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To build or not to build? Megaprojects, resources, and environment: an emergy synthesis for a systemic evaluation of a major highway expansion

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ABSTRACT

Systems thinking and emergy synthesis are applied to transport studies in order to assess the socio-ecological convenience of a civil infrastructure: they are presented as comprehensive evaluation tools to go beyond conventional approaches like cost-benefit analyses, while geobiophysically including the overall resource consumption and the release of pollutants. Focusing on road systems, the massive expansion works on the mountainous section of Italian major highway *A1* are chosen as a case study: such recently completed project is compared with the no-build option, considering alternative scenarios ranging from dedicated mobility policies using the old infrastructure to a partial modal shift to rail transport. Results are expressed in terms of total invested emergy, emergy per passenger-kilometer, and per ton-kilometer; data can be easily read also in terms of environmental, physical, and financial units. The convenience of the expansion works results highly questionable: the annually required emergy is shown to significantly increase: +24% for passengers and +51% for freight averagely (i.e., with or without services besides energy and material inputs). A key role is played by saved travelling time (computed as driving labor), able to mitigate but not to reverse the situation while representing a controversial accounting item. Instead, alternative uses and policies for the old infrastructure would all have yielded significant savings. In light of the above, some conclusions are drawn on societal priorities, including a critical reappraisal of time saving as an often unsustainable driver within a still mostly unquestioned ‘more and faster’ mantra. The need to support ecologically and strategically sustainable societal decision-making in the transportation sector is therefore framed in wider thoughts on economic planning and resource allocation, while envisaging a tranformation towards a prosperous and sustainable future.

1. Introduction

The increasing energy demand and the polluting climate-change emissions are widely considered among the main environmental issues of the 21st century. In this framework, the transportation sector plays a primary role both in energy use and in pollutant emissions. However, resource, energy, and pollution issues related to the transportation sector have been usually addressed separately. Economic-based or network theory approaches are the most common, aimed at maximizing economic and managing efficiencies (see for example Cascetta, 2009; Sussman, 2000). Environmental impact evaluations have been usually addressed to specific situations or specific risk categories, mostly taking into account the downstream impact of transportation methods in terms of assessment of environmental externalities (Rodrigue, 2017). A comprehensive systemic approach aimed at the evaluation of the overall upstream investment is on the other hand still lacking. The aim of this paper is the analysis of road systems with expanded systemic boundaries, providing geo-biophysical information to support suitable and conscious decisions on either the building or the non-building of civil infrastructures, based on a strategical, social and environmental convenience. A real case study is then investigated.

The work by the American biologist Barry Commoner (1971, 1990) may help understand the possible reduction strategies that are or might be undertaken in an industrial sector such as transportation. The total amount of pollution can be expressed by:

Total pollution = (pollution per unit of commodity) · (commodity per capita) · (population). (1)

Following Commoner's equation, we might also claim that energy consumption similarly is:

Total energy consumption = (energy per unit commodity) · (commodity per capita) · (population). (2)

The reduction of both pollution and energy consumption can be therefore addressed by acting on one or more of the three factors. Reducing pollution or energy consumption per unit of commodity is usually delegated to technological advancement; as a matter of fact, however, it should be noted that the commodity itself is often designed to become old soon (planned obsolescence). Concerning the second factor – commodity per capita – the mantra "more is better" is the mindset provided in any mainstream microeconomics class in a college: as a consequence, this appears to be a critical issue to address when setting a strategy to reduce pollution and energy consumption. Finally, global population (hence potential consumers) is another ever-growing factor, both in terms of global numbers and in terms of potential target consumers in a market economy. Therefore, when addressing such issues, the reduction of pollution and energy consumption per unit of commodity appears as the most frequent topic currently discussed by scholars and policy-makers, at least at the mainstream level[1]. However, this does not mean that it ought to be the only factor to address, especially if we aim at achieving effective sustainability within a systemic and comprehensive vision. In the road transportation sector, the reduction of pollution per unit of commodity is generally pursued through proper legislation (European Union directives on vehicle emission standards, European Commission, 2007a, 2007b). Nonetheless, recents scandals on cheating while complying with such regulations – involving several renowned world leading automobile producers (Goel, 2015; Zhang *et al*., 2016; Terry-Armstrong, 2016; EPA, 2017) – let us presume that reality might still be far away from what norms prescribe. It should also be noted that the industry of on-road transportation vehicles is all but free from the logics that of planned obsolescence (cars are often replaced for outdated performances), and socio-economic development and technological advances have tendentially[2] brought us more and bigger and cars (Diez *et al*., 2016; Gao *et al*., 2014; Baker & Hyvonen, 2011; Goel & Guttikunda, 2015; Kolk & Tsang, 2017)[3], thus counterbalancing and potentially nullifying (Goel & Guttikunda, 2015) the benefits of energy efficiency and policies for emissions reduction per vehicle. To allow for more vehicles to drive, bigger and bigger infrastructures are usually needed, requiring huge amounts of materials, energy, and labor to be built and allowing for higher average speeds (usually corresponding to higher levels of fuel consumption and pollutant emissions, see Cristiano, 2016; Fontaras *et al.*, 2017). As to the energy consumption in the transportation industry, possible efforts toward its reduction seem generally delegated to the market, and limited to the appeal of less expensive driving in monetary terms. Conversely, – but still within market dynamics – sometimes a declared care for limiting energy consumption on roads comes from the companies that own and/or manage a highway. This might happen to justify the building up or the modernization of some infrastructures (i.e., what is sometimes referred to as megaprojects), which imply large financial resources as well as years or decades of gigantic civil works. Cost-benefit analyses are generally led to decide for new or renovated transport infrastructures, but their boundary of analysis is usually limited within the financial sphere, thus leaving out essential aspects of sustainability (see e.g. Mishan, 2015). Possible (if not frequent) non-financial criticalities are assigned a role of negative externalities, without exploring more durable and comprehensively sustainable alternatives. In the case of road transport infrastructures, decision making is usually driven by the productivity mantra – both directly (more and faster passenger and freight transport, more work for the building sector, etc.) or indirectly (road safety while driving faster and faster) – yet neglecting important aspects also related to the viability of such facilities in a close future with changing resource scenarios (as in Mohr *et al.,* 2015; Calvo *et al*., 2017). The objective of this

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[1] See for instance the United Nations seventh Sustainable Development Goal (https://sustainabledevelopment.un.org/sdg7)

[2] There is of course a limit that is being met in globally few circumstances, as in some urban contexts in the Global North, where car use is less and less convenient due to congestion, unavailable parking lots, and discouraging public policies (Diez *et al.*, 2016).

[3] Not to mention the increases in the sales of sport utility vehicles (SUVs), as reported for example by Parikh (2016), Saxena & Shukla (2018), and Babones (2018). Plenty of diagrams on the historical evolution and future projections of SUVs sales are available, e.g. by LMC Automotive, providing reports and forecasts of the automobile sales industry (https://lmc-auto.com/segment-trends-cars-and-suvs/). For car size evolution please see also: http://www.teoalida.com/cardatabase/images/Car-Length-Evolution.png

paper is therefore to enlarge the boundaries of the analysis, and evaluate the building up or the expansion of a road infrastructure in a systems thinking framework (Meadows & Wright, 2008) to provide an insight on costs and impacts in their broadest meaning as well as to grasp further essential sustainability aspects of the decision-making process in the allocation of scarce resources. This is done by resorting to the emergy accounting method (see the following section), able to provide important information to integrate preliminary strategical assessments. In particular, one of the main objectives of this study (as many similar ones in the field of emergy accounting) is to help addressing the environmental constraints and the need for corresponding policies aimed at preserving the interested areas. For instance, the emergy descriptive index known as Environmental Loading Ratio (ELR) may address the pressure on the environment, that is, the potential ecosystem stress. Referred to this indicator, the presented results point out an unsustainable sector. On the other hand, this can be – to some finite extent – socio-economically necessary, so that its (un)sustainability must be managed, possibly identifying potential buffer areas to compensate the loading due to the provided service, and designing for real unloading compensation measures elsewhere. The trade-off between environmental stress and land demand is a typical aspect of the policies concerning sustainability, and in this sense the emergy synthesis may also provide a quantification of the land footprint of the systemic service.

The ultimate research question is the scientific information needed to support future decision-making in the field of transportation infrastructures, by understanding and evaluating the possible contribution and side effects of a highway expansion in pursuing (or calling for) a reduction in energy consumption as well as in pollution. Contribution to reduction might come from both reducing their values per unit of commodity and reducing their total values. Our case study is represented by the analysis of costs and effects of major expansion works on a highway section. This is not limited to the evaluation of possible changes in polluting emissions, but also computes the differences in energy consumption in operation as well as the social and environmental investments (energy and material resources, labor, information) that were required for its transformation over the duration of the building site. The environmental services that are needed to make up for the released emissions are also accounted for.

Several scenarios are investigated that include the old infrastructure, the new infrastructure, and a combination of alternatives to the expansion, consisting in partial modal shifts for freight transport as well as in a possible encouragement of shared passenger transportation. All source and calculation data are elaborated through the emergy accounting method.

2. Materials and methods

2.1. Emergy accounting

2.1.1. The method

The analysis we address in this paper is carried out through the emergy synthesis method, thus allowing to quantify under the same unit all the investments that are actually needed to realize the aforementioned civil works. The concept of emergy was introduced by Howard T. Odum (1988, 1996; cf. also Brown & Ulgiati, 2016a, 2016b) and is sometimes considered as an expansion of the embodied energy concept. Emergy is defined as "the available energy of one kind previously used directly or indirectly to generate a service or a product". Emergy allows to measure and compare the performances of systems based on a common energy metrics, i.e., solar equivalent joules (sej). The emergy requirement per unit of output (energy, matter, services, money) is called Unit Emergy Value (UEV), and measured as sej/unit (sej/J, sej/g, sej/€, and so on). Emergy accounting includes the natural processes that were necessary to generate resources over time as well as the antropic activities to extract, manufacture, and delivery such resources. This gives significant importance to the environmental efforts needed – in time and or in concentration – to generate a resource. If compared to the embodied energy method, emergy accounting presents a boundary expansion over time (processes for resource generation) and over resource categories, because it also includes natural flows (sun, wind, rain, deep heat, tidal energy) and material flows (mineral ores, metals). An emergy evaluation process starts with the definition of the boundaries of the system or of the process, along with the drawing of the system diagram. Secondly, the flows of matter, energy, services, and money driving the process are identified and quantified, including renewable resources that are provided for free by the local environment (R), non-renewable resources available locally (N), and imported good and commodities from outside the system (F). Such inputs are then converted into emergy units by means of suitable conversion factors (UEVs), with reference to the geobiosphere global emergy baseline (GEB); in this paper, a GEB of 1.20 E+25 sej/yr is used (Brown *et al.*, 2016). Finally, proper emergy indicators can be calculated (Odum, 1996), such as the emergy yield ratio (EYR), the environmental loading ratio (ELR), the emergy sustainability index (ESI), or more case-specific indicators that might be defined for the study at issue, like in the case presented in this work.

2.1.2. Previous emergy studies dealing with transportation systems

Although with different aims, focuses, and scales of detail, emergy accounting has already been used in previous investigations carried out in the transportation sector or at least including some emergy indicators for paved roads (Roudebush, 1996; Brown & Vivas, 2005; Federici *et al*., 2003, 2005, 2008, 2009; Reza *et al*., 2013, 2014; Threadcraft, 2014). Roudebush's focus is not on a transport system but rather on a section of the road infrastructure industry, i.e., a comparative analysis of costs and impacts of two different tecniques to build road pavements, namely concrete and asphalt. In Brown & Vivas, paved roads, roughly grouped in two-lane and 4-lane, are assigned some not universally used emergy-based values (non-renewable empower density and Landscape Development Intensity coefficient) within a much wider study on the human disturbance of landscapes, thus no calculation detail for the roads is even reported. In Reza *et al.*, paved roads are used to investigate the uncertainties in the emergy approach (2013), and then to compare two road scenarios, mostly from a life cycle assessment perspective. Federici *et al.* and Threadcraft, instead, carry out comparative analyses between road and other transport systems (mainly rail infrastructures). Federici *et al.* consider whole existing infrastructures, while Threadcraft focuses on just one mile for several road types. If only in Federici *et al.* an emergy synthesis is present as it is meant today, transportation is not framed yet into a wider discourse on the allocation of limited resources in a societal system, and does not include environmental services for the dilution of the pollutant emissions nor the driving activity (thus not addressing the issue of time related to people and freight displacement). Although certainly not being an emergy evaluation, an early paper on energy evaluation of transportation projects (Bayley *et al.*, 1977) was also co-authored by future emergy theorist Howard T. Odum. In our study, total inputs and downstream costs and impacts related to the renewed highway section at issue are accounted for while addressing the research gaps detected in literature, in order to extensively assess whether this brings any success in reducing the environmental loading (e.g., by allowing for a lower fuel consumption on the renovated road section) and therefore provide adequate systemic environmental information to propose or support policy making. In parallel to our work and also using a similar approach, an (inevitably rough) analysis has been carried out on the total Chinese road infrastructure network within a larger study on the terrestrial transport modalities in that country, as recently published in a paper (Huang *et al.*, 2018), which the first Author supported with some engineering calculations.

2.1.3. Our emergy synthesis

In this study, emergy accounting is performed following the usual procedure of first diagramming the infrastructure system, then creating a comprehensive inventory of the resources involved in the system operation, and finally determining a set of indicators representing the actual investment efficiency, where the investement accounts for what provided by human economy as well as by the geobiosphere. The evaluation of the investigated civil infrastructure works is led through the comparison of the road sub-system before and after its deviation and expansion. Costs and expected benefits are assessed in terms of materials, energy, and labor respectively needed or saved, so as to provide detailed information for the evaluation of the choice already made and – above all – for responsible future policy-making. Novel indicators have been more specifically designed and calculated for transportation studies (Federici *et al*., 2008, 2009), namely, the emergy per passenger-kilometer (expressed in sej/p-km) and the emergy per ton-kilometer (expressed in sej/t-km). This allows to make the emergy synthesis more suitable for decision-making recommendations, in as much the integrated sustainability of a system must be also expressed in terms of output performaces.

2.2. Case study and analyzed scenarios

Our study addresses the existing case of the Italian *A1* highway, linking Milan to Naples. In particular, its Apennines mountainous passage ("*Variante di valico*") between Bologna and Florence is analyzed before and after the quite recent completion of major deviation and expansion works, namely, the "*A1* var" section, opened in December 2015 (see Figure 1). Its managing authority – the Italian leading company (Bruno, 2016) in the group of the concessionaires for public highways – has claimed that such works would let their customers save up to 100 millions liters of fuel every year (Autostrade per l'Italia, 2015), even though – to the best knowledge of the authors – details have not been published to retrace the calculations that led to such value. No consideration has been made, so far, on the social and environmental costs of the expansion works, that lasted over 10 years and costed 7 billion euros (data from Italy's national public broadcasting company Rai -

Radiotelevisione italiana, 2015). Previous independent studies by one of the Authors (Cristiano, 2012; 2016) provide data to estimate the expected benefits and detriments of the expansion of a consecutive section of the one at issue, in terms of polluting emissions, calculated after a testing campaign in virtual reality (drive simulation) and elaborated through a dynamic model continuously computing the driving behavior of the vehicle. No significant savings in terms of pollution per unit of service (i.e., g/km per vehicle) were observed, while official EU prediction models have been found to averagely underestimate pollutant emissions. At the same time, no hint of significant savings in fuel consumption was evidenced when analyzing the differences in the opening of the throttle valve, although neither of the two studies focused on transforming this information into fuel liters. The present study is based upon both the information provided by the highway managing authority and the aforementioned previous studies, as well as upon our further calculations. Expected benefits following the expansion at issue are calculated and compared with the socio-environmental inputs needed for the construction works.

Fig. 1. Positioning of the *A1 var* section *"Variante di valico"* of the Italian highway A1 (Milan-Naples) [circular highlight on creative commons map by Arbalete; CC BY-SA 4.0]

Two main scenarios have been firstly analyzed, i.e., the old and the deviated/expanded highway at issue. In addition, more scenarios – alternative to the deviation and expansion works – are also considered in order to provide a wider picture of possible different options. Among the alternative scenarios not requiring a new infrastructure are: i) a modal shift (road to rail) for freight and passenger transport; ii) a change in the use of the same infrastructure (i.e., by encouraging car pooling up to the 10% and 20% of transported passengers); iii) an overall decrease of freight transport (–20% and –50%) that may result from different reasons, including a policy-induced modal shift, a spontaneous, increased preference for local products inducing less national or international commodity transportation, or resulting from a slower societal metabolism (e.g., less planned obsolescence, or less commodities per capita).

The diagram for the case study at issue is presented in Figure 2. The system boundary includes the local support area, roughly corresponding to the land alongside the infrastructure track. Modification of this area happens through specific machinery and through the labor of workers, who gradually transform materials and goods into the proper infrastructure ('Road and Assets'), in turn used for the construction itself (the first stretch of highway allow to built the next, and so on) as well as for its maintenance over time. The construction and maintenance process also includes the infrastructure operation. It is worth mentioning that optional facilities such as fuel filling stations are not accounted for in the present study. In fact, the possible presence of such a facility in a relatively short road section would require to calculate its operation on the longer portion of highway it would serve, and this is beyond the purposes of the present study. Moreover, the inputs to build such a station are negligible if compared to the overall construction works (a different discourse can be made for cash inflows deriving from its concession, but such data would not affect our calculations since the emergy associated with the purchased services is computed anyway). The built and maintained road infrastructure allows for the transportation of passengers (also indicated as 'Pax' in the figure) and freight. Transportation represents the core process of the system at issue, and is also driven by vehicles, temporarily entering it, by the labor of their drivers, by fuels and electricity (mostly for the motion of vehicles), and by renewable sources (e.g., the sun, also lighting the road during the day, or the rain, also cleaning the road when dirty). Purchased inputs from outside the system are brought in together with their related services. Monetary inflows are made of governmental funding or concession (a form of indirect funding) as well as of tolls paid by privates for the received service of passenger and/or freight transportation. Monetary outflows pay the services for imported inputs. In this approach, the outputs of the system are considered to be the passenger transportation and the freight transportation services. Their functional units are represented by the passenger-kilometer (p-km) and by the ton-kilometer (t-km). Physically, the chosen system boundary for the emergy synthesis corresponds to the "*A1*" highway section between *Sasso Marconi* and *Barberino del Mugello* (around 55 km), with an average width corresponding to the distance included between the external margins of its side shoulders (in fact, due to the massive presence of tunnels, viaducts, and retaining walls, no much more land is occupied laterally). Temporally, the boundary consists of a period of one year; indeed, most data are available on an annual basis, while investment and construction inputs – generally available per kilometer of infrastructure (differentiated in road surface, tunnels, viaducts) – are divided by the planned or expected useful lifetime of the item to which they refer.

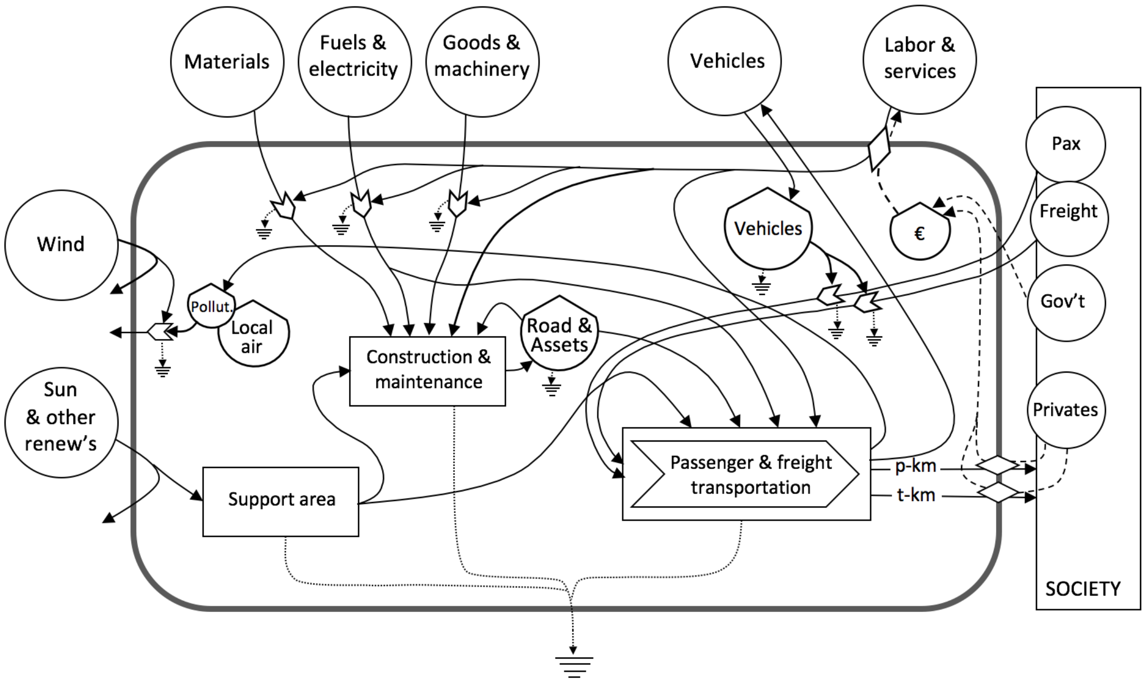


Fig. 2. Systems diagram of a road infrastructure (highway)

Figure 3 shows the flows from which the corresponding emergy quantities are computed to obtain the indicators. Emergy Yield Ratio (EYR) is the ratio between the total emergy yield output (R+N+F) and the one invested from main economy, F. It is a measure of the capability of a process to make available new emergetic resources by investing the already available ones (resources exploitation per unit of input from the economic system). Environmental Loading Ratio (ELR) confronts the emergy from the economy system and from non-renewable resources (F+N) with that coming from local renewables (R), being so related to the presence of an ecosystemic stress. The ratio between EYR and ELR is called Emergy Sustainability Index (ESI), and it is an integrated measure of economic yield and environmental compatibility, putting together the information about local/non-local resources and renewable/non-renewable ones.

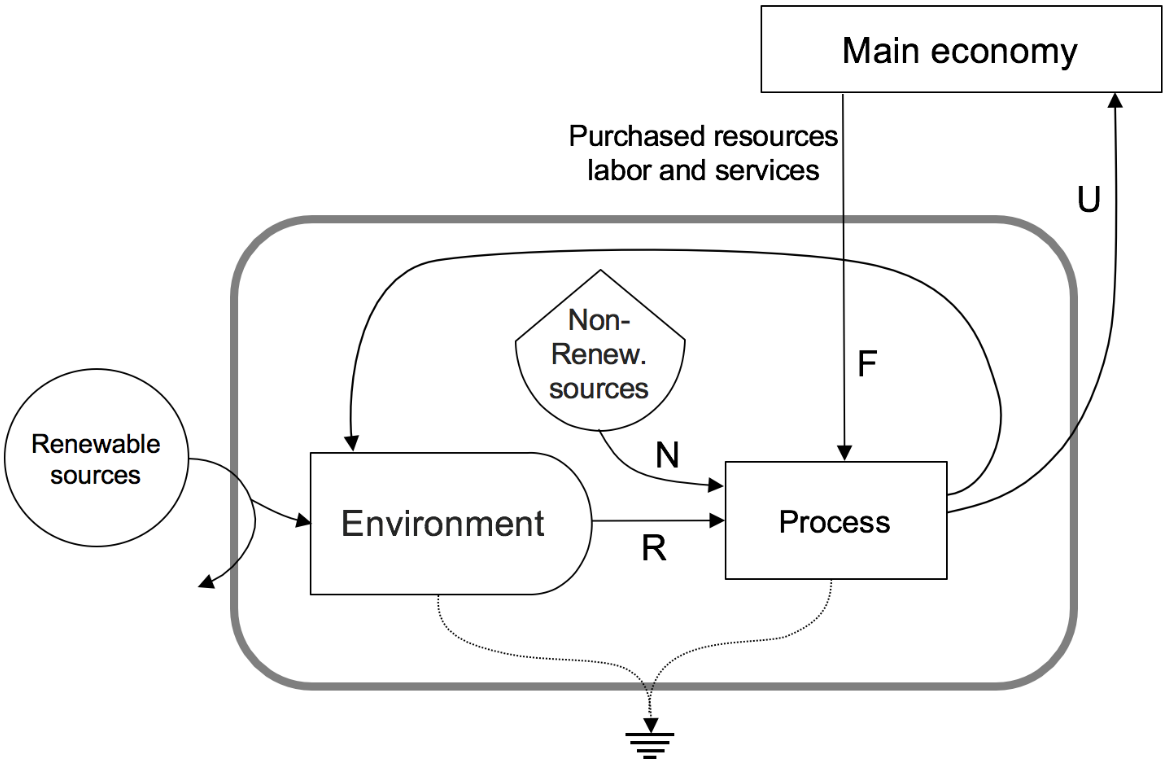


Fig. 3. Main flows for the definition of the usual emergy indices, referred to a generic system.

2.3. Raw data and calculation steps

2.3.1. Inputs for road manufacts building and maintenance

First (two-lane existing highway section) and second (deviated and expanded highway section) scenarios share the inputs for the road manufacts, including the quantities of fuel and electricity needed for its annual maintenance (calculated after Federici *et al.*, 2008) as well as the previously required services for its construction (based on Provincia di Bologna, 2015, with data on tunnels adjusted to our case study). The second scenario has inputs for the expansion works (materials, machinery, energy, services) as well as for the maintenance of the new and renewed sections. Such works are separated in: i) building of the additional (third) lane, ii) building of the brand-new three-lane sections, and iii) building of tunnels and viaducts. In both scenarios, calculations for the road surface are based on project documents from Italian local government agency Provincia Autonoma di Bolzano (2015), those for tunnels and viaducts are based on both project documents and on-site inspections. Road basis is composed of loam and clay, sand, gravel, water, and cement, while top layers are made of loam and clay, sand, gravel, bitumen, and water; drainage works have a concrete structure and plastic tubing. The length of each type of section is provided by the managing authority Autostrade per l'Italia (2015), except for the tunnels and viaducts of the existing section, which derive from Osservatorio Variante di Valico (2001), an observatory specifically established to monitor this project. When necessary, non-tunnel and non-viaduct road section lenghts are accounted bidirectionally since highway has two or more lanes per direction, usually organized in different road manufacts. The useful lifetime of road basis and drainage works is 70 years (Federici *et al.*, 2009), while that of road top layers is 5 years (*ibid.*). Useful lifetimes of tunnels and viaducts are instead set as 100 years (following Italian official guidelines by Consiglio Superiore dei Lavori Pubblici, 2008). More materials are accounted for the expanded section: data for highway furniture (i.e., steel in guardail) and electric cables (i.e., copper) come from the Italian business newspaper Il sole 24 ore (2015), while those for anti-noise barriers come from the managing authority Autostrade per l'Italia (2015); they are all divided by a useful lifetime assumed as 30 years. The inputs of fuel for construction, and of steel for construction machineries are calculated after Federici *et al.* (2008). However, due to the complexity of the mountainous passage in our case study, a closer similarity is found with the data provided for High Speed Train infrastructures on the same Milan-Naples axis: an average steel mass of

9.93E+01 kg/km was then chosen, with a useful lifetime set as 30 years (*ibid.*). The order of magnitude of steel mass in machinery has been double-checked, and corresponds to a relevant use of a tunnel boring machine (TBM). Fuel and electricity inputs for annual maintenance are included also in the calculations for the expanded section (*ibid.*). In light of some preliminary assessment and literature review, the end-of-life phase for the two road infrastructures at issue is not included into our analysis. This is mostly due on the one hand to the fact that demolition, landfilling, and recycling inputs are usually of at least one order of magnitude smaller than the original material inputs (cf. Brown & Buranakarn, 2003), on the other to the fact that an extension of the project lifetime is highly likely for most construction items (van Noortwijk & Frangopol, 2004; Yang *et al*., 2006; Gastineau *et al*., 2013) through the maintenance inputs already included; accordingly, possible extra resources required when no more extension is possible are assumed to be compensated by the lower annual construction input due to the lifetime extension itself.

2.3.2. Inputs for highway use

In both scenarios, the regular highway use is accounted for in terms of vehicles and fuel consumption: the first are computed as the mass of materials in the passenger cars and the freight trucks driving on the section in one year, and only attributed to the system at issue as the total ratio of annual vehicle-km to the expected average mileage travelled in the useful lifetime of a car and of a truck; fuel consumption is accounted based on the vehicle-km recorded on the section in one year for each vehicle category, on its respective fuel performances, and on the average density of oil-derived fuel. The annual distances covered by passenger cars and freight vehicles refer to year 2015 – representative of the traffic flow in the six-year period going from the second semester of 2010 to the first semester of 2016 (AISCAT, 2010-2016); according to such data, the same traffic volume is considered for both scenarios, since no increase has been registered nor – to the best knowledge of the authors – foreseen. Data on the composing materials of an average passenger car come from Lou *et al.* (2015); data of freight vehicles are also based on this, yet adjusted according to a reference average mass of 2.48 tons per truck (Federici *et al*., 2008). Useful lifetimes for passenger cars and trucks are respectively assumed as 150,000 km and 1,000,000 km. The average class of emission of vehicles is set as the EU standard Euro IV (after Automobile Club d'Italia, 2012). Average fuel consumption of middle-sized passenger cars and of trucks derive from the European Environment Agency (EEA) Air Pollutant Emission Inventory Guidebook (European Monitoring and Evaluation Programme [EMEP], 2013), based on a Euro IV gasoline passenger car (cubic capacity between 1.4 and 2.0) and on a Euro IV diesel heavy duty vehicle (<7.5 t), respectively. For seek of simplicity, only oil-derived fuels are considered in our emergy accounting calculations; in fact, natural gas is a less used fuel, and has a UEV very similar to crude oil, while electric cars are still far from being significant on the automobile market (The European House Ambrosetti *et al.*, 2018). The EMEP procedure is based on average speeds, but the correctness of negleting its variation has been questioned (Cristiano, 2016), since lower average speeds would yield lower levels of fuel consumption and pollutant emissions. Yet one of the Authorities studying the expansion works (Osservatorio Variante di Valico, 2001) declares that the reduction of mean speed down to 60 kph for passenger cars and to 40 kph for freight vehicles is caused by frequent levels of congestion on the old section; therefore, our calculations do not automatically use mean speed, but rather conceive three different levels of traffic interference (assumed as involving the same percentage of traffic volume) leading to a reduced mean speed (–50%), to the declared mean speed, and to a higher mean speed due to a lower traffic interference (+50%). Such data have been estimated according to both driving simulation records (Cristiano, 2012, 2016) and to speed-flow diagrams used in transportation engineering (as in the *Highway Capacity Manual* by the Transportation Research Board of the National Academy of Sciences, 2000). For the deviated and expanded section, instead, the expected mean speed is used, as levels of congestion are supposed to significantly decrease.

2.3.3. Free environmental inputs

The study of both scenario 1 and scenario 2 also accounts for the renewable resources from which the section benefits (sunlight, rain geopotential, wind kinetic energy, earth heat) as well as for the air needed for the dilution of CO and NO_x emissions from operation, construction, and maintenance. Data for sunlight, rain, wind, and earth heat are calculated based on data from the United Nations (2016), Pon (1999), Servizio meteorologico regionale dell'Emilia Romagna (1995), Ricerca sul Sistema Energetico – RSE S.p.A. (2016), Miller (1964), and Della Vedova *et al.* (2001). CO and NO_x emissions from passenger cars are calculated based on the related aforementioned category from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EMEP, 2013). Emissions from freight vehicles are estimated through the vehicle specific emission power (VSP), provided by the formula (Zhai *et al*., 2008):

$$VSP = v \cdot (a + 9.81 \cdot \sin(\varphi) + 0.092) + 0.00021 \cdot v^3 \qquad (3)$$

where v is the vehicle speed (m/s), a its acceleration (m/s^2), and φ the road slope. The obtained VSP value is associated with CO and NO_x emission rates as provided by Zhai *et al.* (*ibid.*). The emissions from vehicles for maintenance and construction are based on fuel consumption data by Federici *et al.* (2008), and elaborated based on current EU regulations for road transport emissions (European Commission, 2006); maintenance and construction vehicles are considered as trucks. As downstream inputs, emission impacts are quantified by defining the ecological services required to fix the damages yielded by a process, i.e., to dilute undesired by-products to an acceptable concentration level (Ulgiati *et al*., 1995; Ulgiati & Brown, 2002; Reza *et al*., 2014). Such ecological services are therefore defined as follows:

$$M = d \cdot (W/c) \qquad (4)$$

where M is the mass of air for dilution, d the air density (specifically calculated as 1.19 g/dm^3 in the geographical area of our case study), W the annual amount of pollutant emissions, and c the acceptable concentration from regulations. Finally, again with Ulgiati & Brown (2002), the ecological services to dilute pollutant emissions are obtained by calculating the kinetic energy of the the mass of air necessary to bring emissions within the Italian legal limits on maximum concentration (Presidente della Repubblica Italiana, 2010), using average values for wind speed in the studied area (RSE, 2016). To avoid double counting, only the biggest volume for the dilution of CO or NO_x is ultimately accounted for. Emergy accounting is performed both with and without labor and services.

2.3.4. Services

Services for the building of the different highway sections – both old and new infrastructures – are associated to the average financial expenditure per kilometer, and calculated based on Italian local government agency Provincia di Bologna (2015), with data for tunnels adjusted based on personal interviews with professional engineers; investments are divided by the respective useful lifetimes, as described above. Since works costed more than originally planned as well as more than average, other expenses for road expansion are added, based on data from Italy's national public broadcasting company Rai - Radiotelevisione italiana (2015). Services for vehicles derive from the average cost of a new vehicle (distinguished in a passenger car and a truck), and are computed as a ratio between the total kilometers travelled on the highway section in one year and the average mileage travelled in the useful lifetime of each vechicle category, as detailed above. Finally, drivers' labor is calculated through the number of equivalent working persons in one year. Calculations are based on the annual vehicle-km for each category of vehicles (AISCAT, 2010-2016), on the average speeds reported by the observatory Osservatorio Variante di Valico (2001) for the existing section, on the average speeds registered during a driving simulation campaign on a very similar scenario – same kind of expanded section – on a neighboring section (Cristiano, 2016), and on an assumption of 8 working hours per day, for 240 days per year. Information on the equivalent working persons in one year is therefore computed through the emergy necessary to sustain an average person in Italy (Ascione *et al*., 2009). Emergy inputs for both scenario 1 and scenario 2 are calculated in terms of sej/yr, and separately associated with operational inputs from passenger cars and freight vehicles, when possibile. Data are also calculated in terms of emergy per passenger-km (sej/p-km) and emergy per ton-km (sej/t-km). To do so, the infrastructure inputs of the highway section have been allocated to the two different categories – passenger cars and freight vehicles – based on the same procedure as Federici *et al.* (2008), i.e., considering an average load factor in a single passenger car of 1.8 passengers, an average mass of a passenger of 65 kg, and an average load factor in a single freight truck of 8.79 t. Masses of cars and trucks are already provided earlier in this subsection. Previously separated inputs for cars and trucks are directly allocated to the pertaining categories.

3. Results and discussion

3.1. Results visualization

Data from the emergy accounting of the existing highway section and of the deviated and expanded highway section are illustrated in Tables 1 and 2, respectively. The units and the related UEVs for some construction inputs – i.e., road basis and drainage, road surface (top layers), tunnels, and viaducts – are expressed in km, so as to ease data visualization, to uniform data with the chosen functional units, as well as to allow for future uses of the main road items for a similar highway, including their newly found UEVs. Annex to Table 1 shows such data, referred to two-lane roads (values for three-lane ones are slightly higher.). Additional information regarding intermediate calculations for Tables 1 and 2 is reported in the Appendix.

Table 1. Emergy accounting of the existing highway section

#	Item	Unit	Annual amount	UEV (sej/unit)*	Ref. for UEV	Solar emergy (sej/yr)
Existing section, 2 lanes, construction						
1	Road basis and drainage	km	1.57E+00	6.82E+18	[a]	1.07E+19
2	Road surface, top layers	km	2.20E+01	7.01E+17	[a]	1.54E+19
3	Tunnels	km	2.37E-01	2.51E+20	[a]	5.96E+19
4	Viaducts	km	1.86E-01	2.48E+20	[a]	4.60E+19
5	Guardrails (as steel)	kg	5.06E+03	3.13E+12	[b]	1.58E+16
Maintenance						
6	Fuel for maintenance	kg	1.75E+05	5.79E+12	[c]	1.02E+18
7	Electricity for maintenance	kWh	5.12E+06	5.46E+11	[d]	2.79E+18
Operating phase						
8	Passenger vehicles (cars)	kg	6.53E+06	6.87E+12	[e]	4.48E+19
9	Freight vehicles (trucks)	kg	7.35E+05	6.87E+12	[e]	5.05E+18
10	Fuel for passenger vehicles	kg	4.60E+07	5.79E+12	[c]	2.66E+20
11	Fuel for freight vehicles	kg	4.27E+07	5.79E+12	[c]	2.47E+20
Renewable resources						
12	Sunlight	MJ	4.89E+09	1.00E+06	By def.	4.89E+15
13	Rain, geopotential**	MJ	4.40E+06	1.28E+10	[c]	5.63E+16
14	Wind, kinetic energy	MJ	6.42E+06	7.90E+08	[c]	5.07E+15
15	Earth heat	MJ	1.90E+06	4.90E+09	[c]	9.32E+15
Indirect environmental inputs						
16	Dilution of car emissions	MJ	3.39E+08	7.90E+08	[c]	2.68E+17
17	Dilution of truck emissions	MJ	9.73E+08	7.90E+08	[c]	7.68E+17
18	Dilution of maint. emissions	MJ	1.15E+06	7.90E+08	[c]	9.12E+14
Labor and services						
19	Services for road surface	€	9.39E+06	7.58E+11	[f]	7.11E+18
20	Services for tunnels	€	9.49E+06	7.58E+11	[f]	7.19E+18
21	Services for viaducts	€	4.62E+06	7.58E+11	[f]	3.50E+18
22	Services for cars	€	7.10E+07	7.58E+11	[f]	5.38E+19
23	Services for trucks	€	1.19E+08	7.58E+11	[f]	8.99E+19
24	Services for fuel, cars	€	8.23E+07	7.58E+11	[f]	6.24E+19
25	Services for fuel, trucks	€	6.48E+07	7.58E+11	[f]	4.91E+19
26	Drivers' labor, in cars	items	6.16E+03	2.73E+16	[g]	1.68E+20
27	Drivers' labor, in trucks	items	1.00E+04	2.73E+16	[g]	2.73E+20
Total emergy with labor and services				sej/yr		**1.41E+21**
Total emergy with services, no labor (Drivers')				sej/yr		**9.73E+20**
Total emergy without labor and services				sej/yr		**7.00E+20**
Emergy per pax-km, with labor and services				sej/p-km		**4.95E+11**
Emergy per pax-km, with services, no labor				sej/p-km		**3.64E+11**
Emergy per pax-km, without labor & services				sej/p-km		**2.69E+11**
Emergy per freight ton-km, with labor and services				sej/t-km		**2.34E+11**
Emergy per freight ton-km, with services, no labor				sej/t-km		**1.52E+11**
Emergy per freight ton-km, w/out labor & services				sej/t-km		**1.07E+11**

[a] This work; [b] Brown & Buranakarn, 2003; [c] After DeVilbiss & Brown, 2015; [d] Brown & Ulgiati, 2002; [e] Lou *et al.*, 2015; [f] Buonocore *et al.*, 2015; [g] Ascione *et al.,* 2009.

* Calculated/converted from previous works based on the **GEB2016 of 1.20E+25** sej (Brown *et al.*, 2016)

** Only the driving renewable energy input is used in final calculations (as per Brown & Ulgiati, 2016b).

Table 2. Emergy accounting of the expanded highway section

#	Item	Unit	Annual amount	UEV (sej/unit)*	Ref. for UEV	Solar emergy (sej/yr)
Existing section, 2 lanes, construction						
1	Road basis and drainage	km	1.57E+00	6.82E+18	[a]	1.07E+19
2	Road surface, top layers	km	2.20E+01	7.01E+17	[a]	1.54E+19
3	Tunnels	km	2.37E-01	2.51E+20	[a]	5.96E+19
4	Viaducts	km	1.86E-01	2.48E+20	[a]	4.60E+19
5	Guardrails (as steel)	kg	5.06E+03	3.13E+12	[b]	1.58E+16
Highway expansion, 3 lanes, construction						
6	Additional lane (basis & dr.)	km	7.71E-01	2.48E+18	[a]	1.91E+18
7	Overlay of 2+1 lanes	km	1.08E+01	9.64E+17	[a]	1.04E+19
8	New road basis & drainage	km	9.14E-01	9.31E+18	[a]	8.51E+18
9	New road surface (top layers)	km	1.28E+01	9.64E+17	[a]	1.23E+19
8	New tunnels	km	5.73E-01	3.40E+20	[a]	1.95E+20
9	New viaducts	km	1.64E-01	3.09E+20	[a]	5.07E+19
10	Highway furniture (as steel)	kg	2.83E+04	3.13E+12	[a]	8.87E+16
11	Anti-noise barriers (as alum.)	kg	8.21E+04	9.50E+12	[a]	7.80E+17
12	Copper in electric cables	kg	4.29E+01	3.10E+11	[b]	1.33E+13
13	Machinery (as steel)	kg	3.91E+02	3.13E+12	[b]	1.22E+15
14	Fuel for expansion	kg	2.45E+05	5.79E+12	[b]	1..42E+18
Maintenance						
15	Fuel for overall maintenance	kg	2.45E+05	5.79E+12	[c]	1.69E+18
16	Electricity for overall maint.	kWh	8.47E+06	5.46E+11	[d]	4.62E+18
Operating phase						
17	Passenger vehicles (cars)	kg	6.53E+06	6.87E+12	[e]	4.48E+19
18	Freight vehicles (trucks)	kg	7.35E+05	6.87E+12	[e]	5.05E+18
19	Fuel for passenger vehicles	kg	4.91E+07	5.79E+12	[c]	2.85E+20
20	Fuel for freight vehicles	kg	3.92E+07	5.79E+12	[c]	2.27E+20
Renewable resources						
21	Sunlight	MJ	6.56E+09	1.00E+06	By def.	6.56E+15
22	Rain, geopotential**	MJ	4.70E+06	1.28E+10	[c]	6.02E+16
23	Wind, kinetic energy	MJ	8.61E+06	7.90E+08	[c]	6.80E+15
24	Earth heat	MJ	2.55E+06	4.90E+09	[c]	1.25E+16
Indirect environmental inputs						
25	Dilution of car emissions	MJ	5.66E+08	7.90E+08	[c]	4.47E+17
26	Dilution of truck emissions	MJ	2.49E+08	7.90E+08	[c]	1.96E+17
27	Constr&maint emiss. dilution	MJ	3.51E+06	7.90E+08	[c]	2.78E+15
Labor and services						
28	Services for old road surface	€	9.39E+06	7.58E+11	[f]	7.11E+18
29	Services for old tunnels	€	9.49E+06	7.58E+11	[f]	7.19E+18
30	Services for old viaducts	€	4.62E+06	7.58E+11	[f]	3.50E+18
31	Services for road expansion	€	9.71E+06	7.58E+11	[f]	7.36E+18
32	Services for new tunnels	€	2.87E+07	7.58E+11	[f]	2.17E+19
33	Services for new viaducts	€	5.10E+06	7.58E+11	[f]	3.87E+18
34	Other expansion services	€	3.79E+07	7.58E+11	[f]	2.87E+19
35	Services for cars	€	7.10E+07	7.58E+11	[f]	5.38E+19
36	Services for trucks	€	1.19E+08	7.58E+11	[f]	8.99E+19
37	Services for fuel, cars	€	8.79E+07	7.58E+11	[f]	6.66E+19
38	Services for fuel, trucks	€	5.94E+07	7.58E+11	[f]	4.51E+19
39	Drivers' labor, in cars	items	2.88E+03	2.73E+16	[g]	7.85E+19
40	Drivers' labor, in trucks	items	1.60E+03	2.73E+16	[g]	4.37E+19
Total emergy with labor and services				sej/yr		**1.44E+21**
Total emergy with services, no labor (Drivers')				sej/yr		**1.32E+21**
Total emergy without labor and services				sej/yr		**9.81E+20**
Emergy per pax-km, with labor and services				sej/p-km		**5.08E+11**
Emergy per pax-km, with services, no labor				sej/p-km		**4.47E+11**
Emergy per pax-km, without labor & services				sej/p-km		**3.37E+11**
Emergy per freight ton-km, with labor and services				sej/t-km		**2.36E+11**
Emergy per freight ton-km, with services, no labor				sej/t-km		**2.23E+11**
Emergy per freight ton-km, w/out labor & services				sej/t-km		**1.65E+11**

[a] This work; [b] Brown & Buranakarn, 2003; [c] After DeVilbiss & Brown, 2015; [d] Brown & Ulgiati, 2002; [e] Lou *et al.*, 2015; [f] Buonocore *et al.*, 2015; [g] Ascione *et al.*, 2009.

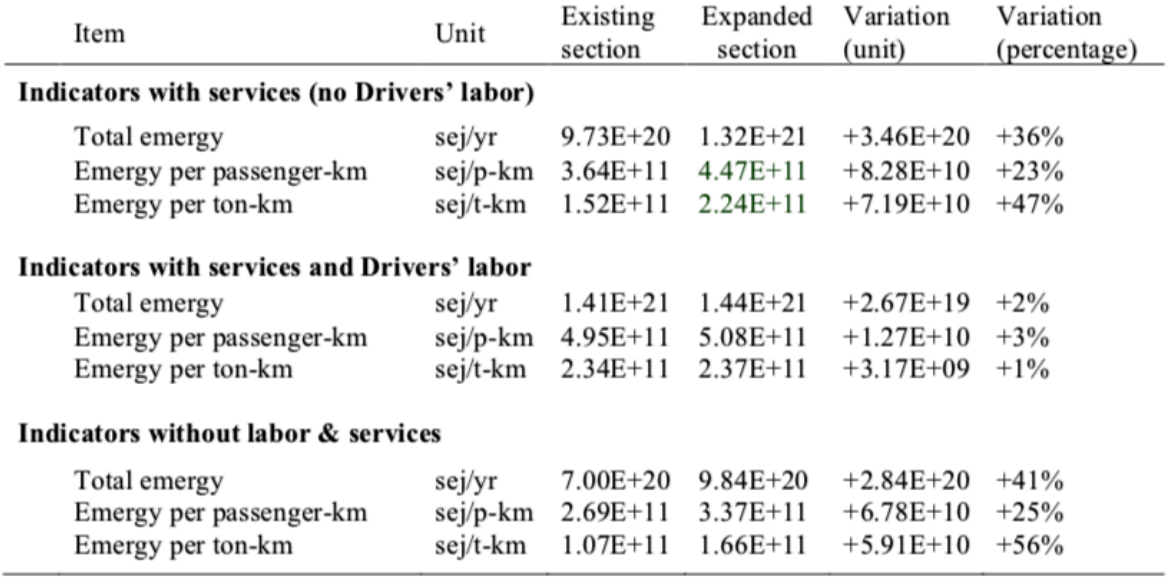
* Calculated/converted from previous works based on the **GEB2016 of 1.20E+25** sej (Brown *et al.*, 2016).

** Only the driving renewable energy input is used in final calculations (as per Brown & Ulgiati, 2016b).

3.2. Results analysis

In terms of emergy, the main inputs come from the building of complex civil infrastructure elements such as tunnels and viaducts, from the fuel used by vehicles (and their related services), and from the drivers labor. Also important are the remaining inputs for the road construction as well as the materials and the services linked to vehicles – both passenger cars and freight vehicles. Data from scenarios 1 and 2 indicate that savings in fuel consumption do happen, yet are very moderate and only referred to freight vehicles (–2.03 E+19 sej/yr, i.e., –8%), while inputs for fuel consumption by passenger cars increase (+1.81 E+19 sej/yr, i.e., +7%), presumably due to the higher speed allowed by the enlarged infrastructure section. The resulting saving (–2.25 E+18 sej/yr, i.e., much less than –1%) is two orders of magnitude smaller than the sole material efforts needed to excavate the new tunnels, normalized on their planned useful lifetime (1.95 E+20 sej/yr). Some related savings are also expected in terms of ecological services needed to dilute emissions – after an increase in emissions from cars and a decrease from trucks – with an overall saving of –1.97 E+17 sej/yr (–23%), unfortunately more than compensated by the costs for the materials and the services involved in the boring of new tunnels (three orders of magnitude higher), thus making the balance negative both if we include labor and services as traditionally done (Federici *et al.* 2008; 2009) and if we exclude labor and services, thus only considering inputs for energy and materials: respectively, emergy values for the building and operation of the expanded section are 36% and 41% higher. Table 3 compares the emergy investment of the highway section before and after the expansion work. Data reported in Table 3 represent a system-specific set of emergy indicators, which address the emergetic investment referred to the actual kind of service provided by the system. Indicators that are more typical of emergy analyses have been also calculated, as shown in Table 4, which reports the comparison of the old and new highway segments in terms of standard emergy indices.

Table 3. Comparison between the highway section before and after the expansion works



Item	Unit	Existing section	Expanded section	Variation (unit)	Variation (percentage)
Indicators with services (no Drivers' labor)					
Total emergy	sej/yr	9.73E+20	1.32E+21	+3.46E+20	+36%
Emergy per passenger-km	sej/p-km	3.64E+11	4.47E+11	+8.28E+10	+23%
Emergy per ton-km	sej/t-km	1.52E+11	2.24E+11	+7.19E+10	+47%
Indicators with services and Drivers' labor					
Total emergy	sej/yr	1.41E+21	1.44E+21	+2.67E+19	+2%
Emergy per passenger-km	sej/p-km	4.95E+11	5.08E+11	+1.27E+10	+3%
Emergy per ton-km	sej/t-km	2.34E+11	2.37E+11	+3.17E+09	+1%
Indicators without labor & services					
Total emergy	sej/yr	7.00E+20	9.84E+20	+2.84E+20	+41%
Emergy per passenger-km	sej/p-km	2.69E+11	3.37E+11	+6.78E+10	+25%
Emergy per ton-km	sej/t-km	1.07E+11	1.66E+11	+5.91E+10	+56%

3.3. Sensitivity analysis

The sensitivity determination of the emergy accounting is a crucial point, on which emergy analysts are still working towards the definition of a reliable standardization (Sharifi, 2016). Aware of the issue of determining the uncertainty of emergy studies with a high number of inputs and assumptions (see for instance Ingwersen, 2010), an ex-post sensitivity analysis has been conducted: among the main inputs, a ±20% variation in the data for the total fuel use (passenger and freight vehicles) determines smaller changes, ranging from ±6% (with labour and services) to ±14% (without labour and services) in the existing scenario before the expansion, and from ±7% to ±10% in the expansion scenario; the same variation (±20%) in the second main input – i.e., the controversial drivers' labour – respectively yields an average ±6% change and less than ±2% change, of course only in the three indicators in which it is computed. A yet significant variation (±20%) in any other input produces very limited changes (lower than ±2%).

Table 4. Emergy indices before and after the expansion works

Indicator	before expansion work	after expansion work
Emergy Yield Ratio EYR = (R+N+F)/F		
without Labor and Services	1.001	1.001
with Labor and Services	1.001	1.001
Environmental Loading Ratio ELR = (N+F)/R		
without Labor and Services	831	1517
with Labor and Services	1680	2224
Emergy Sustainability Index (ESI) = EYR/ELR		
without Labor and Services	negligible	negligible
with Labor and Services	($<10^{-2}$)	($<10^{-2}$)

3.4. An overall disadvantageous megaproject

Generally speaking, the outcomes of the analysis do not indicate any socio-environmentally convenience from the expansion. Benefits from the deviation and expansion works are somehow worth the investment (however still lower than costs) only if labor and services include an additional item, which we call "drivers labor", as described above. In fact, savings in time due to the higher mean speeds achievable on the renovated section make driving activity significantly decrease. This is the sole condition where the balance is almost even, yet it is a very thorny aspect, since it is strictly connected to the average lifestyle of a population expressed in emergy per capita. To allow for a clearer visualization of the data as well as for a comparison with previous studies, results are also organized in terms of emergy per passenger-kilometer (sej/p-km) and emergy per ton-kilometer (sej/t-km), as shown in Table 3. Figure 4 compares the emergy investment values before and after the expansion work as from Table 3 data, with and without Labor and Services contributions. These results address first of all the questionability of a major infrastructure modification from an overall socio-environmental point of view. In this respect, it is worth undelining how the emergy saving in terms of drivers' labor is anyhow not sufficient to overcome the need for a higher emergy demand for the new highway section. Traditional emergy indicators like those reported in Table 4 are usually determined for studying the performances of either ecosystems or productive systems, which is not the case of our study. As one can expects for a socio-economic service provider like a highway, EYR values result very low, meaning that we have to do with a process of transformation and consumption which does not provide net emergy to the economy. On the other hand, very high values of ELR (and thus very low values of ESI) indicate a potentially high ecosystemic stress, and a system typically oriented to the consumption, with non-renewable emergy flows concentrated in relatively small areas. What is important is that a very low ESI value addresses the uncertainty of the long-term sustainability, whereas the economic and social factors which are critical for the system operation are not under control from inside the system itself. ELR is actually a descriptive index, and the presented results point out an unsustainable sector. On the other hand, this is socio-economically necessary, thus its (un)sustainability has to be managed. For example, potential buffer areas might be identified to compensate the loading due to the provided service (and designing for compensation measures). In fact, the trade-off between environmental stress and land demand is a typical aspect of the policies concerning sustainability, and in this sense the emergy synthesis might also provide a quantification of the land footprint of the systemic service. But even if the obtained values, given the nature of the system at issue, do not add particular new information about its performances, the comparison of these indices calculated for the old and the new highway segments may help to frame the complexity of the system, as far as Table 4 confirms an increase of the (however high) ELR indicator.

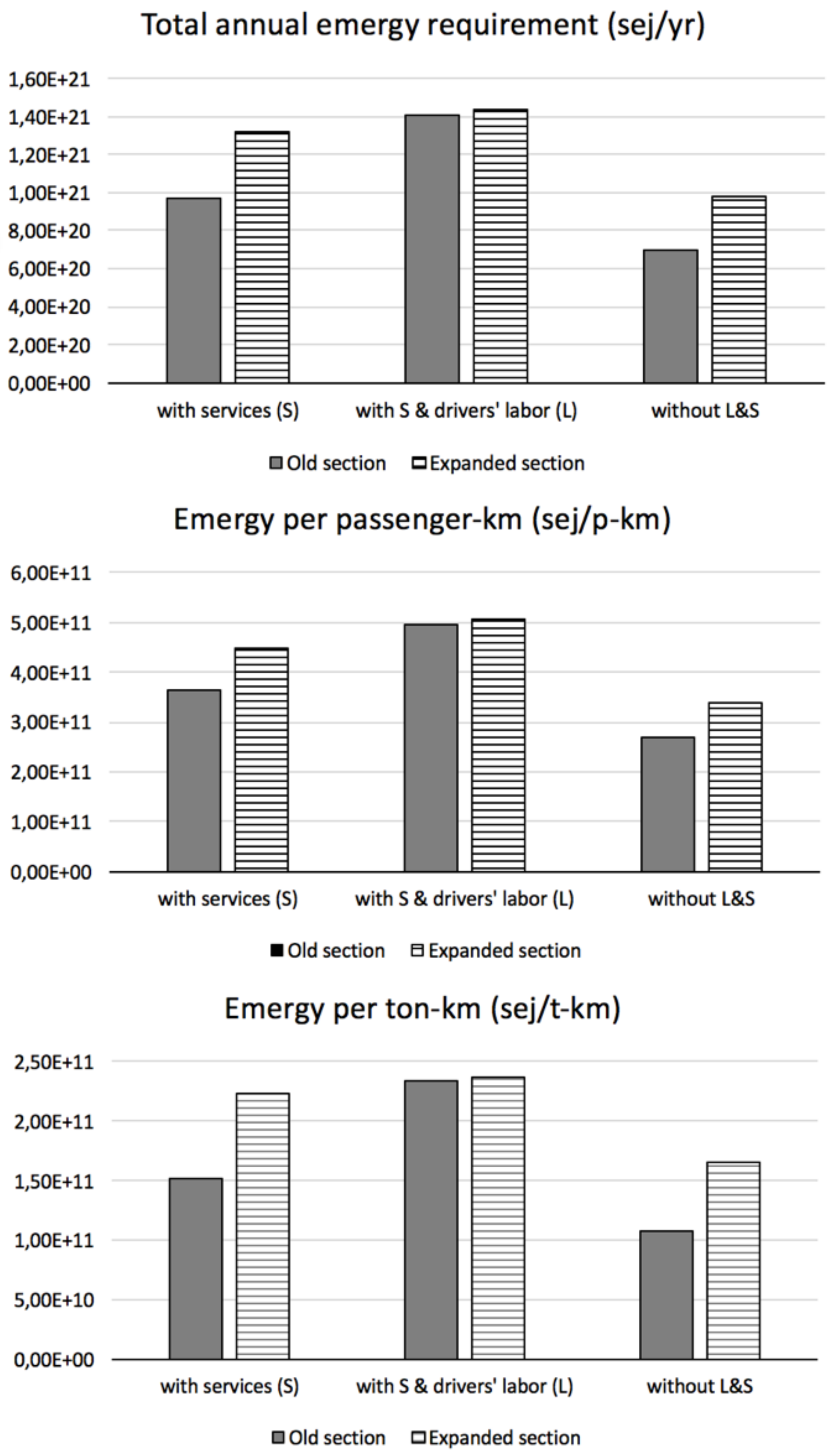
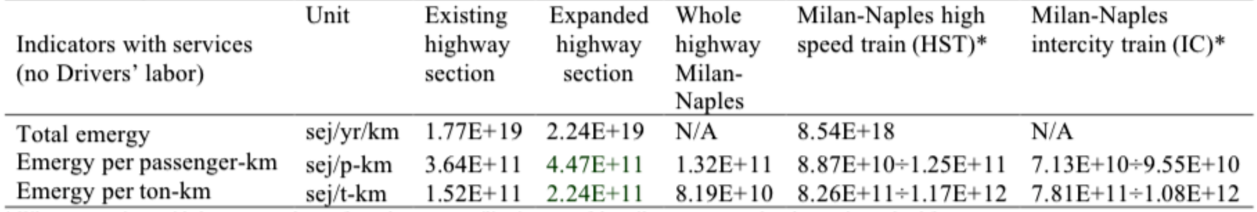


Fig. 4. Comparison between the emergy investment before and after the main expansion work.

3.5. Comparisons with previously published results on the whole Milan-Naples road and rail infrastructures

Based on the total mass (kg-km) transported by passenger cars and freight trucks in one year – calculated inasmuch preparatory to the sej/p-km and sej/t-km values – the final allocation results 24% for the first and 76% for the latter. Table 5 compares our results with the ones by Federici *et al.* (2008) for the whole Milan-Naples highway (of which our case study represents a short yet complex sub-system) and for the Intercity railway (IC) and the high-speed train (HST/TAV) linking the same Italian cities. For our comparisons, such data are adjusted to the current geobiosphere global emergy baseline; they were originally calculated by Federici *et al.* based on an electric drive; for closer examinations, the relating input lists, calculations, and resulting unit emergy values are extensively consultable in their paper (2008). Compared to such railway scenarios, both in terms of emergy per p-km and of emergy per t-km, our section appears generally more emergy-demanding (2.3 times more on the average) than the average whole highway, even before (or without) its renewal, and this could be easily ascribed to the elevation and complexity of the Apennines mountainous crossing. The recent deviation and expansion works only seem to worsen such condition, making passenger and commodity transportation on this sub-system averagely 3.1 times more expensive than on the rest of the highway system. In terms of emergy, passenger transport on the new highway section at issue is also higher than for alternative transportation options, namely, 3.6 and 4.7 higher than on Milan-Naples HST/TAV and IC trains at their current utilization rate, respectively. As a natural consequence, a modal shift is addressed as convenient at least for passenger transportation.

Table 5. Comparison with more scenarios (Federici *et al.*, 2008)



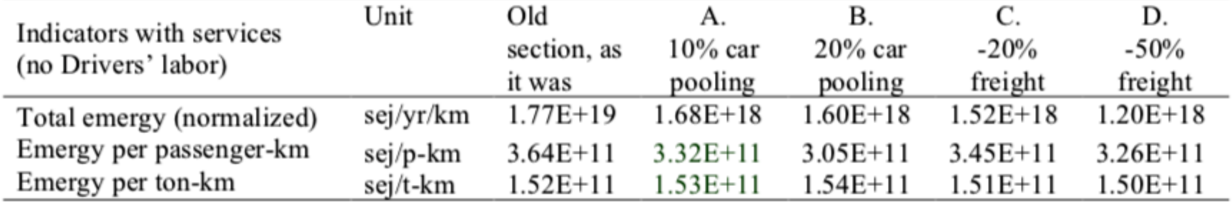
Indicators with services (no Drivers' labor)	Unit	Existing highway section	Expanded highway section	Whole highway Milan-Naples	Milan-Naples high speed train (HST)*	Milan-Naples intercity train (IC)*
Total emergy	sej/yr/km	1.77E+19	2.24E+19	N/A	8.54E+18	N/A
Emergy per passenger-km	sej/p-km	3.64E+11	4.47E+11	1.32E+11	8.87E+10÷1.25E+11	7.13E+10÷9.55E+10
Emergy per ton-km	sej/t-km	1.52E+11	2.24E+11	8.19E+10	8.26E+11÷1.17E+12	7.81E+11÷1.08E+12

* When a range is provided, extreme values refer to the current utilization rate of the railway present and to the maximum load factor

3.6. Alternative options on the old infrastructure

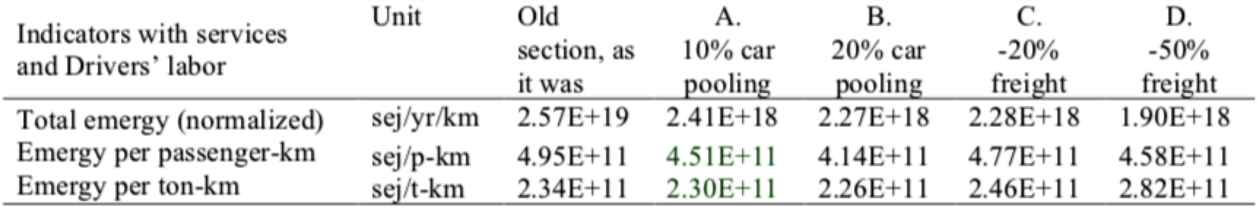
Despite the higher emergy per t-km on commodity trains, the viability of a modal shift for freight transportation could also be considered before deciding for the enlargement of the highway section. In fact, the railway options were already available, and not used at their maximum load factor. The marginal emergy cost to use them at the maximum load factor might reveal a convenience in this solution even without the need to build a new infrastructure: a shift from road to HST/TAV and IC railways might be read as a solution to save respectively 3.44 E+11 and 2.99 E+11 sej/t-km on the commodities already transported on those systems, without the squander of energy and materials for a brand-new civil infrastructure. Among the scenarios to evaluate before opting for a deviation and expansion, alternative ones on the same highway sub-system are also presented, and their benefits calculated, possibly able to improve traffic flow conditions while saving socio-environmental inputs, measured in emergy.

Table 6a. Comparison with possible scenarios alternative to the expansion, using the old highway



Indicators with services (no Drivers' labor)	Unit	Old section, as it was	A. 10% car pooling	B. 20% car pooling	C. -20% freight	D. -50% freight
Total emergy (normalized)	sej/yr/km	1.77E+19	1.68E+18	1.60E+18	1.52E+18	1.20E+18
Emergy per passenger-km	sej/p-km	3.64E+11	3.32E+11	3.05E+11	3.45E+11	3.26E+11
Emergy per ton-km	sej/t-km	1.52E+11	1.53E+11	1.54E+11	1.51E+11	1.50E+11

Table 6b. Comparison with possible scenarios alternative to the expansion, using the old highway



Indicators with services and Drivers' labor	Unit	Old section, as it was	A. 10% car pooling	B. 20% car pooling	C. -20% freight	D. -50% freight
Total emergy (normalized)	sej/yr/km	2.57E+19	2.41E+18	2.27E+18	2.28E+18	1.90E+18
Emergy per passenger-km	sej/p-km	4.95E+11	4.51E+11	4.14E+11	4.77E+11	4.58E+11
Emergy per ton-km	sej/t-km	2.34E+11	2.30E+11	2.26E+11	2.46E+11	2.82E+11

As shown in Table 6a and Table 6b, each of the proposed alternative solutions would yield significant savings (over 90%) in the total emergy driving the functioning of the infrastructure (sej/km), while determining remarkable minor savings also in terms of emergy per passenger-km and per ton-km. Such alternative scenarios consist in the – properly encouraged – car pooling use (10% and 20% of total transported passengers), which would decrease the number of cars on the infrastructure and the related fuel consumption and emissions, while improving the performances in terms of emergy per p-km. Some more benefits would also derive from an improvement of the traffic flow conditions, which are not computed in the presented data but are expected as a natural consequence of the reduction of vehicles. Significant savings could also derive from a reduction (–20%, –50%) of freight vehicles on the section and hand. This could possibly derive from a modal shift to railway, and/or from an overall reduction in the demand for commodity transportation as described above. Among the studied alternative scenarios, the best results for passenger transportation are associated with a 20% of car pooling. As to freight transportation, the trend seems to be "the less, the better": reduction in freight vehicles is accompanied by a significant reduction in both the total emergy driving the sub-system and the emergy per passenger-kilometer, since cars would have acceptable traffic conditions restored, with less fuel consumption and fewer pollutant emissions due to the avoided congestion. The indicators "sej/t-km" seems to reach a minimum, increasing alongside freight vehicles reduction: this is ascribed to an increasing ratio from the road building and maintenance allocated to the fewer vehicles driving on the road section. For this reason, they should not be seen as a negative sign.

A modal shift from road to rail would be highly convenient and beneficial for passenger transportation, and would free an overloaded infrastructure from the exceeding vehicles, thus restoring acceptable levels of service. As per a possible modal shift for commodities, no relevant convenience was found, due to the higher values of emergy per ton-kilometer as reported in the literature. However, such studies underline how those infrastructures are currently not used at their maximum load factor: an increase in their use would therefore let their values of emergy per ton-kilometer decrease. The road-to-rail modal shift could be then seen as an operation whose benefits are represented at the same time by the optimization of commodity transport already happening on freight trains, by the withdrawal from a highway section to improve flowing conditions, and by the saving of further investments – financial and environmental (i.e., what is now trendy to define a win-win strategy). Even if the values of t-km should be higher than the ones for a new or renovated road section, this would be the consequence of an effort already made, and might rather be considered as a minor marginal cost to optimize an investment already done. If this still appears debatable when thinking in terms of p-km and t-km, a reduction in the total emergy driving the different transport systems is instead clear, and does not require interpretation. Even more eloquent are the solutions investigated in this study as possible alternatives to the deviation and expansion works, that could be implemented in parallel to the modal shift. They consist in a change in the use of the same old infrastructure: firstly, the encouragement of extraurban car pooling is analyzed, with scenarios of 10% and 20% of car pooling passengers over the total transported passengers on the our road section. The effects of such policies would yield >90% savings in terms of emergy for the functioning of the road infrastructure, at the same time improving its flowing conditions (i.e., its levels of service) for decreasing the total number of passenger cars on the sub-system. Finally, a possible decrease of freight transport (–20% and –50%) is investigated. This might happen due to either its discouragement (e.g., while encouraging a modal shift instead), might follow a widespread, spontaneous, increased preference – among consumers – for local products, or might rather result from a slower societal metabolism (e.g., less planned obsolescence, less commodities per capita, and so forth). This would of course require policies acting at the cultural level, yet our results show how much they could be effective: again, over 90% savings might be obtained in the use of the road infrastructure, with better results in terms of level of service, since significantly reduced flows of heavy vehicles would allow for significantly higher speeds for everyone on the section, ultimately able to restore the original, planned flowing conditions, while hopefully decrease the number of accidents, too. Of course, pollutant emissions would dramatically decrease in these scenarios, since freight vehicles are the most polluting vehicles.

3.7. Comments on car pooling options

One consideration is anyhow due concerning the possibility of using car pooling as an effective measure for improving integrated performances of highway infrastructures. Besides a more efficient use of private vehicles, car pooling represents also a substitute for the mass-transit services, in particular railway. In this respect, public policy planning has also to take into account the possible reduction of the revenue for long distance transport providers. However, car pooling services must confront the need to assess good and reliable platforms and networks in terms of competitiveness against mass-transit services (prices, trip duration, frequencies, and so on), as well as possible legal restrictions and incentives mechanisms. In general, it is difficult to envisage what could be a possible major role of car pooling in the future scenario of transportation networks. Data on the impact of carpooling on collective transportation are scarce and fragmented. The study on its impact probably require more information about actual car pooling experiments for both urban and non-urban areas, in order to identify the systemic role of this passenger transport way. Presently, the only transportation network for which car pooling has already gained a significant presence is that of France, where more than 8 millions car pooling trips were made in 2015 (Finger *et al.*, 2017). On the other hand, concerning the other examined alternative scenario, given by a freight transport decrease, its viability probably lies on a complex and overall change of the entire socio-economic system, in so exhibiting characteristics and features that deserve a specific study which is beyond the scope of this paper.

3.8. On the sustainability of public transportation systems

A noticeable amount of work has been dedicated in recent years to the sustainability of public transportation systems and networks, evidencing on one hand the need for integrated analytical tools, necessary to plan effective sustainability-oriented actions, and on the other hand the predominance in most of the studies of one of the aspect referred to the sustainability pillars (environmental, social and economic) over the other two (see for example the recent review by Miller *et al.*, 2016, and references quoted therein). A few case studies have been published recently reporting comparative analytical approaches to transportation systems including emergy accounting, yet limited to specific urban areas (see for instance Meng *et al.*, 2017). On the other hand, the analysis presented in this work offers a novel perspective compared to the mainstream literature on non-urban transportation infrastructures. In fact, in an integrated sustainability framework, policy options should be guided by the need to assure to the future generations the same mobility and transport as presently available. In this respect, the integration of the different aspects of sustainability in the managing of transportation systems is far from being well assessed (see Ercan, 2013). As far as the operation of transportation networks is strongly connected to energy networks, agriculture, food and water supply, air quality and pollution, and in general to the well-being of people, any evaluation based solely on economic, fuel-efficiency or environmental aspects tend to be quite site-dependent (Black, 2010). Emergy concept is expected by definition to encompass all the aspects related to the sustainability of a system, and emergy analysis can at least provide a quantitative picture of the complexity of the analysis, useful to assess the overall upstream investment (in its broader sense) that humans and the geobiosphere have to dedicate to a transportation system. Emergy driving the functioning of the infrastructure may therefore constitute a common analytical basis which, possibly integrated with complementary analyses such as multi-criteria and Life-Cycle-based ones, appears to be more and more essential, as a common benchmark for any other evaluation specifically oriented to one single aspect of the infrastructure efficiency. Road transportation networks, especially in European countries, have been rarely planned and established as a single project (like it happens, for instance, in the case of industrial districts). Instead, major highway infrastructures almost always are built without considering temporal and spatial scales of the network, nor the overall systemic assessment of the transportation section at scales larger than single segments. This is also reflected by the presented results (especially, see Table 3), which show the discrepancy existing between a policy planning made on specific short- and medium-term socio-economic convenience, which might be regarded as a successful one, and the effectiveness measured in terms of global long-term sustainability indicators, in the conceptual framework provided by the emergy analysis. Of course, there is a strong need for the ingration of transportation infrastructures policy planning into a more comprehensive scenario that incudes most of all energy and distribution networks, not to mention possible subsidizing actions. In this respect, the increasing attention drawn by genuine circular discourses – when displaying integrated approaches as well as when not just pleasing but rather questioning the current societal metabolic levels – might well be the conceptual framework suitable to juxtapose socio-economical needs and environmental constraints at a larger integrated scale. Even if the role of transportation network planning is well beyond the purpose of this paper, emergy synthesis appears to be one of the possible analystical tools able to address the integration required by the concept of sustainability in terms of its three pillars (environment, society, economy).

4. Conclusions

Emergy accounting has been applied to civil infrastructures for the evaluation of some major deviation and expansion works on an Italian highway road sub-system. The results highlight the potential of an integrated approach like that provided by the emergy accounting method. Such method allows for the evaluation of a set of indicators, from which the various aspects of sustainability can be addressed and discussed. As is typical of other integrated approaches (for example, Life Cycle Thinking-based), the problem of the systemic boundary is a critical issue, since the relative importance of the resource flows in the determination of some indicator may change significantly, depending on the choice of the boundary and therefore of setting a source as external or internal to the system. The uncertainty in the quantitative results of emergy synthesis is another important issue, but a sensitivity analysis provides anyway information about the most important and the most relevant flows of resources the systemic sustainability, so contributing to point out what are the critical issues when planning new transportation infrastructures. The peculiar upstream (donor-side) perspective of emergy synthesis makes it specifically suitable for complementing more well-assessed approaches (e.g., exergy, life cycle assessment, input-output), and for adopting the holistic perspective advocated by H.T. Odum in the debate about systemic sustainability.

Pushed for by the issues of fuel consumption, air pollution and demand satisfaction, the decision to deviate and expand the investigated road section gave rise to alleged net environmental and societal savings, but this socio-environmental success is not registered in any of the calculated indicators, and the renovation of the road sub-system does not appear to be a solution to such problems. A need for a multi-disciplinary approach to the transportation problems emerges from the results, showing that the expansion paradigm is not suitable for infrastructures as – after all – for our societies in general. Actions to reduce the pollution or energy consumption per unit of commodity or service (in our case, transportation) are found to imply – yet indirectly – an increase in commodity per capita (in our case, the extra inputs for a renovated infrastructure) that overcomes the potential benefit, overturning it.

In the short run, a convenient strategy compared to the building of a new infrastructure could be addressed through the encouragement of a partial modal shift to rail as well as of even moderate levels of carpooling. In the long run, a cultural progress towards the decrease of a highly consumerist societal metabolism might be the right answer, with a preference for an even partial relocalization of human production and consumption, that would determine prominent savings also on the transportation infrastructures, with benefits for the residual freight transportation and for those passengers who – for whatever reason – should still not be opting for the more convenient rail option. In this case, biophysics principles seem to be able to support ecologically and strategically sustainable societal decision-making. After all, this looks much related to H.T. Odum's late works on what he called the prosperous way down (Odum & Odum, 2008), as well as to the more and more frequent voices calling for the overcoming of "growth come hell or high water" as a necessary step to imagine and build a sustainable and prosperous future.

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Appendix

Calculation data, additional information, and related references for Table 1 and Table 2 are available in the following Table 7 and Table 8.

Table 7. Data, additional information, and references for Table 1

#	Datum / *additional information*	Value	Reference
1–2	Average length per roadway	55 km	After Autostrade per l'Italia (2015)
	Total length of investigated section	110 km	After Autostrade per l'Italia (2015)
	Useful lifetime of basis & drainage	70 yrs	Federici *et al.* (2009)
	Useful lifetime of top layers	5 yrs	Federici *et al.* (2009)
	UEVs based on intermediate/lower mainly inert layers made of clay, sand, gravel, water, cement (our calculation based on data by Provincia Autonoma di Bolzano, 2015*), top layers containing bituminous material: clay, sand, gravel, bitumen, and water* (idem); *concrete and plastics drainage* works (our calculation).		
3–4	Length of tunnels	23.7 km	After Osservatorio Variante di Valico (2015)
	Length of viaducts	18.6 km	After Osservatorio Variante di Valico (2015)
	Useful lifetime of tunnels and viaducts	100 yrs	After Consiglio Superiore dei Lavori Pub… (2008)
5	Guardrail mass	1.38E+03 kg/km	Our calculation after Marcegaglia (2012)
	Useful lifetime of guardrail	30 yrs	Our assumption
6–7	Diesel for maintenance, annual	1.60E+03 kg/km	After Federici *et al.* (2008)
	Electricity, maintenance, annual	4.65E+04 kg/km	After Federici *et al.* (2008)
8–9	Average traffic: cars, annual	7.10E+08 veh-	After AISCAT (2005)[1]
	Average traffic: trucks, annual	2.96E+08 veh-km	After AISCAT (2005)[1]
	Average mass of cars	1.38E+03 kg	Lou *et al.* (2015)
	Average mass of trucks/freight	2.48E+03 kg	After Federici *et al.* (2009)
10–11	Avg. mileage in car useful lifetime	150,000 km	Our assumption based on interviews
	Avg. mileage in truck useful lifetime	1.0E+06 km	Our assumption based on interviews
	Avg. speed on the section, cars	60 kph	Osservatorio Variante di Valico (2015)
	Avg. speed on the section, trucks	40 kph	Osservatorio Variante di Valico (2015)
	Euro IV vehicles (assumption based on Automobile Club d'Italia, 2012*); based on* Osservatorio Variante di Valico (2015)*, vehicles are assumed to averagely keep such unbundled speeds: 33.4% actually close to mean speed, 33.3% lower due to high levels of congestion, 33.3% higher than mean speed; based on* Osservatorio Variante di valico, 2001*, and on* Cristiano, 2016, *lower and higher speed values are assumed as follows: cars, 18 kph and 103 kph, trucks, 10 kph and 70 kph; emission rates (g/km) are calculated based on* EMEP (2013) *as detailed in §3.3.*		
12–15	Road area out of tunnel	8.36E+05 m^2	Our calculations based on official data
	Average solar radiation in the area	4.9 $kWh/m^2/day$	United Nations (2016)
	Albedo of asphalt	0.12	Pon (1999)
	Average rainfall in the area	1.75 m/yr	Servizio meteorologico regionale dell'Em… (1995)
	Highest elevation	716 m	Autostrade per l'Italia (2015)
	Lowest elevation 1, Sasso Marconi	128 m	Official geographical records
	Lowest elevation 2, Barberino Mugello	371 m	Official geographical records
	Runoff rate on paved roads	0.8	Our estimation based on lack of seepage
	Average density of air in the area	1.19 kg/m^3	Our calculation based on local average elevation
	Average annual local wind velocity	3.5 m/s	Ricerca sul Sistema Energetico – RSE S.p.A. (2016)
	Surface winds / geostrophic wind ratio	0.6	Our assumption based on previous literature
	Drag coefficient	1.00E-03	Miller (1964)
16–18	Local heat flow	70 mW/m^2	After Dalla Vedova *et al.* (2001)
	CO max legal concentration in air[2]	1.0E-02 g/m^3	Presidente della Repubblica Italiana (2010)
	NO_X max legal concentration in air[2]	4.0E-05 g/m^3	Presidente della Repubblica Italiana (2010)
	Average slope uphill	0.03 rad	Our assumption based on project files
	Car emissions from EMEP (2013)*, truck emissions calculated based on* Zhai *et al.* (2008) *(see §3.4) and based on acceleration values of 2.90E-01, 4.50E-01, 9.00E-01* m/s^2 (after Cristiano, 2012). *A slope of 50% uphill and 50% downhill is assumed; only higher values are shown in Table 1, i.e., those for diluting* NO_X.		
19–21	Unit building costs: road surface	3.2E+06 €/km	Our calculation based on Provincia di Bol… (2015)
	Unit building costs: tunnels	4.0E+07 €/km	Our assumption based on interviews
	Unit building costs: viaducts	2.49€+07 €/km	Our calculation based on Provincia di Bol… (2015)
	Useful lifetime of road pack	37.5 yrs	Our calculation based on Federici *et al.* (2009)
	Useful lifetime or tunnels/viaducts	100 yrs	After Consiglio Superiore dei Lavori Pub… (2008)
22–23	Average price of a new car	1.50€+04 €	Our assumption based on market prices
	Average price of a new truck	6.00E+04 €	Our assumption based on market prices
24–25	Avg. price of car fuel (gasoline/diesel)	1.38 €/L	Il Sole 24 ore (2015)
	Avg. price of truck fuel (diesel)	1.29 €/L	Il Sole 24 ore (2015)
26–27	*Number of equivalent working persons, assuming 8 hrs/day, 240 days/yr.*		

[1] Data adjusted to actual section length, i.e., 60% of Bologna-Florence homogeneous statistical section.

[2] According to related Italian law in force.

Avg. = Average

Table 8. Data, additional information, and references for Table 2

#	Datum / *additional information*	Value	Reference
1–5	*See data for Table 1*		
6–7	Length of enlarged highway, total	54 km	Autostrade per l'Italia (2015)
	Brand new highway	64 km	Autostrade per l'Italia (2015)
	Useful lifetimes as in items 1–2		
8–9	Length of new tunnels	57.3 km	Autostrade per l'Italia (2015)
	Length of new viaducts	16.4 km	Autostrade per l'Italia (2015)
	Useful lifetimes as in items 3–4		
10–11	Mass of new guardrail	8.50E+05 kg	Il Sole 24 ore (2015)
	Length of new anti-noise barriers	3.8 km	Il Sole 24 ore (2015)
	Length of new cables	4.60E+02 km	Il Sole 24 ore (2015)
	Mass of new aluminum barriers	6.48E+05 kg/km	Our calculation based on cited official data
12	Average diameter of cables	3.14E-04 m^2	Our assumption
	Useful lifetimes	30 yrs	Our assumption based on interviews
13	Steel in generic building machinery	9.93E+01 kg/km	Federici *et al.* (2008), cf. our §4 for details
	Road length (new + enlarged sections)	118 km	Autostrade per l'Italia (2015)
	Useful lifetime	30 yrs	Federici *et al.* (2008)
14	Diesel use for construction, annual	2.08E+03 kg/km	Federici *et al.* (2008)
15–18	*See data for Table 1*		
19–20	Avg. car speed on expanded section	129.0 kph	Cristiano (2016)
	Avg. truck speed on expanded section	96.4 kph	Our assumption based on Cristiano (2016)
	Fuel consumption based on speed (our calculations based on EMEP (2013)*, as described in our §3.3.*		
21–24	New area (expansion), out of tunnels	1.16E+06 m^2	Our calculation based on cited official data
25–26	*See data for Table 1 for procedure*		
	See 19–20 for new operating speeds		
	CO emissions for constr. & mainten.	2.50 g/kWh	European Commission (2006)
	NO_X emissions for constr. & mainten.	2.75 g/kWh	European Commission (2006)
27–30	*See data for Table 1*		
31	Unit building costs, additional lane	2.00E+06 €/km	Provincia di Bologna (2015)
	Unit building costs, new road laying	4.00E+06 €/km	Our calculation based on Provincia di Bo… (2015)
32–33	Unit building costs, 3-lane tunnel	5.00E+07 €/km	Our calculation based on interviews
	Unit building costs, 3-lane viaduct	3.11E+07 €/km	Provincia di Bologna (2015)
34	Total declared investment	7.00€+09 €	Rai – Radiotelevisione Italiana (2015)
	Total calculated investment	3.74E+09 €	Our elaboration of data above
	Declared – calculated gap (extra costs)	3.26E+09 €	Difference between the 2 items immediately above
	Lifetime of items related to extra costs	86 yrs	Our calculation as average value of building items
35–36	*See data for Table 1*		
37–40	*See data for Table 1 for procedure, new values as described above.*		

Avg. = Average; Constr. = Construction; Mainten. = Maintenance

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