03%	0.67%
1400	1.09	0.41%	0.04%	0.06%	0.02%	0.53%
1800	1.09	0.32%	0.03%	0.05%	0.02%	0.41%
4000	1.01	0.08%	0.01%	0.01%	0.00%	0.11%

[a] Values from Fig. 2a.

Highway

Also in this case the energetic cost of infrastructures is quite low compared to the huge consumption of fuel used directly. As a consequence, the influence of infrastructural changes affects the final values by less than 1.5% (Table A4). On the contrary, an increase of 10% in fuel economy leads to a variation of 8.14% in the final energy intensity.

Table A4
Effect of 10% variation of the infrastructures inputs on the HS energy intensity.

	Reference value [12]	Asphalt + 10%	Steel + 10%	All + 10%
MJ/p-km	1.86	1.865	1.89	1.89
	0.00%	0.02%	1.41%	1.42%

When focus is only placed on embodied energy, the larger direct influence of changes in energy flows supporting the operation phase compared to the energy invested in the construction phase is not unexpected. The same sensitivity method applied to MFA results (with main focus placed on material flows) or Emergy Synthesis results (with focus placed on embodied environmental support to all kind of resource inflows) assigns a smaller weight to variations of pure energy flows and points out the influence of other different kinds of supporting resources, less linearly related to the final results.

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