A THERMODYNAMIC AND ECONOMIC ANALYSIS OF LOCAL TRANSPORT SYSTEMS

M. Federici[*§], F. Ruzzenenti[$], S. Ulgiati[#], and R. Basosi**

** Center for Complex Systems Investigation, University of Siena, Italy*
$Oxford Brookes University, Oxford, U.K.
 # Department of Chemistry, University of Siena, Italy
§ Corresponding Author[1].

> *" We do a disservice to the private automobile to consider it merely as a representative example. That is like calling Superman a decent athlete. In my opinion the car/pickup truck/sport utility vehicle is the most significant environmental problem in developed countries. It is also a leading problem in developing countries. Solving "auto-like" problems is well enough, but until we solve the auto problem itself we are just scratching the surface of a sustainable, just, livable society. The auto combines massive resource requirements (energy, land, materials), massive environmental impacts (land use, materials use, air pollution, wildlife destruction, noise, safety), massive economic forces, massive disruption/reshaping of culture and the way humans interact with one another, fundamental, strong human motivations and wants, and powerful feedback-rich dynamics in its penetration into the market." (Herendeen, 2000[1])*

ABSTRACT

In this work we analyze and compare the transport systems of two different Italian provinces, Brescia and Siena. Our intent is, on the one hand, to increase the integrated use of indicators of thermodynamic efficiency, on the other hand, to improve our understanding of the dynamics of local transport systems. Brescia is located over one of the main traffic, rail and freight axes of Italy, the Turin-Venice axis, and is characterized by widespread industrialization, while Siena is situated in a less accessible zone and its economy is based mainly on agriculture and services. Although far apart by a geographical, morphological and economical point of view, these two provincial districts are similar from the point of view of some macroeconomic variables, like per capita income, and still comparable with respect to the size of the two main towns.

Integrating the energetic analysis with the economic survey of each system and comparing the data relative to each of the two systems with the national case of Italy, enables us to extrapolate some general statements concerning the local transport systems dynamics. The passenger transport system is not significantly affected by the local economic structure and is more related to macroeconomic variables and behavioral factors, while the amount and the efficiency of commodity transport are strictly related to the structure of the economic system itself. Thermodynamic alone (i.e. the performance of engines) does not play a significant role in explaining energy use and traffic dynamics.

1. INTRODUCTION

Transport is a growing and hard-to-deal with problem for urban and extra-urban areas. It is one of the main reasons of energy consumption and environmental impact. Moreover transport affects the daily life of people reducing the time available to other activities. In fact as a consequence of the constant intensification of the road traffic, traffic jams and delays are always more recurrent, thus increasing the time spent travelling. Despite a huge talking of dematerialization, yet modern economies are increasingly based on commuting and freight

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[1] E-mail: federici2@unisi.it; TEL. +0039 0577 234265;

transportation. In particular, cities are very special dissipative systems whose survival is heavily dependent on: (i) input flows of energy, water, commodities, and labor; (ii) output flows of liquid, solid and airborne waste material, and, finally, (iii) active information exchange with the surrounding areas. While the latter is appears performed by means of dematerialized systems (phone, internet), this is simply not true for matter and people, which still generate huge flows of traffic to and from the city. This calls for a highly organized transportation system, in lack of which the very survival of the city would be undermined. However, the presence of such a transportation system requires huge environmental, energy and material support.

In this paper we analyze two main aspects, namely how traffic levels and environmental impact are affected by:

a) the social and economic structure of a territory (production patterns, commodity distribution, individual free time and city life organization); and
b) the thermodynamic and technological performance of the transportation system itself (efficiency, consumption of energy, load effectiveness, speed).

A better understanding of both aspects may lead to appropriate production and organization policies capable to contribute to traffic and emissions decrease, thus complementing the benefits expected from technological improvement.

From 1973 to 1988 the share of travels and freights in the OECD's final energy use rose respectively from 19% to 22% and from 7% to 10% (Shipper, Meyers[2]), totaling a significant 32% of final energy uses. This means that the transport system is the largest cause of energy consumption in the developed countries, followed by the manufacturing sector, 27%. Since the latter also includes the car industry, the total share of the transportation sector is much higher than indicated by direct consumption of energy, and keeps growing.

Although the efficiency of engines has increased during the last three decades, especially in the U.S.A., no significant reduction in the use of energy has followed (IEA [3]). In the particular case of the transport for freight system, for example, a recent improvement of the efficiency of the small size trucks seems to have led to a weakening of the logistic organization in many countries, like Italy and Japan, due to their increasing use instead of larger ones (IEA, [3]). On one hand the efficiency of engines increases, on the other hand the efficiency of the system decreases. Other use patterns, such as the decreasing number of people per vehicle, or the increasing average distance traveled, are well established to be strictly linked with the relative low cost of energy, and the increased efficiency of the engine. Cars that consume less per km appear to encourage people to drive more, paradoxically.

The whole concept of efficiency, in all its shades, appliances, levels as well as the interactions occurring within the system due to the increased efficiency. In particular, the trade-off between the efficiency of a process and the efficiency of a system requires careful investigation.

Many attempts have been done to account for the efficiency of transportation by means of one or more thermodynamic and economic indicators, used separately. These approaches highlight important aspects, but fail in considering other problems. In this work we try to merge economic and thermodynamic aspects in order to yield a more comprehensive picture of both tools and system. In so doing, we try to avoid the construction of a sort of thermodynamic-economical "super" indicator, while instead trying to analyze and compare the information supplied by the different sets of empirical indicators. In fact the process of building an aggregate indicator may destroy the existing information rather than create a new one. As Shipper and Meyers [2] pointed out, in fact :"There is not a good measure of the overall activity for transportation. While economic output in transport is a standard category in national accounts statistics, this quantity refers only to enterprises engaged in the transport business and does not correspond well to total transportation activity. The very different natures of passenger and freight transport make construction of a single transport indicator impossible" .

2. THE CASE STUDY

Two geographical and administrative areas of Northern and Central Italy (Brescia and Siena) were investigated, characterized by different size, structure, and economic development, in order to explore the interplay of their economic structure and transport systems. Table 1 shows the main economic indicators characterizing the investigated areas, compared with the Italian average ones.

Table 1. Selected economic indicators for Brescia, Siena and Italy (1999)

	Brescia	Siena	Italy
Population	1,088,346	252,069	59,272,613
Total working population	464,000	110,000	20,692,000
in agriculture	3%	8%	5.5%
In industrial sector	48.5%	30.2%	32.6%
other activities	48.4%	61.9%	61.9%
Yearly per capita income (Italian £[2])	25,876,000	25,199,000	22,659,000
Running vehicles per 1000 inhabitants*	668.1	255.1	554
Indicator of local road network development (§), km/km^2	1.19	0.43	n.a.
Fraction of vehicles with gasoline engines higher than 2000 c.c.	1.66 %	0.69%	n.a.

*Figures calculated from data supplied by Automobile Club Italia, www.aci.it/studiericerche/Frame_autoritratto.asp

(§) Average amount of linear kms of road per square km of surface.

Source of Data: Chamber of Commerce, Brescia, [16]; Chamber of Commerce, Siena, [17] ; ISTAT [9]; Istituto Tagliacarne, [23].

The province of Brescia has a surface of 4784 km^2 (55% mountain, 16% hills and the remaining 29% plain). The population density is about 231 persons per km^2 (1.22 times the Italian average value of 190 persons/km^2, ISTAT [4]) and its economy structure is mainly based on a well developed industrial sector (iron and steel manufacture, machinery, textile and local clusters specialized in producing components for the big industries). This huge economic activity generates critical levels of chemical and dust emissions, production of waste, and road traffic. In the urban area, the attention and alarm thresholds of airborne chemicals concentration are very often exceeded. In the last winter, in order to reduce the airborne concentration, cars in the city have been stopped for several days.

The transport sector contributes to about the 28% of the total Brescia energy consumption, while it is 33% in Italy. This should not be attributed to a lower traffic pressure compared to other developed economic areas of Italy, but it is mainly due to the particularly large energy demand of the residential sector (28% Brescia versus 23% in Italy). Road and railway subsystems are the main transportation patterns in the area. The plain landscape is crossed by one of the main Italian highways, the Turin-Venice, and by one of the main Italian railway line connecting the North-West with the North-East of Italy. In the plain, the high density of population and industrial activities required the development of a web system of roads, city ring-roads, highway junctions, for a total length of 5700 km of roads, as well as a developed railway system composed by a national high-speed line and several minor lines for local transport. In the mountain area, in consequence of the territory structure and the lower density of people and industrial activities, the transport sector must rely on steep and tortuous mountain roads and a single-track railway, used by old diesel locomotives. Passenger transportation totals about 10.1E9 p-km/yr (passenger per Km per year). Road transportation by car accounts for 89.7%, while it is about 4,3% by bus, and 6% by railway. Commodities (32.8 E9 t-km/yr, ton per Km per year) travel by road for the 98%.

The province of Siena has a surface of 3820 km^2, dominated by a hilly landscape (92%). The economic structure of the district is centered on a well developed and high added value agricultural activity as well as on a service sector displaying banking, university and health care

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[2] Data refer to Italian £ since they where published before the conversion to the European currency (1 € = 1936.27 It £).

activities. A not negligible tourist flow also supports commercial activities. A low population density (66 persons per km^2) and a small industrial activity, make the level of pollution (traffic, noise, production of waste, release of chemicals, etc) low and quite acceptable (people perceive it as acceptable). The transport sector contributes to about the 39% of total energy consumption and related airborne emissions. This is confirmed by published data on the state of the environment in Tuscany (ARPAT, Environmental protection Agency of the Tuscany region, [5]). The human presence and activities in the area are therefore very far from being critical (Basosi and Verdesca, [6],[7]). The physical nature of the district requires a web-shaped system of roads all over the territory (1630 km). The road system is integrated by a minor railway system centered in Siena and splitting into three different directions (Florence, Rome and the coastal city of Grosseto), for a total length of 227 km. The railway system is based on an old fleet of diesel-powered trains, mainly used for the transport of daily commuters to their villages outside of Siena. Passengers (3.75E9 p-km/yr) and commodities (2.85E9 t-km) travel mainly by means of road transportation systems (respectively 91.25% and 87.8%). A minor fraction of passenger traffic (4.16%) uses the system of buses that link Siena with the surrounding villages. Only 4.59% of total p-km and 12.19% of total t-km travel by train.

In both areas the technological level of individual road transportation is relatively good, also due to the incentives offered by the Italian government to favor the decommissioning of old cars. Old cars replaced by new models in the last five years, are 35% of total circulating fleet in Siena and 33% in Brescia. However, the transport system is perceived by the population as the main environmental problem of both areas, although Brescia is also heavily affected by industry-related pollution.

3. THE EVALUATION APPROACH.

The approach that is used in the evaluation of the case studies compares and integrates the results of several different methods (mass, energy, exergy, and emergy accounting) that are deeply rooted in the principles of Thermodynamics (Ulgiati, [8]). As it clearly appears from the diagram of A First-Law inventory of mass and energy flows is preliminarily performed, to become the basis for a following Second-Law evaluation based on both user-side (exergy) and donor-side (emergy) approaches. Conversions from First to Second-Law patterns as well as from local to global scales are performed by means of intensity coefficients (specific exergy and transformity) from scientific literature. This paper explores the consistency of the results from several evaluation approaches, trying to get complementary information about the thermodynamic efficiency of the investigated transportation system and the sustainability of different passenger and commodity transport options.

4. THE INVESTIGATED TRANSPORTATION SYSTEMS: STRUCTURE, MAINTENANCE AND USE DYNAMICS.

As already pointed out, the investigated transportation systems in the Siena and Brescia areas are divided in two main sub-systems, i.e. road and railway. For each of them several sub-units were considered: (a) constructions of infrastructures and machinery (roads, tracks, cars, trains, etc), (b) maintenance, and (c) use for transport of commodities and passengers. The systems diagrams in Figures 2 and 3 show the main components of each pattern as well as the flows of energy and materials among them.

Figure 1. Diagram of material and energy flows into the Diesel railway system (system symbols from Odum, [20], [21]). The product flows are units of passengers (p-km) and commodities (t-km) transported. V_1 and V_2 are the annual fractions of vehicles allocated to each subsystem. Dashed lines indicate flows of completely degraded resources

Figure 2. Diagram of material and energy flows into the road system (system symbols from Odum, [20], [21]). The product flows are units of passengers (p-km) and commodities (t-km) transported. V_1, V_2 and V_3 are the annual fractions of vehicles allocated to each subsystem. Dashed lines indicate flows of completely degraded resources.

4.1 Construction of infrastructures and vehicles

The analysis of road construction is based on average inputs and design used in Italian road-making engineering. Input material for the construction of road layers is accounted for. A lower road layer is mainly made with compacted gravel and other inert materials, for which an average lifetime of 50 years is assumed. The lower layer is then covered by upper layers made with bituminous materials, to which a 5-years turnover time is assigned. Concrete reinforcement banks are also built when this is required by the slope or the nature of the soil. This occurs in about 10% of total road length in the area. The machinery used for road construction has been also accounted for, and a life-time of 30 years has been assumed. Data for road construction have been supplied by private companies operating in the field.

The analysis of the railway system construction is performed in a similar way. A lower layer of gravel and small stones supports the track structure made with steel and cement, for which a lifetime of 30 years is assumed. Railway construction data have been provided by the Trenitalia Spa., a public Company managing the rail transport in Italy.

Resources used in the construction of road vehicles have been approximately estimated assuming that they are 80% iron and still and 20% plastic material including tires. Instead, a 100% steel content is assumed for trains, considering the mass of (plastic) seats and other materials (copper, etc) negligible. Energy costs have been calculated accordingly.

A lifetimes of 10 years is assumed for cars, 15 years for buses, 20 years for trucks, and finally 30 years for trains.

4.2 Maintenance

Road and tracks maintenance is accounted for in the different lifetime assumed for these infrastructures (see above). A shorter lifetime implies an additional effort for substitution and repair.

Standard maintenance inputs are assumed for cars, averaging over car makes and lifetimes, based on interviews to car-repair dealers. Instead, information about maintenance of buses and trains was supplied by the personal communication with the Companies operating in the area (TRAIN Siena, ASM Brescia for buses; Trenitalia Spa and FNM for trains).

4.3 Use

A weighed average of fuel consumption was performed over the most commonly used cars in Italy. Calculation also took into account average distances covered[3] yearly according to the monitoring of the National Institute of Statistics (ISTAT, [9]), assuming an average speed around 70 km/hr. These average performance data were applied to the local fleets in Siena and Brescia, in order to estimate the total fuel consumption by cars. Estimates based on actual fuel sale in each area did not provide reliable results due to a significant flow of through-traffic. Diesel fuel consumption of buses and trains was directly supplied by the operating Companies.

The oversize power of the locomotives used, with respect to the amount of people transported by train, penalizes the railway system compared with the bus system. In particular, the diesel engines of the locomotives are designed for optimum performance when they carry about 8 carriages, while instead the coach number is very seldom higher than 3 for most of the daily trips. In Brescia the railway system is composed by a hold diesel track (with the same locomotives running in Siena) connecting the city of Brescia with the alpine zone (108 km length) and other modern electric tracks used for local and through-traffic. The electric trains used have a medium power of 6-8MW and are very often underutilized with respect to their potential.

Information about commodity transportation refers to the Energy Plan of the Tuscany Region for the year 1995 for Siena, while the Brescia data were supplied by the to Italian Highway Society and the Union of the Chambers of Commerce of the Region Lombardia

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[3] (15000 km/yr for gasoline cars, 20000 km/yr for diesel cars)

(http://www.lom.camcom.it). Medium load factor of 8,78 t/v-km (ton per vehicle per km) and 11,2 t/v-km were calculated respectively for Brescia and Siena. This depends on the different trip lengths (250 km/trip Brescia and 170 km/trip Siena) and the different trip frequency. In fact, the presence of a web-shaped road system in Brescia and people concentration in the plain area make truck trips easier than in Siena, where hilly landscape and narrower roads push for increased optimization of each trip. Average-size trailer trucks and a yearly distance covered of 150,000 km per truck are assumed as reported by specialized Journals in the field (TUTTOTRASPORTI [10], [11]).

4.4 Allocation of inputs among sub-systems

Since transportation systems are used both for passengers and commodities, the correct allocation of the resources and energy used to each sub-system is crucial and may affect the final results. We allocated all construction, maintenance and use costs in proportion to the intensity of use. An average passenger weigh of 65 kg was assumed, in order to calculate the total passenger mass transported versus commodity mass and allocate inputs accordingly. We are aware that this allocation procedure is questionable and may significantly affect the performance indicators calculated in this paper, by assigning a larger share of input to the transport of commodities. A different allocation procedure might be based on the total time spent travelling by each transportation pattern in the investigated year. This procedure would assign more of the input to the passenger system, but would not properly account for the impact of heavier commodity loads on the whole infrastructure and vehicle life-time.

5. DISCUSSION OF RESULTS

An annual flow of about 3.74 billion p-km (passengers) and 2.85 billion t-km (commodities) characterized the Siena transport system in the year 2000. Road traffic was respectively 96.1% and 87.7% of total passenger and commodity flows transported in Siena and 84% and 98% in Brescia (Table 2), thus indicating a dominant role of road transportation compared with railway. Table 2 also shows that the material size of the whole transportation system in Siena was 66.4 million tons and 221,8 million of tons in Brescia (all vehicles and infrastructures, including roads and tracks). When this material amount is used to calculate the local material intensity (Table 3), the average lifetime of each component was considered. The total amount of fuel used at Siena and Brescia are respectively the 0,46% and the 1,16% of total fuel used for transports in Italy (Ministero dell' Ambiente, [12]).

Table 2. Mass flow accounting of transportation systems.

	Passenger flow (10^9p-km/yr)	Commodity flow (10^9t-km/yr)	System mass (*) (10^9 kg/yr)	Total fuel used ($^\$$) (10^5 toe/yr)
Siena				
Road traffic	3.57	2.5	1.71	1.77
Railway traffic	0.17	0.35	0.35	0.07
Brescia				
Road traffic	8.49	32.7	9.50	4.13
Railway traffic	0.57	0.08	0.91	0.61

(*) = vehicles and infrastructures ($^\$$) = electricity included

Table 3 shows a comparative view of the results of the investigation in order to evaluate the performance of individual and mass transportation systems at Siena and Brescia on a multi-criteria multi-scale basis. It is possible to assess: (a) the performance of different transportation typologies within the same province, and (b) the performance of the same typology in the two investigated provinces.

Table 3. Performance of the whole transportation system at Siena and Brescia, Italy.

	unit	**Mass Flow Accounting** Local scale (*) (kg/unit)	**Energy Accounting** Local scale (MJ/unit)	**Energy Accounting** Global scale (MJ/unit)	**Exergy Analysis** Local scale (MJ/unit)	**Emergy Analysis** Global scale (10^{11} sej/unit)
				Siena		
Passenger transport (*)						
Road individual transport	(p-km)	0.19	1.75	2.10	1.63	1.66
Road mass transport	(p-km)	0.07	0.49	0.62	0.47	0.60
Railway (diesel)	(p-km)	0.12	0.61	0.73	0.58	0.74
Commodity transport (*)						
Road	(t-km)	0.50	1.59	1.66	1.29	3.11
Railway (diesel)	(t-km)	0.95	0.30	0.42	0.28	4.17
				Brescia		
Passenger transport (*)						
Road individual transport	(p-km)	0.17	1.76	2.12	1.74	2.47
Road mass transport	(p-km)	0.06	0.12	0.21	0.11	0.37
Railway (diesel)	(p-km)	0.61	0.18	0.85	0.17	3.58
Railway (electric)	(p-km)	0.14	0.52	1.76	0.47	1.87
Commodity transport (*)						
Road	(t-km)	0.27	1.68	2.08	1.61	1.91
Railway (diesel)	(t-km)	9.21	1.90	2.70	1.89	39.82
Railway (electric)	(t-km)	2.10	0.14	0.67	0.13	13.34

(*) MFA is only calculated here on the local scale, and indicates the mass of system allocated to each unit of product. Other MFA analysts account for the total mass directly and indirectly involved at larger scale (LCA scope) (Hinterberger F.and Stiller H., [22]).

As far as passenger transportation is concerned, it clearly appears that the individual way (cars, motorcycles) is the one generally showing the highest material, energy, and exergy intensities at the local scale (a part for the Brescia diesel railway, which will be discussed below). The local-scale energy intensity of individual passenger transport matches very well the Italian average figure of 1.7 MJ/p-km (Malosti and Romanazzo, [13]). The individual transportation also shows the highest energy as well as emergy intensity (i.e. the highest demand for environmental support = highest ecological footprint) at the global scale of the biosphere.

Buses and diesel trains have a higher medium load factor higher in Brescia than in Siena, which results into a lower energy demand per passenger transported (the electric railway cannot be compared since Siena only has diesel trains). Anyway, in both cities the best performance (all indicators) is shown by the road mass transportation system. These results are somehow surprising, as it is a common belief that the railway transport is characterized by higher efficiency and can be partially explained by the oversize design of the railway system, compared to actual intensity of use.

Commodity transportation requires a more careful interpretation of data. First of all, it must be recalled that a larger amount of inputs are always allocated to the commodity railway subsystem than to the passenger railway subsystem, as indicated in the above Section 4.4. In addition, a larger demand of material and emergy input per t-km is generally shown by the railway sub-systems, compared with the road ones, due to the significantly higher amount of matter (steel and construction material) invested in railway vehicles and infrastructures. Notwithstanding this, the railway energy and exergy indicators in Siena still are much better than those shown by the road subsystem. The reason of this result relies on the very efficient way commodity traffic is organized in Siena, with an exact matching of offer and demand, so that trains always travel full-loaded. Instead, due to a larger use of truck transport, the Brescia diesel railway is very underutilized. Performance indicators are therefore heavily affected by the small number of commodities to which the inputs can be allocated. As a consequence of the combined lower intensity of use and higher allocation to commodities than to passengers, the diesel commodity transport in Brescia shows the worst performance indicators. Since the typology of the Siena and Brescia diesel railway is very similar, the different performance cannot come out of anything else than the lower intensity of use. As far as Brescia electric railway is concerned, it must be noted that is not a locally significant sub-system, since the most of the passenger and commodity traffic is through-traffic, qhich was not assigned to the economy of Brescia.

5.1. Further large-scale results

Table 3 also helps quantify the increase of energy intensities when the attention shifts from local to global scale. These expected increase of energy cost is due to the inclusion of the indirect energy required to sctually make and supply goods and fuels to each process. The sub-systems, which show small increases, are those transport typologies where fuel is the dominant input, since the indirect energy cost of fuel is generally low. Instead, higher increase is shown by those sub-systems involving larger structures or infrastructures, with a non-negligible embodied energy content, or those running on electricity (due to the low efficiency of the fuel-to-electricity conversion).

An interesting picture of the relationship between the system and the environment can be finally reached by disaggregating the emergy indicators (Table 4). This Table requires a careful reading, due to the convergence and overlapping of different factors affecting each figure. Expressing data in energy units makes easier the comparison of inputs of different nature. There is no doubt that the emergy per unit of transport related to the structure (vehicle) decreases with increased use, due to its allocation to a larger amount of product (p-km and t-km). There is also no doubt that the direct emergy use (fuels and electricity) is proportional to the amount of kilometers run and therefore to the intensity of use. This also applies to the emergy input associated to the labor of drivers, which is presented in the Table in aggregated form with the indirect labor (services).

Services include more than one factor among which the indirect labor of providing fuels, vehicles and infrastructure. Since the emergy of fuel and direct labor increase and the emergy of vehicles decreases with intensity of use, so does the emergy of their related services. Infrastructures are instead affected by two opposite drivers: the increased allocation to a given transport typology with increased use (see above Section 4.4) is contrasted by a loss of percent importance within the typology itself, mainly due to the increased weight of fuels.

In conclusion, (a) the renewable emergy input is always negligible (the system is far from being a sustainable natural system); (b) the role of the emergy of vehicles decreases with increased use (suggesting the need of implementing vehicle use optimization strategy); (c) the emergy of fuels increases with use (which calls for higher efficiency engines); the emergy of infrastructures, although allocated in a larger fraction to those typologies with higher intensity of use, ultimately becomes less important within a given typology when fuel emergy increases. Those cases for which the infrastructure emergy remains relevant when compared with direct emergy of fuels suggest that the infrastructure is oversized with respect to the actual needs.

Table 4. Allocation of emergy input ti transport typologies, disaggregated into the main input categories.

Emergy Allocation	Renewable (§)	Structure (*)	Infrastructure (**)	Directly Energy Use (°)	Labor and services (#)
Road transport, Siena					
Individual Transport	0.008%	12.68%	3.18%	49.43%	33.77%
Road Mass Transport	0.032%	6.76%	13.31%	64.28%	14.80%
Road Goods Transport	0.097%	0.37%	40.48%	34.02%	22.54%
Road transport, Brescia					
Individual Transport	0.002%	13.28%	0.89%	52.15%	33.59%
Road Mass Transport	0.014%	29.05%	5.92%	25.68%	38.73%
Road Goods Transport	0.044%	1.72%	17.83%	69.94%	8.63%

Diesel Railway Transport Siena					
Railway Mass Transport	0.01%	6.48%	28.31%	26.59%	38.61%
Railway Goods Transport	0.02%	0.16%	70.12%	1.70%	27.99%
Diesel Railway Transport Brescia					
Railway Mass Transport	0.01%	20.83%	53.32%	7.99%	17.82%
Railway Goods Transport	0.02%	0.24%	74.28%	2.97%	22.45%
Electric Railway Transport, Brescia					
Railway Mass Transport	0.01%	0.34%	36.62%	13.53%	49.15%
Railway Goods Transport	0.02%	0.07%	62.16%	18.60%	19.13%

(§) Only the direct solar radiation impinging on the interested area is accounted for as Renewable Emergy. This corresponds to the solar emergy driving the sustainable ecosystem previously existing in this area, before the system of roads and railway were constructed.

(*) Only vehicles (cars, trains, trucks) are included in this item. Emergy supporting labor and services is not included.

(**) All kinds: roads, bridges, railway, etc are included. Emergy supporting labor and services is not included.

(°) Fuel and electricity.

(#) Includes direct labor as well as indirect labor quantified as services and measured by the economic value of the items supplied.

5.2 Improvement potential

Although the above results are rich with information and interesting policy consequences, a further step ahead in our understanding of the system performance is still possible. First and second order exergy efficiencies are compared in Table 5. The first order exergy efficiency (= work actually delivered/work potentially deliverable) indicates the average distance of the investigated process (real case) from a reversible one (ideal case). This distance could be decreased by means of technological improvement and use optimization, but cannot be completely cancelled due to thermodynamic reasons. However, this task belongs to engine and car designers more than to transport planners. Instead, the second order exergy efficiency (η) indicates the distance of the present system (all used vehicles + infrastructures) from a possible system where less efficient vehicles are replaced by the best ones already available, used according to an optimal use pattern (full load). This distance can potentially be decreased in a short time by redirecting the customer preferences toward cars that are more exergy efficient instead of more powerful and fast. The reference system is not an ideal system, but can be as real as the investigated one. The lower the second order exergy efficiency, the higher the potential improvement (and saving) that can be obtained. The chosen reference vehicles are: the car VolksWagen Lupo 1.2 Tdi, the bus Fiat Iveco 8460.31X and the diesel locomotive ALN 663. These vehicles are already in use in the areas, but their number is small. Table 6 shows that the road individual sub-system still offers huge improvement potentialities. The Brescia bus transport shows the best second order exergy efficiency; it is very important to underline that buses running in Siena are more modern that the Brescia ones (buses registered after 1998 are 45% and 35% respectively, ACI [14]), so the main factor affecting the η value is the load factor. Therefore, also in this case technology improvement is not important in itself.

Table 5. First order and second order exergy efficiencies of the passenger transportation systems at Siena, Italy.

	Road individual transport	Road mass transport	Railway mass transport
Siena			
ε (*)	26.00%	40.00%	30.00%
η (#)	16.00%	40.00%	60.00%
Brescia			
ε (*)	26.00%	40.00%	85.00%
η (#)	16.00%	96.98%	21.49%

(*) Average values (Tuttotrasporti [10], 2000; Quattroruote,[23]; Trenitalia Spa, [24])

(#) Calculated in this work. The reference vehicles and use pattern are described in the text.

Finally, the second-order exergy efficiency of the passenger railway system, assuming a relatively modern electric 4 MW locomotive E444R as the reference vehicle operating in average Italian conditions would be about 60% at Siena. Increasing the efficiency of the Siena system toward the reference case would require the electrification and modernization of the whole line. In order for this to be possible, a huge material and emergy investment in the form of high quality steel, copper and cement would be needed, much larger than the present diesel-based emergy costs indicated in Table 3, also assuming a 30% increase in the number of passengers and p-km transported. However, the new and ideal system would only improve the energy and exergy performances of commodity transport, while remaining unable to compete with the diesel option for passengers. Therefore, even if the second-order exergy efficiency suggests that a significant improvement is in principle possible based on average performance data for Italy, all the other indicators do not confirm it as a viable alternative for the investigated case, due to factors of scale and intensity of use.

6. ECONOMIC COMPLEXITY AND TRANSPORTATION SYSTEMS.

One of the most important issues arising from the mass flow analysis (Table 2) is the huge gap in the amount of freight transported within the two provinces. It may be obvious that an industrial economy like Brescia is much freight traffic intensive than a rural and service oriented one, like Siena. Yet, the extent of the difference is surprising, since it seems to be more than proportional to the size of the local industrial sector. In fact, if the proportion between the industrial local net values (GDP minus external costs) is 8 to 1 (18,872,930 and 2,341,259 millions of 1998 Italian liras), the proportion between the two amounts of t-km of freight delivered per year inside the province is 13 to 1 ([15]; [16]). Although there are some similarities between the two provinces, such as the per capita income or the consumption of gasoline per vehicle (Table 1) and strong differences as well, such as the distribution of the working population over economic sectors or the development of roads infrastructure (Table 1), a very different level of internationalization of the economy is shown. This seems to affect the freight transport system much more than industrialization itself. Both economies showed a remarkable growth in the last decade. However, in Brescia the amount of export is strictly related to the amount of import, whilst in Siena exports appear decoupled from imports (Table 6).

According to the Chambers of Commerce, Siena's exports increased by 237 % while imports only increased by 42 % between 1992 and 2000. The Export/GP and the Total Trade/GP ratios indicate that the burden of international exchanges are almost equally distributed between exports and imports in the economy of Brescia as well as of Italy, while in the local economy of Siena exports take the largest share. This is partially due to the structure of the two economies. In Siena the main products for export are agricultural (mainly wine) and mono-modular manufacturing products, like crystals artifacts. The mono-modular manufacturing transforms directly the raw materials into the final product, which is therefore the output of the process, while the multi-modular manufacturing is involved in a wide and pluri-located process of transformation. In other words, trade in Siena concerns only the down stream of production, whilst in Brescia both down stream and up stream are involved.

Table 7. International trade in Brescia, Siena and Italy in the year 1999 (Italian £)

	Brescia	Siena	Italia
Import	8.52 E12	2.94 E11	3.94 E14
Export	1.34 E13	1.52 E12	2.42 E13
Balance	4.86 E12	1.22 E12	2.43 E13
Export /GP (#)	38.6 %	17.0 %	23.0 %
Total Trade/GP (*)	63.9 %	20.4 %	43.4 %

(#) Export/Gross Product of the area referred to.

(*) (Export + Import)/Gross Product of the area referred to.
Ref.: (Istituto Tagliacarne, Rome, www.tagliacarne.it [22])

Moreover, mainly local raw materials are manufactured in Siena and then used locally or exported, while Brescia imports raw materials to be processed locally. International trade attitude is shared by the big industrial firms of the province as well as by the small and medium enterprises in the area (82.2% of total industrial activity). For the abovementioned reasons trade of products and supplies is directed to and from foreign countries or other regions of Italy. In economic theory this process of trade internationalization is called “outsourcing”. The data analyzed here show that international outsourcing affects the economic structure in a fashion, which intensifies freight transport. Data demonstrate that a network economic structure, like an outsourcing system, is more “traffic intensive” than a linear productive process, like the mono-modular (and mono-located) systems of Siena.

Does the productive system also affect the transport of people? The T.G.M (Transito Giornaliero Medio, i.e. Daily Average Traffic) of ten main provincial roads, shows that Brescia is more overloaded than Siena, since in Brescia the average value is 13.821 running cars per day (A.N.A.S., [17]) whilst in Siena it is 6.084 cars per day. The same did not happen in Siena, in which the size has been stationary over the last few decades. In addition, the concentration of vehicles and people in the urban area (1.436 and 243 vehicles per km^2 ; 2.109 and 457 inhabitants per km^2 respectively in Brescia and Siena) also lead us to conclude that the town of Brescia is more congested than Siena, thus reinforcing what already appeared from mass and thermodynamic indicators shown above. Yet, the passenger transport system appears more related to macroeconomic variables and behavioral factors. In fact, the influence of the increased size and complexity of the structure, that would lead to an increase in length and number of travels, is offset by certain local constrains or specific dynamics, such as, the amount of cars running within the urban area, which has already been saturated since a long time, or the moving of traffic attractors (like hospitals, leisure centre, offices) from the centre to the periphery, for which it is not easy to establish the ultimate effect on traffic intensity.

It is possible to say that the economic structure clearly affects freight traffic intensity due to its complexity, but it is rather more difficult to maintain the same statement for the passenger transport system. Maybe such issue (i.e. a link between structure and passenger traffic) could be demonstrated, within a larger scale system, like a regional, national or international one, where natural and historical barriers are less binding. Certainly, as it appears from this analysis, the economic structure directly affects systematic movements, like commuters, rather than the use of cars for leisure, which still tends to be more related to individual income. In Siena for example, despite a better supply of public transport, car use in terms of time, gasoline, and distance, is quite the same than in Brescia. In both cities, individual cars are always preferred to mass transport, whenever this is possible depending on individual income, no matter the mass transportation tool is efficient, modern or comfortable (such as Brescia’s trains and Siena’s city buses). A better understanding of the reasons of individual preferences towards car use instead of mass transport and walking is needed, before any effective policy is enforced. However, individual use of cars is restricted in Siena downtown, due to protection of the historical sites, which increases the use of city buses. In some a way, the success of this option suggests the adoption and effectiveness of norms and regulations constraining traffic development, when there is a clear awareness of a possible improvement of the quality of life. The car based system clearly appears less thermodynamically efficient than mass transportation, yet this is not a significant factor, in order to orient people preferences. Cars are preferred for reasons that are not technical or thermodynamic, but appear more related to comfort, aesthetics, status symbol, and flexibility. In addition, technological improvements of car engines (more km per liter) contribute to consider the energy factor as unimportant and economically affordable.

7. CONCLUDING REMARKS

The economic and thermodynamic survey performed in this paper lead to three major conclusions:

a) Brescia appears to be much more loaded by traffic than Siena. However, since railway and road network in Brescia are much more developed than in Siena, this could be considered an indicator of higher efficiency of Brescia's transport system, under "economic" the point of view of "accessibility" of sites (Ruzzenenti, [18]).
b) Use of cars always appears the preferred transportation pattern whenever this is possible based in individual income. This preference is not apparently driven by any other reason than comfort, aesthetics, status symbol, and flebibility.
c) On the other end, commodity transportation is determined by the complexity and structure of the economic system. Choices again do not appear to be oriented by the thermodynamic aspects, but instead by economic factors (lower cost and economic links to outside the productive area).

Therefore, if a traffic policy for commodities, aimed at a more efficient and environmentally sound use of resources, is to be effective, the very structure of the productive system should be reorganized and redesigned toward this goal (suitable clusters of firms and markets). This does not occur spontaneously today due to the relatively low cost of fossil energy.

Instead, if redirecting shares of passenger traffic from individual to mass transportation tools is the goal, individual preferences (shortening of travel time, higher comfort, etc) must be taken into proper account. Since these actions are never easy or inexpensive (better trains cost more in economic and environmental terms; some destinations cannot be reached by train, etc) other patterns need also to be explored (inter-modal nodes redesigning of urban areas, reorganization of services, reorganization of food and commodity distribution, etc). In other words, it is necessary *"…to reorganize the automobile cultures of the developed nations. First there can be reduction of unnecessary horsepower, followed by reduction of autos. Private cars save individual time, but other measures can substitute including more use of communication in place of transportation, people moving closer to work, and more shopping on line." ([19])*

It clearly appears that an effective traffic polity cannot only be based on increased efficiency and substitution of a fuel with another. Although these policies can generate steps ahead towards lower energy costs and better air quality, dramatic improvements can only be provided by redesigning the productive structure (for what relates to commodity transport) and the urban structures and life style (for what relates passenger traffic). Thermodynamics cannot solve the entire problem, however it can provide useful indicators to measure our progresses towards a better use of available resources.

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