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Energy savings by light-weighting - 2016 Update

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Abbreviations

BEV	Battery Electric Vehicle
CN	China
CO_2	Carbon Dioxide
EPA	US Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FTP-75	EPA Federal Test Procedure
GEM	Greenhouse Gas Emissions Model
GHG	Greenhouse Gases
HDUDDS	Heavy Duty Urban Dynamometer Driving Schedule
HDV	Heavy Duty Vehicle
HHDDT Transient	Heavy Heavy-Duty Diesel Truck Schedule
HWFT	Highway Fuel Economy Test
IAI	International Aluminium Institute
ICE	Internal Combustion Engine
ICE3	Intercity-Express (3rd Generation)
IEA	International Energy Agency
LCA	Life-Cycle Assessment
LDV	Light Duty Vehicles
M1	Passenger vehicles <3.5 Tonnes
MLTB	Millbrook London Transport Bus Cycle
N1	Goods vehicles < 3.5 Tonnes
NEDC	New European Driving Cycle
NO	Norway
OECD	Organisation of Economic Co-Operation and Development
PMR	Primary Mass Reduction
RWUTC	Real World Urban Transient Cycle
SE	Secondary Effects
US06	Supplemental Federal Test Procedure
VECTO	Vehicle Energy Consumption Calculation Tool
WHVC	World Harmonized Vehicle Cycle
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure

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Executive Summary

Current political targets and societal voices call for a substantial reduction in energy consumption and greenhouse gas emissions from the transport sector. The reduction of the weight of transport vehicles is one way to reduce the energy consumption and thus CO_2 emissions caused by transport vehicles and associated upstream processes. Several studies have already been carried out by ifeu to investigate potential energy savings by light-weighting (see [ifeu, 2004a], [ifeu, 2004b], [ifeu, 2005]). Since the previous studies were conducted more than ten years ago and modelling capacities for more differentiated and better comparable results have advanced, an update of reference values of specific energy savings by light weighting has been undertaken. Also corresponding use cases for life-time energy and CO_2 savings have been calculated. The means by which the weight of vehicles is reduced (e.g. material choices, specifics of component design, etc.) have not been considered in this study.

The modelling approach followed in this study delivers consistent energy saving reference values for a range of drive cycles. These include data on hybrid and electric vehicles, which have been underrepresented in previous studies. The following conclusions for light-duty vehicles can be drawn from the results:

- As expected, direct fuel savings are highest for dynamic applications at low speed (e.g. WLTP Urban, FTP-75 and JP10-15 cycle) and lower for highway driving (e.g. WLTP Highway). A sensitivity analysis for road conditions has also been undertaken for light duty vehicles as part of this update. The results show that fuel savings from driving in poor road conditions can be about 20 % higher compared to good paved roads.
- The modelling results for light duty vehicles also show a potential of secondary effects (i.e. maintaining the original power-to-weight-ratio) of light weighting, which increases the specific fuel savings, but to a lesser extent than as stated in the literature ([Casadei, / Broda, 2008; Delogu, et al., 2016; Ika, 2014; Kim, et al., 2016; Kim, / Wallington, 2016]).
- Modelled fuel saving values by primary mass reduction on the other hand, are mostly higher than those stated in the aforementioned literature. Specific total fuel savings for light-duty vehicles with conventional combustion engines are in most cases slightly lower than previously assessed, which can be attributed to generally lower fuel consumption level.
- The modelling results for hybrid passenger cars vary significantly by vehicle model and driving cycle. On average, however, fuel savings for gasoline hybrid passenger cars are about 20 % lower compared to conventional gasoline vehicles due to the generally lower fuel consumption level. Due to the high sensitivity of fuel savings the derivation of a single reference value, however, is not meaningful.
- Electric light-duty vehicles generally show less sensitivity to the driving cycle due to the generally high engine efficiency and potential for regenerative breaking. Electricity savings are mostly stable in the range of 0.6 kWh/ (100 km*100 kg).

Results for specific fuel savings for heavy duty vehicles are mostly comparable to previous reference values and literature data, too. Here, results produced by the ifeu vehicle simulator VEHMOD have also been checked for compatibility with results produced by VECTO, the designated official tool to play a crucial role in the European type approval procedure. From the result differences below 2 % a good compatibility between VEHMOD and VECTO can be concluded. As part of this study a more detailed sensitivity to various driving cycles has been undertaken with VEHMOD:

- As expected, fuel savings are highest in urban cycles and lowest for highway cycles. The highest primary CO_2 savings are found for the city bus with almost 0.2 kg l / (100 km*100 kg) in an urban cycle, while the lowest values are found for heavy trucks (mostly below 0.1 kg l / (100 km*100 kg)).
- Potentially three times higher fuel savings for trucks can be realised in case of weight limited cargo, because less vehicle-km are needed to transport the same amount of goods over a given distance. For fully load heavy trucks, fuel savings would be about 0.16 l/100 km and 100 kg in the WHVC and thus considerably higher than for volume limited cargo.
- Again hybrid and electric versions have been additionally analysed for city buses and light trucks. Differences between the driving cycles for the electric version appear to be higher as for passenger cars. The absolute energy savings level, however, is likewise in the range of 0.6 kWh/ (100 km*100 kg).

While for road vehicles a wealth of recent literature is available (see above), few such reference values for weight reduced trains exist or have been published. The available recent studies, as well as an additional modelling of a high speed train, however, show very stable values for energy savings by light-weighting of trains. Differences are rather found in the specific use cases, also being determined by lifetime distance.

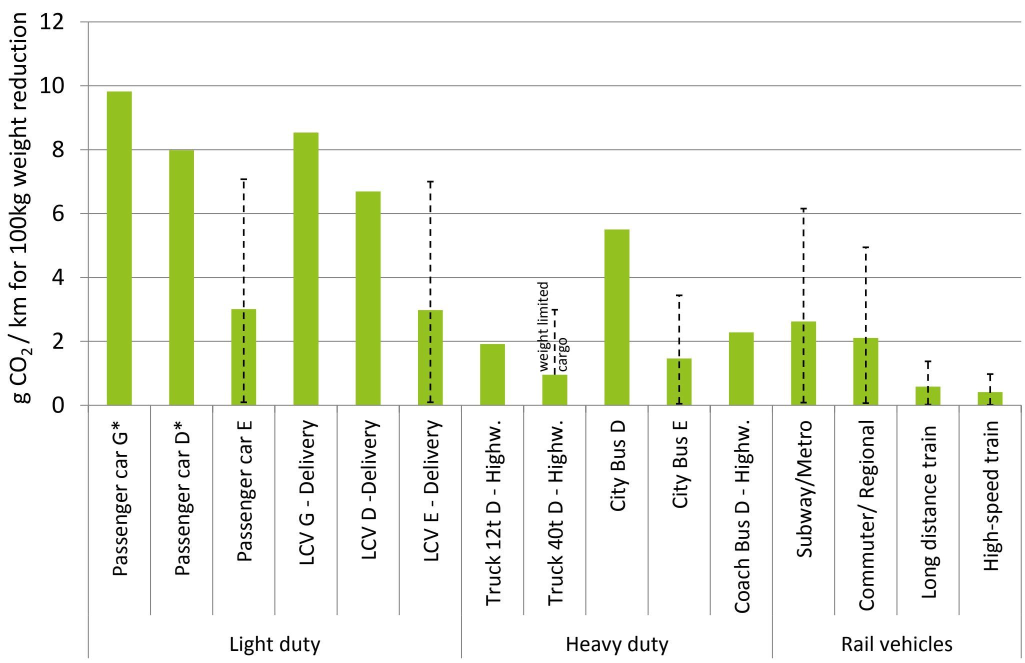

Figure 1: Specific primary CO_2 savings per km for a 100 kg weight reduction for selected vehicle use cases (EU28 electricity, electric vehicles range between energy supply in China (upper value) and Norway (lower value), reference year 2013)
* for passenger cars secondary effects by maintaining the power-to-weight ratio of the vehicle are considered

Specific primary CO_2 savings per km (including upstream processes) can now be calculated for a 100 kg weight reduction based on the specific fuel saving reference values (see selected use cases in Figure 1). For electricity generation, large country specific differences can be found which are displayed as error ranges representing China and Norway (reference year 2013). Specific CO_2 savings are highest for conventional passenger cars if secondary effects are included, but also light-commercial delivery vehicles and city buses show high specific savings, while long-distance vehicles have generally lower specific CO_2 savings.

A comparison of the lifetime CO_2 savings potential for a 100 kg weight reduction for selected use cases (see Figure 2), on the other hand, shows by far the highest savings potential for rail vehicles, due to the high life-time distance travelled. Among rail vehicles, however, the savings potential is higher for subways and regional trains than for long distance and high speed trains, despite the lower lifetime distance travelled. Further installation of low carbon electricity capacities over the lifetime of the vehicles, however, would decrease this potential. A detailed country specific analysis of such scenarios is beyond the scope of this study.

Among road vehicles, city buses and long distance coaches have the highest lifetime savings potential. For the electric versions, life-time primary CO_2 savings depend largely on the electricity split (see ranges in Figure 2) and can be significantly higher than for conventional cars (e.g. in China), but also lower (e.g. in Norway).

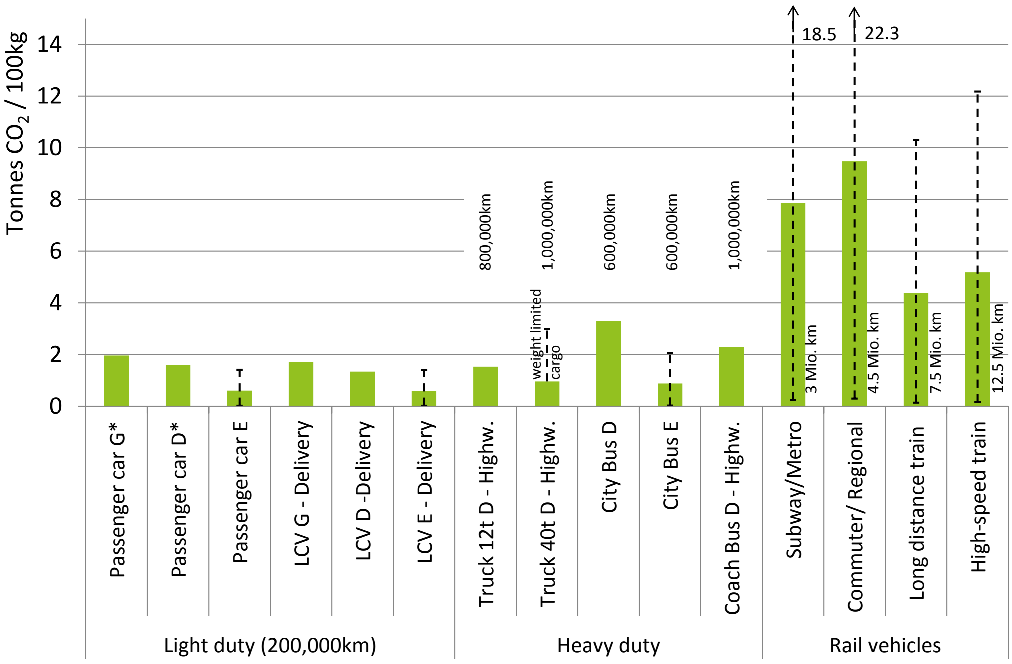

Figure 2: Life-time CO_2 savings by a 100 kg weight reduction for selected vehicle use cases (constant lifetime electricity split 2013 with EU28 electricity, electric vehicles range between energy supply in China (upper value) and Norway (lower value))
* for passenger cars secondary effects by maintaining the power-to-weight ratio of the vehicle are considered

1 Introduction

Mobility is an important requirement for many economic and private activities and thus is a crucial part of our life. However, mobility is also energy consuming and can lead to substantial environmental problems. Final energy consumption of the world wide transport sector has constantly risen during the last decades. Also the share of transport on the total world- energy consumption has increased and is now about 28 % ([IEA, 2015a]). Energy consumption in transport today is not only a cost factor, but is also mostly associated with the use of fossil energy carriers and thus leads to CO_2 emissions.

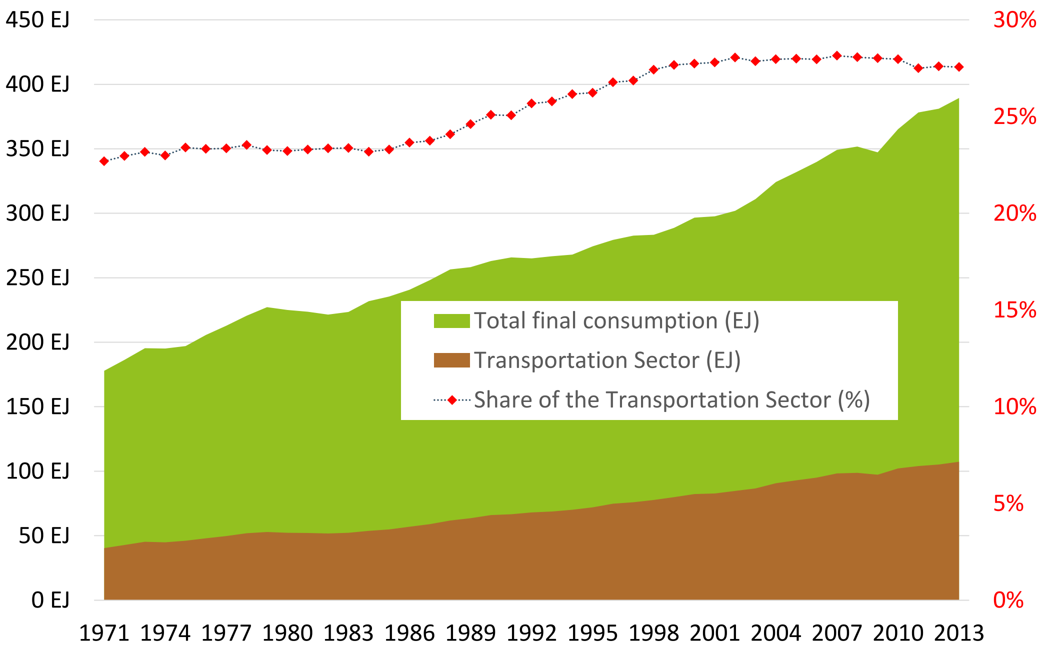

Figure 3: Worldwide final energy consumption (total and share of transport) from 1971 to 2013.
Source: [IEA, 2015a]

Current political targets, however, require a significant reduction of greenhouse gas emissions in the future. This is a call to action for the transport sector to find ways to save energy resources and reduce associated greenhouse gas emissions. For instance, the European Union has set a target of 95 g CO_2 emissions per km for the average passenger car vehicle fleet in 2021 ([EU, 2014]). A further tightening of emission targets for passenger cars in the EU is currently discussed. US fuel economy standards are subsequently tightened along the model years and for passenger cars will be slightly above 46 mpg in 2021 (see [NHTSA, 2012]), which translates to 142 g CO_2 per km.

Efficiency or CO_2 standards have also been introduced for trucks in some countries such as Japan, USA, Canada and China. The Chinese "National Standard" refers to the fuel consumption of all new registrations from 2015 and covers a broad range of vehicles from

rigid trucks over buses to articulated trucks. Fuel consumption limits vary by vehicle type and gross vehicle weight. For 40 t articulated trucks, the fuel consumption limit is currently 42 l per 100 km (see [Huoa, et al., 2012]). The current US regulation targets fuel consumption and CO_2 emissions of medium and heavy-duty vehicles per tonne-mile (defined as a ton of freight transported one mile) with a gross vehicle weight above 8,500 lbs (almost 4 tonnes). The fuel consumption limit for class 8 trucks currently is between 17 and 23 litre per 1,000 tonne-kilometre, depending on the vehicle configuration (see [EPA/NHTSA, 2011]). In the EU, a monitoring of CO_2 emissions from heavy trucks is on the way using the calculation tool VECTO and binding CO_2 targets are being discussed.

In this context, this study examines the impacts of weight reduction of transport vehicles on energy consumption and thus CO_2 emissions. In addition to the physical energy demand of the vehicles, a life-time perspective also takes into account the energy consumption of upstream processes. This includes extraction and processing of fuels as well as the generation of electricity.

The International Aluminium Institute (IAI) and European Aluminium commissioned a number of studies from ifeu on the potential energy savings of transport vehicles and containers by light-weighting (see [ifeu, 2004a], [ifeu, 2004b], [ifeu, 2005]). Furthermore, a peer reviewed article on energy savings by light-weighting has been published in the "International Journal of LCA" [ifeu, 2007].

These studies are now over ten years old and there is a need to understand how changes in vehicle design and vehicle weights have the potential to impact potential energy and greenhouse gas savings today (2016). The availability of standardized driving cycles and advances in modelling capabilities over the past decade also allow for more differentiated and comparative results.

This study therefore summarises and compares literature data as well as modelled values for energy savings by light-weighting in order to derive representative values for a range of different uses cases. **How light-weighting is realised is not part of the study.** Goal and scope of the study are defined in the following chapter 2 and the general background and approach for specific energy savings and use cases for life-time energy savings is described in chapter 3. Afterwards, energy savings by light-weighting are analysed for road vehicles (chapter 4) and rail vehicles (chapter 5). Finally, the saving potentials are compared between different vehicle types and uses cases and the main conclusions are summarised (chapter 6). The report has a focus on the concise presentation of main results. A detailed model description, illustration of considered driving cycles and further results in a tabular overview are documented in the Annex.

2 Goal and Scope

This study aims at an update of a broad and differentiated set of values for specific and potential life-time energy and CO_2 savings by a weight reduction of transport vehicles. The goal is to cover a broad range of vehicle types and uses, from passenger cars over trucks to high speed rail systems. Recent developments in vehicle technology as well as an improvement of modelling capacities compared to preceding studies are to be taken into account. The scope of the study is the energy and CO_2 savings by light-weighting across drive train concept, driving cycle and vehicle segment sensitivities.

Almost three-quarters of the world-wide transport energy consumption is due to road transport, of which 54 % can be attributed to light-duty vehicles (passenger cars and light commercial vehicles) and 46 % to heavy duty vehicles. The coverage of vehicles, technologies and classes is summarized in Table 1.

Vehicle category	Technology	Size/Class
Passenger cars (EU M1)	ICE Gasoline ICE Diesel EV Hybrid	Small (City car – A Segment) Medium (Compact car – C Segment) Large (Luxury car –E Segment)
Light commercial vehicles (EU N1)	ICE Gasoline ICE Diesel EV	Gross vehicle weight < 3.5 t; EU N1, U.S. class 1 and 2
Light trucks (EU N2)	ICE Diesel EV Hybrid	Gross vehicle weight 3.5-12 t; EU N2, U.S. class 2-6
Heavy trucks (EU N3)	Diesel	Gross vehicle weight > 12 t; EU N2, U.S. class 7 and 8
City buses	ICE Diesel EV Hybrid	12 m (40 ft.)
Regional (coach) buses	ICE Diesel	12 m (40 ft.)

Table 1: Scope of vehicle categories, propulsion technologies and vehicle sizes

Furthermore, several rail systems have been analysed, which can be grouped as follows:

- Subway/Metro
- Commuter/Regional trains
- Long distance trains
- High speed trains

Among the long distance trains, high speed rail systems are of growing importance and are currently mainly used in Japan, China, South Korea and several European countries. In order to validate the available literature data, a further modelling of energy savings for an ICE3 train has been undertaken.

Several test procedure driving cycles were developed in respect to different vehicle types and their various driving patterns in certain countries around the globe. Several driving cycles have been identified as particularly relevant for the calculation of a range of energy and CO_2 savings by light weighting for representative use cases. These cycles are summarised in the Annex (see Table 10). Due to the fact that not all countries define or derive representative driving cycles considering the real traffic situations in the field, the focus is on North America and Europe, which are currently responsible for the highest transport related energy consumption (see Figure 4). For each vehicle type a large number of use cases has been calculated, of which several representative cases are illustrated and discussed in detail.

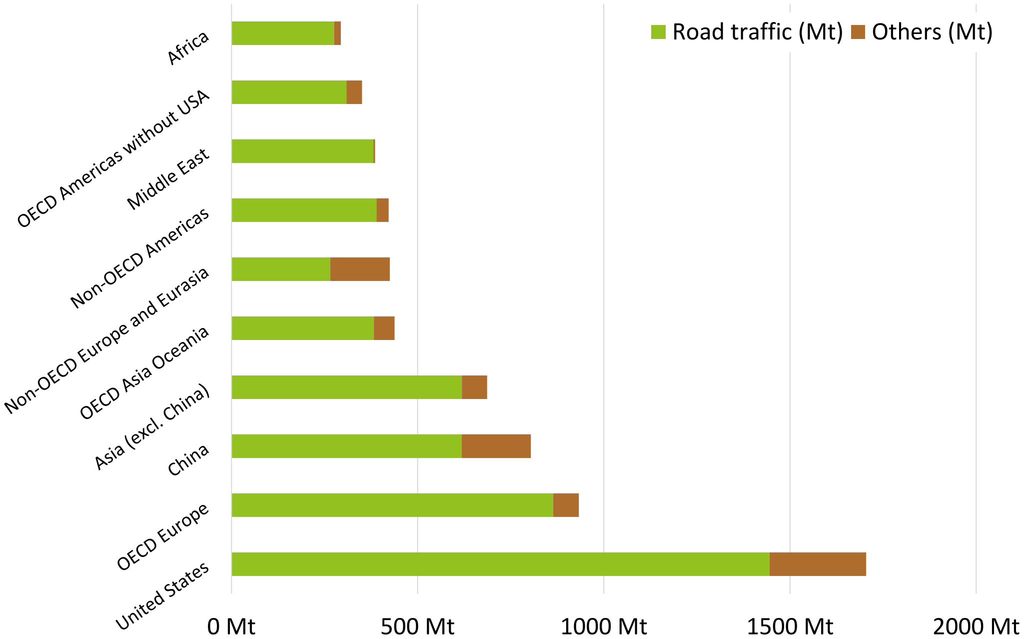

Figure 4: Carbon dioxide (CO_2) emissions by region, country or economical group of the transportation sector in 2013. Source: [IEA, 2015b]

3 Background and approach

This study deals with the energy and CO_2 savings during the operational life of weight reduced transport vehicles. Besides a broad literature research, a modelling approach is employed for the dominating road vehicles (see Annex). For high speed trains a modelling approach has also been undertaken in order to validate the literature results. A weight reduction directly reduces the energy consumption at the wheel of the vehicle, because the physical resistances a vehicle has to overcome in operation are in large part proportional to the weight of the vehicle. The potential lifetime energy savings depend on the specific energy savings and the lifetime mileage of the respective vehicles:

$$Lifetime\ energy\ savings\left[\frac{MJ}{100kg}\right] = Specific\ energy\ savings\ \left[\frac{MJ}{100kgxkm}\right]\ x\ Lifetime\ mileage\ [km]$$

The total energy consumption and savings by weight reduction of a vehicle are also determined by the efficiency of the engine and transmission, as well as energy supply. To consider the overall energy savings and allow for a comparison of the results, lifetime primary energy savings, which take into account the upstream energy consumption by the extraction, processing and distribution of fossil fuels and electricity generation for electric vehicles, are also determined.

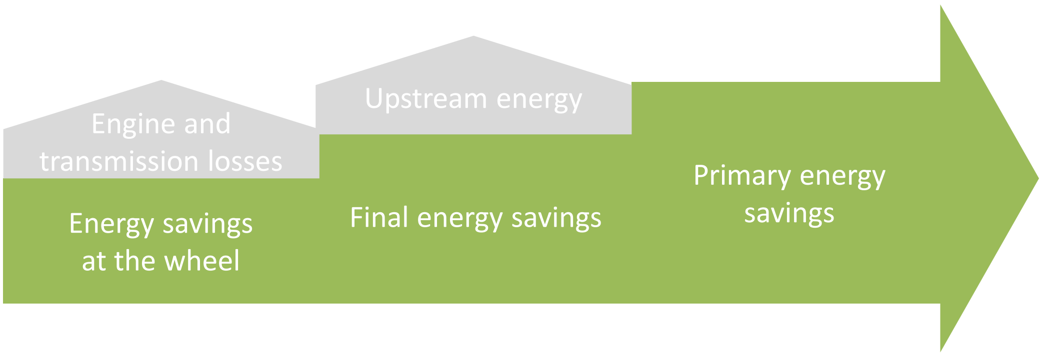

Figure 5: Schematic energy chain from savings at the wheel to primary energy savings

The efficiency of electricity generation, in particular, varies significantly between both regions and countries. For the presentation of upstream energy consumption and CO_2 emissions in this study, gasoline and diesel values from DIN EN 16258 [DIN, 2012] and the EU28 electricity split are used as a base case (Table 2). The EU28 electricity split is mostly comprised of coal, nuclear and renewable power generation which each in 2013 contributed about 27 %. Energy and CO_2 values are calculated with an UMBERTO© based LCA "master network" (see [ifeu, et al., 2016]). This model has been maintained by ifeu since 2001 and can be used to model the impacts of specific electricity mixes. The model consists of basic power plants and raw material upstream processes. The percentage of electricity from the different plants as well as fuel supply, plant efficiency, exhaust gas treat-

ment and electricity losses are varied for the different regions. For presentation of results in this study, the EU28 electricity split is used as the mid-range value. The potential range of CO_2 emissions savings is illustrated at the upper end by a Chinese 2013 grid mix, with a very coal intensive electricity generation, and at the lower end by Norway, using mostly hydro power.

	Well-to-Tank energy	Well-to-Tank CO2
Gasoline (EN 16258)	5.5 MJ/l	0.46 kg CO_2/l
Diesel (EN 16258)	6.8 MJ/l	0.56 kg CO_2/l
Electricity (EU28)	2.62 kWh/kWh	0.47 kg CO_2/kWh
Electricity (China)	3.55 kWh/kWh	1.10 kg CO_2/kWh
Electricity (Norway)	1.22 kWh/kWh	0.01 kg CO_2/kWh

Table 2: Energy consumption and CO_2 emissions of upstream processes (Source: [DIN, 2012] and [ifeu, et al., 2016])

Specific energy savings

As a first step, the specific end energy savings by a weight reduction are analysed for selected "typical" vehicles for each category and relevant drive trains, using simulated and measured data from the literature. Such data is usually normalized for a 100 kg weight reduction for road vehicles and a 1,000 kg weight reduction for rail vehicles. These specific energy savings of weight reduced vehicles depend on the use pattern (e.g. expressed as an average driving cycle) and a range of technical vehicle parameters. The basic energy consumption of ground vehicles at the wheel is due to several resistance factors the vehicle has to overcome during its operation. The main resistance factors are rolling resistance, gradient resistance, acceleration resistance and aerodynamic resistance (see Figure 6).

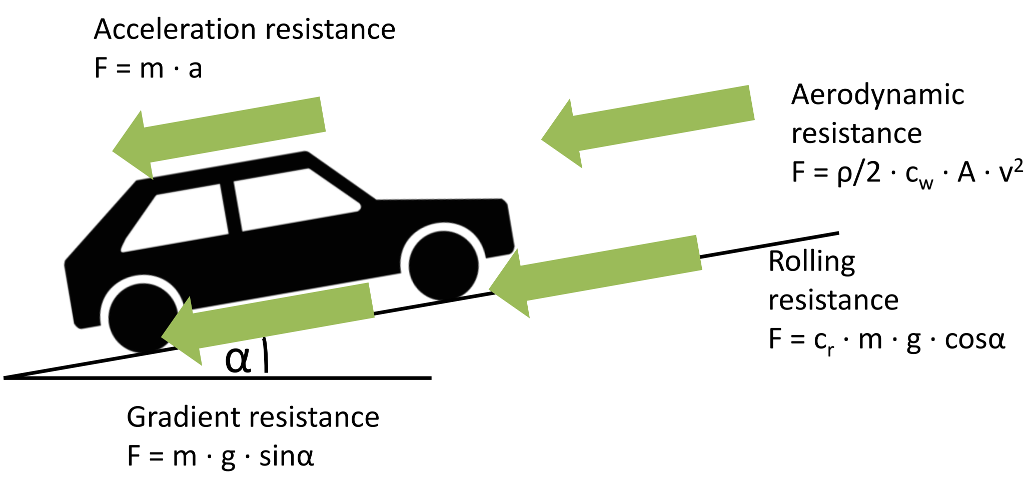

Figure 6: Overview of physical resistance factors

With the exception of aerodynamic resistance, all resistance factors are dependent on the mass of the vehicle. The aerodynamic resistance, however, depends on the dimensions of the vehicle and the square of speed. Therefore, besides mass, speed, acceleration and

gradient also determine energy consumption. They are highly dependent on the driving situation and driving behaviour:

- Fast vehicles with a steady speed (e.g. high speed trains or passenger cars on highways) have a high aerodynamic resistance and low acceleration resistance and thus tend to have relatively lower specific energy savings by weight reduction.
- Slow vehicles with frequent stops and accelerations (e. g. city buses or subways/ urban trains) have a high accumulated acceleration resistance and a lower aerodynamic resistance and thus, because of the dissipation of the braking energy, they exhibit relatively high specific energy savings by weight reduction. With advancing powertrain electrification efforts, those energy losses may be reduced which affects the impact of lightweight construction on energy efficiency.

Use cases for lifetime energy savings

Once the weight of a vehicle has been reduced, specific energy savings are realised over the entire vehicle life. The overall efficiency of weight reduction efforts thus also depends on the lifetime mileage of vehicles. The lifetime mileage is influenced by the durability and use intensity of vehicles, which in turn is determined by the area of application (e.g. private vs. commercial, urban vs. long-distance) and has to consider the full lifetime of the vehicle. Data for the lifetime mileage of the covered vehicle categories and use patterns has been selected in order to define several meaningful use cases. Changes over the vehicle life in relevant factors such as the electricity split are possible. The consideration of such effects, however, would require a more detailed scenario analysis and therefore has been neglected.

While private vehicles, like passenger cars, are parked most of the time rather than used on the road, commercial vehicles usually have a higher use intensity to generate the maximum revenue. Furthermore, passenger cars tend to be used less (often only 30 km daily) in comparison with long-distance, high speed trains, which are almost continuously used and easily accumulate more than 1,500 daily kilometres for high speed trains.

Thus the lower specific energy savings by light weighting for vehicles such as high speed trains, compared to passenger cars, can lead to much higher total savings over their significantly longer accumulated mileage.

4 Energy savings by light-weighting of road vehicles

Specific energy savings of road vehicles depend on a range of parameters such as vehicle size (influencing vehicle weight and aerodynamic drag), drive train and gear ratios, which also depend on the manufacturer philosophy. Furthermore, external conditions are of importance, for instance road conditions which also influence the rolling resistance. Not all parameters are accurately covered by literature on a comparative basis. For new alternative drive train concepts such as hybrid and electric vehicles, hardly any literature data is available. Therefore a differentiated modelling of light and heavy-duty vehicle examples has been conducted with the Matlab® based Vehicle Simulator VEHMOD which has been developed by ifeu as part of several research projects (see Annex).

4.1 Light-duty vehicles

4.1.1 Specific energy savings of light-duty vehicles

A range of generic passenger car and light commercial vehicle examples has been defined for modelling in order to cover different size classes, drivetrains and manufacturers (see Annex). These vehicles have been modelled with different vehicle weights in order to identify fuel savings by primary mass reductions against several driving cycles. Besides the European NEDC and the new Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), also specific parts of the WLTP (urban and highway) and international cycles like the US06, FTP-75 and JP10-15 have been modelled. A detailed description of the driving cycles can be found in Table 10 in the Annex.

The results show that fuel savings are sensitive mainly to the driving cycle and fuel type (gasoline or diesel) or drive train (conventional vs. hybrid). Fuel savings are highest for dynamic applications at low speed (see WLTP Urban, FTP-75 and JP10-15), in other words urban driving. Lower savings are identified for highway driving (see WLTP Highway). Despite more dynamic driving, results for the total WLTP show lower fuel savings compared to the NEDC results. This is due to the significantly higher average speed of the WLTP leading to more weight independent air drag (see Table 10).

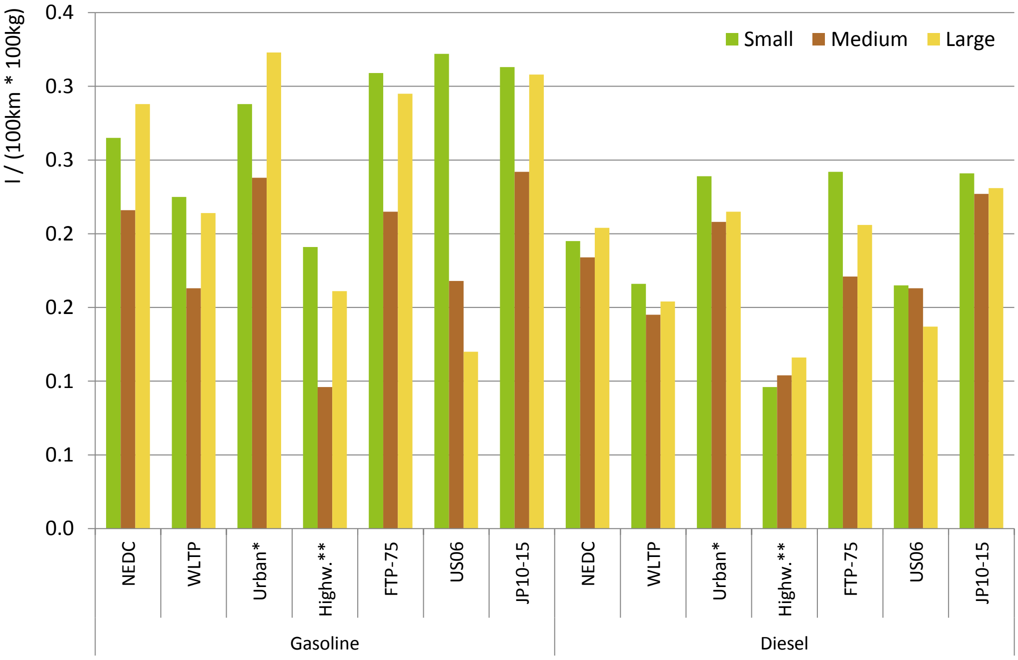

Figure 7: Fuel savings per 100 km and a 100 kg primary weight reduction for conventional internal combustion engine (ICE) passenger cars; * "Low" part of WLTP Class 3 with speeds below 60 km/h; ** "Extra High" part of WLTP Class 3 with speeds above 100 km/h

Generally fuel savings are higher for gasoline vehicles, compared to diesel vehicles. This mainly reflects the generally higher fuel consumption level. The vehicle size does not directly influence the modelled fuel savings. It has been observed in previous studies, that fuel savings for passenger cars more or less "*…are independent of the vehicles' absolute weight level*" [ifeu, 2004a]. Differences between specific vehicle models are nevertheless obvious, but rather depend on manufacturer and model specific parameters. This is also reflected in the analysed literature values (see Figure 8).

To validate the modelled energy savings by light-weighting, a profound literature research was carried out. Results from [Casadei, / Broda, 2008; Delogu, et al., 2016; Ika, 2014; Kim, et al., 2016; Kim, / Wallington, 2016] have been analysed to provide reasonable reference values which can also be compared to modelled values. Figure 8 shows the normalised mean fuel savings per 100 km and 100 kg weight reduction grouped by fuel type, vehicle class and driving cycle. Each bar in Figure 8 represents the mean literature fuel savings value in the corresponding group, while the ranges indicate the highest and lowest fuel savings value found in the given configuration. The results of the different driving cycles show that the potential of light-weighting in driving cycles with frequent stops and acceleration phases (NEDC/FTP-75) exceeds the potential of highway driving cycles (HWFT). Furthermore, fuel savings of gasoline engines are slightly higher than for diesel engines, but to a lesser extent than observed in the modelled values.

Some literature results differentiate between fuel savings due to primary mass reduction (PMR) and secondary effects (SE). The first include no adjustments to the vehicle despite the light-weighting, whereas secondary effects may include motor downsizing or adjustments of the torque curve. Secondary effects, however, aren't always exactly specified; their implementation varies between different sources and in practice may also depend on the manufacturer strategy. This is also reflected in the wide range of fuel savings values including secondary effects. Downsizing may be used to match the vehicles baseline accel-

eration performance [Casadei, / Broda, 2008] or to minimize fuel consumption [Delogu, et al., 2016]. Secondary effects of literature values are therefore difficult to interpret and are displayed separately in Figure 8. If secondary effects are included, fuel savings for a 100 kg weight reduction can be up to 0.4 l/100 km for gasoline and up to 0.3 l/100 km for diesel cars.

In common with the ifeu modelling results, literature values mainly differ by driving cycle, with lower values for highway driving (HWFT) compared to mixed cycles (NEDC and FTP-75). ifeu modelling results are between 30 % and 80 % higher than the literature values for primary mass reductions. It is assumed that most literature values are determined under rather optimised conditions comparable to current homologation practices, while parameters for the ifeu modelling values have been selected to reflect more realistic road conditions. Literature differences between the vehicle size classes, as for the ifeu modelling, do not have a clear tendency. This supports the assumption that manufacturer and vehicle specific differences have a greater influence than the general vehicle size class.

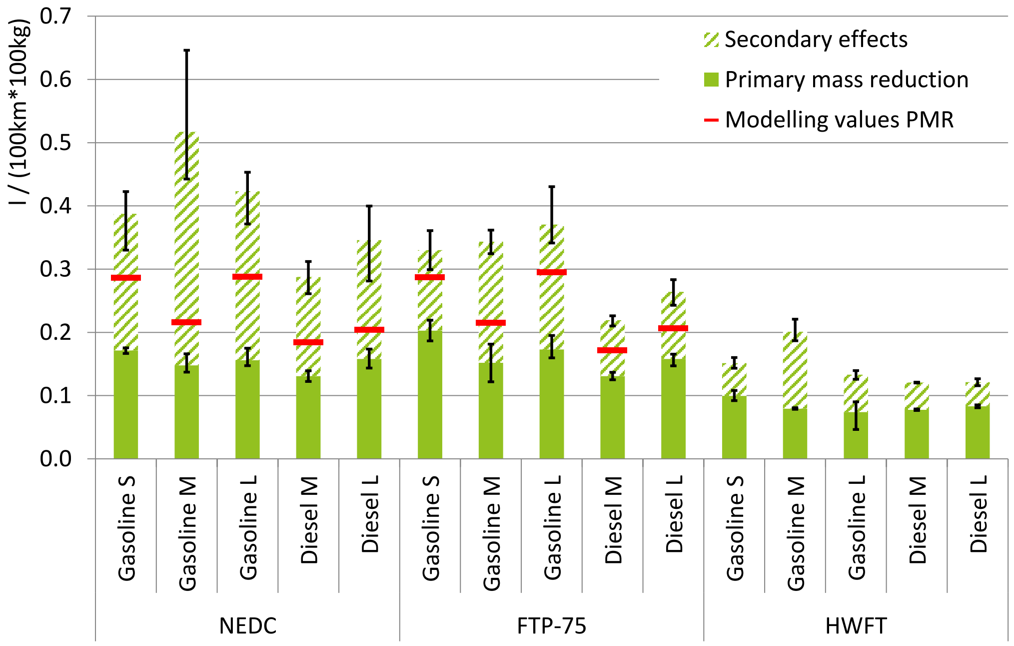

Figure 8: Fuel savings literature values for passenger cars (error ranges signify minimum and maximum literature values) Sources: [Casadei, / Broda, 2008; Delogu, et al., 2016; Ika, 2014; Kim, et al., 2016; Kim, / Wallington, 2016]

One important factor influencing fuel consumption and fuel savings by light-weighting .is road condition, reflected in the rolling resistance co-efficient. Generally paved roads in reasonable condition are assumed (c_r = 0,012). Poorer road conditions, however, exist in many countries, from frequent potholes to concrete or even gravel roads. Therefore a sensitivity for poorer road conditions (c_r = 0,018) has been calculated (see Figure 9). For conventional combustion engines, fuel savings in poor road conditions are on average about 20 % higher compared to the good paved conditions.

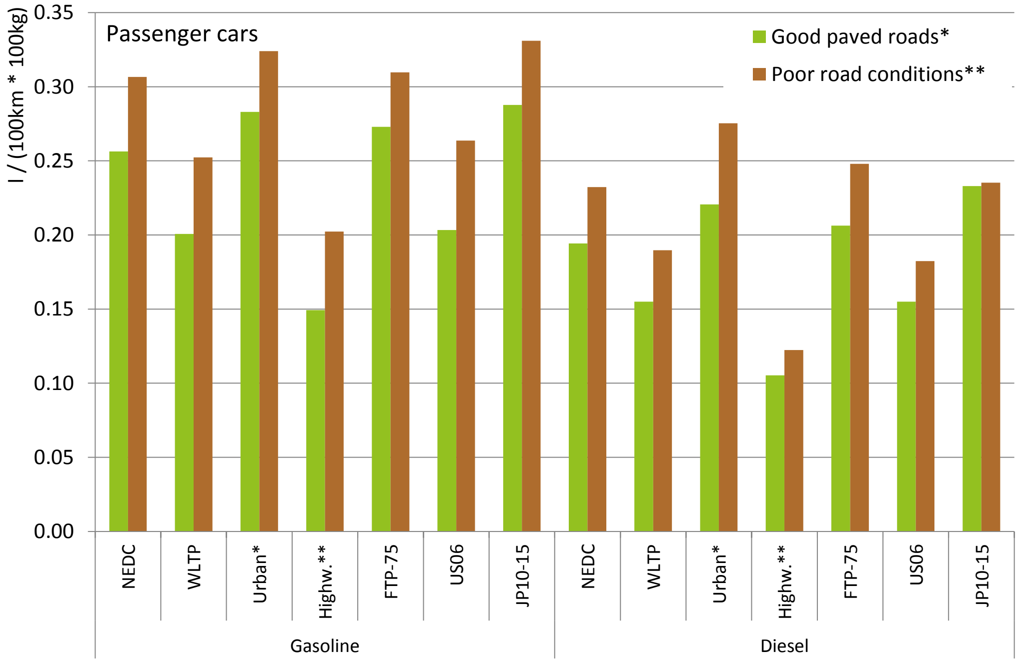

Figure 9: Sensitivity of fuel savings to road conditions (good paved roads c_r = 0,012; poor road conditions c_r = 0,018)
* "Low" part of WLTP Class 3 with speeds below 60 km/h; ** "Extra High" part of WLTP Class 3 with speeds above 100 km/h

The literature research has shown that potentially significant additional savings can be achieved by adjusting the weight reduced vehicle performance to the new vehicle weight. Literature sources, however, are mostly unspecific about the modifications, which partly also include further optimization. Therefore additional modelling has been undertaken with an adjusted power-to-weight ratio of the vehicles. This modelling was only undertaken for conventional gasoline and diesel cars. Such secondary effects are expected to be less significant for hybrid and electric vehicles, due to the generally higher and more stable efficiency of the electric engine. Light weight electric vehicles, however, require less battery packs for the same electric driving range, thus having potential for further weight reduction (see [Faßbender, et al., 2012]).

The results for vehicles with a maintained power-to-weight ratio indeed show significant additional savings (see Figure 10) so that total fuel savings for a 100 kg weight reduction are in a range between 0.25 and 0.35 l per 100 km for gasoline cars and 0.2 and 0.25 l per 100 km for diesel cars. These total values are more in line with the total literature values shown in Figure 8 including secondary effects and can also be used accordingly to calculate lifetime energy and CO_2 savings. Modelled secondary effects by an adjusted power-to-weight ratio are lower compared to additional effects stated in the literature. These literature values, however, show a large bandwidth and appear often to include further optimization or even further weight reduction. Therefore the secondary effects shown in Figure 10 can be seen as rather conservative values, while the potential for further secondary effects is discussed in [Aluminium, 2015].

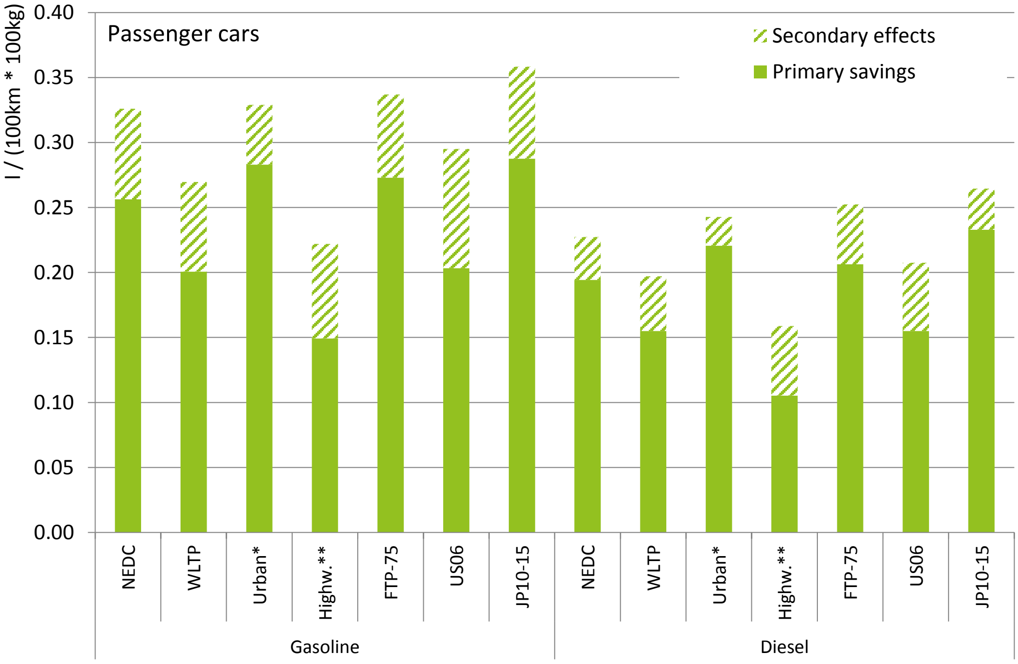

Figure 10: Estimated secondary fuel savings for average passenger cars by adjusting the power-to-weight ratio

Further modelling has been undertaken for hybrid passenger cars. The general picture is more ambiguous due to very different operation strategies and the possibility for temporal storage of energy in the battery. An evaluation based on a single vehicle and cycle is therefore often not meaningful. Furthermore, small changes in vehicle weight can lead to very different and even adverse results for hybrids, therefore the results shown in Figure 11 are average figures for the three analysed passenger cars and are based on modelling over three to ten continuous cycles with a weight reduction of 300 kg and have been normalised to 100 km and 100 kg weight reduction.

In such an average analysis, fuel savings for hybrids are demonstrably lower than for conventional gasoline cars due to the high efficiency of the electric engine in dynamic situations and the possibility for regenerative breaking. Depending on the cycle, fuel savings are in the range of 20 % lower than for the conventional version. Due to the high sensitivity of fuel savings to vehicle and operation specific parameters, however, it is concluded that the estimation of a single reference value for life-time energy savings of hybrid cars in chapter 4.1.2 would not be meaningful.

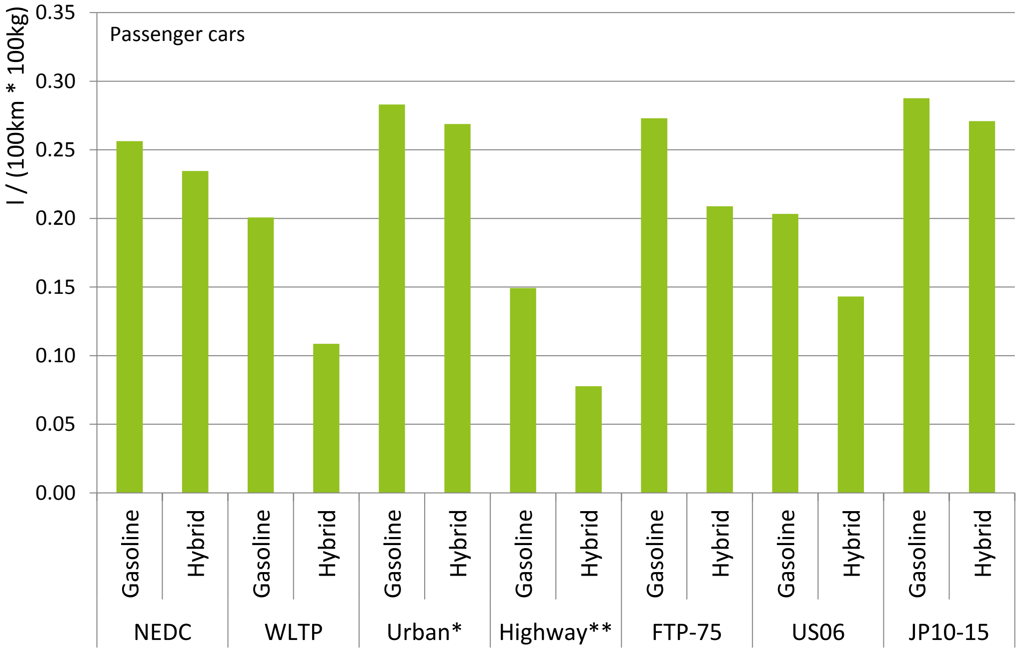

Figure 11: Comparison of average fuel savings for conventional and hybrid gasoline passenger cars
* "Low" part of WLTP Class 3 with speeds below 60 km/h; ** "Extra High" part of WLTP Class 3 with speeds above 100 km/h

Modelling results for light commercial vehicles show a pattern very similar to passenger cars (see Figure 12). Fuel savings are generally higher for the gasoline version compared to the diesel. Furthermore, fuel savings differ considerably by driving cycle. Again, dynamic applications at low speed (e.g. urban delivery vehicles), as represented by the WLTP urban part as well as the FTP-75 and JP10-15, tend to have much higher savings than highway use. The fuel saving values are mostly lower than for passenger cars, which is attributable to the higher air drag or potentially engine optimisation for higher gross weights.

The modelling results for electric vehicles differ far less compared to the results for vehicles with internal combustion engines (ICE) (see Figure 13). Electric engines generally have a higher efficiency over large parts of the use spectrum. Furthermore, braking energy is partly recovered. Therefore driving cycle differences are far less apparent; only highway driving values are significantly lower. As for ICE vehicles differences between the size classes are small, with most results in the range of 0.6 kWh per 100 km and 100 kg weight reduction (as shown in Figure 13).

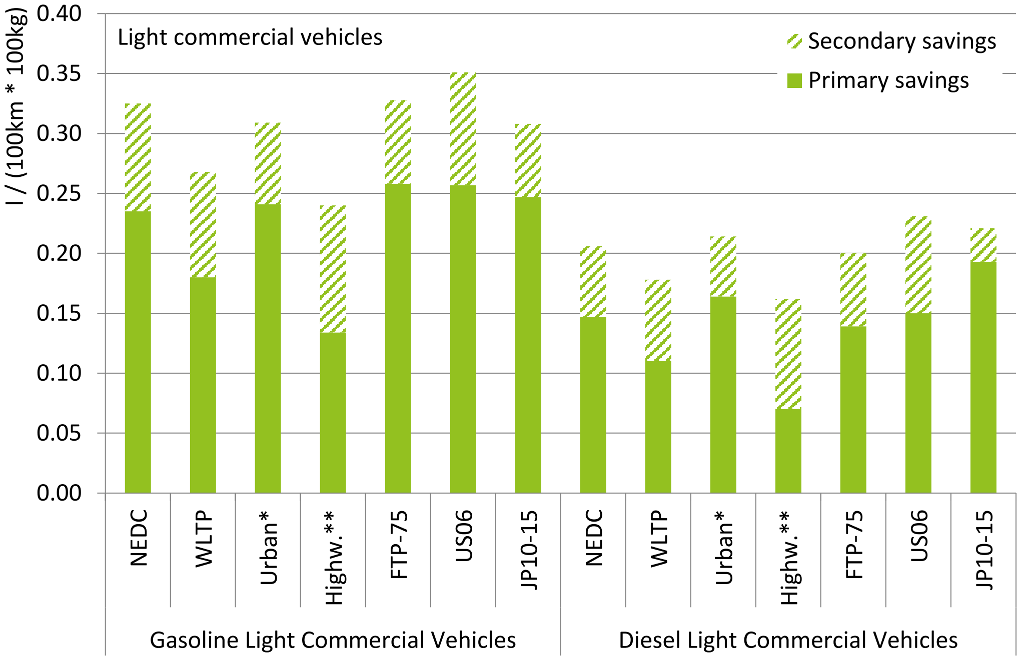

Figure 12: Fuel savings per 100 km and for a 100 kg weight reduction for combustion engine (ICE) light commercial vehicles
* "Low" part of WLTP Class 3 with speeds below 60 km/h; ** "Extra High" part of WLTP Class 3 with speeds above 100 km/h

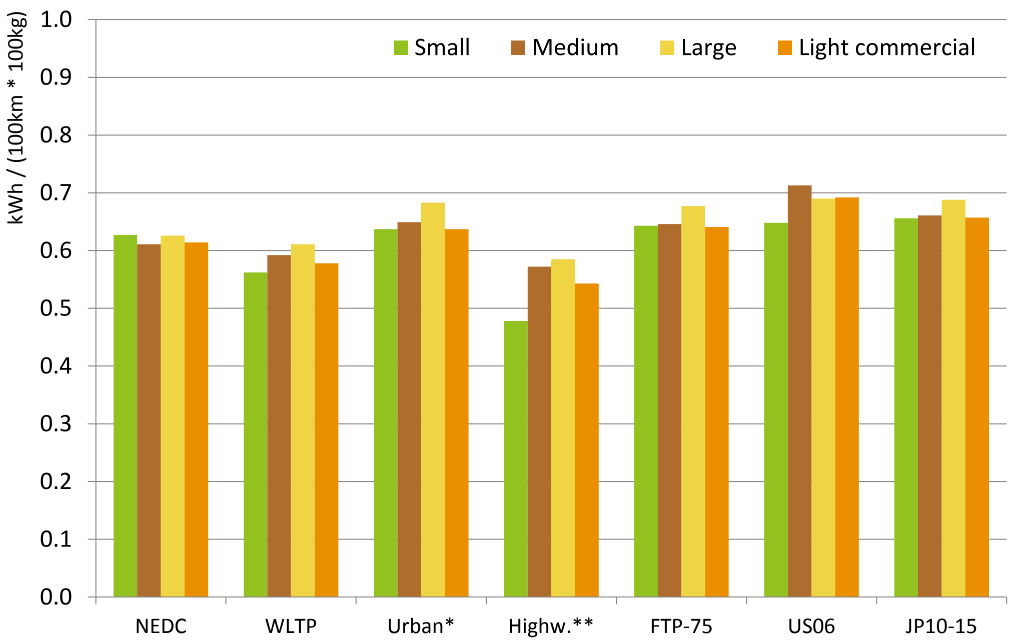

Figure 13: Energy savings per 100 km and for a 100 kg weight reduction for light-duty battery electric vehicles (BEV)
* "Low" part of WLTP Class 3 with speeds below 60 km/h; ** "Extra High" part of WLTP Class 3 with speeds above 100 km/h

As a consistent framework of reference values for further use and communication it is suggested to use a mean value from the modelled cycles, representing mixed driving. The appropriate driving cycle for specific regions, however, may differ from this reference value. Additionally, values for the urban and highway part of the WLTP could be used to illustrate the range for specific uses and are therefore documented. For gasoline and diesel

cars, fuel savings including secondary effects are also presented and are used for the calculation of lifetime savings in the following chapter. Overall values including secondary effects (SE), realised as an adjustment to the original power-to-weight ratio, are slightly lower compared to those suggested by ifeu in earlier studies (e.g. [ifeu, 2004a]), which is probably due to a generally lower fuel consumption level.

	Mixed Use	*Urban (WLTP)*	*Highway (WLTP)*	Previous values
PC Gasoline PMR	**0.24 l/100km**	0.28 l/100km	0.15 l/100km	NA
PC Diesel PMR	**0.19 l/100km**	0.22 l/100km	0.11 l/100km	NA
PC Gasoline with. SE	**0.32 l/100km**	0.33 l/100km	0.22 l/100km	0.35 l/100km
PC Diesel with SE	**0.23 l/100km**	0.24 l/100km	0.16 l/100km	0.30 l/100km
PC Electric	**0.64 kWh/100km**	0.65 kWh/100km	0.54 kWh/100km	NA
LCV Gasoline PMR	**0.24 l/100km**	0.24 l/100km	0.13 l/100km	NA
LCV Diesel PMR	**0.15 l/100km**	0.164 l/100km	0.07 l/100km	NA
LCV Gasoline with SE	**0.32 l/100km**	0.31 l/100km	0.24 l/100km	NA
LCV Diesel with SE	**0.21 l/100km**	0.21 l/100km	0.16 l/100km	0.30 l/100km
LCV Electric	**0.64 kWh/100km**	0.64 kWh/100km	0.54 kWh/100km	NA

Table 3: Suggested energy savings reference values for light-duty vehicles (Previous values from [ifeu, 2004a], [ifeu, 2004b])
PMR = Primary mass reduction; SE = Secondary effects

4.1.2 Use cases for lifetime primary energy savings of light-duty vehicles

The total lifetime energy and CO_2 savings of light-duty vehicles depend on the specific fuel savings analysed in detail in the previous chapter and the lifetime mileage of the respective vehicle. Furthermore, additional upstream energy consumption and CO_2 emissions for fuel production and electricity generation are taken into account. Lifetime energy savings are therefore highly dependent not only on the driving cycle but also on the lifetime mileage. To illustrate the potential differences, five main use cases for passenger vehicles have been defined for illustration in this chapter:

- **Average family car** with mixed use and with a lifetime mileage of 200,000 km
- **Second car** in urban use and with a limited lifetime mileage of only 100,000 km
- **Taxi** in urban use and with a high lifetime mileage of 300,000 km
- **Business car** in highway use (e.g. salesperson) and with a lifetime mileage of 300,000 km

Furthermore two cases of lifetime energy and fuel savings for light-duty vehicles are shown:

- **Light commercial vehicle** for urban delivery with a lifetime mileage of 200,000 km
- **Light commercial vehicle** for long distance transports on a highway with a lifetime mileage of 300,000 km

Numerous further use cases are possible for which lifetime energy and CO_2 savings are fully documented in the Annex (see Table 11 and Table 12).

Figure 14 shows that the lifetime primary energy savings for a 100 kg weight reduction are mostly above 10 GJ. Especially heavy urban uses like the taxi lead to high energy savings up to over 30 GJ, while energy savings for the highway use case with the same assumed lifetime mileage are only slightly higher than for the average family car. If potential secondary effects are fully realised, even the family car can achieve lifetime primary energy savings up to almost 25 GJ and urban taxis or business cars even up to 40 GJ. Light commercial vehicles can also realise high lifetime energy savings, especially as urban delivery vehicles (see Figure 15). As for the specific fuel savings, lifetime energy primary energy savings are generally higher for light-weighting of gasoline cars than for diesel and electric cars.

The pattern of lifetime CO_2 savings basically follows the lifetime energy savings. For combustion engine vehicles, CO_2 emissions are largely tail pipe emissions with only limited additional upstream savings. CO_2 emissions of electric vehicles, in contrast, only arise in the upstream electricity sector and are therefore largely dependent on the local electricity power mix. Due to the over 50 % share of renewable and nuclear electricity generation, lifetime CO_2 savings of electric vehicles operated in the EU28 on average are lower compared to the lifetime energy savings. Further installation of renewable energy capacities would decrease this potential even more. Battery electric vehicles operated in China, however, may show much higher life-time primary CO_2 emissions, if the electricity power mix does not shift significantly away from coal over the operational lifetime of the vehicle.

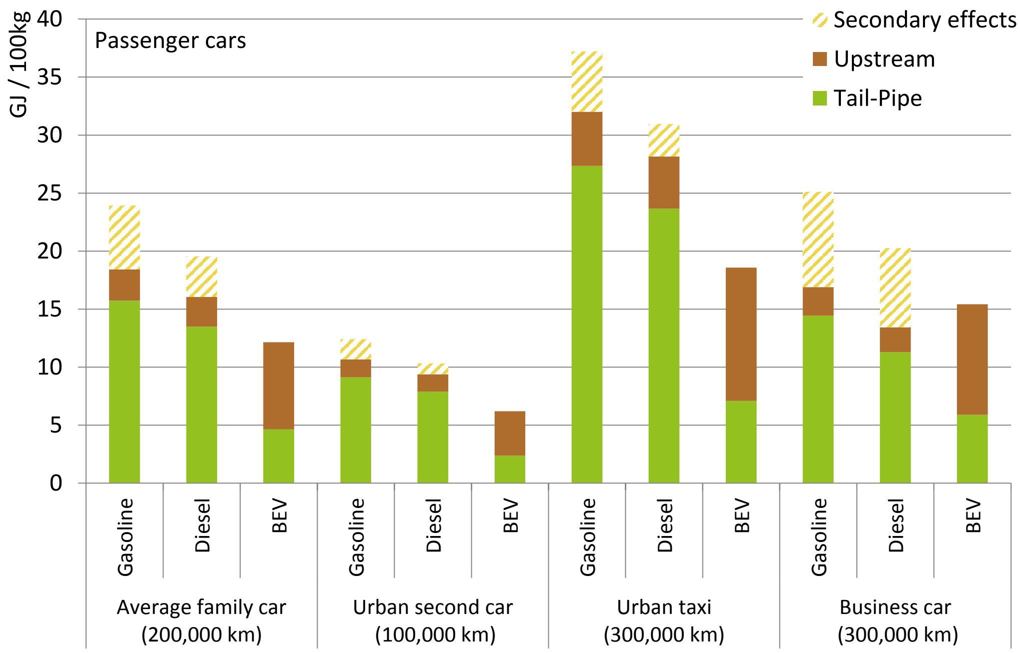

Figure 14: Lifetime primary energy savings of weight reduced passenger cars for selected use cases (EU28 energy supply)

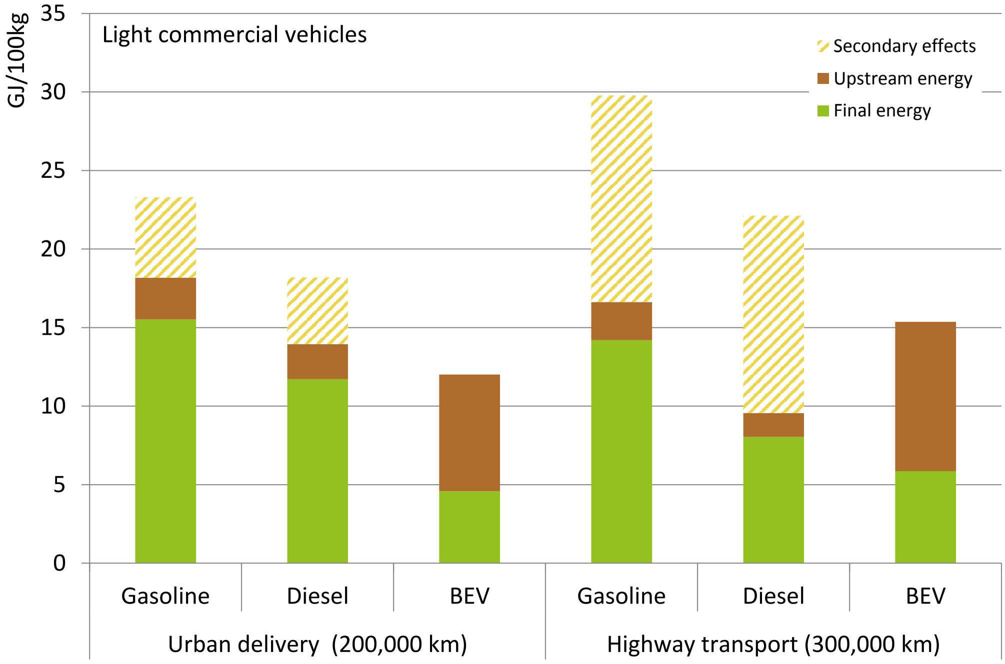

Figure 15: Lifetime primary energy savings of weight reduced light commercial vehicles for selected use cases (EU28 energy supply)

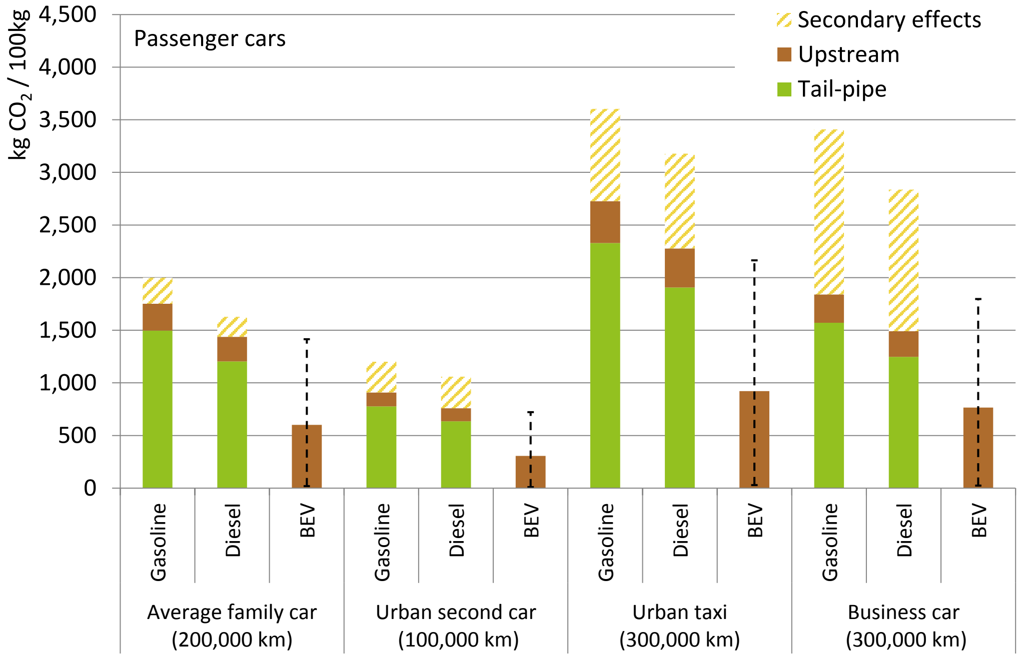

Figure 16: Lifetime CO_2 energy savings of weight reduced passenger cars for selected use cases (constant lifetime electricity split with EU28 electricity, range of electricity supply power mix influence illustrated by China (upper value) and Norway (lower value))

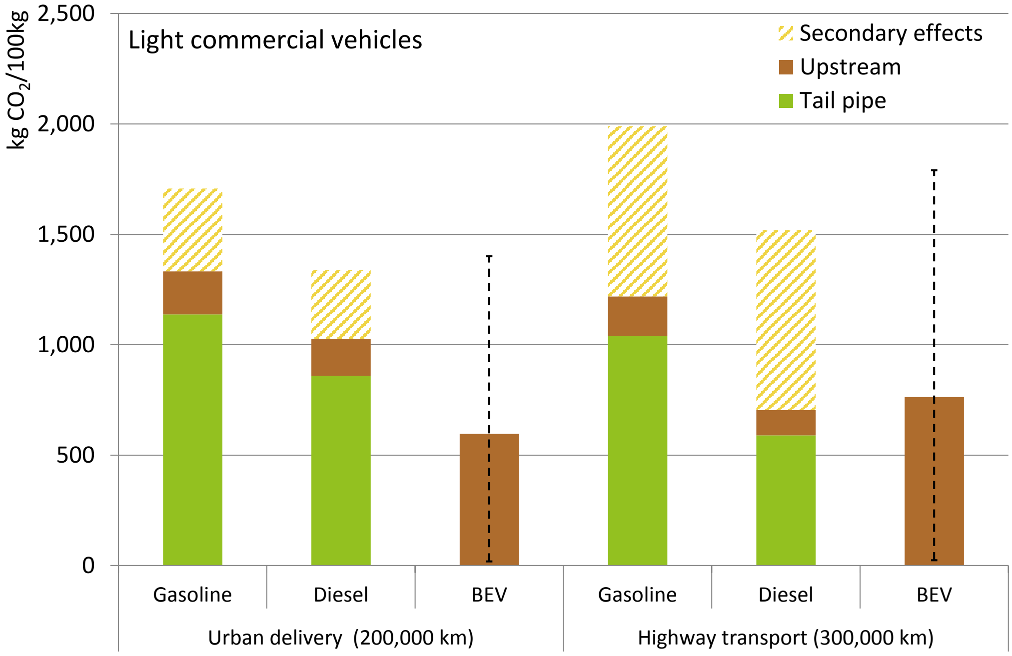

Figure 17: Lifetime CO_2 savings of weight reduced light commercial vehicles for selected use cases (constant lifetime electricity split with EU28 electricity, range of electricity supply power mix influence illustrated by China (upper value) and Norway (lower value))

4.2 Trucks and Buses

4.2.1 Specific energy savings of trucks and buses

Modelling of specific fuel savings by light-weighting has also been undertaken for trucks and buses. Here, results produced by the ifeu vehicle simulator VEHMOD have been checked for compatibility with results produced by VECTO, the designated official tool to play a crucial role in the European type approval procedure. From the resultant differences of less than 2 % a good compatibility between VEHMOD and VECTO can be concluded.

Heavy trucks with a gross vehicle weight up to 40 t and light trucks with a gross vehicle weight up to 12 t are analysed. Furthermore city buses and coach buses are distinguished. Specifications of the baseline vehicles for derivation of modelling parameters can be found in Table 8 in the Annex. Since gross vehicle weights are considerably higher than for passenger cars, a weight reduction by 500 kg has been modelled and normalised to 100 kg in order to be comparable to passenger cars and literature values. To be able to compare the results for trucks and buses, the entire set of truck and bus driving cycles has been modelled, regardless of the original target vehicle. The considered driving cycles reflect more dynamic/urban driving (HD-UDDS, Braunschweig, HHDDT Transient and WHC Urban) as well as mixed (WHVC) and highway driving (WHVC Extra Urban). Generally an average load of 50 % has been considered for trucks and buses alike.

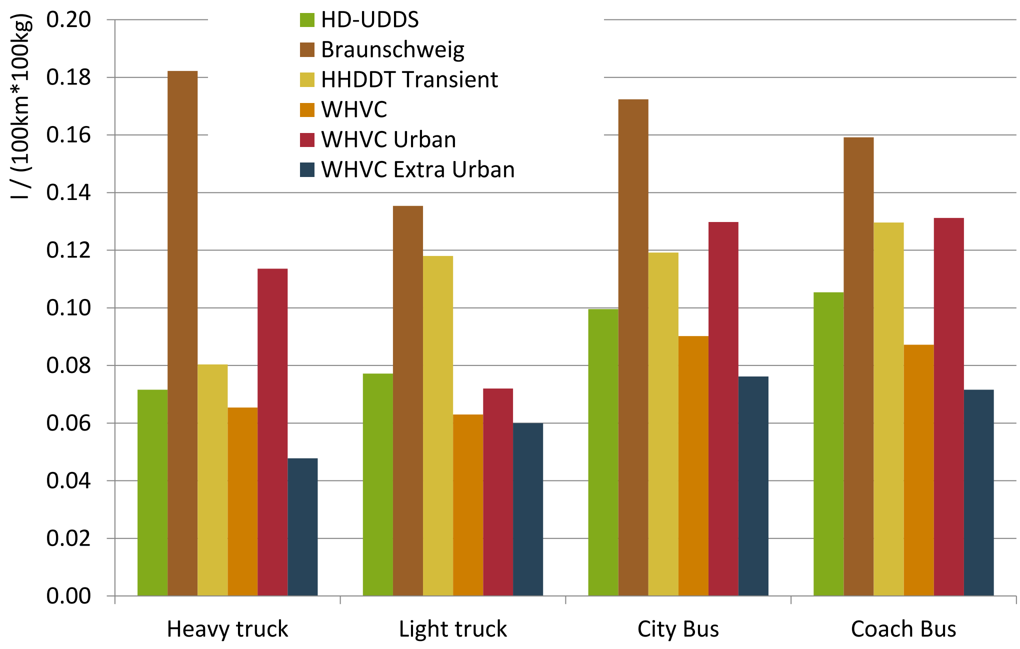

Figure 18: Fuel savings per 100 km and 100 kg weight reduction for trucks and buses with conventional diesel engines

Large differences in fuel savings are found by vehicle type as well as driving cycle. The higher fuel savings are found for the city bus with up to almost 0.2 l / (100 km*100 kg) in the Braunschweig cycle, while the lowest values are found for trucks (mostly below 0.1 l / (100 km*100 kg)). Differences between the driving cycles are also considerable, with savings highest in the urban Braunschweig cycle and lowest for the WHVC Extra Urban cycles.

For the light truck, the pattern is somewhat less apparent than for the other vehicles, which may also be due to specific vehicle configurations.

Fuel savings for trucks shown in Figure 18 refer to the case of volume limited cargo, whereas potentially higher fuel savings can be realised in the case of weight limited cargo, which more likely applies to heavy trucks. In this case less vehicle-km are needed to transport the same amount of goods over a given distance. Fuel consumption of an entire and fully loaded vehicle can be saved. For fully loaded heavy trucks, fuel savings would be about 0.16 l/100 km and 100 kg in the WHVC and thus considerably higher than for volume limited cargo ([European Aluminium, 2014a], [European Aluminium, 2014b]).

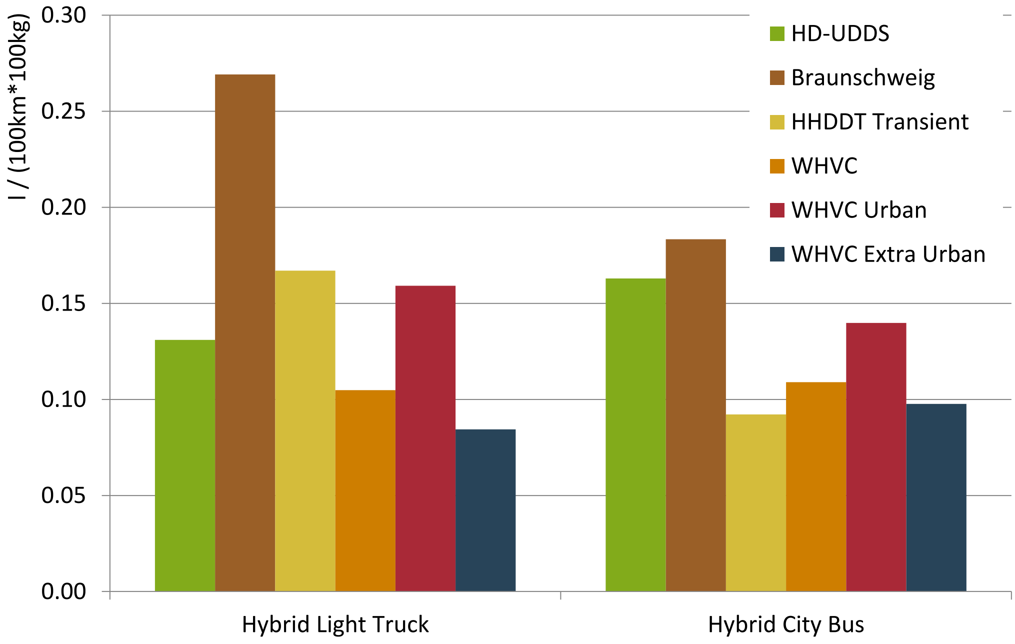

Figure 19: Fuel savings per 100 km and 100 kg weight reduction for trucks and buses with hybrid diesel engines

Hybrid light trucks and city buses have also been modelled (Figure 19). As for passenger cars, fuel savings turn out to be lower than the conventional value. Sensitivity to the specific operation strategy and driving cycle is very high, therefore it is possible that specific vehicles may realise very different fuel savings in specific situations. It is therefore concluded that the estimation of a single reference value for life-time energy savings of hybrid trucks and buses in chapter 4.2.2 would not be meaningful.

For the electric light truck and city bus (Figure 20), energy saving differences between the cycles are larger than observed for the electric passenger cars with energy savings again being highest for the urban Braunschweig cycle and lowest for the WHVC highway cycle.

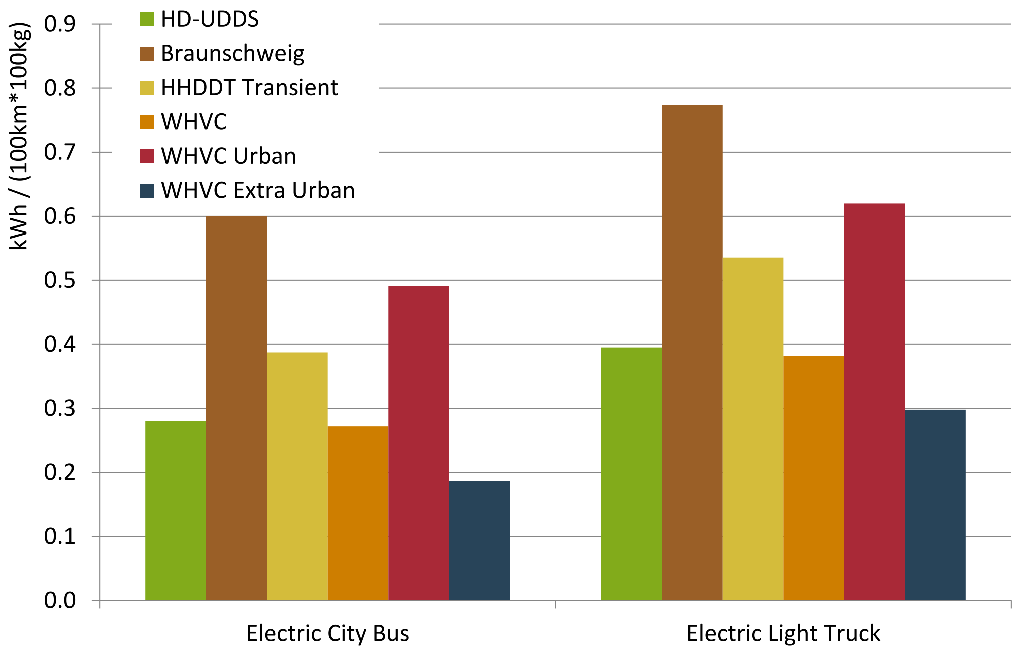

Figure 20: Energy savings per 100 km and 100 kg weight reduction for trucks and buses with electric engine (EU28 energy supply)

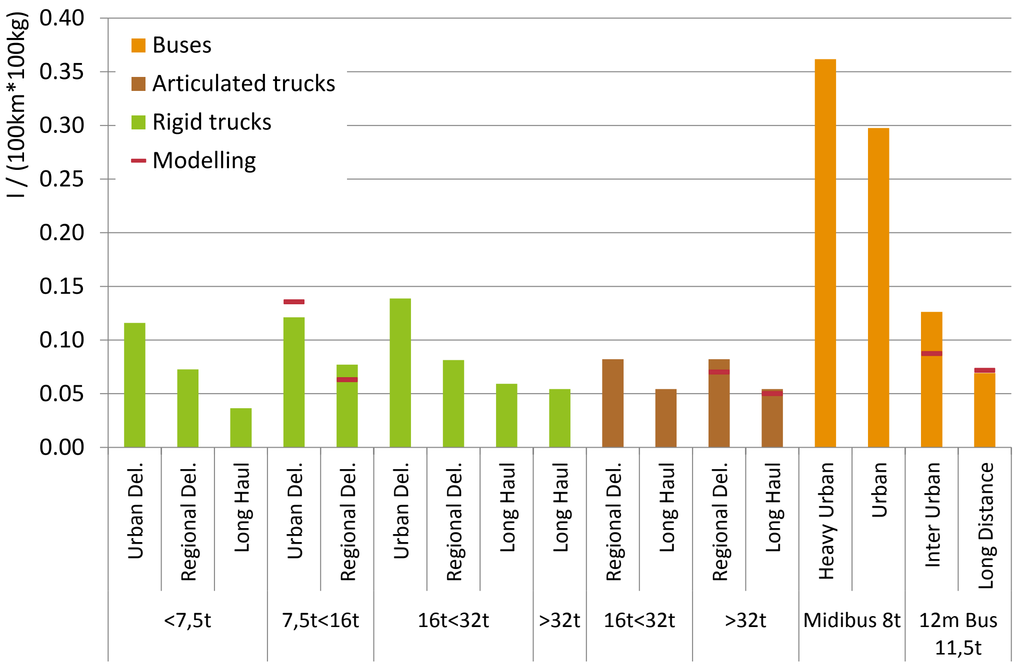

Figure 21: Fuel saving literature values for trucks and buses per 100 km and for a 100 kg weight reduction
Source: [Nikolas, et al., 2015a]

As for passenger cars, the modelled fuel saving values for heavy duty vehicles have been compared to literature reference values. The availability of recent comparable literature values, however, proved to be more limited than for passenger cars. [Nikolas, et al., 2015b] has been identified as the most suitable data source, describing CO_2 emission savings by light weighting of heavy duty vehicles due to light-weighting, which have been translated to fuel savings. The CO_2 emission savings in [Nikolas, et al., 2015a] are based on

VECTO simulations and Millbrook vehicle tests using the RWUTC (Rigid trucks), FIGE (Articulated trucks) and MLTB (Busses) driving cycle and their differentiated phases. The savings focus is on the primary mass reduction potential. It should be noted, that secondary effects of a weight reduction can mostly not be realized for heavy duty vehicles, since additional load (goods or passengers) differs far more than for passenger cars.

Figure 21 shows a very high fuel savings potential for midi buses in heavy urban use, which exceeds specific fuel savings for passenger cars and other heavy duty vehicles. This is mainly due to the very frequent stops and acceleration phases combined with a low mean velocity while driving. Since truck driving cycles contain fewer stops in urban areas than bus driving cycles, their fuel savings potential is much smaller compared to passenger cars. On the other hand, the total weight reduction potential should be higher than for passenger cars due to the considerably higher gross vehicle weight. Modelled fuel saving values for light and heavy diesel trucks and long distance coaches are very similar to literature values.

As a consistent framework of reference values for further use and communication it is suggested to use the full WHVC cycle to represent mixed driving. Additionally, values for the Braunschweig cycle are suggested for heavy urban use and the extra urban parts of the WHVC for highway use. These reference values can illustrate the range of specific uses and are therefore documented in Table 4. The new reference values for mixed use are slightly higher for the heavy truck than the previously derived ifeu value, due to a higher share of dynamic situations. The city bus value in urban driving and also the coach bus on highway have now been assessed to be significantly higher than estimated in previous studies. The light truck savings value, on the other hand is now slightly lower than previous estimates, also in urban driving.

	Mixed Use	Urban*	Highway**	Earlier ifeu values
Heavy truck 40t Diesel	0.07 l/100km	0.18 l/100km	0.05 l/100km	0.06 l/100km***
Light truck 12t Diesel	0.09 l/100km	0.14 l/100km	0.06 l/100km	0.2 l/100km**
Light truck 12t Electric	0.44 kWh/100km	0.77 kWh/100km	0.30 kWh/100km	NA
City Bus Diesel	0.10 l/100km	0.17 l/100km	0.08 l/100km	0.15 l/100km*
City Bus Electric	0.31 kWh/100km	0.60 kWh/100km	0.19 kWh/100km	NA
Coach Bus Diesel	0.11 l/100km	0.16 l/100km	0.07 l/100km	0.04 l/100km*

Table 4: Suggested energy savings reference values for light-duty vehicles (*Braunschweig Cycle; ** WHVC Extra Urban cycles)
* [ifeu, 2004a], ** [ifeu, 2004b], *** [ifeu, 2005], # EU28 energy supply

4.2.2 Use cases for lifetime primary energy savings of trucks and buses

The total lifetime energy and CO_2 savings of trucks and buses depend on the specific fuel savings analysed in detail in the previous chapter and the lifetime mileage of the respective vehicle. Furthermore, additional upstream energy consumption and CO_2 emissions for fuel production and electricity generation need to be taken into account. Lifetime energy savings are therefore highly dependent not only on the driving cycle but also on the lifetime mileage. To illustrate the potential differences, several use cases have been defined for discussion in this chapter, which basically differ by use intensity (i.e. lifetime mileage) and use pattern (driving cycle). Commercial heavy duty vehicles generally have a higher lifetime mileage compared to private passenger cars, ranging up to 1 million kilometres for

long-haul trucks or international coach buses. Additionally, lower use intensities and appropriate driving cycles are illustrated in the following figures. Numerous further use cases are possible for which lifetime energy and CO_2 savings are fully documented in the Annex.

Among the trucks, lifetime energy savings are generally higher for light trucks compared to heavy trucks since specific energy savings are considerably higher (see Figure 22). Though heavy trucks may have a very high lifetime performance of up to 1 million kilometres, lifetime savings remain limited because most of the mileage is on highways. An intensive mixed use with 600,000 km lifetime mileage, however, will lead to roughly the same lifetime savings as an urban or mixed light truck with 400,000 km mileage. The analysed electric light truck shows higher lifetime energy savings compared to its diesel counterparts. The picture for CO_2 savings (see Figure 23) for light-weight trucks is comparable, but savings for electric trucks with EU28 electricity are lower compared to the energy savings, due to the shares of renewable and nuclear electricity. The CO_2 savings potential in China, however, is currently considerably higher, but depends on the development of the electricity split over the lifetime of the vehicle.

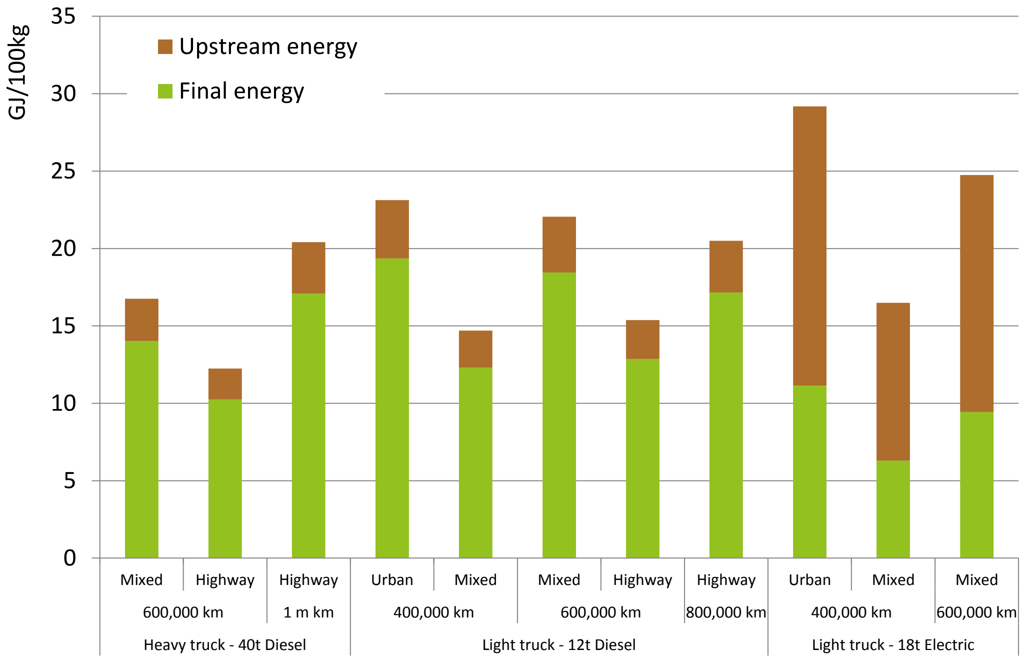

Figure 22: Lifetime primary energy savings of weight reduced trucks for selected use cases (EU28 energy supply)

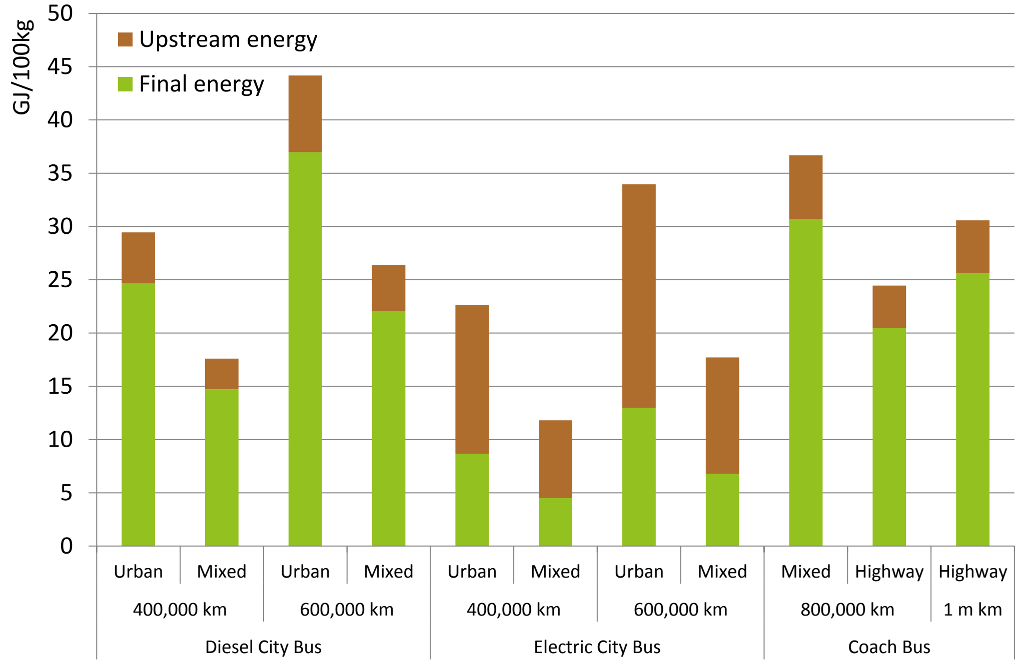

Figure 23: Lifetime primary energy savings of weight reduced buses for selected use cases (EU28 energy supply)

Lifetime energy savings of diesel and electric city buses (see Figure 24) is comparable and thus depend mainly on the individual use profile (urban only or rather mixed use) and the accumulated lifetime mileage. Lifetime mileage can generally be expected to be higher for long-distance national and international coach buses which can reach up to 1 million kilometres. Due to the lower specific lifetime savings on highways, the savings potential is not higher than most displayed city bus use cases. A mixed use with also urban shares of driving, however, increases this energy savings potential drastically. Again lifetime CO_2 savings follow a similar pattern (see Figure 25) with CO_2 savings of electric city buses with EU28 electricity split being lower compared to the energy savings potential. The CO_2 savings potential in China, again, is currently considerably higher, but depends on the development of the electricity split over the lifetime of the vehicle.

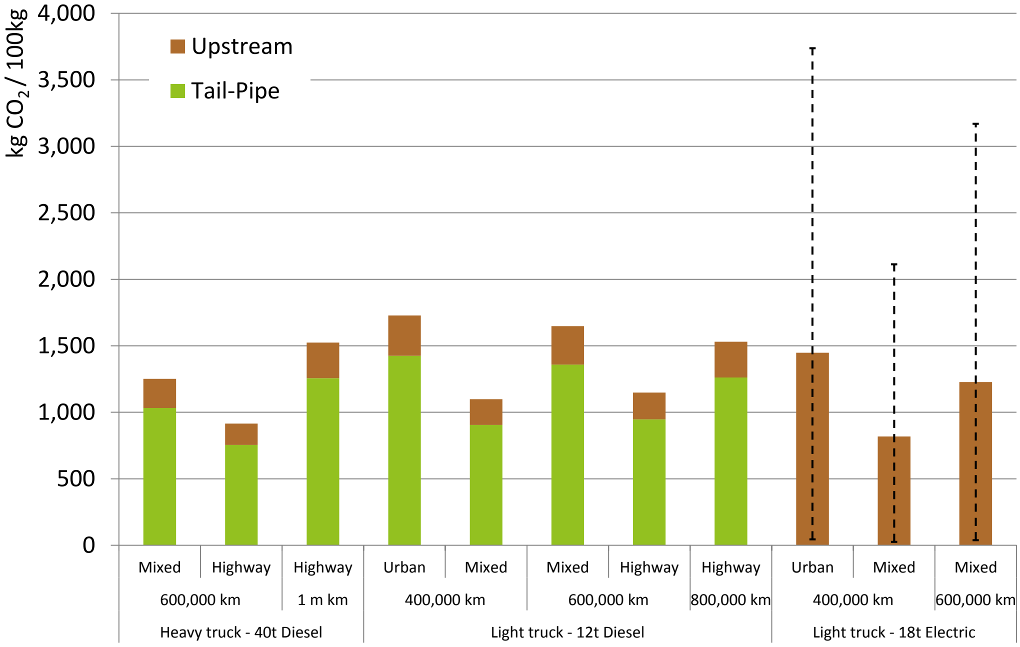

Figure 24: Lifetime primary CO_2 savings of weight reduced trucks for selected use cases (constant lifetime electricity split with EU28 electricity, range of electricity supply power mix influence illustrated by China (upper value) and Norway (lower value))

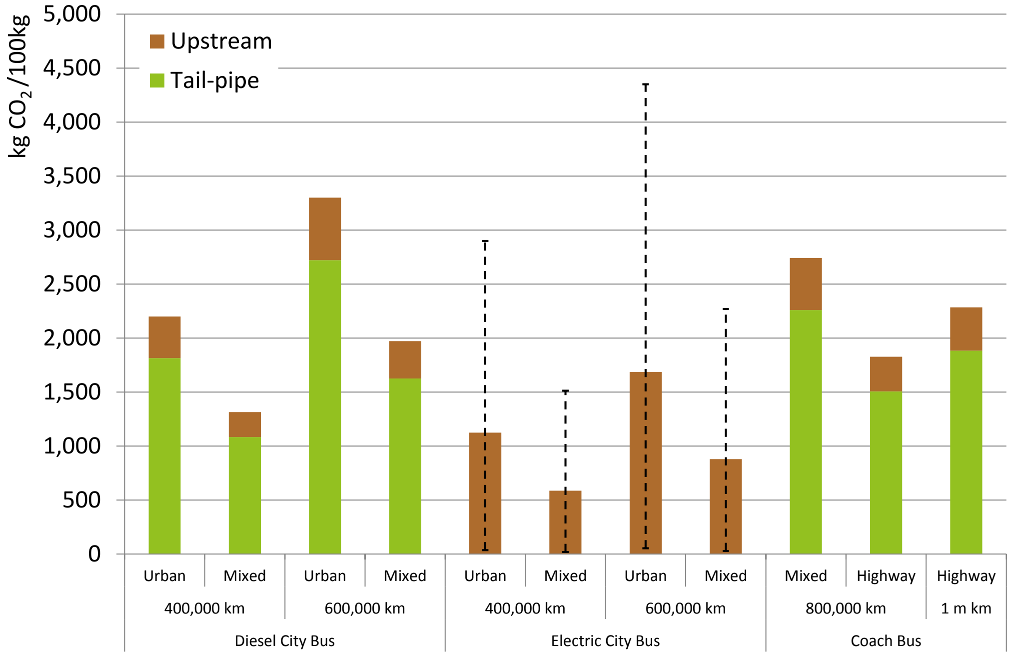

Figure 25: Lifetime primary CO_2 savings of weight reduced buses for selected use cases (constant lifetime electricity split with EU28 electricity, range of electricity supply power mix influence illustrated by China (upper value) and Norway (lower value))

5 Energy savings by light-weighting of rail vehicles

5.1 Specific energy savings for rail vehicles

Compared to the literature already analysed for previous studies and summarised in [ifeu, 2007], literature availability has not increased significantly for rail vehicles. A recent study by [Dittus, / Pagenkopf, 2013] has discussed additional modelling data for several train types and cycles. The results have been clustered by general train type including commuter/regional trains, long-distance trains and high-speed trains. Results for those vehicles are further investigated with respect to typical driving cycles and compared to previously estimated values (see Figure 26).

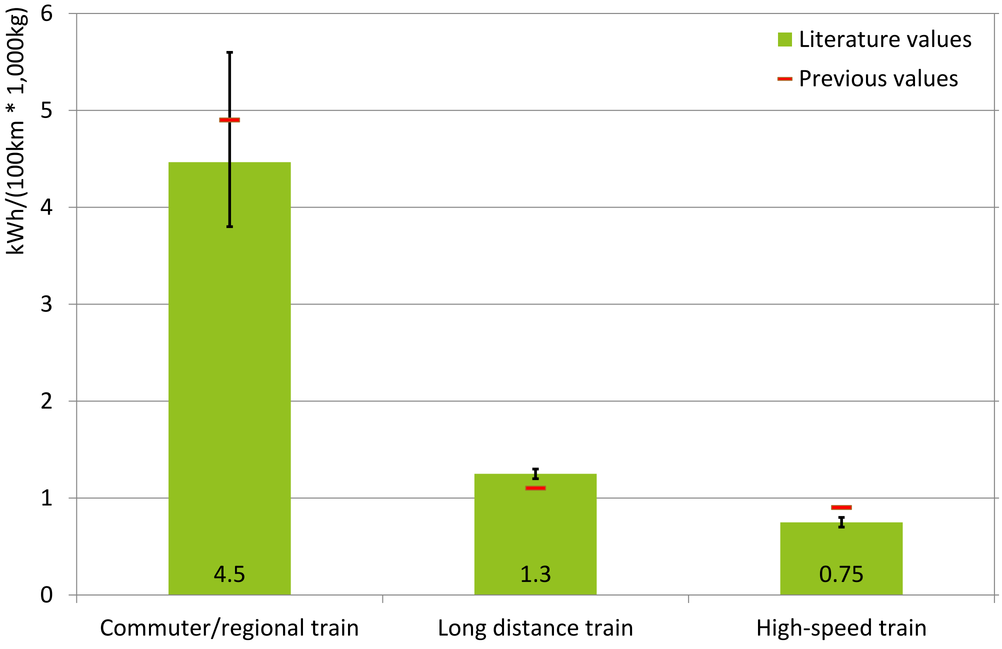

Figure 26: Literature values for energy savings for different train types by a weight reduction of 1 Tonne
Sources: [Dittus, / Pagenkopf, 2013], [ifeu, 2007]

Energy savings have been normalised to a weight reduction of 1,000 kg and a distance of 100 km. For each train type, the corresponding use pattern has been assigned, so that single typical values for each train type are derived. Subways/metros follow an urban cycle, commuter/regional trains a suburban/regional cycle and long distance trains may follow either the intercity/long distance cycle or in case of high-speed trains a specific high-speed train cycle with maximum distances between the stations and velocities over 300 km/h. The lifetime potentials are calculated with respect to these use patterns.

As expected, specific energy savings are highest for commuter/regional trains in a mixed suburban/regional driving cycle. These driving cycles have a maximum speed up to 120 and 140 km/h and distance between stations is between 2 km and 10 km (see Table 5). Specific energy savings for long distance and high speed trains amount to only about one quarter of the commuter/regional train savings. Here maximum speeds are up to 200-300 km/h and distances between the stations up to 60 km for long distance and 210 km for high speed trains.

These additional values are in line with previously derived figures (see [ifeu, 2007]). Due to the growing importance of high speed rail systems, a validation by modelling has been undertaken for a high speed train (see Annex for details on train modelling). Energy consumption and specific energy savings for a 1 tonne weight reduction have been modelled for an ICE3 for a comparable driving cycle. The result of 0.7 kwh/(100 km*1,000 kg) is almost equivalent to literature values. Overall, the values shown in Figure 26 proved to be very stable.

	Suburban	Regional	Long distance	High-speed
Maximum speed [km/h]	120	140	200	300
Total distance [km]	40	70	250	300
Number of stations	12	15	10	3
Min. station distance [km]	2	2	15	90
Max. station distance [km]	7	10	60	210

Table 5: Literature driving cycles for railway vehicles from [Dittus, / Pagenkopf, 2013]

5.2 Use cases for lifetime energy savings of trains

To derive life-time energy savings, a best estimate for the typical annual mileage of each train type has been identified and is summarised in Table 6. Besides various grey internet sources, this estimate is also based on [Handelsblatt, 2013], [Dittus, / Pagenkopf, 2013], [ifeu, 2007]. Lifetime energy savings for further lifetime mileages are documented in the Annex and can be used for analysis of different specific situations.

	Annual mileage	Operational life	Lifetime mileage
High speed (ICE)	500,000 km	25 years	12.5 Mio. Km
Long distance	250,000 km	30 years	7.5 Mio. km
Regional trains	150,000 km	30 years	4.5 Mio. Km
Subway/Metro	100,000 km	30 years	3 Mio. km

Table 6: Estimated life-time mileage of selected train types
Sources: [Handelsblatt, 2013], [Dittus, / Pagenkopf, 2013], [ifeu, 2007] and various grey internet sources

The use cases show higher lifetime primary energy savings for subways and regional trains, despite the considerably lower lifetime mileage (see Figure 27). Lifetime energy savings of

normal long distance trains and high speed trains are comparable, thus the mostly higher annual mileage of high speed trains offsets for the lower expected specific energy savings.

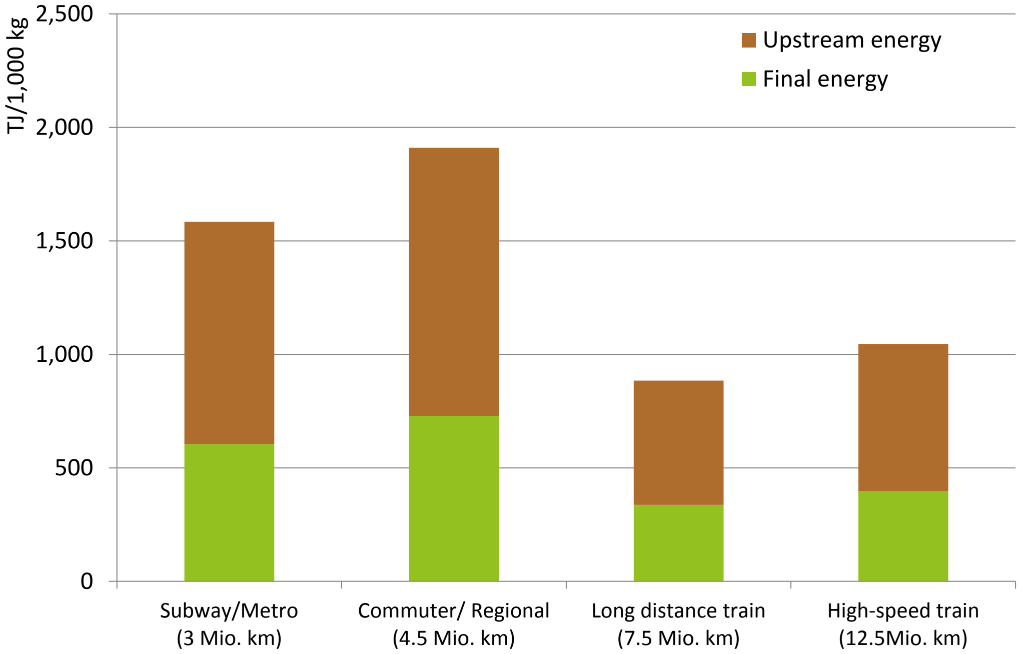

Figure 27: Lifetime primary energy savings of weight reduced train types (EU28 energy supply) [1]

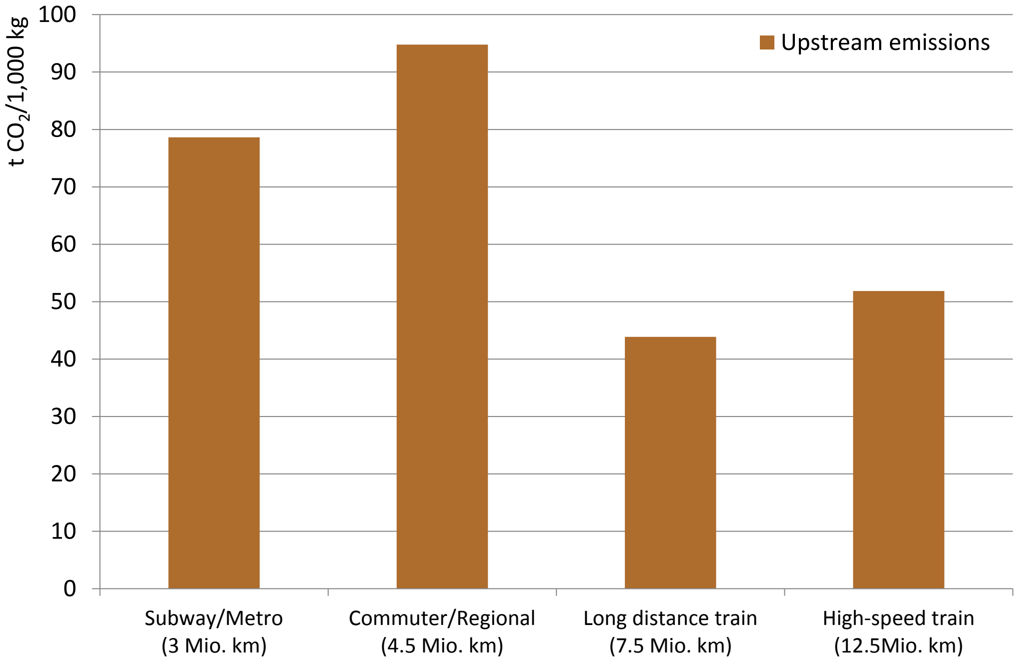

Figure 28: Lifetime CO_2 savings of weight reduced train types (EU28 energy supply)

[1] Since no recent publications on specific energy savings of light-weighting of Subways/Metros has been available, the reference value of 5.6 kWh/(100 km*1,000kg) from [ifeu, 2007] has been used.

CO_2 savings displayed in Figure 28 show a very similar picture, but are only valid for the EU28 region. Even within this region, CO_2 savings vary significantly depending on the respective national electricity split (see Figure 29). While CO_2 savings will be significantly lower in France due to a high share of nuclear energy, the savings potential is slightly higher in the United Kingdom and significantly higher in Poland, China and India. Higher emission savings are generally due to the higher share of fossil electricity generation. CO_2 emissions by electricity generation, however, are expected to decrease in the future, which will also lead to a lower CO_2 savings potential. The relevance of railways is also very different in the exemplified states, with the railway network being largest in the US and China.

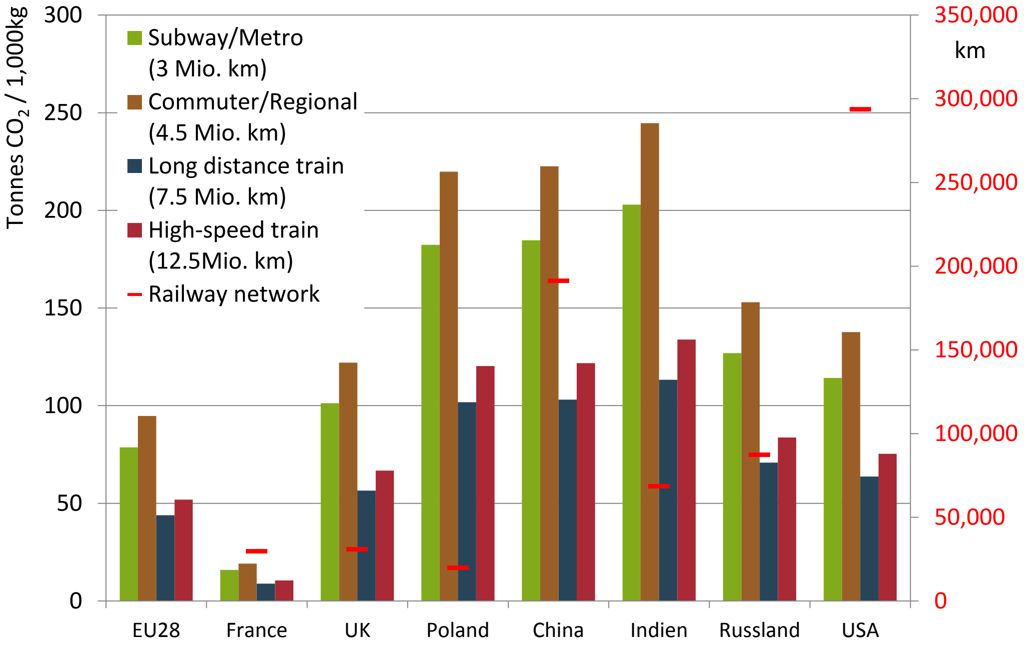

Figure 29: Lifetime CO_2 savings of weight reduced train types and railway network in selected countries Electricity split and corresponding CO_2 emissions based on [ifeu, et al., 2016], Railway network [CIA, 2016])

6 Conclusions

Current political targets and societal voices call for a substantial reduction in energy consumption and greenhouse gas emissions from the transport sector. The reduction of the weight of transport vehicles is one way to reduce the energy consumption and thus CO_2 emissions caused by transport vehicles and associated upstream processes. Several studies have already been carried out by ifeu to investigate potential energy savings by light-weighting (see [ifeu, 2004a], [ifeu, 2004b], [ifeu, 2005]). Since the previous studies were conducted more than ten years ago and modelling capacities for more differentiated and better comparable results have advanced, an update of reference values of specific energy savings by light weighting has been undertaken. Also corresponding use cases for life-time energy and CO_2 savings have been calculated. The means by which the weight of vehicles is reduced (e.g. material choices, specifics of component design, etc.) have not been considered in this study.

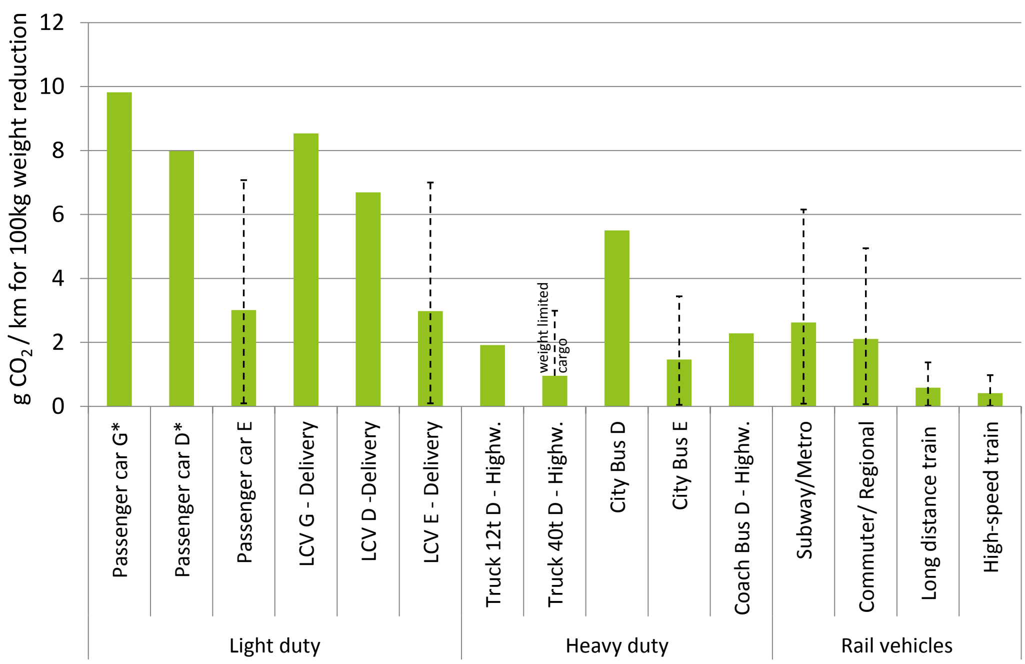

Figure 30: Specific primary CO_2 savings per km for a 100 kg weight reduction for selected vehicle use cases (EU28 electricity, electric vehicles range between energy supply in China (upper value) and Norway (lower value), reference year 2013)
* for passenger cars secondary effects by maintaining the power-to-weight ratio of the vehicle are considered

Primary CO_2 savings (including upstream processes) can now be calculated based on the specific fuel saving reference values (see selected use cases in Figure 30). For electricity generation, large country specific differences can be found which are displayed as ranges representing China and Norway (reference year 2013). Specific energy savings are highest for conventional passenger cars if secondary effects are included, but also light-

commercial delivery vehicles and city buses show high specific CO_2 savings, while long-distance vehicles have generally lower specific CO_2 savings.

A comparison of the lifetime CO_2 savings potential for a 100 kg weight reduction for selected use cases (see Figure 32), on the other hand, shows by far the highest savings potential for rail vehicles, due to the high life-time distance travelled. Among rail vehicles, however, the savings potential is higher for subways and regional trains than for long distance and high speed trains, despite the lower lifetime distance travelled. Further installation of low carbon electricity capacities over the lifetime of the vehicles, however, would decrease this potential. A detailed country specific analysis of such scenarios is beyond the scope of this study.

Among road vehicles, city buses and long distance coaches have the highest lifetime savings potential. For the electric versions, life-time primary CO_2 savings depend largely on the electricity split (see ranges in Figure 31) and can be significantly higher than for conventional cars (e.g. in China), but also lower (e.g. in Norway).

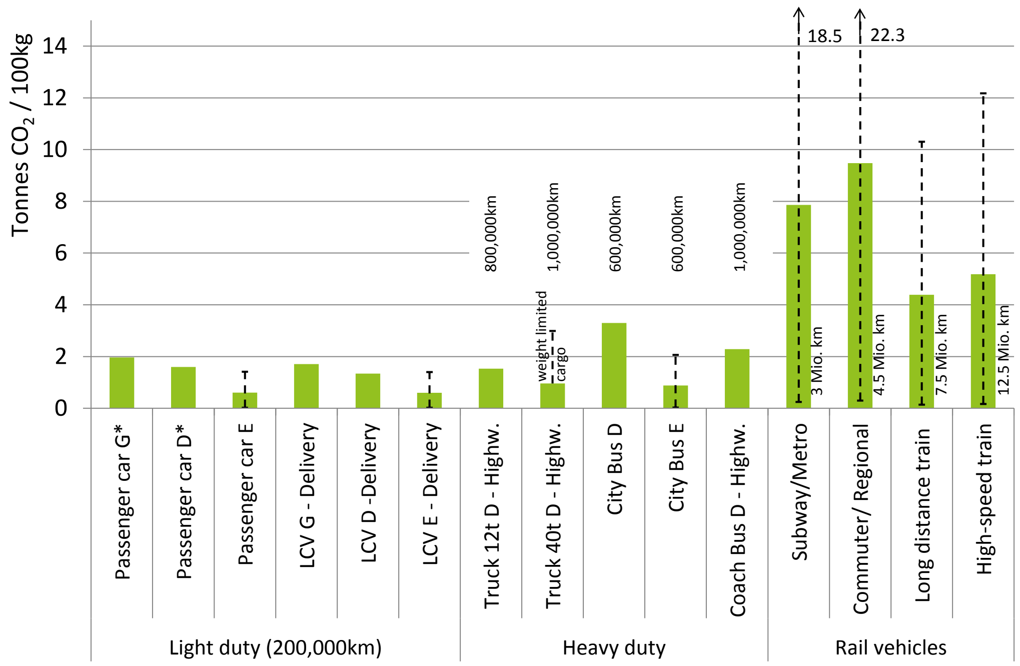

Figure 31: Life-time CO_2 savings by a 100 kg weight reduction for selected vehicle use cases (constant lifetime electricity split 2013 with EU28 electricity, electric vehicles range between energy supply in China (upper value) and Norway (lower value))
* for passenger cars secondary effects by maintaining the power-to-weight ratio of the vehicle are considered

References

Aluminium, E. (2015): Aluminium in cars - Unlocking the light-weighting potential. *http://european-aluminium.eu/media/1326/aluminium-in-cars-unlocking-the-lightweighting-potential.pdf*.

Casadei, A. / Broda, R. (2008): Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures. *http://www.drivealuminum.org/research-resources/PDF/Research/2008/2008-Ricardo-Study.pdf*.

CIA (2016): The World Fact Book. *https://www.cia.gov/library/publications/the-world-factbook/rankorder/2121rank.html*.

Delogu, M. / Del Pero, F. / Pierini, M. (2016): Modelling of use stage in lightweight automotive LCA perspective: estimation of mass-induced fuel consumption reduction for gasoline turbocharged vehicles. In: *Journal of Cleaner Production*. Vol. 139, S. 28.

DIN (2012): DIN EN 16258 - Methode zur Berechnung und Deklaration des Energieverbrauchs und der Treibhausgasemissionen bei Transportdienstleistungen (Güter- und Personenverkehr). DIN - German Institute for Standardization.

Dittus, H. / Pagenkopf, J. (2013): Lightweight Design in Railway Vehicles – Energy and Cost Potential Assessment.

EPA/NHTSA (2011): Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. In: *Federal Register/Vol. 76, No. 179, 15. September 2011*.

EU (2014): Regulation 333/2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. European Union.

European Aluminium (2014a): Moving up to aluminium high payload, safe and sustainable road transport. Brussels.

European Aluminium (2014b): Present and future CO2 reduction potential thanks to aluminium in European articulated trucks. Brussels.

Faßbender, S. / Hartmann, B. / Urban, P. / Eckstein, L. / Bröckerhoff, M. (2012): Investigation of the Trade-off Between Lightweight and Battery Cost for an Aluminium-intensive Electric Vehicle.

Handelsblatt (2013): Welche Strecke legt ein Zug insgesamt zurück? In: *Handelsblatt*. http://www.handelsblatt.com/technik/das-technologie-update/weisheit-der-woche/schienenverkehr-welche-strecke-legt-ein-zug-insgesamt-zurueck/8896436.html (22.11.2016).

Huoa, H. / Heb, K. / Wang, M. / Yaod, Z. (2012): Vehicle technologies, fuel-economy policies,

and fuel-consumption rates of Chinese vehicles. In: *Energy Policy*. Vol. 43, S. 30–36.

ICCT (2015): Heavy Duty Vehicle Fuel Efficiency Simulation: A Comparison of US and EU Tools.

IEA (2015a): IEA Headline Energy Data. Paris.

IEA (2015b): CO2 emissions from fuel combustion - Highlights. Paris.

ifeu (2004a): Energy Savings by lightweighting. ifeu - Institut für Energie- und Umweltforschung. Heidelberg.

ifeu (2004b): Energy savings by light-weighting - II. ifeu - Institut für Energie- und Umweltforschung. Heidelberg.

ifeu (2005): Energy savings by light-weighting for European articulated trucks. Heidelberg.

ifeu (2007): The potential contribution of light-weighting to reduce transport energy consumption. In: *The International Journal of Life Cycle Assessment*. Vol. 12, S. 58–64.

ifeu / INFRAS / IVE (2016): Ecological Transport Information Tool for Worldwide Transports Methodology and Data Update Environmental ifeu Heidelberg Methodology and Data. *http://www.ecotransit.org/download/ETW_Methodology_Background_Report_2016.pdf*.

Ika (2014): CO2-Emissionsreduktion bei Pkw und leichten Nutzfahrzeugen nach 2020. Aachen.

Kim, H. C. / Wallington, T. J. (2016): Life Cycle Assessment of Vehicle Lightweighting: A Physics-based Model to Estimate Use-Phase Fuel Consumption of Electrified Vehicles - Support information. In: *Environmental Science & Technology*. Vol. 49, No.16, S. acs.est.6b02059.

Kim, H. C. / Wallington, T. J. / Sullivan, J. L. / Keoleian, G. A. (2016): Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model To Estimate Use-Phase Fuel Consumption of Electrified Vehicles. In: *Environmental Science and Technology*. Vol. 49, No.16, S. 11226–11233.

NHTSA (2012): NHTSA and EPA Set Standards to Improve Fuel Economy and Reduce Greenhouse Gases for Passenger Cars and Light Trucks for Model Years 2017 and Beyond Benefits and Costs of the New CAFE Standards Benefits to Consumers. National Highway Traffic Safety Administration. *https://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE_2017-25_Fact_Sheet.pdf*.

Nikolas, H. / Norris, J. / Kirsch, F. / Dun, C. / Mcgregor, N. / Pastori, E. / Skinner, I. (2015a): Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO2 emissions.

Nikolas, H. / Norris, J. / Kirsch, F. / Dun, C. / Mcgregor, N. / Pastori, E. / Skinner, I. (2015b): Light weighting as a means of improving Heavy Duty Vehicles ' energy efficiency and overall CO2 emissions.

Schach, R. / Jehle, P. / Naumann, R. (2006): Transrapid und Rad-Schiene-Hochgeschwindigkeitsbahn. Berlin Heidelberg.

Steimel, A. (2014): Electric Traction. Munich.

Annex 1: Vehicle modelling methodology

Road vehicle modelling

Since there is no globally standardised model available for all vehicle types, the calculation of fuel consumption and CO_2 emissions has been conducted with a Matlab® based Vehicle Simulator which has been developed by ifeu as part of several research projects. The schematic operation of the model is shown in Figure 32. Energy consumption and carbon dioxide emissions of the following propulsion systems for road vehicles can be simulated with various drivetrain configurations, such as

- Conventional vehicles with internal combustion engine (ICE),
- Hybrid electric vehicles (HEV) and
- Battery electric vehicles (BEV).

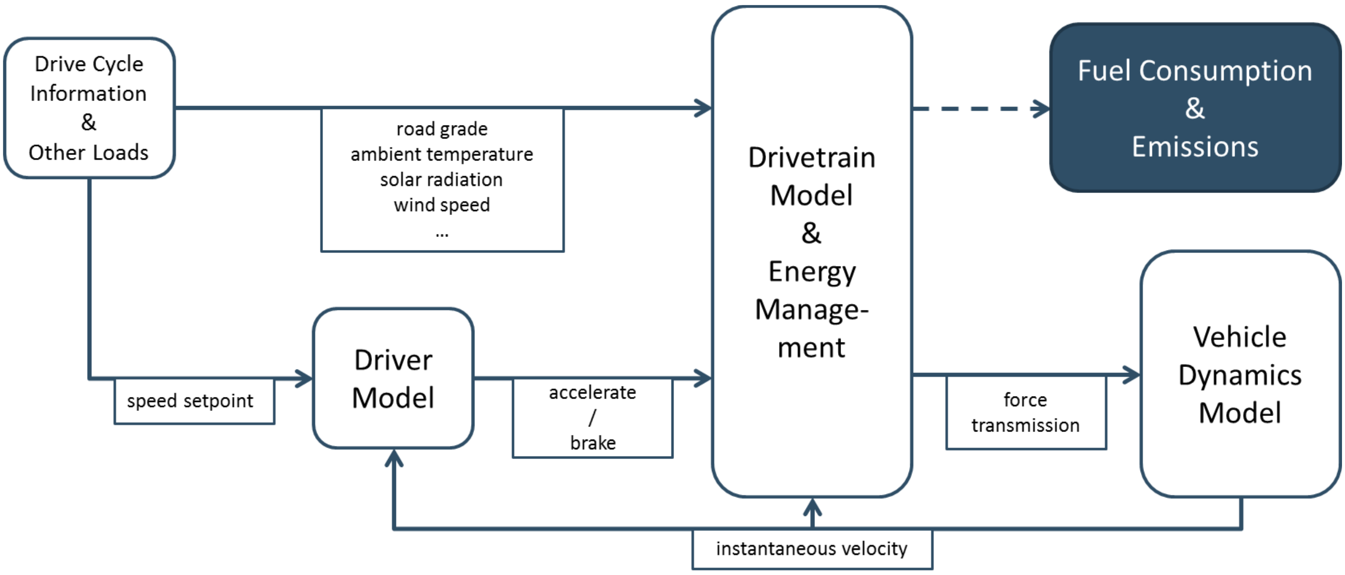

Figure 32: Schematic mode of operation of the ifeu vehicle model (VEHMOD)

Figure 33 shows the simulation procedure and highlights the main steps for calculating the vehicle fuel consumptions and green-house-gas-emissions: After parametrisation of a reference vehicle with corresponding and required properties, generic engine or motor maps are loaded. By comparison of the simulation results with the stated consumption values from actual measurements during type approval or test cycle runs, the model parameters are adjusted. Once the parameter set produces results within the accepted uncertainty range (validated configuration), the vehicles mass will be varied in further simulations with certain drive cycles.

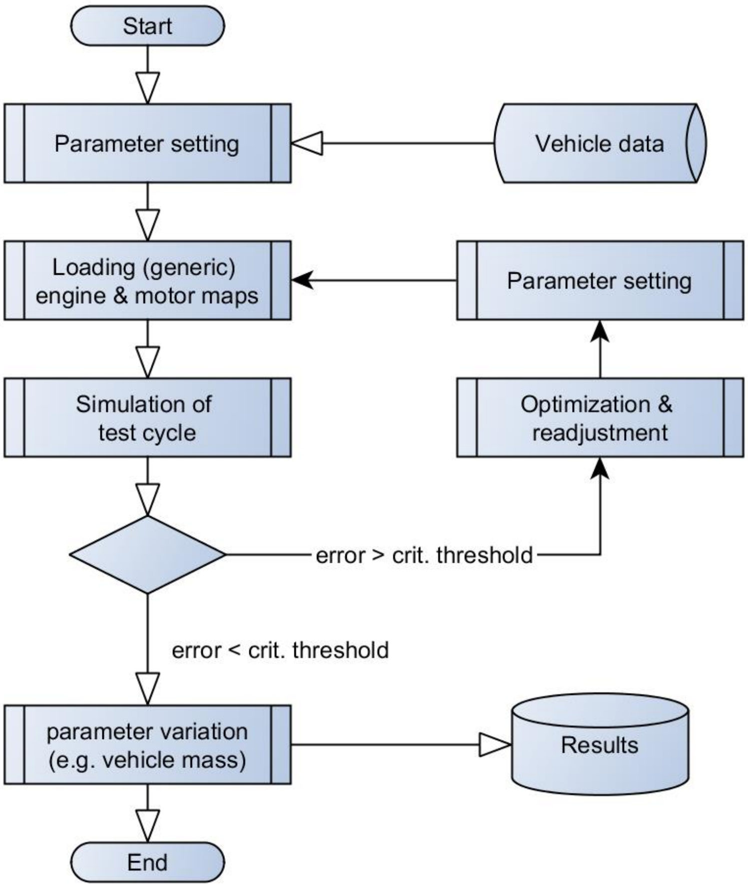

Figure 33: Simulation procedure for calculating the vehicles' fuel consumptions and green-house-gas-emissions.

A range of passenger car and light commercial vehicle examples has been selected to identify suitable parameter settings for the different size classes. Thereby different drivetrains and manufacturers are covered (see Table 7). Several main parameters could be adopted from the available manufacturer specifications and type approval documentations, such as

- coast down values of the vehicles, which were determined for type approval tests to determine the driving resistance values,
- vehicle weight
- tyre diameters,
- gear ratios and
- main engine performance parameters like rated power, rated torque and rounds per minutes.

Unknown parameters were estimated by typical values for the vehicle size class and varied in the calibration process to meet official type approval consumption values as shown in Figure 33. Afterwards, the values have been kept stable for the calculation of light-weighting emission savings. It is important to note that the vehicles summarised in Table 7 are rather examples for their class. Results can therefore not be necessarily interpreted as an emission savings potential of this particular vehicle.

Size class	Drive train	Parameter set
Small passenger car	ICE Gasoline	Fiat 500
	ICE Diesel	Fiat 500
	BEV	Fiat 500e
	Hybrid Gasoline	Toyota Yaris
Medium passenger car	ICE Gasoline	Volkswagen Golf 1.2 TSI BMT
	ICE Diesel	Volkswagen Golf 2.0 TDI
	BEV	Nissan Leaf
	Hybrid Gasoline	Toyota Auris
Large passenger car	ICE Gasoline	Mercedes Benz E 400
	ICE Diesel	Mercedes Benz E 250 d
	BEV	Tesla Model S
	Hybrid Gasoline	Toyota Prius +
Light commercial vehicles	ICE Gasoline	Mercedes Benz Sprinter
	ICE Diesel	Mercedes Benz Sprinter
	BEV	Nissan eNV200

Table 7: Overview of modelled light-duty vehicle examples

As for passenger cars, also heavy duty vehicle examples have been selected to identify suitable parameter settings for the different vehicle types (see Table 8).

	Drive train	Vehicle model specification
Heavy truck 40t	Diesel	Mercedes Actros 1845
Delivery Truck	Diesel	MAN TGM (12 t)
	Hybrid Diesel	Freightliner M2106 Hybrid (12 t)
	Electric	E-Force (18t)
City Bus	Diesel	MB Citaro
	Hybrid Diesel	Volvo 7900
	Electric	BYD (40ft)
Coach Bus	Diesel	Volvo B11R

Table 8: Overview of modelled truck and bus examples

Comparison of VECTO and VEHMOD

VECTO is the designated official tool that aims to play a crucial role in the European type approval procedure of heavy duty vehicles in the near future. VECTO thus is specialized, but also limited to the calculation of the fuel consumption and greenhouse-gas-emissions of heavy duty vehicles. VEHMOD on the other hand is a vehicle simulator developed as part of several ifeu research projects to calculate the fuel consumption and greenhouse-

gas-emissions of various vehicles in different environmental and driving situations. VEHMOD thus is not limited to heavy duty vehicles, but also not officially used and less specialized than VECTO.

To analyze the compatibility of simulation results between VECTO and VEHMOD a comparison approach described in [ICCT, 2015] has been adopted. Two trucks (Vehicle ID 1 and 2), further defined in [ICCT, 2015], were selected and VEHMOD has been accordingly as close as possible. Some parameters had to be transposed into VEHMOD equivalents values or derived from GEM[1]. A limited selection of key figures is shown in Table 9.

Parameter	Truck I (ID 1)	Truck II (ID 2)
Engine power [kW]	339	339
Rated engine speed [rpm]	2200	2200
Number of gears	10	10
Final drive ratio	2.64	2.64
Total weight [kg]	31978	30277
Tire rolling resistance [kg/kg]	0.006	0.006
Frontal area of vehicle [m2]	10.4	7.7
Loaded tire radius [m]	0.489	0.489
Coefficient of aerodynamic drag	0.6	0.6

Table 9: Key parameters of selected trucks for the result comparison between VECTO and VEHMOD

The simulations were conducted with the World Harmonized Vehicle Cycle (WHVC, see example for Truck I in Figure 34) and compared to the results generated by VECTO (see Figure 35). The fuel consumption by VECTO of "Truck I" is about 344 g/km whereas "Truck II" consumes 319 g/km. The fuel consumption values calculated with VEHMOD are slightly higher and are about 350 g/km (+ 1.9 %) with "Truck I" and 322 g/km (+ 1.0 %) with "Truck II".

Despite of the slightly difference in the simulation results for each truck, it could be demonstrated that VEHMOD produces results very comparable to VECTO and also reflects the vehicle differences (mass and aerodynamic drag) appropriately. Remaining result differences could be based on uncertainties in gear shifting strategies and generic engine maps.

[11] The Greenhouse Gas Emissions Model (GEM) is compared to VECTO in the ICCT's study and provided by the US EPA.

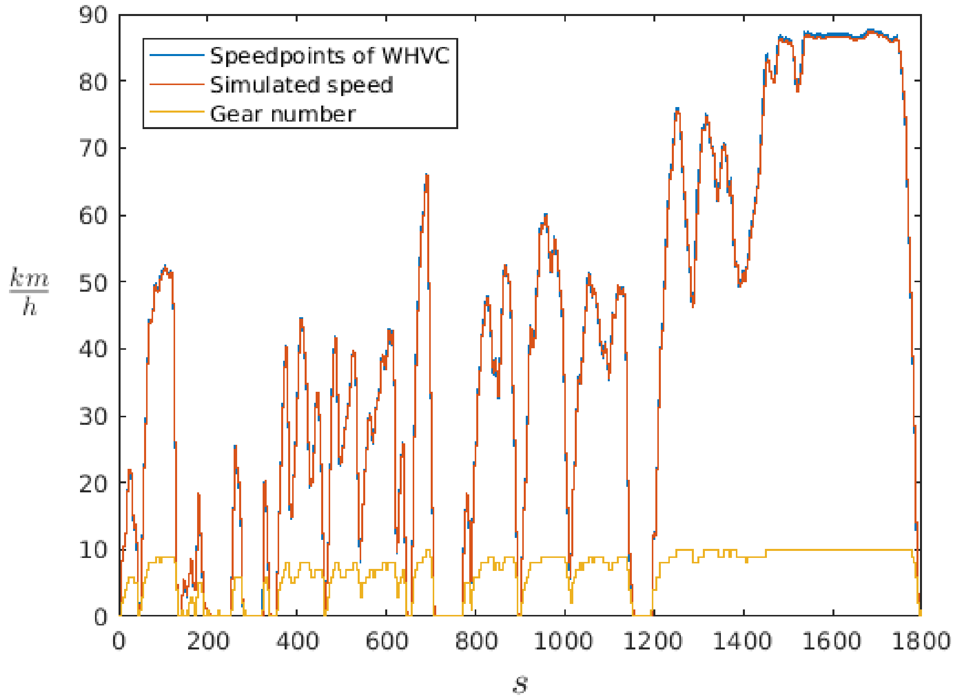

Figure 34: Simulated WHVC with Truck I

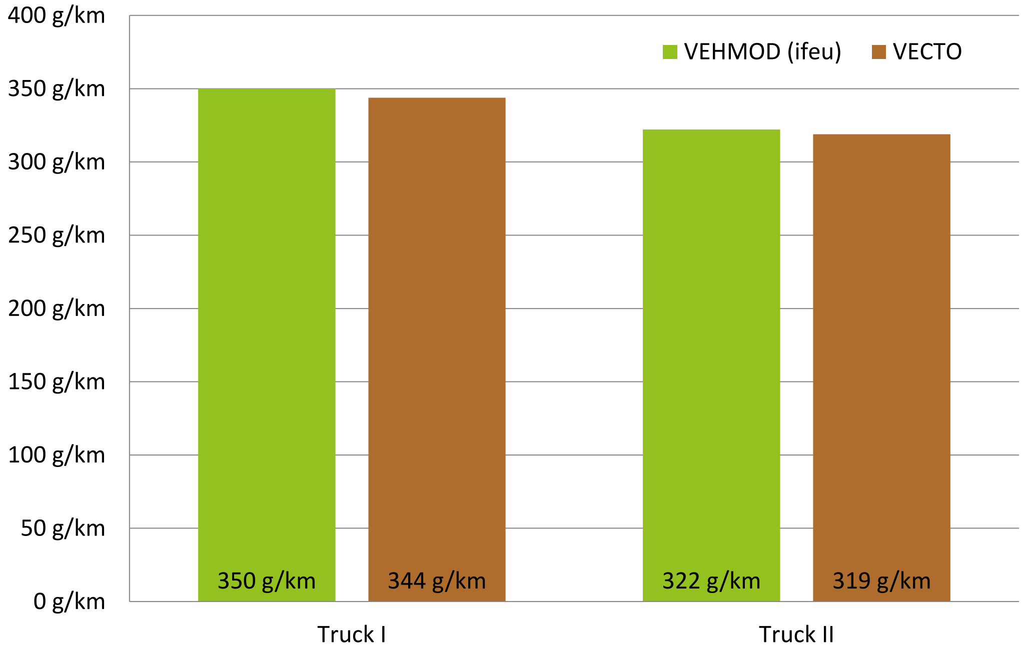

Figure 35: Simulation results of VECTO and VEMOD using the World Harmonized Vehicle Cycle (WHVC)

Rail vehicle modelling

For validation of literature values for high speed trains, a simplified modelling of the energy consumption of an ICE3 was undertaken within the same modelling environment. To calculate the trains driving resistance the following equations based on [Steimel, 2014] were used:

- Train Rolling Resistance:

$$W_r = \left[1 + k_1 * v_{Train} + k_2 * \frac{n + k_3}{G_{Train}} * k_4 * (v_{Train} + k_5)^2\right] * G_{Train}$$

- Curve Resistance:

$$W_c = \begin{cases} \frac{650}{r - 30} * G_{Train}, if\ r \geq 300m \\ \frac{500}{r - 55} * G_{Train}, if\ r < 300m \end{cases}$$

- Gradient Resistance:

$$W_g = s \cdot G_{Train}$$

- Acceleration Resistance:

$$W_a = \frac{a}{9.81} * \varphi * 1000 * G_{Train}$$

Where $k_{1...5}$ are empirical resistance parameters, v_{Train} is the speed of the train n the number of wagons, r is the radius in meter, s the slope of the track, a the trains acceleration, φ the allowance for rotating masses and G_{Train} the weight force due to the trains mass. To determine the parameters $k_{1...5}$ the resistance values for an ICE3 from [Schach, et al., 2006] were used to carry out a global minimization of the deviations to the overall resistance at the given speed levels under the same conditions as described there.

To estimate the energy losses in the powertrain a generic model of the efficiency characteristics of motor and power electronics has been used. For the braking phase, the capacity of the regenerative braking system was respected by adding additional braking forces by an eddy-current brake as well as a pneumatic disk brake with their individual maximal speed-force-characteristic.

Annex 2: Driving cycles for road vehicles

Table 10 summarises the modelled driving cycles for light- and heavy duty road vehicles. Speed profiles of the driving cycles are shown in Figure 36 to Figure 44.

Cycle	Description	Country/ Region	Average speed
Light duty vehicles			
NEDC	New European Driving Cycle: Mixed cycle for EU homologation since 1992	EU	32.5 km/h
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure: Mixed cycle for EU homologation from 2017		46.1 km/h
WLTP Low	WLTP part with speeds below 60 km/h for urban driving	EU	18,2 km/h
WLTP Extra High	WLTP part with high speeds mostly above 100 km/h		89.8 km/h
FTP-75	Federal test procedure of the US EPA reflecting urban driving	US	34.1 km/h
US06	Supplemental Federal Test Procedure of the US EPA, reflecting mixed driving also with high speeds above 100 km/h	US	77.2 km/h
JP10-15	Japanese light-duty vehicle test cycle reflecting mixed driving	Japan	25.6 km/h
Heavy duty vehicles			
HD-UDDS	EPA Urban Dynamometer Driving Schedule (UDDS) for heavy duty vehicles	US	30.3 km/h
Braunschweig	Braunschweig City Driving Cycle cycle for urban buses	Germany	22.5 km/h
HHDDT Transient	Transient part of the CARB Heavy Heavy-Duty Diesel Truck Schedule reflecting dynamic driving	California	24.6 km/h
WHVC	World Harmonised Vehicle Cycle based on the World Harmonized Transient Cycle (WHTC) reflecting mixed driving	EU, US, etc.	40.1 km/h
WHVC Urban	Urban part of the WHVC		21.3 km/h
WHVC Highway	Highway part of the WHVC		77.2 km/h
Train			
High Speed	Time-speed correlation for high speed trains (generic)	N.A.	254.5 km

Table 10: Overview of modelled driving cycles

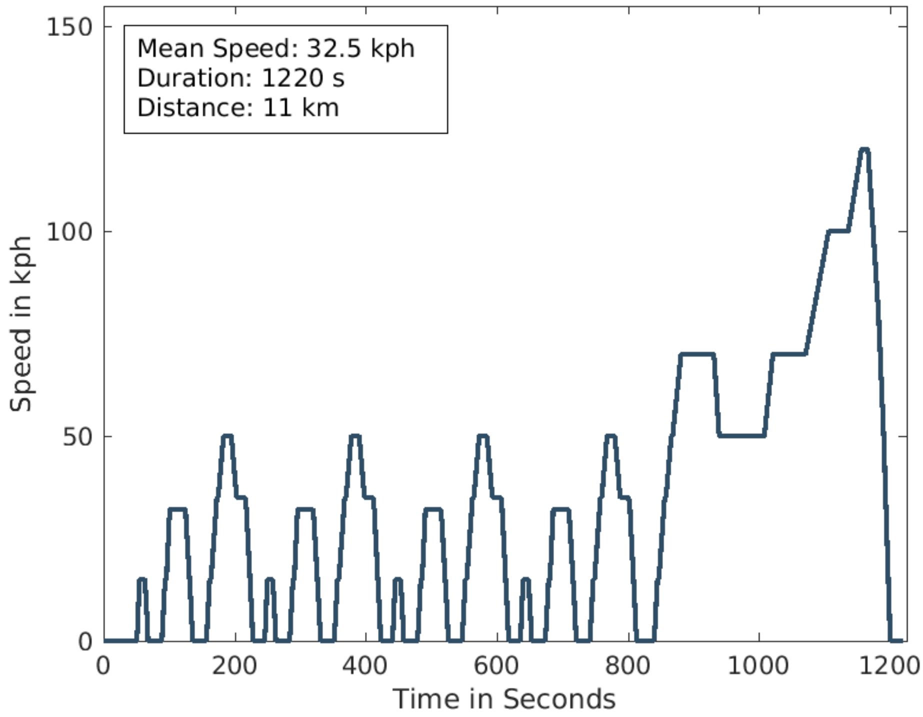

Figure 36: New European Driving Cycle (NEDC)

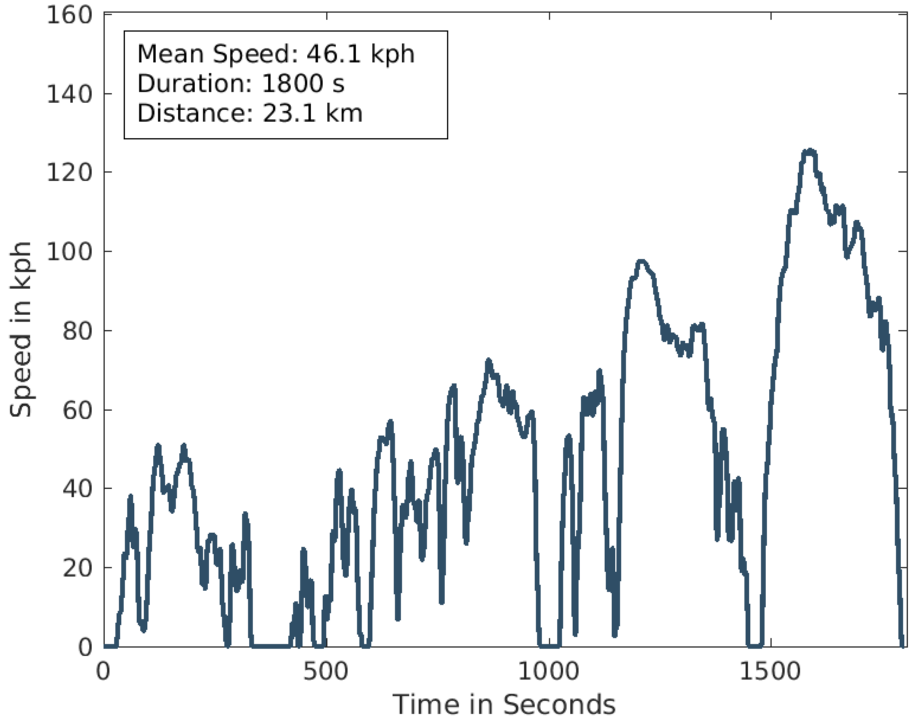

Figure 37: Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP)

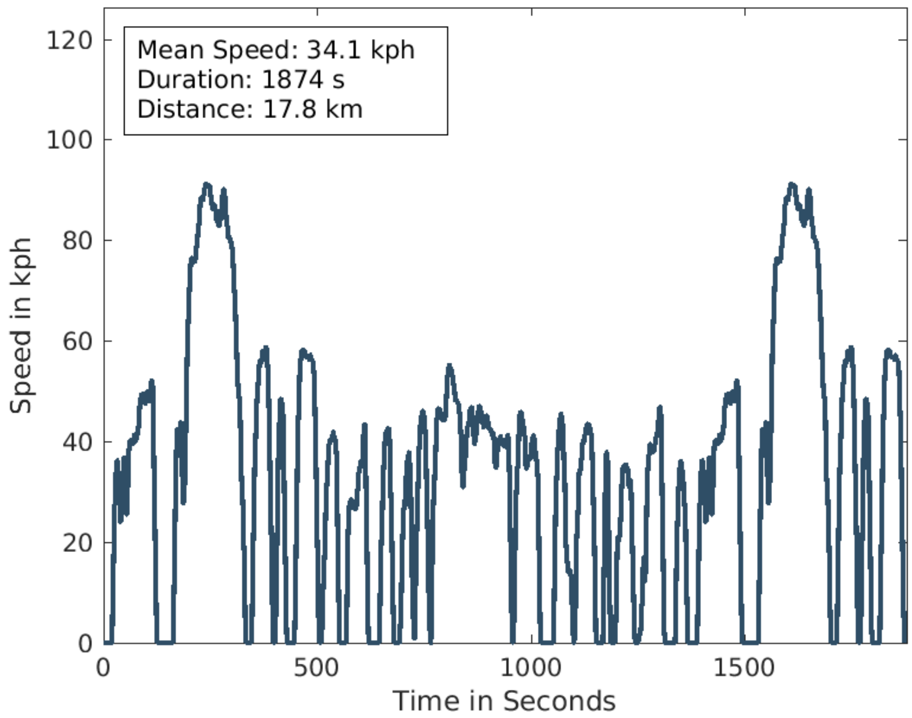

Figure 38: EPA Federal Test Procedure (FTP-75)

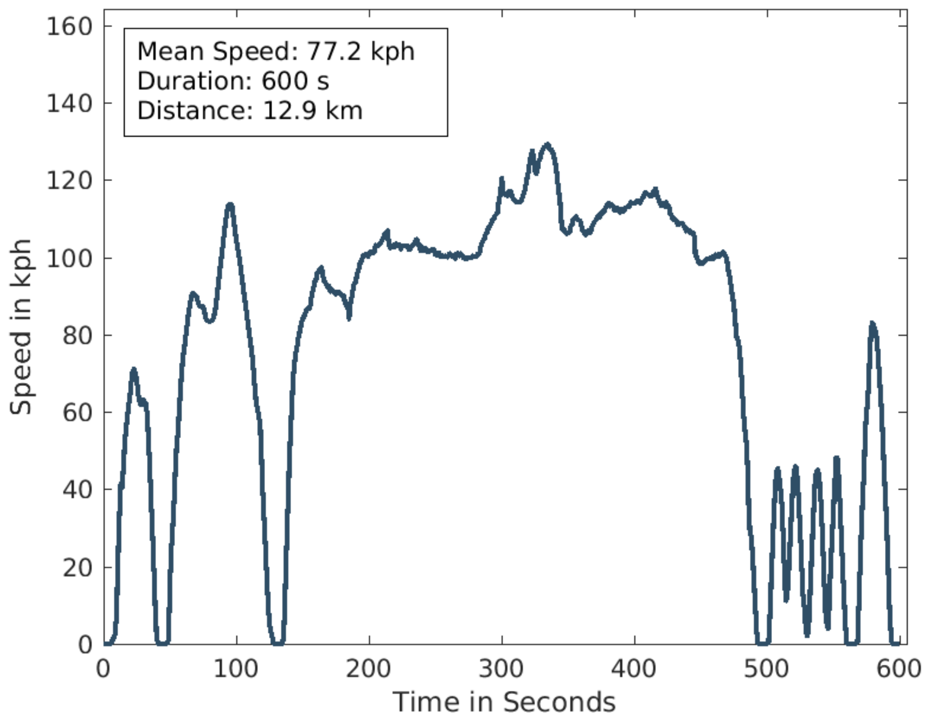

Figure 39: EPA Supplemental Federal Test Procedure (US06)

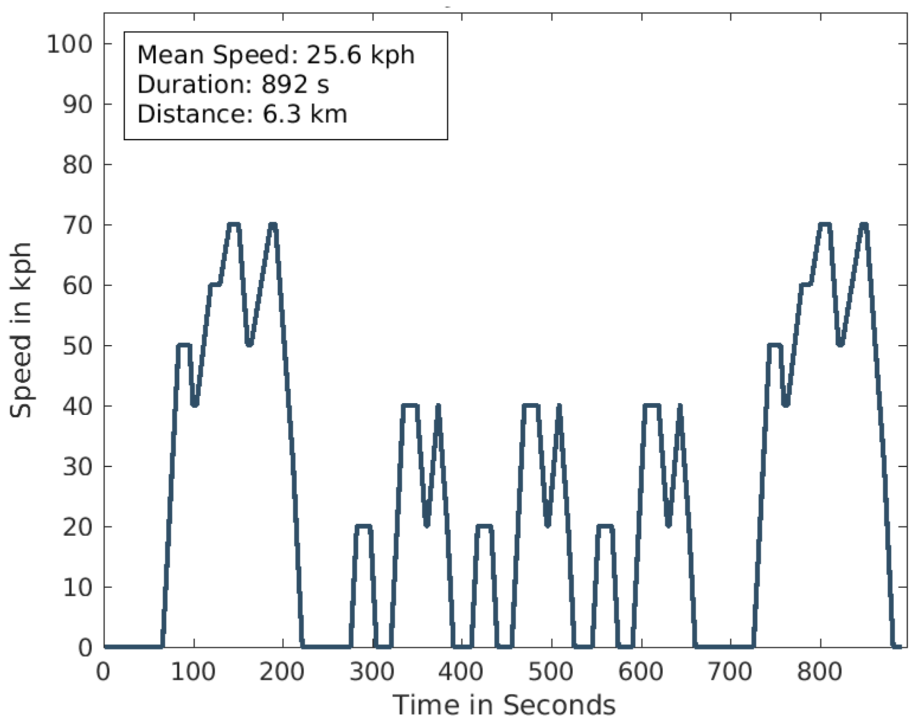

Figure 40: Japanese light-duty vehicle test cycle (JP10-15)

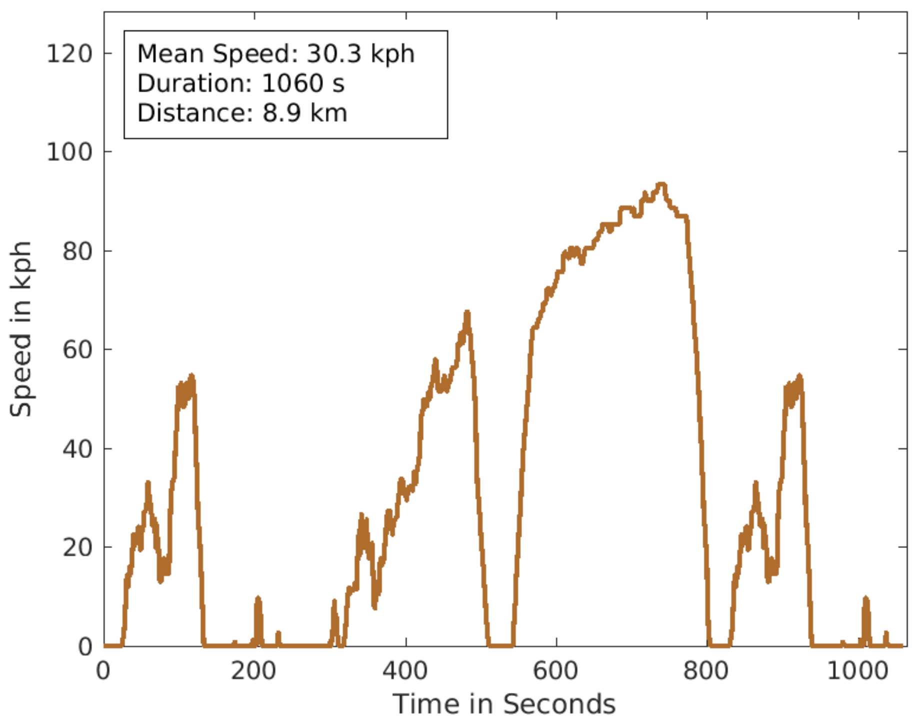

Figure 41: EPA Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS)

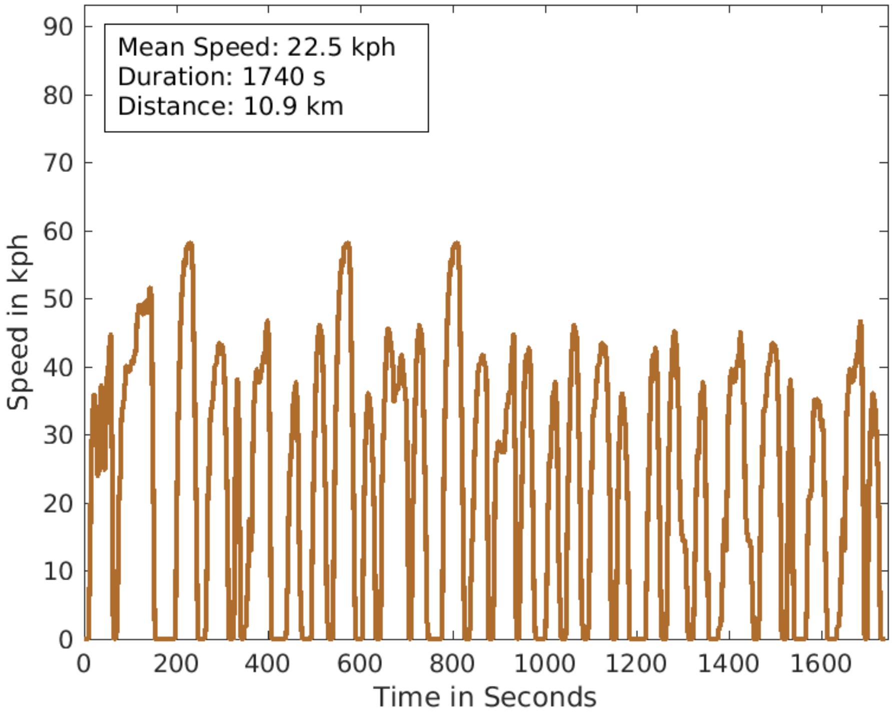

Figure 42: Braunschweig City Driving Cycle cycle for urban buses

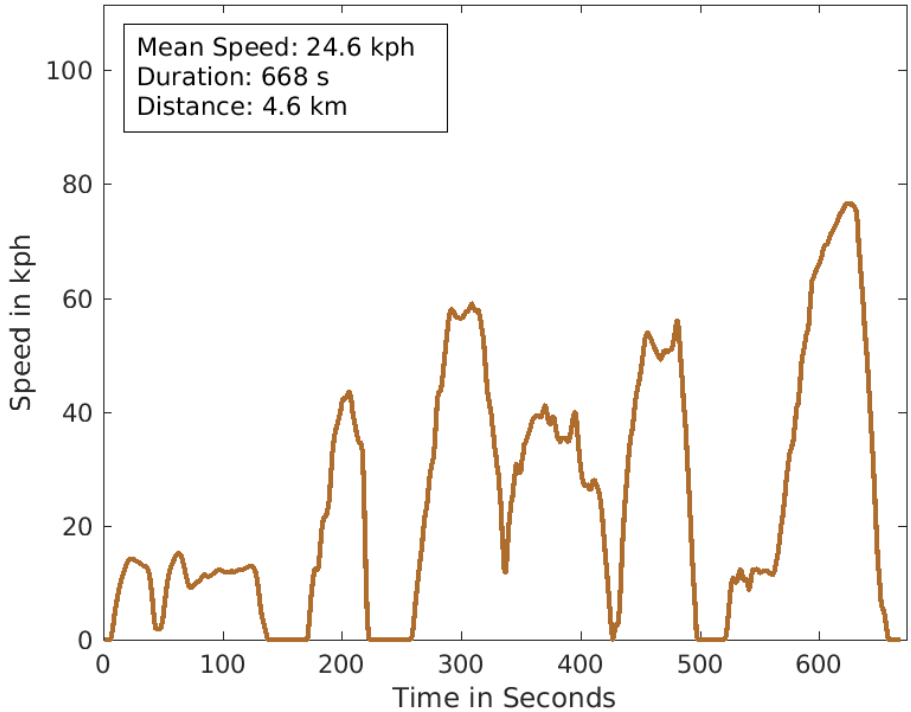

Figure 43: Transient part of the CARB Heavy Heavy-Duty Diesel Truck Schedule (HHDDT Transient)

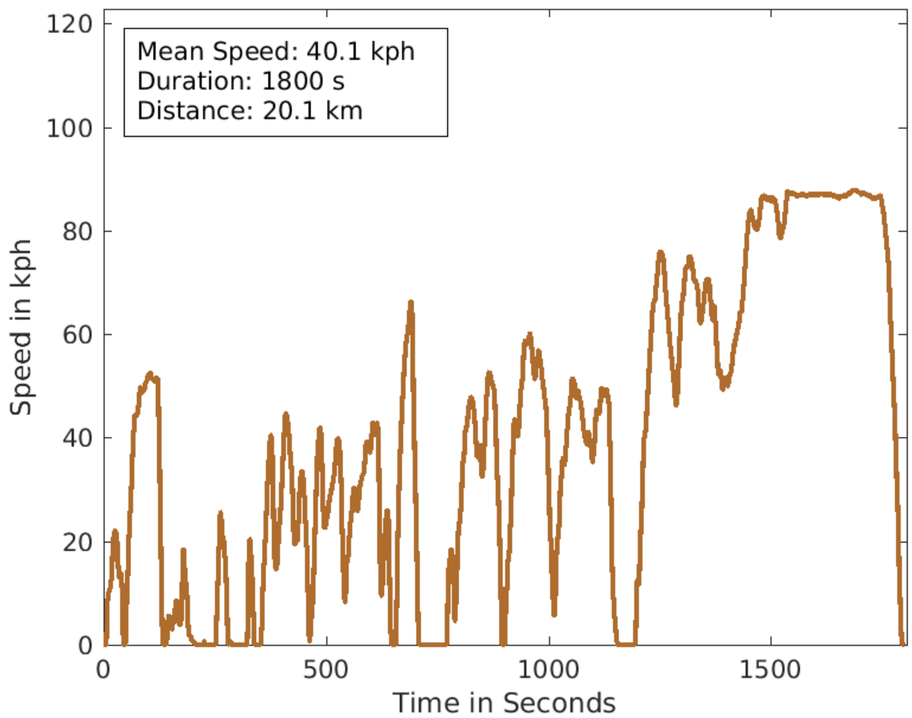

Figure 44: World Harmonised Vehicle Cycle (WHVC)

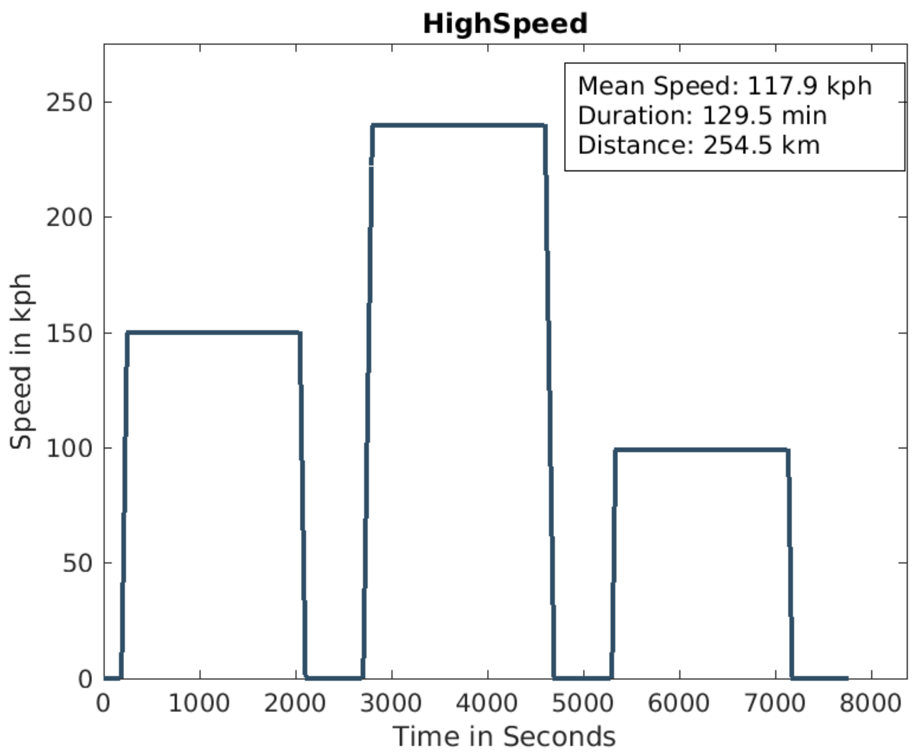

Figure 45: Generic cycle for high speed trains

Annex 3: Data tables

The following tables document numerous cases for lifetime energy and CO_2 savings as a matrix of the analysed vehicle types and drive train combinations by assumed lifetime mileage. CO_2 savings vary significantly for electric vehicles (road vehicles and trains) depending on the electricity supply power mix.

MJ/100kg	Gasoline			Diesel			BEV		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
50,000	5,979	6,202	4,185	4,883	5,158	3,376	3,034	3,095	2,570
100,000	11,958	12,403	8,369	9,766	10,316	6,752	6,069	6,191	5,140
150,000	17,938	18,605	12,554	14,649	15,474	10,128	9,103	9,286	7,711
200,000	23,917	24,807	16,739	19,532	20,631	13,504	12,137	12,381	10,281
250,000	29,896	31,008	20,924	24,415	25,789	16,880	15,171	15,476	12,851
300,000	35,875	37,210	25,108	29,298	30,947	20,256	18,206	18,572	15,421
350,000	41,855	43,412	29,293	34,181	36,105	23,632	21,240	21,667	17,992
400,000	47,834	49,613	33,478	39,064	41,263	27,008	24,274	24,762	20,562

Table 11: Lifetime primary energy savings of passenger cars (EU 28 energy supply)

kg CO_2/100kg	Gasoline			Diesel			BEV		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
50,000	438	455	307	359	380	248	151	154	128
100,000	876	909	613	719	759	497	301	307	255
150,000	1,315	1,364	920	1,078	1,139	745	452	461	383
200,000	1,753	1,818	1,227	1,437	1,518	994	602	614	510
250,000	2,191	2,273	1,534	1,797	1,898	1,242	753	768	638
300,000	2,629	2,727	1,840	2,156	2,277	1,491	903	921	765
350,000	3,068	3,182	2,147	2,515	2,657	1,739	1,054	1,075	893
400,000	3,506	3,636	2,454	2,875	3,036	1,987	1,204	1,229	1,020

Table 12: Lifetime primary CO_2 savings of passenger cars (EU28 energy supply)

kg CO_2/100kg	Mixed			Urban			Highway		
km	EU28	CN	NO	EU28	CN	NO	EU28	CN	NO
50,000	151	354	5	154	362	5	128	300	4
100,000	301	709	9	307	723	10	255	600	8
150,000	452	1,063	14	461	1,085	14	383	901	12
200,000	602	1,418	19	614	1,446	19	510	1,201	16
250,000	753	1,772	24	768	1,808	24	638	1,501	20
300,000	903	2,126	28	921	2,169	29	765	1,801	24
350,000	1,054	2,481	33	1,075	2,531	34	893	2,101	28
400,000	1,204	2,835	38	1,229	2,892	38	1,020	2,401	32

Table 13: Lifetime primary CO_2 savings of electric passenger cars in different countries

MJ/100kg	Diesel 40 t			Diesel 12 t			BEV 18 t		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
300,000	8,378	23,340	6,123	11,025	17,345	7,686	12,373	21,884	8,427
400,000	11,170	31,120	8,164	14,700	23,126	10,248	16,497	29,179	11,235
500,000	13,963	38,900	10,205	18,375	28,908	12,810	20,621	36,474	14,044
600,000	16,755	46,680	12,246	22,050	34,689	15,372	24,746	43,768	16,853
700,000	19,548	54,460	14,287	25,725	40,471	17,934	28,870	51,063	19,662
800,000	22,341	62,240	16,328	29,400	46,253	20,496	32,994	58,358	22,471
900,000	25,133	70,019	18,370	33,075	52,034	23,058	37,119	65,652	25,280
1,000,000	27,926	77,799	20,411	36,750	57,816	25,620	41,243	72,947	28,088

Table 14: Lifetime primary energy savings of trucks (EU28 energy supply)

kg CO_2/100kg	Diesel 40 t			Diesel 12 t			BEV 18 t		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
300,000	626	1,744	457	824	1,296	574	614	1,086	418
400,000	835	2,325	610	1,098	1,728	766	819	1,448	557
500,000	1,043	2,906	762	1,373	2,160	957	1,023	1,810	697
600,000	1,252	3,487	915	1,647	2,592	1,148	1,228	2,172	836
700,000	1,460	4,069	1,067	1,922	3,023	1,340	1,432	2,534	976
800,000	1,669	4,650	1,220	2,196	3,455	1,531	1,637	2,896	1,115
900,000	1,878	5,231	1,372	2,471	3,887	1,723	1,842	3,258	1,254
1,000,000	2,086	5,812	1,525	2,746	4,319	1,914	2,046	3,620	1,394

Table 15: Lifetime primary CO_2 savings of trucks (EU28 energy supply)

kg CO_2/100kg	Mixed			Urban			Highway		
km	EU28	CN	NO	EU28	CN	NO	EU28	CN	NO
300,000	614	1,445	19	1,086	2,556	34	418	984	13
400,000	819	1,927	26	1,448	3,408	45	557	1,312	17
500,000	1,023	2,408	32	1,810	4,260	57	697	1,640	22
600,000	1,228	2,890	38	2,172	5,112	68	836	1,968	26
700,000	1,432	3,372	45	2,534	5,964	79	976	2,296	31
800,000	1,637	3,854	51	2,896	6,816	91	1,115	2,624	35
900,000	1,842	4,335	58	3,258	7,668	102	1,254	2,953	39
1,000,000	2,046	4,817	64	3,620	8,520	113	1,394	3,281	44

Table 16: Lifetime primary CO_2 savings of an 18 t electric trucks in different countries

MJ/100kg	Diesel City Bus			Electric City Bus			Diesel Coach Bus		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
300,000	13,194	22,084	9,761	13,758	20,394	9,172	8,857	16,978	5,269
400,000	17,592	29,446	13,015	18,344	27,191	12,229	11,809	22,637	7,025
500,000	21,991	36,807	16,269	22,930	33,989	15,287	14,761	28,296	8,781
600,000	26,389	44,169	19,522	27,516	40,787	18,344	17,713	33,955	10,537
700,000	30,787	51,530	22,776	32,102	47,585	21,401	20,666	39,614	12,294
800,000	35,185	58,892	26,030	36,688	54,383	24,459	23,618	45,274	14,050
900,000	39,583	66,253	29,284	41,274	61,181	27,516	26,570	50,933	15,806
1,000,000	43,981	73,615	32,537	45,860	67,978	30,573	29,522	56,592	17,562

Table 17: Lifetime primary energy savings of buses (EU28 energy supply)

kg CO_2/100kg	Diesel City Bus			Electric City Bus			Diesel Coach Bus		
km	Mixed	Urban	Highway	Mixed	Urban	Highway	Mixed	Urban	Highway
300,000	986	1,650	729	1,028	1,524	685	439	842	261
400,000	1,314	2,200	972	1,370	2,031	914	586	1,123	349
500,000	1,643	2,750	1,215	1,713	2,539	1,142	732	1,404	436
600,000	1,971	3,300	1,458	2,056	3,047	1,370	879	1,685	523
700,000	2,300	3,850	1,702	2,398	3,555	1,599	1,025	1,966	610
800,000	2,629	4,400	1,945	2,741	4,063	1,827	1,172	2,246	697
900,000	2,957	4,950	2,188	3,083	4,571	2,056	1,318	2,527	784
1,000,000	3,286	5,500	2,431	3,426	5,078	2,284	1,465	2,808	871

Table 18: Lifetime primary CO_2 savings of buses (EU28 energy supply)

kg CO_2/100kg	Mixed			Urban			Highway		
km	EU28	CN	NO	EU28	CN	NO	EU28	CN	NO
300,000	439	1,034	14	842	1,983	26	261	615	8
400,000	586	1,379	18	1,123	2,644	35	349	820	11
500,000	732	1,724	23	1,404	3,305	44	436	1,026	14
600,000	879	2,069	28	1,685	3,966	53	523	1,231	16
700,000	1,025	2,414	32	1,966	4,627	62	610	1,436	19
800,000	1,172	2,758	37	2,246	5,288	70	697	1,641	22
900,000	1,318	3,103	41	2,527	5,949	79	784	1,846	25
1,000,000	1,465	3,448	46	2,808	6,610	88	871	2,051	27

Table 19: Lifetime primary CO2 savings of an electric city buses in different countries

MJ	Subway/Metro	Commuter/regional train	Long distance train	High-speed train
3 Mio. Km	1,584,576	1,273,320	353,700	212,220
5 Mio. Km	2,640,960	2,122,200	589,500	353,700
7 Mio. Km	3,697,344	2,971,080	825,300	495,180
9 Mio. Km	4,753,728	3,819,960	1,061,100	636,660
11 Mio. km	5,810,112	4,668,840	1,296,900	778,140
13 Mio. km	6,866,496	5,517,720	1,532,700	919,620

Table 20: Lifetime primary energy savings of different train types (EU28 energy supply)

kg CO_2	Subway/Metro	Commuter/regional train	Long distance train	High-speed train
3 Mio. Km	78,624	63,180	17,550	10,530
5 Mio. Km	131,040	105,300	29,250	17,550
7 Mio. Km	183,456	147,420	40,950	24,570
9 Mio. Km	235,872	189,540	52,650	31,590
11 Mio. km	288,288	231,660	64,350	38,610
13 Mio. km	340,704	273,780	76,050	45,630

Table 21: Lifetime primary CO_2 savings of different train types (EU28 energy supply)

	EU28	France	Italy	UK	Germany	Poland	China	Indien	Russland	USA
Subway/Metro (3 Mio. km)	79	16	86	101	108	182	185	203	127	114
Commuter/Regional (4.5 Mio. km)	95	19	104	122	131	220	223	245	153	138
Long distance train (7.5 Mio. km)	44	9	48	57	61	102	103	113	71	64
High-speed train (12.5Mio. km)	52	10	57	67	72	120	122	134	84	75

Table 22: Lifetime primary CO2 savings of typical train uses in selected countries

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