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ORIGINAL RESEARCH

What price of speed? A critical revision through constructal optimization of transport modes

Michele Trancossi

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Abstract The use of energy by the major modes and the environmental impact of freight transportation is a problem of increasing importance for future transportation policies. This paper aims to study the relative energy efficiency of the major transport modes, setting up an impartial analysis, improving previous literature substantially. Gabrielli and von Karman have studied the relationship between speed and energy consumption of the most common transport modes. From this pioneering activity different methods for evaluating the energetic performance of vehicles have developed. Initially the maximum vehicle power and theoretical performance limits have been calculated in terms of weight and payload. Energy efficiency has then been evaluated in terms of the first principle of thermodynamics as the mass of the vehicle times distance moved divided by thermal energy used. A more effective analysis can be performed both in terms of vehicle life cycle and in terms of second principle considering the quality and the amount of dissipated amount of useful energy. This paper defines an LCA based model, which could allow an effective comparison between different transport modes classifying them in terms of exergy destruction. In this case, an effective comparison, which considers the quality of used energy, can be performed allowing precise politics for a future more effective evaluation of the transport modes.

Keywords Transport · Energy efficiency · Velocity · Consumption · Exergy · Gabrielli–Von Karman

List of symbols

DT	Delivery time (S)
E_{kin}	Kinetic energy (MJ)
E_D	Energy dissipation against drag (MJ)
E_{ROL}	Rolling energy (MJ)
$Ex_{payload}$	Exergy dissipated by payload (MJ)
Ex_{res}	Exergy from resources (MJ)
$Ex_{service}$	Exergy dissipated during service (MJ)
$Ex_{vehicle}$	Exergy dissipated by vehicle (MJ)
N	Number of travels
m_p	Mass of payload (kg)
m_v	Mass of vehicle (kg)
MPST	Mass per single transport (ton)
P_{max}	Maximum power (kW)
TD	Total distance (km)
TM	Total mass (Ton)
TD	Total distance (S)
V	Velocity (m/s)
v_{av}	Average velocity
v_{max}	Maximum velocity (m/s)
W	Weight (N)
ε	Specific resistance of vehicle
ε_f	Fuel transport effectiveness
ζ	Energy per unit volume of fuel (MJ/kg_{fuel})
η	Distance traveled per unit volume of fuel (Km/kg_{fuel})

Abbreviations

EMIPS	Exergetic material input pro unit of service
LCA	Life cycle assessment
LHV	Low heating value
GHG	Green house gas

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M. Trancossi (✉)
Di.S.M.I., University of Modena and Reggio Emilia,
Via Amendola n. 2, 42100 Reggio Emilia, Italy
e-mail: michele.trancossi@unimore.it

Introduction

Energy demand is growing, affordable and secure energy supply are fundamental to global economic growth and human development. The scenario described by "World Energy Outlook 2013" [1] (WEO 2013) together with the forecasts by "2014 World Energy Issues Monitor" [2] (2014 WEIM) presents large uncertainness about future and a dramatic increase in terms of energy demand, driven by non-OECD economic growth. Figure 1 shows historical data by WEO 2013 and Fig. 2 present provisional data by 2014 WEIM.

Future energy perspectives present diffused uncertainness related to the high volatility of energy prices, the lack of global agreement on climate change mitigation, the necessary demand for new energy infrastructures, too slow development of Carbon capture technologies, and the necessity of increasing energy efficiency.

It is evident that the provisions for the future are out of the sustainability of the planet, both in terms of destruction of resources and in terms of climate change, which directly related to the emission in terms of GHG.

Transport sector overview

Even if it is not the main contributor to the energy consumption, the transport sector will play a fundamental role for the future wellness of the humanity. In particular, energy use in the transportation sector includes energy consumed in moving people and goods by road, rail, air, water, and pipeline. Those transportation systems are essential in an increasingly globalized world, as well as for enhancing standards of living.

Trade and economic activity seem the most significant factors increasing demand for freight transportation. The factors that will affect the demand of passenger transportations appear much more complex and include uncertain parameters such as travel behavior, land use patterns, and urbanization. This increased complexity presents a larger uncertainness about—the effects of passenger transportation in terms of macroeconomic and fuel market impacts.

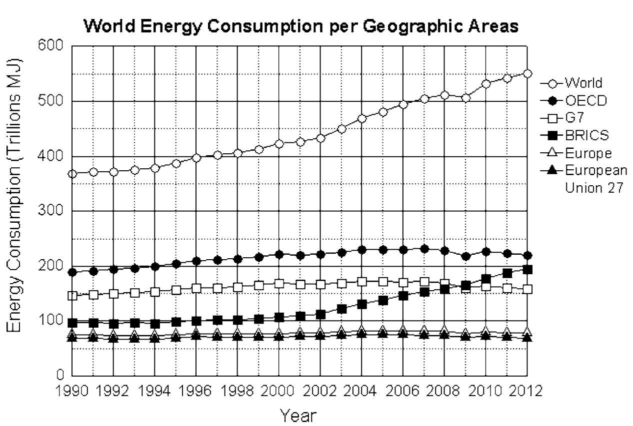


Fig. 1 World Energy Consumption historical trend (data from IEA WEO 2013)

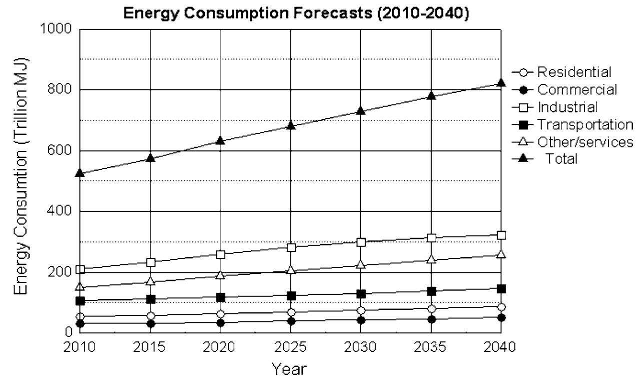


Fig. 2 Energy consumption Forecast 2010-2040 (data by 2014 WEIM)

Any possible analysis of energetic impact of transport modes must necessary consider different modes and their energy efficiency to allow the definition of effective strategies to reduce the energy consumption, by adopting the two main decisional elements for the future. In particular, they are a short-term strategy based on a better planning of transport modes and on a long-term strategy based on substantial improvements of vehicles.

Any analysis about transport modes must considers two fundamental parameters they are speed and energy intensity. Increasing speed increases social efficiency and allows reducing costs for both public and private institutions and for citizens. On the other side, energy consumption causes economic, environmental and social costs.

An overview of scientific literature

The first fundamental attempt to analyze the relations between speed and energy consumption of different transport modes has been produced by Gabrielli and von Karman [3]. This analysis introduces a physical parameter, named specific resistance of vehicle ε, which is defined as the ratio of motor output power $P_{\max}$ divided by the product of total vehicle weight W by maximum speed $V_{\max}$.

$$\varepsilon = \frac{P_{\max}}{W \cdot V_{\max}} \tag{1}$$

It is fundamental to notice that Gabrielli and Von Karman consider the gross weight of the vehicle, because "exact information about the useful load of vehicles was not available to the authors." They have clearly demonstrated that specific resistance has a minimum value, which applies to all the examined transport modes, which appears as a physical limit of all transport modes. It corresponds to the line of equation

$$\varepsilon_{\min} = A \cdot V_{\max}, \quad (2)$$

where $A = 0.000175$ h/mile. The Gabrielli–von Karman limit line of vehicular performances depicts this relationship. It is the diagonal line indicated in Fig. 3.

Stamper [4] reconsidered Gabrielli–von Karman results in terms of ratio between payload weight and fuel consumption, introducing one of the future trends of transport energy efficiency in terms of payload of the different vehicles, without considering the vehicle as a part of the transported weight. Stamper has defined "useful transport work" by multiplying payload weight and distance traveled and "transport efficiency" as the ratio of useful transport work to thermal energy expended. This model is useful on a logistic point of view but losses any physical connection to the real nature of transport which is composed by two fundamental elements, the vehicle and the payload.

In a subsequent analysis, Teitler and Proodian [5] have categorized military vehicles and have considered a new characteristic dimension, which has named "specific fuel expenditure", which can be defined as

$$\varepsilon_{F} = \frac{\zeta}{\eta \cdot W_{P}} \quad (3)$$

where ζ is the energy per unit volume of fuel η is the distance traveled per unit volume of fuel, and W_P is the weight of the payload. A new variable has been introduced it is the reciprocal of ε_F has been defined as "fuel transport effectiveness", which relates directly to the cruising speed of the vehicle V_C by a factor of proportionality C_F :

$$\frac{1}{\varepsilon_{F}} = \frac{1}{C_{F} \cdot V_{C}} \quad (4)$$

This definition allows defining the factor of proportionality C_F as the "the next level of fuel transport effectiveness to be used as a future standard", which is represented in Fig. 4, with the dashed diagonal line [6].

Referencing Gabrielli–von Karman [1] and Teitler and Proodian [3], Minetti [7], Young [8] and Hobson [9] have considered A or C_F as a factor describing an experiential performance limit and ε_F^{-1} or ε_F as a general performance parameter.

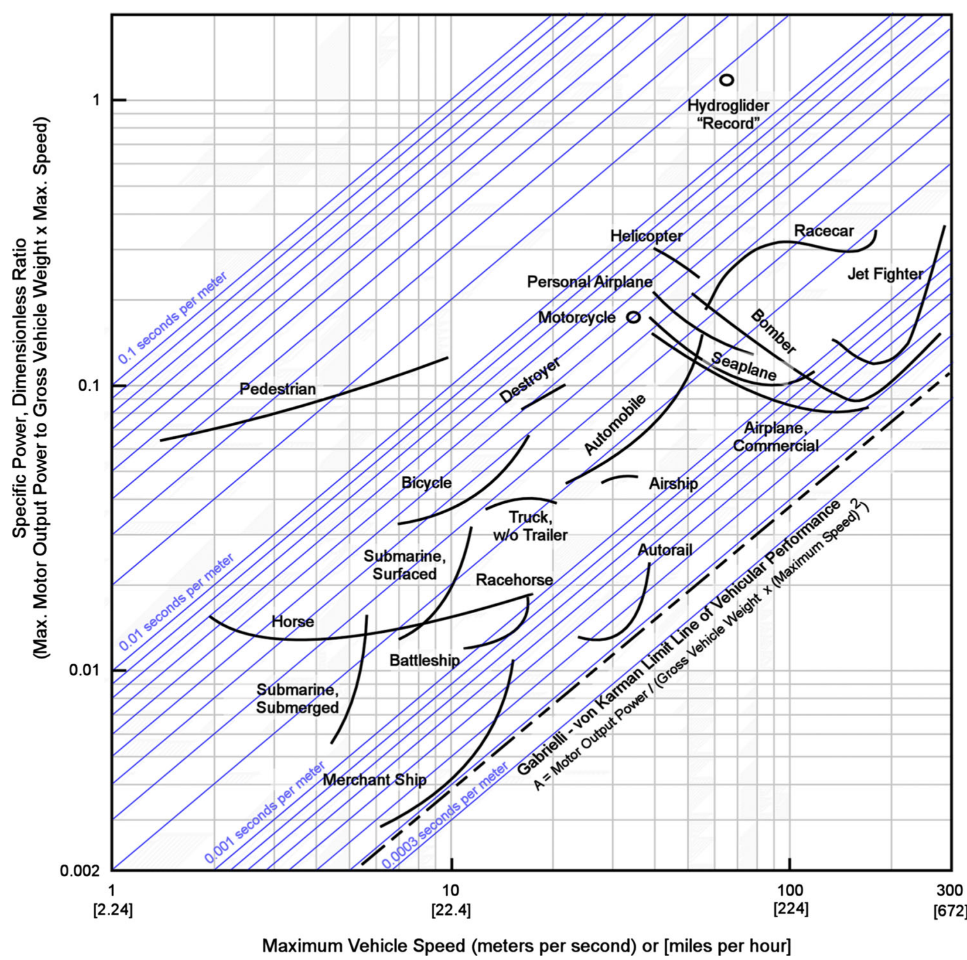


Fig. 3 Gabrielli–Von Karman graph (from Neodymics [4])

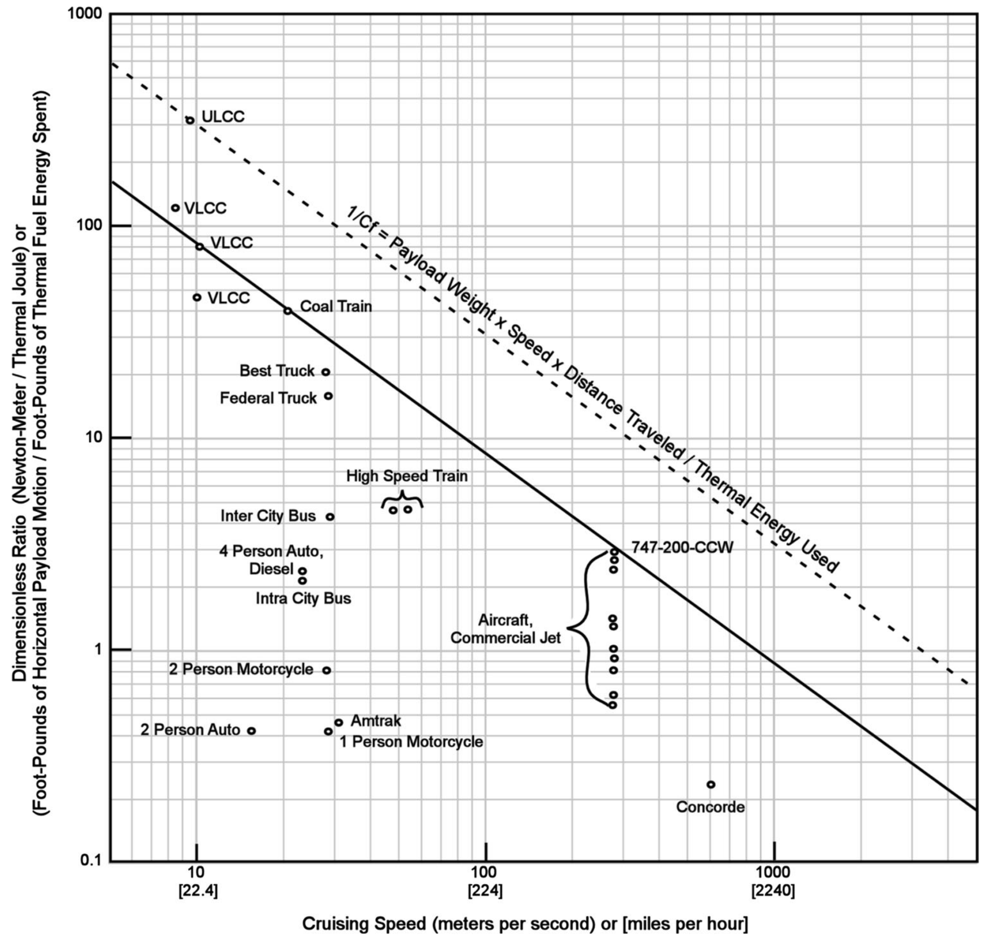


Fig. 4 Dimensionless fuel transport effectiveness plotted as a function of cruise speed (adapted from Teitler and Proodian [5] by Neodymics [4])

Radtke [10] has produced a further development of the above models. He observed that by combining speed and energy expenditure it could be obtained a novel performance parameter ε_F, which considers payload and energy needs under cruising conditions. Those considerations allow obtaining a new performance parameter Q_C obtained by treating the payload as a mass (denoted M_P) rather than a weight yields a performance parameter Q with units of time. For cruise conditions, Q_C has been obtained:

$$Q_C = \frac{g_o}{C_F} = V_C \cdot M_P \cdot \frac{\eta}{\zeta} \tag{5}$$

Radtke has used certified data such as the EPA fuel economy ratings to represent how vehicles are actually used. In particular, he adopted the highway rating which is used to describe free flow traffic at highway speeds [11]. He has the produced an energetic analysis of different vehicles including aircrafts and electric vehicles.

Dewulf and Van Langenhove [12] have adopted a completely different approach based on an elementary exergetic analysis. They present an effective assessment of the sustainability of transport technologies in terms of resource productivity, based on the concept of material input per unit of service (MIPS). If MIPS evaluation is quantified in terms of the second law of thermodynamics, it is possible to calculate both resource input and service output in exergetic terms. It leads to the concept of EMIPS (acronym of Exergetic Material Input per Unit of Service) specifically defined for transport technology. It takes into account the total mass to be transported and the total distance, but also the mass per single transport and the speed, allowing an effective comparison between railway, truck, and passenger car transport.

Transport modes and vehicles has been then evaluated in terms of exergetic material input pro unit of service (EMIPS):

$$R/S = \frac{\mathrm{Ex}_{\mathrm{resources}}}{\mathrm{Ex}_{\mathrm{service}}} = \mathrm{EMIPS} \tag{6}$$

The amount of resources extracted from the ecosystem to provide the transport service has quantified defining an inventory of all exergetic resources in the whole life cycle.

The method allows evaluating cumulative exergy consumption also introducing an effective differentiation between non-renewable and renewable resource inputs according to Gong and Wall [13].

Dewulf has evaluated the exergy associated with the transport to overcome aerodynamic resistance, inertia effects and friction to bring a total mass (TM) in a number of transports (*N*) with a mass per single transport (MPST) within a delivery time (DT) over a total distance (TD). The physical requirement is the exergy to accelerate and to overcome friction. If one is able to define the exergy associated to this service, being a function of TM, MPST, DT, and TD, then the exergetic efficiency of transport technology can be determined:

$$R/S = \mathrm{EMIPS} = \frac{\mathrm{Ex}_{\mathrm{resources}}}{\mathrm{Ex}_{\mathrm{service}}(\mathrm{TM,MPST,DT,TD})} \quad (7)$$

Dewulf takes into account two types of dissipations: E_{kin}, kinetic energy, and E_{D} to overcome the aerodynamic drag.:

$$E_{\mathrm{d}} = E_{\mathrm{kin}} + E_{\mathrm{D}}$$

where the kinetic energy depends on the maximum speed $v_{\max}$ during the trajectory:$v = v_{\max}$ if $v \neq 0$ and $dv/dt = 0$.

$$E_{\mathrm{kin}} = \frac{1}{2} m \cdot v_{\max}^2$$

On the other hand, for a given shape vehicle aerodynamic resistance causes an energetic loss

$$E_{\mathrm{D}} = \int_0^{t_{\mathrm{tot}}} \left(\frac{1}{2} \cdot C_{\mathrm{D}} \cdot \rho \cdot A \cdot v^2 \right) \cdot v \cdot dt$$

where C_{D} is the drag coefficient, *A* is the cross section, and ρ is the density of air. It can be observed that high speed is very unfavorable, because the energy losses due to aerodynamic resistance relates to v^3. Wind direction has been reasonably neglected assuming that it varies casually with an almost uniform distribution and that the number of transports inwind is the same as the ones upwind.

The final expression of the exergy service has been expressed as:

$$\mathrm{Ex}_{\mathrm{service}} = \frac{\mathrm{TM}}{\mathrm{MPST}} \left(\frac{1}{2} \mathrm{MPST} \frac{\mathrm{TD}^2}{\mathrm{DT}^2} + \frac{1}{2} C_{\mathrm{D}} \rho A \frac{\mathrm{TD}^3}{\mathrm{DT}^2} \right) \quad (8)$$

Chester and others [13–15] have studied the environmental life cycle assessment (LCA) of transportation systems. They create a framework for assessing the energy use and resulting environmental impacts of passenger and freight mobility, comparing the equivalent energy or environmental effects of different technologies or fuels. They have produced an effective LCA framework for the assessment of transportation systems, which includes vehicle technologies, engine technologies, fuel/energy pathways, infrastructure, and supply chains. This research has been focused on developing a suitable LCA framework for policies and decisions. In particular, different energetic consumption has been evaluated all over the whole product lifecycle. Figure 5 shows a sample of the analysis, which can be produced by applying Chester methodology [15].

Objectives

This research, aims to produce a robust model, which can allow comparing different transport modes and overcome the limits of preceding research.

It aims to define an effective model with a set of fundamental goals. In particular, it aims defining an effective and robust model, which takes into account the complexity of the energetic factors related to transport.

Referring to preceding literature, it aims to overcome the generality of the Gabrielli–von Karman analysis [3], but it aims to consider the vehicle as a whole, such as they do. They miss an effective evaluation of the energy necessary for moving the vehicle itself and the energy necessary for moving the payload.

The proposed analysis is fundamental for understanding future directions of vehicle improvement. It aims to overcome the analysis by the author, influenced by logistical issues, which refers the energy consumption to the payload [4–10]. It also aims improving both Dewulf exergetic analyses by considering a more analytical differentiation of energy dissipations during service. It appears clear that Dewulf model misses an evaluation of rolling dissipation, which are not negligible and could not be merged with aerodynamic drag, because of a completely different nature and physical law.

Even if it moves in the direction traced by Chester [13–15], it aims to consider also the necessary amount of energy for dismantling and recycling the materials of the vehicle, opening the road to a better LCA management.

Comparing Dewulf and Chester results, which are completely compatible it appears evident the differences between exergetic and energetic analysis, even if both evidences the dominant contributions to energy consumption and GHG emissions for on-road and air modes are from components that relate directly to transport operations.

General analysis

Energy efficiency of transport modes

The necessity of focusing the attention on the transport sector is clearly stated by IPCC Fourth Assessment Report:

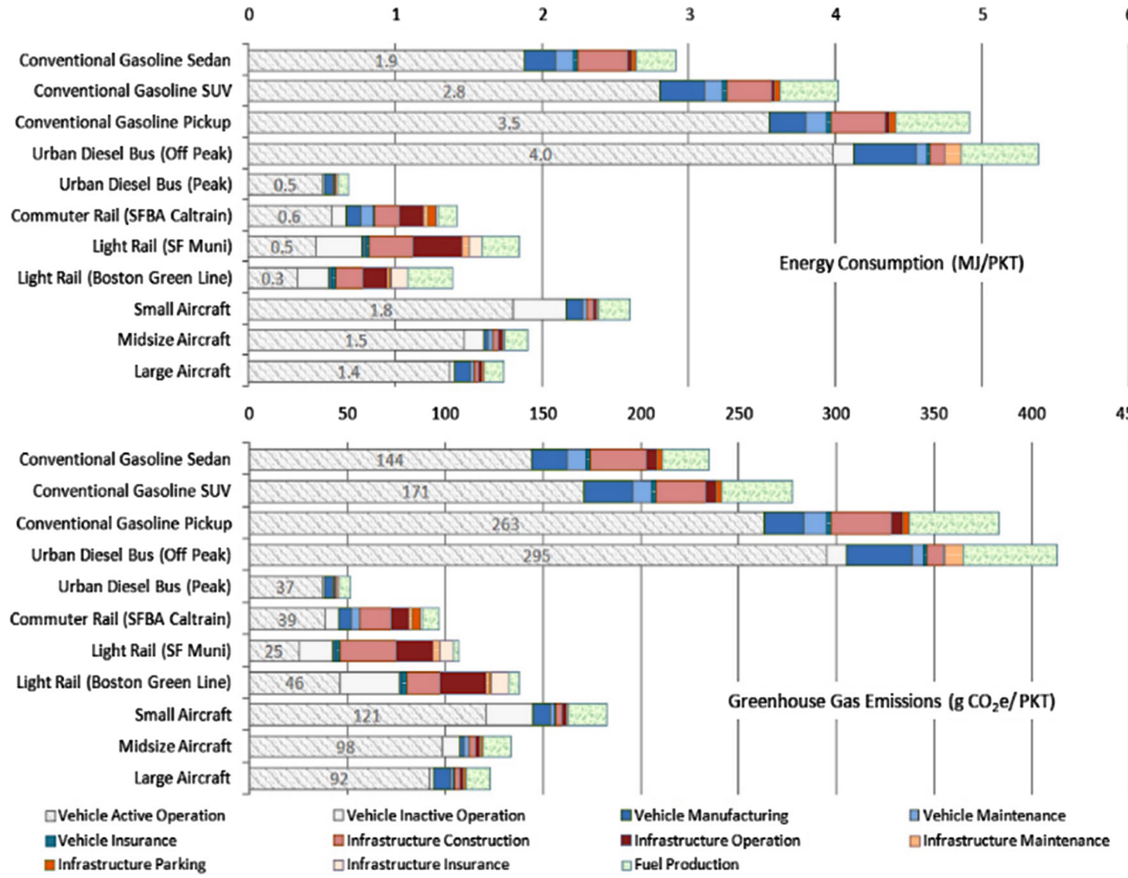
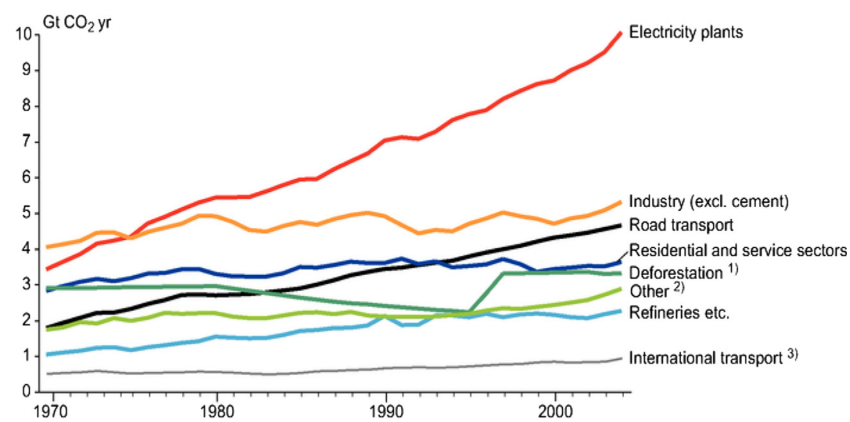


Fig. 5 Energy consumption and GHG emissions by different transport modes (from Chester and others [15])

Fig. 6 World GHG emissions (source: IPCC Fourth Assessment Report: Climate Change 2007)



Climate Change 2007 [15] and by U.S. Energy Information Administration International Energy Outlook 2013 (IEO2013) [16]. They clearly demonstrate that transport sector is the first contributor in terms of GHG emissions (Fig. 6) excluding electricity production. It has been verified that road transport is the higher component of the emissions related to transport sector.

A preliminary analysis has been produced at energetic level. Different transport modes has been compared by the well tested method by Chester. It has been completed by introducing the dismantling and recycling energetic fees to define a fully sustainable life cycle assessment of the different transport systems. Service energy dissipation has also been divided into requirements for the vehicle and requirements for the payload [17]. Dewulf indicates two dissipative terms kinetic and aerodynamic. In the case of ground vehicles and during takeoff and landing operations performed by aircrafts it is necessary to consider also a rolling dissipative term, which depends on the friction of the wheels with the terrain. A more complete analysis in terms of energetic loads can be then performed and they are:

1.

$$\text{Kinetic term} \quad E_{\text{kin}} = \frac{1}{2} \cdot (m_{\text{v}} + m_{\text{p}}) \cdot v_{\text{max}}^2 \tag{9}$$

2.

$$\text{Rolling term} \quad E_{\text{rol}} = c \cdot \left(m_{\text{v}} + m_{\text{p}}\right) \cdot g \cdot v_{\text{av}} \cdot t \tag{10}$$

3.

$$\text{Aerodynamic term} \quad E_{\text{D}} \cong \frac{1}{2} C_{\text{D}} \cdot A \cdot \rho \cdot v_{\text{av}}^3 \cdot t \tag{11}$$

In the case of aircraft, it has been considered tree different moments:

1. Take off: all terms are present and also lifting component of forces must be considered,
2. Flight: aerodynamic term is dominant,
3. Landing: all terms are present and lifting component of forces must be considered.

In the case of ships only kinetic and hydrodynamic term are present (dimensionally equal to the aerodynamic one).

The other energetic terms not directly related to motion have been evaluated according to Chester. In particular, Chester analysis has been implemented by considering also the necessary energy amount for dismantling and recycling the vehicles. Chester uses a hybrid LCA model for this analysis. The components are evaluated from the materials extraction through the final industrial product including supply chains. For example, the evaluation of automotive manufacturing includes the energy and emissions from extraction of raw materials (i.e., iron ore for steel) through the assembly of that steel in the vehicle. End of life phases are not included due to the complexities of evaluating waste management options and material reuse. Indirect impacts are included, i.e., the energy and emissions resulting from the support infrastructure of a process or product, such as electricity generation for automobile manufacturing. For each component in the mode's life cycle, environmental performance is calculated and then normalized per passenger kilometer traveled (PKT). The energy inputs and emissions from that component may have occurred annually (such as from electricity generation for train propulsion) or over the component's lifetime (such as train station construction) and are normalized.

Equation (1) provides the generalized formula by Chester for determining component energy or emissions.

$$\text{EM} = \sum_{\text{c}}^{\text{C}} \frac{\text{EF}_{\text{M,c}} \times U_{\text{M,c}}(t)}{\text{PKT}_{\text{M}}(t)}$$

where

- $\text{EF}_{\text{M,c}}$ is total energy or emissions per *PKT* for mode *M*;
- *M* is the set of modes {sedan, train, aircraft, etc.};
- c is vehicle, infrastructure, or fuel life cycle component,
- EF is environmental (energy or emission) factor for component c,
- *U* is activity resulting in EF for component c;
- PKT_{M} is PKT performed by mode M during time *t* for component c.

The environmental factors used for energy and emissions evaluations come from a variety of sources. In particular, it has been massively used the data obtained by Australian Environmental Protection Authority [18], Nissan-Global [19].

In particular, Choate and others [20] allow deriving a detailed data table about energy saving by recycling different materials. Table 1 shows energy savings comparing different management strategies for material used in automotive industry.

According to these data and assuming a specific mass balance from different authors [21–24] an effective evaluation of End of Life operations of different kinds of vehicles, including possible recycling of components and materials can be performed. This analysis allows defining the energetic parameters related to the entire lifecycle of the vehicle and considered an initial sample of about 50 vehicles chosen on their representation of the category. Fuels have been evaluated using the values in Table 2, which have been defined by Tupras report [37]. Other relevant energy losses have been evaluated according to Chester [13–15], including infrastructure. Averaged data for vehicle category have been reported in Fig. 7. Results that are more detailed have been presented in "Appendix 1".

Further considerations allow to go forward considering the general expression of the kinetic and rolling term of the dissipative terms.

The general expression of the dissipative term is then

$$\text{Ex}_{\text{service}} = \text{Ex}_{\text{rol}} + \text{Ex}_{\text{kin}} + \text{Ex}_{\text{D}}$$

In addition, two different terms referred to the vehicle and payload can be determined. In particular,

$$\text{Ex}_{\text{vehicle}} = m_{\text{v}} \left(\text{cg} v_{\text{av}} t + \frac{1}{2} v_{\text{max}}^2 \right) + \frac{1}{2} C_{\text{D}} A \rho_{\text{air}} v_{\text{av}}^3 t \tag{12}$$

is the component due to vehicle even at zero payload, and

$$\text{Ex}_{\text{payload}} = m_{\text{p}} \left(\text{cg} v_{\text{av}} t + \frac{1}{2} m_{\text{p}} v_{\text{max}}^2 \right) \tag{13}$$

is the component due to payload.

Table 1 Energy consumed/avoided from different waste involved in vehicle industry and different management options (Million Btu/Ton)

Material	Source reduction for current mix of inputs	Recycling	Combustion	Landfilling
Aluminum	−126.18	−206.42	0.12	0.53
Steel	−30.79	−19.97	−17.54	0.53
Copper	−122.31	−82.59	0.1	0.53
Glass	−7.53	−2.13	0.08	0.53
HDPE	−63.68	−50.9	−6.66	0.53
LDPE	−73.92	−56.01	−6.66	0.53
PET	−70.67	−52.83	−3.46	0.53
Paper	−36.58	−10.08	−2.13	0.13
Mixed metals	NA	−102.99	0.39	0.53
Mixed plastics	NA	−52.42	−5.09	0.53
Mixed recyclables	NA	−16.91	−2.06	0.36
Mixed organics**	NA	0.58	−0.58	0.41
Personal computers	−950.16	−43.43	−0.55	0.53

**The composition of organic material is subject to a great variability. It has been assumed a value derived from EU average waste composition

Table 2 Properties of different fuels adopted

Fuel forms	LHVs (MJ/kg)	Exergy factors	Exergy (MJ/kg)	Density (kg/m^3)
Gasoline	43.1	1.06	45.7	737
Diesel oil	42.7	1.07	45.6	870
Kerosene	43.1	1.07	46.1	790
Fuel oil	41.8	1.06	44.3	890
Natural gas	38.1	1.04	39.6	0.9
LPG	50.2	1.06	53.2	2.1
Other petroleum products	42.0	1.06	44.5	930

This analysis on energy needs for moving the vehicle and energy needs for moving the payload can be produced for different kinds of vehicles.

It allows a better comprehension of energy dissipations of different class of vehicles and allows understanding losses due to today's vehicle industrial concepts. Results have been reported in tabular form in "Appendix 2", both in MJ/t km and in percent comparison.

Life cycle analysis of transport modes

An analysis on energy impact of different transport modes must necessarily consider the intensity of different transport modes on a global scale. They have been obtained by [26] and [27] and reported in Table 4.

Table 3 refers to energetic values in terms of fuel needs and do not consider life cycle needs. Considering the precedent preliminary impacts of different energy dissipations, a complete evaluation of the entire life cycle of existing transport modes have been produced.

These considerations force to actualize the values in Table 3 referring them to the full life cycle of today's circulating fleets, and values are reported in Table 4.

Environmental considerations

Taking into account the Greet 1 Model [28] by Argonne National Laboratory, the Greenhouse Gas Protocol [29], and American Petroleum Institute [30], it is possible to extend the analysis by an evaluation of the emissions of different transport modes per km. The properties of the most used fuels have been presented in Table 5.

Default fuel economy factors for different types of mobile sources and activity data have been modeled according to EPA [31] and reported in Table 6 (Fig. 8).

The evaluation of energetic impact of different transport modes on global scale allows understanding that the larger impact on the energetic issues is caused by ground transports and in particular by cars. Interpolating the data in Table 6 it can be expressed the CO_2 emissions as a function of vehicle consumption in km/l (Fig. 9).

The data in Table 6 and in Fig. 9 shows an anomaly constituted by Diesel busses, which is clearly caused by the operational behavior of this vehicle and its mission, which are characterized by frequent stops and go.

The most important result of this analysis has been the definition of an interpolating function, which allows an approximate estimation of emissions as a function of the fuel consumed for moving.

Considering the vehicles previously estimated this system for predicting allows obtaining the general results reported in "Appendix 3". Looking at the results it is evident that emission and energy consumption for ton of payload is much more important for ground transportation and personal transports rather than for other systems. It is also evident that the energy consumed and emissions are lower for freight transport systems rather than for passenger transport. The values in Table 6 take into account an estimation of the whole life cycle emissions.

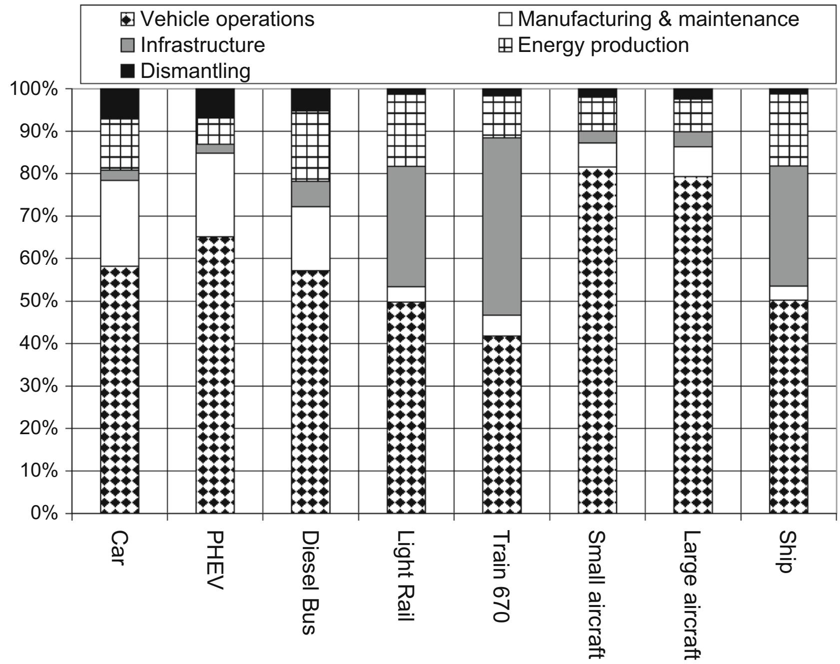


Fig. 7 Percent values of Energy consumption for different transport modes

Table 3 Default fuel economy factors for different types of mobile sources and activity data (derived from [25])

Vehicle characteristics			CO_2 emitted gCO_2/km
Vehicle type	km/l	MJ/km	
Light motorcycle	25.64	1.03	93.0
New small gas/electric hybrid	23.81	1.11	100.1
Small gas auto, hwy	13.7	1.93	175.1
Medium gas auto, hwy	12.82	2.06	186.8
Medium station wagon, hwy	11.49	2.30	207.5
Small gas auto, city	11.11	2.38	215.5
Large gas automobile, hwy	10.64	2.48	224.1
Diesel automobile	10.2	2.59	233.0
Mini van, hwy	10.2	2.59	233.5
Medium gas auto, city	9.35	2.82	254.7
Mid size pick-up trucks, hwy	9.35	2.82	254.7
LPG automobile	8.93	2.96	266.0
Med station wagon, city	8.47	3.12	280.1
Large gas automobile, city	7.63	3.46	311.3
Mini van, city	7.63	3.46	311.3
Large van, hwy	7.63	3.46	311.3
Large pick-up trucks, hwy	7.63	3.46	311.3
Pick-up trucks, city	7.25	3.64	329.6
Large pick-up trucks, city	6.37	4.14	373.5
Diesel light truck	6.37	4.14	374.0
Gasoline light truck	5.95	4.44	400.0
Large van, city	5.95	4.44	400.2
Diesel heavy truck	2.98	8.86	870.0
Diesel bus	2.85	9.26	1,034.6
Gasoline heavy truck	2.55	10.35	924.0

Discussion of life cycle results

The results of this analysis of transport modes shows that energy consumption and pollution are mostly caused by ground transportation. In addition the show that energy dissipated for moving road vehicles is much higher than the one for moving their payload ("Appendix 2"). Considering different kinds of vehicles further considerations can be performed. "Appendix 3" reports evaluation of life cycle energetic performances in terms of vehicle, payload and total, together with relative emissions.

It is clear that high payload vehicles perform unitary results much better than light payload ones. Those evaluations consider all life cycle energy and are based on the passenger loads or freight payloads used by all, considered by Radke. Several vehicles have been added to the analysis taking directly data by producers and by Strickland [31]. Radke and Strickland analyses have been improved by taking into consideration the amount of energy to produce vehicles, transportation infrastructure, and combustibles. Leisure vehicles have not been considered in this analysis because they have a marginal contribution to the global emissions.

Looking at global data it is possible to give the following interpretation of the result. Most people travel individually when possible. It has been also evidenced that that personal cars and trucks cause most of energy consumption and emissions. It is then fundamental to focus the attention on these systems verifying how they can be improved reducing their global impact without limiting their flexibility.

Table 4 World transport energy use by mode (2004)

Mode	Energy use (EJ)	Share (%)
Passenger transport	49.11	63.89
Car	34.20	44.49
Busses	4.76	6.19
Air	8.95	11.64
Other personal transports	1.20	1.56
Passenger and freight transport	1.19	1.55
Rail	1.19	1.55
Freight transport	26.57	34.56
Heavy freight trucks	12.48	16.24
Medium freight trucks	6.77	8.81
Shipping	7.32	9.52
Total	76.87	100.00

Table 5 Emission factors and LHV for common fuels

	Based on LHV kg CO_2/GJ	GJ/l
Gasoline/petrol	69.25	0.0344
Kerosene	71.45	0.0357
Jet fuel	70.72	0.0343
Aviation gasoline	69.11	0.0343
Diesel	74.01	0.0371
LPG	63.2	0.0249
Natural gas*	56.06	0.0350

* GJ/standard cubic meter

Table 6 Life cycle energy needs by circulating vehicles

Modes	Energy use (EJ)	Share (%)
Car	58.73	47.90
Other personal transports	1.84	1.50
Busses	8.33	6.79
Trucks	21.84	17.81
Rail	2.85	2.32
Air	14.45	11.79
Ship	14.58	11.89
Total	122.63	100.00

Ground transport in detail

Impact of ground transportation

The present study has evidenced the criticality in terms of emissions and energetic need of ground transport. A milestone study on future development of transport sector has been produced by EU Transport GHG: Routes to 2050 II project [32] founded by EU. This analysis takes into account

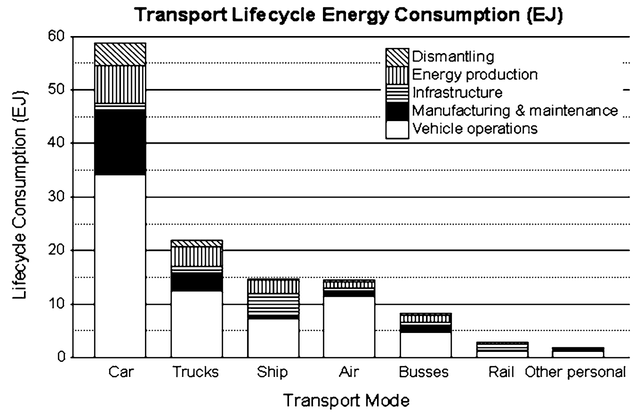


Fig. 8 Energetic requirements over the complete lifecycle of different transport modes

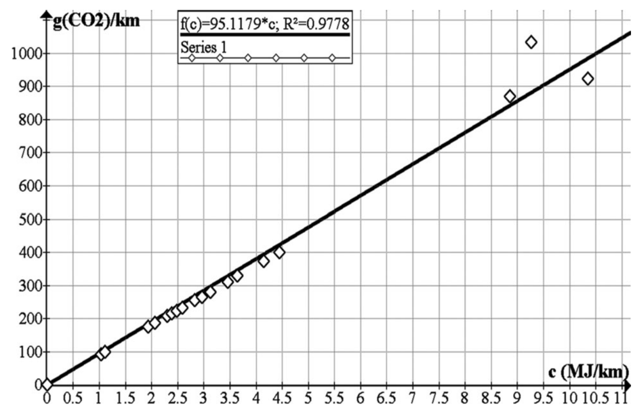


Fig. 9 Interpolation of CO_2 emissions for common motor vehicles (ref. Table 6)

2010 standard transport situation vs. expected standards up to 2050. A synthetic representation is reported in Fig. 10.

This paper takes into account a different method that is the analysis of different kinds of vehicles. Focusing on specific benefit, which could be possible by an effective optimization of internal combustion vehicles that are the most critical in terms of both energy efficiency and emissions.

It has been considered the full vehicle taking into consideration the energy losses for moving the vehicle. A schema of the power train indicating the different losses is provided in Fig. 11.

Losses depend on the regime in which the vehicle operates (i.e., urban, highway or composite). The valuation of power needs can be performed by Eq. (14)

$$\mathrm{Ex}_{\mathrm{vehicle}} = m_{\mathrm{tot}}\left(\mathrm{cg}v_{\mathrm{av}}t + \frac{1}{2}v_{\max}^2\right) + \frac{1}{2}C_{\mathrm{D}}A\rho_{\mathrm{air}}v_{\mathrm{av}}^3 t \quad (14)$$

It can be also possible to write the energy losses due to engine and to power train:

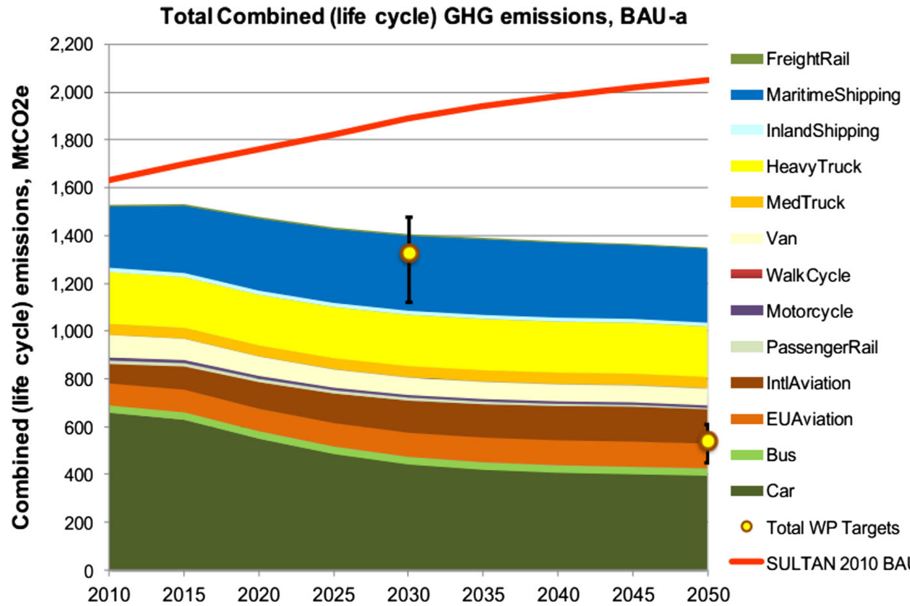


Fig. 10 Expected growth in GHG emissions by transport mode (EU Transport GHG: Routes to 2050 II project)

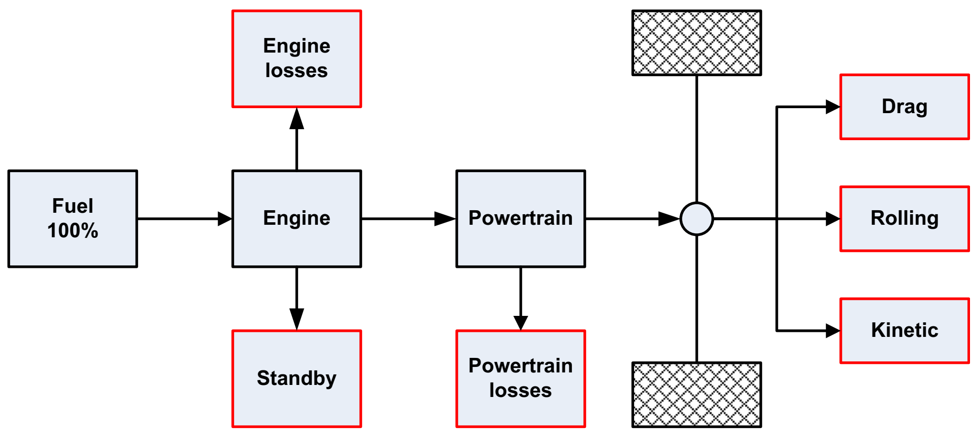


Fig. 11 Losses in a ground vehicle

$$\mathrm{Ex}_{\mathrm{vehicle}} = \mathrm{Ex}_{\mathrm{fuel}} - L_{\mathrm{engine}} - L_{\mathrm{stanby}} - L_{\mathrm{Powertrain}} \quad (15)$$

According to Eqs. (9, 10, 11) it is possible to perform a more sophisticated analysis about performances during operations of different vehicles in service conditions. In particular, cars, busses, and trucks have been considered, because they seem the less performing on an energetic and environmental point of view.

Preliminary calculations have been performed against Sovran and Bohn [33]. The results have been shown in Table 7. They show the full energetic value of the fuel and results appear perfectly in-line with Sovran and Bohn ones. Calculations have been performed for an average car, a truck, and a bus. A midsize car (1.3 ton), a heavy truck (40-ton full payload), and a bus (16 ton) have been considered as preliminary references.

Table 7 allows making further analysis about optimization of the vehicle as it is.

In particular, data for different vehicles have been calculated iteratively according to the above calculation method obtaining results that can be applied to most vehicles. They are reported in "Appendix 4". The same vehicles considered in Table 3 have been considered even if they are listed in a different order.

Optimization of ground vehicles

Actual vehicle market seems to have reached a high degree of technological maturity. Most of vehicles have reached a standardized configuration with only minor upgrades possible and mostly relating the user interface, and some minor safety issues and some minor reductions in terms of energy consumption.

Bejan [34–38] has defined constructal theory, which is an effective method to understand the elementary logic of natural evolution and to allow design of more efficient

Table 7 Reference values of energy consumption (%) in city, highway, and composite regimes

		Car			Truck			Bus		
		City (%)	H way (%)	Comp (%)	City (%)	H way (%)	Comp (%)	City (%)	H way (%)	Comp (%)
	Fuel Tank	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Engine	Engine	74.0	70.0	72.0	65.0	60.0	62.5	62.0	60.0	61.0
	Standby	6.0	0.5	3.3	5.0	1.0	3.0	8.0	1.5	4.8
	Output	20.0	30.5	25.3	30.0	39.0	34.5	30.0	38.5	34.3
Power train	Driveline	4.0	5.0	4.5	8.0	5.0	6.5	8.0	5.0	6.5
	Output	16.0	25.5	20.8	22.0	34.0	28.0	22.0	33.5	27.8
Operations	Rolling	4.4	9.0	6.3	4.4	11.1	7.7	4.4	12.1	8.3
	Drag	2.9	12.9	6.2	4.4	18.7	11.6	3.6	18.6	11.1
	Kinetic	8.7	3.7	8.2	11.0	2.6	6.8	14.0	2.8	8.4

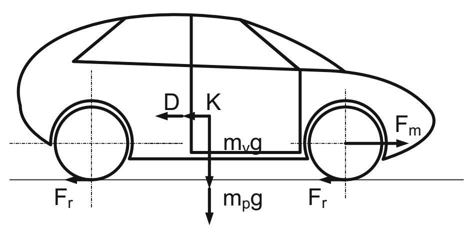


Fig. 12 Main forces acting on a ground vehicle during service

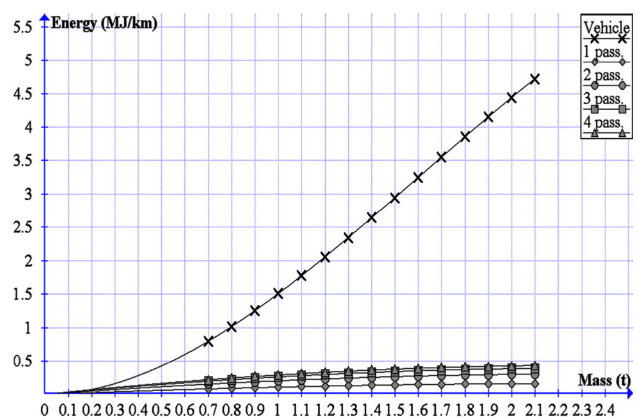


Fig. 13 Influence of the mass of a car on energy consumption and related consumption for passenger

mechanical and thermodynamic systems. In particular, Bejan [37, 38] has argued that constructal law governs the natural evolution and motion efficiency.

Dumas [39, 40] and Trancossi [41, 42] have defined a technical design methodology for transport vehicle obtaining in the case of airships an effective optimization up to energy complete self-sufficiency by photovoltaic energy. This activity demonstrated that constructal law could produce surprising results in the optimization of transport vehicles.

Constructal can thus define effective guidelines for the future development of transport vehicles allowing also the definition of breakthrough configurations, which can produce major advantages if compared to the technological maturity scenario, in which today transport industry is operating.

Recent improvements on vehicles have focused on several modules but have not produced some fundamental results, which could be fundamental to produce an effective energetic benefit.

Optimization proposed actually is general, even if it opens the possibility of performing an effective analysis at vehicle level. In particular, it has taken into account the results in "Appendix 2", Fig. 14, for such vehicles. They express the influence of payload for different kinds of vehicles, which have obtained by Eq. 12 and 13.

The calculation schema is reported in Fig. 12, where Fr is the friction with ground, D is the aerodynamic drag, K is the term due to acceleration to the maximum velocity, and Fm is the force produced to the engine that moves the car.

For the considered vehicles, it is possible to make specific evaluations. They have been reported in "Appendix 4", Table 10. A more detailed evaluation based on the energy dissipation modes during service has been presented in "Appendix 4", Table 11. Data have been interpolated in the case of cars, which are the most impacting transport mode. They allow evaluating the influence of the mass of the vehicle on the energy consumption. These data originated by an effective calculation have been plotted in Fig. 13.

These results will allow focusing in design vehicles more effectively in terms of operational efficiency. It is clear that considering Eq. (12) and (13) the most important factors, on which an effective optimization could focus on weight and aerodynamics. In particular, focusing on light vehicles weight appears to be the most important element optimize in ground vehicles, while aerodynamics is most important for heavy vehicles. In particular, these directions of optimization presents an effective divergence with the vehicle development in the last 30 years, which has produced an effective increase in terms of mass, contrasting with the necessity of reducing energetic impact.

Conclusions

This paper has presented an effective analysis of energetic needs of different transport modes, starting from the pioneering work of Gabrielli and von Karman.

This activity has produced an effective comparison between different transport modes. Looking at global impacts in terms of energy consumption and emissions of GHG gas has focused on the necessity of producing advancements on higher impact transport modes. It has then focused on the problem of reducing the energy consumption of ground vehicle stating the preliminary basis for a future and effective constructal optimization of ground vehicles.

This paper aims then to be continued by an effective and future activity focused on an effective methodology for optimizing ground and ICE vehicles, and overcoming the actual technological maturity scenario of this industrial sector.

It appears clear that industrial strategy in the direction though standardization of components is producing a general reduction in terms of an effective minimization of costs but is producing much reduced advantages on an energetic point of view because of the consequent increase of the weight of vehicles, which accompanies this new technological scenario.

Acknowledgments A special thanks to Prof. Adrian Bejan for encouraging the activity for this paper. In particular, the main objective of this paper is to verify the algorithms for future performing of an effective energetic comparison of the MAAT cruiser/feeder airship transport with commonly used transport modes. The present work has been performed as part of Project MAAT | Multibody Advanced Airship for Transport | with ref. 285602, supported by European Union through the 7th Framework Program.

Appendix 1

See Table 8.

Table 8 Energy balance

Service	Propulsion MJ/km	Manufacturing and maintenance MJ/km	Infrastructure MJ/km	Energy production MJ/km	Dismantling MJ/km	Total MJ/km
Human walking	0.208443	0	0	0	0	0.208443
Airliner, 747-200-CCW Freight	287.1104	13.54294	18.96012	28.44018	4.74003	352.7937
Airliner, 747-8, 10 lb/ft3 Freight	448.4198	21.15188	29.61263	44.41894	7.403157	551.0064
Boeing 777-300ER	390.8451	18.43609	25.81053	38.71579	6.452632	480.2602
Boeing 737-800	144.4899	6.815559	9.541783	14.31267	2.385446	177.5453
Airbus A320	165.2058	7.792726	10.90982	16.36472	2.727454	203.0005
Boeing 767-400ER	273.1941	12.88651	18.04112	27.06168	4.51028	335.6937
Boeing 747-8	483.3383	22.79897	31.91856	47.87785	7.979641	593.9133
Airbus A340-600	439.7822	20.74445	29.04222	43.56334	7.260556	540.3928
Airbus A330-200	350.1383	16.51596	23.12234	34.68351	5.780586	430.2407
Concorde	473	43.43878	67.57143	43.43878	15.20357	642.6526
Bombardier Q300 (DHC-8-300)	63.4	2.990566	4.186792	6.280189	1.046698	77.90425
Eclipse 500	7.11	0.491758	0.245879	0.696657	0.172115	8.716409
Diamond DA-42 Twin Star (economy)	4.22	0.291873	0.145937	0.413487	0.102156	5.173452
Diamond DA-42 twin Star (80 % power)	5.26	0.363804	0.181902	0.515389	0.127331	6.448427
Columbia 400 turbocharged 310 hp	5.98	0.413602	0.206801	0.585937	0.144761	7.331101
Columbia 400 turbocharged 310 hp	7.49	0.51804	0.25902	0.73389	0.181314	9.182265
Beechcraft duchess	7.94	0.549164	0.274582	0.777983	0.192207	9.733937

Table 8 continued

Service	Propulsion MJ/km	Manufacturing and maintenance MJ/km	Infrastructure MJ/km	Energy production MJ/km	Dismantling MJ/km	Total MJ/km
Piper Navajo	14.7	1.016715	0.508357	1.440346	0.35585	18.02127
Beechcraft King Air B-100	24.5	1.694524	0.847262	2.400576	0.593084	30.03545
Cessna 172	5.97	0.412911	0.206455	0.584957	0.144519	7.318841
Airship, 1936	663.461	31.29533	43.81346	65.72019	10.95337	815.2434
Zeppelin NT	16.76395	0.790752	1.107053	1.66058	0.276763	20.5991
Airship GoodYear 1969	39.7	1.872642	2.621698	3.932547	0.655425	48.78231
Bicycle, touring	0.055509	0.002618	0.003666	0.005499	0.000916	0.068208
Bicycle, racing	0.080786	0.003811	0.005335	0.008002	0.001334	0.099268
Bicycle, touring	0.084872	0.004003	0.005605	0.008407	0.001401	0.104289
Bicycle, touring	0.126038	0.005945	0.008323	0.012485	0.002081	0.154872
Bicycle, electric cyclemotor	0.325464	0.015352	0.021493	0.032239	0.005373	0.399922
1982 New flyer trolley bus	9.84	2.589474	1.035789	2.848421	0.906316	17.22
Bicycle, electric cyclemotor	1.675	0.079009	0.110613	0.16592	0.027653	2.058196
2005 (and later) new flyer low floor trolley bus	7.7	0.363208	0.508491	0.762736	0.127123	9.461557
MCI 102DL3 diesel bus in commuter service	15	0.707547	0.990566	1.485849	0.247642	18.4316
MCI 102DL3 CNG/diesel bus	18.6	0.877358	1.228302	1.842453	0.307075	22.85519
Diesel bus in local and express service	24.3	1.146226	1.604717	2.407075	0.401179	29.8592
Smart fortwo cdi (0.8 L diesel, 40 hp, 6-speed)	1.52	0.071698	0.100377	0.150566	0.025094	1.867736
VW Golf TDI (1.9L diesel, automatic)	1.9	0.089623	0.125472	0.188208	0.031368	2.33467
Smart fortwo cdi (0.8 L diesel, 40 hp, 6-speed)	1.44	0.067925	0.095094	0.142642	0.023774	1.769434
Corporate car 1990	2.73	0.128774	0.180283	0.270425	0.045071	3.354552
Porsche boxster S	3.42	0.161321	0.225849	0.338774	0.056462	4.202406
Ford Explorer (4.6L V8)	3.49	1.146124	0.103254	0.826036	0.401143	5.966558
Corporate car average fuel 1978	4.18	0.19717	0.276038	0.414057	0.069009	5.136274
Porsche carrera GT	7.27	2.387485	0.215089	1.72071	0.83562	12.4289
Tesla roadster	0.46	0.138754	0.015082	0.043738	0.048564	0.706138
Toyota prius	1.58	0.548163	0.06449	0.328898	0.191857	2.713408
Sikorsky S-76C ++ twin turbine helicopter	45.5	2.146226	3.004717	4.507075	0.751179	55.9092
Bell longranger IV	25.5	1.20283	1.683962	2.525943	0.420991	31.33373
Griffon 2000TD hovercraft	22.5	1.556196	0.778098	2.204611	0.544669	27.58357
Griffon 8000TD hovercraft	101	11.88235	101	23.76471	4.158824	241.8059
Siemens SD160 (42 ton 24.82 m LRV	11.6	0.84878	6.601626	3.960976	0.297073	23.30846
Siemens combino 28 ton 27 m LRV	5.51	0.403171	3.135772	1.881463	0.14111	11.07152
Siemens Combino 28 ton 27 m LRV	6.62	0.48439	3.76748	2.260488	0.169537	13.30189
Skytrain vancouver	8.69	0.635854	4.945528	2.967317	0.222549	17.46125
London underground	10.2	0.746341	5.804878	3.482927	0.26122	20.49537
Suzuki GS500(motorcycle with 0.5 L gasoline engine)	1.25	0.433673	0.05102	0.260204	0.151786	2.146684
Honda gold wing(motorcycle with 1.8 L 6-cylinder)	2.3	0.797959	0.093878	0.478776	0.279286	3.949898

Table 8 continued

Service	Propulsion MJ/km	Manufacturing and maintenance MJ/km	Infrastructure MJ/km	Energy production MJ/km	Dismantling MJ/km	Total MJ/km
Wasp scooter	1	0.346939	0.040816	0.208163	0.121429	1.717347
Tanker, VLCC Class	12029.94	1415.287	12029.94	2830.574	495.3504	28801.09
Tanker, ULCC Class	24812.6	2919.13	24812.6	5,838.259	1,021.695	59,404.29
Cunard queen mary 2 ocean liner	10000	1176.471	10000	2352.941	411.7647	23941.18
BC Ferries spirit class car ferries	3063	360.3529	3063	720.7059	126.1235	7333.182
SeaBus	302	35.52941	302	71.05882	12.43529	723.0235
Train, Avg Freight	70	8.235294	70	16.47059	2.882353	167.5882
Train, dense freight (Coal)	74	8.705882	74	17.41176	3.047059	177.1647
TGV Duplex trainset (300 km/h bi-level, seats 545)	64.8	7.623529	64.8	15.24706	2.668235	155.1388
TGV Atlantique trainset (300 km/h, seats 485)	47.52	5.590588	47.52	11.18118	1.956706	113.7685
AVE 300 km/h trainset on Madrid-Seville line	57.17	6.725882	57.17	13.45176	2.354059	136.8717
TGV Paris Sud-Est trainset (TGV, 270 km/h, seats 368)	63.72	7.496471	63.72	14.99294	2.623765	152.5532
ICE trainset (280 km/h, seats 645,12 coaches)	86.72	10.20235	86.72	20.40471	3.570824	207.6179
Colorado railcar	79.8	5.839024	45.41463	27.24878	2.043659	160.3461
Swedish railways X2000 200 km/h tilting train	42.7	5.023529	42.7	10.04706	1.758235	102.2288
Danish railways Copenhagen-Malmö	24.1	2.835294	24.1	5.670588	0.992353	57.69824
Swedish railways regina electric multiple-unit train	21.3	2.505882	21.3	5.011765	0.877059	50.99471
Colorado railcar	34.9	4.105882	34.9	8.211765	1.437059	83.55471
Swedish railwaysregina electric multiple-unit train	22.5	2.647059	22.5	5.294118	0.926471	53.86765
Truck, avg intercity	45.52	5.355294	45.52	10.71059	1.874353	108.9802

Appendix 2

See Figs. 14 and 15.

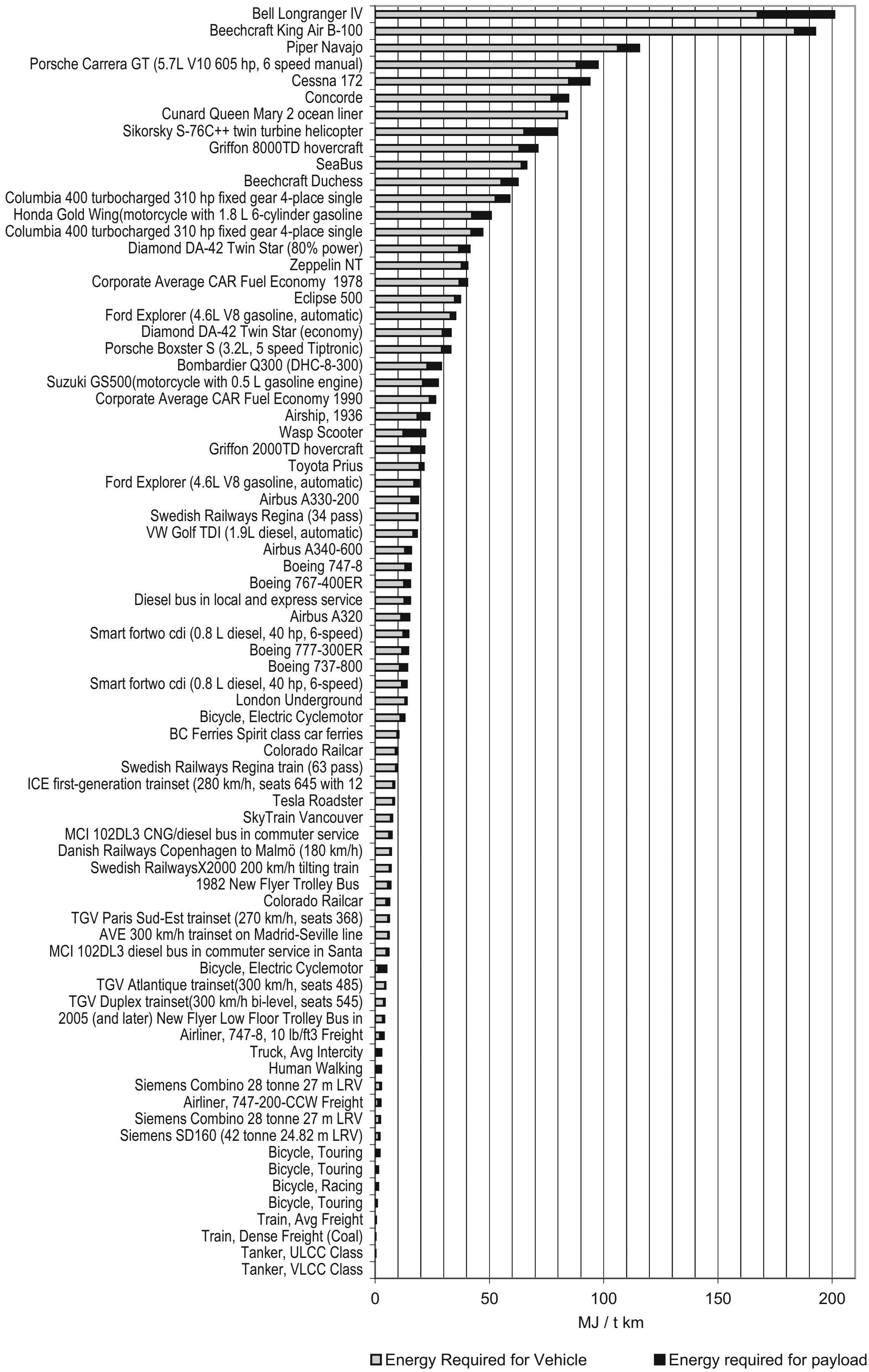


Fig. 14 Cumulative evaluation of energy dissipation for vehicle movement and for freight movement (MJ/t km)

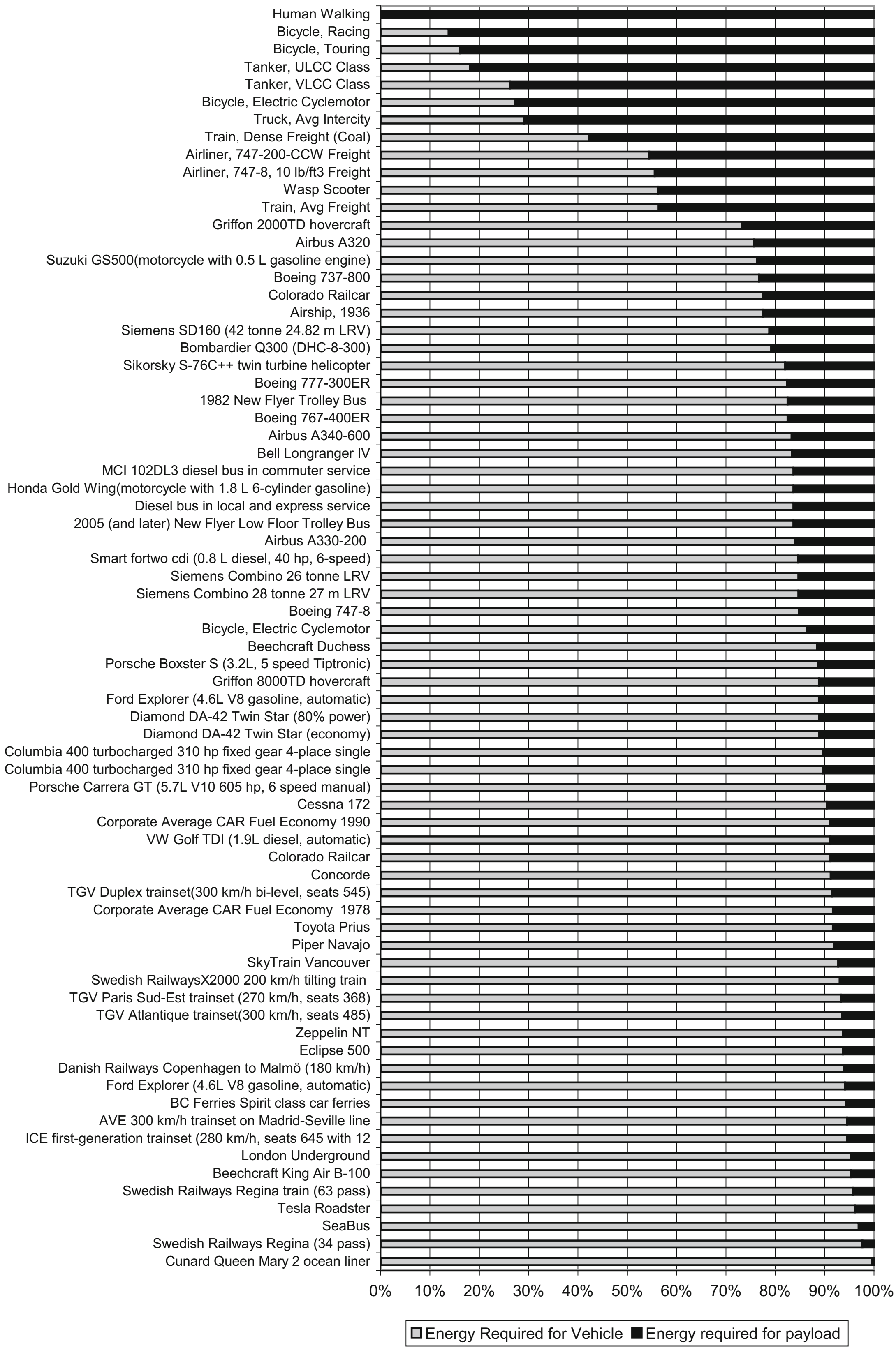


Fig. 15 Evaluation of energy dissipation for vehicle movement and for freight movement (%)

Appendix 3

See Table 9.

Table 9 Energy consumption for unit of load and emissions

Service	Energy consumption	Emissions	Mass			Energy consumptionper unit of load			Emissions per unit of load		
	Total MJ/km	Total Kg(CO_2)/km	Vehicle t	Payload t	Total T	Vehicle MJ/t km	Payload MJ/t km	Total MJ/t km	Vehicle g(CO_2)/t km	Payload g(CO_2)/t km	Total g(CO_2)/t km
Tanker, VLCC class	28801.086	2739.499	76000	214500	290500	0.035	0.099	0.134	0.003	0.009	0.013
Tanker, ULCC class	59404.287	5650.411	76000	343200	419200	0.031	0.142	0.173	0.003	0.013	0.016
Train, Dense freight (Coal)	177.165	16.852	550.00	750	1300	0.100	0.136	0.236	0.010	0.013	0.022
Train, avg freight	167.588	15.941	550.00	427	977.5	0.221	0.171	0.392	0.021	0.016	0.037
Bicycle, touring	0.068	0.006	0.02	0.08	0.10	0.178	0.696	0.874	0.017	0.066	0.083
Bicycle, racing	0.099	0.009	0.01	0.08	0.09	0.183	1.141	1.324	0.017	0.109	0.126
Bicycle, touring	0.104	0.010	0.02	0.08	0.09	0.216	1.121	1.337	0.021	0.107	0.127
Bicycle, touring	0.155	0.015	0.02	0.08	0.09	0.320	1.665	1.986	0.030	0.158	0.189
Siemens SD160 (42 ton 24.82 m LRV)	23.308	2.217	42.00	11.31	53.31	1.62	0.44	2.06	0.154	0.042	0.196
Siemens Combino 28 ton 27 m LRV	11.072	1.053	28.00	5.07	33.07	1.85	0.33	2.18	0.176	0.032	0.208
Airliner, 747-200-CCW Freight	352.794	33.557	172.00	144	316.00	1.33	1.12	2.45	0.127	0.106	0.233
Siemens Combino 28 ton 27 m LRV	13.302	1.265	28.00	5.07	33.07	2.22	0.40	2.62	0.211	0.038	0.250
Human walking	0.208	0.020	0.00	0.08	0.08	0.00	2.67	2.67	0.000	0.254	0.254
Truck, avg intercity	108.980	10.366	16.00	39.00	55.00	0.81	1.98	2.79	0.077	0.188	0.266
Airliner, 747-8, 10 lb/ft3 freight	551.006	52.411	180.00	144	324.00	2.13	1.70	3.83	0.202	0.162	0.364
2005 New flyer low floor trolley bus	9.462	0.900	12.00	2.34	14.34	3.38	0.66	4.04	0.322	0.063	0.385
TGV Duplex trainset(300 km/h bi-level, seats 545)	155.139	14.756	400.00	37.06	437.06	3.83	0.35	4.19	0.364	0.034	0.398
TGV Atlantique trainset(300 km/h, seats 485)	113.768	10.821	360.00	24.74	384.74	4.30	0.30	4.60	0.409	0.028	0.437
Bicycle, electric cyclemotor	0.400	0.038	0.03	0.08	0.11	1.36	3.64	5.00	0.130	0.346	0.475
MCI 102DL3 diesel bus in commuter service	18.432	1.753	16.00	3.12	19.12	4.94	0.96	5.91	0.470	0.092	0.562
AVE 300 km/h trainset on Madrid-Seville line	136.872	13.019	392.00	22.61	414.61	5.72	0.33	6.05	0.544	0.031	0.576
TGV Paris Sud-Est trainset (270 km/h, seats 368)	152.553	14.511	350.00	24.99	374.99	5.70	0.41	6.10	0.542	0.039	0.581
Colorado railcar	160.346	15.252	87.50	25.50	113.00	4.87	1.42	6.29	0.463	0.135	0.598
1982 New flyer trolley bus	17.220	1.638	12.00	2.55	14.55	5.57	1.18	6.75	0.530	0.113	0.642
Swedish railways X2000 200 km/h tilting train	102.229	9.724	200.00	14.96	214.96	6.36	0.48	6.83	0.605	0.045	0.650
Danish railways (180 km/h)	57.698	5.488	126.00	8.25	134.25	6.57	0.43	7.00	0.625	0.041	0.666
MCI 102DL3 CNG/diesel bus in commuter service	22.855	2.174	16.00	3.12	19.12	6.13	1.20	7.33	0.583	0.114	0.697
SkyTrain vancouver	17.461	1.661	30.00	2.34	32.34	6.92	0.54	7.46	0.658	0.051	0.710

Table 9 continued

Service	Energy consumption	Emissions	Mass			Energy consumptionper unit of load			Emissions per unit of load		
	Total MJ/km	Total Kg(CO_2)/km	Vehicle t	Payload t	Total T	Vehicle MJ/t km	Payload MJ/t km	Total MJ/t km	Vehicle g(CO_2)/t km	Payload g(CO_2)/ t km	Total g(CO_2)/ t km
Tesla roadster	0.706	0.067	2.10	0.09	2.19	7.98	0.32	8.31	0.759	0.031	0.790
ICE trainset (280 km/h, seats 645, 12 coaches)	207.618	19.748	430.00	24.65	454.65	7.97	0.46	8.42	0.758	0.043	0.801
Swedish railways Regina train (63 pass)	50.995	4.851	120.00	5.36	125.36	9.12	0.41	9.52	0.867	0.039	0.906
Colorado railcar	83.555	7.948	87.50	8.50	96.00	8.96	0.87	9.83	0.852	0.083	0.935
BC ferries spirit class car ferries	7333.182	697.517	11681	712.50	12393.5	9.70	0.59	10.29	0.923	0.056	0.979
Bicycle, electric cyclemotor	2.058	0.196	1.02	0.16	1.18	11.11	1.75	12.86	1.057	0.167	1.224
London underground	20.495	1.949	30.00	1.48	31.48	13.18	0.65	13.83	1.254	0.062	1.315
Smart fortwo cdi (0.8 L diesel, 40 hp, 6-speed)	1.769	0.168	0.70	0.13	0.83	11.74	2.14	13.88	1.117	0.203	1.320
Boeing 737-800	177.545	16.888	41.40	12.60	54.00	10.80	3.29	14.09	1.028	0.313	1.340
Boeing 777-300ER	480.260	45.681	155.00	33.25	188.25	11.89	2.55	14.44	1.131	0.243	1.374
Airbus A320	203.001	19.309	42.00	13.50	55.50	12.39	2.26	14.65	1.082	0.348	1.430
Diesel bus in local and express service	29.859	2.840	10.00	1.95	11.95	11.38	3.66	15.04	1.219	0.238	1.456
Boeing 767-400ER	335.694	31.930	103.00	21.85	124.85	12.67	2.69	15.36	1.206	0.256	1.461
Boeing 747-8	593.913	56.492	211.00	38.00	249.00	13.24	2.39	15.63	1.260	0.227	1.487
Airbus A340-600	540.393	51.401	170.40	34.20	204.60	13.16	2.64	15.80	1.252	0.251	1.503
VW Golf TDI	2.335	0.222	1.30	0.13	1.43	16.68	1.64	18.31	1.586	0.156	1.742
(1.9L diesel, automatic)											
Swedish railways regina (34 pass)	53.868	5.124	120.00	2.89	122.89	18.20	0.44	18.64	1.731	0.042	1.773
Airbus A330-200	430.241	40.924	120.00	22.80	142.80	15.86	3.01	18.87	1.508	0.287	1.795
Ford explorer (4.6L V8, automatic)	6.562	0.624	2.70	0.34	3.04	17.14	2.16	19.30	1.630	0.205	1.836
Toyota prius	2.713	0.258	1.40	0.13	1.53	19.51	1.78	21.28	1.855	0.169	2.024
Griffon 2000TD hovercraft	27.584	2.624	3.50	1.28	4.78	15.86	5.78	21.63	1.508	0.549	2.058
Wasp scooter	1.717	0.163	0.10	0.08	0.18	12.37	9.65	22.02	1.177	0.918	2.094
Airship, 1936	815.243	77.544	118.00	34.20	152.20	18.48	5.36	23.84	1.758	0.509	2.267
Corporate average Car fuel economy 1990	3.355	0.319	1.30	0.13	1.43	23.96	2.35	26.31	2.279	0.224	2.503
Suzuki GS500	2.147	0.204	0.25	0.08	0.33	20.98	6.54	27.52	1.995	0.623	2.618
(motorcycle 0.5 L)											
Bombardier Q300 (DHC-8-300)	77.904	7.410	10.25	2.70	12.95	22.84	6.02	28.85	2.172	0.572	2.744
Porsche Boxster S (3.2L, 5 speed Tiptronic)	4.202	0.400	1.00	0.13	1.13	29.23	3.73	32.96	2.781	0.355	3.135
Diamond DA-42 twin star (economy)	5.173	0.492	1.25	0.16	1.41	29.49	3.68	33.16	2.805	0.350	3.154
Ford Explorer (4.6L V8 gasoline, automatic)	5.967	0.568	2.70	0.17	2.87	33.02	2.08	35.10	3.141	0.198	3.338
Eclipse 500	8.716	0.829	3.50	0.23	3.73	34.92	2.33	37.25	3.321	0.222	3.543
Corporate average car fuel economy 1978	5.136	0.489	1.40	0.13	1.53	36.92	3.36	40.28	3.512	0.320	3.832
Zeppelin NT	20.599	1.959	7.60	0.51	8.11	37.85	2.54	40.39	3.600	0.242	3.842
Diamond DA-42 twin star (80 % power)	6.448	0.613	1.25	0.16	1.41	36.75	4.59	41.34	3.496	0.436	3.932
Columbia 400 turbocharged 310 hp	7.331	0.697	1.34	0.16	1.50	42.09	4.90	46.99	4.004	0.466	4.470

Table 9 continued

Service	Energy consumption	Emissions	Mass			Energy consumptionper unit of load			Emissions per unit of load		
	Total MJ/km	Total Kg(CO_2)/km	Vehicle t	Payload t	Total T	Vehicle MJ/t km	Payload MJ/t km	Total MJ/t km	Vehicle g(CO_2)/t km	Payload g(CO_2)/ t km	Total g(CO_2)/ t km
Honda Goldwing (motorcycle 1.8 L)	3.950	0.376	0.40	0.08	0.48	42.38	8.26	50.64	4.031	0.786	4.817
Beechcraft Duchess	9.734	0.926	1.20	0.16	1.36	52.72	6.14	58.86	5.252	0.683	5.935
SeaBus	723.024	68.772	341.00	10.92	351.92	55.22	7.18	62.40	6.102	0.195	6.298
Griffon 8000TD hovercraft	241.806	23.000	27.00	3.40	30.40	64.16	2.05	66.21	6.008	0.757	6.765
Sikorsky S-76C ++ twin turbine helicopter	55.909	5.318	3.20	0.70	3.90	63.17	7.95	71.12	6.213	1.363	7.575
Cunard Queen Mary 2 ocean liner	23941.176	2277.234	76000	285	76285	65.31	14.33	79.64	7.960	0.030	7.990
Concorde	642.653	61.128	78.70	7.60	86.30	83.69	0.31	84.00	7.335	0.708	8.043
Cessna 172	7.319	0.696	0.74	0.08	0.81	77.11	7.45	84.56	8.070	0.855	8.925
Porsche Carrera GT (5.7L V10 605 hp)	12.429	1.182	1.20	0.13	1.33	84.84	8.99	93.83	8.382	0.891	9.272
Piper Navajo	18.021	1.714	1.78	0.16	1.94	88.12	9.36	97.48	10.104	0.884	10.988
Beechcraft KingAir B-100	30.035	2.857	3.21	0.16	3.37	106.22	9.30	115.52	17.465	0.849	18.314
Bell Longranger IV	31.334	2.980	0.78	0.16	0.94	183.61	8.92	192.53	15.921	3.184	19.105

Appendix 4

See Tables 10 and 11.

Table 10 Energy consumption repartition for different kinds of vehicles

Vehicle characteristics Vehicle type		MJ/km	Engine MJ/km	Standby MJ/km	Powertrain MJ/km	Rolling MJ/km	Drag MJ/km	Kinetic MJ/km	CO_2 emitted g CO_2/km
Light motorcycle	comb	1.04	0.74	0.03	0.05	0.06	0.06	0.08	93.00
New small gas/electric hybrid	comb	1.12	0.80	0.04	0.05	0.07	0.07	0.09	100.10
Small gas auto	hwy	1.95	1.35	0.01	0.10	0.17	0.25	0.07	175.10
	city	2.38	1.76	0.14	0.10	0.10	0.07	0.21	215.50
	comb	2.17	1.56	0.08	0.10	0.14	0.16	0.14	195.30
Medium gas auto	hwy	2.08	1.44	0.01	0.10	0.19	0.27	0.08	186.80
	city	2.82	2.09	0.17	0.11	0.12	0.08	0.25	254.70
	comb	2.45	1.76	0.09	0.11	0.15	0.17	0.16	220.75
Medium station wagon	hwy	2.30	1.70	0.14	0.09	0.10	0.07	0.20	207.50
	city	3.15	2.18	0.02	0.16	0.28	0.40	0.12	280.10
	comb	2.73	1.94	0.08	0.12	0.19	0.23	0.16	243.80
Large gas automobile	hwy	2.41	1.61	0.09	0.11	0.19	0.27	0.14	224.10
	city	3.42	2.40	0.19	0.21	0.15	0.13	0.34	311.30
	comb	2.92	2.01	0.14	0.16	0.17	0.20	0.24	267.70
Diesel automobile	hwy	2.21	1.53	0.01	0.11	0.20	0.28	0.08	197.17
	city	2.99	2.22	0.18	0.12	0.13	0.09	0.26	268.83
	comb	2.71	1.92	0.11	0.13	0.17	0.19	0.19	233.00
Mini van	hwy	12.52	2.07	0.26	2.19	3.05	3.87	1.08	233.50
	city	3.46	2.56	0.21	0.14	0.15	0.10	0.30	318.38
	comb	7.99	2.31	0.23	1.16	1.60	1.99	0.69	275.94
Mid size. pick-up trucks	hwy	2.85	1.97	0.01	0.14	0.25	0.36	0.10	254.70
	city	3.77	2.79	0.23	0.15	0.17	0.11	0.33	346.65
	comb	3.31	2.38	0.12	0.15	0.21	0.24	0.22	300.67
Large LPG automobile	hwy	2.40	1.61	0.09	0.11	0.19	0.27	0.14	222.68
	city	3.45	2.55	0.21	0.14	0.15	0.10	0.30	309.32
	comb	2.91	2.00	0.14	0.16	0.17	0.20	0.24	266.00
Large van	hwy	3.50	2.42	0.02	0.17	0.31	0.45	0.13	311.30
	city	4.62	3.42	0.28	0.18	0.20	0.13	0.40	425.32
	comb	4.06	2.92	0.15	0.18	0.26	0.29	0.27	368.31
Large pick-up truck	hwy	3.68	2.55	0.02	0.18	0.33	0.47	0.13	329.00
	city	4.14	3.06	0.25	0.17	0.18	0.12	0.36	329.60
	comb	3.91	2.81	0.13	0.17	0.25	0.29	0.25	329.30
Diesel light truck	hwy	3.27	2.27	0.02	0.16	0.29	0.42	0.12	291.29
	city	4.41	3.26	0.26	0.18	0.19	0.13	0.38	405.43
	comb	4.16	2.99	0.15	0.18	0.26	0.30	0.27	377.32
Gasoline light truck	hwy	3.51	2.43	0.02	0.17	0.31	0.45	0.13	313.84
	city	4.73	3.50	0.28	0.19	0.21	0.14	0.41	376.20
	comb	4.46	3.20	0.15	0.20	0.29	0.34	0.28	375.86
Diesel heavy truck	hwy	6.82	4.16	0.07	0.35	0.77	1.30	0.18	680.37
	city	9.22	6.13	0.47	0.75	0.41	0.41	1.04	925.91
	comb	8.02	5.14	0.27	0.55	0.59	0.86	0.61	870.00
Diesel bus	hwy	6.68	4.01	0.10	0.33	0.81	1.24	0.19	706.91
	city	9.10	5.64	0.73	0.73	0.40	0.33	1.27	1034.60
	comb	7.89	4.83	0.41	0.53	0.60	0.79	0.73	870.75
Gasoline heavy truck	hwy	7.96	4.86	0.08	0.40	0.90	1.51	0.21	722.60
	city	10.77	7.16	0.55	0.88	0.48	0.48	1.21	983.38
	comb	10.12	6.73	0.52	0.83	0.46	0.46	1.14	924.00

Table 11 Energy consumption repartition for different kinds of vehicles

Vehicle characteristics		Vehicle mass	Payload	Total Mass	Total data					Vehicle				Payload		
					Total energy	Rolling	Drag	Kinetic	Total	Rolling	Drag	Kinetic	Total	Rolling	Kinetic	Total
Vehicle type		T	T	t	MJ/t km	MJ/t km	MJ/t km	MJ/t km		MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km
Light motorcycle	comb	0.120	0.080	0.200	5.176	0.324	0.319	0.422	1.0661	0.1947	0.3193	0.2534	0.7674	0.1298	0.1689	0.299
New small gas/electric hybrid	comb	1.350	0.240	1.590	0.702	0.044	0.043	0.057	0.1445	0.0373	0.0433	0.0486	0.1292	0.0066	0.0086	0.015
Small gas auto	hwy	1.100	0.240	1.340	1.456	0.130	0.186	0.053	0.3687	0.1064	0.1858	0.0437	0.3360	0.0232	0.0095	0.033
	city	1.100	0.240	1.340	1.776	0.078	0.052	0.155	0.2842	0.0642	0.0515	0.1268	0.2425	0.0140	0.0277	0.042
	comb	1.100	0.240	1.340	1.616	0.104	0.119	0.104	0.3264	0.0853	0.1187	0.0853	0.2892	0.0186	0.0186	0.037
Medium gas auto	hwy	1.400	0.240	1.640	1.270	0.113	0.162	0.046	0.3216	0.0965	0.1620	0.0397	0.2982	0.0165	0.0068	0.023
	city	1.400	0.240	1.640	1.720	0.076	0.050	0.150	0.2751	0.0646	0.0499	0.1277	0.2422	0.0111	0.0219	0.033
	comb	1.400	0.240	1.640	1.495	0.094	0.106	0.098	0.2983	0.0805	0.1060	0.0837	0.2702	0.0138	0.0143	0.028
Medium station wagon	hwy	1.600	0.240	1.840	1.250	0.055	0.036	0.109	0.2000	0.0478	0.0363	0.0946	0.1786	0.0072	0.0142	0.021
	city	1.600	0.240	1.840	1.714	0.153	0.219	0.063	0.4341	0.1327	0.2187	0.0546	0.4060	0.0199	0.0082	0.028
	comb	1.600	0.240	1.840	1.482	0.104	0.127	0.086	0.3170	0.0903	0.1275	0.0746	0.2923	0.0135	0.0112	0.025
Large gas automobile	hwy	2.100	0.240	2.340	1.030	0.082	0.114	0.060	0.2565	0.0737	0.1145	0.0537	0.2419	0.0084	0.0061	0.015
	city	2.100	0.240	2.340	1.462	0.065	0.054	0.146	0.2647	0.0584	0.0540	0.1307	0.2431	0.0067	0.0149	0.022
	comb	2.100	0.240	2.340	1.246	0.074	0.084	0.103	0.2606	0.0660	0.0842	0.0922	0.2425	0.0075	0.0105	0.018
Diesel automobile	hwy	1.600	0.240	1.840	1.201	0.107	0.153	0.044	0.3042	0.0930	0.1533	0.0382	0.2845	0.0140	0.0057	0.020
	city	1.600	0.240	1.840	1.627	0.072	0.047	0.142	0.2603	0.0622	0.0472	0.1231	0.2325	0.0093	0.0185	0.028
	comb	1.600	0.240	1.840	1.471	0.091	0.103	0.105	0.2986	0.0789	0.1025	0.0916	0.2731	0.0118	0.0137	0.026
Mini van	hwy	2.200	0.240	2.440	5.130	1.252	1.587	0.443	3.2816	1.1285	1.5872	0.3993	3.1149	0.1231	0.0436	0.167
	city	2.200	0.240	2.440	1.418	0.062	0.041	0.123	0.2269	0.0563	0.0411	0.1112	0.2086	0.0061	0.0121	0.018
	comb	2.200	0.240	2.440	3.274	0.657	0.814	0.283	1.7542	0.5924	0.8141	0.2553	1.6618	0.0646	0.0278	0.092
Mid size. pick-up trucks	hwy	2.300	2.000	4.300	0.663	0.059	0.085	0.024	0.1679	0.0316	0.0846	0.0130	0.1291	0.0275	0.0113	0.039
	city	2.300	2.000	4.300	0.876	0.039	0.025	0.076	0.1402	0.0206	0.0254	0.0408	0.0868	0.0179	0.0355	0.053
	comb	2.300	2.000	4.300	0.770	0.049	0.055	0.050	0.1540	0.0261	0.0550	0.0269	0.1080	0.0227	0.0234	0.046
Large LPG automobile	hwy	2.100	0.240	2.340	1.027	0.082	0.114	0.060	0.2556	0.0735	0.1141	0.0536	0.2411	0.0084	0.0061	0.015
	city	2.100	0.240	2.340	1.474	0.065	0.043	0.128	0.2358	0.0582	0.0427	0.1151	0.2160	0.0067	0.0131	0.020
	comb	2.100	0.240	2.340	1.242	0.073	0.084	0.102	0.2597	0.0658	0.0839	0.0919	0.2417	0.0075	0.0105	0.018
Large van, hwy	hwy	3.000	0.500	3.500	0.999	0.089	0.128	0.037	0.2531	0.0763	0.1275	0.0314	0.2351	0.0127	0.0052	0.018
	city	3.000	0.500	3.500	1.321	0.058	0.038	0.115	0.2113	0.0498	0.0383	0.0985	0.1866	0.0083	0.0164	0.025
	comb	3.000	0.500	3.500	1.160	0.074	0.083	0.076	0.2322	0.0630	0.0829	0.0649	0.2109	0.0105	0.0108	0.021

Table 11 continued

Vehicle characteristics		Vehicle mass	Payload	Total Mass	Total data					Vehicle				Payload		
					Total energy	Rolling	Drag	Kinetic	Total	Rolling	Drag	Kinetic	Total	Rolling	Kinetic	Total
Vehicle type		T	T	t	MJ/t km	MJ/t km	MJ/t km	MJ/t km		MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km	MJ/t km
Large pick-up truck	hwy	3.000	2.200	5.200	0.708	0.063	0.090	0.026	0.1792	0.0363	0.0903	0.0149	0.1416	0.0267	0.0110	0.038
	city	3.000	2.200	5.200	0.796	0.035	0.023	0.069	0.1274	0.0202	0.0231	0.0400	0.0833	0.0148	0.0293	0.044
	comb	3.000	2.200	5.200	0.752	0.049	0.057	0.048	0.1533	0.0283	0.0567	0.0275	0.1124	0.0207	0.0201	0.041
Diesel light truck	hwy	2.300	2.000	4.300	0.761	0.068	0.097	0.028	0.1928	0.0362	0.0971	0.0149	0.1483	0.0315	0.0130	0.044
	city	2.300	2.000	4.300	1.025	0.045	0.030	0.089	0.1639	0.0241	0.0297	0.0477	0.1015	0.0210	0.0415	0.062
	comb	2.300	2.000	4.300	0.967	0.061	0.069	0.063	0.1936	0.0328	0.0691	0.0338	0.1357	0.0285	0.0294	0.058
Gasoline light truck	hwy	2.300	3.100	5.400	0.650	0.058	0.083	0.024	0.1646	0.0246	0.0829	0.0101	0.1177	0.0332	0.0137	0.047
	city	2.300	3.100	5.400	0.875	0.039	0.025	0.076	0.1400	0.0164	0.0254	0.0324	0.0742	0.0221	0.0437	0.066
	comb	2.300	3.100	5.400	0.826	0.054	0.062	0.052	0.1685	0.0229	0.0623	0.0223	0.1075	0.0309	0.0300	0.061
Diesel bus	hwy	18.000	2.400	20.400	0.328	0.040	0.061	0.009	0.1098	0.0350	0.0610	0.0081	0.1040	0.0047	0.0011	0.006
	city	18.000	2.400	20.400	0.446	0.020	0.016	0.062	0.0981	0.0173	0.0161	0.0551	0.0885	0.0023	0.0073	0.010
	comb	18.000	2.400	20.400	0.387	0.030	0.039	0.036	0.1039	0.0261	0.0385	0.0316	0.0962	0.0035	0.0042	0.008
Diesel heavy truck	hwy	16.000	40.000	56.000	0.122	0.014	0.023	0.003	0.0401	0.0039	0.0231	0.0009	0.0280	0.0098	0.0023	0.012
	city	16.000	40.000	56.000	0.165	0.007	0.007	0.019	0.0333	0.0021	0.0074	0.0053	0.0148	0.0053	0.0132	0.019
	comb	16.000	40.000	56.000	0.143	0.011	0.015	0.011	0.0367	0.0030	0.0153	0.0031	0.0214	0.0076	0.0078	0.015
Gasoline heavy truck	hwy	16.000	0.240	16.240	0.490	0.055	0.093	0.013	0.1615	0.0545	0.0932	0.0128	0.1605	0.0008	0.0002	0.001
	city	16.000	40.000	56.000	0.192	0.009	0.009	0.022	0.0389	0.0025	0.0087	0.0062	0.0173	0.0062	0.0155	0.022
	comb	16.000	40.000	56.000	0.181	0.008	0.008	0.020	0.0366	0.0023	0.0081	0.0058	0.0163	0.0058	0.0145	0.020

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