IFEU -
Institut für Energie-
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Heidelberg GmbH

Energy savings by light-weighting

Final report

Commissioned by the

International Aluminium Institute (IAI)

Heidelberg, January 2003

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Final report

IFEU

Institute for Energy- and Environmental Research

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Content:

Abbreviations

ABA	American Bus Association
APT	Advanced Passenger Train
ATA	American Trucking Association
BGL	Bundesverband Güterkraftverkehr Logistik und Entsorgung
BMVBW	Bundesministerium für Verkehr, Bau- und Wohnungswesen
BMW	Bayerische Motorenwerke
BTS	Bureau of Transportation Statistics
BUWAL	Bundesamt für Umwelt, Wald und Landschaft
BVG	Berliner Verkehrsbetriebe
CCFA	Comité des Constructeurs Français d'Automobiles
CNG	Compressed Natural Gas
DB	Deutsche Bahn
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EC	European Commission
EU	European Union
EUDC	Extra Urban Driving Cycle
FALKE	FAhrLeistung, Kraftstoffverbrauch, Emission
FTP	Federal Test Procedure
GEMIS	Globales Emissions-Modell Integrierter Systeme
IAI	International Aluminium Institute
IC/ EC	Inter City/ Euro City
ICE	Inter City Express
IEA	International Energy Agency
IFEU	Institut für Energie- und Umweltforschung Heidelberg (Institute for Energy and Environmental Research Heidelberg)
KBA	Kraftfahrt-Bundesamt
LCA	Life-Cycle Assessment
LPG	Liquefied Petroleum Gas
MAN	Maschinenfabrik Augsburg-Nürnberg
MWV	Mineralölwirtschaftsverband (German Petroleum Trade Association)
NEDC	New European Driving Cycle
OECD	Organisation for Economic Cooperation and Development
SGKV	Studiengesellschaft für den kombinierten Verkehr
SUV	Sport Utility Vehicle
TREMOD	Transport Emission Estimation Model
UBA	Umweltbundesamt
UCTE	Union for the Co-ordination of Transmission of Electricity
UIC	Union Internationale des Chemins de Fer
UITP	International Association of Public Transport
UNFCCC	United Nations Framework Convention on Climate Change
VDV	Verband Deutscher Verkehrsunternehmen
VW AG	Volkswagen plc
WMATA	Washington Metropolitan Area Transit Authority

1 Introduction

At the third session of the conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 in Kyoto, Japan, the text of the so called “Kyoto Protocol” was adopted. With the “**Kyoto Protocol**” many states have made the commitment to comply with targets for climate protection and the conservation of natural resources.

The transport sector contributes significantly to the total global energy consumption and greenhouse gas emissions. According to the International Energy Agency (IEA), nearly 26 % of the global energy production and nearly **58 % of the global oil production have been consumed by transport in 2001**. In the industrialised OECD (Organisation for Economic Cooperation and Development) countries even one third of the energy is consumed by transport ([IEA 2002]).

This is a call for action for the transport sector to find ways to save primary energy resources and reduce greenhouse gas emissions. The **reduction of the weight** of transport vehicles is **one important method to reduce the energy consumption** and the CO_2 emissions caused by the transport sector. It is particularly effective because if energy demand at the wheel is reduced all the energy consumption associated with upstream processes such as the extraction and processing of fuels and electricity, the distribution and conversion into mechanical energy will be reduced over the whole operational life-time of the vehicle.

This study therefore aims to analyse the general energy savings by a weight reduction with a special **focus on road and rail vehicles**. This also allows for a comparison of the different potential energy and emission savings by weight reduction for different vehicles. The means by which the weight reduction is **technically realised**, e. g. if the weight reduction is achieved by the use of lighter materials or by other means, **are not part of this study**. This can be determined for interesting sub sectors with a high saving potential on the basis of this study. This analysis, however, can help to identify the priorities regarding future usage of aluminium in the transport sector.

The study features an **executive summary** with an overview and a comparison of the results (**2**) at the beginning. The **goal and scope definition** (**3**) and the scientific and **technical background** (**4**) are explained in following sections and subsequently, an **analysis for the different road (5) and rail (6) transport vehicles and a comparison of subsystems (8)** is undertaken. The **conclusion** (**9**) sums up the most important findings of the study.

2 Executive Summary

2.1 Introduction

This study deals with the energy savings during the operational life of weight reduced transport vehicles. A weight reduction directly reduces the energy consumption because the energy required to move a vehicles is, except for the aerodynamic resistance, directly proportional to the weight of the vehicle, thus avoiding environmental impacts of all upstream activities (fuel supply, energy conversion in the engine, etc.). The potential **life-time energy savings** depend on the specific energy savings and the life-time performance of the respective vehicles.

The total energy consumption and savings of a vehicle are also determined by the **efficiency and impacts of the transmission, engine and energy supply**. Differences mainly depend on the energy carrier used. To allow for a comparison of the results we will determine the primary energy savings which take into account the efficiencies of transmission, engine and energy supply.

As a first step, the **specific primary energy savings** by a **100 kg weight reduction** and the **life-time performance** of selected, "typical" vehicles for each category are compared using simulated and measured data from literature, statistics as well as expert estimates. It must be mentioned that an absolute weight reduction by 100 kg implies different relative weight reductions with respect to the total weight of the vehicle and therefore has a different significance.

Subsequently, the **life-time primary energy and CO_2 savings** of the representative vehicle examples are calculated. Additionally, the life-time primary energy savings of 10 % weight reduced new registrations of one year are calculated exemplary for the situation in Germany. The following **road and rail vehicles** have been selected for a comparison in this study:

Road vehicles:

- Cars (gasoline)
- Cars (diesel)
- City buses
- Long distance buses
- Articulated trucks

Rail vehicles:

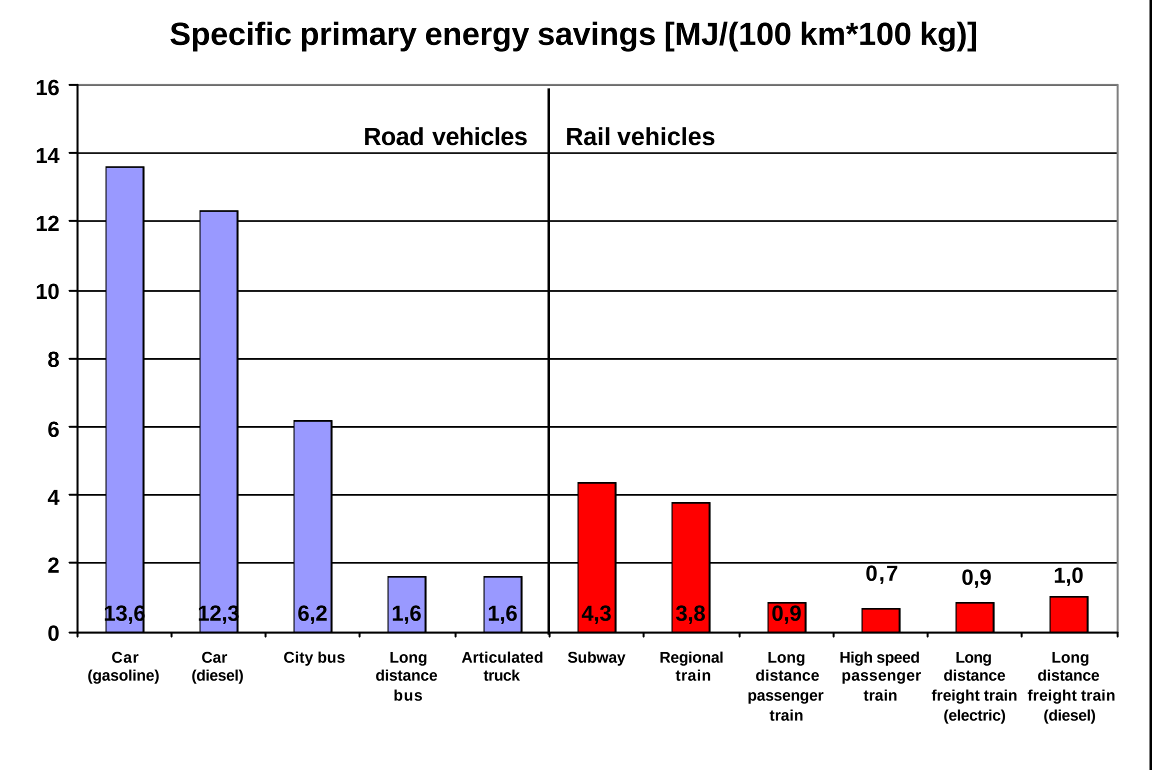
- Subways/ Urban trains
- Regional trains
- Long distance passenger trains
- High speed passenger trains
- Long distance freight trains (electric)
- Long distance freight trains (diesel)

2.2 Specific energy savings

Specific energy savings for a 100 kg weight reduction of one vehicle mainly depend on its use and the general physical specifics. Highest energy savings can be found for vehicles which are used with frequent stops and accelerations. Therefore cars and city buses have the highest specific energy savings among the road vehicles and regional trains and subways/ urban trains among the rail vehicles (**Chart 1**). For other vehicles with a more steady and higher speed, like long distance buses, trucks and trains, the weight independent aerodynamic resistance consumes a greater share of energy.

Passenger cars have particularly high specific energy savings, because additional energy savings can be achieved by maintaining the performance of the original vehicle (e. g. by adjustments of engine size or axle transmissions). Such effects have not been considered for other vehicles by the analysed literature.

Chart 1: Specific primary energy savings for the use of selected vehicle examples



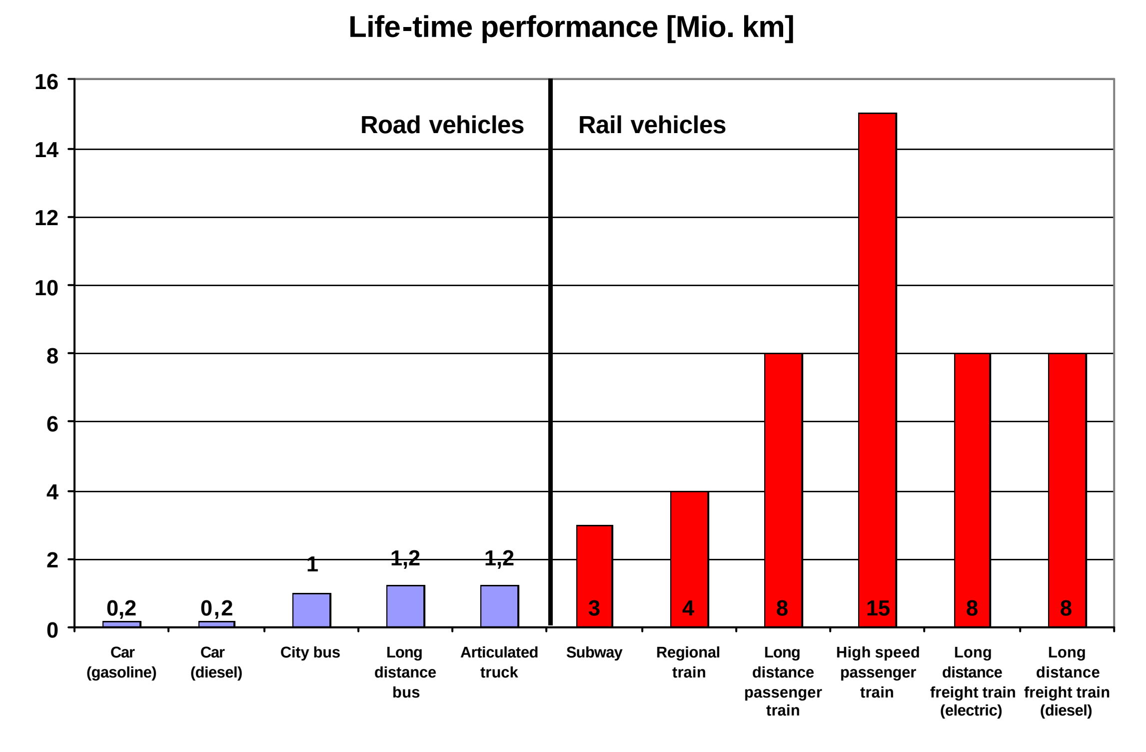
Source: IFEU 2002 from various sources IFEU 2003

Besides direct energy savings (**Chart 1**), a weight reduction permits a higher payload. In case of weight limited transport for an articulated truck and freight train respectively three and four times the direct energy savings can be achieved. Therefore the life-time energy savings in section **2.4** consider the share of weight limited transport.

2.3 Life time performance

The total life-time performance of a vehicle depends on its daily use, rather than the life-time itself. While private vehicles, like passenger cars, are parked most of the time rather than used, commercial vehicles are used as much as possible to generate the maximum revenue. Passenger cars with a daily performance of about 30 kilometres are used very little compared to long distance trains, which are used most of the time with up to more than 1’500 daily kilometres for high speed trains.

Chart 2: Average life-time performance of selected vehicle examples



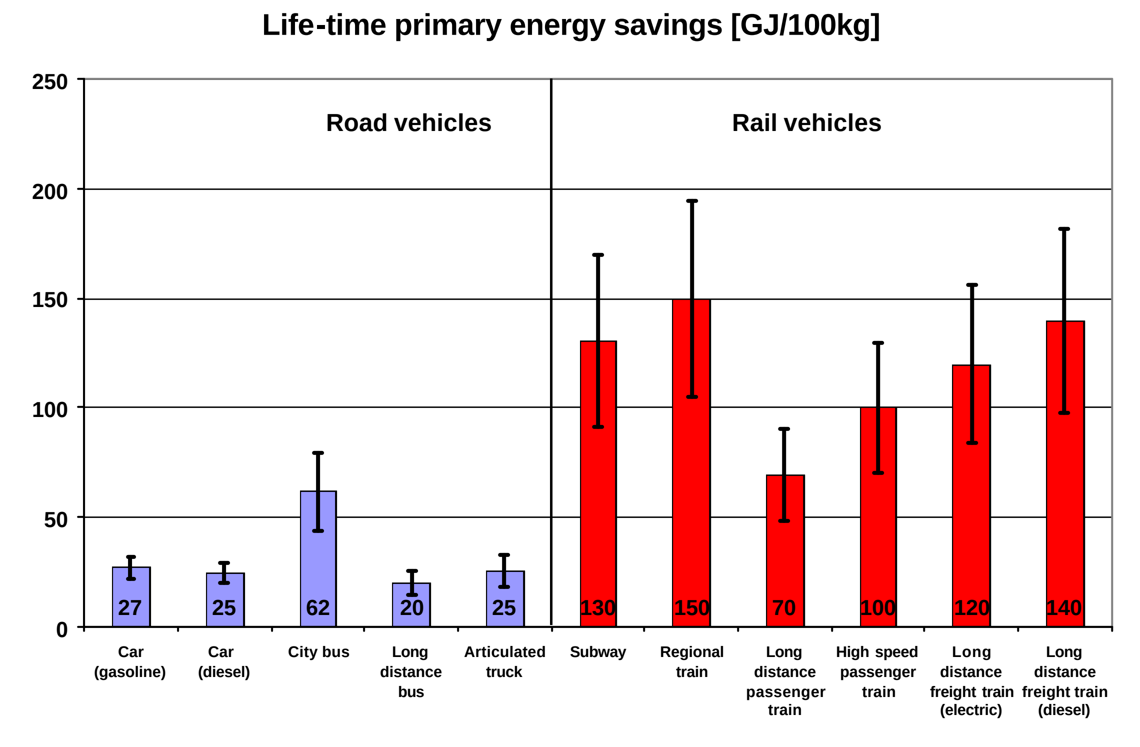
Source: IFEU 2002 from various sources IFEU 2003

The average life-time performance is **higher for rail vehicles** compared to road vehicles (**Chart 2**), not only because of their high annual performance but also due to their long operational life-time in the range of 30 years.

2.4 Life time energy and CO_2 savings for selected vehicles

The specific energy savings and the life-time performance are variables which result in the life-time operational energy savings for a 100 kg weight reduction (**Chart 3**). Cargo vehicles like trucks and freight trains can also achieve indirect energy savings by a capacity for a higher payload in the case of weight limited cargo. This has been taken into account based on the assumptions made in the respective sections. The life-time energy savings are generally higher for rail vehicles compared to road vehicles, mainly due to the higher life-time performance. Regional trains have over seven times higher life-time primary energy savings than long distance buses because of their high specific energy savings in addition to a high life-time performance. Only city buses have outstandingly high energy savings among the road vehicles. This is also due to the combination of high specific energy savings in addition to a high life-time performance. Since rail vehicles do not generally have higher specific energy savings, their great potential for energy savings by weight reduction **mainly results from the high life-time performance**. Freight trains have higher life-time energy savings because of their possibility for the transportation of a higher payload.

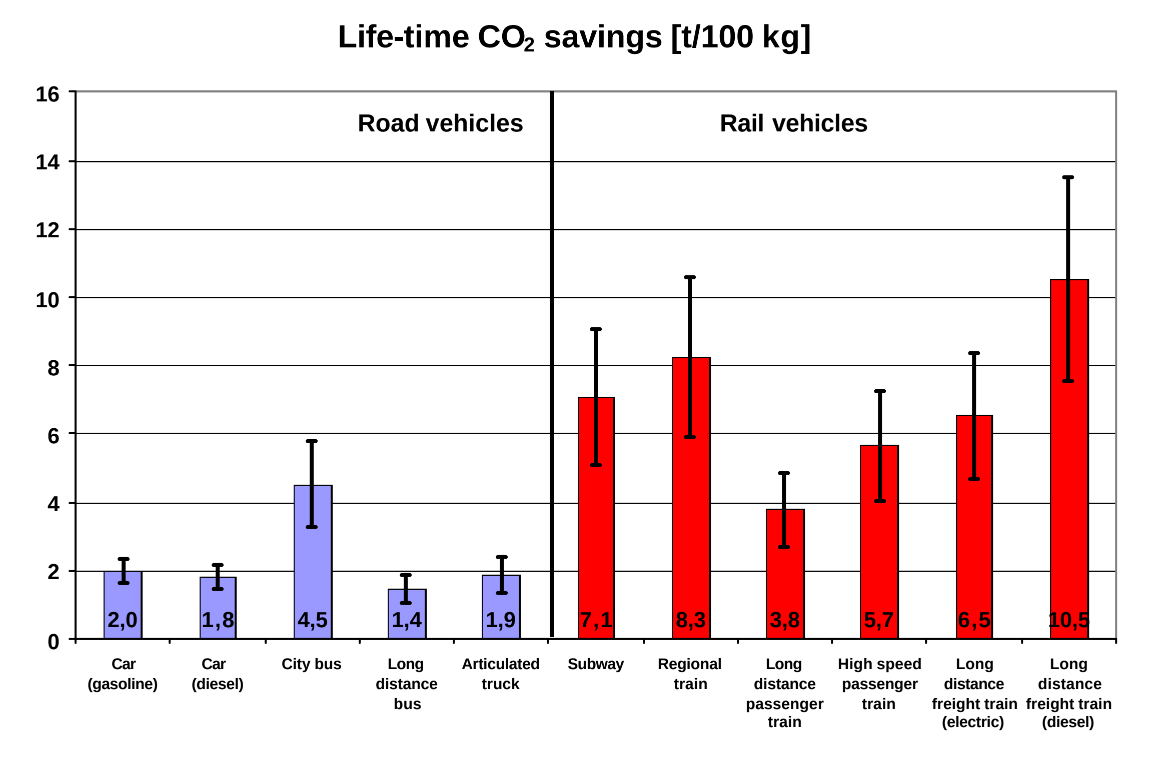
Chart 3: Life time primary energy savings of the use phase for selected vehicle examples



Source: IFEU 2002 from various sources (Figures rounded) IFEU 2003
Remark: Error ranges signify the sensitivity to uncertainties in basic data

The CO_2 savings depend on the final energy savings and the emissions from the energy supply. While refineries are similar in most countries, power plants vary by the primary energy source. Generally **the energy split** used to generate the power **determines the CO_2 emissions**. In countries with a high share of regenerative or nuclear power, CO_2 emission savings will be significantly lower than in countries which generate their power by the use of fossil fuels. For this analysis we use the **energy split of the EU 15** with 34.3 % nuclear energy ([EC 2002]). Adjustment in the CO_2 emission factors can be made for the respective energy split for country based case studies.

Chart 4: Life-time CO_2 savings of the use phase for selected vehicle examples



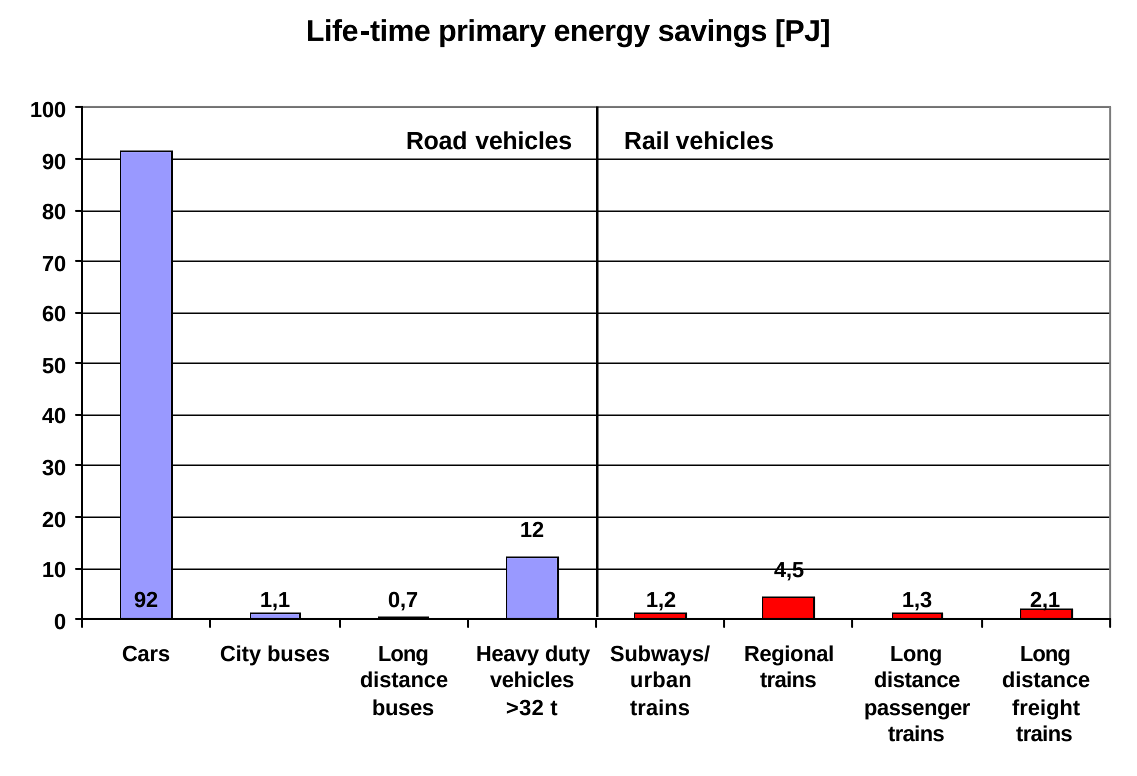
Source: IFEU 2002 from various sources IFEU 2003
Remark: Error ranges signify the sensitivity to uncertainties in basic data

Road vehicles increase their CO_2 saving potentials in comparison to the primary energy savings in our scenario. This is due to the share of nuclear and hydro power, which create almost no CO_2 emissions in comparison with energy derived from fossil fuels. For the life-time CO_2 savings in **Chart 4** it is also assumed that the electricity mix and the emission factors will remain at their current level over the whole life-time of the vehicle. A steady reduction in the CO_2 emission factor by 50 % over the life-time of the vehicle means that only 75 % of the CO_2 savings stated in **Chart 4** will be achieved. While all figures for road vehicles in **Chart 4** are calculated for fossil fuels, the share of bio-diesel and other alternative fuel options may be changing as well.

2.5 Life time energy and CO_2 savings for the new registrations of one year

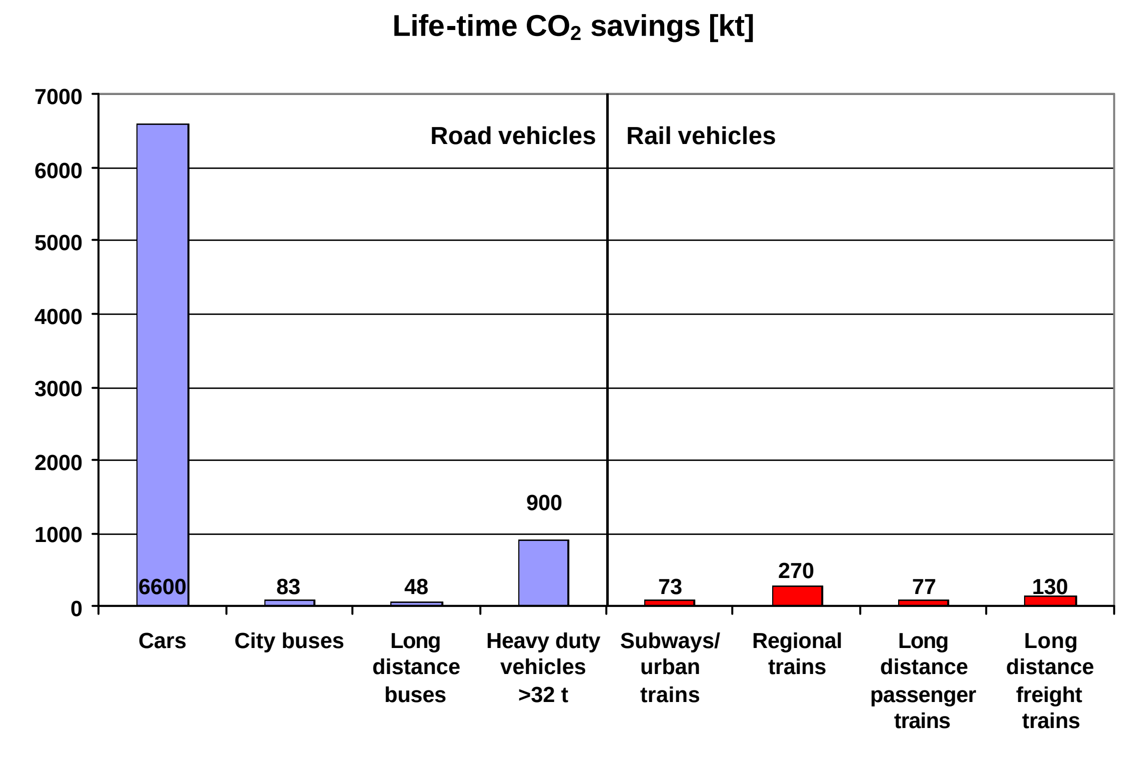
The preceding sections have dealt with the primary energy savings for single vehicles by an absolute weight reduction of 100 kg. The selected vehicles, however, differ very much in terms of total weight and total numbers. While 100 kg is a significant weight reduction and difficult to achieve for a passenger car, it is easily achieved for long distance trains. A **relative weight reduction of 10 %** takes into account the potential of heavier vehicles for a higher absolute weight reduction. On the other hand, passenger cars exist in greater numbers and can achieve higher energy savings as a subsystem. The life-time energy savings of the **annual nation-wide new registrations** have been estimated as a **scenario** with the assumption that all vehicles are weight reduced by 10 % compared to today's average. This shows the **significance and potential of the different transport subsystems** in a country like Germany, which has been selected for exemplification (**Chart 5** & **Chart 6**). Energy and CO_2 savings are outstandingly high for transport subsystems with a great share of the total energy consumption of transport, like passenger cars.

Chart 5: Scenario for the life-time primary energy savings of 10 % weight reduced annual new registrations in Germany 2000



Source: IFEU 2002 from various sources IFEU 2003

Chart 6: Scenario for the life-time CO_2 savings of 10 % weight reduced annual new registrations in Germany 2000



Source: IFEU 2002 from various sources (Figures rounded) IFEU 2003

3 Goal and scope definition

The objective of this literature study is to determine the energy and CO_2 emission savings by weight reduction for the whole operational life-time of selected transport vehicles. Therefore, the energy savings for single vehicles as well as the life-time energy savings for the annual new registrations of a whole country (Germany has been selected for exemplification) have been analysed.

The energy savings for a single vehicle directly depend on the specific energy savings by weight reduction and the life-time performance of the vehicles. Both variables are also influenced by a number of sub-parameters a selection of which are listed in **Fig. 1**. For the energy savings of the annual new registrations, a relative weight reduction of 10 % was assumed.

Fig. 1: Important Parameters of the life-time energy and CO_2 savings

Life-time energy/ CO_2 savings **=**	Specific energy/ CO_2 savings *****	Life-time performance
	• Use pattern (driving cycle)	• Durability of the vehicle
	• Driving behaviour (sporting, economical, etc.)	• Daily performance
	• Resistance factors	• Possibility for revision/ re-use of components
	• Tank-to-wheel efficiency	• Climate
	• Efficiency of energy supply (well-to-tank)	•
	• CO_2 intensity of used fuels (coal, petrol, etc.)	
	•	
Source: IFEU 2002		IFEU 2003

Other specifications, like the power to weight ratio of the vehicle, change with the weight of the vehicle. This means that the performance of the original vehicle and thus the functional unit is not maintained. This is not as important for cargo vehicles, which are designed to carry their maximum load, as it is for passenger vehicles. For these vehicles adjustments to the new power to weight ration **maintain the performance of the original vehicle** and therefore **conserve the functional unit**. This effect has been taken into account for passenger cars only. No data, however, is available for other passenger vehicles like buses and passenger trains. The performance of these vehicles will improve by a weight reduction and the full energy savings can not be achieved. Though this effect is hardly significant for a 100 kg weight reduction in the heavier vehicles, it may be of importance e. g. for a 10 % weight reduction of passenger trains.

With road and rail vehicles we are comparing **two different transport systems**. While most **road vehicles** are defined units with good data for the average weight and energy consumption, **trains** are composed of locomotives as well as rail cars. The total weight, energy consumption and energy savings can therefore be very different. In contrast to the specific fuel savings in l/ (100 km*100 kg) for the well defined road vehicles, we will use relative energy savings in % per 10 % weight reduction for the rail vehicles and apply these relative energy savings to a representative train relation for exemplification.

To determine the actual **specific savings**, either **measured data from tests or simulated data** obtained from complex models can be used. To date, most energy savings by weight reduction have been calculated by a regression line from the weight of different vehicles. This method seems to be unsuitable for a precise determination of energy savings, because differences between the vehicles (technical variations, dimensions, etc.), which are relevant for the energy consumption, are not considered [EBERLE & FRANZE 1998]. This method should therefore only be used if no simulation or measurement results are available. For some vehicles a range of estimates on weight induced energy savings can be found in the relevant literature. These estimates lack a scientific chargeable basis, but will be used for comparison or if no tests or simulations are available.

The life-time performance is of great influence on the life-time energy savings. Specific energy savings are of great importance only with a life-time performance in the same order of magnitude. For the **life-time performance**, the whole life of the vehicle has to be considered. Even if a vehicle starts its "career" as a commercial vehicle in the U.S. and continues to operate for several years in rural Mexico as a taxi, the weight reduced option will continue to save energy without any further maintenance. No definite statistics for the global average of the entire life-time performance exist. Estimates are based on national statistics, communication with experts from associations and operators as well as analyses of used vehicle trade markets.

The total energy consumption and savings of a vehicle are also determined by the **efficiency of the transmission, engine and energy supply**. These efficiencies vary for the different vehicles, mainly depending on the energy carrier used. To allow for a comparison of the results we will determine the primary energy savings, which take into account the structure of the energy supply (e. g. the energy split for electricity production), as well as CO_2 emissions which take into account the carbon intensity of the fuel production. Therefore, we include the production and distribution of the energy carriers in our **system boundaries**.

The **data** used in this study are from a variety of sources and are of different qualities. The main focus is on North America and Europe due to availability of data and the importance and number of transport vehicles in these countries. Data have been gathered mainly by **literature research** (scientific publications and published documents from political and industrial organisations) **and communication** with associations, industry and research institutes. Data on

- the specific weight induced energy savings per 100 kg or 10 % weight reduction and
- the life-time performance

have been gathered, documented and analysed. Data gaps have been filled by using expert judgements, data extrapolation or system modelling. The data quality, however, is very different, depending on the vehicles as well as the parameters. The appraisal of the potential life-time energy savings is undertaken on the basis of this unequal data.

Data uncertainties arise from a number of sources. For the **specific energy savings**

of road vehicles good data are available for passenger cars only. The weight induced energy savings with adjustments in the axle transmission, however, have been studied by few sources only, while the debate on the functional unit of passenger cars is still going on. For other vehicles, no adjustments have been taken into account by the analysed literature, the performance of passenger vehicles will therefore change with a weight reduction. For freight transport a higher payload will in many cases maintain the functional unit. Specific energy savings for other road vehicles are rather estimates than precise scientific chargeable tests or simulations. Good data for the relative energy savings of rail vehicles are available mainly for short distance trains with frequent stops and accelerations. For other vehicles estimates with uncertainties have been undertaken as well. Relative energy savings have a maximum range between 0% and 10% and the values used in this study are plausible in comparison with values verified in tests and simulations. Uncertainties, however, arise from the ascertainment of the total weight and energy consumption of the train relations, because trains vary much, mainly depending on the number of rail cars they are composed of.

Data uncertainties in the **life-time performance** of road vehicles arise from the share and the use of exported used vehicles. Differences between countries are also considerable, depending on the infrastructure, climate, lifestyle, age of the vehicles and legislation. For rail vehicles, a “real” value for the life-time performance is critical because locomotives and rail cars may have a very different life-time. Some rail vehicles have a very high life-time performance due to a revision after 20 or 30 years. For a weight reduced vehicle it has to be considered if the weight reduction is maintained after the revision (e. g. previous weight reduction by a lighter chassis).

4 Scientific and technical background

In this section, the basic scientific and technical background of the results will be presented briefly. First, the physical resistance factors will be explained to have a better understanding of the basic energy consumption and weight induced energy savings. Afterwards the **efficiency of engines and energy supply** will be discussed for the different energy sources to have a better understanding of the differences between basic, final and primary energy. Finally, the potential of secondary effects by weight reduction will be considered.

4.1 Resistance factors

Energy consumption can be distinguished at three different levels. These levels are

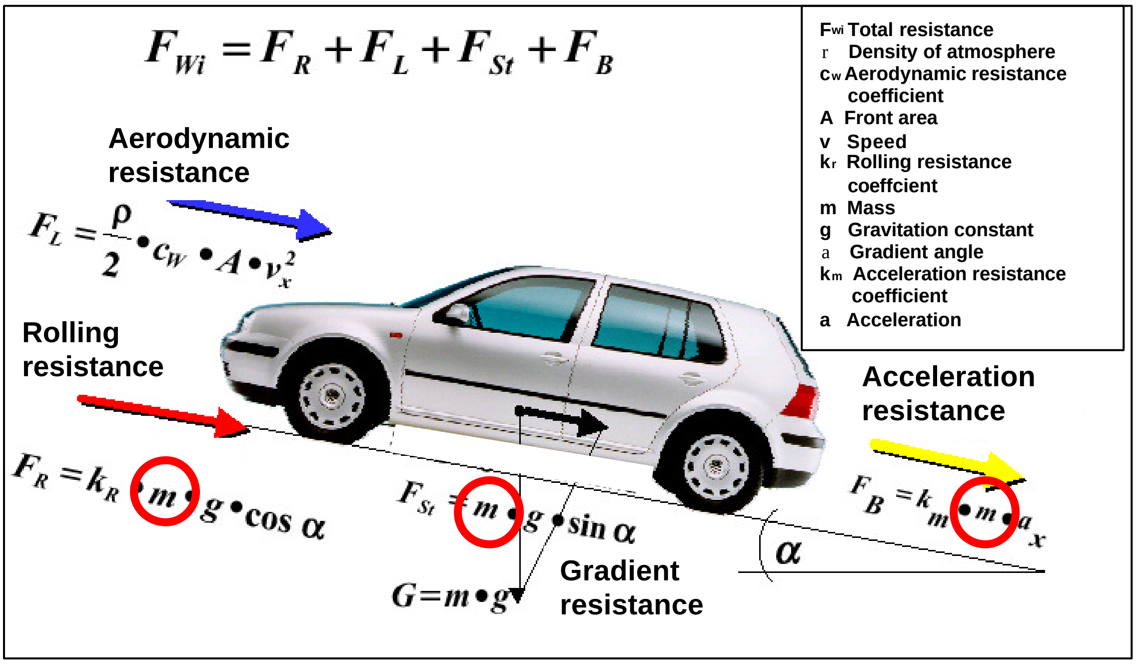
- the **basic energy consumption** 'at the wheel' (determined by the resistance factors),
- the total **final energy consumption** at the engine of the vehicle (also influenced by the efficiency of the transmission and the engine) and
- the **primary energy consumption** (also influenced by the efficiency of energy supply).

The basic energy consumption of ground vehicles is due to several resistance factors that a vehicle has to overcome during its operation. The main resistance factors are:

- Rolling resistance
- Gradient resistance
- Acceleration resistance
- Aerodynamic resistance

Fig. 2: Overview of resistance factors

Overview of resistance factors

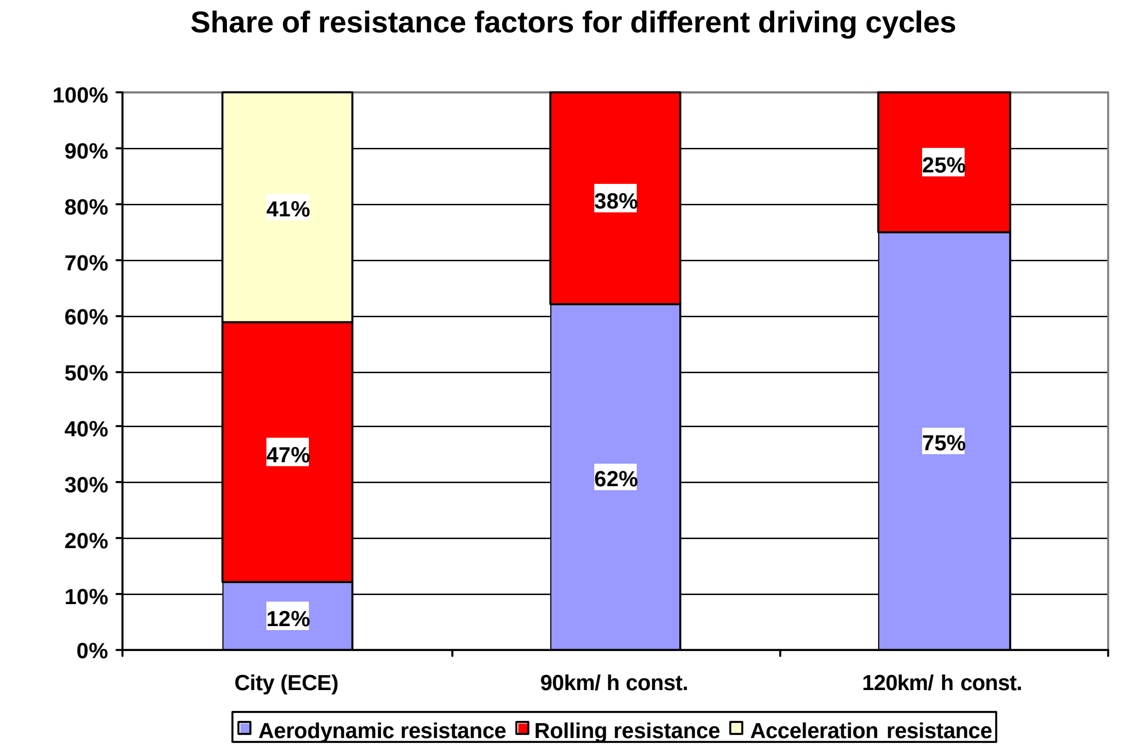


Source: [VW AG 2002] IFEU 2003

Fig. 2 exemplifies the resistance factors for a passenger car. **With the exception of aerodynamic resistance, all resistance factors are linear dependent on the mass of the vehicle** (encircled in **Fig. 2**). The aerodynamic resistance, however, depends on the dimensions of the vehicle and the square of speed. Therefore, besides the mass, speed and acceleration determine the energy consumption as well. They are highly dependent on the driving situation and driving behaviour for the vehicles. With the same driving situation and behaviour assumed, the correlation between energy consumption and vehicle weight is linear ([EHINGER et al. 2000], [EBERLE & FRANZE 1998]) for vehicles with the same dimensions. Therefore, the absolute **weight induced basic energy savings for a 100 kg weight reduction in the same driving cycle and with the same technical specifications are independent of the vehicles' absolute weight level**.

Fast vehicles with a steady speed (e.g. high speed trains or cars on highways) will therefore have a high aerodynamic resistance and low acceleration resistance and thus **low specific energy savings** by weight reduction. **Slow vehicles with frequent stops and accelerations** (e. g. city buses or subways/ urban trains) will have a high accumulated acceleration resistance and a low aerodynamic resistance, thus **high energy savings** by weight reduction. Rail vehicles, however, tend to have a lower share of aerodynamic resistance at the same speed than road vehicles, because of their small front compared to the length and the weight of the train.

Fig. 3: Share of resistance factors for different driving cycles of a passenger car example



Source: [VW AG 2002] IFEU 2003

The **share of resistance factors** for a passenger car in three different driving cycles is illustrated in **Fig. 3**. In the city driving cycle aerodynamic resistance is very low (12%) because of the low speed, but acceleration and rolling resistance are high. With a steady speed of 120 km/ h (e. g. on highways) the share of aerodynamic resistance is about 75 %, energy consumption is thus mainly due to the weight independent aerodynamic resistance. For high speed trains running at 250 - 300 km/ h the share of aerodynamic resistance can be even higher, according to [HAIGERMOSER 2000] around 85 %. "*However, air resistance has also a considerable influence on the energy consumption of slower trains, in particular on freight trains. Freight trains have usually not a very good or optimised aerodynamic design*" [ANDERSSEN 2000].

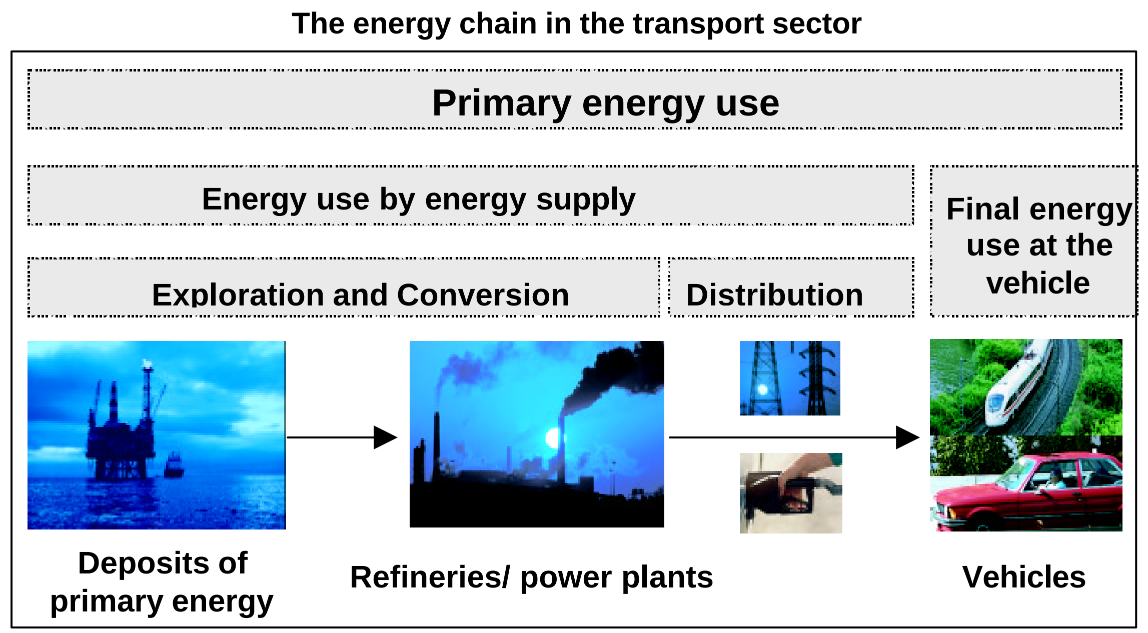
For energy savings we distinguish **specific energy savings** per 100 km and an absolute weight reduction by 100 kg and **relative energy savings** in % by a relative weight reduction by 10 %. Relative energy savings would be 0 % for a weightless vehicle which faces only aerodynamic resistance and 10 % for a vehicle which faces only weight dependent resistance factors and no aerodynamic resistance at all. The absolute and relative values can not be directly compared.

In contrast to combustion engines, for electric engines **energetic recovery systems** are already in use. In principle, the kinetic and potential energy can be fed back, with exception of losses due to electrical systems and running resistance, but in practice the regeneration of energy is limited ([ANDERSSEN 2000]). An average of 20 % and up to 25 % ([EHINGER et al. 2000], [SCHWANHÄUSSER et al. 1990]) or even 27 % ([ALBERT et al. 1997]) of the energy which is lost can be recovered and used for the next acceleration or ascending period. The energetic recovery systems are already used in rail vehicles and are **often already reflected in the data used for this study**.

4.2 Energy supply

To move ground vehicles, the basic amount of energy needed at the wheel is determined by the resistance factors stated above. The **basic energy consumption** is therefore directly affected by a weight reduction of the vehicle. Some energy, however, is lost during the transmission from the engine to the wheel and within the engine itself. The total **final energy consumption** at the engine of the vehicle is therefore higher than the basic energy consumption at the wheel. Energy is also needed for the energy supply of the vehicle, mainly the exploration, conversion and distribution of a primary energy carrier (e. g. in power plants or refineries) (**Fig. 4**). The total **primary energy consumption** is therefore higher than the final energy consumption. The **difference between the energy input and the energy output of a certain process** (power plant, refinery, engine or transmission) is called **efficiency** and will be stated as energy output in percent of the original energy input. While there are no differences between relative final and primary energy savings (in % per 10 % weight reduction), the specific end and primary energy savings (per 100 km and 100 kg weight reduction) are influenced by the efficiencies.

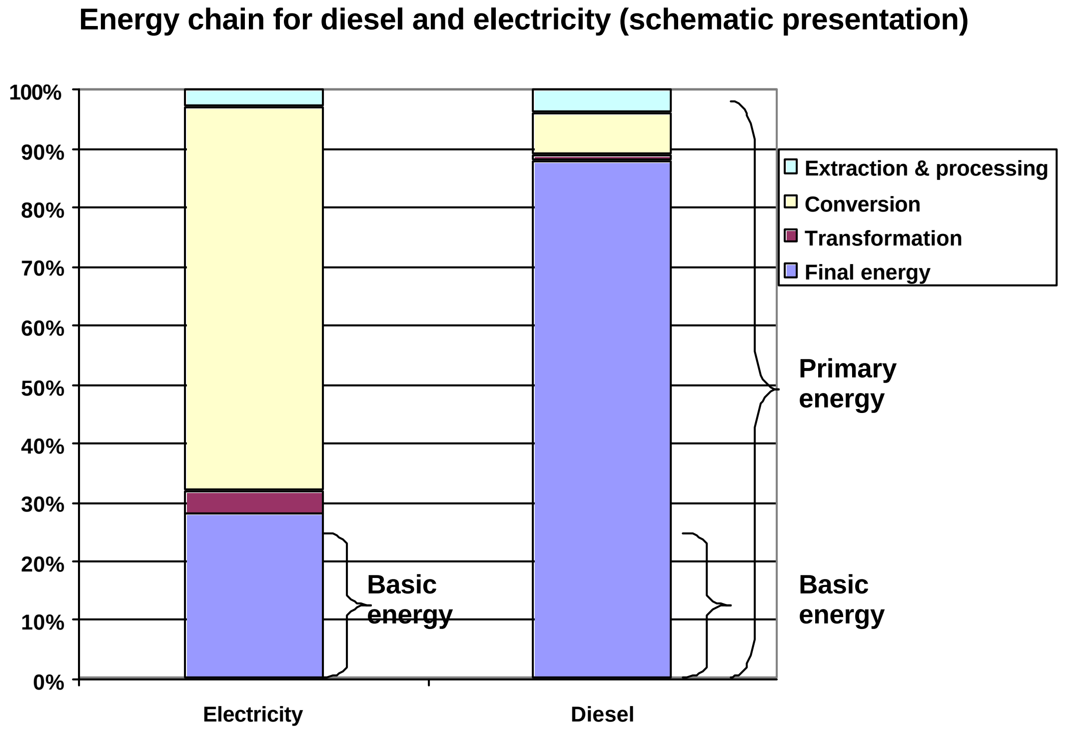
Fig. 4: The energy chain in the transport sector



Source: [IFEU 2002b] IFEU 2003

This study mainly deals with fuels (diesel and gasoline) and electricity as final energy carriers. The efficiency of energy supply is higher for fuels (refineries) and lower for electricity (power plants). The efficiency of electric engines, however, is over 90 % and therefore higher than the efficiency of combustion engines with less than 30 % ([DLR 2001]). While the basic energy consumption at the wheel is independent of the type of engine, the final energy consumption is very different. Differences in energy consumption between combustion engines and electric engines mainly show up in the final energy (**Fig. 5**).

Fig. 5: Energy chain for diesel and electricity (schematic presentation)



Source: [IFEU & SGKV 2002] with modifications IFEU 2003

Most road vehicles to date are fuel (either gasoline or diesel) powered and most rail vehicles have electric engines. The German Petroleum Trade Association ([MWV 2002]) assumes that the share of alternative engines for passenger cars in Germany will remain lower than 2 % until 2015. To compare vehicles with different final energy carriers, the energy savings have to be converted to equal energy units, for instance kJ. The **differences in the efficiency of energy supply and CO_2 emissions between fuels and electricity** are shown in **Tab. 1**. For this analysis we use the energy split for the EU 15 with 34.3 % nuclear energy and 13.6 % hydro energy ([EC 2002]). The thermal efficiency is 39.9 % and 33 % and 100 % efficiency are assumed for nuclear and hydro energy respectively.

Tab. 1: Efficiency of energy supply and CO_2 emissions in Europe

Final energy carrier	Efficiency (Final energy/ primary energy)	g CO_2/MJ final energy
Diesel	87 %	83.4
Gasoline	83 %	87.0
Electricity	46 %	118.7

Source: [GEMIS 2000], [TREMOD 2001] & [EC 2002] IFEU 2003

Adjustment in the CO_2 emission factors have to be made for the respective energy split and efficiencies if the results of this study are used for a specific country. Switzerland, for example, had a share of hydro power of 60 % in 2001 ([UCTE 2002]). For the exemplification of the reductions of new registrations the efficiency factors of the German electricity mix ([TREMOD 2001]) are used.

4.3 Secondary effects of weight reduction

With the reduction of weight, other effects can be achieved and thus more energy be saved. First of all, **less material has to be produced and recycled or disposed**. However, the production of light-weight materials, which are in many cases used to achieve a weight reduction, normally consumes more energy than the production of heavier components. Therefore this secondary effect is normally having a contrary impact, with more energy being consumed for the production of the lighter vehicle. This effect is part of a full life cycle assessment and will not be considered here.

In the use phase, some secondary modifications can be realised if the vehicle is supposed to achieve the performance of the original vehicle. This applies to the **tuning of the engine** and **adjustments in the transmission** to the new power-to-weight ratio. Only with these modifications, the full potential of the weight reduction can be taken advantage of.

Other secondary effects are more complicated and change the functional unit. Possibilities are the **downsizing of the engine**, so that it will have the same power-to-weight ratio, which will result in even less final energy consumption and a further weight reduction. Other components, like the frame, can be adjusted as well. These possible **secondary saving effects**, which require a new vehicle design, have been assessed to be in the range **between 16 % and 50 %** of the primary saving effects of weight reduction ([EBERLE 1999]).

Cargo vehicles will normally take a payload up to the maximum allowance if possible (e. g. 40 t for articulated trucks). Especially **for freight trains** the maximum **cargo is rather weight-limited than volume-limited** [STODOLSKY et al. 1998]. In this case the weight reduction permits the **transportation of a higher payload** and thus e. g. less vehicles are needed to transport a certain amount of goods from one place to another. These **indirect energy savings** for weight limited transport are the result of a lower mileage for the same transport performance and can be calculated in comparison to the driving distance without weight reduction, the original functional unit. This effect has been calculated for trucks and freight trains in the respective sections.

5 Road Vehicles

In road traffic, a broad spectrum of vehicle types is in use. In this study the potential for energy savings by weight reduction is analysed for **typical vehicles**, which represent the **most common uses**[1]:

- Passenger cars (Diesel/ Gasoline)
- City buses
- Long distance buses
- Articulated trucks

To date, these vehicles are almost completely **powered by either diesel** (buses, trucks and passenger cars) **or gasoline fuel** (passenger cars), with only a small global share of compressed natural gas (CNG), liquefied petroleum gas (LPG), bio-diesel or other fuels. Only motor vehicles with diesel and gasoline fuels are considered for the calculation of the primary energy and CO_2 emission savings in this study.

The use of vehicles and therefore also the potential energy savings by weight reduction differs between countries as well as between the different vehicles of one country. The main influences for a given vehicle are the **purpose and location of use** and the **driving behaviour**. Therefore, the general conditions for the calculations in this study are specified for each vehicle in the following sections.

5.1 Passenger cars

The **global stock of passenger cars** has been estimated to be approximately **466 Mio. in 2000** [CCFA 2000]. These passenger cars range from compact cars with less than 800 kg[2] to heavy vehicles with more than 2500 kg. The weight of the growing numbers of Sportive Utility Vehicles (SUV) is even higher than 2500 kg. The composition of the vehicle stock differs between countries. On the average, heavier vehicles are used in the U.S. in comparison with Europe. Within Europe heavier vehicles are rather used in Northern Europe than in Southern Europe.

The life-time and annual performance is different for private and commercial vehicles. The following passenger cars have been selected for the illustration of these influences on the potential energy savings by weight reduction:

Typical private car with average use: A typical **midsize gasoline and diesel car** will be analysed. A weight of 1300 kg will be assumed for the gasoline car. For diesel cars the weight is slightly higher with 1400 kg.

Commercial use: Heavier vehicles are used as business and **company cars** as well as **taxis**. In many European countries diesel cars are used as commercial vehicles due to their longer durability and lower fuel consumption. Their weight is assumed to be 1600 kg[3].

Infrequent use: Mainly **compact cars** are used as second cars with a low performance. Their weight is assumed to be 1000 kg.

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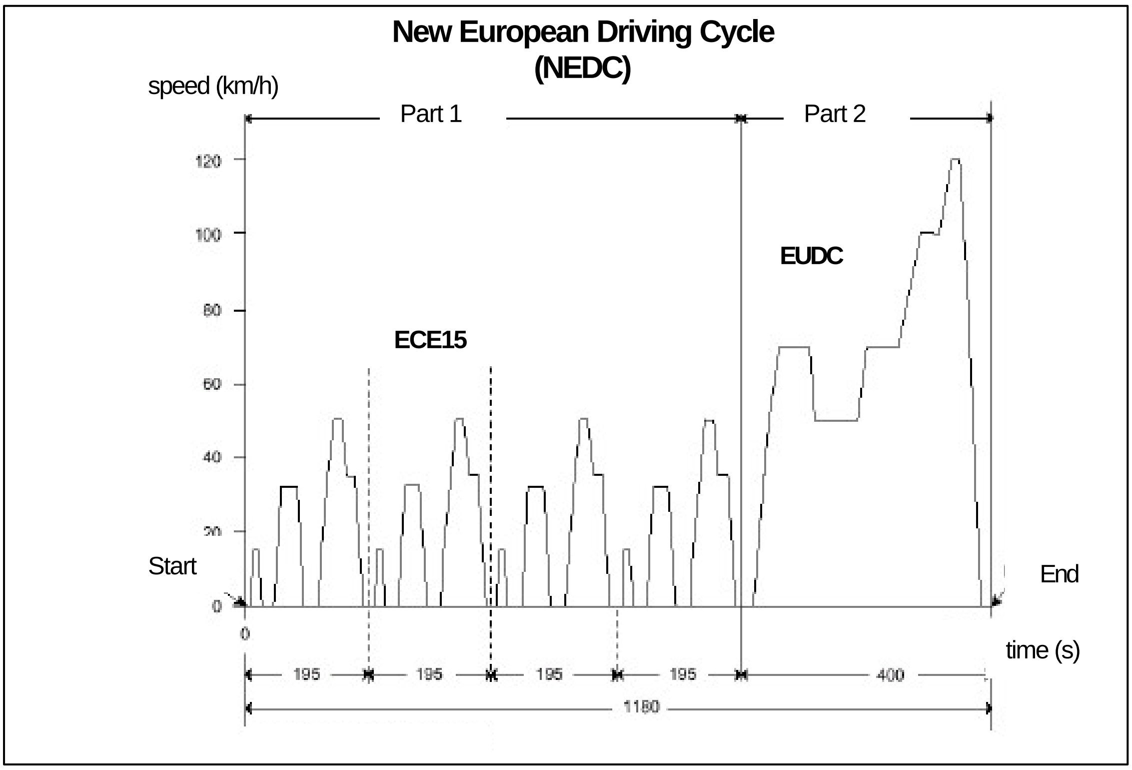
1 The vehicles will be described in detail in the respective sections.
2 e. g. Micro Compact Car Smart, Daihatsu Cuore, Lupo 3l
3 e. g. Mercedes Benz C 220

5.1.1 Fuel consumption and driving cycles

Fuel consumption of the selected vehicles depends on many parameters like the use and the driving behaviour. **Driving cycles** for several uses have been designed to control emission regulations and compare the fuel consumption of different passenger cars. The ECE15 is taken as a typical cycle for urban roads, the EUDC (**E**xtra **U**rban **D**riving **C**ycle) for rural main roads. The **NEDC** (**N**ew **E**uropean **D**riving **C**ycle (Directive 97/24/EC)) (**Fig. 6**) adds up both and will in most cases be used as average data for specific fuel savings. The most common cycles in the U.S. are the **FTP75** (Federal Test Procedure 75) and the **Highway** cycle, which have been considered only by [WALLENTOWITZ et al. 1996]. They represent an urban and a highway pattern and not, like the NEDC, both use patterns.

Fig. 6: The New European Driving Cycle (NEDC)



Source: [KBA 2002] IFEU 2003

Though driving cycles like the NEDC are supposed to represent the average driving in certain use patterns, they have been criticised for not being realistic in comparison with cycles recorded in road tests. The real **driving behaviour has great influence on the fuel consumption** which may be reduced by 25 % with an economical driving behaviour ([WALLENTOWITZ & NEUNZIG 2002]). [EBERLE 2000] therefore also uses an economical and a sporting driving cycle. These results, however, congregate around the results for the NEDC, which will therefore be used as an average.

Emission models like [TREMOD 2001] estimate the average fuel consumption by using highly differentiated consumption factors for different traffic situations. Data for the fuel consumption of the selected passenger cars are based on literature research and models. The total consumption is validated using the national energy statistics.

5.1.2 Specific energy savings by light-weighting

Specific energy savings by weight reduction have been determined by **tests and simulations** ([EBERLE 2000] & [WALLENTOWITZ et al. 1996]) as well as estimated in the relevant literature ([BUXMANN & GEDIGA 1998], [VW AG 2002], [REPPE et al.1998], [KIEFER et al. 1998] & [PETERSEN 2000]). [EBERLE 2000] found a wide range of **estimates** stated for weight induced fuel savings from 0,15 to 1 l/ (100 km*100 kg). Most of these estimates, however, lack a scientific chargeable and practical approved basis and depend on the specific interests involved ([EBERLE & FRANZE 1998]).

The results are stated in l fuel savings per 100 km for a 100 kg weight reduction [l/ (100 km*100 kg)] mainly for the tests and simulations and in % energy savings per 10 % weight reduction [%/ 10 %] for most estimates. The **two in-depth studies** of [EBERLE 2000] and [WALLENTOWITZ et al.] will be discussed here in detail, while other studies are cited in a **tabular overview**.

Eberle ([EBERLE & FRANZE 1998], [EBERLE 1999], [EBERLE 2000]) studied the weight induced fuel savings for BMW vehicles in the NEDC with the simulation programme FALKE (**FA**hr**L**eistung, **K**raftstoffverbrauch, **E**mission) and validated the results in several tests for the BMW 528i. In order to show differences in fuel savings for different driving behaviours, an **economical** and a **sporting driving cycle** have been recorded in road tests and simulated as well. The linear correlation between fuel consumption and vehicle weight described in section **4** has been verified by Eberle's tests for the BMW528i [EBERLE 2000]. The simulations also show that the fuel savings are independent from the absolute vehicle weight (**Chart 7**): "*There couldn't be established neither a correlation between the weight nor the power or the specific power-to-weight ratio and the fuel reduction coefficients of various vehicles*" [EBERLE & FRANZE 1998].

Specific fuel savings have been tested and simulated **with and without adjustment in the rear axle transmissions**. Adjustments in the rear axle transmission maintain the performance of the original vehicle (a secondary effect of the weight reduction). While "*a reduction in weight leads to an improvement of performance … an extension of the rear axle transmission ratio tends by and large to reduce the standard of performance. Adjusting the rear axle transmission ratio of a lighter vehicle in order to achieve the performance of the original vehicle, one can indeed achieve a further reduction of fuel consumption…*" [EBERLE 1998].

Weight induced fuel savings with adjusted rear axle transmission are up to three times higher as for vehicles without adjustments. The savings potential is highest for the sporting driving cycle, because of the importance of acceleration and braking procedures. While the fuel savings in the sporting cycle are up to 75 % higher compared to the NEDC, smaller differences are found between the NEDC and the economical cycle. Fuel savings for the economical driving cycle are between 16 % lower and 5% higher than for the NEDC. Overall fuel savings with adjustments in the rear axle transmission range **from 0,346 l in the economical to 0,510 l in the sporting driving cycle** (**Tab. 2**).

Tab. 2: Fuel savings test results for selected driving cycles [l/ 100 km*100 kg]

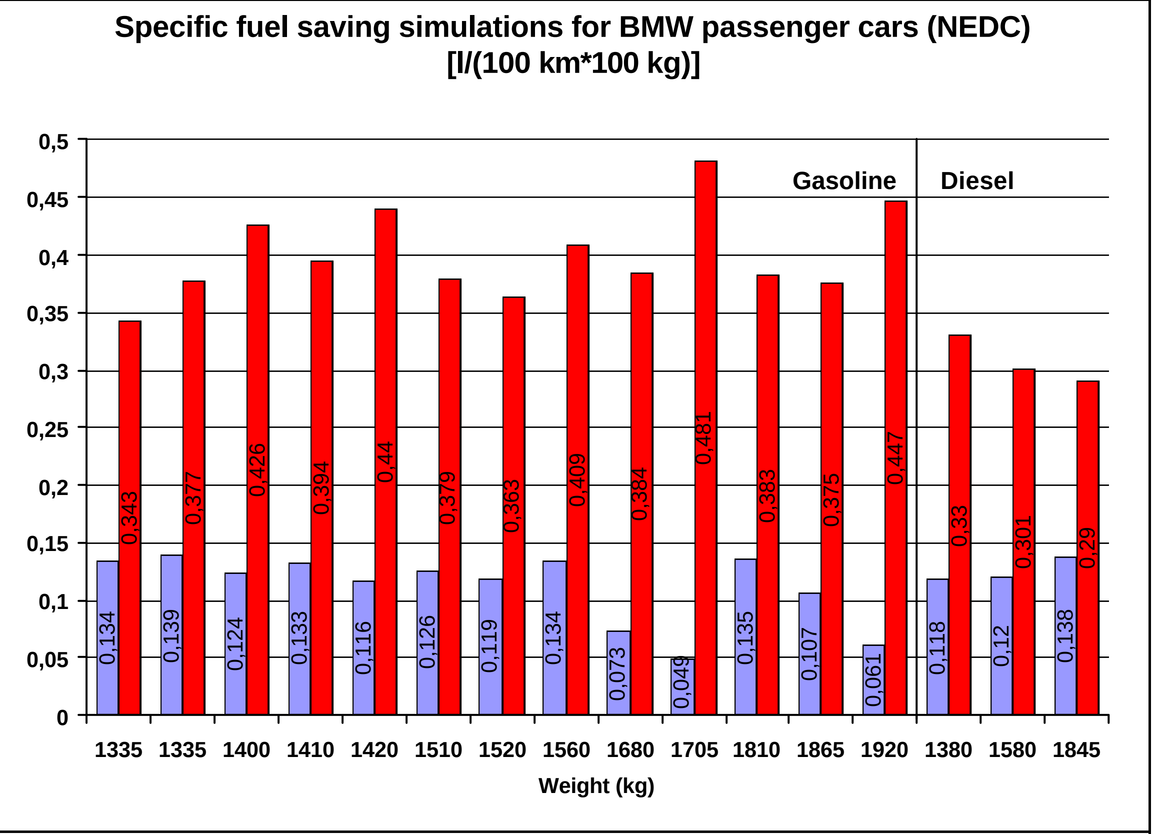
Vehicles	NEDC	econ. cycle	sport. cycle
*BMW 528i **without** modification (gasoline)*	0.134	0.141	0.235
*BMW 528i **with** modification (gasoline)*	0.409	0.346	0.510
Source: [EBERLE 2000]			IFEU 2003

Fuel savings simulated for other BMW vehicles with FALKE show similar results in the **range from 0.34 to 0.48 l/ (100 km*100 kg)** in the NEDC. **Fuel savings for diesel vehicles are somewhat lower** at 0.29 to 0.33 l/ (100 km*100 kg). Here it must be noted, however, that diesel fuel has a higher density than gasoline fuel and therefore specific energy savings for gasoline and diesel fuels are in the same range. No relative energy savings, however, can be calculated for the tests for comparison due to the lack of data on the total fuel consumption of the respective vehicles.

The reduced energy consumption is "*… attributable approximately one-third to the primary reduction of weight and two-thirds to the extension of the rear axle*" [EBERLE 1998]. Experts assume that differences in fuel savings with and without adjustments are rather decreasing because general optimisation of the transmission in passenger cars ([HAGEN 2002] & [EBERLE 2002]).

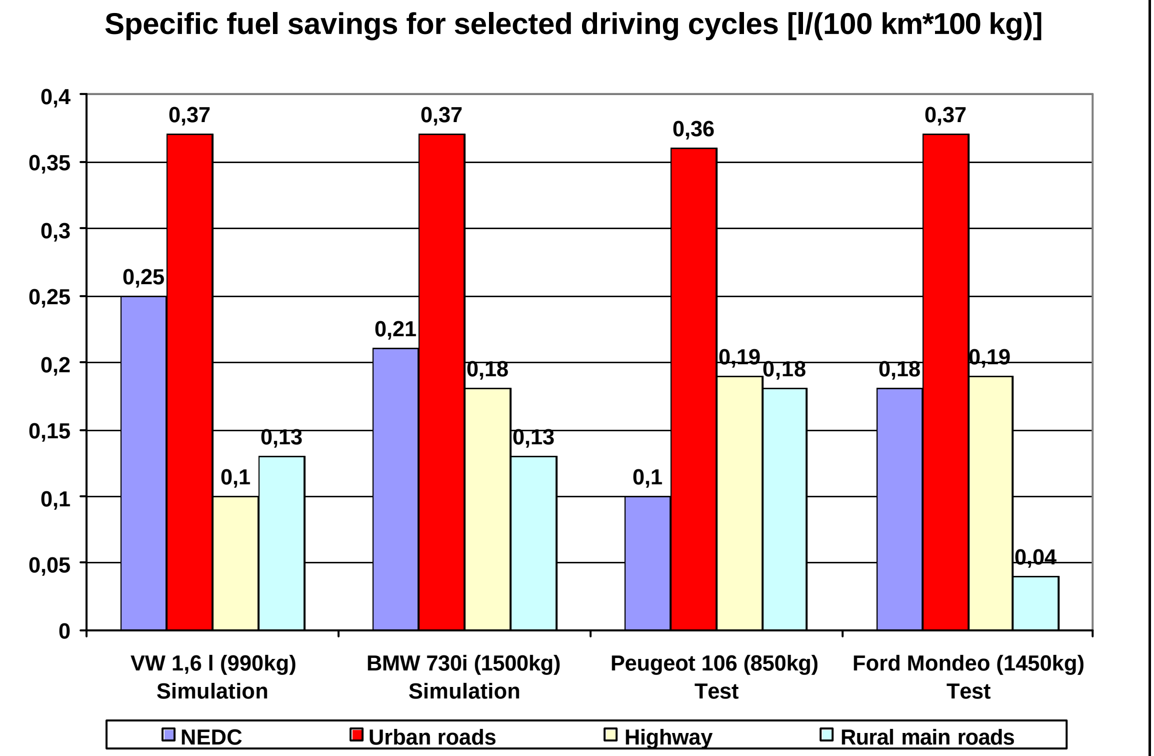
The "Institut für Kraftfahrwesen Aachen" (ika) studied the fuel saving potential by weight reduction in simulations and tests for vehicles without modifications in the axle transmission [WALLENTOWITZ et al. 1996]. Two weight reduced vehicles (VW 1,6l (990 kg) and BMW 730i (1500 kg)) have been simulated and two (Peugeot 106 (850 kg) and Ford Mondeo (1450 kg)) have been tested for validation in several driving cycles. The simulations show 0.25 and 0.21 l/ (100 km*100 kg) fuel savings in the NEDC. The simulations also show clear **differences between the different driving cycles** (**Chart 8**) with **fuel savings** being **highest for the urban roads**, lower for the highway and lowest for the rural main road.

Chart 7: Specific fuel saving simulations for BMW passenger cars (NEDC)



Source: [EBERLE & FRANZE 1998] IFEU 2003

Chart 8: Specific fuel savings for selected driving cycles (gasoline cars)



Source: [WALLENTOWITZ et al. 1996] IFEU 2003

Besides these two in depth studies ([EBERLE 2000] & [WALLENTOWITZ et al. 1996]) other values can be found in the relevant literature ([BUXMANN & GEDIGA 1998], [VW AG 2002], [REPPE et al.1998], [KIEFER et al. 1998] & [PETERSEN 2000]). These sources (**Tab. 3**), however, are rather estimates and rules of thumb which are, for example, used for life-cycle assessment. The origin and validity of these values is not specified in the respective sources.

Tab. 3: Overview of specific and relative fuel and energy savings for passenger cars

Source	Specific fuel savings [l/(100 km*100 kg)]	Relative energy Savings [%]
[EBERLE 2000] (NEDC Test) ***without*** *adjusted rear axle transmission*	0.134	2.1[1)]
[EBERLE 2000] (NEDC Simulation) ***without*** *adjusted rear axle transmission*	0.049 - 0.139	
[EBERLE 2000] (NEDC Test) ***with*** *adjusted rear axle transmission*	0.409	6.4[1)]
[EBERLE 2000] (NEDC Simulation) **with** adjusted rear axle transmission	0.343 - 0.481	
[EBERLE 2000] (NEDC Simulation for ***diesel*** *vehicles)* ***with*** *adjusted rear axle transmission*	0.29 - 0.33	
[WALLENTOWITZ et al. 1996] (NEDC Tests and Simulations)	0.1 - 0.25	1.37[1)] - 3.7[1)]
[BUXMANN & GEDIGA 1998] Estimate	0.25 - 0.5	
[VW AG 2002] Estimate		4
[REPPE et al.1998] Estimate		4
[KIEFER et al. 1998] Estimate		4.5
[PETERSEN 2000] Estimate		4

1) IFEU calculation based on the source IFEU 2003

A relative value of about 4 % fuel savings for a 10 % weight reduction is often stated as rule of thumb and reflects a commonly accepted coefficient of weight induced energy savings for passenger cars. While the **relative energy savings** for a weight reduction without any modifications are in the range of 2 % - 4 %, a much higher value of **over 6 % can be achieved with a modification of the rear axle transmission**. [EBERLE 2000] is the only source providing data for weight induced fuel savings for vehicles with a modified rear axle transmission, meaning data with the performance of the original vehicle maintained.

As can be seen in **Chart 7** and **Chart 8**, absolute fuel savings in l/ (100 km*100 kg) better represent the fuel savings than relative numbers due to the independence of fuel savings of the absolute weight level of the vehicle. Therefore, we assume **0.35 l specific fuel savings for gasoline and 0.3 l specific fuel savings for diesel cars** per

100 kg*100 km[4]. These, however, are rather conservative values of the data for passenger cars with modified rear axle transmission.

5.1.3 Life-time performance

Most passenger cars operate up to 15 years in the industrialised countries of Europe and North America. It is difficult to quantify the share of vehicles which exceed this age and are, for example, exported to other countries. The average annual performance of passenger cars is very different for the respective countries and varies between 10'000 and 15'000 km.

200'000 km (or 120'000 mi which is equivalent to 193'000 km) is **a widely accepted life-time performance** for average passenger cars in Europe as well as the US ([REPPE et al. 1998], [RIDGE 1997], [KELLY & DAVIS 1998]). Special vehicles (e.g. taxis or company cars), however, have a much higher annual performance of up to 100'000 km. Other vehicles may only be used as second cars or on weekends and may have a much lower annual performance (e. g. half of the average performance).

We will therefore, in addition to the gasoline and diesel car with average performance, **exemplify the possible range of life-time energy savings in two examples**. On the higher end of the spectrum we will look at a diesel taxi (it is assumed that cars with high performances will be diesel cars) with a life-time performance of 800'000 km. On the lower end we look at a light gasoline car with only 100'000 km life-time performance.

5.1.4 Life-time energy savings

Final and primary energy savings for a 100 kg weight reduction vary significantly for the defined vehicles. Over 4 times the life-time energy savings of typical private vehicles (25 - 27 GJ) can be achieved by the high performance taxi (115 GJ), mainly due to the higher life-time performance. In addition to the high life-time performance, also higher specific energy savings have been assumed, because taxis mainly operate in an urban driving cycle.

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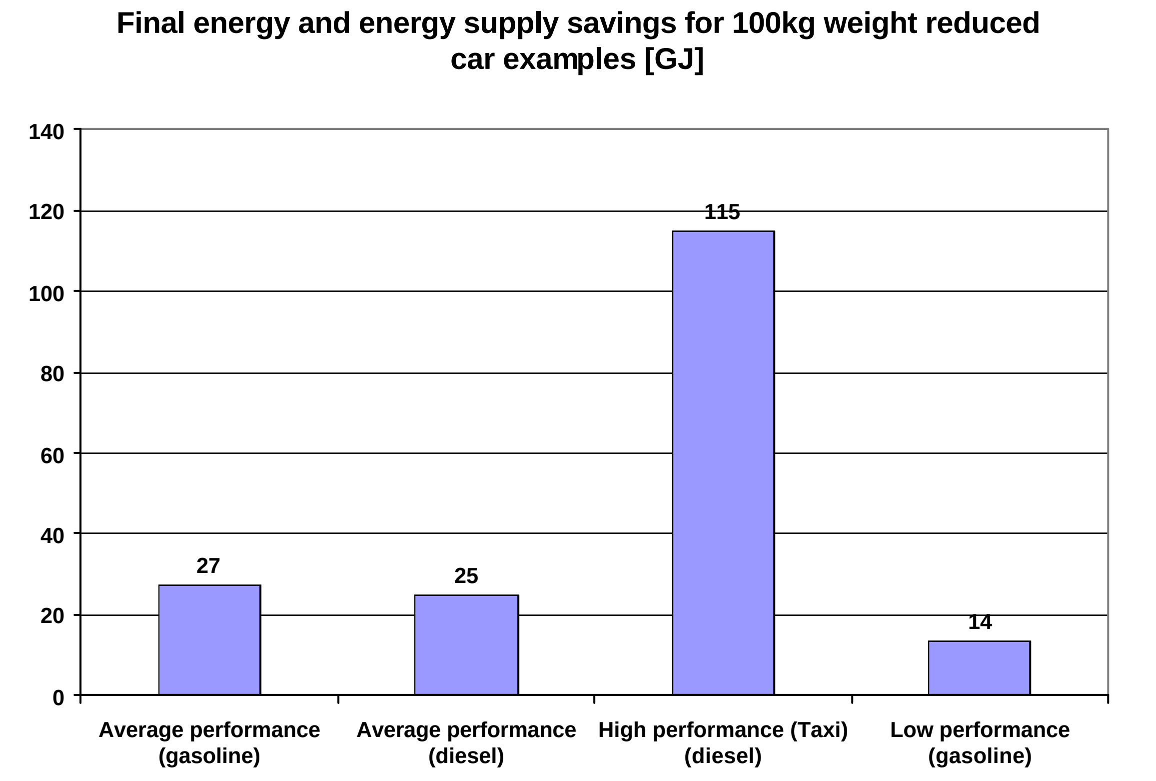
4 For further calculations in section 7.2, relative energy savings (%/10 % weight reduction) will be required. Taking the average weight of the German passenger vehicle fleet of 1310 kg, a share of 40 % Diesel vehicles and an average consumption of 7.6 l/ 100 km, these absolute reduction numbers correspond to 5.7 % which will be used in the calculation in section 7.2.

Tab. 4: Overview of data for exemplification of energy and CO_2 savings from a 100 kg weight reduction

	Average performance (gasoline)	Average performance (diesel)	Taxi (diesel)	Low performance (gasoline)
Fuel consumption (l/100 km)	9	7	9	6
Weight (kg)	1300	1400	1600	1000
Specific fuel savings (l)	0.35	0.3	0.35	0.35
Life-time performance (km)	200'000	200'000	800'000	100.000
Life-time final energy savings (MJ)	23'000	21'000	100'000	11'000
Life-time primary energy savings (MJ)	27'000	25'000	115'000	14'000
Life-time CO_2 savings (t)	2.0	1.8	8.4	1.0

Source: IFEU 2002 from various sources IFEU 2003

Chart 9: Final energy and energy supply savings for 100 kg weight reduced car examples



Source: IFEU 2002 from various sources IFEU 2003

5.2 City buses

Mini buses, standard buses and articulated buses are used for urban public transport and have different dimensions, total weight and engine power. A standard city bus with a **net weight of 15 t** will be exemplified.

Diesel buses dominate the global share of buses to date, while other fuels like CNG and LPG as well as bio-diesel are less significant. The fuel consumption of buses differs with the geographical environment, the traffic situation and the distance between stops, not only between, but also within cities. Based on the analysis of data from transport operators, a **fuel consumption of 40 l diesel fuel per 100 km** will be assumed for exemplification [IFEU 2002].

5.2.1 Specific energy savings

No studies based on tests or simulations on the specific fuel savings for city buses have been found. Values stated by the bus manufacturer MAN as well as the Association of German Transport Operators ("Verband Deutscher Verkehrsunternehmen" (VDV)) in **Tab. 5** are estimates on the basis of expert judgement.

Tab. 5: Specific and relative fuel savings of city buses

Source	Specific fuel savings [l/(100 km*100 kg)]	Relative energy savings [%/10 %]
[MAN 2002]	0.2	7.5
[VDV 2002]	0.1 – 0.2	3.75 – 7.5
Extrapolation with data from [INFRAS 1999b]	0.1	3.75
		IFEU 2003

In addition to these sources, an **extrapolation** of the fuel consumption of empty and full city buses, based on data from [INFRAS 1999b], has been undertaken. The value of 0.1 l/(100 km*100 kg) is **in the same range** as data from [VDV 2002], but has uncertainties in the number and weight of the passengers. Taking into account all sources, a value of **0.15 l/(100 km*100 kg)** will be used for exemplification. Relative energy savings have been calculated based on the assumptions for our exemplification (40 l fuel consumption and 15 t weight). The values between 3.75 and 7.5 % fuel savings for a 10 % weight reduction of standard city bus are in the same range as the relative energy savings for passenger cars with axle transmissions.

5.2.2 Life-time performance and energy savings

The **annual performance** of a standard city bus in Germany has been estimated in the range between 50'000 and 80'000 km ([MAN 2002], [VDV 2002]). On the assumption of a **life-time of 8 to 15 years**, the life-time performance will be between 0.4 and 1.2 Mio. km. The U.S. Bureau of Transport Statistic ([BTS 2002]) states a long time average age of more than 8 years for full size transit buses in the U.S. which is equivalent to a life-time of about 16 or 17 years. City buses of the Berlin municipal transport services ([BVG 2002]) operate between 12 – 14 years and achieve a life-time performance of about 800'000km before they are sold to countries in eastern Europe. [INFRAS 1999a] states a life-time performance of only 0.54 Mio. km for city buses in Switzerland, but Internet trade markets (e. g. http://www.yakoub.de/index.html; http://cat.workingwheels.com; http://www.used-buses.net) also sell used city buses with a performance of over 0.8 Mio. km. No information, however, is available on the further use of these buses. The value of 1 Mio. km used for exemplification is based on the assumption of a continued use of a relevant share of buses after their first use phase.

Tab. 6: Life-time performance of city buses

Source	Annual performance [km]	Years in operation	Life-time performance [km]
[BVG 2002]		12 - 14	800'000
[KING & HUTTON 2000]	84'000		
[MAN 2002]	50'000 – 80'000	8 - 15	400'000 – 1'200'000
[VDV 2002]	60'000	10 - 14	600'000 – 1'000'000
[WMATA 2002]		15	> 672'000
			IFEU 2003

Tab. 7: Overview of data for exemplification of an average city bus

Fuel consumption (l/100 km)	**40**
Weight (t)	**15**
*Specific fuel savings (l/(100 km*100 kg))*	**0.15**
Relative energy savings (%/10 %)	**5.6 %**
Life-time performance (km)	**1'000'000**
Life-time final energy savings (MJ)	**54'000**
Life-time primary energy savings (MJ)	**62'000**
Life-time CO_2 savings (t)	**4.5**
Source: IFEU 2002 from various sources	IFEU 2003

The **life-time primary energy savings** are much higher for city buses than for passenger cars. This is due to the **combination of high specific fuel savings and a high life-time performance**. Data quality, however, is much lower in comparison to data for passenger cars. Especially the specific fuel savings used for city buses are estimates without scientific chargeable tests or simulations.

5.3 Long distance buses

Long distance buses are similar to standard city buses in technical specifications, but, due to a more comfortable interior, slightly heavier. A net **weight of 18 t** will be used for exemplification.

Fuel consumption will be less on highways and rural main roads than in an urban use pattern. An analysis of extensive tests ([LASTAUTO OMNIBUS]) as well as calculations of the average fuel consumption in Germany resulted in a value of **30 l of diesel fuel** consumed per 100 km ([TREMOD 2001]) which is used for exemplification. A similar value of 29 l is also stated by [GREENFLEET 2002].

5.3.1 Specific energy savings

Long distance buses are mainly used for interurban travel in a more steady flow of traffic. Weight induced energy savings are therefore lower than for city buses. Estimates from [MAN 2002] state fuel savings of 0,04 l for a 100 kg weight reduction. This value amounts 20 % of the fuel savings stated for the standard city bus. Therefore also relative energy savings in the range of 2.4 % are lower than assumed for the city bus.

Tab. 8: Specific and relative fuel savings of long distance buses

Source	Specific fuel savings [l/(100 km*100 kg)]	Relative energy savings [%]
[MAN 2002]	0.04	2.4
		IFEU 2003

5.3.2 Life-time performance and energy savings

Long distance buses are generally only used for a few years by major bus operators. Afterwards, due to customer demands in respect to comfort, many buses are sold to smaller operators or exported. Manufacturers assume that these buses have an annual performance of about 100’000 to 120’000 km and are sold after 3 to 6 years ([MAN 2002]). These figures are also confirmed by Internet trade markets (e. g. http://www.yakoub.de/index.html; http://cat.workingwheels.com; http://www.used-buses.net) which sell many buses of this age and with the same performance. Some vehicles are sold with a performance of up to 1.2 Mio. km. Estimates of the Association of German Transport Operators (“Verband Deutscher Verkehrsunternehmen” [VDV 2002]) state life-time performances of 0.8 to 1.1 Mio. km in Germany. The “Motorcoach Census 2000” of the American Bus Association ([ABA 2000]) states that the average bus travelled about 81’000 km in 1999. The range of annual performance, however, is between less than 16’000 km and over 160’000 km. The average value is in line with the values stated by the Association of German Transport Operators ([VDV 2002]).

Tab. 9: Life-time performance of long distance buses

Source	Annual performance [km]	Years in operation	Life-time performance [km]
[ABA 2000]	80’000		
[GREENFLEET 2002]	54’000		
[MAN 2002]	100'000 - 120’000	3 - 6	300’000 - 720’000
[VDV 2002]	80’000	10 - 14	800’000 - 1’120’000
			IFEU 2003

A life-time performance of 1.2 Mio. km is assumed for a typical long distance bus. This estimate already considers that some buses are exported to developing countries and achieve even higher life-time performances.

Tab. 10: Overview of data for exemplification of average long distance bus

Fuel consumption (l/ 100 km)	**30**
Weight (t)	**18**
*Specific fuel savings (l/(100 km*100 kg))*	**0.04**
Relative energy savings (%/10 %)	**2.4 %**
Life-time performance (km)	**1’200’000**
Life-time final energy savings (MJ)	**17’000**
Life-time primary energy savings (MJ)	**20’000**
Life-time CO_2 savings (t)	**1.4**
Source: IFEU 2002 from various sources	IFEU 2003

The life-time primary energy savings are lower compared to city buses, despite the high life-time performance. This is due to lower specific energy savings which amount for only about 25 % of the specific energy savings of the standard city bus.

5.4 Articulated Trucks

Trucks vary from light-duty to heavy-duty and articulated trucks. Trucks may also be used in different ways from urban delivery use to international long distance transport. An **articulated commercial truck with an average load and maximum total weight of 40 t** will be considered here. An articulated truck is composed of a tractor and a trailer. Large trucks are the dominant modes of road transport in Europe as well as the U.S. and account for a significant portion of the transportation sector's fuel usage. It is assumed that these trucks mainly drive on highways.

5.4.1 Specific energy savings

Either direct or indirect energy savings can be achieved by weight reduction. If "*… the vehicle is lighter, energy use for hauling is reduced (if the cargo is volume-limited), or additional cargo can be carried (if weight-limited). In either case, the energy use per ton-mile carried is reduced*" [STODOLSKY et al.1998]. We will deal with the two options for energy savings separately. First we will discuss the direct fuel savings by weight reduction (for volume-limited cargo) and afterwards indirect fuel savings by additional cargo (for weight limited cargo).

Volume-limited cargo

Fuel savings by weight reduction are estimated **by extrapolation** of the energy consumption of trucks with different loads and by considering the share of aerodynamic resistance and other resistance factors on the fuel consumption. A comparison with long distance buses is also undertaken.

The fuel consumption of trucks is highly dependent on the load. The values in **Tab. 11** are based on tests of today's articulated trucks and show that the fuel consumption of a fully loaded truck (40 t) is more than 30 % higher for highways and even 60 % higher for urban roads compared to the empty truck. On the basis of [IFEU & SGKV 2002], the **specific fuel savings** on a highway by a weight reduction of 100 kg are estimated to be around **0.038 l/ 100 km**. This extrapolation may be critical due to the different driving behaviour depending on the load, but has also been suggested by experts ([EBERLE 2002]).

Tab. 11: Fuel consumption of articulated trucks

Load of Truck	Total weight [t]	Highway [l/100 km]	Rural main roads [l/100 km]	Urban roads [l/100 km]
Empty (0 % load)	14 t	29.3	30.4	37.1
Average (47 % load)	27 t	34.0	36.0	47.7
Full (100 % load)	40 t	39.2	42.4	59.6
*Extrapolation [l/(100km*100kg)]*		0.038	0.046	0.086
Source: [IFEU & SGKV 2002]				IFEU 2003

Approximations may also be made from the share of the weight independent aerodynamic resistance of the total resistance. The average **share of aerodynamic resistance** for articulated heavy trucks at highway speeds is estimated in the range of 60%

[IEA & OECD 1993] and 65 % ([McCALLEN et al. 1999]). This would signify relative fuel savings of 4 % or 3.5 % for a 10 % weight reduction. For a truck with an average load, a fuel consumption of about 35 l/ 100 km and a total weight of about 27 t, specific fuel savings are about **0.05 l/ (100 km*100 kg).** For urban trucks the share of aerodynamic resistance will be rather lower and therefore the specific weight induced fuel savings higher. Results from the Cooperative Automotive Research (CAR) Programme suggest 3.4 % relative energy savings ([FCVT 2000]), which is in the same range as our extrapolation and the value derived from aerodynamic resistance. These values are also in the same range as the fuel savings which have been estimated by [MAN 2002] for long distance buses. Because the driving pattern and the aerodynamic resistance are similar, we use 0.04 l/ 100 km fuel savings for a 100 kg weight reduction.

Tab. 12: Specific fuel and end energy savings for articulated trucks by estimation method

Approximation method	Specific fuel savings l/(100 km*100 kg)	Relative energy savings (%)
Extrapolation	0.038	2.9
Aerodynamic resistance (65 %)	0.05	3.5
[FCVT 2000]		3.4
Source: IFEU 2002 from various sources		IFEU 2003

5.4.2 Life-time performance and energy savings

The conditions of use differ between countries and continents depending on the quality of infrastructure as well as the legislations. An annual performance of new articulated trucks over 150’000 Miles (241’000 km) is common in the U.S. (http://www.trucktraderonline.com). Vehicles with a performance of over 900’000 km and in extreme cases up to 1.4 Mio. km are still sold for further use.

Tab. 13: Life-time performance of long articulated commercial trucks

Source	Annual performance (km)	Years in operation	Life-time performance (km)
[ATA 1999]	> 100’000		
[BGL 2002]	130’000	7	910’000
[GREENFLEET 2002]	90’000		
[LASTAUTO OMNIBUS]	150’000	4	600’000
[VDA 1998]	120’000		
			IFEU 2003

A class 8 truck[5] averaged well over 100’000 km in 1996 according to the “American Trucking Association” ([ATA 1999]). The annual performance of articulated long distance trucks in Europe is estimated in the range of 130’000 - 150’000 km with a life-time of 4 to 7 years, but annual performances of up to 200’000 km are common in transcontinental transport [BGL 2002]. It can be assumed that the annual performance of class 8 trucks in long distance transport in the U.S. is in a similar range. These data, however,

[5] gross weight 33'000 lbs or higher

consider only the first use phase. Often vehicles with a performance of over 800’000 km are sold for further use in Europe as well. Therefore it must be assumed that many trucks continue to operate either in the country of first registration or in other countries. The life-time performance will therefore be well over 1’000’000 km, maybe up 1’500’000 km. The exemplification (**Tab. 14**) uses a life-time performance of 1.2 Mio. km. The **life-time primary energy savings** of the articulated truck example will be around **20 GJ** for a 100 kg weight reduction.

Tab. 14: Overview of data for exemplification of articulated commercial trucks (50 % load)

Fuel consumption (l/ 100 km)	**35**
Weight (t)	**27**
*Specific fuel savings (l/ (100 km*100 kg))*	**0.04**
Relative energy savings (%/ 10 %)	**3.1 %**
Life-time performance (km)	**1’200’000**
Life-time final energy savings (MJ)	**17’000**
Life-time primary energy savings (MJ)	**20’000**
Life-time CO_2 savings (t)	**1.4**
Source: IFEU 2002 from various sources	IFEU 2003

Weight limited cargo

Cargo vehicles will normally take a payload up to the maximum allowance if possible (e. g. 40 t for articulated trucks in Germany). In this case the weight reduction permits the **transportation of a higher payload** and thus less vehicle-km are needed to transport a certain amount of goods. Therefore not only the energy consumption due to weight dependent resistance factors is reduced, but the total energy consumption of the saved transport-km. Energy savings for weight limited cargo are therefore higher than energy savings for volume limited cargo.

A weight reduction by 100 kg also allows for a higher payload of 100 kg with the total weight, thus also the energy consumption per vehicle-km, maintained (**Tab. 15**). On the other hand 120’000 t-km transport performance can, based on the assumption of a constant maximum load, be saved during the life-time of the vehicle. This is the equivalent 4600 vehicle-km of fully loaded articulated truck with a fuel consumption of 40 l/ 100 km. This results in **76 GJ primary energy** savings in this extreme case.

Tab. 15: Life-time performance with different payloads

Net vehicle weight [t]	Maximum payload [t]	Life-time transport performance [t-km]
14	26	31’200’000
13.9	26.1	31’320’000
Source: IFEU 2002 from various sources		IFEU 2003

In this extreme scenario more than three times the direct energy savings could be achieved. [STODOLSKY et al.1998] concluded that a weight reduction of about 1t would decrease the fuel use of weight limited transport per t-km by more than 3 %. For the same life-time performance as assumed above, this would result in **59 GJ primary energy savings**, a similar figure as calculated above. In reality, the energy savings will be lower, because "*… the maximum benefit of increased payload efficiency is not realized for loads that occupy the maximum volumetric capacity of the vehicle unless the maximum allowable weight is reached. Given that a significant portion of freight transported by heavy trucks is volume-limited … estimates of the benefits of reduced tare weight need to reflect this reality*" ([FCVT 2000]). The total energy savings including energy savings by a higher payload will only be significantly higher than direct energy savings, if the truck drives a high share of the life-time performance with a full load. If we assume 10 % weight limited transport and 90 % volume limited transport, life-time energy savings for our example will be around **25 GJ as opposed to 20 GJ** for volume limited transport only.

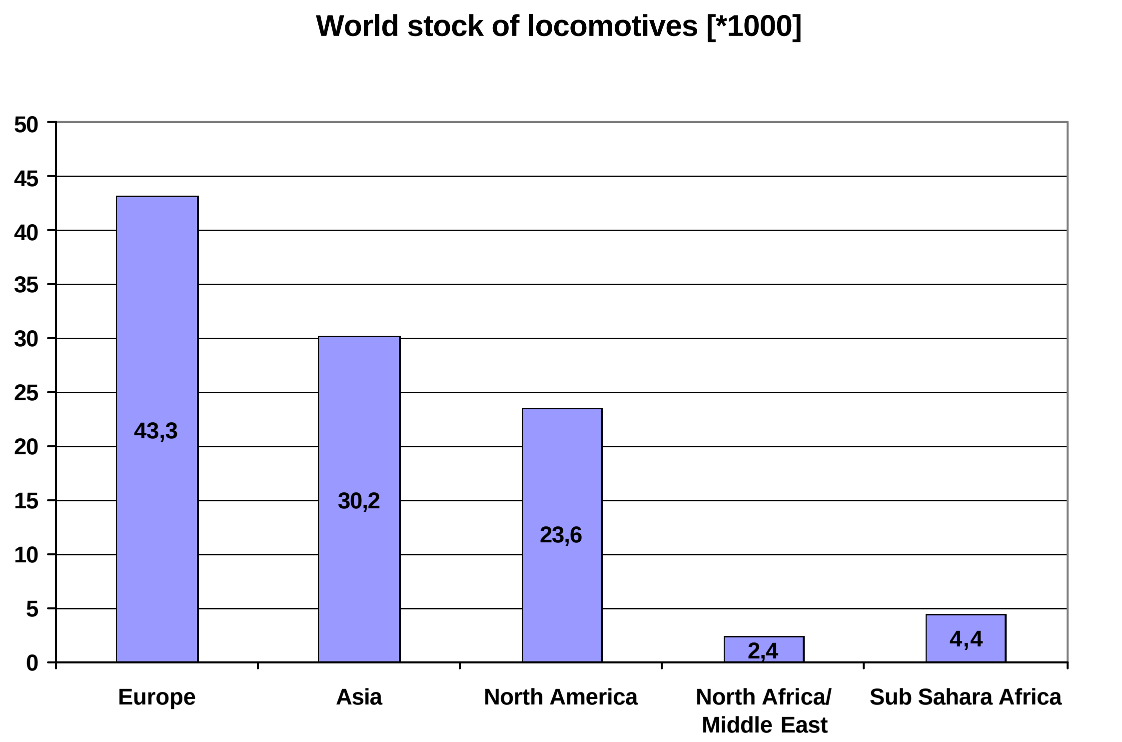
Tab. 16: Life-time energy savings of volume and weight limited transport with articulated trucks

	Volume limited transport	**Weight limited transport**
Life-time primary energy savings	20 GJ	76 GJ
Share of vehicle-km	90 %	10 %
Life-time primary energy savings	25 GJ	
Source: IFEU 2002 from various sources		IFEU 2003

6 Rail vehicles

Judging from the world stock of locomotives, **rail transport systems are of highest importance in Europe, followed by Asia and North America** (**Chart 10**). Data for multiple unit sets reflects a similar picture ([UIC 2000]). It is therefore not surprising that many data have been gathered from Europe and will be discussed in this section.

Chart 10: World stock of locomotives



Source: [UIC 2000] IFEU 2003

Trains are composed of several elements, generally locomotives and rail cars. Since rail cars do not have an engine of their own, all energy will be consumed and saved via the locomotive. Therefore, whole trains will be considered for a realistic estimate of the energy savings by weight reduction. These trains, however, will show **great variations in terms of weight and energy consumption**, mainly **depending on the number of rail cars** they are composed of. „*It is* [therefore] *proposed that the energy consumption be used in the units of kJ/tonne-km. By making the consumption mass specific, the major factor in determining the energy consumption, the train mass, has been normalized out of the calculation. In these terms, energy consumption for different train types becomes more similar, and correlations based on mass specific energy consumption will be applicable to a wider range of trains*" [JORGENSEN & SORENSON 1997]. **Final energy savings for rail vehicles are** thus much rather **stated as relative energy savings** in % final energy savings per 10 % weight reduction [%/10 %] instead of kJ or kWh per 100 km and 100 kg weight reduction. This procedure allows to calculate the specific energy savings directly from the specific energy consumption.

Mainly electric trains have been investigated because they are the most common options in Europe with a high data availability. First we will discuss the relative energy savings for all rail vehicles in % per 10 % weight reduction. Afterwards, the following train types and their average energy consumptions and savings will be dealt with separately:

- Short distance passenger trains
  - o Subways/ Urban trains (electric)
  - o Regional trains (electric)
- Long distance passenger trains
  - o Average passenger trains (electric)
  - o High speed trains (electric)
- Long distance freight trains
  - o Electric freight trains
  - o Diesel freight trains

6.1 Relative energy savings for rail vehicles

Only few tests and simulations have been carried out for the relative energy savings of rail vehicles ([BÜTTNER 1998], [BÜTTNER & HEYN 1999], [EHINGER et al. 2000]). **Tab. 17** shows the existing data. The weight "*… is most important for stopping trains, in particular commuter and local trains stopping each 2-4 km. In such cases repeated accelerations may contribute to 70-80 % of energy consumption*" ([ANDERSSEN 2000]). Data for **short distance** regional trains and subways/ urban trains are therefore on the **high end of the spectrum** and range **between 6.6 % and 8.6 % for a 10 %** weight reduction. Two different values are stated for subways and urban trains, which may be due to energetic recovery systems, the age of trains and the geographical location. Subways and urban trains can be assumed to have higher relative energy savings than regional trains because of their more frequent accelerations. Therefore 8 % relative energy savings will be used for subways and 7 % for regional trains.

High speed passenger trains are on the low end of the spectrum due to their high and steady speed. Relative energy savings for normal long distance passenger trains will be a little bit higher, but still considerably lower than for short distance trains. A figure of **4 % will be used for the average long distance passenger train**. This figure is also in line with the share of aerodynamic resistance consuming more than 50 % of the total energy consumption according to [ANDERSSEN 2000] and [BRUNNER & GARTNER 1999].

Tab. 17: Overview of relative energy savings for rail vehicles

Train type	Source	Relative energy savings [%/ 10%]
Subway/ Urban train	[EHINGER et al. 2000]	8.6
Subway/ Urban train	[BÜTTNER & HEYN 1999]	6.6
Regional train	[BÜTTNER & HEYN 1999]	7
High speed passenger train	[BÜTTNER & HEYN 1999]	3.2
		IFEU 2003

Currently **no studies are available** on the relative direct energy savings by weight reduction **for freight trains**. Communication with experts ([LUKASZEWICZ 2002], [EHINGER 2002]) showed that indirect rather than direct energy savings are the primary focus of a weight reduction for freight trains. Direct energy savings have thus not been studied. From the average consumption of a DB long distance train with 1000t gross weight of 21 Wh/ gross t-km, the energy consumption (EC) as a function of the weight in analogy to the method in [SCHWANHÄUSSER et al. 1986] and [TEMA 2000] for electric traction [IFEU & SGKV 2002] (see values in **Tab. 25**) has been estimated:

$$\mathbf{EC_{train}\ [wh/\ km] = 315 * M_{train}\ [t]^{0,6}}$$

EC_{train} specific energy consumption per train-km
M_{train} total gross weight of train in t

Specific energy savings can be calculated for a 10 % weight reduction. For this calculation it is not considered if the weight will be reduced at the locomotive or the wagons. The energy consumption will be reduced by 6 % for a 10 % weight reduction.

According to [ANDERSSEN 2000], **aerodynamic resistance still contributes 40 - 50 % of the total energy consumption** of average European freight trains, because of disadvantageous aerodynamics. This supports the calculation above, though it must be noted that aerodynamic resistance is also linear dependent on the length of the train [LUKASZEWICZ 2001]. A conservative value **of 5 % will be used for exemplification**, because the share of acceleration resistance will be lower for U.S. freight trains as for European freight trains. This value is also plausible, because it is between the values for passenger trains with higher speed and the regional trains with more stops. Freight train characteristics can also be very different, e. g. with much **longer and slower trains in the U.S.** compared to European trains. Indirect energy savings by a higher cargo capacity are of great importance. The indirect energy savings will be dealt with in the corresponding section. The values for relative energy savings in **Tab. 18** will be used as reference data for the different rail vehicle categories.

Tab. 18: Overview of relative specific energy savings for exemplification

Train type	Relative energy savings [%/ 10%]
Subways/ Urban trains	8
Short distance trains	7
Long distance passenger trains	4
High speed passenger train (ICE)	3.2
Long distance freight trains (electric)	5
Long distance freight trains (diesel)	5
Source: IFEU 2002 from various sources	IFEU 2003

6.2 Short distance passenger trains

6.2.1 Specific energy consumption

Subways/ urban trains and regional trains will be considered as short distance passenger trains. They will be **differentiated in terms of specific energy consumption, specific energy savings and life-time driving performance**. It is assumed that all these vehicles are electric. The specific energy consumption for both vehicles is stated by the literature in the range of 200 to 340 kJ/ t-km (**Tab. 19**). Most values, however, congregate around 250 kJ/ gross t-km. This results in specific energy savings of about **2.000 kJ for subways/urban trains** and **1.750 kJ for regional trains** (**Tab. 19**).

Tab. 19: Final energy consumption of short distance trains

Source	Train type	Final energy [kJ/ gross t-km]
[ALBERT et al. 1997]	Subways	340
[BÜTTNER & HEYN 1999]	Regional trains	250
[BÜTTNER & HEYN 1999]	Subways	253
*[IFEU 2002b]**	Regional train	190-195
[JORGENSEN & SORENSON 1997]	Urban trains	200-270
[JORGENSEN & SORENSON 1997]	Subways	261
Value used in this study for short distance passenger trains		250
		IFEU 2003

6.2.2 Life-time performance and energy savings

For subways, a comprehensive worldwide survey has been undertaken by the International Association of Public Transport (UITP). The average age of vehicles is 15.6 years and the average annual performance 101'000 km ([ALBERT et al.]). Assuming a life-time of 30 years, the life-time performance will be around 3'000'000 km. According to [BÜTTNER & HEYN 1999], regional trains have an annual performance of about 150'000 km over a period of about 30 years. Other sources [INFRAS 1999a], however, state a life-time for rail cars of up to 50 years. After 25 years, these vehicles will undergo a total revision and then typically be applied not as express train, but as regional train rail cars. Data on life-time performances of different short distance trains are listed in **Tab. 20**. The average age of commuter locomotives and passenger coaches in the U.S. is available from the Bureau of Transportation Statistics [BTS 2001]. While locomotive have a long time average age of almost 15 years, coaches reach even 19 years. A total life-time of about 30 years for locomotives and almost 40 years for coaches can thus be concluded.

Tab. 20: Performance of short distance trains

Source	Vehicle type	Annual performance [km]	Years in operation	Life-time performance [Mio. km]
[ALBERT et al. 1997]	Subway	100'000	30	3
[BÜTTNER & HEYN 1999]	Urban train	130'000	30	4
[BÜTTNER & HEYN 1999]	Regional train	150'000	30	4.5
[SCHMID et al. 1999]	Urban train	90'000	30	2.7
[INFRAS 1999a]	Locomotive			9.6
[INFRAS 1999a]	Regional train			1.16
[FBS 2002]	Tram	50'000	30	1.5
[FMT 2002]	Tram		30 - 60	over 2
				IFEU 2003

Values of 3 Mio. km for the subway/ urban train and 4 Mio. km for the regional train (considering higher speed and less stops) are used for the exemplification. Life-time energy savings for regional trains based on these assumptions are slightly higher than for subways/ urban trains.

Tab. 21: Overview of data for exemplification of short distance passenger trains

	Subway/ Urban train	Regional train
Specific final energy consumption [kJ/gross t-km]	250	250
Relative energy savings [%/10%]	8	7
*Specific final energy savings (kJ/ (100km*100kg))*	2'000	1'750
Life-time performance (km)	3'000'000	4'000'000
Life-time final energy savings (MJ)	60'000	70'000
Life-time primary energy savings (MJ)	130'000	150'000
Life-time CO_2 savings (t)	7.1	8.3
Source: IFEU 2002 from various sources		IFEU 2003

6.3 Long distance passenger trains

6.3.1 Specific energy consumption

Long distance passenger trains will be differentiated in normal passenger trains with maximum speeds between 150 and 200 km/h and high speed trains with maximum speeds over 200 km/ h. [JORGENSEN & SORENSON 1997] have analysed the specific end energy consumption of various European passenger trains. The overview in **Tab. 22** shows that the values congregate around 80-110 kJ/ gross t-km for a high speed train like the ICE and around 100 to 160 kJ/ gross t-km for a normal passenger train. While [JORGENSEN & SORENSON 1997], [KÖSER et al. 2002] and [IFEU 2002b] derived average values for an ICE, [BÜTTNER & HEYN 1999] are using data from a specific testing relation. This may explain for the different figures for the ICE. Differences between the countries may be due to different use patterns, train technologies or analysis methods. Much higher values for trains in Switzerland is due to gradients in the route characteristics. The lower values for the German IC/ EC in comparison with the Swedish and Danish train probably results from less frequent stops of the IC/ EC. Passenger trains out of Europe are believed to have a lower specific energy consumption, due to slower and more steady speeds. We will therefore use a value of **100kJ/gross t-km for both trains**. This value has also been stated by the only source covering both options ([JORGENSEN & SORENSON 1997]) with a similar methodology.

Tab. 22: End energy consumption of long distance passenger trains

Source	Train type	Specific energy consumption [kJ/ gross t-km]
[BÜTTNER & HEYN 1999]	ICE (Germany)	82
*[IFEU 2002b]**	ICE (Germany)	110
[JORGENSEN & SORENSON 1997]	ICE (Germany)	99
*[KÖSER et al. 2002]**	ICE (Germany)	100
[JORGENSEN & SORENSON 1997]	IC/ EC (Germany)	99
[JORGENSEN & SORENSON 1997]	IC3/ APT (Denmark)	120
*[INFRAS 1999a]***	IC 2000 (Switzerland)	162-180
[JORGENSEN & SORENSON 1997]	RC (Sweden)	109-124
Value used in this study for long distance passenger trains		100

* IFEU calculation based on the source ** mountainous routes IFEU 2003

6.3.2 Life-time performance and energy savings

The ICE has a very high life-time performance due to the high annual performance from 450’000 km ([EHINGER et al. 2000]) up to over 500’000 km ([BÜTTNER & HEYN 1999, INFRAS 1999a]) and thus a daily performance of over 1300 km. The life-time of the ICE trains is estimated around 30 years, because of intensive maintenance and mechanical wear, and the life-time performance will therefore be around 15’000’000 km.

Normal passenger trains have a lower annual and daily performance, but in some cases a higher life-time. The long term average age of Amtrak vehicles in the U.S. is about 13 years for locomotives and 21 years for rail cars ([BTS 2001]). A realistic estimate of up to 30 years life-time for locomotives and about 40 years for rail cars can be concluded from this data as well. An allocation of the annual Amtrak train km to the number of locomotives available for service results in an annual performance of over 200'000km and thus over 6 million km life-time performance ([BTS 2001]). Railway associations in state a life-time performance of about 8'000'000 km for the most common locomotives [EFH 2002], while [INFRAS 1999a] even uses a value of 9.6 Mio. km. The life-time performance of long distance passenger trains seems to be higher in Europe due to a busier railway system. Since passenger rail transport is most important in Europe a conservative European value of 8'000'000 km for the life-time performance is used for exemplification.

Tab. 23: Performance of short distance trains

Source	Vehicle type	Annual performance [km]	Years in operation	Life-time performance [Mio. km]
[EFH 2002]	Locomotive			8
[BTS 2002]	Locomotive	200'000	30	6
[INFRAS 1999a]	Locomotive			9.6
[INFRAS 1999a]	ICE 2			15
[EHINGER et al. 2000]	ICE	450'000		
[BÜTTNER & HEYN 1999]	ICE	500'000	30	15
				IFEU 2003

The **life-time primary energy savings** are higher for **high speed trains (104 GJ)** compared to **average passenger trains with 83 GJ**. This results from the higher life-time performance of the high speed trains.

Tab. 24: Overview of data for exemplification of long distance passenger trains

	High speed train (ICE)	Normal passenger train
Specific final energy consumption [kJ/gross t-km]	100	100
Relative energy savings [%/10%]	3.2	4
*Specific final energy savings (kJ/ (100 km*100 kg))*	320	400
Life-time performance (km)	15'000'000	8'000'000
Life-time final energy savings (MJ)	48'000	32'000
Life-time primary energy savings (MJ)	100'000	70'000
Life-time CO_2 savings (t)	5.7	3.8
Source: IFEU 2002 from various sources		IFEU 2003

6.4 Long distance freight trains

Freight trains differ significantly in size (number of rail cars) and use pattern. The main factors of influence on the energy consumption are the

- traction type (diesel/ electric),
- train length and total weight,
- route characteristics,
- driving behaviour (speed and acceleration) and
- aerodynamic resistance.

Freight trains in the U.S. are on the average assumed to be **longer and slower than in Europe** and generally diesel trains. The main indicator for calculating energy and emission savings of rail transport is the energy consumption of the complete train, which is depending on the total weight of the train.

6.4.1 Direct energy savings for volume limited cargo

Different average energy consumption data is available which already includes the main influencing factors ([IFEU & SGKV 2002]), such as the

- average annual consumption of typical freight transport of different companies,
- average specific consumption of the DB (German Railways, [DB 1993]) and
- calculation models for specific energy consumption of rail transport ([SCHWANHÄUSSER et al. 1986], [TEMA 2000]).

The differences are considerable, but it must be noted that even for the specific energy consumption an "*… important parameter is the total train weight. The higher the weight of the train the lower is the specific energy consumption per gross ton km*" [IFEU & SGKV 2002]. This may also explain the low specific energy consumption for the US freight trains which are, on the average, believed to be longer and heavier (here about ten times heavier in comparison with the freight trains studied by [SCHWANHÄUSER et al. 1990]).

There is no empirically representative "real" energy consumption data for rail transport. The specific final energy consumption of diesel and electric freight trains is very different. The influence of the different efficiencies in energy supply, however, leads to smaller differences in terms of primary energy consumption. **Tab. 26** gives an overview on the specific energy consumption of different freight trains. We determine the consumption from typical average consumption data; additionally, important parameters for the energy consumption are considered. An important parameter is the total train weight. The higher the weight of the train the lower is the specific energy consumption per gross t-km. This dependency, as presented in [SCHWANHÄUSER et al. 1990] and [TEMA 2000], is also a result of modelling train transportation and was analysed in [IFEU 1999].

Tab. 25: Final energy consumption of long distance freight trains

Source	Train type	kJ/gross t-km
[IFEU & SGKV 2002]	Freight trains (electric) 600 t	96
[IFEU & SGKV 2002]	Freight trains (electric) 1000 t	76
[IFEU & SGKV 2002]	Freight trains (electric) 1500 t	63
[TEMA 2000]	Freight trains (electric) 1000 t (Denmark)	61
[DB 1993]	Freight trains (electric) long distance	71-93
[JORGENSEN & SORENSON 1997]	Freight trains (electric)	85-102
[SCHWANHÄUSER et al. 1990]	Freight trains (electric)	71-87
[SCHWANHÄUSER et al. 1990]	Freight trains (diesel)	162-201
[STODOLSKY et al. 1998]	Freight trains (diesel) U.S.	91
		IFEU 2003

The energy consumption (EC) has also been estimated as a function of weight in analogy to the method in [SCHWANHÄUSER et al. 1986] and [TEMA 2000] for electro traction [IFEU & SGKV 2002] (see values in **Tab. 25**):

$$\mathbf{EC_{train}\ [wh/\ km] = 315 * M_{train}\ [t]^{0,6}}$$

EC_{train} specific energy consumption per train-km
M_{train} total gross weight of train in t

A value of 5 % energy savings for a 10 % weight reduction, which is independent of the total train weight, has been identified for exemplification (see section **6.1**) and 80 kJ/gross t-km will be used for electric trains and 180 kJ/gross t-km for diesel trains. Since a figure of 8’000’000 km life-time performance has been identified for the most common locomotives, this will be used for long distance freight trains as well. In our example the **life-time primary energy savings** for a 100 kg weight reduction are about **70 GJ for electric and 83 GJ for diesel trains** (**Tab. 26**).

Tab. 26: Overview of data for exemplification of long distance freight trains

	Freight train (electric)	Freight train (diesel)
Specific final energy consumption [kJ/gross t-km]	80	180
Relative energy savings [%/ 10%]	5 %	5 %
*Specific final energy savings (kJ/(100km*100kg))*	480	1080
Life-time performance (km)	8’000’000	8’000’000
Life-time final energy savings (MJ)	32’000	72’000
Life-time primary energy savings (MJ)	70’000	83’000
Life-time CO_2 savings (t)	3.8	6.1
Source: IFEU 2002 from various sources		IFEU 2003

6.4.2 Indirect energy savings for weight limited cargo

A weight reduction by 100 kg also allows for a higher payload of 100 kg with the total weight, thus also the energy consumption per vehicle-km, maintained (**Tab. 27)**. An **example from freight transport in the U.S.** has been treated by [STODOLSKY et al. 1998]. Diesel locomotives are used and **trains are very long** with at least three locomotives and 68 railcars. At an **average speed of 35 km/ h** freight trains are also very slow. A **literature survey of the fuel consumption** for freight trains in the U.S. found a range between 0.003 and 0.015 l/ t-km or **107 - 536 kJ/t-km** end energy. A typical **baseline train** with 100 (67.5 t) railcars and nearly 3000 t of load consumes about 0.005 l/ t-km or 178 kJ/ t-km. With a total weight of 7000 t the specific end energy consumption is about 91 kJ/ gross t-km. This end energy consumption is much lower than the value identified for European freight trains, because of the much higher total weight and the more steady and slower speed of the baseline train. The locomotives have a very long life-time of 30-40 years.

Tab. 27: Life-time transport performance with different maximum load

Net vehicle weight [t]	Payload [t]	Life-time transport performance [t-km]
4000	3000	24’000’000’000
3999,9	3000.1	24’000’800’000
Source: IFEU 2002 from various sources		IFEU 2003

A 100 kg weight reduced freight train can have an up to 800’000 t-km higher life-time transport performance (**Tab. 27**). This is the equivalent of 267 vehicle-km or 335 GJ of final energy and 386 GJ primary energy during its life-time. For this train, more than **four times the direct energy savings** (about 83 GJ) can be achieved indirectly. In reality, the indirect energy savings will be lower, because freight trains do not always carry the maximum load. A full load will normally only be achieved outward bound but not during the return trip. On the return trip, however, direct energy savings will be achieved anyway. In reality the share of indirect energy savings determines the increase of energy savings compared to direct energy savings only. If we assume 20 % weight limited transport and 80% volume limited transport our diesel freight train example would achieve 143 GJ and a similar electric freight train about 121 GJ life-time primary energy savings.

Tab. 28: Life-time energy savings of volume and weight limited transport with freight trains

	Volume limited transport	Weight limited transport
Share of vehicle-km	80 %	20 %
Life-time primary energy savings (Diesel freight train)	83	386
Life-time primary energy savings (Diesel freight train)	140	
Life-time primary energy savings (Electric freight train)	70	325
Life-time primary energy savings (Electric freight train)	120	
Source: IFEU 2002 from various sources		IFEU 2003

7 Sensitivity of data

The previous chapters have analysed the weight induced energy savings of 100 kg weight reduced vehicle examples. **Vehicle specifications have been defined and discussed for exemplification**. Apart from the vehicles themselves, especially the use of vehicles (driving pattern and annual performance) can be very different, depending on the respective countries and uses. These differences are also influenced by the standard of infrastructure and exist therefore especially between industrialised and developing countries. The existence or absence of motorways and well paved roads and the general level of traffic have an influence on the driving pattern as well as the annual performance. These **uncertainties significantly affect the results** in respect to weight induced energy savings.

Though there are no hard data for a global average of vehicles and their use, this report has tried to **identify typical vehicles** and usages. These vehicles may be close to the average situation at least for the industrialised countries of Europe and North America, where the most vehicles exist and good data are available. To estimate the discrepancies between the defined typical vehicles and a supposed average vehicle an uncertainty for the parameters is estimated.

The life-time energy and CO_2 savings depend on **two parameters of equal importance, but with different uncertainties**. Both parameters will be increased and decreased by a fixed percentage. The sensitivity to these uncertainties will be calculated based on the assumption of a standardised normal probability distribution of the uncertainties. The calculation thus follows the Gauß formula $\Delta c = \sqrt{(\Delta a^2 + \Delta b^2)}$ for $c = a \cdot b$.

The sensitivity of life-time energy and CO_2 savings have been calculated from the uncertainties as described above. Since scientific chargeable data exist mainly for passenger cars from tests as well as simulations, the uncertainty of specific energy savings is estimated to be around 10 % for passenger cars. For all other vehicles 20 % uncertainty is assumed. For the life-time performance of passenger cars 15 % and for all other vehicles 20 % uncertainty are estimated (**Tab. 29**).

Tab. 29: Sensitivity of life-time energy savings for selected vehicles

Vehicle	**Sensitivity of specific energy savings**	**Sensitivity of life-time performance**	**Sensitivity of life-time energy savings**
Car (gasoline)	10 %	15 %	18 %
Car (diesel)	10 %	15 %	18 %
City bus	20 %	20 %	28 %
Long distance bus	20 %	20 %	28 %
Articulated truck	20 %	20 %	28 %
Subway	20 %	20 %	28 %
Regional train	20 %	20 %	28 %
Long distance passenger train	20 %	20 %	28 %
High speed passenger train	20 %	20 %	28 %
Long distance freight train (electric)	20 %	20 %	28 %
Long distance freight train (diesel)	20 %	20 %	28 %

Source: IFEU estimates IFEU 2003

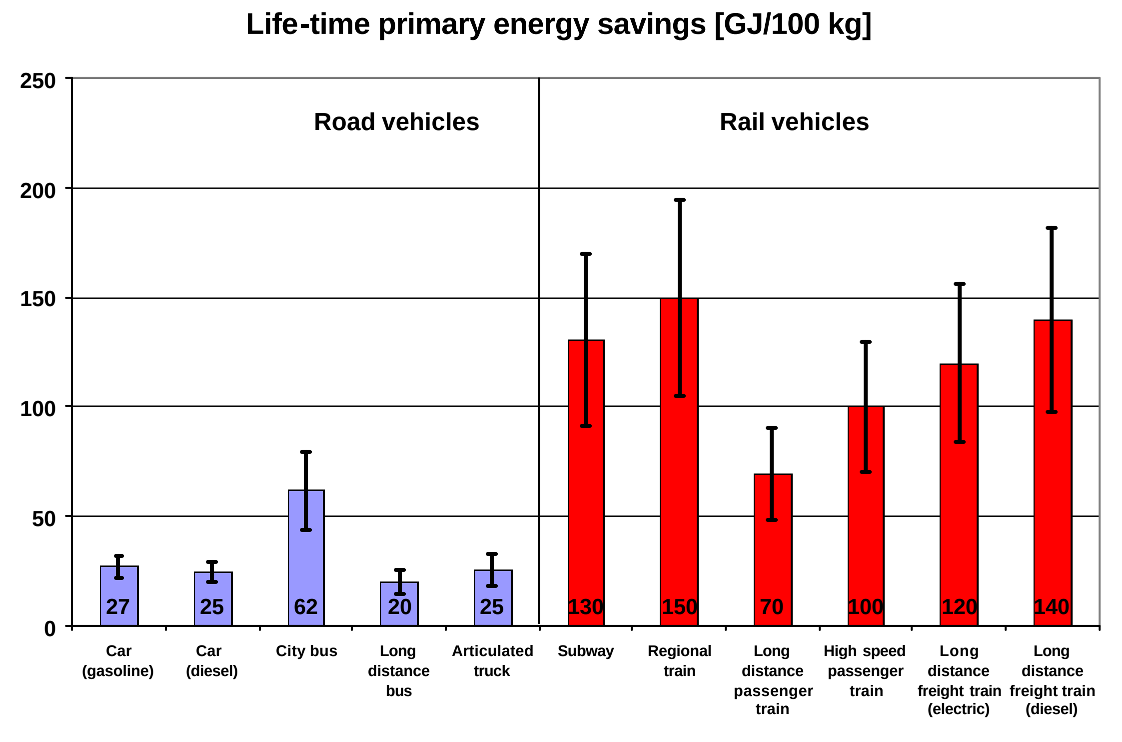
8 Light-weighting potential of transport subsystems

In the preceding sections, specific energy savings, life-time performances and resulting life-time energy savings for different, individual vehicle types were derived. In **8.1** we will summarise these findings. In section **8.2** we will then calculate achievable reductions for the all new registrations of Germany for exemplification. The absolute mass and number of vehicles will now be taken into account.

8.1 Life time energy and CO_2 savings for selected vehicles

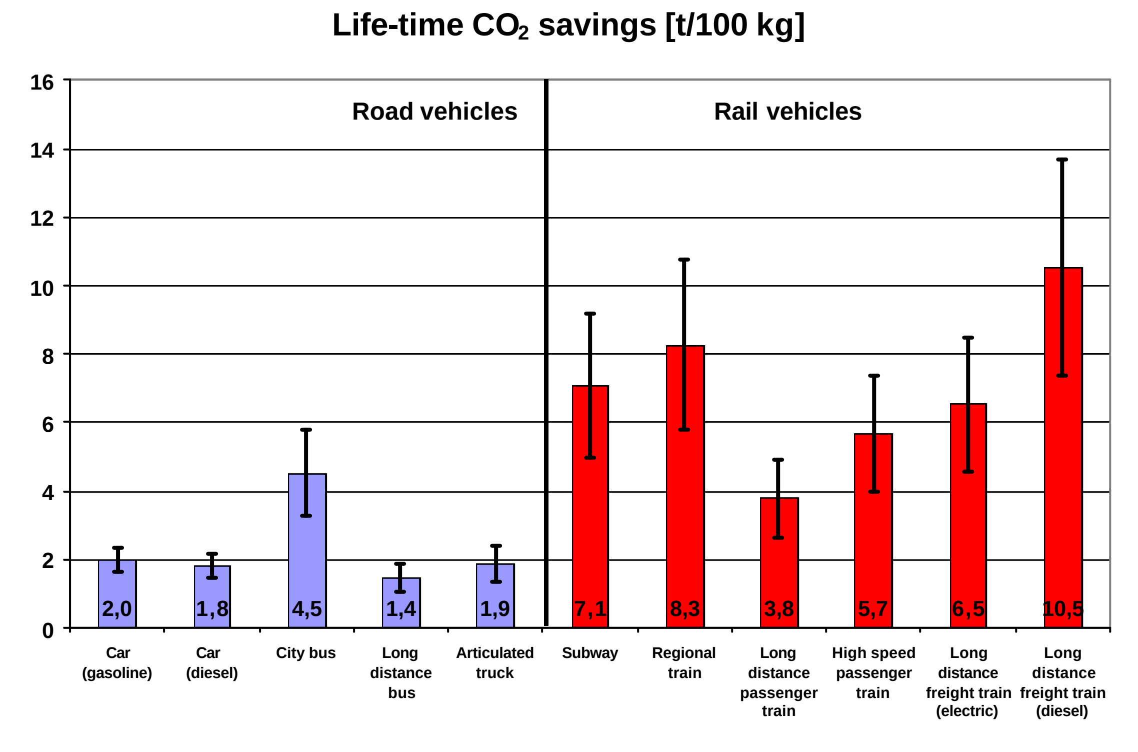
The life-time energy savings are the result of the product of specific energy savings and the life-time performance. They are **generally higher for rail vehicles** compared to road vehicles, mainly due to the significantly higher life-time performance. Regional trains have about six times higher life-time primary energy savings because they have high specific energy savings in addition to a high life-time performance. Only city buses have outstandingly high energy savings among the road vehicles. This is also due to the combination of high specific energy savings in addition to a high life-time performance.

Chart 11: Life time primary energy savings for 100 kg weight reduced vehicles



Source: IFEU 2002 from various sources (Figures rounded) IFEU 2003
Remark: Error ranges signify the sensitivity to uncertainties in basic data

Chart 12: Life-time CO_2 savings for 100 kg weight reduced vehicles



Source: IFEU 2002 from various sources IFEU 2003
Remark: Error ranges signify the sensitivity to uncertainties in basic data

Road vehicles increase their CO_2 saving potentials in comparison to the primary energy savings in our scenario. This is due to the share of nuclear and hydro power, which create almost no CO_2 emissions in comparison with energy derived from fossil fuels. For the life-time CO_2 savings in **Chart 12**, it is also assumed that the electricity mix and the emission factors will remain at their current level over the whole life-time of the vehicle. A steady reduction in the CO_2 emission factor by 50 % over the life-time of the vehicle means that only 75 % of the CO_2 savings stated in **Chart 12** will be achieved. While all figures for road vehicles in **Chart 12** are calculated for fossil fuels, the share of bio-diesel and other alternative fuel options may be changing as well.

In addition to the direct energy savings by a weight reduction stated so far, indirect energy savings can be achieved by freight vehicles by the transportation of a higher payload. In the extreme scenario of a permanent fully loaded truck and freight train, respectively, three and four times the direct energy savings can be achieved. In reality, the indirect energy savings will be lower, because hardly any truck will drive its entire life-time with a full load. The total energy savings including energy savings by a higher payload will only be significantly higher than direct energy savings if the truck drives a high share of the life-time performance with a full load.

8.2 Potential total energy savings contribution of transport subsystem

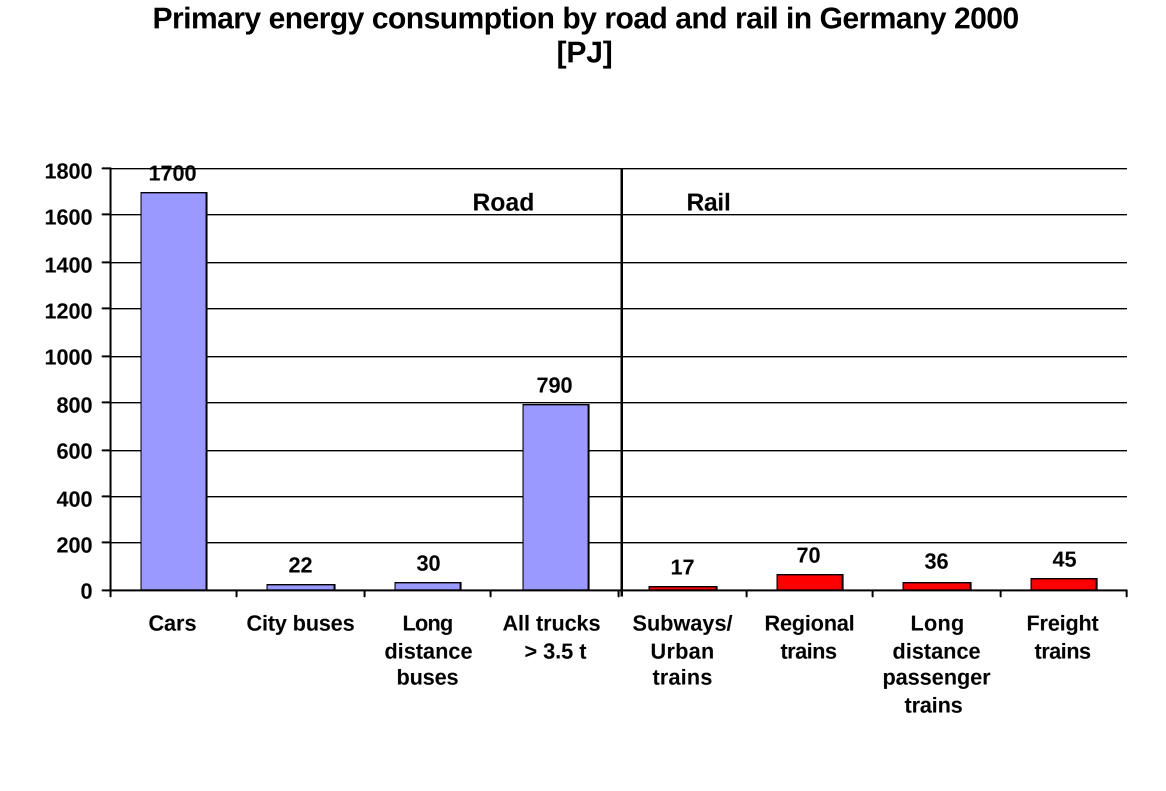
In the preceding section, the potential energy savings by the same absolute weight reduction (100 kg) for **typical single vehicles** have been calculated. To determine the total achievable energy and CO_2 savings by weight reduction we have to take into account the **absolute mass** which can be reduced in one vehicle and the **total number of vehicles**. On the one hand a heavy vehicle like a passenger train has a higher potential for an absolute weight reduction compared to a light vehicle like a passenger car. A general weight reduction of all passenger cars, on the other hand, results in a high total weight reduction due to the great numbers of cars.

To quantify these effects we analyse a **scenario for Germany** and calculate the life-time energy and CO_2 emission savings for an assumed **10 % weight reduction** of all new registrations of the year 2000. It has to be mentioned that these energy and CO_2 savings will be realised during a longer period of time, determined by the life-time of the vehicles. Please note that this study does not deal with the technical realisation and market feasibility of a 10 % weight reduction.

The scenario takes into account that the vehicles described in the preceding sections have a **different share of the total primary energy use** and CO_2 emissions, due to different shares of the transport performance. The calculation shows the significance of the reduction potential for the different vehicle categories.

Today's passenger and freight transport in Germany is **dominated by road vehicles**. Rail transport accounts for only 6 % of the primary energy consumption of road vehicles (**Chart 13**). Road vehicles are dominated by **passenger cars with 63 %** and heavy duty vehicles with 29 % of the primary energy consumption. City and Long distance buses account only for about 1 % of the primary energy consumption each. The different shares of primary energy consumption also point out the different uses and performances of the vehicles which signifies a different potential for weight induced energy and emission savings.

Chart 13: Primary energy consumption by transport systems (Germany 2000)



Source: [TREMOD 2001] (Figures rounded) IFEU 2003

The **total annual primary energy consumption** depends on the vehicle stock, the annual vehicle performance and the specific energy consumption. The energy consumption is also depending very much on the mass of the vehicle. **Vehicle stock, annual performance and total weight** of the vehicles are therefore taken into account by calculating our scenario on the basis of the total annual primary energy consumption. The **share of new registrations**, used to estimate the energy consumption of new vehicles, is taken from [BMVBW 2000] for road vehicles and estimated for rail vehicles on the basis of a life-time of 30 years. In this scenario a steady annual performance and specific energy consumption of all vehicles is assumed. The share of energy consumption by new registrations will therefore 3.33 % for rail vehicles.

A relative weight reduction affects passenger vehicles with small differences in net and gross weight not in the same way as freight vehicles with large differences in net and gross weight. A 10 % reduction of the net weight of a passenger car (1310 kg) with its driver (75 kg) results in 9.5 % reduction of its gross weight. A 10 % net weight reduction of an articulated truck (12 t) with a payload of 14t (average load) results in a 5 % reduction of the gross weight and for a payload of 28 t (full load) only in a weight reduction by 3 %[6]. For long distance and city buses a 9 % reduction of the gross weight is assumed. This is the equivalent of about an average of 20 passengers. The same value is taken for passenger rail vehicles as well. The average ratio between load and gross weight without locomotive for German railways (DB Cargo) is 0.48

[6] Only heavy trucks (> 32 t) are considered in this scenario due to different load to net weight ratios and different driving cycles of light duty trucks

[TREMOD 2001]. A value 55 % net weight share of the total gross weight including locomotive has been calculated. This signifies a 5.5 % reduction of the gross weight for a 10 % net weight reduction.

The **relative energy savings** for a 10 % weight reduction have been derived in sections **5** and **6**. For the heavy trucks and freight trains we use relative energy savings which take into account a 10 % and 20 % share of weight limited transport respectively. The annual savings will be projected to the **total life-time of the vehicles** derived in sections **5** and **6** as well.

Tab. 30: Scenario of life-time primary energy savings for new road vehicles in 2000

Vehicle	Passenger Cars	City buses	Long distance buses	Heavy duty vehicles***
Primary energy consumption (2000) [PJ]	1700	22	30	412
Share of new vehicles*	6.7 %	7.2 %	7.2 %	15 %
Annual energy consumption of new registrations [PJ]	113.1	1.6	2.2	61.9
Reduction of gross weight	9.5 %	9.0 %	9.0 %	5.0 %
Relative energy savings [%/ 10% weight reduction]**	5.7 %	5.6 %	2.4 %	4.0 %
Annual energy savings of 10% weight reduced new registrations [PJ]	6.10	0.08	0.05	1.22
Life-time [years]	15	14	14	10
Life-time primary energy savings [PJ]	91.6	1.1	0.7	12.2
Life-time CO_2 savings [kt]****	6600	83	48	900

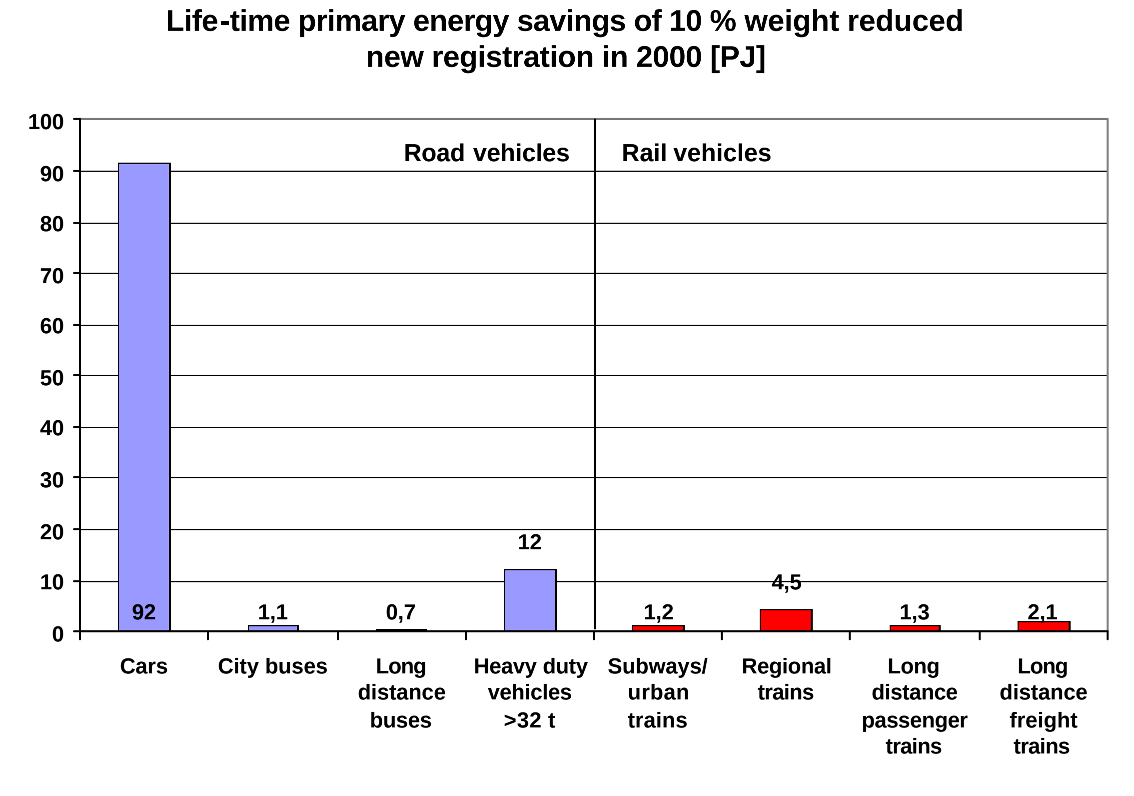
Source: IFEU 2002 from various sources
IFEU 2003
* derived from [BMVBW 2000]
** derived from absolute fuel savings in section 5
*** vehicles > 32 t maximum gross weight
**** Figures rounded

Tab. 31: Scenario of life-time primary energy savings for new rail vehicles in 2000

Vehicle	Subways/ urban trains	Regional trains	Long distance passenger trains	Long distance freight trains
Primary energy consumption [PJ]	17	71	36	45
Share of new vehicles*	3.3 %	3.3 %	3.3 %	3.3 %
Annual energy consumption of new vehicles [PJ]	0.6	2.4	1.2	1.5
Reduction of gross weight	9.0 %	9.0 %	9.0 %	5.5 %
Relative energy savings [%/ 10% weight reduction]	8.0 %	7.0 %	4.0 %	8.7 %
Annual energy savings of 10% weight new registrations [PJ]	0.04	0.15	0.04	0.07
Life-time [years]	30	30	30	30
Life-time primary energy savings [PJ]	1.2	4.5	1.3	2.1
Life-time CO_2 savings [kt]**	73	270	77	130

Source: IFEU 2002 from various sources IFEU 2003
* derived from the assumption of a 30 year operational life-time
** Figures rounded

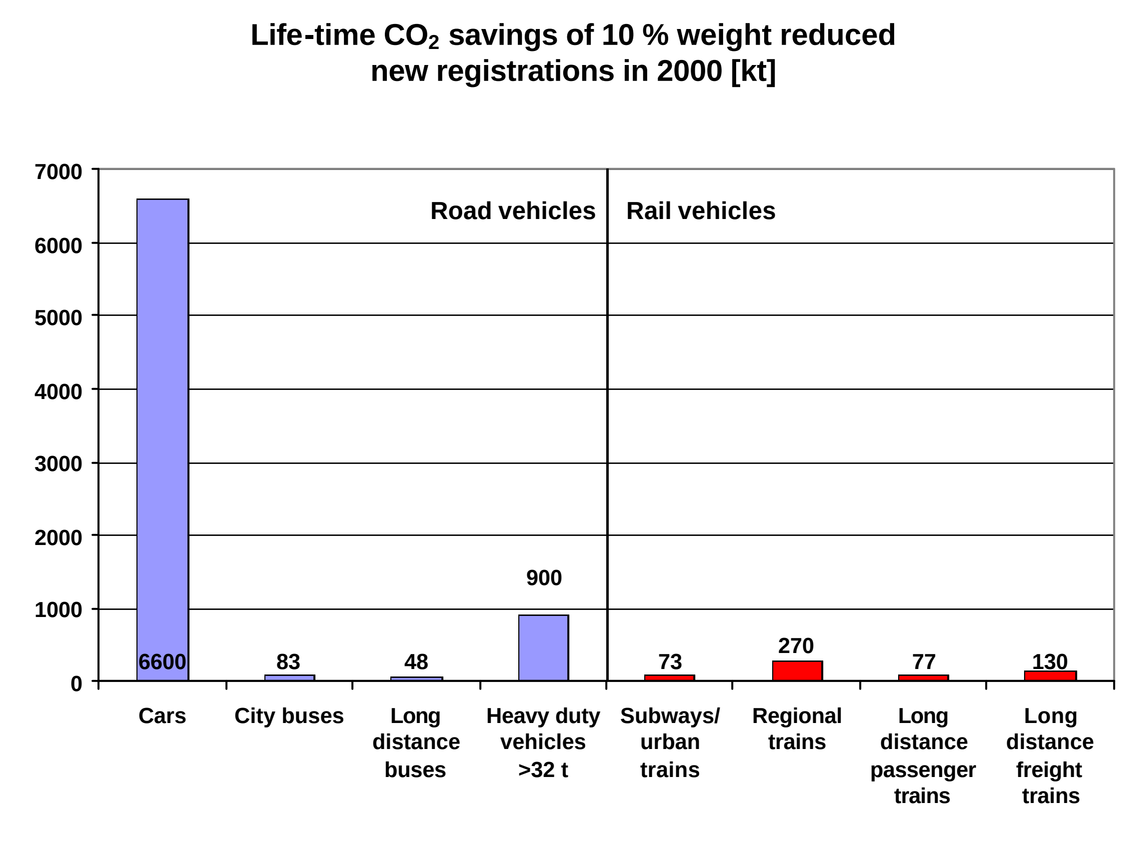
Chart 14: Life-time primary energy savings of 10 % weight reduced new registration in 2000



Source: IFEU 2002 from various sources IFEU 2003

From **Chart 14** it can be concluded that the **highest weight induced energy savings** by a 10 % net weight reduction **can be achieved for the subsystem passenger cars**. This is mainly due to the high total energy consumption of passenger cars due to their great numbers. The **total life-time** primary energy savings of 10 % net weight reduced annual new registrations of passenger cars account for over 5 % of the **total annual** energy consumption of all passenger cars in Germany. All other subsystems have considerably lower energy savings. It has to be noted, however, that only heavy trucks (> 32t) have been considered here. The potential energy savings of all trucks will be higher. Regional trains have the highest savings among the rail vehicles. This is due to their high absolute energy consumption, high relative energy savings and high net weight compared to the gross weight. **Road vehicles increase their CO_2 saving potentials in comparison to the primary energy savings in our scenario**. This is due to the share of nuclear and hydro power, which create almost no CO_2 emissions in comparison with energy derived from fossil fuels (**Chart 15**). For the values in **Chart 15** the energy split and emission factors for Germany 2000 have been used.

Chart 15: Life-time CO_2 savings of 10 % weight reduced annual new registrations



Source: IFEU 2002 from various sources (Figures rounded) IFEU 2003

These results, however, do not reflect the efforts to achieve a weight reduction as such, for instance the impacts of light-weight materials production. This issue has to be analysed within the framework of a Life Cycle Assessment which is beyond the scope of this study.

9 Conclusions

The purpose of this study is to provide an overview on the potential energy savings by a weight reduction of road and rail vehicles. The life-time primary energy savings mainly depend on the specific primary energy savings and the life-time performance.

Though there are considerable differences between the vehicles and within the vehicle categories, the best available data for typical vehicles have been identified and compared. Even with the sensitivities taken into account several trends can be identified. For an absolute weight reduction the main findings are:

- The **life-time energy savings by 100 kg weight reduction are generally higher for rail vehicles** because of the high life-time performance.
- Among the road vehicles **city buses show outstandingly high life-time energy savings** mainly due to the combination of a high life-time performance and high specific energy savings.
- Among the rail vehicles the **short distance trains show high energy savings** despite their lower life-time performance in comparison with long distance trains. This is because of their much higher specific energy savings.
- **Some vehicles have a life-time performance very different from the average vehicle** in the respective category and may therefore have a high potential for energy savings as a subcategory, like taxis.

Generally, the same findings are true for life-time CO_2 emissions. However, in addition, the structure of the energy supply, e. g. the carbon content of the fuels and the share of regenerative primary energy carriers have to be considered. This introduces a further country-specific parameter. Generally, **road vehicles will increase the CO_2 saving potentials compared to the primary energy savings** due to the lower CO_2 factor per primary energy unit for electricity production.

For the potential energy savings of vehicle categories, the total energy consumption of the categories becomes of increasing importance. Furthermore it has to be taken into account that it in many cases, a higher absolute weight reduction can be achieved in heavier vehicles. This implies that **high total energy savings can be mainly achieved** by vehicles with a great total share of the energy consumption, like passenger cars. The change in the share between total energy consumption and total energy savings is determined by the relation of net weight to gross weight and the relative energy savings. The share increases for short distance passenger trains and decreases for long distance road vehicles like buses and trucks.

Especially for the **life-time performance, data are scarce** and may be very different even within the vehicle categories and different countries. This has been visualised by sensitivity ranges in several charts. Despite data uncertainties and great variations, the presented data is believed to provide a **solid overview of the average situation**. For special vehicles or uses as well as countries with highly specific circumstances which differ from the average adjustments in the individual parameters should be taken into account.

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11 Charts, Figures and Tables

Charts:

Figures:

Tables: