Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Energy 33 (2008) 760–775
ENERGY
www.elsevier.com/locate/energy

A thermodynamic, environmental and material flow analysis of the Italian highway and railway transport systems

M. Federici[a,*], S. Ulgiati[b], R. Basosi[a]

[a]*Department of Chemistry, Center for Complex System Investigation, University of Siena, Via Alcide De Gasperi 2, 53100 Siena, Italy*
[b]*Department of Sciences for the Environment, "Parthenope" University of Napoli, Centro Direzionale, Isola C4-I-80143 Napoli, Italy*

Received 5 May 2006

Abstract

The goal of this work is to provide a multi-method multi-scale comparative picture of selected terrestrial transport modalities. This is achieved by investigating the Italian transportation system by means of four different evaluation methods: material flow accounting (MFA), embodied energy analysis (EEA), exergy analysis (EXA) and emergy synthesis (ES). The case study is the main Italian transportation infrastructure, composed by highways, railways, and high-speed railways (high-speed trains, HST) sub-systems supporting both passengers and freight transport. All the analyses have been performed based on a common database of material, labor, energy and fuel input flows used in the construction, maintenance and yearly use of roads, railways and vehicles. Specific matter and energy intensities of both passenger and freight transportation services were calculated factors affecting results as well as strength and weakness points of each transportation modality were also stressed. Results pointed out that the most important factors in determining the acceptability of a transportation system are not only the specific fuel consumption and the energy and material costs of vehicles, as it is common belief, but also the energy and material costs for infrastructure construction as well as its intensity of use (with special focus on load factor of vehicles). The latter become the dominant factors in HST modality, due to technological and safety reasons that require high energy-cost materials and low intensity of traffic. This translates into very high thermodynamic and environmental costs for passenger and freight transported, among which an embodied energy demand up to 1.44 MJ/p-km and 3.09 MJ/t-km, respectively.

Keywords: Energy analysis of transport; Highway; Railway; HST

1. Introduction

Transport is one of the main sectors affecting world energy demand and environmental impact, covering, alone, a significant 32% of final energy uses worldwide [1] followed by the manufacturing sector, with a 27% share. Since the latter also includes the vehicle industry, the total share of the transportation sector is much higher than indicated by direct energy use. Solutions indicated by car producers in order to reduce transport energy demand and the consequent greenhouse gas emissions mainly rely on efficiency improvement of vehicles and implementation of new catalysers for exhaust gases, a so-called end-of-pipe approach. On the other hand, policy makers try to meet such a strategy of car makers by encouraging the replacement of old cars with new ones, in some cases by means of economic incentives (as for Italy, with past and present norms about decommissioning of old vehicles) and most often applying traffic restrictions to oldest and non-catalyzed vehicles. Another traffic-reduction strategy, often indicated by policy makers, is the construction of new and fast trains with the aim of shifting a fraction of road traffic to electricity powered railway.

Although the energy efficiency of engines (expressed as the ratio between the useful energy at the driving shaft and the fuel supplied) steadily increased during the last three decades, especially in the USA, no significant energy use reduction was reached [2]. In the investigated Italian case, in spite of the introduction of the European standards for specific vehicle emission and fuel consumption, sales of gasoline and diesel for transport increased on average

---

[*] Corresponding author. Tel.: +39 0577 234265; fax: +39 0577 234233.
E-mail address: federici2@unisi.it (M. Federici).

0360-5442/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2008.01.010

by 2% per year in the last 10 years [3]. Statistical traffic data [4] confirm a trend of decreasing number of people transported per vehicle and increasing average distance traveled. Such a trend suggests a kind of traffic rebound effect [5], due to the relative low fuel cost, and the increased efficiency of the engine. Vehicles with lower consumption per km appear to encourage people to drive more.

As an alternative to combustion engines, electric trains have always been considered as a more environmentally friendly solution to the problems of terrestrial transport, both for passengers and commodities, maybe because they do not release exhaust gases directly. Trains are also perceived as low energy intensive vehicles and this is because, most often, energy analyses of transport devices only used the "local-scale investigation mode", focusing to direct consumption of fuels and electricity and disregarding energy and material input flows required for the construction of infrastructures and vehicles. The role of infrastructure as well as the efficiency of electricity generation is clearly exemplified by the preference given to diesel trains and air transport in countries characterized by large distances to be covered, such as the USA and Australia. Such a strategy aims at skipping the heavy costs for infrastructure construction and maintenance as well as the fossil energy losses in power plants.

In this work, we attempt to get a comprehensive understanding of road and railway transport systems in Italy, although we believe that several European countries share similar transportation characteristics and problems (e.g., the planned European high-speed trains (HST) project which will link Lisboa, Portugal, and Kiev, Ucraine, also crossing a large number of European countries including Italy). We apply in the assessment several thermodynamic methodologies at different investigation scales, building on previous results obtained at regional scale [6,7]. Such preliminary results made it evident that the complexity of transportation service cannot be captured only on the basis of fuel economy of vehicles, but that the thermodynamic and environmental performance of the system is highly dependent on the comprehensive assessment of vehicle, infrastructure and management, together. The economic dynamics and the physical structure of a region heavily affect the choice and final performance of transport modalities with consequences on the efficiency, the effectiveness and the environmental load of the whole transport system. Keeping in mind the strict relationship between local specific features and transportation performance, in the present study we try to broaden our picture towards more general results, less affected by local characteristics and "bottom noise". The focus of the present investigation is placed on the main Italian national transportation axis, i.e., the 800 km system of highway and railway linking Milano (Northern Italy), Roma (Central Italy) and Napoli (Southern Italy), characterized by long distance traveling, high speed, and very intensive traffic. The case study allows a fair comparison of the energy intensity and the environmental load of road and railway systems at their best possible performances.

2. The case study

The Milano–Napoli transport infrastructure is the main Italian traffic line connecting the economic core of Northern Italy, the Milano industrial and financial area, with the biggest and more populated cities of Central and Southern Italy, Roma and Napoli. Firenze and Bologna are also served by this transportation infrastructure, which crosses the Appennini Mountains in the regions Emilia Romagna and Toscana, thus requiring the construction of energy and matter intensive galleries. The axis is composed with three parallel sub-systems: the A1 Toll-Highway, the present electric railway (Inter-City line), and the high-speed HST/TAV[1] railway, still under construction and fully operating only over 250 km.

In the year 2001, the highway supported a traffic of 11.9×10^9 v-km (vehicle-km) with a total passenger traffic of 21.0×10^9 p-km (passenger-km); traffic for commodity transportation was 4.09×10^9 v-km with 36.1×10^9 t-km (tons-km). Data clearly show an average car occupancy equal to 1.8 passengers per car and equal to 8.8 t of commodities per vehicle. Over the whole period 1995–2001 traffic on this highway increased by 27% [8]. In the same period, passenger transport by railway decreased by 2.3% while the railway commodity transport increased by 8.3% [9].

The HST/TAV railway is still under construction and therefore no traffic data are available, but only uncertain estimates from different sources. Our calculations were therefore performed according to two low and high use scenario hypotheses: (a) an intensity of use similar to the one of the already existing Inter-City line [10,11], and (b) the maximum theoretical use rate (maximum loading factor, maximum possible use of rail track). We tested the latter assumption also for the existing Inter-City line. Passenger traffic range is therefore estimated between 1.09×10^{10} p-km and 1.52×10^{10} p-km, while the commodity transport range is between 3.84×10^9 t-km and 5.84×10^9 t-km. Main differences between HST/TAV and existing electric railway are: a higher power of the locomotive (8.8 MW versus 4–6 MW) and a much higher number of tunnels required to prevent losses of train speed. Moreover, due to physical and design constraints, HST/TAV vehicles carry a maximum number of passengers equal to 594 units, which is 70% of the present "carrying capacity" of Inter-City trains.

3. The approach

As already pointed out, the investigated transportation system can be divided in three main sub-systems, i.e., highway, railway and HST/TAV. For each of them, several

---

[1] TAV—Treno Alta Velocità (HST—high-speed train).

sub-steps were considered: (a) construction of infrastructures and machinery (roads, tracks, cars, trains, etc.), (b) maintenance, and (c) operation (annual use for transport of commodities and passengers). The approach used in the evaluation compares and integrates the results of several different methods (material flow (MFA [12]), energy (EEA [13]), exergy (EXA [14,15]), and emergy accounting (ES [16])) all of which are deeply rooted in the principles of thermodynamics [17]. Description of theory and inner assumptions of each method can be found in the cited literature, and they cannot be repeated here in details. However, a summary of methods is provided in Appendix.

In short, a first-law inventory of mass and energy flows is preliminarily performed, to become the starting point of a large-scale assessment of indirect material flow demand (MFA) and embodied energy (EEA). The inventory also provides the basis for a second-law evaluation, performed by means of both user-side (EXA) and donor-side (ES) approaches (Fig. 1). Conversion from first- to second-law patterns as well as from local to global scales is performed by means of intensity coefficients (material intensity factors, oil equivalent factors, specific exergies, and transformities or specific emergy factors, the values of which are listed in Table 1) available from scientific literature, referred to in the footnotes.

For each analysis method used, calculation is performed according to the following equation:

$$F_J = \sum F_{J,i} = \sum f_i \times c_{J,i}, \quad i = 1, \ldots, n, \tag{1}$$

where J refers to MFA, EEA, EXA, ES, emissions; F is the total material, energy, exergy, emergy input to, or total emission of each chemical species from, the process; f_i is the ith input or output flow of matter or energy; and c_i is the conversion coefficient of the ith flow (i.e., material, energy, exergy, emergy or emission intensity factors, from literature or calculated in this work).

Application of Eq. (1) to the inventory of flows of investigated systems translates into total material requirement, embodied energy, exergy and emergy tables, based on the same set of input and output data. Such values, F_J, are finally divided by the total supported product (transportation service), measured as the amount of functional units (p-km and t-km). As a consequence,

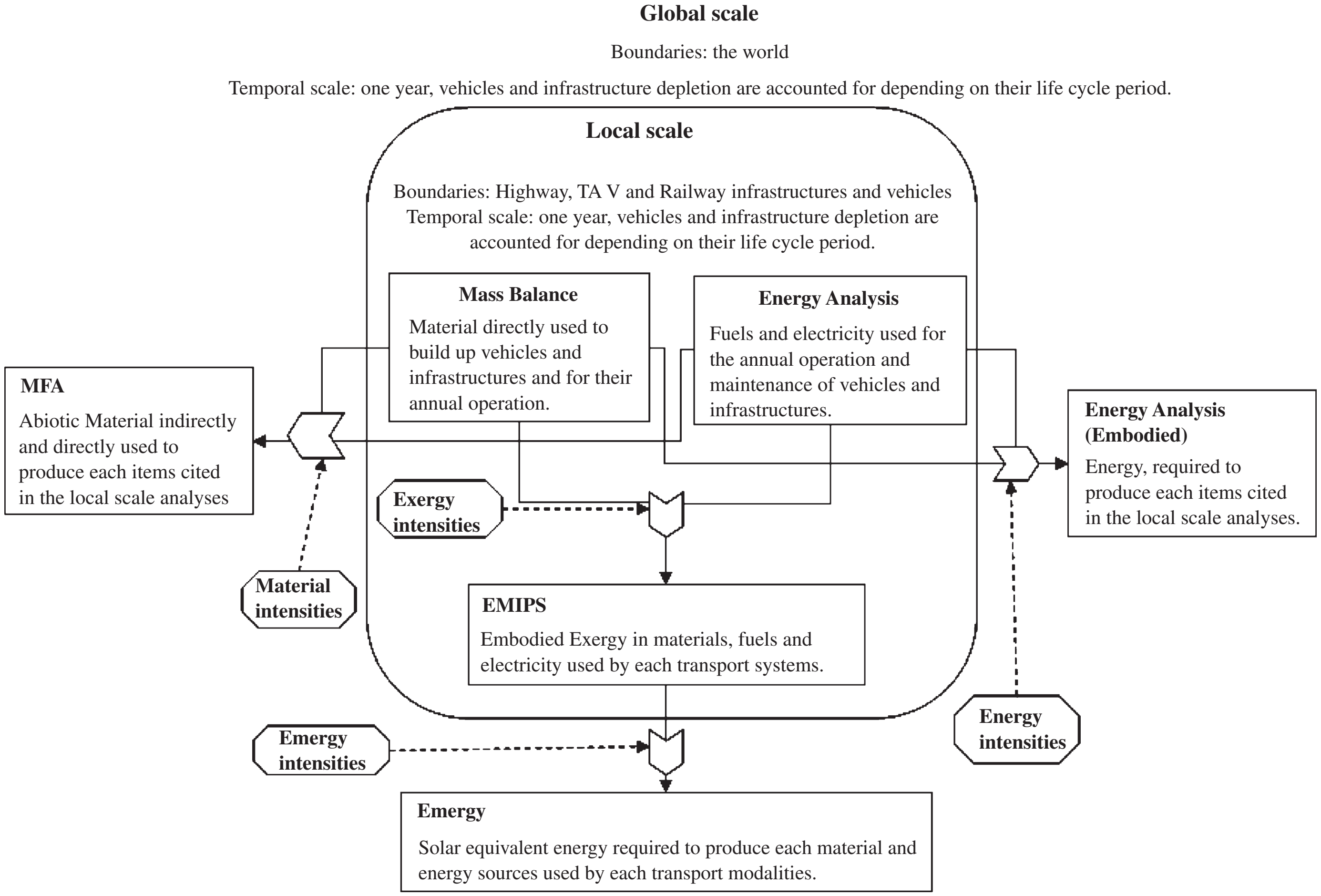

Fig. 1. Local-scale framework encompasses the direct inputs supporting the transport activities: mass balance, energy analysis and EMIPS are used in this context. Global scale framework takes into account the indirect and hidden material and energy flows supporting the transportation process. Specific material, energy and emergy intensities are used to shift from local to global scale.

Table 1
Material, energy, exergy and emergy intensities of main input flows used in this paper

Flow and unit	Material intensity (abiotic) (kg/unit)	Material intensity (water) (kg/unit)	Material intensity (air) (kg/unit)	Ref. MIs	Energy intensity (MJ/unit)	Ref. EEA	Specific exergy (MJ/unit)	Ref. EXA	Emergy intensity (seJ/unit)	Ref. ES
Sand and gravel (kg)	1.44	5.6	0.03	a	0.01	b	0.31	h	5.00E+11	i
Concrete (Portland) (kg)	3.22	16.90	0.33	a	4.60	b	0.64	h	1.03E+09	l
Asphalt (kg)	1.291	2.47	0.014	a	1.14	b	2.29	d	3.47E+05	l
Copper (kg)	348.47	367.20	1.63	a	132.75	b	2.11	e	6.80E+10	l
Steel (kg)	8.14	63.71	0.44	a	79.95	b	7.10	e	6.70E+12	l
Methane (kg)	1.11	0.3	0.29	a	57.35	b	51.98	e	5.22E+04	i
Diesel (kg)	1.37	9.70	3.40	a	53.58	b	44.40	f	6.60E+04	i
Gasoline (kg)	1.32	9.70	3.12	a	53.58	b	43.20	f	6.60E+04	i
Electricity (kWh)	4.22	72.5	0.607	a	12	c	3.6	f	5.40E+11	m

a: Wuppertal Institute. Material intensity of materials, fuels, transport services. www.wupperinst.org/uploads/tx_wibeitrag/MIT_v2.pdf.

b: Boustead I., Hancock G.F., 1979. Handbook of industrial energy analysis. Ellis Horword Limited, p. 442.

c: Estimate based on literature data (ENEA 2005. Rapporto Energetico ed Ambientale (in Italian). http://www.enea.it/com/web/pubblicazioni/REA_05/Dati_05.pdf.

d: Szargut et al., 1988. From calculation performed in this work, based on the exergy of component of stone, p. 185.

e: Ayres R.U., Ayres L.W. 1996. Industrial Ecology. Towards closing the material cycle EDS. Edwar Elgar Publishing Ltd. UK, p. 379.

f: Estimate based on literature data (Shieh and Fan, 1982. Estimation of energy (enthalpy) and exergy (availability) contents in structurally complicated materials. Energy Sources 6, No. 1/2. Crane Russak & Co. and Szargut J., Morris D.R., Steward F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes: Springer, pp. 297–304.

h: Szargut J., Morris D.R., Steward F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes: Springer, pp. 297–304.

i: Odum H.T., 1996. Environmental Accounting. Emergy and Environmental Decision Making. Wiley, New York, USA. Pp.370.

l: Brown M.T., Arding J., 1991. "Transformities". Working Paper. Center for Wetlands, University of Florida, Gainesville, USA.

m: Calculation performed in this work.

Table 2
Material flows directly used for the construction of 1 km of highway, HST/TAV and Inter-City railway infrastructures, allocated over lifetime

Items	Lifetime (year)	Highway (kg/km/year)	Lifetime (year)	HST/TAV (kg/km/year)	Inter-City train (kg/km/year)
Sand and gravel	70	1.16×10^{6}	50	6.59×10^{6}	6.96×10^{6}
Moved soil	70	1.11×10^{6}	50	2.45×10^{6}	1.94×10^{6}
Concrete	70	5.60×10^{4}	50	9.18×10^{5}	7.20×10^{5}
Reinforced concrete	70	5.57×10^{3}	50	7.04×10^{4}	6.91×10^{4}
Steel in tunnel reinforcement	70	1.92×10^{4}	50	6.25×10^{4}	4.54×10^{4}
Diesel	1	3.37×10^{1}	1	2.08×10^{3}	2.20×10^{3}
Steel in construction machineries	30	1.07×10^{0}	30	3.31×10^{0}	3.59×10^{0}
O_2	1	1.16×10^{2}	1	7.06×10^{3}	7.49×10^{3}
N_2	1	5.00×10^{-1}	1	3.09×10^{1}	3.28×10^{1}
Reinforced concrete in traffic divider	10	3.30×10^{4}	n.a.	n.a.	n.a.
Steel in traffic divider	10	2.69×10^{3}	n.a.	n.a.	n.a.
Steel in guardrail	10	5.37×10^{3}	n.a.	n.a.	n.a.
Asphalt	5	1.88×10^{6}	n.a.	n.a.	n.a.
Steel in track	n.a.	n.a.	10	2.31×10^{4}	2.34×10^{4}
Steel in electric poles	n.a.	n.a.	10	$1.56\text{E} \times 10^{3}$	1.36×10^{2}
Copper in electric cables	n.a.	n.a.	10	4.83×10^{2}	4.86×10^{2}

n.a.: not applicable.

results of calculation procedures are consistent and comparable, and jointly provide a reliable and comprehensive picture of the whole system (Tables 2 and 3).

Due to space constraints, calculations and worksheets reported here only deal with the HST/TAV transportation modality. Tables 4–7 refer, respectively, to MFA, embodied energy, exergy and emergy analyses of such a system. Showing calculation procedure and results for process emissions would require a table for each chemical species and many tables for each transportation modality. Therefore, for lack of space, these data are only presented in aggregated form in Table 9.

Table 3
Yearly inventory of material and energy flows for each transport system

Infrastructures construction	Highway	HST/TAV	Inter-City train
Sand and gravel (kg/year)	9.26×10^8	5.27×10^9	1.55×10^9
Moved soil (kg/year)	8.89×10^8	1.96×10^9	5.57×10^9
Asphalt (kg/year)	1.50×10^9	n.a.	n.a.
Concrete (kg/year)	4.48×10^7	7.34×10^8	5.76×10^8
Reinforced concrete (kg/year)	3.09×10^7	5.53×10^7	5.53×10^7
Copper in electric cables (kg/year)	n.a.	3.86×10^5	3.89×10^5
Steel in electric poles (kg/year)	n.a.	1.25×10^6	1.09×10^5
Steel in tracks (kg/year)	n.a.	1.85×10^7	1.87×10^7
Steel in guardrails (kg/year)	6.45×10^6	n.a.	n.a.
Steel in tunnel reinforcement (kg/year)	1.54×10^7	5.00×10^7	3.63×10^7
Diesel (kg/year)	2.69×10^4	1.66×10^6	1.66×10^6
Steel in machineries (kg/year)	8.53×10^2	2.65×10^3	2.87×10^3
Yearly maintenance			
Diesel (kg/year)	1.28×10^6	3.67×10^4	3.67×10^4
Electricity (MJ/year)	1.34×10^8	2.10×10^7	2.10×10^7
Yearly individual passenger transport on highway			
Steel in vehicles (kg/year)	7.04×10^7	n.a.	n.a.
Gasoline (kg/year)	5.34×10^8	n.a.	n.a.
Diesel (kg/year)	7.84×10^7	n.a.	n.a.
Natural gas (kg/year)	1.74×10^7	n.a.	n.a.
Tyres (kg/year)	7.13×10^6	n.a.	n.a.
Lubricants (kg/year)	1.31×10^6	n.a.	n.a.
Yearly mass passenger transport			
Steel in vehicles (kg/year)	6.30×10^5	1.74×10^6	1.67×10^6
Diesel (kg/year)	1.18×10^7	n.a.	n.a.
Tyres (kg/year)	1.38×10^5	n.a.	n.a.
Lubricants (kg/year)	3.17×10^4	n.a.	n.a.
Electricity (MJ/year)	n.a.	4.15×10^9	3.41×10^9
Yearly freight transport			
Steel in vehicles (kg/year)	8.45×10^6	4.39×10^5	2.05×10^5
Gasoline (kg/year)	7.78×10^7	n.a.	n.a.
Diesel (kg/year)	6.46×10^8	n.a.	n.a.
Tyres (kg/year)	9.04×10^6	n.a.	n.a.
Lubricants (kg/year)	2.48×10^6	n.a.	n.a.
Electricity (MJ/year)	n.a.	8.44×10^8	8.44×10^8
Total	9.39×10^9	8.10×10^9	7.81×10^9

3.1. *Construction of infrastructures*

For all the transport sub-systems presented in this paper, data related to the construction of galleries were accounted for. Unfortunately, it was not possible to obtain precise and detailed data about piers used for bridges and viaducts construction because each of them shows very different characteristics (mainly dependent from length, height and ground composition) and were constructed by different enterprises during a wide period of time. It was impossible to contact all of them to obtain the precise project tenders. This lack of data unavoidably leads to underestimate absolute results, anyway the relative comparison between road and railway systems should not be significantly affected because roads and railways lay very often on the same tracing layout.

The Milano–Napoli Highway covers a length of 800 km, out of which 60 km of tunnels. Road construction data were mainly available from tenders and designs developed by the owner company, Autostrade SpA [8], for road-making engineering and were integrated, when needed, by further data provided by sub-contracting 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.[2] 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. This applies to about 10% of total road length. The machinery used for road

---

[2] All assumptions about the lifetime of vehicles and infrastructures used in this paper are average estimates based on collected information about maintenance and turnover time as well as on expert interviews to people working in the field.

Table 4
Total (local and large-scale) material requirement for the HST/TAV[a]

Description of flow	Units of inputs	Yearly amount (local scale)	Mass abiotic global scale (g/year)	Mass water global scale (g/year)	Mass air global scale (g/year)
Natural input					
Rain	g/year	8.76×10^{12}	0	8.76×10^{12}	0
Infrastructures construction					
Sand and gravel	g/year	5.27×10^{12}	6.75×10^{12}	1.05×10^{13}	6.85×10^{10}
Moved soil	g/year	1.96×10^{12}	1.96×10^{12}	0	0
Concrete	g/year	7.34×10^{11}	2.36×10^{12}	1.24×10^{13}	2.42×10^{11}
Reinforced concrete	g/year	5.53×10^{10}	1.86×10^{11}	9.19×10^{11}	2.26×10^{10}
Diesel	g/year	1.66×10^{9}	2.38×10^{9}	1.85×10^{10}	5.63×10^{9}
Steel in machineries	g/year	2.65×10^{6}	1.59×10^{7}	3.02×10^{7}	4.98×10^{6}
Steel in tracks	g/year	1.85×10^{10}	1.12×10^{11}	2.11×10^{11}	3.48×10^{10}
Steel in electric poles	g/year	1.25×10^{9}	7.55×10^{9}	1.43×10^{10}	2.36×10^{9}
Steel in tunnel reinforcement	g/year	5.00×10^{10}	3.01×10^{11}	$5.\ 70 \times 10^{11}$	9.39×10^{10}
Copper in electric cables	g/year	3.86×10^{8}	1.34×10^{11}	1.42×10^{11}	6.29×10^{8}
O_2	g/year	5.65×10^{9}	0	0	5.65×10^{9}
N_2	g/year	2.47×10^{7}	0	0	2.47×10^{7}
Yearly maintenance					
Electricity	kWh/year	5.84×10^{6}	1.22×10^{10}	3.42×10^{10}	2.15×10^{9}
Steel in vehicles used for the maintenance	g/year	3.67×10^{7}	2.21×10^{8}	4.18×10^{8}	$6.\ 89 \times 10^{7}$
Yearly mass passenger transport					
Steel in vehicles	g/year	1.74×10^{9}	1.05×10^{10}	1.98×10^{10}	3.26×10^{9}
Electricity	kWh/year	1.15×10^{9}	2.40×10^{12}	6.75×10^{12}	4.25×10^{11}
Yearly freight transport					
Steel in vehicles	g/year	4.39×10^{8}	2.64×10^{9}	5.00×10^{9}	8.24×10^{8}
Electricity	kWh/year	2.34×10^{8}	4.89×10^{11}	1.37×10^{12}	8.65×10^{10}
Total	g/year	1.69×10^{13}	1.47×10^{13}	4.18×10^{13}	9.95×10^{11}
Hypothesis: (a) current utilization rate					
Passenger yearly traffic	p-km/year	1.09×10^{10}			
Freight yearly traffic	t-km/year	3.84×10^{9}			
Global mass per p-km	kg/p-km	1.40			
Global mass per t-km	kg/t-km	8.65			
Hypothesis: (b) maximum load factor					
Passenger yearly traffic	p-km/year	1.52×10^{10}			
Freight yearly traffic	t-km/year	5.48×10^{9}			
Global mass per p-km	kg/p-km	1.00			
Global mass per t-km	kg/t-km	6. 06			

[a] Abiotic, water and air intensive factors used for the calculations are shown in Table 1.

construction was also accounted for, and a lifetime of 30 years was assumed.

The Milano–Napoli Inter-City railway covers a total length of 778 km: tunnels and viaducts account, respectively, for 141.7 km and 73.7 km. A lower layer of gravel and small stones supports the track structure made with steel and cement: a lifetime of 50 and 10 years is assumed for the underground layer and for the track, respectively. Railway construction data were provided by RFI SpA,[3] the public company managing the rail transport in Italy. Railway requires a higher amount of material compared to the highway and this is mainly due to the higher number of tunnels. The length of the Milano–Napoli TAV is 772 km, of which tunnels account for 195.2 km while viaducts account for 73.7 km. A higher number of galleries is required than for Inter-City line, in order to reduce slope changes, a prerequisite for keeping the highest possible train speed constant. Assumptions for the lifetime of HST/TAV infrastructures are the same used for the Inter-City railway. Main differences are the higher amount of steel in tunnels and poles for electric line, and the higher amount of soil excavated, for HST/TAV.

Material inputs related to highway, Inter-City railway and TAV infrastructures are shown in Table 2.

3.2. Construction of vehicles

Resources used in the construction of road vehicles were estimated, assuming that they are 80% iron and steel

---

[3] RFI—Rete Ferroviaria Italiana.

Table 5
Embodied energy analysis of HST/TAV Mi–Na

Description of flow	Unit of input	Amount	Energy (MJ/year)
Infrastructures construction			
Sand and gravel	kg/year	5.27×10^{9}	5.27×10^{7}
Concrete	kg/year	7.34×10^{8}	3.38×10^{9}
Reinforced concrete	kg/year	5.53×10^{7}	1.50×10^{9}
Diesel	kg/year	1.66×10^{6}	8.87×10^{7}
Steel in machineries	kg/year	2.65×10^{3}	2.12×10^{5}
Steel in tracks	kg/year	1.85×10^{7}	1.48×10^{9}
Steel in electric poles	kg/year	1.25×10^{6}	1.00×10^{8}
Steel in tunnel reinforcement	kg/year	5.00×10^{7}	4.00×10^{9}
Copper in electric cables	kg/year	3.86×10^{5}	5.12×10^{7}
Yearly maintenance			
Electricity	kWh/year	5.84×10^{8}	7.01×10^{7}
Steel in vehicles used for the maintenance	kg/year	3.67×10^{4}	2.93×10^{6}
Yearly mass passenger transport			
Steel in vehicles	kg/year	1.74×10^{6}	1.39×10^{8}
Electricity	kWh/year	1.15×10^{9}	1.38×10^{10}
Yearly freight transport			
Steel in vehicles	kg/year	4.39×10^{5}	3.51×10^{7}
Electricity	kWh/year	2.34×10^{8}	2.81×10^{9}
Total			2.76×10^{10}
Hypothesis: (a) current utilization rate			
Passenger yearly traffic	p-km/year	1.09×10^{10}	
Freight yearly traffic	t-km/year	3.84×10^{9}	
Gross energy per p-km	MJ/p-km	1.44	
Gross energy per t-km	MJ/t-km	3.09	
Hypothesis: (b) maximum load factor			
Passenger yearly traffic	p-km/year	1.52×10^{10}	
Freight yearly traffic	t-km/year	5.48×10^{9}	
Gross energy per p-km	MJ/p-km	1.02	
Gross energy per t-km	MJ/t-km	2.17	

and 20% plastic material including tires. Smaller fractions of aluminum, copper and glass were not included in the assessment. Instead, a 100% steel content was assumed for trains, considering the mass of (plastic) seats and other materials negligible. Energy costs were calculated accordingly. A lifetime of 10 years was assumed for cars, 15 years for buses, 20 years for trucks, and finally 30 years for trains.

3.3. *Maintenance*

Data about yearly maintenance input for road and track infrastructures were directly provided by managing companies [8,9]. Standard maintenance inputs were assumed for cars, averaging over car makes and lifetimes, based on personal detailed interviews to car-repair dealers. Instead, information about maintenance of buses and trains was supplied by local and national companies operating in the bus and train transportation business [18] for buses; [9,10] for trains.

3.4. *Operation*

Since highway traffic statistics only account for total number of vehicles and do not provide any information about vehicle size and categories (i.e., how many diesel car greater than 2000 cm^3 or how many gasoline car greater than 1400 cm^3 and so on), data about fuel and resource consumption by car traffic were estimated by crossing information from the ISTAT [19], Autostrade SpA (the company that manages the Italian highways [8]) and Automobil Club Italia [20]. These data were used to define a virtual ‘‘weighted average highway car’’ with average fuel performance, average size and emissions. Load factor per cars running on the highway is significantly higher than on local road (1.8 versus 1.4 persons per vehicle [19]): this is because highway trips are in general longer than local ones.

In a very similar way, data about commodity highway traffic were estimated: average load factor is 8.79 t/v-km and the average mass of vehicle is 2.48 t per truck.

Energy and resource consumption data for passenger and commodity transport on the Milano–Napoli Inter-City railway sub-system were provided directly by the managing company Trenitalia SpA. Instead, data related to the Milano–Napoli high-speed railway were estimated by the authors from the executive and business plans of the HST/TAV managing company [10].

Table 6
Exergy analysis of HST/TAV Mi–Na

Description of flow	Unit	Amount	Exergy (MJ/year)
Infrastructures construction			
Sand and gravel	kg/year	5.27×10^9	1.63×10^9
Concrete	kg/year	7.34×10^8	4.66×10^8
Reinforced concrete	kg/year	5.53×10^7	1.07×10^8
Diesel	kg/year	1.66×10^6	7.35×10^7
Steel in machineries	kg/year	2.65×10^3	1.88×10^4
Steel in tracks	kg/year	1.85×10^7	1.32×10^8
Steel in electric poles	kg/year	1.25×10^6	8.90×10^6
Steel in tunnel reinforcement	kg/year	5.00×10^7	3.55×10^8
Copper in electric cables	kg/year	3.86×10^5	8.15×10^5
Yearly maintenance			
Electricity	kWh/year	5.84×10^6	2.10×10^7
Steel in vehicles used for the maintenance	kg/year	3.67×10^4	2.60×10^5
Yearly mass passenger transport			
Steel in vehicles	kg/year	1.74×10^6	1.23×10^7
Electricity	kWh/year	1.15×10^9	4.15×10^9
Yearly freight transport			
Steel in vehicles	kg/year	4.39×10^5	3.11×10^6
Electricity	kWh/year	2.34×10^8	8.44×10^8
Total			7.81×10^9
Hypothesis: (a) current utilization rate			
Passenger yearly traffic	p-km/year	1.09×10^{10}	
Freight yearly traffic	t-km/year	3.84×10^9	
Exergy per p-km	MJ/p-km	4.22×10^{-1}	
Exergy per t-km	MJ/t-km	8.36×10^{-1}	
Hypothesis: (b) maximum load factor			
Passenger yearly traffic	p-km/year	1.52×10^{10}	
Freight yearly traffic	t-km/year	5.48×10^9	
Exergy per p-km	MJ/p-km	3.01×10^{-1}	
Exergy per t-km	MJ/t-km	5.87×10^{-1}	

Inventories of mass and energy flows to construction, maintenance and yearly operation for all the sub-systems considered are shown in Table 3.

3.5. Allocation of inputs among use modalities

Roads and railways 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 (e.g., according to the economic value associated to transported items), we decided to allocate according to total weight of vehicles considered as the weight of machine plus the weight of passengers or commodities transported. This is because the infrastructure is degraded over time mainly due to the weight of vehicles running (e.g., worn surface, vibrations, etc.). The problem is that (a) passengers are never accounted for by their weight and (b) the need for providing suitable comfortable space prevents from full use of available coach space. In order to compare passengers and freight transport and allocate infrastructure and maintenance inputs accordingly, an average passenger weight of 65 kg was assumed. In this way, the final weight of a passenger train is about 576 t (out of which only 6% is passenger weight) versus an average weight of 984 t for a freight one (55% commodities transported, 45% train mass). On the basis of the above assumption that the damage generated by 1 t of commodities is equivalent to that generated by 13.4 passengers, p-km units were converted into t-km units. This translates, for the highway sub-system, into a total passenger traffic of 1.41×10^9 t-km (3.76% of total weight transported) compared with a commodity traffic of 36.1×10^9 t-km (96.24% of total weight transported). Instead, for the existing Inter-City railways passenger traffic accounts for the 20.2% of total transported weight. Finally, in the case of future high-speed railway, passenger traffic can be estimated as about 15.6% of total transported weight, even assuming the maximum load capacity (i.e., the maximum number of passengers which can be transported at full load and assuming the maximum traffic on the line consistent with safety requirements).[4]

---

[4] At the moment, trains on TAV and Inter-City lines are scheduled as one each 15 min. This time distance is considered as absolutely necessary to avoid train crashes in case of accident (for example, in case of simple

Table 7
Emergy analysis of HST/TAV Mi–Na

Description of flow	Unit	Amount	Emergy (seJ/year)
Solar energy	J/year	5.30×10^{16}	5.30×10^{16}
Rain	J/year	4.32×10^{13}	7.87×10^{17}
Earth heat	J/year	2.89×10^{13}	1.75×10^{17}
Infrastructures construction			
Sand and gravel	kg/year	5.27×10^{9}	2.64×10^{21}
Moved soil	J/year	4.42×10^{16}	3.27×10^{21}
Concrete	kg/year	7.34×10^{8}	7.56×10^{20}
Reinforced concrete	kg/year	5.53×10^{7}	7.26×10^{19}
Diesel	J/year	8.87×10^{13}	5.85×10^{18}
Steel in machineries	kg/year	2.65×10^{3}	1.78×10^{16}
Steel in tracks	kg/year	1.85×10^{7}	1.24×10^{20}
Steel in electric poles	kg/year	1.25×10^{6}	8.40×10^{18}
Steel in tunnel reinforcement	kg/year	5.00×10^{7}	3.35×10^{20}
Copper in electric cables	kg/year	3.86×10^{5}	2.62×10^{16}
Service	€/year	3.68×10^{8}	4.78×10^{20}
Labor	J/year	5.16×10^{10}	6.65×10^{17}
Yearly maintenance			
Electricity	J/year	2.10×10^{13}	3.15×10^{18}
Steel in vehicles used for the maintenance	kg/year	3.67×10^{4}	2.46×10^{17}
Service	€/year	3.81×10^{6}	4.95×10^{18}
Labor	J/year	8.30×10^{10}	1.07×10^{18}
Yearly passenger transport			
Steel in vehicles	kg/year	1.74×10^{6}	1.16×10^{19}
Electricity	J/year	4.15×10^{15}	6.23×10^{20}
Service	€/year	7.35×10^{7}	9.55×10^{19}
Labor	J/year	5.77×10^{12}	7.45×10^{19}
Yearly freight transport			
Steel in vehicles	kg/year	4.39×10^{5}	2.94×10^{18}
Electricity	J/year	8.44×10^{14}	1.27×10^{20}
Service	€/year	2.85×10^{6}	3.71×10^{18}
Labor	J/year	4.78×10^{12}	6.17×10^{19}
Total			8.70×10^{21}

4. Results

Table 8 shows a comparative overview of results obtained. Indicators are referred to the usual units of product transported, p-km and t-km. The values of each indicator reflect overall results from all investigated steps (construction, maintenance and operation). This is an important aspect, because most often comparative studies only take into account the direct fuel consumption by vehicles disregarding the environmental load due to material and energy inputs for infrastructure and vehicle construction with consequent strong underestimate of results and misleading conclusions. In fact, accounting for infrastructures cannot be avoided, considering that vehicles without roads and tracks cannot run. The higher is the traffic intensity supported by roads or railways, the lower will be the relative importance of infrastructure material and energy within the final value of each indicator.

4.1. Mass balance

Mass balance accounts for all material resources directly used up by transport systems for passengers and commodities transportation, expressed as kilograms of each kind of mass consumed per unit transported. Such flows are referred to in Table 8 as local-scale matter flows. Bus transport shows the lower material intensity per passenger transported, while the higher value is shown by individual car transport. Inter-City railway and HST/TAV transport, at the current utilization rate, show values comparable with the car modality; instead, if HST/TAV vehicles could run at the maximum load factor, their material intensity would decrease by as much as 30%.

Commodity transport patterns by Inter-City railway and HST/TAV are instead more matter intensive than transport by truck: this is mainly due to the large mass of trains (each coach is about 40 t) which is cumulatively added to the mass of goods transported.

(*footnote continued*)
unplanned stop to the first train, distance time is necessary to warn all the following trains). So at the moment, the maximum passenger traffic assumed for calculation appears as insuperable limit.

Table 8
Performance results for passenger and commodity transport by means of the different transportation modalities

Transport modality	Load factor (passenger per trip)	Mass balance local scale (kg/p-km)	MFA global scale (kg/p-km)	Energy analysis local scale (MJ/p-km)	Energy analysis global scale (MJ/p-km)	Exergy analysis global scale (MJ/p-km)	Emergy analysis global scale (10^{11} seJ/p-km)
Passenger transport							
Highway (car)	1.8	0.13	0.53	1.37	1.87	1.31	1.74
Highway (bus)	50	0.03	0.11	0.24	0.33	0.25	0.24
Railway[a]	400–750	0.08–0.11	0.69–0.85	0.16–0.20	0.62–0.77	0.19–0.23	0.94–1.26
HST/TAV[a]	250–594	0.08–0.12	1.00–1.40	0.27–0.38	1.02–1.44	0.30–0.42	1.17–1.65
	(tons per trip)	(kg/t-km)	(kg/t-km)	(MJ/t-km)	(MJ/t-km)	(MJ/t-km)	(10^{11} seJ/t-km)
Commodity transport							
Highway	8.79	0.18	0.60	0.91	1.25	1.01	1.08
Railway[a]	350–500	1.2–1.65	5.35–7.65	0.17–0.24	1.79–2.5	0.55–0.76	10.3–14.3
HST/TAV Mi–Na[a]	350–500	1.25–1.78	6.06–8.65	0.17–0.24	2.17–3.09	0.59–0.83	10.9–15.5

[a] Value range is referred to the current utilization rate of railway, and the maximum load factor.

4.2. Material flow accounting

Since all material and energy flows can be associated to indirect matter flows on the larger regional and global scales (see MFA, in Appendix), the amount of matter indirectly degraded in support of each unit of transport performed translates into so-called material intensities (amount of matter degraded) for each transport modality.

The highway sub-system is characterized by 0.53 kg/p-km and 0.60 kg/t-km equal to four and three times higher material intensities for passenger and good transport, respectively, compared to local-scale values. Railway and HST/TAV transport show an even higher increase up to 7 and 11 times, respectively. The main reason for the much higher increase of MI's of Inter-City railway and TAV from local to global scale is the huge amount of steel used by railway systems for both infrastructures and vehicle construction, compared to highway system. Steel production, in fact, requires a huge amount of material consumption that is not accounted for in the local-scale mass balance [21], since it also includes large amounts of coal and a huge water demand for generation of electricity used in steel-making. Again buses show the lowest material intensity per p-km. Table 9 shows the airborne emissions calculated on the global scale, expressed as kg of released chemical species per unit transported. Specific emission factors for the different materials and fuels are taken from Refs. [22,23].

Commodity transportation by means of railway and HST/TAV trains shows the highest amount of emission (with CO_2 emissions more than twice that of highway trucks). Clearly, each kind of chemical shows different figures, because of the different emission rate in each step of the process. For example, emissions of PM_{10} for trains are mainly due to steel and concrete industries, while in the case of road transport PM_{10} release is mainly generated by direct vehicles operation. CO_2 emissions, as expected, are strictly correlated to the total energy consumption of the process considered.

4.3. Energy analysis at local scale

Local-scale energy analysis accounts for direct energy use of systems. Input flows locally considered are fuels and electric energy used for the construction of infrastructure (mainly for machinery) and by running of vehicles. It is the latter which is the most common kind of energy accounting procedure, and the results are strictly related to the specific fuel or electricity consumption of vehicles and their average load factors.

Passenger transport by car represents the more energy intensive modality, while Inter-City railway represents the lowest one, quite advantageous compared with bus transport. HST/TAV shows higher energy consumption relative to Inter-City railway and bus, due to higher speed and much lower load factor. Commodity transportation by train modality is definitely less energy intensive than truck transport (as far as direct use of energy is concerned).

4.4. Energy analysis at global scale (embodied energy)

Within the larger scope of EEA [13,24] all material and energy flows supporting each step of the investigated sub-systems are accounted for according to their specific, gross energy cost. The aim of this analysis is to provide an estimation of the global energy requirement, from cradle to grave, of the product or service considered. Obviously, results provided by EEA are higher then local-scale ones, mainly due to the energy embodied in infrastructure materials. Specific energy intensities were taken from Ref. [25], integrated and updated with data from selected other authors [26,27]. Table 10 shows the ratio between global and local-scale energy intensities, highlighting a huge increase of energy demand at larger scale, where indirect energy input is accounted for. The enlargement of scale does not affect in the same way each transport modality. As expected, infrastructure plays a major role in embodied energy demand, also depending on the quality of materials used and the level of technology. This is the reason why

Table 9
Main global-scale emissions for the Milano–Napoli axis related to the different transportation modalities

Transport modalities	CO_2	CO	NO_x	PM_{10}	VOC	SO_x
Passengers						
Highway (cars) (kg/p-km)	8.94×10^{-2}	6.68×10^{-3}	1.61E−03	6.94E−05	5.17×10^{-4}	2.38×10^{-4}
Railway (kg/p-km)	3.03×10^{-2}	7.56×10^{-6}	5.79×10^{-5}	1.46×10^{-4}	6.22×10^{-7}	3.39×10^{-4}
HST/TAV (kg/p-km)	4.82×10^{-2}	1.01×10^{-5}	8.87×10^{-5}	1.81×10^{-4}	7.92×10^{-7}	5.64×10^{-4}
Highway (trucks) (kg/t-km)	7.21×10^{-2}	9.03×10^{-4}	6.59×10^{-4}	6.41×10^{-4}	1.25×10^{-4}	2.06×10^{-4}
Railway (kg/t-km)	1.50×10^{-1}	1.09×10^{-4}	4.16×10^{-4}	2.11×10^{-3}	9.29×10^{-6}	8.55×10^{-4}
HST/TAV (kg/t-km)	1.89×10^{-1}	1.45×10^{-4}	5.36×10^{-4}	2.54×10^{-3}	1.18×10^{-5}	1.05×10^{-3}

Table 10
Global to local energy intensity ratios

Transport modalities	Ratio
Passenger transport	
A1 Highway car	1.36
A1 Highway bus	1.37
Railway	3.85
TAV	3.78
Commodity transport	
A1 Highway	1.37
Railway	10.41
TAV	12.87

Inter-City railway and HST/TAV, due to large amounts of steel for rail and reinforced concrete for galleries and viaducts, show increases of global energy intensity from 10 to 13 times, respectively, while highway transportation of passengers and commodities shows a smaller average increase of 36–37%.

4.5. *Exergy analysis*

Table 8 shows the results of the so-called exergetic material input per unit of service [15,28]; this method accounts for the total exergy of the material and energy flows used up by the systems. In the investigated transport sub-systems, EMIPS results are very similar to local-scale energy intensities (third column in Table 8); main reason is that according to the exergy method, energy sources (fuels and electricity) are characterized by higher specific exergy intensities than material flows. Being the EMIPS indicators defined at local scale, vehicles and infrastructures do not affect the results to any significant extent.

Exergy (a measure of work potential) could be better applied in order to calculate the thermodynamic efficiency of the engine/process and help identify existing bottlenecks and efficiency drops. Exergy is, by definition, a measure of maximum work obtainable in an ideal, reversible process (see Appendix). Since transport processes and tools are never ideal, the comparison of available work potential (exergy of fuel) and work actually obtained would indicate the so-called exergy loss, i.e., is the destruction of work potential due to irreversibilities occurring at system level (within the engine or due to the use of conversion tools that are not appropriate to the goal). In the case of transport processes/engines, it is impossible to assign an exergy content to the product (i.e., to the p-km or t-km supported) and therefore the exergy efficiency cannot be defined in the usual way. By the way, if the exergy efficiency is only calculated at the level of the engine (ratio of exergy delivered at the driving shaft to the exergy of the fuel), the indicator leaves the dynamics of the surrounding system (transport infrastructure) unaccounted for.

A more flexible (and very telling) approach is the comparison of the actual exergy cost per unit of product (J_{ex}/p-km) to the exergy cost calculated on the basis of the performance claimed by the vehicle constructors. We assume the latter as the upper limit to the vehicle performance, because constructors always advertise their cars with the best results they obtain in car tests. Such a comparison translates into the ratio of quasi-ideal (claimed) exergy costs, $\mathrm{Ex}^*_{\text{p-km}}$ to real (system level) exergy cost, $\mathrm{Ex}_{\text{p-km}}$:

$$\varepsilon = \frac{\mathrm{Ex}^*_{\text{p-km}}}{\mathrm{Ex}_{\text{p-km}}} = \frac{\mathrm{Ex}_{\min}}{\mathrm{Ex}_{\text{real}}} \qquad (2)$$

which provides a measure of how far the system-level performance, $\mathrm{Ex}_{\text{real}}$, is from the engine-test performance, $\mathrm{Ex}_{\min}$, considered as the reference performance. Of course, accepting the constructor-claimed performance of the vehicle as reference performance makes the threshold very subjective and likely to change in the future, thus requiring new calculations. However, the assumption does not affect the meaning of the present evaluation, which compares the actual exergy expenditures with the results theoretically achievable if the transport system does not add further sources of irreversibility to those already accounted for by the vehicle-test. In short, the smaller the ratio, the higher the improvement potential *at system level*.

For our calculation, we identified as $\mathrm{Ex}_{\min}$ the exergy performance (expressed as the minimum exergy required to move a p-km) of the best performing vehicle yet available on the market, running at maximum payload capacity, chosen from careful reading of vehicle specialized press. $\mathrm{Ex}_{\text{real}}$ is the actual average exergy requirement to move a p-km, calculated according to real data. Exergy associated to vehicle and infrastructure is not included in the accounting, so that the difference between $\mathrm{Ex}_{\min}$ and $\mathrm{Ex}_{\text{real}}$ is only due to irreversibilities generated by traffic problems and transportation dynamics, driver behavior, state of the car, load factor, etc. Results are shown in Table 11.

Cars show an ε value of 21% and this means that the 79% of exergy used by cars to move peoples is squandered for system-generated irreversibilities; this is mainly due to the fact that the medium load factor for car running on the highway is 1.8 persons per vehicle versus the 4 persons per vehicle used to calculate the reference value as well as to further sources of irreversibility generated by traffic dynamics. Load factor and people behavior are more important and relevant than specific vehicle fuel consumption: this means that each technological improvement of engines will be made negligible if cars are still used as single-seat vehicles and if the driver does not adopt an appropriate driving behavior.

The higher ε value for buses indicates that they are used closely to their claimed best performance; in this case, improvements aimed at exergy conservation can only be obtained by means of technological improvements.

Reference value for Inter-City and HST/TAV trains is assumed to be an electric train with a 4 MW power locomotive: for Inter-City, the main reason of inefficiency is due to the lower load factor, while for HST/TAV inefficiencies are due both to the lower load capacity (594 versus 750 persons for trip) and higher power (8.8 MW) of locomotives.

A "realistic" reference for commodity transportation is very difficult to identify because the best option could be represented by the big road trucks with very high load capacity factor (more than 32 t per trip). This kind of trucks cannot be chosen as reference because they cannot be used for short distance or for inside-the-city transport, due to their encumbering size. On the other hand, small delivery vans can be used both for urban and extra-urban transport, but their exergetic performances comes out to be very bad because of their specific fuel consumption for ton transported; moreover, they cannot be compared with trains. Heavy trucks and small delivery vans cover, respectively, the 6% and 68% of vehicles used for commodity transport in Italy, in so identifying very distinct sub-sectors of the commodity transport sub-system. The only way to perform such a calculation would be to deal with trucks in the same way we did for cars (i.e., identifying the best claimed performance for each sub-sector, and so on). Since the procedure would not add any new insight to the previous results, we do not perform this last calculation in the present paper. The interested reader can refer to Ref. [5] for further details in this regard.

Table 11
Second order efficiency for passenger transport on Milano–Napoli axis

Transport modalities	Ex_{min} (MJ/p-km)	ε (%)
Highway (car)	0.42	21
Highway (bus)	0.29	95
Railway[a]	0.21	80–90
TAV[a]	0.21	57–80

[a] Higher and lower range value are referred to maximum and actual utilization rate, respectively.

4.6. Emergy analysis

The emergy accounting procedure projects local input flows to the scale of biosphere, by converting mass, energy and exergy flows into emergy units that are summed up to yield the total emergy (environmental support) driving a production process. Emergy is defined as "*the amount of available energy*[5] *of one kind, usually solar, that is directly or indirectly required to make a given product or to support a given flow*" [29–31]. In this method all materials, energy sources, human labor and services required directly and indirectly to build a product or to provide a service are expressed in terms of solar equivalent joules (seJ). All the material and energy sources that are not of solar origin are expressed as solar equivalent energy by means of suitable transformation coefficients called *solar transformity* (Tr, seJ/J) or *specific emergy intensity* (seJ/unit). Further details can be found in Appendix.

In the investigated sub-systems, the useful products are the p-km and the t-km transported. Passenger transport by car shows the higher emergy intensity, while the best performance is shown by bus transport. Trains perform better than cars only in the scenario with maximum load factor. The different performances between the existing Inter-City railway line and HST/TAV are due to the much higher electric power of TAV engines (with consequent much higher energy and material demand for tunnels and vehicles).

Results for commodity transport are absolutely negative for both railway options: the expected shift of fractions of road traffic to the railway systems, in order to decrease the environmental impact of commodity transport, does not appear as being a feasible option. In fact, the specific emergy of railway transport is 10–15 times higher than for the road system.

5. Discussion of results

It is shown in the paper that specific energy consumption of vehicles is not always the most important factor affecting the choice of a transportation system. Other parameters, namely load factor of vehicles, power of engines appropriate to use, energy and material cost of infrastructures must be taken into proper account for environmentally sound transport policy making. Results are always space- and time-scale specific. When only local-scale dynamics is investigated (e.g., direct fuel consumption), several important aspects are disregarded and results do not provide a comprehensive picture of the whole set of problems/constraints involved. When indirect energy and material costs are taken into account (MFA, EEA, ES

---

[5] In Odum's original definition (Odum, 1996, p. 13, Table 1.1), the term *available energy* refers explicitly to exergy.

methods), the role of infrastructures as well as the impossibility of increasing the load factor of some of the modalities investigated (e.g., HST/TAV) heavily affect the performance indicators and raise several questions on the actual viability and improvement potential of some transportation patterns.

Things appear very different when the global energy and material requirement are accounted for, using the "global scale approach", in that two different new effects can be observed: (a) specific intensities show always higher values than expected; and (b) according to the infrastructure utilization rate, the same vehicle, running on different road or railway systems, may show very different performances. In fact, cars running on the highway show generally lower material and energy intensities than cars running on rural roads or city streets because of a higher load factor on the "highway path" and a more stable trip speed.

Results do not only suggest strategies based on improved engine performance (although the advantage of technical improvements cannot be denied), but strongly point out the need for appropriate use of each transport tool as well as the existence of material, energy and use constraints which cannot easily be removed and which should be taken into account for environmentally sound transport policy choices. A system view is needed, in order to look at the process under different aspects. The multi-method and multi-scale approach used in the investigation provides a clear understanding of the fact that a system cannot be investigated only at local or process scale (direct use of input flows) nor under a mono-dimensional point of view (energy demand) as none of the applied methods can be considered exhaustive in itself to define the best solution. For example, when only direct energy demand is accounted for, Table 8 shows that electric Inter-City railway is by far the best way to transport people and commodities, which is in general the most common opinion. Instead, if the picture is enlarged from direct use to embodied energy, the picture changes radically and indicates buses and trucks as the most appropriate tools. This is not because of an inherent higher suitability of the tool itself, but it is a direct consequence of the increased role of infrastructure and engine power required by the train system. Other large-scale methods (MFA, ES) provide more or less the same results, with HST/TAV ranking very low and buses showing the best performance.

National and European regulations, eco-labels, local traffic restrictions and the whole debate around strategies for sustainable transport, are mainly focused only on the specific performances of the vehicles. Typical examples are the specific amount of different pollutants expressed as g/v-km, which are the indicators on which the European eco-labels for road vehicles are based on. Since the final goal of transportation is not to move a vehicle over a certain distance, but to move passengers and goods, p-km and t-km, not v-km, should be the most appropriate reference units to better identify sustainable strategies. The paradoxical result is that CO_2 emissions (similarly to other performance indicators) calculated as g/p-km for a modern and high efficiency car only carrying one passenger, will be always higher than those calculated for a 10-year-old car with two or three passenger on board. Policies should address the load-factor issue, not only low specific consumption of fuels (which does not include the issue of materials used as well as embodied energy, material and environmental costs) and encourage full-load use of vehicles. Moreover, improving the loading factor of cars and trucks is likely to lead to decreased number of circulating vehicles—in spite of rebound effect concerns–and in turn finally affecting total fuel use.

Time issue, meant as duration of trip, as well as travel comfort is not included in the present study. There is no doubt that a very comfortable car (e.g., SUV) with modern equipment and HST/TAV provide faster and more comfortable travel conditions. The problem here is two-fold and would also deserve much higher attention from transport policy makers:

(a) The practical impossibility to use the infrastructure at higher load factor than described in this study places a higher limit to further time improvement and increased number of possible users, unless much higher resource investment is applied. As a consequence, faster and more comfortable transportation tools are and will be used by a minority of users. This is also due to high economic cost, which is in turn caused by higher energy, material and technological costs which are very unlikely to decrease at the present trend of increasing costs of fossil fuels, steel and copper in the international market.

(b) Implementing high embodied-resource modalities diverts energy, material and financial investments from less intensive patterns. The latter would provide maybe smaller benefits to a majority of users, but would translate into a much higher global benefit for society and environment. In times of declining cheap resource availability, the stability of a system relies more on the globality and effectiveness of the service provided than on high technological individual performances which leave the rest of the system unchanged.

6. Conclusion

Specific results indicate bus transport as the best solution to move people, while train performances are affected by a wrong focus of the whole railway system on speed instead of on reliability and maximum load factor: high-speed trains will never be the "energy saving" alternative to cars, because their power and their energy requirement will always be too high compared to the kind of service that they are able to provide. Focus should never be on technical achievement decoupled from effectiveness of service.

As far as passenger transport is concerned, a suitable integration between light train, with lower power and higher transport capacity, and buses may well result in a lower material, energy, and emergy cost per unit of transport service and still keep the comfort and flexibility of traveling at an acceptable level, while being competitive with the private car option. Instead, the transport of commodities by means of tools other than trucks at competitive resource (material and fuel) costs does not seem at the moment a likely alternative, which may in turn call for a different commodity policy (encourage the use of local commodities instead of long-distance transport of commodities favored by still cheap oil available). In conclusion, sustainable transport is not only and not always the consequence of higher performance tools, but depends on system's properties and global design of its structure and dynamics.

Finally, we believe that the most important result of our study is not the unexpected ranking of transport modalities (which might change over time depending on different organization of the individual sub-systems and the whole transport sector), but instead the clear evidence that mono-dimensional measures are unable to support any reliable policy choice. The integrated framework of the present study helps identifying hidden costs, environmental impact and demand for environmental support, which is a prerequisite for deeper understanding of the system and appropriate policy-making.

Appendix

Summary of the different methods used are as follows.

MFA—material flow accounting

Quantifying input and output mass flows is a preliminary step. We need to assess not only the amount of input materials, but to the highest possible extent the amount of outputs (products, co-products, and emissions). The latter are important for the evaluation of the different possible kinds of environmental impact. In addition, when we expand our scale of investigation, we realize that each flow of matter supplied to a process has been extracted and processed elsewhere. Additional matter is moved from place to place, processed and then disposed of to supply each input to the process. Sometimes a huge amount of rock must be excavated per unit of metal or chemical element actually delivered to the user. Most of this rock is then returned to the mine site and the site reclaimed, but its stability is lost and several chemical compounds become soluble with rainwater and may affect the environment in unexpected ways. Accounting for the material directly and indirectly involved in the whole process chain has been suggested as a measure of environmental disturbance by the process itself [32]. A quantitative measure is provided by means of material intensity factors (MIF) calculated for several categories of input matter, namely abiotic, biotic, water, and air [33]. The total mass transfer supporting a process indirectly measures how the process affects the environment due to resource withdrawal.

EEA—embodied energy analysis

First-law heat accounting is very often believed to be a good measure of energy cost and system efficiency. The energy invested into the overall production process is no longer available. It has been used up and it is not contained in the final product. The actual energy content (measured as combustion enthalpy, HHV, LHV, etc.) of the product differs from the total input energy because of losses in many processes leading to the final product. Energy analysts refer to the total energy required in the form of crude oil equivalent as to "embodied energy" [13]. In general, EEA accounts for the total amount of commercial energy (mainly fossil fuels or equivalent energy) expressed in terms of gram oil equivalent or MJ. Energy Intensity is the amount of raw oil (g or MJ) needed per unit of product.

EXA—exergy analysis

Not all forms of energy are equivalent with respect to their ability to produce useful work. While heat is conserved, its ability to support a transformation process must decrease according to the second law of thermodynamics (increasing entropy). This is very often neglected when calculating efficiency based only on input and output heat flows (first-law efficiency) and leads to an avoidable waste of still usable energy and to erroneous efficiency estimates. The ability of resources to supply useful work or to support a further transformation process must be taken into account and offers opportunities for inside-the-process optimization procedures, recycle of still usable flows, and downstream allocation of usable resource flows to another process.

The ability of driving a transformation process and, as a special case, producing mechanical work, may be quantified by means of the exergy concept. According to Szargut et al. [14] exergy is "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature". Chemical exergy is the most significant free energy source in most processes. Szargut calculated chemical exergy as the Gibbs free energy relative to average physical and chemical parameters of the environment.

By definition, the exergy (ability of doing reversible work) is not conserved in a process: the total exergy of inputs equals the total exergy of outputs (including waste products) plus all the exergy losses due to irreversibility. Quantifying such exergy losses (which depend on deviations from an ideal, reversible case) for a process offers a way to calculate how much of the resource and economic cost of a product can be ascribed to the irreversibility affecting the specific technological device that is used as well as to figure out possible process improvements and optimization procedures aimed at decreasing exergy losses in the form of waste materials and heat. Exergy losses due to irreversibilities in a process are very often referred to as ‘‘destruction of exergy.’’ Exergy efficiency is therefore defined as the ratio of the exergy of the final product to the exergy of input flows.

ES—emergy synthesis

The same product may be generated via different production pathways and with different resource demand, depending on the technology used and other factors, such as boundary conditions that may vary from case to case and process irreversibility. In its turn, a given resource may require a larger environmental work than others for its production by nature. As a development of these ideas, Odum [29–31] introduced the concept of *emerg*y, i.e., ‘‘the total amount of available energy (exergy) *of one kind (*usually *solar)* that is directly or indirectly required to make a given product or to support a given flow’’. In some way, this concept of embodiment supports the idea that something has a value according to what was invested into making it. This way of accounting for required inputs over a hierarchy of levels might be called a ‘‘donor system of value’’, while EXA and economic evaluation are ‘‘receiver systems of value’’, i.e., something has a value according to its usefulness to the end user. S*olar emergy* was therefore suggested as a measure of the total environmental support to all kinds of processes in the biosphere, including economies. Flows that are not from solar source (like deep heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients [29].

The amount of input emergy dissipated per unit output exergy is called *solar transformity*. The latter can be considered a ‘‘quality’’ factor which functions as a measure of the intensity of biosphere support to the product under study. The total solar emergy of a product may be calculated as: (solar emergy) = (exergy of the product) × (solar transformity). Solar emergy is usually measured in solar emergy joules (seJ), while the unit for solar transformity is solar emergy joules per joule of product (seJ/J). Sometimes emergy per unit mass of product or emergy per unit of currency are also used (seJ/g, seJ/$, etc.). In doing so, all kinds of flows to a system are expressed in the same unit (seJ of solar emergy) and have a built-in quality factor to account for the conversion of input flows through the biosphere hierarchy.

Values of transformities are available in the scientific literature on emergy. When a large set of transformities is available, other natural and economic processes can be evaluated by calculating input flows, throughput flows, storages within the system, and final products in emergy units. As a result of this procedure, a set of indices and ratios suitable for policymaking [16] can be calculated.

Intensity factors

Each method uses intensity factors for calculation of input and output flows. Table 1 lists Factors used in the present investigation. Most values are from published literature, while others were calculated in this work. Since all intensity factors are by definition system, location, boundary and technology specific, the choice of factors requires a preliminary check about the characteristics of process and procedure where they come from. In the presence of uncertainty, average values were adopted.

References

[1] Shipper C, Meyers H. Energy efficiency and human activity: past trends, future prospects. Cambridge, UK: Cambridge University Press; 1992.

[2] IEA. Indicators of energy use and efficiency. See also: 〈http://www.iea.org/textbase/stats/index.asp〉.

[3] ENI. Results and Strategy 2006. See also: 〈http://www.eni.it〉.

[4] ENEA. Report on energy and environment (Rapporto Energia e Ambiente, in Italian). See also: 〈http://www.enea.it/com/web/pubblicazioni/REA_04/Dati_04.pdf〉.

[5] Ruzzenenti F, Federici M, Basosi R. Energy efficiency and structural change in production: an analysis of long-term impacts in the road freight transport sector. In: Ulgiati S, Bargigli S, Brown MT, Giampietro M, Herendeen R, Mayumi K, (Eds)., editors. Advances in energy studies. Perspectives on energy future, Portovenere, Italy, 2006, in press.

[6] Federici M, Ulgiati S, Verdesca D, Basosi R. Efficiency and sustainability indicators for passenger and commodities transportation systems: the case of Siena, Italy. Ecol Indicators 2003;3(3): 155–69.

[7] Federici M, Ruzzenenti F, Ulgiati S, Basosi R. A thermodynamic and economic analysis of local transport systems. In: Ulgiati S, Brown MT, Giampietro M, Herendeen RA, Mayumi K, editors. Advances in energy studies. Reconsidering the importance of energy. Padova, Italy: SGE Publisher; 2003. p. 433–46.

[8] Autostrade SpA. Italian highway statistics (Autostrade in Cifre, in Italian), 〈http://www.autostrade.it/serv_info/rete_index.html〉, 2002.

[9] Trenitalia SpA. Environmental declaration (Rapporto Ambientale, in Italian), 〈http://www.trenitalia.it/it/703c2939f7b36010VgnVCM10000045a2e90aRCRD.shtml〉, 2002.

[10] TAV SpA. Interview and personal communication.

[11] TAV SpA. Eco-balance rudiments for comparing purpose (Elementi di Ecobilancio Comparato, in Italian). Internal Pamphlet, 1995.

[12] Bargigli S, Raugei M, Ulgiati S. Mass flow analysis and mass-based indicators. In: Sven E, Jorgensen RC, Xu F-L, editors. Handbook of ecological indicators for assessment of ecosystem health. CRC Press; 2005. p. 353–78.

[13] Herendeen AR. Prospective/retrospective on strategies. In: Ulgiati S, Brown MT, Giampietro M, Herendeen RA, Mayumi K, editors. Advances in energy studies. Exploring supplies, constraints, and strategies. Padova, Italy: SGE Editoriali Publisher; 2000. p. 343–8.

[14] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical and metallurgical processes. London: Hemisphere Publishing Corporation; 1988.

[15] Sciubba E, Ulgiati S. Emergy and exergy analyses: complementary methods or irreducible ideological options? Energy 2005;30(10): 1953–88.

[16] Brown MT, Ulgiati S. Emergy analysis and environmental accounting. In: Cleveland C, editor. Encyclopedia of energy. Oxford, UK: Academic Press, Elsevier; 2004. p. 329–54.

[17] Ulgiati S. Energy flows in ecology and in the economy. Encyclopedia of physical science and technology, vol. 5. Academic Press; 2002. pp. 441–460.

[18] ASM Brescia SpA. Interview and personal communication.

[19] ISTAT. Transport statistics (Statistiche dei trasporti) ISBN: 88-458-0890-4, Istat publishing, Rome, 2005 (in Italian).

[20] ACI, Annual Report (Annuario Statistico 2005, in Italian). See also: 〈http://online.aci.it/acinet/cd/datiestatistiche/Frame_Annuario_2005.asp〉.

[21] Wuppertal Institute. Material intensity of materials, fuels, transport services. 〈www.wupperinst.org/uploads/tx_wibeitrag/MIT_v2.pdf〉.

[22] EPA. 1996. United States Environmental Protection Agency. Compilation of air pollutant emission factors, vol.1, 5th ed. Point Sources AP-4.

[23] EPA. 〈http://www.epa.gov/ttn/chief/ap42/index.html〉.

[24] Herendeen AR. Embodied energy, embodied everything…now what? In: Ulgiati S, Brown MT, Giampietro M, Herendeen RA, Mayumi K, editors. Advances in energy studies. Energy flows in ecology and economy. Roma, Italy: MUSIS Publisher; 1998. p. 13–48.

[25] Boustead I, Hancock GF. Handbook of industrial energy analysis. Ellis Horword Limited; 1979. pp. 442.

[26] SimaPRO 7, software database. PRè Consultants, 2006, the Netherlands. See also: 〈http://www.pre.nl/simapro/default.htm〉.

[27] Schleisner L. Life cycle assessment of a wind farm and related externalities. Renew Energy 2000;20(3):279–88.

[28] Dewulf J, Van Langenhove H. Exergetic material input per unit of service for the assessment of resource productivity of transport commodities. Resour Conservat Recycl 2003;38(2):161–74.

[29] Odum HT. Environmental accounting: emergy and environmental decision making. New York: Wiley; 1996.

[30] Odum HT. Environment, power and society for the twenty-first century. Columbia University Press; 2007. p. 68.

[31] Brown MT, Herendeen RA. Embodied energy analysis and EMERGY analysis: a comparative view. Ecol Econ 1996;19(3):219–35.

[32] Hinterberger F, Stiller H. Energy and material flows. In: Ulgiati S, Brown MT, Giampietro M, Herendeen RA, Mayumi K, editors. Advances in energy studies. Energy flows in ecology and economy. Roma, Italy: Musis Publisher; 1998. p. 275–86.

[33] Wuppertal Institute, 〈www.wupperinst.org/Projekte/mipsonline/download/MIWerte〉, 2003.