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Fuel Savings Potential and Costs Considerations for US Class 8 Heavy Duty Trucks through Resistance Reductions and improved Propulsion Technologies until 2020

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Abstract

This study explores the different possibilities for fuel savings in US class 8 heavy-duty trucks (GVW[1] > 33,000lbs). Better fuel economy resulting from reduced driving resistances and diesel hybrid technology are compared. Important differences from passenger cars are explained. Fuel cell technology is described. Other factors such as improvements of driver skills are discussed.

On the basis of a Matlab-Simulink program issued by L. Guzzella and A. Amstutz of ETHZ [6], possible fuel savings through aerodynamic drag and rolling resistance reduction for diesel trucks as well as diesel hybrids are compared and put into relation with the corresponding increased investment costs. Two driving cycles are used for comparison – a highway and an urban cycle adapted to the slower accelerating heavy vehicles.

Compared to a baseline truck with a C_d-value of 0.62 and a rolling resistance coefficient (RRC) of 0.007 fuel consumption savings of up to 25% seem possible merely by reduced driving resistances (C_d-value = 0.4, RRC = 0.005). Improved engine efficiency and introduction of hybrid technology in combination with resistance reduction measures could increase fuel economy up to 38% in highway driving and up to 50% in urban driving.

Fuel consumption reduction measures are put into relation to their costs, and modeling results show that driving resistance reduction measures are particularly interesting for long haul steady speed operations, whereas hybrid technology is more effective in urban frequent stop delivery use.

[1] The gross vehicle weight GVW is the maximum allowable overall fully loaded weight of a vehicle.

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ANL	**A**rgonne **N**ational **L**aboratory
BFS	**B**undesamt **f**ür **S**tatistik (Swiss federal bureau of statistics)
CARB	**C**alifornia **a**ir **r**esources **b**oard
CCE	**C**ost of **c**onserved **e**nergy (is similar to retail price increase RPI)
CH_2	**c**ompressed hydrogen (**H_2**)
CNG	**C**ompressed **n**atural **g**as (mainly CH_4)
CO	**C**arbon mon**o**xide
COE	**C**ab-**o**ver-**e**ngine design
DOE	**D**epartment **o**f **E**nergy (US)
DOT	**D**epartment **o**f **T**ransportation (US)
EJ	**E**xa**j**oules (1 EJ = 10^{15} J)
EPFL	**E**cole **P**olytechnique **F**édérale de **L**ausanne
ETH	**E**idgenössische **T**echnische **H**ochschule (Swiss Federal Institute of Technology)
GVW	**G**ross **v**ehicle **w**eight (maximum allowable fully laden weight of a truck and its trailers)
HC	**H**ydro**c**arbons
HDV	**H**eavy-**d**uty **v**ehicle (generally more than 19500lbs / 8500kg)
HEV	**H**ybrid **e**lectric **v**ehicle
HHV	**H**igher **h**eating **v**alue
ICE	**I**nternal **c**ombustion **e**ngine
LCA	**L**ife **c**ycle **a**nalysis
LH_2	**L**iquefied hydrogen (**H_2**)
LHV	**L**ower **h**eating **v**alue
MIT	**M**assachusetts **I**nstitute of **T**echnology
NiMH	**Ni**ckel **m**etal **h**ydride battery
NMHC	**N**on **m**ethane **h**ydro**c**arbons
NO_x	**N**itrogen **o**xides
PEMFC	**P**roton **e**xchange **m**embrane **f**uel **c**ells (sometimes only PEM)
PM	**P**articulate **m**atter
PSI	**P**aul **S**cherrer **I**nstitut
QSSA	**Q**uasi **s**teady **s**tate **a**pproximation
RPM	**R**evolutions **p**er **m**inute
SOC	**S**tate **o**f **c**harge (battery)
SUV	**S**port **U**tility **V**ehicle
TRRL	**Tr**ansport and **R**esearch **L**aboratory
Trsp	Transport
VSZV	**V**erkehrs**s**icherheits-**Z**entrum **V**eltheim
ZEV	**Z**ero **e**mission **v**ehicle

1. Road freight transportation energy use and trends

1. Introduction and overview

Overall final energy consumption in the US can be roughly divided into industry, transportation and the residential and commercial sectors. These three sectors are shown in Figure 1, which shows total US energy consumption for the period of 1970 to 1998.

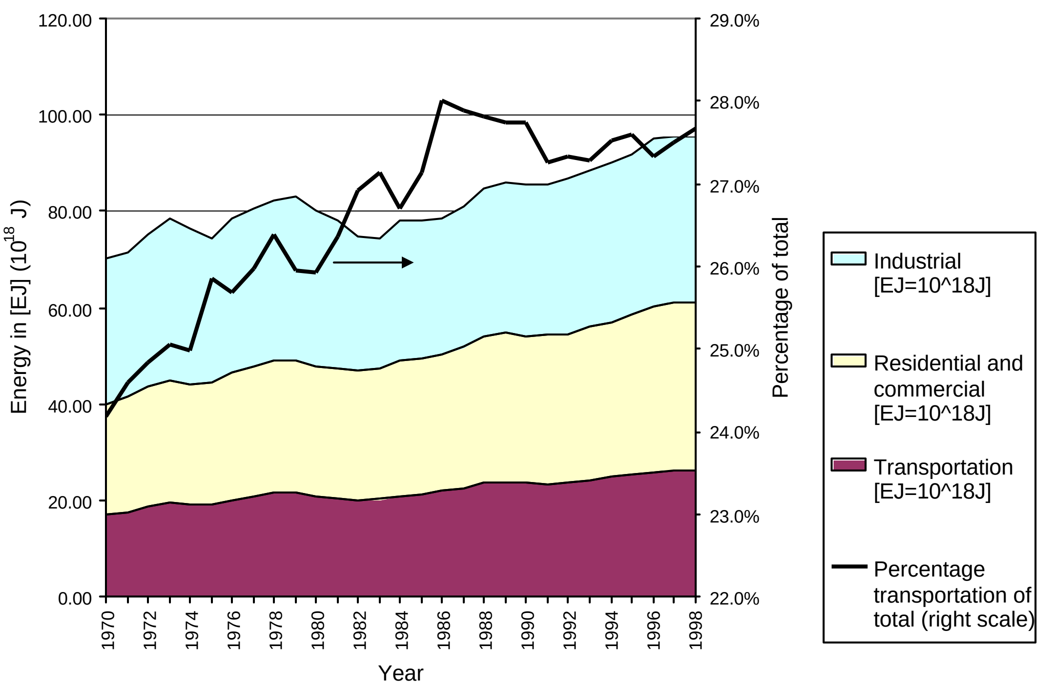

Figure 1: Consumption of Total Energy by End-Use Sector (US), 1970-98 (Energy in EJ) [1, Table 2.3]

It can be seen that the transportation part has remained nearly constant at about 27% beginning in the mid eighties. The average annual percentage change in transportation (1.2% for 1988-98) increases at the same pace as the total energy consumption for the same period (1.2% for 1988-98).

Figure 2 shows highway energy use by mode[2]. The share in energy use of light and heavy trucks increases during the considered time period.

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[2] Highway mode includes all non-offroad use

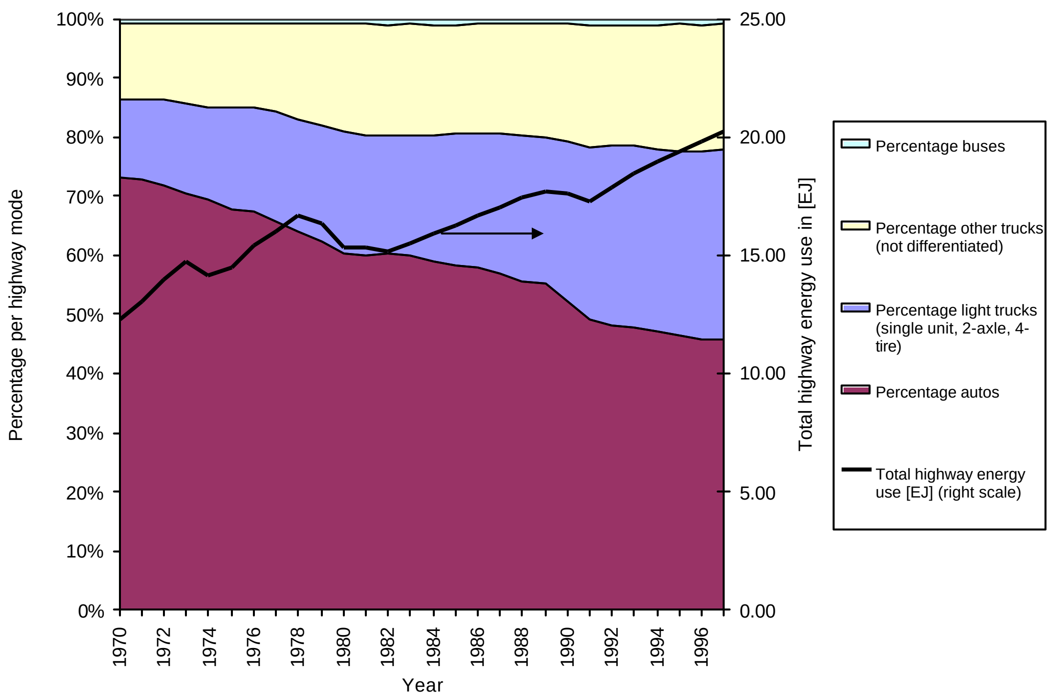

Figure 2: Percent Highway Energy Use by Mode[3] (US), 1970-97 [1, Table 2.7]

Road freight transportation by trucks can be divided into the eight US truck classes by weight as shown in Table 1.

Weight Class	1	2	3	4	5	6	7	8
Weight in pounds	up to 6,000	6,001-10,000	10,001-14,000	14,001-16,000	16,001-19,500	19,501-26,000	26,001-33,000	more than 33,000

Table 1: US truck weight classes

Within the past 20 years a shift towards smaller trucks can be seen (Figure 2 & Figure 3). One of the reasons for this shift is the increasing popularity of pick-up trucks and sport utility vehicles for passenger transport in the US.

[3] Light trucks include pickups, vans and SUVs; motorcycles are not considered in this diagram

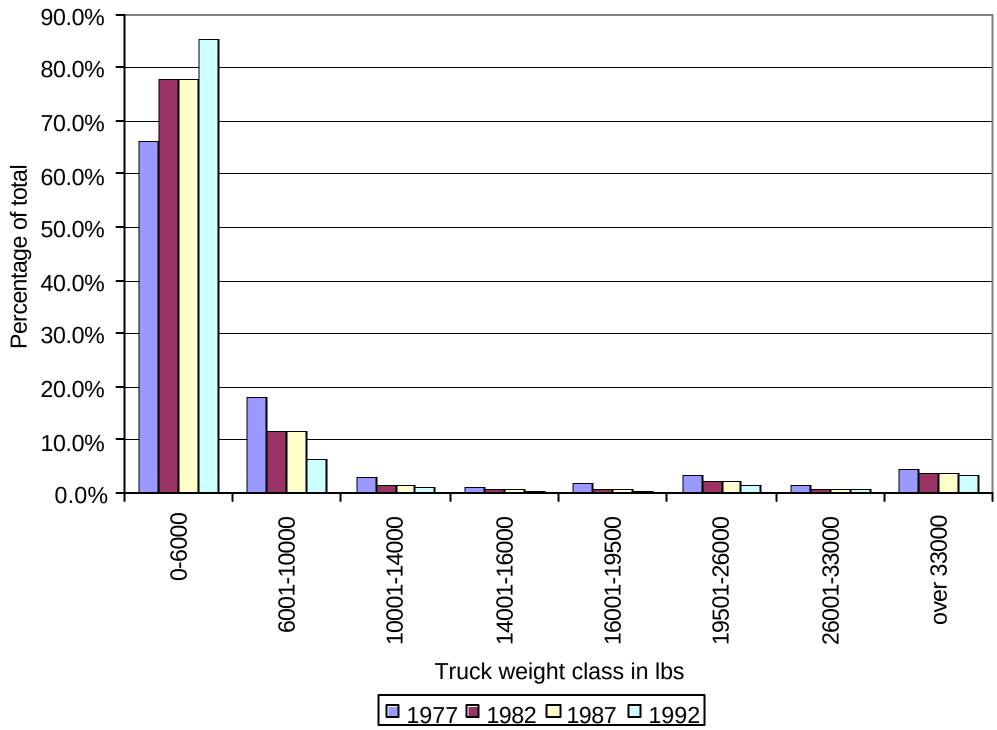

Figure 3: Percentage[4] of numbers of trucks by US size class as reported by respondents to Truck Inventory and Use Survey (TIUS), 1977,82,87,92 [1, Table 8.4]

The contribution of the lightest category trucks with a gross vehicle weight of up to 6,000 lbs has increased steadily. Vehicles in this category account for 44.8% of total truck fuel use (1992), by far the largest contributor. Nevertheless, fuel use of the heaviest class which only accounts for about 3% of the total truck fleet, is up to 21.8% (Figure 4), indicating that this class has a much bigger overall miles-per-truck ratio; actually 69,553 mi/truck-year for the heaviest class, vs 12,739 mi/(truck-year) for the lightest class [1,Tables 8.1, 8.4]. These numbers show two large groups of trucks, which are of particular interest: the light trucks with a GVW of up to 10,000 pounds - because their number is very high; and the heavy duty trucks with a GVW greater than 33,000 pounds - because their fuel use is high. Figure 4 illustrates these characteristics.

[4] not GVW, see text

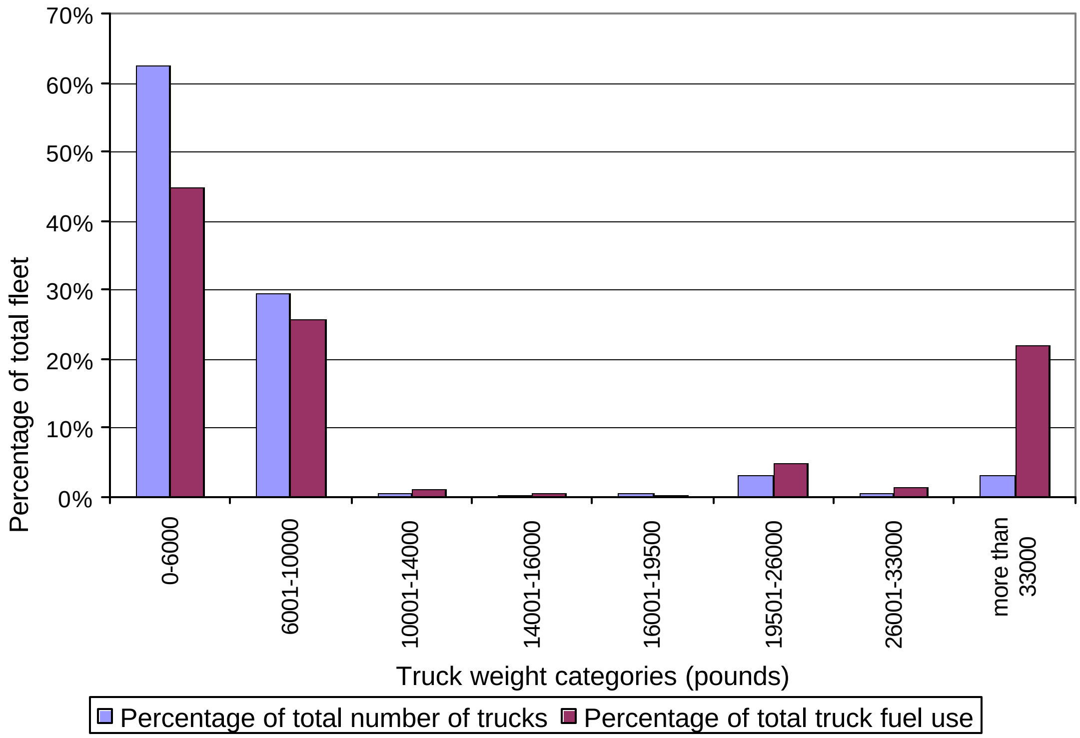

Figure 4: US Truck Statistics by GVW (percentage of vehicles and respective fuel consumption, 1992 [1,Table 8.4]

According to Komor [2], freight truck transportation in the United States represents about 29% of total transported goods in ton-km (metric ton * km) and it consumes about 83% of all the energy consumed by the freight transportation sector (excluding passenger-only trucks, natural gas and water pipelines and international transport), see Table 2. This study shows, that road freight transport is about 11 times more energy intensive than rail transport. However, the road transportation system has the important advantage of being very flexible and not depending on railway lines. Therefore the products transported in the different modes differ.

Mode	Freight movements (% of total ton-km)	Energy use (% of total)	Energy intensity (kJ/ton-km)	Index (relative to railway mode)
Rail	30	7	309	1
Freight truck	29	83	3,566	11.5
Water (domestic)	24	6	292	0.9
Air cargo	<1	1	6,914	22.4
Oil pipelines	16	3	198	0.6
Total	$4.9*10^{12}$ ton-km	6.2 EJ		

Table 2: Freight transport energy intensities[5]

In general, road transport is transporting high value-added goods such as machinery, processed construction materials and foods, whereas barges and trains are used for commodities like coal or other raw materials. This modal split can be attributed to the high flexibility that the road transport system can provide.

Statistics of the European Union show similar numbers to those presented for the US [26]. Road transports increased steadily during the last 30 years to reach a percentage of about 43.6% in ton-km ($1,151*10^9$ ton-km) in the year 1996. Road transport in EU moves most of the machinery and other manufactured products as well as agricultural goods. An important part of goods ($1,070*10^9$ ton-km = 40.6%) in the EU-15 states is transported by interstate sea mode, but these are mostly bulk materials like coal and raw construction materials. The actual tons transported are low ($750*10^6$ tons) compared to the tons transported by road mode ($10,600*10^6$ tons), but the average haulage distance (1,430 km/ton for sea trsp vs 110 km/ton for road trsp) gives it a high ton-km importance [27].

[5] taken from Komor [2], excludes passenger transport light trucks, natural gas and water pipelines.

Data on the use of the different vehicle categories show that light trucks with a GVW up to 10,000 pounds travel no further than 50 miles in 75% of the cases; transports within this class for more than 200 miles only contribute for barely 8% of all trips. The heavy class trucks with a GVW higher than 26,000 pounds travel for 56% within a range of 50 miles but spend a considerable part of their operation on longer trips. (Figure 5). Ranges of more than 200 miles make up some 20% of overall transport operation [1, Table 8.9].

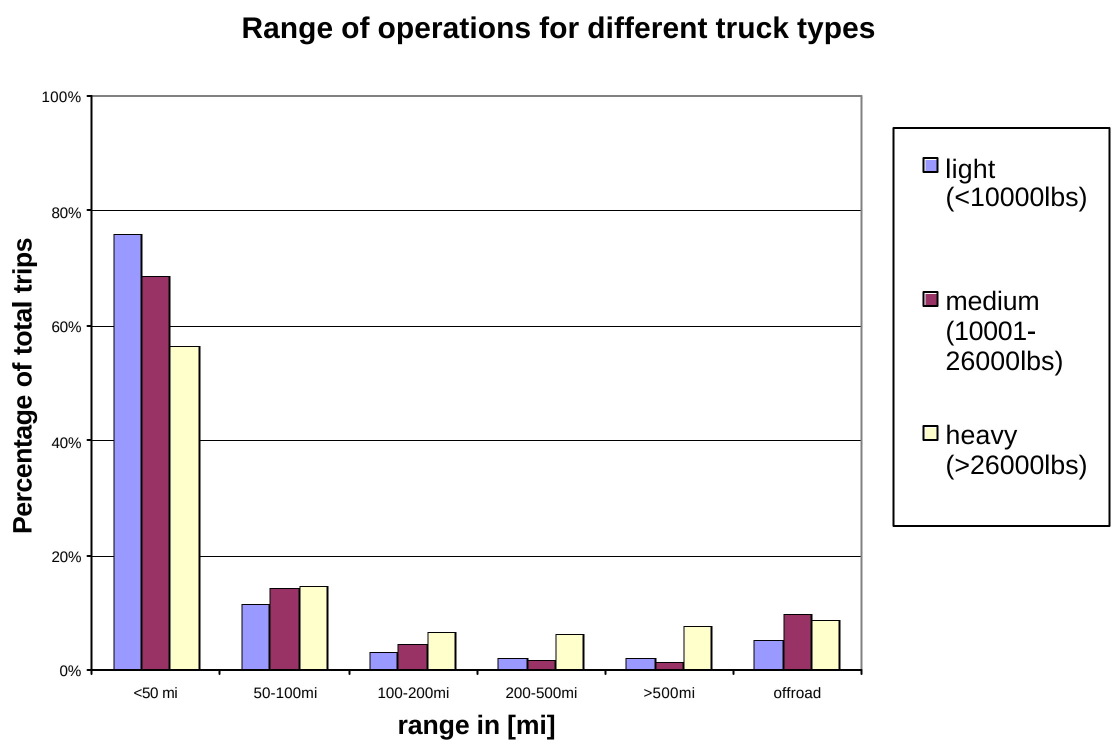

Figure 5: Percentage use (number of trips) for different truck types in function of range [TIUS; 1, Table 8.9]

These different ranges can also be explained by the actual use of the transports. Light trucks are usually used for personal transportation (74% of the time), followed by construction, services and agricultural use (7%, 5%, 5% respectively). Heavy duty trucks are used for three main areas: for-hire use, construction and agriculture (about 18%) wholesale, retail, personal and services and manufacturing (5 to 8%) [1, Table 8.11].

Figure 3 shows the actual survey weights of US trucks while on duty [19] and not GVW. Therefore these numbers differ from Figure 4 in the sense that a shift towards smaller weights occurs, because the GVW is not always reached during use (see also baseline vehicle section). This is especially true for high volume low-mass transports (e.g. breakfast cereal packages) where vehicles get "cubed out[6]" before reaching GVW.

The general statements in this study also have importance to the European transportation sector, which shows the same shift towards road transport as its US counterpart.

While the market of bulk products is estimated to grow at 1.3% per year, higher value added products are foreseen to grow at a faster rate of 1.5 to 4% [2]. This implies a high probability for a future shift towards the road transportation sector, since the high-growth products are basically transported on the road. With this transportation shift there can also be a larger impact of emissions caused by the increasing contribution of road transport. Hence, the essential goal of this study is to show possible fuel efficiency improvements of this fast-growing transportation sector, essentially with means of technology.

Several different goals promote such an approach. Reducing the emission of greenhouse gases, in particular carbon dioxide, as well as pollutants such as nitrogen oxides and particulates is an important environmental issue. The depletion of non-renewable oil is not only of environmental concern. The dependence on foreign oil and the stability of oil prices can have a primary impact on the domestic and the worldwide economy. On a smaller scale, fuel economy especially for heavy duty trucks is a crucial factor for competitiveness of a truck operator.

There are also means of policy, such as price increase for fuels, for example, which will not be considered in the study. Many studies exist on fuel efficiency improvements for passenger cars. A recent ANL study by Stodolsky et al [17] looked at fuel efficiency improvements for classes 3 to 7 delivery trucks through hybrid technology.

In this study focus is projected on the class 8 heavy-duty trucks. The special use patterns shall be especially outlined and implemented into a typical test driving cycle (see chapter 2.3).

[6] "cubed out" means that a vehicle load is limited by the available volume

2. Measures to reduce CO_2 emissions

2.1 Overview

There are several ways to improve fuel efficiency and decrease CO_2-emissions of freight transport. They include:

- Technological measures
  - More efficient engines
  - Improved transmissions
  - Reduction of driving resistances
- Other factors
  - Improved driver skills and change in behavior (e.g. avoid "unnecessary" engine idling)

There are also other possibilities, such as the introduction of low-carbon fuels (natural gas, hydrogen, methanol) and new power units like fuel cells, which could not be considered in this study with the time and resources available. The potential to improve fuel efficiency through these measures not only is restricted by technology itself, but also by their respective costs. It is relatively inexpensive to improve the skills of a professional driver, to teach him or her how to run a vehicle in the most fuel saving manner, or to change the behavior – that is a question of will or choice, not money. In contrast, technical measures to improve fuel efficiency of a vehicle can be expensive. This is not only true for the vehicle purchaser, but also for the providers of the necessary infrastructure (see chapter on FCs). The best results in CO_2-emission reduction can be achieved if the possible measures are combined. For large improvements through technical measures, both optimized drivetrains and resistance reductions should be applied. However, costs can increase considerably with improved technologies, and fuel consumption reductions must always be weighed against the corresponding costs.

2.2 Specification of a baseline vehicle

A starting point of this study must be the characterization of the different truck classes, i.e. the definition of a baseline vehicle. We concentrated on a class 8 truck because of its large share of fuel use, as shown in Figure 4. According to Truck Inventory and Use Survey (TIUS) [19, tables2a & 7] a class 8 baseline vehicle can be characterized as a diesel engine powered truck-tractor with single trailer combination with 5 or more axles and an average weight of 60,000 to 80,000 lbs. (27 –36 tons).

Figure 6: Typical US class 8 truck[7]

A 30,000 kg (66,140lbs) truck is used as a standard truck. Class 8 trucks may reach a GVW of 36,287kg (80,000lbs), but since they are not always "weighted out" (meaning that they have reached the maximum allowable weight GVW), this average number has been chosen. Trucks can also be limited by volume "cubed out" or by area if they transport light and voluminous or bulky goods. Based on these numbers and on data from Spec Manager™ and Information[8] from Argonne National Laboratory, the baseline class 8 truck we have chosen for analysis in this report has the following characteristics.

[7] Shown vehicle does not correspond to the chosen imaginary baseline vehicle. (picture taken from www.macktrucks.com)

[8] personal communication by Frank Stodolsky, principal investigator at ANL, December 1999

Characteristic	Class 8
GVW [kg] ([lbs])	36,287 (80,000)
Vehicle empty weight [kg] ([lbs])	11,000 (24,250)
payload [kg] ([lbs])	25,287 (55,750)
Used average weight [kg] ([lbs]) 75% payload	30,000 (66,140)
CD [-]	0.62 (roof deflector)
Trailer gap [m] ([in])	1.02 (40)
Vehicle height [m] ([in])	4.09 (13'5")
Vehicle width [m] ([in])	2.59 (102")
Frontal area [m^2]	10
Engine	Diesel engine[9] 321 kW (430hp) @ 1,800rpm; 2,101Nm (1,550 lb-ft) @ 1,200rpm (turbocharged and inter-cooled)
Displacement [L]	12.7
Cylinders	I 6
Tires	Low profile radials
Wheel radius [m]	0.5
RRC [-]	0.007
Transmission [# of gears]	Fuller RTLO-14610A; 10
Gear ratio 1st gear	9.91
Gear ratio highest gear	0.76
axle ratio	3.9
Retail price (US$)	167,000

Table 3: Baseline vehicle specifications (including trailer)

The frontal area is based on a height of 4m (13'5") a width of 2.6m (102"): the area under the vehicle between the wheels is subtracted. Note that the length does not influence the simulations since wind yaw angles are not simulated.

[9] Based on Detroit Diesel Series 60

2.3 Typical driving cycle for class 8 HDVs

Long haul trucking shows different driving characteristics than passenger transport. Long distances are typically traveled at a certain constant speed. Therefore a very simple driving cycle is used to simulate the fuel consumption for heavy-duty vehicles (based on the SAE J1376 HDV driving cycle).

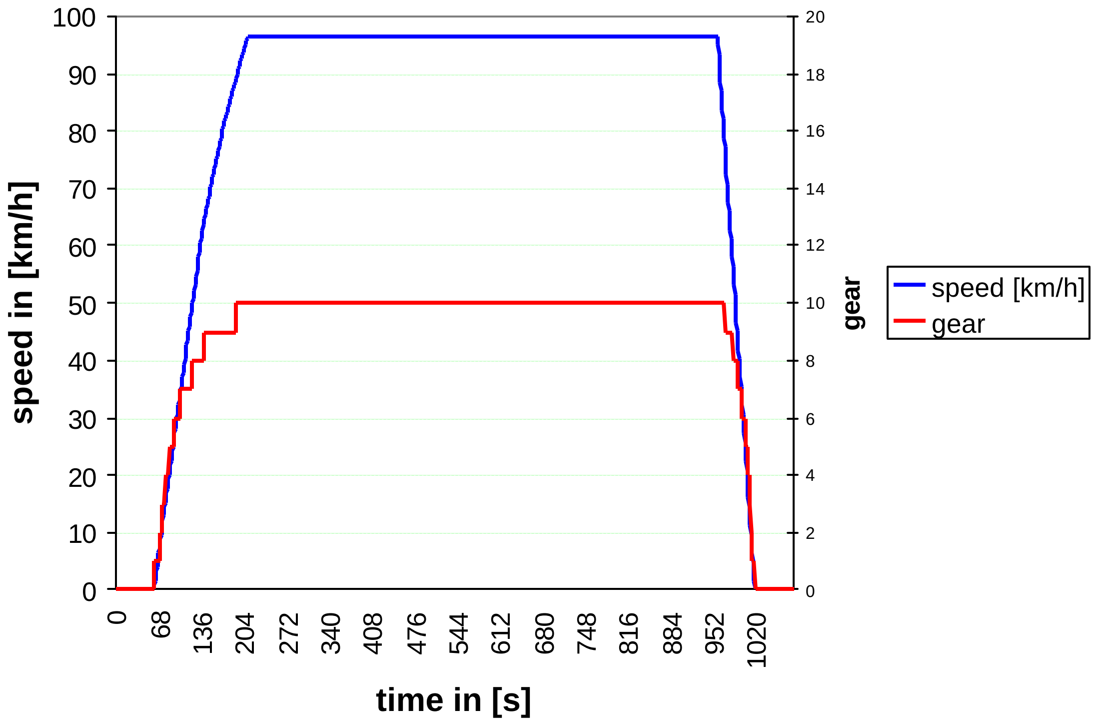

Figure 7: HDV highway driving cycle

This driving cycle describes an acceleration to a certain cruise speed (97km/h, 60 mi/h chosen as a standard) followed by cruising at constant speed and a deceleration. Fuel consumption predictions depend largely on the chosen driving cycle for the simulation.

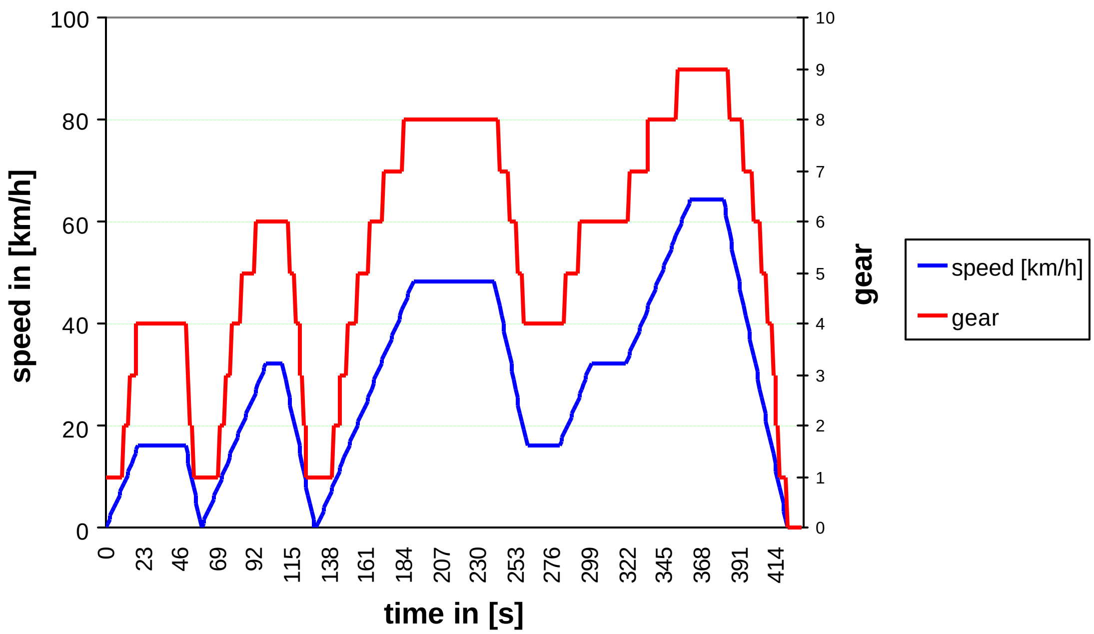

Figure 8: HDV urban driving cycle

For comparison purposes a second driving cycle is used, which simulates suburban driving by trucks making deliveries. Speeds are chosen not to exceed 65 km/h (40mi/h). It includes a combination of accelerations and decelerations and short passages at constant speed as shown in Figure 8.

2.4 Emission standards

Emission standards from the California Air Resources Board (CARB) are given in grams per brakehorsepower-hour[10] (g/bhp-hr) and are tabulated in the following table applicable to heavy truck engines from 1998 – 2003 [1]:

pollutant	HC	CO	NO_x	PM
standard	1.3	15.5	4.0	0.10

Table 4: Diesel emission standards by CARB

[10] 1 g/bhp-hr = 1.34 g/kWh

These standards apply to diesel, methanol and all applicable gaseous-fueled heavy duty truck engines. They would also apply to the proposed diesel hybrid propulsion technologies. Hydrogen powered fuel cell (FC) emissions are extremely low, whereas methanol or gasoline fueled on board reforming FC systems have non negligible emissions – most of all CO. Future more stringent standards would give the hydrogen FC system a low-emission advantage.

Recently Crow and Dodge [36] proposed technology advancements to improve engine efficiency and emission controls. Among these are exhaust gas recirculation (EGR), variable geometry turbochargers, advanced fuel injection systems (common rail), turbo compounding, lean NO_x catalysts and particulate traps. Some of these propositions are already implemented in recent truck engines. These authors assume NO_x reductions of a factor of 40 to be possible, hence achieving NO_x emissions as low as 0.1g/bhp-h within the next decade (2010). The particulate matter emissions were assumed to drop to a value of 0.01 g/bhp-h – a factor 10 improvement. Engine efficiency was assumed to increase. This shows, that diesel engines could still become much cleaner with the introduction of new technologies and their pollution penalty compared to "clean technologies" like the fuel cell would decrease. However, there is always a trade-off between fuel efficiency and low emissions. If emission standards are chosen at very low values, fuel consumption penalties must be accepted (see section 3.2).

2.5 Technologies considered

In this report the following technologies shall be considered:

Fuels	Powertrains	Vehicle characteristics
Diesel	Diesel ICE	Conventional
(Methanol)	Diesel hybrid	Cab-over-engine design
(Hydrogen)	(Fuel cell)	Rolling resistance
		Aerodynamic drag
		Lightweight
		APUs[11]

Table 5: considered technologies

Diesel oil and diesel ICE are the standard fuel and propulsion system used. Methanol and hydrogen and the fuel cell technology are introduced on a qualitative basis for comparison. The different influences of vehicle characteristics are evaluated for different driving cycles.

[11] **A**uxiliary **p**ower **u**nits

2.6 Differences from passenger cars

Trucks differ from passenger cars in many ways. Table 6 gives an impression of typical differences:

Typical characteristic	Passenger car	Class 8 truck
Annual usage [mi] (1997)	11,574	69,553[12]
Lifetime usage [mi]	150,000	1,000,000
Cost [$]	18,000	167,000
Empty weight [kg]	1,333	11,000
Typical payload [kg]	110	19,000
Payload to total weight ratio (typical, not GVW)	8%	63%
Fuel used	Gasoline	Diesel
Fuel economy (mpg, year)	24.6 (1999)	6.1 (1997)
Fuel costs ($/mi @ 1.2 $/gal)	0.05	0.20
Percentage of fuel costs of total operating costs	14%	31%

Table 6: Differences between passenger car and heavy-duty truck (sources: [1], [15])

The most obvious difference is the weight, which is about an order of magnitude higher for class 8 trucks than for passenger cars. The increased weight raises chassis stiffness requirements and makes the introduction of some safety accessories necessary.

[12] according to [1, table 8.1 for combination trucks]

2.6.1 Braking system

The most important one is the braking system. Cars have normally two brakes which include the “normal” brake (usually a hydraulic braking system with disc and/or drum brakes) and an emergency brake. In a heavy truck, there must be additional brakes that ensure safe downhill driving on long slopes with continuous wear-free braking systems.

This is achieved with an engine exhaust brake and/or a retarder [45]. Figure 9 shows the three external forces acting on a descending vehicle: aerodynamic drag force, rolling resistance force, and gravity. It also shows the necessary wear free braking force.

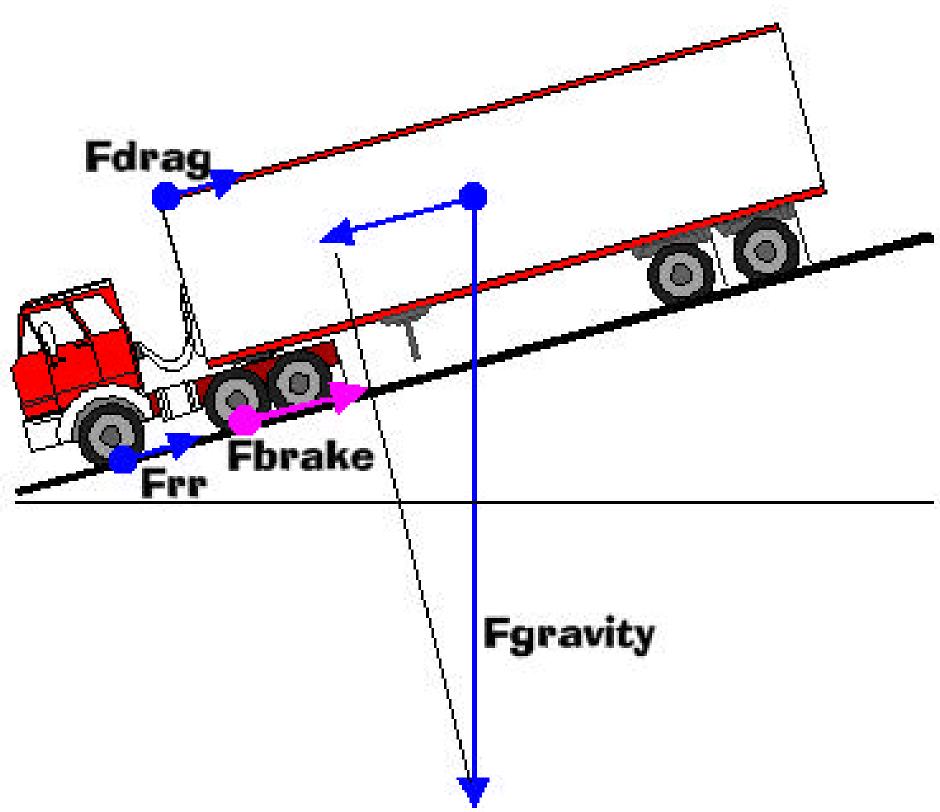

Figure 9: Forces acting on descending truck

At constant speed the three forces plus the wear free breaking force must yield a zero vector, i.e. the sum of all the forces must be zero. One can see that the weight force is the only downward directed force.

The resulting equation from this force analysis, which determines the necessary braking power, is therefore:

$$m_{veh} \cdot \vec{g} \cdot \sin a + \vec{F}_{drag} + \vec{F}_{rr} + \vec{F}_{brake} = \vec{0} \qquad (1)$$

$$\Rightarrow F_{brake} = m \cdot g \cdot \sin a - F_{drag} - F_{rr} \qquad (2)$$

$$\Rightarrow P_{brake} = F_{brake} \cdot v_{veh} \qquad (3)$$

where:	F_{rr}	Rolling resistance force	[N]
	F_{drag}	Air resistance force	[N]
	F_{brake}	Braking force	[N]
	P_{brake}	Braking power	[W]
	v_{veh}	Vehicle speed	[m/s]
	m_{veh}	Vehicle mass	[kg]
	g	Gravitational constant	[m/s^2]
	α	Grade angle[13]	[-]

The engine brake is basically a throttle valve in the exhaust that can be closed in order to get draw back pressure in the cylinders. A retarder is an additional unit and acts either with a hydraulic fluid comparable to a water wheel or an electrodynamic retarder, which dissipates the energy through movement in electromagnetic fields producing heat. Figure 10 shows necessary power requirements for a weighted out 36,287 kg (80,000 lbs) truck descending a hill of slopes ranging from 1.5 to 6% at different speeds. The truck is assumed to have a RRC of 0.007, a C_d of 0.62, and a frontal area of 10 m^2. The necessary braking power is considerable.

[13] For small angles <15° one assumes sin α = tan α = grade in %

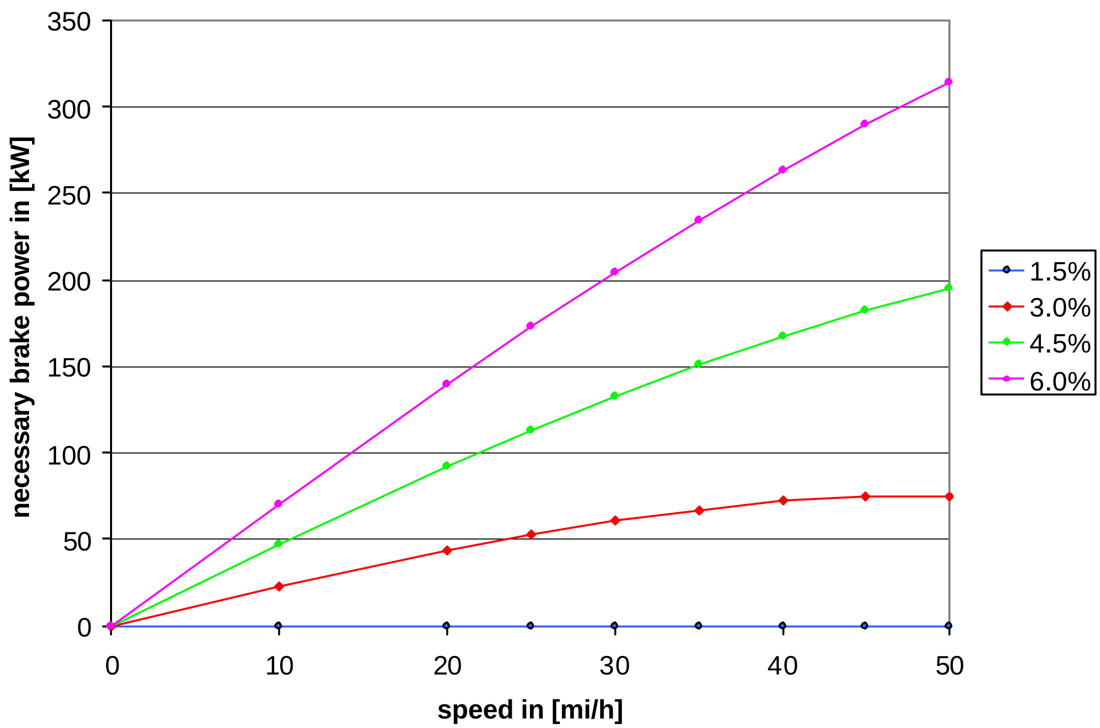

Figure 10: Wear-free brake power requirements for truck[14]

Note that below a certain threshold (e.g. 1.5%) there is no power needed, but especially for steep slopes, there is a high power demand. It is not contradictory that the brake power need decreases at speeds beyond 40 mph (in the 3% slope case) since the aerodynamic drag force increases with the square of the speed (power increases with the third power of speed) and is in the opposite direction of travel.

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[14] see appendix and text for details

2.6.2 Payload to weight ratio

Another weight related difference is the payload to total weight ratio, which is much higher for trucks compared to that of passenger cars:

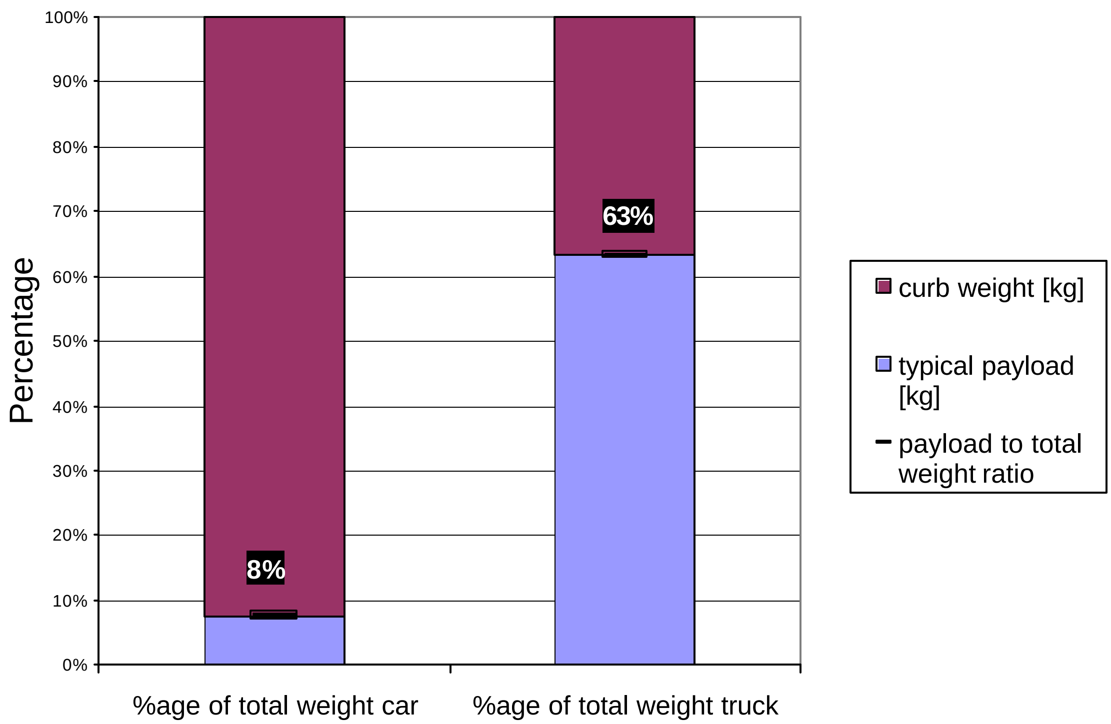

Figure 11: Typical payload to total weight ratio of passenger car vs heavy duty truck

The numbers of Table 6 and the fact that trucks are always tried to be weighted out, suggest that trucks do not offer such a large weight reduction potentials as passenger cars. Truck operators always try to weight out their trucks for hauling purposes to the legally allowable weight. Therefore weight reductions in trucks would not directly affect fuel economy measured in L/100km or miles per gallon, but would increase the possible payload of the truck. The fuel consumption per ton of freight would decrease. (see chapter 7.4)

2.7 Models used

Two models are used to predict the fuel economy of trucks on different driving cycles. The first model is a Matlab-Simulink file programmed by L. Guzzella and A. Amstutz of ETHZ, which was modified for the truck purposes, and the second is Spec Manager™ provided by Detroit Diesel Corporation. The Spec Manager™ was used essentially for data purposes whereas the Matlab program was used as the basic simulation tool.

2.7.1 Model description

The Guzella-Amstutz model is a quasi steady state approximation (QSSA) program, which models the fuel consumption of a vehicle on a flat route considering C_d, RRC, vehicle mass, frontal area, engine and transmission performance, and driving cycle. The whole vehicle can be specified and values can be introduced for all the necessary specifications. The simulation of fuel consumption is then performed through the addition of all resistances the vehicle must overcome, including intrinsic vehicle resistances like transmission losses, which are entered as average constants.

If $^{\Delta v}/_{\Delta t}$ gets infinitesimally small, equation (10) on page 49 is exactly satisfied. To reduce calculation complexity the quasi steady state approximation is applied. This means that for a certain lapse of time, e.g. one second, the acceleration behavior of the vehicle is thought to be constant. The intervals applied to the model prevent the use of continuous functions of time and instead make possible the introduction of data for time, speed and gears in arrays or vectors.

2.7.2 Model application

The model was applied to simulate a conventional mechanical drivetrain diesel engine powered truck and a parallel diesel-electric hybrid. In the conventional arrangement, the aerodynamic drag and the rolling resistance coefficient were varied in the range of available data, from 0.62 (baseline) to 0.4 (advanced truck [51]) for the C_d value and from 0.007 to 0.005 for the RRC. The engine, based on data from Detroit Diesel [52], was not modified according to decreasing power needs with reduced resistances. As defined in the baseline vehicle chapter 2.2, a 321kW (430hp) @ 1800 rpm, 2101 Nm (1550 lb-ft) 12.7 L displacement inline-6 cylinder engine was used. In both cases, auxiliary power requirements were set to an average value of 10 kW.

The lines of constant engine efficiency [g/kWh] are assumed to be horizontal in the engine map whereas they are actually rising with increasing rpm (representing better fuel economy for same power outputs at lower rpm). Hence the program doesn't take into account the improved efficiency at lower rpm and low rpm ecolomic[15] driving cannot be simulated.

For the hybrid configuration the power of the diesel ICE was downsized to fit power requirements for cruise speed. A 187 kW (250 hp) @ 1900 rpm, 1085 Nm @ 1200 rpm 8.7 L diesel engine is used based on an International engine (Detroit Diesel Series 40E). The additional electric motor has a constant torque of 1029 Nm up to 1200 rpm and a power output of 137 kW (184 hp) @ 1800 rpm to meet the same power output as the baseline diesel, when combined with the downsized ICE.

Under a certain power threshold, which was fixed at 50 kW in order to optimize fuel consumption for the corresponding driving cycle, the vehicle is only propelled by the electric motor. (This is of importance especially in congested traffic, where power requirements stay below this limit most of the time, and ICE idling can be avoided completely). Above this threshold the truck is powered only by the ICE. Whenever the power requirement of the truck exceeds the capacity of the ICE (e.g. during rapid acceleration), the electrical motor power is added to the ICE's. With this arrangement the truck can cruise for most of the time in the chosen highway driving cycle on the downsized ICE only. The same configuration is used in the urban driving cycle. If battery state of charge SOC at the end of the simulation was lower than in the beginning, a diesel energy equivalent was added to the fuel consumption in order to take into account the energy drawn from the battery. (Calculated with 40% ICE, 85% electric motor and 90% battery charging efficiency).

[15] see chapter 5.1 for explanation

The transmission is not changed. Optimization of transmission and axle ratio is also an issue of fuel efficiency, but is not considered in this study. Gears are shifted according to Spec Manager™ shifting schedule as shown in Table 7:

Gear	Speed @ 1200 rpm	Speed @ 1800 rpm	Speed @ gear change
1	3.7	5.6	5
2	4.9	7.4	7
3	6.6	9.9	9
4	8.8	13.2	12
5	11.8	17.8	16
6	15.6	23.5	21
7	20.7	31.1	27
8	27.6	41.3	36
9	36.9	55.4	49
10	48.9	73.4	

Table 7 : Operating range of gears

2.7.3 Model validation

In order to test the accuracy of the model, historical values for C_d, RRC and engine efficiency have been introduced into the model and the results were compared to actual fuel consumption values based on TIUS [1]. This comparison should not be considered as a proof for the quality of the model, but should show that its results are close to reality. The difference between the simulation result and the historical values is always within 10%. It must be said that different vehicle characteristics are compared on this basis and that its outcome cannot be identical.

year	*Cd*	*RRC*	*ICE efficiency*	*Fuel cons. modeled*	*fuel cons. (TIUS)*
1977	0.78	0.007	40	50.6	49.0
1982	0.74	0.006	41.5	45.8	45.2
1987	0.7	0.0058	43	42.8	44.4
1992	0.66	0.0056	46	38.7	42.8
1997	0.62	0.0054	48	35.8	38.6

Table 8: Input values and outcome of model validation

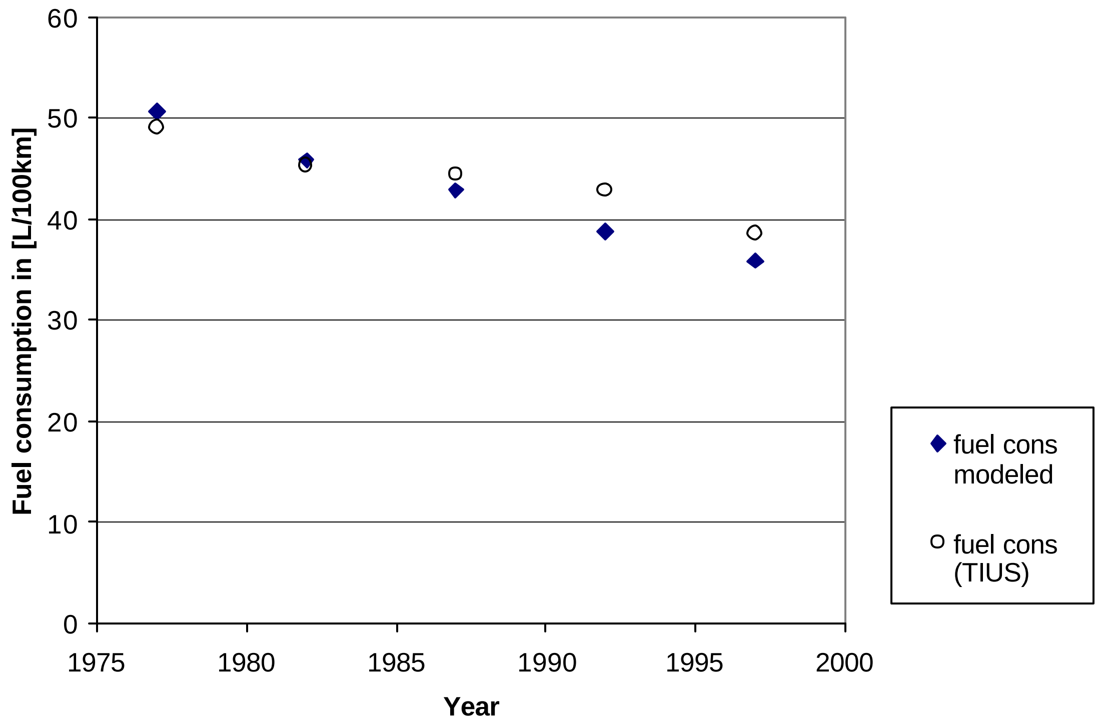

Figure 12: Program validation results

The modeled fuel consumption was found on the basis of a 30,000 kg truck with historical values for C_d, RRC and engine efficiency presented in sections 3 and 4. The chosen values are best possible values per year. Hence, the simulation results should show a lower fuel consumption compared to the TIUS values, which are fleet average values. The TIUS values are taken for class 8 trucks and represent an average for all trips and trucks (empty trips included). In addition, the load factors of trucks have increased steadily, so that the average weight of the trucks has increased during the period of 1977 to 1997. This could be a reason, why the TIUS fuel consumption values of 1977 and 1982 are lower than the modeled ones, since the actual average weight of these trucks was considerably lower than 30,000 kg. Other reasons could be the lower power output of older engines (all simulations run with the 321 kW engine) and the less stringent emission standards.

Table 8 and Figure 12 show the results of the model validation and the chosen input values.

3 Propulsion systems

3.1 Overview

Diesel ICEs are the propulsion technology of choice in most of today's heavy-duty truck transportation applications. The biggest advantage of the diesel engine is the higher efficiency compared to that of gasoline engines, which influences the operating costs of these high mileage vehicles such that the higher purchase price for the engine is quickly offset by the saved fuel costs. There has been considerable progress in the past that increased the overall class 8 trucks fuel economy by about 27% from 1977 until 1997 [1, TIUS] (see Figure 13).

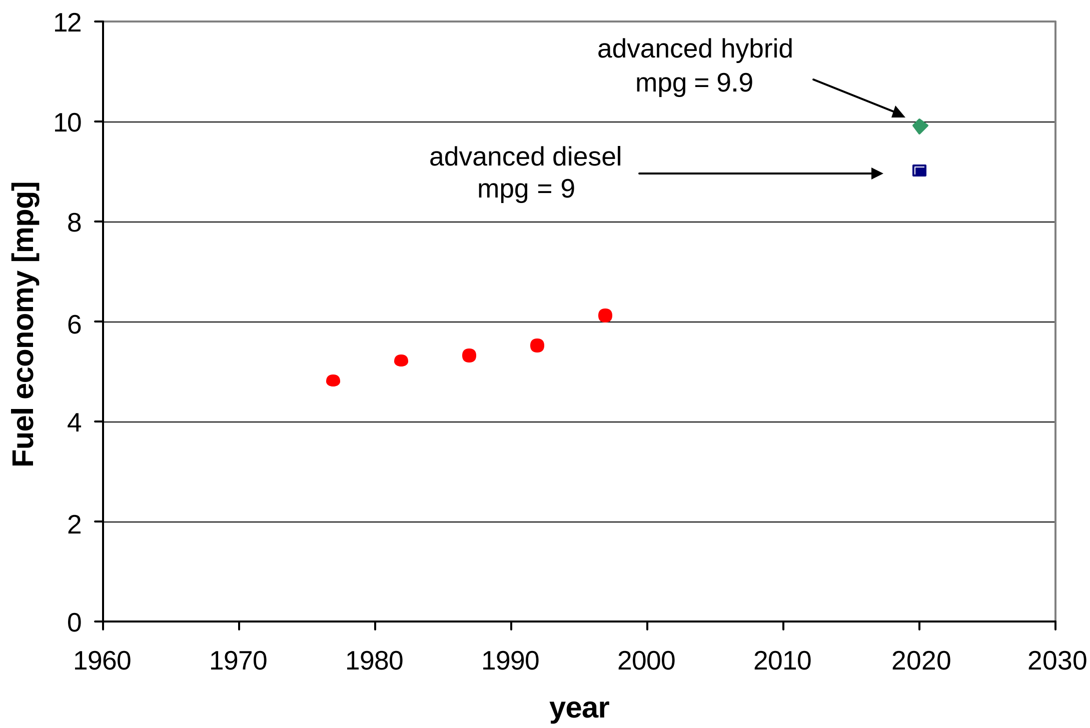

Figure 13: Fuel economy evolution [mpg][16]

Engine efficiency has increased steadily with the introduction of turbochargers, inter-coolers, and the turbo compound diesel engine (Scania, 1991) to reach full load effi-

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[16] historic values taken from TIUS [1], 2020 values from simulation

ciencies of 48% today (used as baseline), which corresponds to a specific fuel consumption of 175 g/kWh. Introduction of variable geometry turbochargers, high pressure injection systems (common rail) in combination with optimized turbocompounding and controls and reduced heat losses can improve efficiency even further. Gaines et al [54] estimate fuel efficiencies of 55% to be possible in 2020. Because of its high thermal efficiency, potential fuel flexibility, durability and reliability, the diesel ICE has the potential to dominate the truck sector until at least 2020 [20].

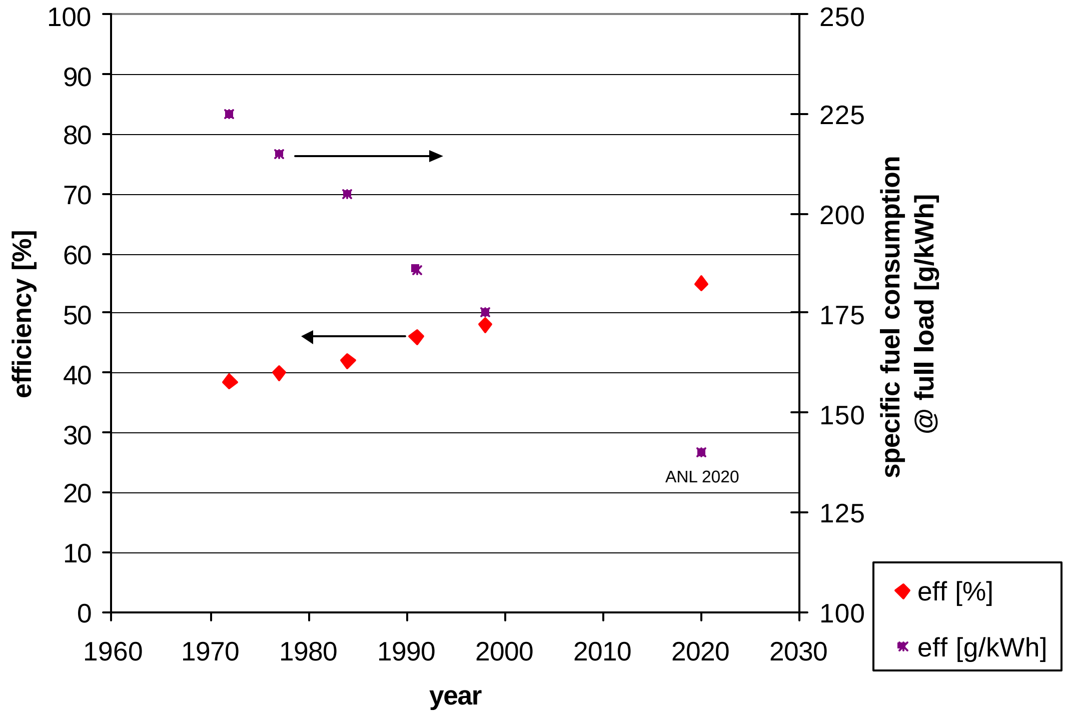

Figure 14: Evolution of engine efficiency from 1970 - 2020[17]

[17] Sources: Scania for historic values and ANL for 2020 value.

3.2 Mechanical propulsion system with Diesel-ICE

Mechanical propulsion systems consist of the power source, mostly a diesel ICE, clutch or torque converter, transmission, driveshaft, axle differentials and wheels. There is a wide variety of transmission and corresponding axles, which can satisfy the broad range of applications of HDVs. Most trucks have manual transmissions because of fuel economy considerations (manual transmissions with clutches are more efficient than automatic transmissions with torque converters). Various manufacturers developed "thinking" electronically controlled transmissions, which help the driver in choosing the best gear for a certain driving mode (e.g. electronic power shifting EPS by Mercedes).

The central piece of the mechanical drivetrain is the ICE. HDV diesels have higher compression ratios (up to 16 for vehicle applications) than gasoline engines (9-11) [23,24] and are nowadays almost exclusively turbocharged. The higher compression ratio of the diesel versus the gasoline engine yields higher pressures at the end of the compression stroke and as a consequence, produces higher expansion stroke work. Thus the energy conversion efficiency of the engine is increased. But this is not the only reason. Diesels have a better part load efficiency since they do not have throttle valves in the air intake as does the gasoline engine, which cause substantial pressure drops and higher pumping losses over the exhaust and intake strokes.

The higher peak combustion temperatures of the diesel engine result in higher NO_x-emissions compared to those from gasoline engines. Since the fuel is generally burned overall with excess air (more oxygen available than theoretically necessary to completely burn the fuel) three way catalytic converters, which are used for gasoline engines in a slightly reductive environment (stoichiometric) are not suitable for diesel exhaust gases. The reduction of nitrogen oxides to harmless nitrogen is a much more difficult task, which has not been solved to this date. This explains the higher NO_x-loads of diesel vs gasoline engines, which operate at stoichiometric conditions ($\lambda=1$), where there is exactly enough O_2 to completely burn the gasoline. To catalyze exhaust emissions most efficiently (in particular NO_x) the mixture should be stoichiometric. Lean burning ($\lambda>1$) engines like diesels therefore sometimes use additional diesel fuel to provide a reducing agent (fuel) in the exhaust gases ($\lambda \rightarrow 1$) in order to further decrease NOx emissions. This degrades the fuel economy.

3.3 Hybrid electric powertrains

A hybrid electric powertrain is a combination of a "normal" ICE and an electric motor. With this arrangement, the advantages of both the zero-tailpipe emissions of the electric motor and the long range of the ICE can be combined. Since it is a combination of these two systems, there are many possibilities ranging from a hybrid that is close to a conventional mechanical system with only a small electric motor to an almost purely electric vehicle with only a small APU. The ultimate design choice depends on the end use application, but it seems to be most attractive to build a vehicle that is close to the conventional mechanical system [17].

Electric vehicles powered by batteries have the disadvantages of limited range constrained by battery weight and dependence on grid accessibility for recharging. The recharging process for batteries is slow compared to the refueling of a liquid fuel powered vehicle. Considering the 90kWh battery being charged overnight within ten hours, a power stream of 90 kW must be supplied to charge the battery theoretically from 0 to 100%. If we consider the 100-gallon diesel tank that is filled within 5 minutes and divide the energy content (13.3 GJ) through the filling time, a power stream of 44.3 MW results. Therefore purely electric vehicles are not feasible for truck use, since the percentage time in service is a very important economic issue and hence trucks cannot be recharged for a whole night period. Additionally the energy storage capacity would be too low for the battery (see Figure 17).

Vehicles are subjected to minimum performance criteria, including accelerations, gradeability, and maximum speeds, including trucks. Since the maximum peak load of the engine is not used most of the time, all vehicles today, including trucks, tend to have oversized engines that do not run in their most efficient modes – low rpm, high torque, high load – for most of the time. Introducing hybrid technology could downsize the engine to make the whole vehicle system more efficient by providing the peak power needed for acceleration and slope climbing with a supplemental electric motor. Olikara et al [37] state possible fuel efficiency gains with optimized series hybrid (see 3.2.1 on series hybrid) arrangements of up to 20 %. Gilbert and Gunn [38] predict up to 50% fuel efficiency gains and considerable reductions in emissions for a CNG-ICE series hybrid for a 24,000 lbs hybrid electric bus application (remember that for diesel engines this value is likely to be smaller, since its part load efficiency is better). In 1995 Volvo Truck Corporation introduced their Environmental Concept Truck (ECT) as well as a similar bus (ECB) based on a series hybrid powered by a gas turbine with integrated high-speed generator. Resulting from experiences with the ECT, the FL6 Hybrid - a distribution truck - was developed in 1997 by Volvo Trucks. Two prototype trucks are currently running in daily distribution traffic in Göteborg. The truck is a series hybrid (see 3.2.1) powered by a diesel engine and batteries, and is able to run for short periods on batteries only (inner-city use for example), hence acting as a quasi-ZEV. Volvo states that the main focus of the FL6 hybrid was to develop a zero emission truck for environmentally sensitive city centers. According to Volvo simulation, fuel consumption values in a typical urban distribution driving cycle are considerably lower (10-38%) even if the GVW of the hybrid truck had a 3,000 kg weight penalty (14,000kg vs 11,000kg) caused by the battery packs and the electric motor [39,40]. Toyota and Honda introduced the Prius and Insight gasoline engine hybrid technology passenger cars, which achieved significantly increased fuel economy (66mpg according to Toyota [41] for the Prius and 61-70 mpg for the Insight according to Honda [42]). This does not prove that hybrid technology can be introduced without problems in the truck industry, but it does prove that limited and subsidized mass production of hybrid technology is feasible.

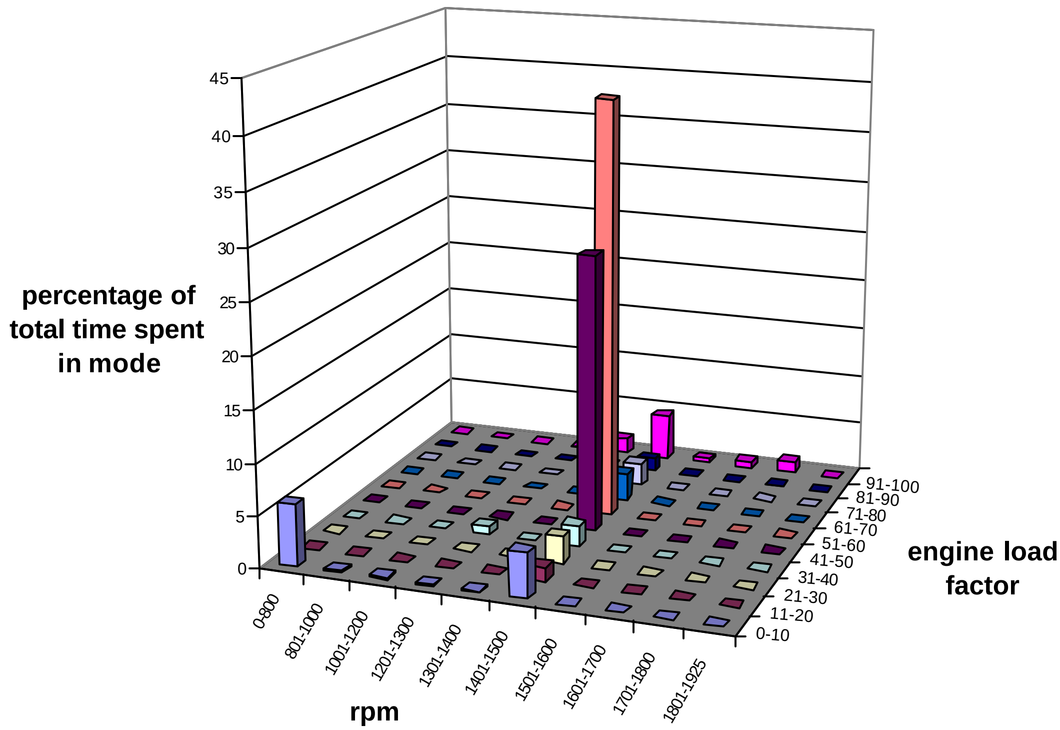

Figure 15: Percentage engine load and rpm factors of a HDV on a flat route[18]

Figure 15 and Figure 16 show engine load characteristics for a 80,000 lbs tractor trailer rig with a full aerodynamic package and a 370 hp engine, on a flat and a mountainous route respectively, modeled with Spec Manager™ program provided by Detroit Diesel Corp. They show a particular feature of inefficient use of ICEs. In the case of the flat route the engine is used 66% of the time in a 40 to 60% engine load factor mode and on the mountainous route it is used for up to 50% of the time in a mode of less than 50% load. During this low load operation (downhill driving) only few fuel is consumed. However, since ICEs are most efficient at full load, the engines are not operating at ideal conditions – best fuel efficiency - for a considerable amount of total use, but are oversized, especially in the flat route case. However, the high engine power is needed for gradeability, acceleration and startability, as can be seen in the mountainous case,

[18] Data from Spec Manager™ by Detroit Diesel Corp. for a 80000 lbs truck cruising from Washington DC to Miami FL (I95)

where the engine runs for a considerable amount of time at full load (up to 27%), which justifies the large engine size.

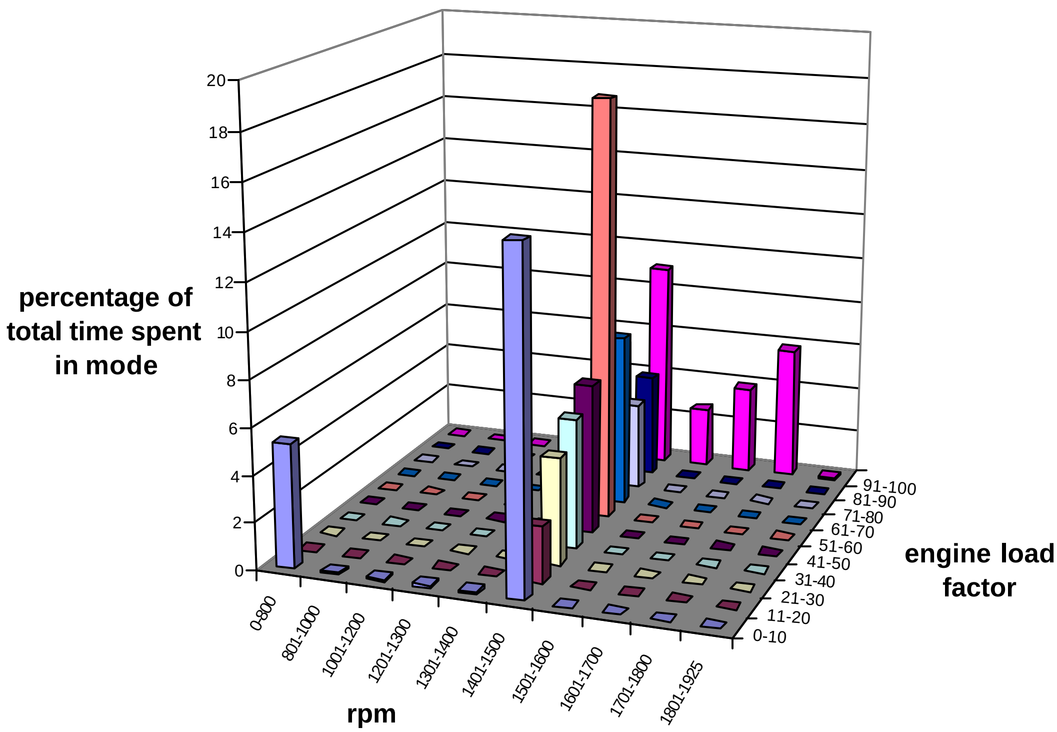

Figure 16: Percentage engine load and rpm factors of a HDV on a mountainous route[19]

There could still be significant improvement if the engine were downsized to run at full load for most of the time and a second power plant were used to provide power for peak loads. An important part of such a hybrid arrangement would be the electronics to control the whole system. For example, the integration of new technologies like global positioning system (GPS), which could possibly anticipate slopes to insure that battery charge is on its maximum when the truck starts to climb up a hill. Regenerative braking could be used both as a wear-free brake, which is necessary for heavy trucks (see chapter 2.6.1), and to increase fuel efficiency. Tanja [47] states that regenerative braking in stop and go driving cycles can reduce fuel consumption of up to 30%. Another impor-

[19] Data from Spec Manager™ by Detroit Diesel Corp. for a 80000 lbs truck cruising from Los Angeles CA to Albuquerque NM (I10, I15, I40)

tant advantage of hybrids over conventional ICE vehicles is the ability to shut down the engine when it is not used such as during idling and coasting. In inner-city stop and go cycles, hybrids can run on their electric motor only and hence increase the overall fuel efficiency and at the same time reduce local emissions drastically. The energy storage capacity required for regenerative braking, which can be provided by either batteries, supercapacitors or flywheels, can be calculated by multiplying the necessary braking power with the time during which the wear-free brake is used. The different storage devices have inherent advantages and disadvantages. Batteries function on the basis of chemical reactions and have therefore an efficiency penalty for charging and discharging, but they have a high energy density and are safe. Flywheels have high energy and power densities but safety considerations (bursting wheels can have disastrous effects) make them difficult to contain. Ultracapacitors, on the one hand, have a high efficiency in their charging and discharging cycles. Energy is basically stored in a physical way by separating charges and thus creating a potential that can be used as a power source later on. No chemical reactions take place. On the other hand, ultracapacitors have low energy densities despite their potentially high power density.

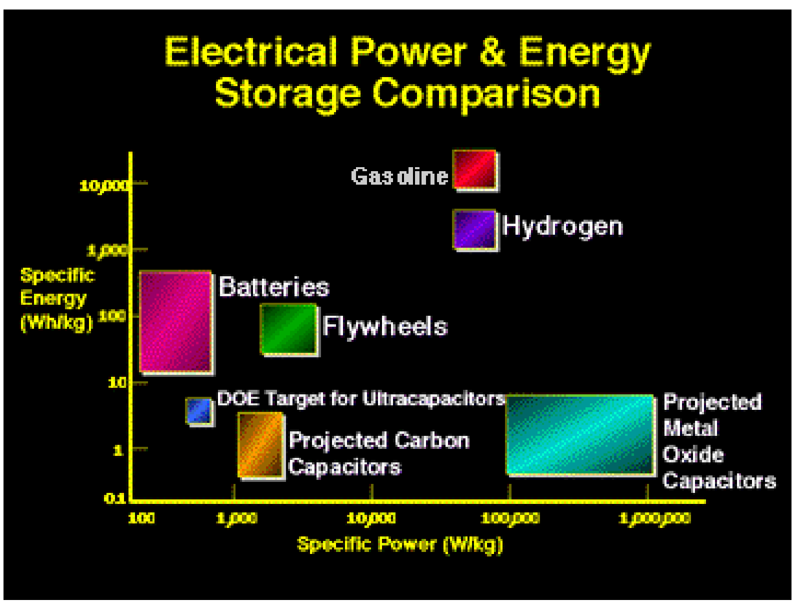

Figure 17: Energy and power densities of storage devices[20]

[20] taken from www.hev.doe.gov/components/storage.html

In a chosen example (see appendix) of the baseline truck described in chapter 2.2 on a 6% slope braking for two minutes, the required energy storage device must be able to absorb 10.5 kWh of energy. For a lead acid battery with an energy density of 35 Wh/kg [all battery data from 49] this is a theoretical additional weight of 300 kg. Battery power density is 200 W/kg and hence the above battery would provide electrical peak power of 60 kW. Considering current nickel metal hydride (NiMH) batteries with an energy storage capacity of 70 Wh/kg, the necessary weight for the same example goes down to 150 kg. Nevertheless with the lower energy capacity of only 150 W/kg the peak power of the electric motor would be 22.5 kW – considerably lower than in the first case. Using advanced NiMH batteries with 120Wh/kg and 220 W/kg the needed battery weight drops down to 87.4 kg and the theoretical peak power is 19.2 kW. These battery packs have power densities far below the needed 313kW. Therefore, even in the case of the 165kW battery used for the simulation in section 7, not all the energy can be absorbed by the batteries during downhill braking. Some energy must be dissipated as heat or might be stored in capacitors for short time braking. The battery pack cannot be designed as indicated with the above example however. It is a trade-off between needed peak power, energy storage and battery weight and costs (See section 7.1 for details). This study will not deal with this optimization.

Electric motors can provide high torque even at very low rpm. ICEs on the other hand have a poor efficiency at low load and are therefore unsuitable for stop and go cycles. For delivery trucks (e.g. UPS, FedEx, Postal delivery), hybrids would present an excellent system to decrease fuel costs [17]. Additional improvements in aerodynamic drag should be possible due to reduced radiator size of a smaller engine [37].

There are three basic types of hybrid vehicle configurations – a series, a parallel and a power split hybrid.

3.3.1 Series hybrid

In the series hybrid, a combustion engine is connected to an electric generator, which can directly provide electrical energy for the electric propulsion motors or charge a battery pack if less power is needed. The main advantage of this setup is that there is only one drivetrain – electric - that goes to the wheels, which offers the possibility to introduce small and efficient wheel motors. Note that the whole mechanical driveshaft and axle differentials can be omitted in this system.

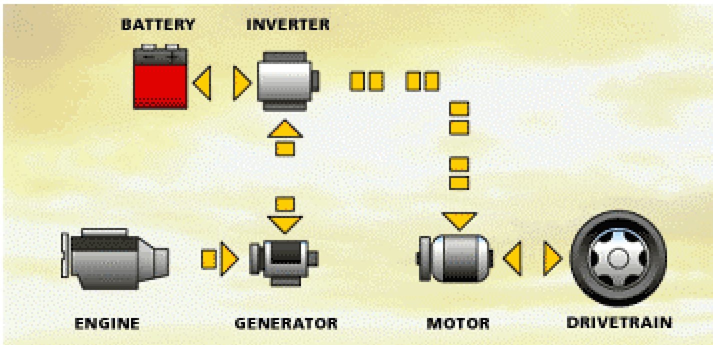

Figure 18: Series hybrid scheme[21]

Other important advantages are that the engine always runs at a constant load and can therefore be very efficiently designed, and the possibility to implement new power plants other than ICEs, in particular FCs (see section 3.3). Disadvantages include the necessity of an electric motor and a generator, whereas in the parallel case there is only one unit serving as generator as well as motor.

3.3.2 Parallel hybrid

In the parallel hybrid system the conventional drivetrain remains and the electric motor is added in parallel to the ICE.

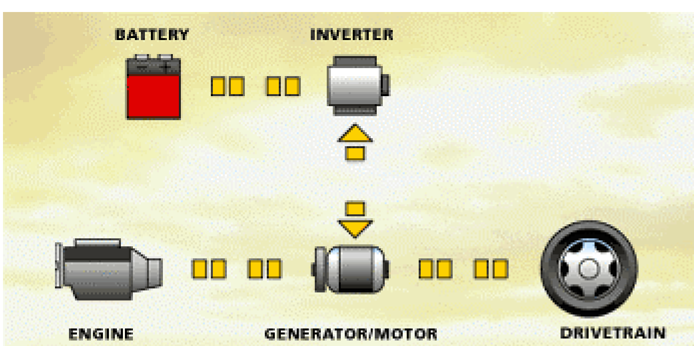

Figure 19: Parallel hybrid scheme

The mechanical drive shaft can therefore be powered by the ICE, the electric motor, or both, as peak power is required. The electric motor acts as the generator as well

[21] all hybrid schemes taken from: www.toyota.com

as the additional power source, and is not divided in two units as in the series case. The advantage of this system is the direct connection between the ICE and the wheels, which avoids the efficiency losses of the continuous charging and discharging process of the batteries. The ICE is supposed to run most of the time, but is downsized compared to a conventional ICE mechanical drivetrain. For slow stop-and-go driving the engine is stopped and the electric motor should be designed to provide all the power needed up to a certain threshold. With this arrangement the unnecessary idling of the ICE can be avoided. A parallel hybrid arrangement is used in the simulation for the hybrid truck.

3.3.3 Power split hybrid

The power split hybrid system is somewhat a mixture between the two basic configurations but it is closer to the parallel hybrid. An additional planetary gear constantly distributes the power from the ICE to the generator and directly to the wheels.

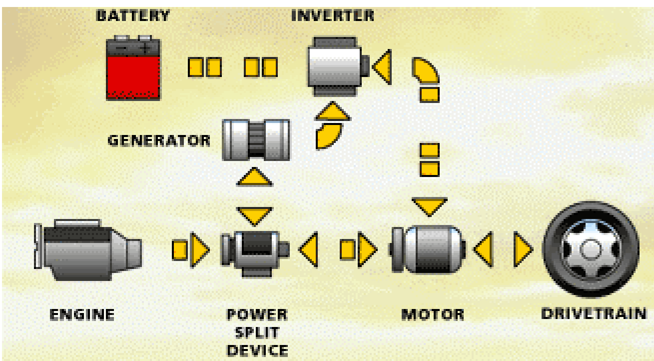

Figure 20: Power split hybrid scheme

Thus part of the energy is converted to electricity and stored in the batteries and the other part is provided to the drive shaft (The Toyota Prius is equipped with this latter system).

3.4 Fuel cells

Another promising technology, which could not yet be simulated with the Matlab model, shall be described qualitatively at this place. Fuel cells are electrochemical devices able to convert gaseous fuels directly to electric energy without combustion. Therefore they are not limited by the law of the Carnot cycle, but the energy content in the fuel can theoretically be used up to its heating value less the losses due to the irreversibility of the chemical reaction. This theoretical efficiency, which is about 85% of the energy content in the fuel, cannot be reached in real applications since efficiency drops if power (current) is drawn from the cell. The higher the current the lower the potential, and thus there is a maximum of power at an efficiency of about 60% of the theoretical chemical potential of the cell[22].

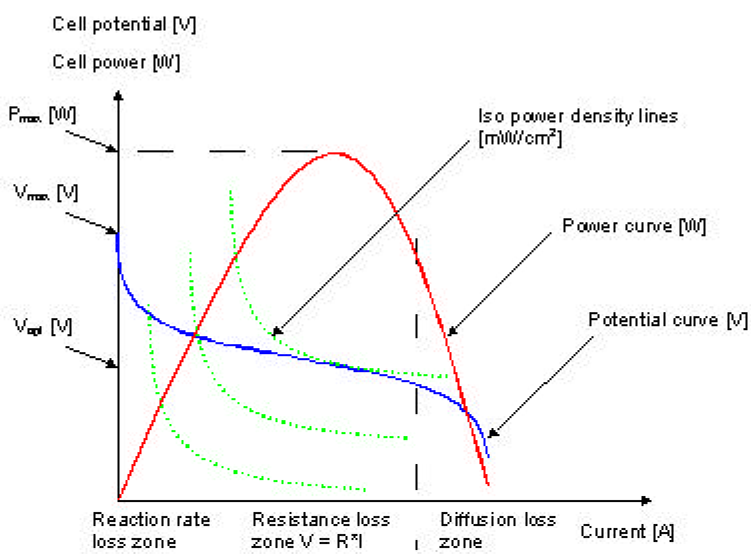

Figure 21: Fuel cell (PEM) performance for air-H_2 fuel mix[23]

There are three regions in the potential curve of the FC. The first drop in potential is caused by the chemical reaction rate limitations. In the second zone the potential drops

[22] Personal communication, James Cross, A.D.Little, Inc.
[23] The drop in potential due to diffusion does not appear if pure oxygen is used

linearly with increasing current according to Ohm's law. The third drop is caused by diffusion problems. If air is used as a source of oxygen, the potential can fall to zero. If pure oxygen is used, this drop would not occur and the ohmic linearity would prevail. The theoretical potential of the chemical reaction V_{max} is only reached for zero current.

There exist a current and voltage where the power density of the fuel cell is maximal, i.e. the most power per area unit can be drawn from the cell. A FC should run near this point indicated in Figure 21 as V_{opt}. The operating efficiency of the FC can be determined as follows:

$$h_{cell} = \frac{V_{applied}}{V_{\max}} \qquad (4)$$

Therefore, the overall efficiency on a fuel energy content basis is calculated by multiplying the theoretical maximal efficiency with the operating efficiency (equation 4) depending upon operating conditions. Proton exchange membrane fuel cells (PEMFC) seem to be the technology of choice for the near term future for transportation purposes. Their ability to operate at moderate temperatures (20-120°C) and to respond quickly to varying power demands provide an advantage over other FCs such as phosphoric acid, molten carbonate, solid oxide or alkaline FCs [20,21,22]. PEMFCs have come down in price during the past years and research is aiming for further cost reduction [20,21].

Since current diesel drivetrains already have high efficiencies of about 35-40% [20, p.5.14], FCs will have to be very fuel efficient (more than 45%) in order to be competitive in the trucking transportation sector. PEMFCs could cost about 50-200 $/kW, even with mass production according to the "five lab study" [20]. This is double to tenfold the cost of ICEs.

As indicated in chapter 3.2.1, a combination of the FC in hybrid would be an attractive solution on a fuel efficiency basis. The steady state operation of the FC combined with regenerative braking should perform at efficiencies above 60%.

Recently Ballard Power Systems, the market leader in PEMFCs, developed the fourth generation of their PEM stacks which have a power density of 0.88 kW per liter (1.18 hp) [30]. This order of magnitude is comparable to today's ICEs and therefore these engines could be implemented in the same space in a vehicle. Ballard has already shown a heavy-duty application with their first ZEV bus [31] and the 275 horsepower NEBUS [32].

The problems of fuel cells are not only related to the technology itself (high price) but to the necessary infrastructure, which is currently not in place. Today's fuel cells need hydrogen gas as fuel. This hydrogen can either be supplied in the form of gaseous or liquefied hydrogen or from a hydrocarbon fuel, processed in a small quantity chemical reactor – a reformer – on board of the vehicle. The most obvious disadvantage of gaseous or even liquefied hydrogen is the very low energy density compared to liquid fuels like diesel or gasoline (see chapter 5.3 on fuels). Hydrogen energy density on a volume basis is about an order of magnitude smaller than it is for hydrocarbons. Hence even if a fuel cell is about twice as efficient as an ICE – which is a very optimistic assumption – the energy storage system would be almost five times the volume of a diesel tank. In addition, the storage tank for gaseous H2 (compressed @ 350 bar) is 5 to 10 times more expensive [49] than a conventional liquid tank. There is a possibility to avoid these large energy storage devices by introducing the hydrogen in a form other than H_2 – as a liquid fuel like methanol, diesel or gasoline. But there are several problems with this alternative. As stated, the FC only works with hydrogen, and in addition, this hydrogen gas stream must not contain CO lest the catalysts on the surfaces of the membrane would become deactivated (intoxicated) quickly and the FC would lose its efficiency. Reformers must therefore provide a very clean H_2 stream that is "free" (lower than 10ppm) from CO – a catalyst poison (other gases like nitrogen, oxygen or even CO_2 may be part of this H_2-gas stream since they do not adsorb as strongly on the catalytic surface as CO does). Generally the reforming process is the production of syngas (mixture of CO and H_2) with possibly any compound containing carbon and hydrogen atoms by partial oxidation or steam reforming.

The governing chemical reactions are as follows (partial oxidation) for CH_4 as a template carbohydrate [48]:

$$CH_4 + 2 \cdot O_2 \rightarrow CO_2 + 2 \cdot H_2O \qquad \Delta H = -520 \text{ [kJ/mol]} \qquad (5)$$

$$CH_4 + H_2O \rightarrow CO + 3 \cdot H_2 \qquad \Delta H = 206 \text{ [kJ/mol]} \qquad (6)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H = -41 \text{ [kJ/mol]} \qquad (7)$$

The partial exothermic oxidation of the carbohydrate (5) is used in an autothermal reaction scheme to provide the necessary energy for the endothermic reaction (6), which produces the syngas. In the shift reaction (7) the CO is transformed into CO_2, which is not a catalyst poison and can be in the fuel stream for the FC. The control of this process is a difficult task especially for a vehicle where the demand for energy supply is changing at all times. An intermediary storage unit for gaseous H_2 seems to be unavoidable, so that the reformer can be driven at somewhat steady state conditions. Otherwise the performance of the reformer may be very poor (for transient cycles). Large-scale production of hydrogen can strongly improve the efficiency of the reformer. Current natural gas reformers are highly efficient units that can be tuned for steady state operation (see chapter 5.3.2 on fuel cycles).

Introducing a reformer into the vehicle can solve the energy density problem of hydrogen but it gives the whole FC system an overall efficiency and emissions penalty. Not only is the fuel cell less efficient, but the weight of the vehicle also increases. The reformer adds weight and the fuel cell must be bigger in order to provide the same power as a FC running on pure H_2. DOE sources [49] state a 10% weight increase for a methanol reforming FC car and a 19% weight increase for a gasoline reforming FC vehicle compared to a H_2 FC system. Since the vehicle weight distribution of a truck is different, these percentages are lower for HDVs (see chapter 2.6.2).

4 Driving resistances

4.1 Influencing factors

The total power needed to propel a vehicle must overcome four primary components:

- *Aerodynamic drag*, caused by the friction of air moving around the vehicle while in movement
- *Vehicle inertial mass* while it is accelerating
- *Tire rolling resistance*, which is the frictional loss of the tires
- *Mechanical losses*, which include all parasitic losses of the engine, transmission, as well as auxiliary power needs of fan, alternator, fuel pump, air compressor, and air conditioner

Other factors contribute in important ways to the overall fuel economy [15]; some of them shall be described in this section.

4.2 Aerodynamic drag

Aerodynamic drag becomes especially important at high travel velocities [13,14]. Generally, it can be described by the following formula[24]:

$$F_D = \frac{1}{2} \cdot r_a \cdot v_{rel}^2 \cdot c_D(f) \cdot A(f) \qquad (8)$$

where:	F_D	aerodynamic drag force	[N]
	ρ_a	air density	[kg/m^3]
	v_{rel}	relative velocity of vehicle	[m/s]
	c_D	aerodynamic drag coefficient	[-]
	A	cross sectional area exposed to wind	[m^2]
	ϕ	wind yaw angle	[°]

[24] All presented formulas are taken from the Matlab model

Early studies have shown potential for aerodynamic drag reduction [8]. Newer extended studies [9,10,11,12,18] showed the different technological improvements, which make possible reductions in aerodynamic drag, and their respective fuel economy effects. The introduction of roof top deflectors and fairings, cab-side extenders, tapering rears of the trailer, underside and trailer side wall improvements are described based on wind tunnel experiments with a 1:2.5 tractor-semitrailer model (no effects of "moving" road) as well as on the road tests with "real" trucks [10]. Fuel economy improvements of up to 15% on the basis of a Mercedes Benz 1735 S tractor semitrailer combination have been found in the experimental road tests by the introduction of fairings, side skirts, reduced trailer gap, wheel covers and tapering rears. The importance of wind yaw angles is shown [11]. This is one of the differences to passenger cars. Trucks are long vehicles therefore the wind yaw angle can influence fuel consumption drastically if the vehicle is not attacked by frontal winds in a perpendicular way. The actual cross sectional area increases and the area where winds attack can become a multiple of the theoretical area calculated by multiplication of height and width of the vehicle (see chapter 4.5). Aerodynamic drag has been reduced by about 40% within the last 30 years. Starting with a C_d-value of 1.0 for a truck without any aerodynamic gear, the introduction of roof deflectors after the 1970ies oil crisis reduced the value down to 0.7 – 0.8. Today's best conventional tractor-trailers reach C_d-values of 0.6. Further increase in this area is possible and probable.

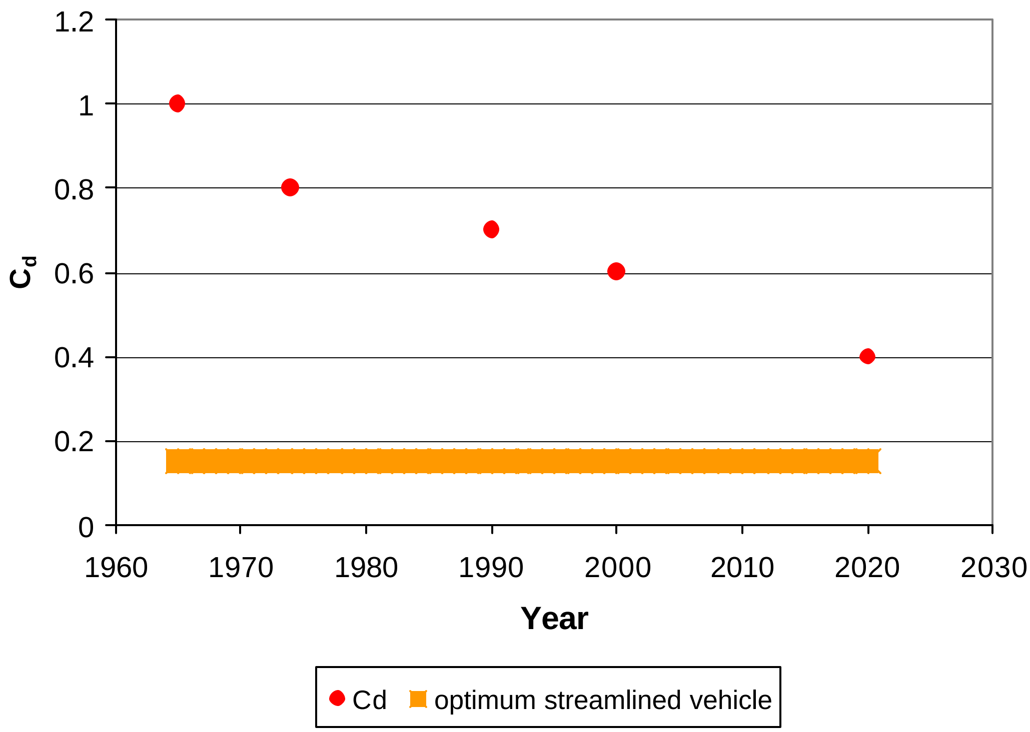

Figure 22: Evolution of C_d

With cab-over-engine design, values down to 0.5 can be reached today (trucks have values in this range in Europe, where cab-over-engines designs are standard). Scania is talking about C_d-values in the passenger car range for their 2010 concept truck. Based on these data and data in Petrushov [51], an estimate of 0.4 is used for an advanced truck in the simulations. Trailers are currently made separately from the tractors. C_d-values as low as 0.4 can only be reached if the whole tractor trailer combination is optimized as a whole. Closer cooperation between truck and trailer manufacturers is needed in order to achieve the projected value.

The measures added to the baseline vehicle can be characterized as follows:

Measure	Corresponding C_d-value
Full aero package tractor	0.58
Reduced trailer gap, ca. 0.5m (18")	0.56
Cab over engine design	0.51
Improved trailer (side skirts)	0.45
Integrated advances full vehicle	0.4[25]

Table 9: Aerodynamic drag reduction measures and corresponding Cd-values[26]

4.2 Vehicle inertial mass

Vehicle weight is another important factor influencing fuel consumption, especially while the vehicle is accelerating. The inertial mass of the vehicle must be overcome by the engine power while it is accelerating and dissipated by brakes during deceleration. In a quasi steady state approximation, as simulated in the model, this behavior can be expressed by the following equation:

$$F_{Inertia} = m_{veh} \cdot \left(1 + \frac{\%m_{rot}}{100}\right) \cdot v' \cong m_{veh} \cdot \left(1 + \frac{\%m_{rot}}{100}\right) \cdot \frac{\Delta v}{\Delta t} \qquad (9)$$

where:			
	$F_{Inertia}$	Force caused by inertial mass of vehicle	[N]
	m_{veh}	Vehicle mass	[kg]
	$\%m_{rot}$	Percentage of rotating mass on vehicle	[-]
	v'	(Exact) acceleration	[m/s^2]
	Δv	Change in speed	[m/s]
	Δt	Lapse of time for corresponding speed change	[s]

[25] Lower values can be reached. For mass production however, 0.4 should be attainable.
[26] Data taken from Spec Manager™

Not only must the vehicle as a whole be accelerated in the forward direction, but each rotating device (wheels, shafts, engine, etc.) must also be accelerated in its rotating direction. This is the reason for the $\%m_{rot}$ term, which takes into account this acceleration of the rotating masses as a certain percentage of the whole vehicle (a constant of 3.5% of the GVW is used in the simulation).

The same force acts on the vehicle during braking and must be dissipated in the brakes (see sections 2.6.1).

4.3 Rolling resistance

The weight also goes into the calculation of the tire rolling resistance. Equation (10) shows that the rolling resistance of the vehicle is directly proportional to the RRC, which is a coefficient influenced by the frictional properties of the road and the tire. According to Petrushov [51] and the Bosch handbok [45], this RRC is a function of vehicle speed. Nevertheless it is assumed to be constant at any speed in the simulation and the following more general formula is used:

$$F_{rr} = m_{veh} \cdot g \cdot \mu \qquad (10)$$

where:	F_{rr}	Rolling resistance force	[N]
	m_{veh}	Vehicle mass	[kg]
	g	Gravitational constant	[m/s^2]
	μ	Rolling resistance coefficient (RRC)	[-]

Considerable work has been done in this area to reduce RRC. Bias ply tires have been supplanted by radials and now give way to low profile radials. Super single tires compete with “normal” doubles. Sachs et al [15] speak of a possible fuel economy gain of 3% by improved tires. Thompson et al [28] estimate that a 10% reduction in RRC yields a 2 percent change in the vehicle’s fuel consumption. Note that this study was made for passenger cars, but Sachs also cites a 1% truck fuel economy gain for a 2.6% RRC reduction. Generally, it can be said that the rolling resistance becomes more and more important the heavier the vehicle gets. Nevertheless, the rolling resistance is not only governed by the intrinsic properties of the tires, but by their maintenance. Accurate pressure in all tires of the vehicle is important to meet predicted fuel economies and avoid irregular wear, which can provoke increased RRC and is also an important safety issue, especially for single tires. Mismatching tires on doubles can create slip of the smaller tire and put more weight on the bigger tire causing detrimental effects to fuel economy and overall tire cost [29]. Based on Bosch's Automotive Handbook and values from ANL [45,54], RRCs of 0.005[27] to 0.007 are used for modeling purposes. Truck wheels generally have smaller RRCs than passenger car wheels [45]. Rolling resistance has been drastically reduced in the 1970ies with the introduction of radial tires.

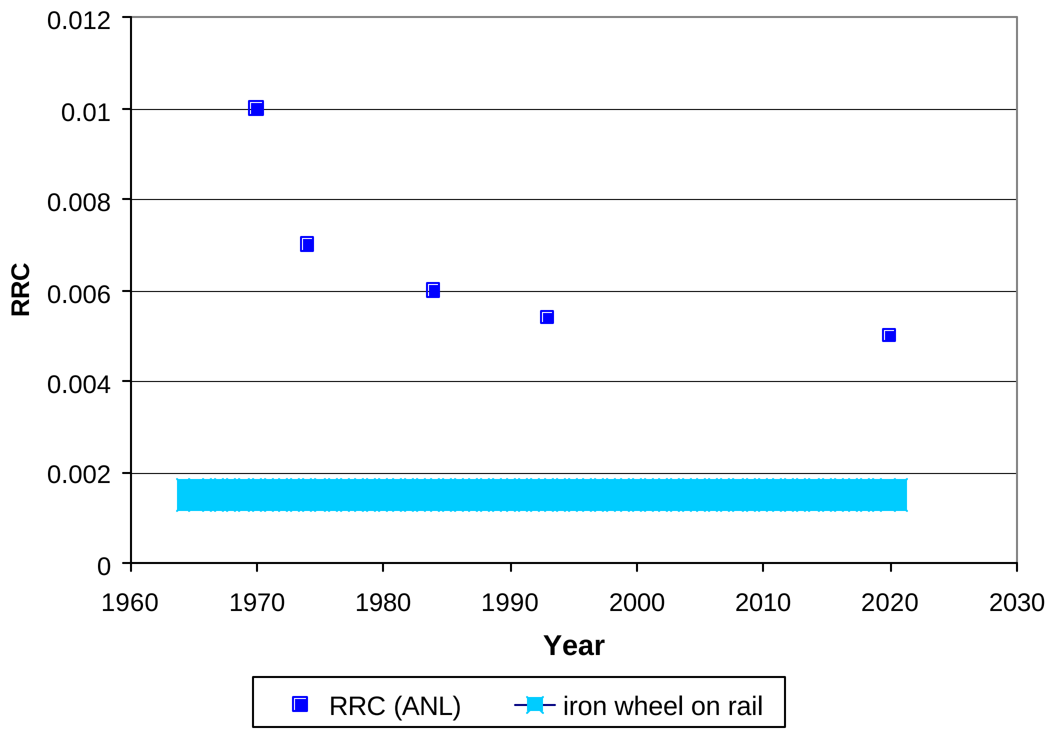

Figure 23: Evolution of RRC[28]

[27] The value of 0.005 is not reached today and is assumed as an optimistic future value
[28] historical data from ANL

Whereas bias-ply tires had RRCs of 0.01 or more, the radials came down to 0.007. Low profile radials got down to 0.006, and most recent types to 0.0054. RRCs of 0.005[29] were estimated possible on the basic value for the best tires of 0.0054 reached today. This represents an improvement of 7.5% on a time horizon of 2020. Current tires have RRCs between 0.007 and 0.008, depending upon the position on the truck. Trucks use different tires on drive and steer axles as well as on the trailer. According to Michelin[30], the chosen 0.005 is a possible optimistic value.

The RRC-values are listed in Table 10:

Measure	Corresponding RRC
Today's best radials largely spread on the US market	0.006[31]
Today's best radials (possible)	0.0054
Future super single radials	0.005

Table 10: Tire improvements and corresponding RRCs

4.4 Vehicle cross sectional area

The vehicle cross sectional area, which is generally the product of height and width, does influence fuel consumption as indicated in equation (8). The larger this area, the more power is necessary to propel the vehicle. The height depends largely upon the specific application and customer's preferences. For transportation companies, volume capacity can be a crucial competitive factor, and therefore reductions in cross sectional area are impractical and will not be considered in this study. A standard width of 2.6m (102") and a height of 4.08m (13'5") is assumed based on Spec Manager™ data and will be used as the baseline values in the simulation to give a cross sectional area of 10 m^2. (The open area under the vehicle between the wheels (0.6 m^2) is subtracted).

[29] A comparison with a railroad RRC of 0.001 - 0.002 shows that this is already a low value.
[30] Personal communication, Olivier Brauen, Michelin France, March 2000
[31] Personal communication, Jack McCammond, Michelin USA, March 2000

4.5 Vehicle length

Vehicle length is especially important for trucks compared to passenger cars in the presence of side winds. Increasing side wind yaw angles can significantly increase fuel consumption. Krämer and Göhring [9] show the importance of side wind effects and the impacts of measures to reduce side wind drag effects. Introducing side skirts for tractor and trailer – including tapering rears - reduces drag by up to 40% (note that this is not a direct fuel economy gain). Most of the time some side wind effects are present in real driving, so that the effects of side skirts can be even more important than the here applied model would predict, as side winds are not considered in the model. Porth et al [11] show fuel economy gains of 9% in real driving tests for a vehicle including side skirts compared to one without. Vehicle length reductions are limited for the same reasons as cross sectional area, i.e. freight capacity. The importance of vehicle length is not considered in the simulation and neither are wind yaw angles. Since these restrictions apply to all of the considered propulsion technologies in the same manner, the effects would also be similar for all of them.

5 Other factors

5.1 Driver skills

Driver skills can have a considerable impact on fuel economy[32]. This includes progressive shifting and low rpm cruise, and avoiding “red line” high rpm accelerations and long idle periods. A new word used for this style of driving is “ecolomic” driving, meaning a combination of economic and ecological improvements in driving behavior. Sachs et al [15] present an estimate of up to 20% in fuel economy only by enhanced driver skills. The Verkehrs-Sicherheitszentrum Veltheim (VSZV) in Veltheim, Switzerland provides courses in ecolomic driving, and truck fleet operators can save in average 5 to 10% in fuel consumption costs after one year of having their personnel educated in ecolomic driving[33]. Another study performed by VSZV in a 12 bus fleet in the city of Grenchen (Switzerland) showed a 45% fuel consumption reduction for idle periods if drivers put the gear from “D” to “N” (neutral gear in the automatic transmission, avoiding energy dissipation in the torque converter). For the considered small fleet this presented a 1,700 L “free” fuel saving only by switching the gear.

The amount of energy that can be saved by avoiding long idle periods – such as overnight constant idle to keep cab heating or A/C and other accessories running – shall be considered in the next chapter.

5.2 Engine idling and auxiliary power units (APUs)

According to estimates by Argonne National Laboratory [43], the average long-haul truck idles away up to $1,790 in profits each year. Instead of letting their engines idle, operators of class 7 and 8 trucks should consider using separate devices for cab heating and cooling and engine warming. The payback period for such devices could be as short as one year, depending on use.

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[32] Personal experience and communication

[33] Personal communication by Mr. Peter Koch, Instructor VSZV

Devices on the market include direct-fired burners for cab and engine-block heating, thermal storage devices for heating and cooling, and auxiliary power units for heating, cooling, and electrical power. Typically, they consume 80-90% less fuel than a truck diesel engine[34], produce very low emission and are silent. Reducing idling would have significant environmental and economic benefits on the national level as well. If all class 7 and 8 long-haul trucks (about 480,000 vehicles) used these devices, the total fuel savings would be as much as 0.6% of all fuel used for surface transportation in the United States [43]. By reducing idling, truckers have the opportunity to reduce costs on fuel, increase the overall energy efficiency, and reduce air and noise pollution.

[34] A heavy diesel engine used for cab heating is only about 8% efficient.

5.3 Fuels

5.3.1 Fuels and their emissions

Trucks contribute up to about half of all NO_x emitted by the transportation sector today [46]. They are expected to have a major contribution in the future when gasoline passenger cars get even cleaner and diesel HDVs cannot meet the same standards (see chapter 2.4.1 on mechanical drive trains and diesel ICEs for explanation). The freight sector could become a major contributor for GHG and other emissions, and it is critical to envisage these aspects now. Several other fuels can be used for transportation purposes in internal combustion engines as well as in other power generators such as fuel cells (FCs). Table 11 shows energy properties and emissions of the considered fuels. Note that on a per kg basis, hydrogen is by far the fuel with the highest energy density. The problem is that even in the liquefied state, hydrogen has a very low mass density, hence the required volume for the fuel storage on a vehicle is big compared to conventional fuels like diesel or gasoline. This is one important disadvantage of hydrogen with respect to other fuels.

This table is a comparison of the possible fuels on a 100-gallon energy equivalent of diesel fuel (13.3 GJ). It does not take into account the efficiency of the propulsion system however. This means that a more efficient diesel-hybrid or a FC system would need less fuel than the given 100-gallon diesel equivalent. Note that the table does not show the overall CO_2 emissions of the entire fuel cycle (see next section). One can see the high energy density of H_2 on a per mass basis and its low energy density on a per volume basis, which is the value of interest for transportation purposes. By comparing the different fuels based on the energy content per volume, the outcome is considerably different.

Fuel	Chemical formula	Energy content LHV [MJ/kg]	Fuel weight [kg]	Tank weight [kg]~	Total fuel system weight [kg]	density [kg/m^3]	Volume of fuel [gal]	Volume of fuel [L]	Energy density [MJ/L]	CO_2 emissions [kg/kg]@	CO_2 emissions [kg/MJ]@
Diesel	$C_{11}H_{20}$	41.7+	320	42	362	856	100	379	35.7+	3.19	0.076
Gasoline	C_7H_{13}	42.4	315	42	357	738	113	426	31.3	3.05	0.071
Methanol	CH_3OH	20.1+	660	70	730	792	220	833	15.9+	1.38	0.07
Natural gas (CNG)	CH_4	47.7#	280	238	518	168*	440	1666	8.0*	2.75	0.05
LH_2 @ 20K	H_2	120.2+	120	133	253	31^	940	3558	3.7^	0	0
CH_2 @ 207bar	H_2	120.2+	120	448	568	14^	2160	8176	1.6^	0	0
CH_2 @ 690 bar	H_2	120.2+	120	511	631	24^	1220	4618	2.9^	0	0

Table 11: On board storage capacities, specific heat output and CO_2 emissions at point of use for different fuels [5]

~ values calculated on a basis for 5 gal diesel tank; assumption volume increase by 20 (=2.7^3), tank (area) increase by 7 (=2.7^2)
@ data from [4]
+ data from [34]
# CNG LHV [5; p.197]
* data calculated based on [5; p.292], CNG @ 15°C and 220 bar
^ data calculated based on [5; p.454]

5.3.2 Fuel cycles

To benchmark different propulsion and fuel systems, an overall "well to wheels" life cycle analysis (LCA) for any considered fuel system must be performed. This means that not only the emissions and energy efficiency of the vehicle must be looked at but also the energy used to produce and deliver the fuel from the well to the refueling station. This has an essential impact on the overall fuel efficiency of a particular technology.

For certain fuel systems like diesel or even gasoline, the fuel production part of the cycle is rather efficient, since these fuels exist almost "as are" in petroleum and do not need to be synthesized (this is only partially true for reformulated gasoline). On the other hand the efficiency of the vehicle part of the cycle is poor compared to the fuel cell. In contrast, hydrogen can theoretically achieve a very high efficiency in the vehicle part of the cycle. But since it does not naturally exist in its elementary state, it must be produced synthetically, which gives the overall fuel cycle a heavy emission burden and can make the whole technology look much more inefficient than it would seem if only the vehicle cycle were assessed. (This is true if H_2 is produced by steam reforming of natural gas. If hydrolysis is employed as the technology to produce H_2, then it depends on the type of energy power stations that produce the necessary electrical energy.)

Based on data from different sources, Table 12 was established[35]. The fuel cycles of the considered technologies are compared and the whole image is presented. It can be seen that the conventional gasoline and diesel fuels have the best production energy efficiency of up to 88% (about 12% of the energy content in the primary fuel is lost during production) for diesel fuel and 84% for gasoline. For the Fischer-Tropsch conversion of natural gas to diesel fuel, the energy consumed per MJ loaded onto the vehicle is more than 0.5 MJ, which is more than one third, or an efficiency of 66%.

[35] table provided by Darian Unger, Energy Laboratory, MIT, March 2000; might be subject to changes.

		Per MJ of Fuel Loaded onto Vehicle			
Fuel		**Energy Consump-tion**	**GHG emis-sions**	**NOx emissions**	**PM 10**
		(MJ)	(g C as CO2)	(mg)	(mg)
Gasoline from Petroleum	Feedstock (Recovery + Transport)	0.04	0.9	16.8	1.1
	Refining	0.14	3.4	17.1	8.7
	Transport & distribution	0.01	0.3	5.8	12.7
	Total	0.19	4.6	39.7	22.5
	Range of totals	*0.13-0.22*	*2.4-5*	*24-54*	*0-32*
Diesel from Pe-troleum	Feedstock (Recovery + Transport)	0.04	1.0	13.2	0.3
	Refining	0.08	2.2	9.3	1.6
	Transport & distribution	0.01	0.3	4.4	10.7
	Total	0.13	3.5	26.9	12.6
	Range of totals	*0.09-0.15*	*1.5-6*	*18-48*	*0-15*
Diesel from NG	Feedstock (Recovery + Transport)	0.08	1.6	31.5	0.6
	Refining	0.43	7.9	29.5	1.3
	Transport & distribution	0.03	0.8	4.6	10.7
	Total	0.54	10.3	65.6	12.6
	Range of totals	*0.54*	*10.3*	*65.6*	*12.6*
Methanol from NG	Feedstock (Recovery + Transport)	0.07	1.7	13.4	8.7
	Production	0.47	4.2	28.4	13.4
	Transport & distribution	0.03	0.8	6.2	7.3
	Total	0.57	6.7	48.0	29.4
	Range of totals	*0.44-0.73*	*1.7-7*	*30-234*	*1-43*
Hydrogen from NG	Feedstock (Recovery + Transport)	0.06	1.1	9.9	0.3
(gaseous H2)	Production	0.36	14.2	22.4	0.8
	Compression, transport & distribution	0.18	8.4	115.9	6.6
	Total	0.60	23.6	148.2	7.7
	Range of totals	*0.44-0.65*	*23.6*	*148.2*	*7.7*
Hydrogen from electrolysis	Feedstock	0.00	Depends on mining of fuel for electric generation		
(gaseous H2)	Production	1.72	64		
	Transport & distribution	0.93	35		
	Total	2.65	99		
	Range of totals	*2.65*	*99*		

Table 12: Energy and emissions from well to tank [34]

Methanol from natural gas requires 30 to 42% of the energy content in the gas to produce the methanol that could be filled into the vehicle's tank. This represents an efficiency of 58 to 69%. Hydrogen production through steam reforming has about the same efficiency. Hydrogen from electrolysis depends on the efficiency of the electricity available. Even with today's most efficient combined cycle gas turbines with efficiencies of 60%, for every MJ of hydrogen produced in the electrolysis plant, one needs 1.7 MJ energy equivalent of gas to produce the necessary electricity for H_2 production. With a today's typical US electricity mix that uses 3 MJ oil equivalent to produce 1 MJ of electricity and an assumed 20% transportation loss one finds an energy intensity per MJ of H_2 loaded onto the vehicle of 3.6 MJ. This shows the high energy intensity of this technology, which initially appeared to be the cleanest. For the emissions, one finds a similar pattern in the sense that the conventional fuels have an advantage over the alternates. An exception to that trend are the particulate emissions from Fischer-Tropsch synthesis which are low (natural gas is used as a feed stock for this process).

6. Cost and profitability considerations

Sachs et al [15] present a comparison of fuel efficiency improvements and their relative costs as cost of conserved energy (CCE) expressed as dollars per gallon of fuel saved. CCE is independent of fuel prices and can be compared to present or expected future prices. On the basis of annual miles, the payback time of various fuel-saving technologies can be calculated and the profitability assessed. A small CCE means that the price for a particular measure to reduce fuel consumption is low and therefore an attractive one. A similar profitability factor shall be introduced in chapter 7.5, where the percentage of fuel saved is put into relation with the retail price increase (RPI) compared to the baseline vehicle. If this factor is equal to one, the percentage fuel economy increase equals the retail price increase. Numbers bigger than one represent technologies that give a higher percentage of fuel economy increase per RPI. If the profitability factor is smaller than one, it means that fuel economy increase percentage is smaller than the respective RPI percentage. This profitability factor does not depend upon fuel prices and miles driven but upon the application, i.e. driving cycle. It cannot be taken as an absolute value, but it can be used to compare technology options within a defined application. To get the actual return on investment of a certain technology and application, the truck purchaser should multiply the fuel consumption improvement with the miles driven per year to find the fuel savings related to the technology in question and compare it to the RPI. Tanja [47] gives qualitative low cost estimates for air resistance measures, optimized maximum power levels, speed limiters and cruise controllers. It gives medium to high cost estimates for mass reduction efforts, RRC improvements, electronic gear shifting and regenerative braking.

Another important cost issue is prolonged engine idling for cab-heating purposes (see chapter 5.2).

Assumptions from Stodolsky et al [17] for the hybrid case have been applied. The data for electric motor and inverters was extrapolated from data in [17], without taking into account possible economies of scale. The following table show costs for the original equipment manufacturer (OEM) as well as the corresponding retail prices and RPI for the hybrid versus the diesel, considering current prices for ICEs and electric motors and an estimated (low) price for the NiMH-battery of $115/kWh(DOE [49]):

Propulsion system	Diesel	Diesel hybrid
ICE	17,000[36]	7,000[37]
Electric motor	0	4,000
Inverter	0	6,000
Battery pack (750kg)	0	15,500[38]
Additional controls	0	2,000
Total cost	17,000	(34,500)
Total price[39]	22,100	38,100
RPI vs diesel	0	16,000

Table 13: RPI for hybridization

These costs must be added to the common costs for a truck with a retail price of about $ 137,000, depending upon the size of order and manufacturing availability. Another 30,000 dollars must be added for the trailer. These prices can be considered as standard "on the market" prices, but they do not contain any rebates. The cost of the baseline vehicle was calculated based on retail price data from Freightliner for the tractors and Century Trailer for trailers. The baseline trailer was estimated to cost $ 30,000. A 15% price increase for side skirts was added to obtain the 0.45 value for aerodynamic drag coefficient. Another 7% price increase was assumed to improve the whole vehicle in its aerodynamics to the target C_d of 0.4 (it is less expensive to improve the whole vehicle, since a big part of the costs is not directly C_d-related, i.e. engine, cab equipment, chassis, drivetrain).

[36] Engine cost provided by Detroit Diesel Corp.
[37] Retail price provided by International Diesel Engines (not multiplied with 1.3, see text)
[38] The actual cost is $ 10,000 for the battery data in 5.1; multiplied by a factor of 1.5, thus considering battery lifetime [17]
[39] Costs multiplied by 1.3 taking account of R&D, warranty, profit, etc. [17]

Table 14 shows the truck retail prices that were used:

Truck	**RP truck**[40]	**RP trailer**	**Price "advances"**	**Total price**
Baseline	137,468	30,000	-	167,468
Aero cab	140,574	30,000	-	170,574
Gap seals, skirts	147,680	30,000	-	177,680
COE, seals, skirts	140,944	30,000	-	170,944
Adv. aero trailer	140,944	34,500	-	175,444
Adv. aero vehicle	140,944	34,500	12,281 (7%)	187,725
"baseline hybrid"	153,468	30,000		183,468
Hybrid	156,468	34,500	12,281	203,249

Table 14: Truck prices

The vehicle configuration called "baseline hybrid" can be considered as the baseline truck without any added resistance reduction features, but with hybrid technology. The "hybrid" can be referred to model run # 12, presented in section 7.2, using a diesel engine with the same efficiency as the baseline truck in order to get comparable economic data of what would be possible today. (The same comparison could be made with about the same results for cases ② and ④ or ③ and ⑤ in 7.2). In section 7.5 estimations of RPI shall be given considering the results of the simulation according to the different fuel saving measures.

[40] Personal communications, Dave Cirillo, Boston Freightliner Inc., March 2000

7. Results and discussion

7.1 Simulated vehicles

As presented in the introduction, different measures allow fuel economy gains. Among the described, only some, where simulation data was available to “prove” assumptions could be studied more precisely. For other technologies, published literature data from other sources is used for comparison (FC, section 3). The following factors were used as variables in the simulation:

1. Propulsion technology
   - Diesel:
     ⇒ ICE: 12.7 L 2,101 Nm @ 1,200 rpm, 321 kW @ 1,800 rpm
   - Diesel-electric hybrid with:
     ⇒ ICE: 8.7 L 1,072 Nm @ 1,200 rpm, 184 kW @ 1,800 rpm
     ⇒ Electric motor: 1,029 Nm @ 1,200 rpm, 137 kW @ 1,800 rpm
     ⇒ NiMH battery pack: 750 kg, 120 Wh/kg, 220 W/kg, 115 $/kg
2. Driving cycle
   - HDV highway driving cycle
   - HDV urban driving cycle
3. Driving resistance factors
   - C_d-values from 0.62 (baseline) to 0.4 (advanced truck)
   - RRC-values from 0.007 (baseline) to 0.005 (advanced single tires)

The following vehicles are considered and “driven” in the simulation:

Vehicle	Engine peak efficiency	RRC	C_d-value
Baseline diesel 2000	48 % (175 g/kWh)	0.007	0.62
Advanced diesel 2020	52 - 55% (155 - 140 g/kWh)	0.005	0.4
Hybrid 2020 (parallel)	52 - 55% (155 - 140 g/kWh)	0.005	0.4

Table 15: Simulated vehicles

Results shall be given not only for the above vehicles, but also for measures that can be introduced “on the way” to the advanced diesel 2020. Decreases of C_d and RRC have been simulated separately and combined. Potential savings can be even higher since if resistances are reduced, the power needs for vehicle propulsion are lowered, i.e. the engine can be smaller and hence in general less consuming. For simplicity and comparison reasons, this has not been introduced though and the same engines are used all the time.

The baseline diesel is based on the chosen ICE with an assumed peak efficiency of 48%. The same engine was used, but with an efficiency of 52 and 55% for the advanced 2020 diesel.

The hybrid has been defined as follows. The ICE was chosen to sustain cruise speed power and torque for the baseline truck (184 kW @ 1800 rpm, 1085 Nm @ 1200 rpm). The power of the electric motor (137 kW @ 1800 rpm, 1029 Nm @ 1200 rpm) is then added in order to match the necessary torque of 2101 Nm and the peak power of 321 kW of the baseline diesel. A NiMH battery pack was added to the electric motor, capable of providing the 137 kW to the motor; the peak motor torque is multiplied by an efficiency factor of 1.2 (battery discharging losses and motor efficiency) to yield 165 kW battery peak power.

Based on DOE data for a projected NiMH battery [49] the following battery characteristics were used.

Battery type	Specific energy density [Wh/kg]	Specific power density [W/kg]	Price [$/kWh]
NiMH	120	220	115

Table 16: Battery specifications

With these data the battery pack used weighted 750kg and could provide theoretically 90 kWh at a price of $10,350.

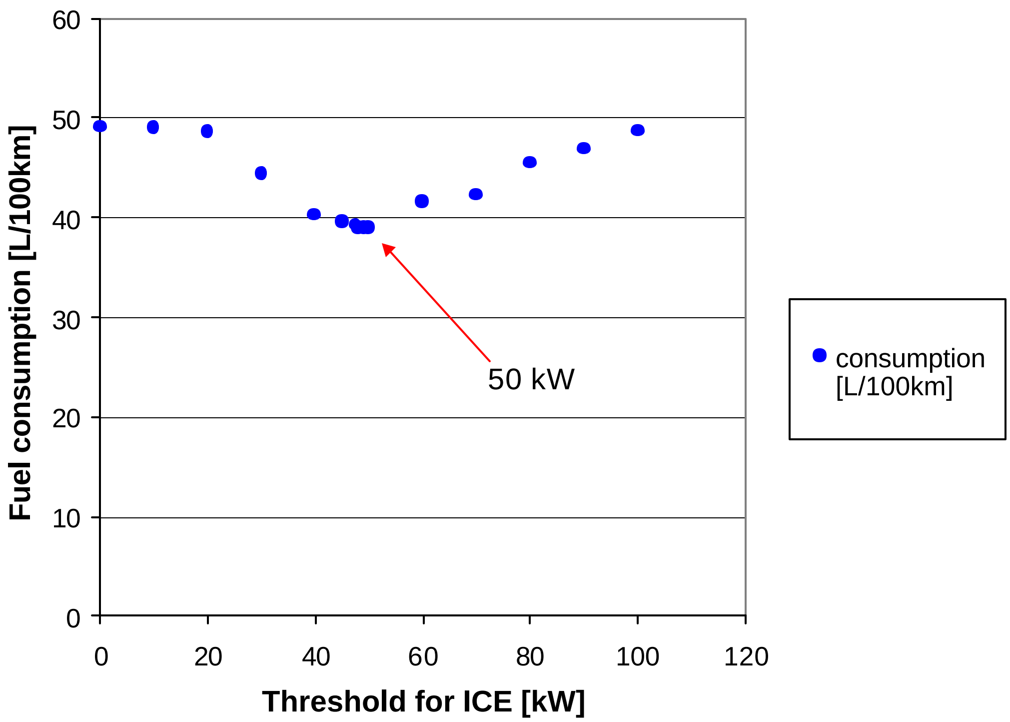

Figure 24: Sensitivity study to determine ICE threshold power

A sensitivity study was performed based on the fully loaded truck in the urban driving cycle to determine the threshold below which only the electric motor should provide power. The urban driving cycle was chosen because it is much more sensitive to the change in this threshold than the highway cycle, when most of the time the vehicle is powered only by the ICE. The threshold of 50 kW was chosen according to the sensitivity study results shown in Figure 24:

It is important to note that no optimizations were performed and all the data are therefore first estimates. Engine, motor and battery sizes and costs must be considered for the optimization of a hybrid vehicle, in order to find minimum costs and best possible fuel economy. The downsized ICE-electric motor combination for the hybrid was chosen to reach same power outputs as the baseline diesel. Reduced driving resistances however would offer an additional downsizing of the engine. The conventional diesel could also be downsized to meet the same driving performance as the more powerful baseline engine.

7.2. Simulation results

7.2.1 Highway driving

The following results have been found for C_d and RRC reductions and the implementation of the hybrid drive using the highway driving cycle:

run	C_d [-]	RRC [-]	Fuel cons. [L/100km]	Fuel economy [mpg]	Drive-train	% gain	ICE eff. [%]
1 ①	0.620	0.0070	38.1	6.2	conv.	0%	48
2	0.580	0.0070	37.2	6.3	conv.	2%	48
3	0.560	0.0070	36.8	6.4	conv.	4%	48
4	0.510	0.0070	35.6	6.6	conv.	7%	48
5	0.450	0.0070	34.3	6.9	conv.	10%	48
6	0.400	0.0070	33.1	7.1	conv.	13%	48
7	0.400	0.0060	31.5	7.5	conv.	17%	48
8	0.400	0.0055	30.6	7.7	conv.	20%	48
9	0.400	0.0050	29.8	7.9	conv.	22%	48
10 ②	0.400	0.0050	27.5	8.5	conv.	28%	52
11③	0.400	0.0050	26.0	9.0	conv.	32%	55
12	0.400	0.0050	27.3	8.6	hybrid	28%	48
13 ④	0.400	0.0050	25.2	9.3	hybrid	34%	52
14 ⑤	0.400	0.0050	23.8	9.9	hybrid	37%	55

Table 17: Influence of technological measures on fuel economy on highway driving cycle for 30,000kg truck.

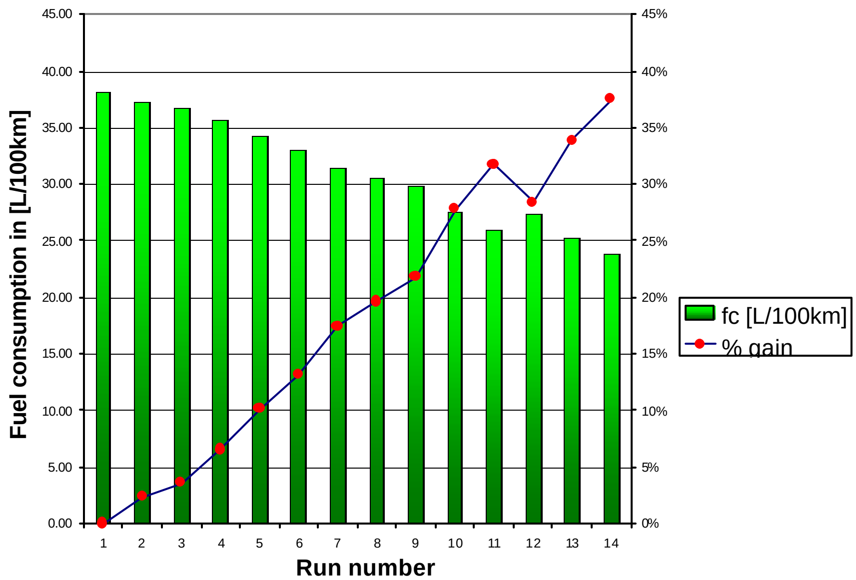

Figure 25: Fuel consumption reduction potential with considered technological measures on highway driving cycle (refer to Table 17)

For the considered vehicles, the following table gives fuel consumption values:

Vehicle	Engine peak efficiency [%]	Fuel consumption [L/100km]	Fuel economy [mpg]	Improvement [%]
Baseline diesel 2000 ①	48 (175 g/kWh)	38.1	6.2	0
Advanced diesel 2020 ②	52 (155 g/kWh)	27.5	8.5	28
Advanced diesel 2020 ③	55 (140 g/kWh)	26.0	9	32
Hybrid 2020 (parallel) ④	52 (155 g/kWh)	25.2	9.3	34
Hybrid 2020 (parallel) ⑤	55 (140 g/kWh)	23.8	9.9	37

Table 18: Fuel economy of considered vehicles in highway driving

Table 17 and Figure 25 show the fuel consumption according to different measures implemented into the vehicle for a partially loaded truck with a typical weight of 30,000 kg (66,140 lbs) on the highway driving cycle. The hybrid configuration chosen was described in 7.1.

The values found for the advanced 2020 diesels (②,③) and hybrids (④,⑤) represent conservative values of what is possible in fuel economy, since the possible downsizing of the engines due to reduced resistances is not accounted for.

If case ② is compared to case ④ in Table 18 it might seem that there is only a 6% reduction for the hybrid versus the advanced diesel. However, if case ② is taken as baseline, then the possible reduction is about 9% for the hybrid ④ versus the diesel with the same specifications.

7.2.2 Urban driving

The following results have been found for C_d and RRC reductions and the implementation of the hybrid drive using the urban driving cycle:

run	C_d [-]	RRC [-]	Fuel cons. [L/100km]	Fuel economy [mpg]	Drive-train	% gain	ICE eff. [%]
1 ①	0.62	0.0070	53.1	4.4	conv.	0%	48
2	0.58	0.0070	52.9	4.4	conv.	0%	48
3	0.56	0.0070	52.9	4.4	conv.	0%	48
4	0.51	0.0070	52.7	4.5	conv.	1%	48
5	0.45	0.0070	52.5	4.5	conv.	1%	48
6	0.40	0.0070	52.3	4.5	conv.	1%	48
7	0.40	0.0060	51.5	4.6	conv.	3%	48
8	0.40	0.0055	51.2	4.6	conv.	4%	48
9	0.40	0.0050	50.9	4.6	conv.	4%	48
10 ②	0.40	0.0050	47.0	5.0	conv.	11%	52
11 ③	0.40	0.0050	44.4	5.3	conv.	16%	55
12	0.40	0.0050	30.2	7.8	hybrid	43%	48
13 ④	0.40	0.0050	28.3	8.3	hybrid	47%	52
14 ⑤	0.40	0.0050	27.0	8.7	hybrid	49%	55

Table 19: Influence of technological measures on fuel economy on urban driving cycle

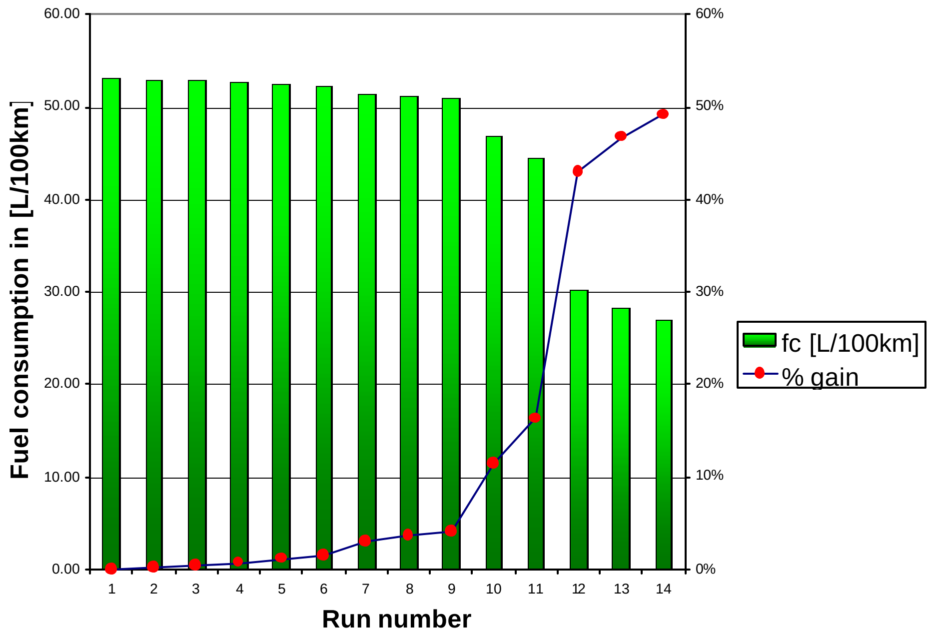

Figure 26: Fuel consumption reduction potential with considered technological measures on urban driving cycle

Vehicle	Engine peak efficiency [%]	Fuel consumption [L/100km]	Fuel economy [mpg]	Improvement [%]
Baseline diesel 2000 ①	48 (175 g/kWh)	53.1	4.4	0
Advanced diesel 2020 ②	52 (155 g/kWh)	47.0	5	11
Advanced diesel 2020 ③	55 (140 g/kWh)	44.40	5.3	16
Hybrid 2020 (parallel) ④	52 (155 g/kWh)	28.3	8.3	47
Hybrid 2020 (parallel) ⑤	55 (140 g/kWh)	27.0	8.7	49

Table 20: Fuel economy of considered vehicles in urban driving

7.3 Comparison between urban and highway driving

It can be seen in urban driving, where only low speeds are reached and accelerations are numerous, the effects of resistance reductions on fuel consumption are small. (Table 19, Figure 26) The implementation of more efficient drivetrains however, can increase fuel efficiency by a large amount. Fuel economy gains due to aerodynamics and improved tires can only attain about 4% increase, even for the most sophisticated cases. Improvements through better engines or hybrid technology can reach values of almost 50% for case ⑤. These findings show the hybrid technology potential for delivery trucks, which has also been found by other authors [17].

In the highway driving cycle, the results are somewhat contrary to the findings in urban driving. Fuel efficiency can be increased by 20% merely through reduced driving resistances, i.e. improved aerodynamics and rolling resistance of tires. Hybrid drivetrain gains are smaller than in the urban case, where a lot of stop and go driving is present. Fuel savings of about 9% can be achieved with hybrid drives compared to diesels. In comparison, for the urban case, the fuel efficiency improvement for the hybrid to the comparable diesel is much higher – 40%.

Hybridization is therefore more attractive for non-highway applications. If driving resistances are reduced, the cruise power needs drop by 30%. Hence the ICE could be downsized even further and thus give an even bigger advantage to the hybrid by increasing the ICE's efficiency while it runs at higher load.

For a fully loaded class 8 baseline truck (36,287 kg), the required engine brake power in the highway driving cycle is 268 kW (360 hp) for peak power and 152 kW (204 hp) for cruising at 97 km/h (Figure 27).

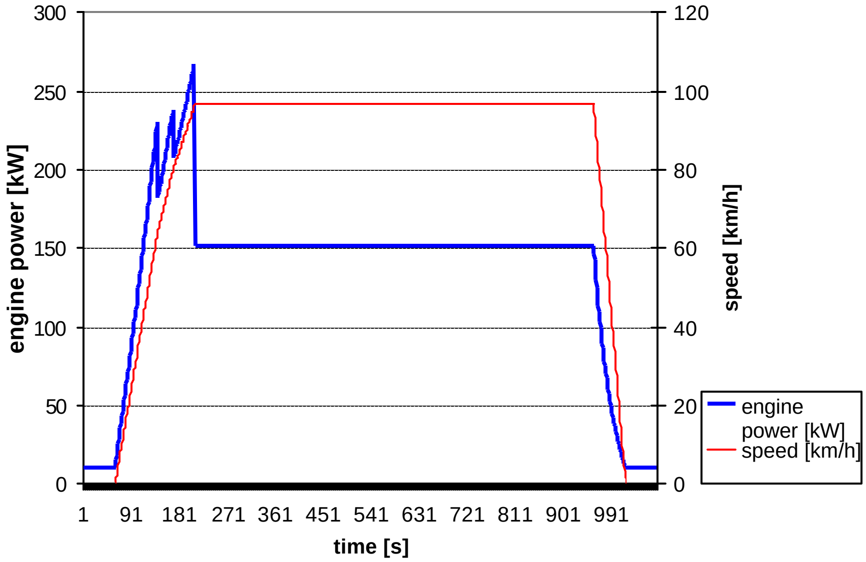

Figure 27: Required engine power for baseline truck in highway driving cycle

For the advanced truck these power requirements go down to 222 kW (298 hp) and 106 kW (142 hp) respectively (Figure 28).

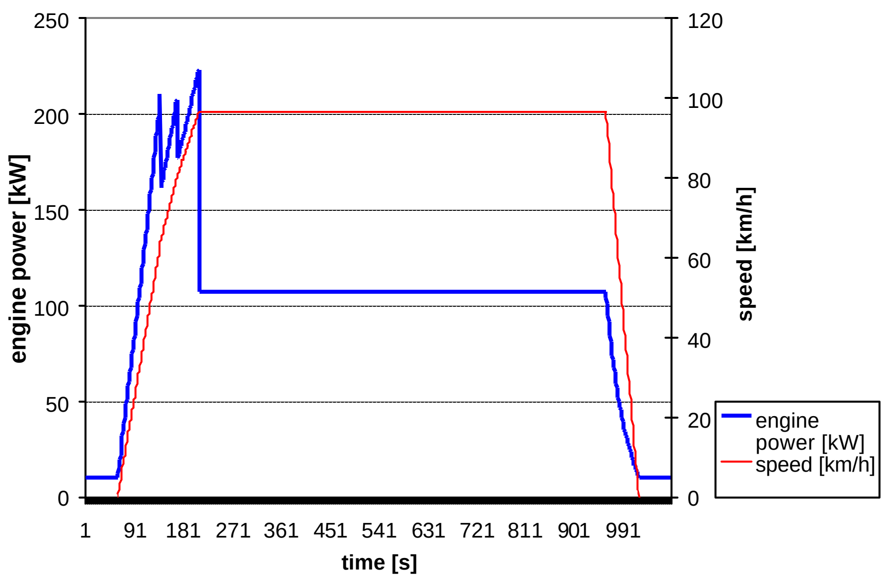

Figure 28: Required engine power for advanced truck in highway driving cycle

This is a 17% reduced power need for acceleration and a 30% reduced power need for cruising.

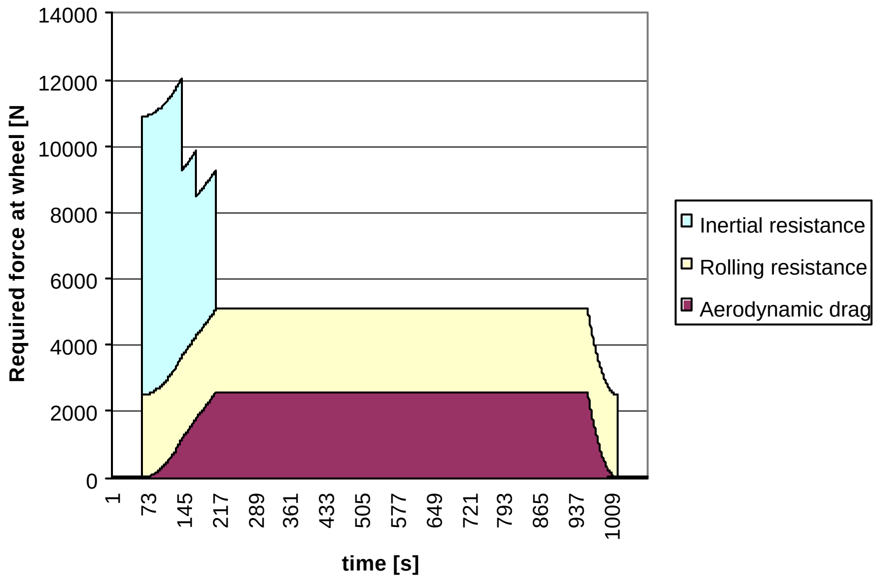

Figure 29: Resistance contributions for baseline truck in highway driving cycle

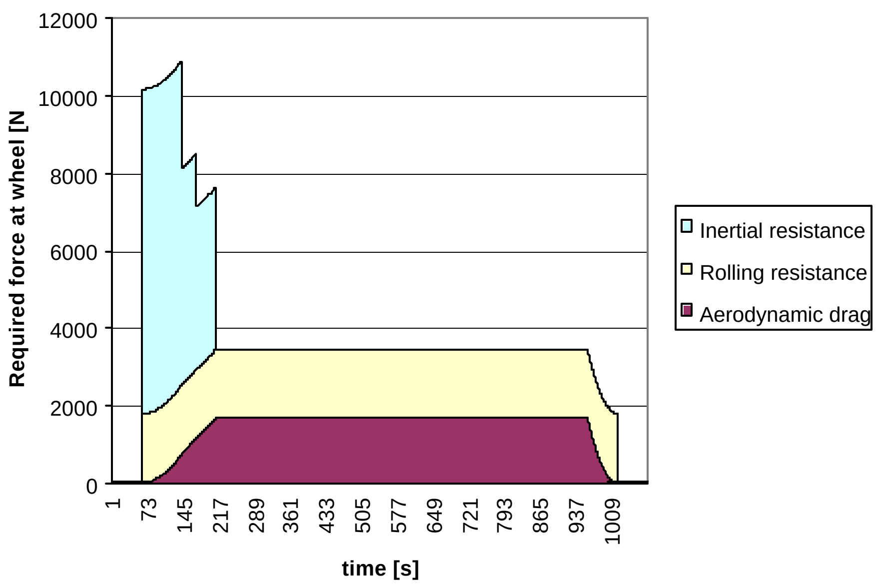

Figure 30: Resistance contributions for advanced truck in highway driving cycle

These percentages differ since the mass stays the same and, as can be seen in Figure 29 and Figure 30, the mass inertial contribution during acceleration is by far the biggest, and aerodynamic drag and rolling resistance only make up about 1/3 of the total force needed. This effect is more pronounced for the advanced case.

The baseline diesel could therefore be downsized by about 17% and the ICE of the hybrid could be downsized in power by 30% for the advanced body truck.

The influence of weight on fuel economy is considerable also for highway driving since the weight is a factor for the rolling resistance (equation 11).

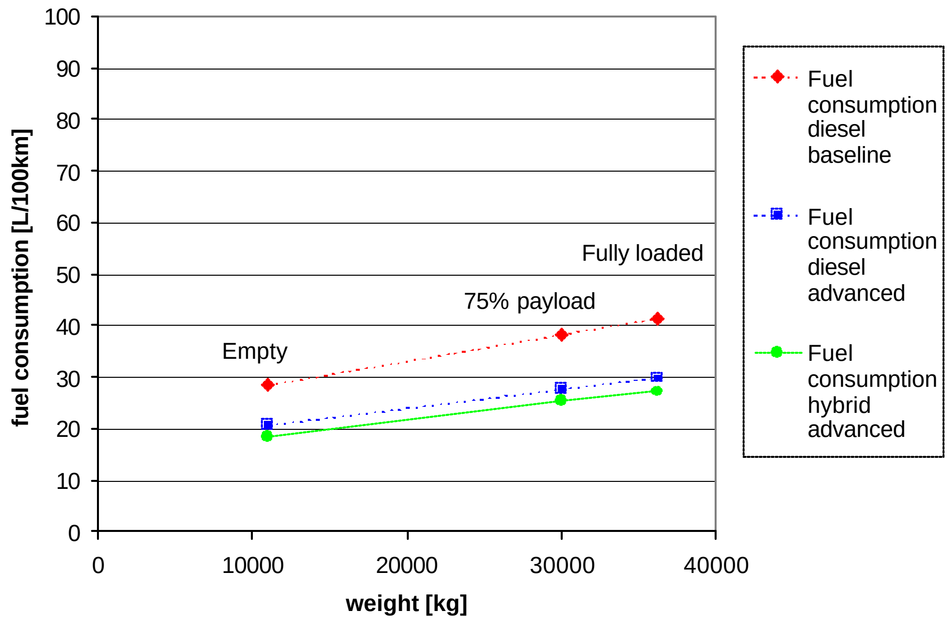

Figure 31: Influence of weight on fuel consumption (cases ①, ②, ④)

Chapter 7.4 explains more on vehicle weight of trucks.

7.4 Vehicle curb weight reduction

Mass reduction has not been investigated so far in this study. Since the payload to weight ratio is much bigger for a truck than for a passenger car, weight reductions are not as attractive. In addition truckers always try to reach the GVW in order to get the most efficient transport. Therefore weight reductions would not necessarily decrease the fuel consumption of the truck in terms of [L/100km] or [mpg], but in terms of fuel used per ton of freight transported [L/(ton*km)][41]. If iron and steel were partially replaced by aluminum, weight reductions for HDVs in the range of 15% seem possible [54]. Using magnesium may increase this number to over 20%. However, today's trucks already have a high percentage of aluminum integrated in their bodies. According to Freightliner brochures, 90 weight-% of a Century class cab is aluminum [35]. Many parts in the chassis are made of high strength steel.

If the weight were reduced by 15% on the basis of an 11,000 kg tractor-trailer combination, 1,650 kg could be saved and "turned" into increased payload capacity. Hence the payload to GVW ratio would increase from 70% to 74%. This means that in terms of fuel used per ton-km transported for a fully loaded truck, a reduction of 4.5% in fuel used per ton of payload transported would be possible according to equation (11):

$$\text{payload specific fuel consumption} = \frac{\text{fuel consumption in} \left[{}^{\text{L}}\!/\!{}_{\text{km}}\right]}{\text{payload}\left[\text{tons}\right]} \qquad (11)$$

This weight reduction would therefore give an economic advantage to a lighter truck, if it could be loaded to it's GVW. If the baseline 2000 truck with the 30,000 kg were built 1,650 kg lighter, then its weight would be 28,350 kg. On the highway cycle it would consume 37.71 $^{L}/_{100km}$ which is decrease of about 1% compared to the 30,000 kg truck. This shows that weight reductions are not as attractive for class 8 trucks as for passenger cars, where the weight influence is bigger because of the low payload to weight ratio. Nevertheless, a lower curb weight is a competition factor because of the increased payload.

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[41] In this expression the tons refer to payload

7.5 Retail price increase vs fuel economy gains

In order to present a sort of “return on investment” for increased purchase prices of advanced trucks, the possible fuel economy gains shall be plotted against the retail price increase for the respective technology. It must be differentiated between the long haul and the urban delivery application.

Prices of aerodynamic measures are estimated on the basis of current Freightliner Trucks (Century and Argosy class), where its new “Argosy” cab-over-engine type tractor was assumed to have a C_d of 0,51[42]. More advanced C_d-values down to 0.45 were estimated for an optimized trailer.

It must be stated that low C_d-values would be reachable even before 2020 and are not only restrained by technology. Cab-over-engine (COE) design is less popular for reasons such as lower resale price, concerns about decreased driver safety in case of an accident and more complicated maintenance (the cab must be tipped open to entirely reach the engine compartment). Therefore it is not only an economic evaluation that is made by truck purchasers, but more “practical” arguments are also part of the decisions involved when buying a truck. However, if vehicle length were limited by law, the COE design would get an important advantage, since it can provide shorter tractor lengths (this may be another reason, why European trucks have mostly COE design).

It can be seen that fuel consumption reductions through aerodynamic drag reductions can be achieved through moderate investments of up to 7% RPI for the conventional vehicle. If the conventional design is changed to COE design, a fuel economy gain of 7% can be reached with an investment increase of 2%.

Rolling resistance reduction can already be achieved today down to RRCs of 0.0054. However it is once again the safety issue that prevents the spread for low RRC super single tires. The latter do not have the redundancy of doubles and are therefore considered to be less safe. The increased costs for low RRC tires are also low – prices of low resistance tires are about the same as for normal tires[43]. Increasing fuel prices could in-

[42] Note that this is an estimate based on general data and not a measured value.

[43] Personal Communication, Jack McCammond Michelin, Feb. 2000

crease the prices for low RRC tires however. Hence a 0.5% RPI was assumed for the projected 0.005 RRC tire.

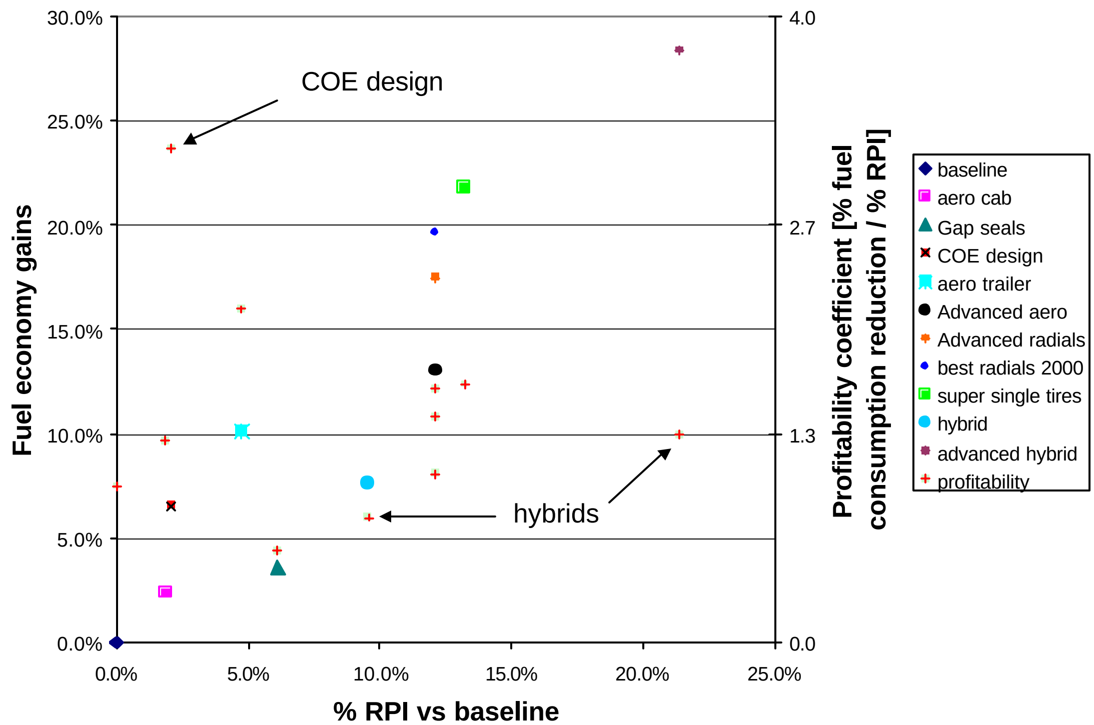

Figure 32: Fuel consumption reduction & profitability factor[44] vs % RPI of baseline vehicle in highway case

Introduction of all resistance reduction technologies can save 22% in the highway and about 4% in the urban case for the most sophisticated type of vehicle considered.

[44] See text for more explanations (section 3)

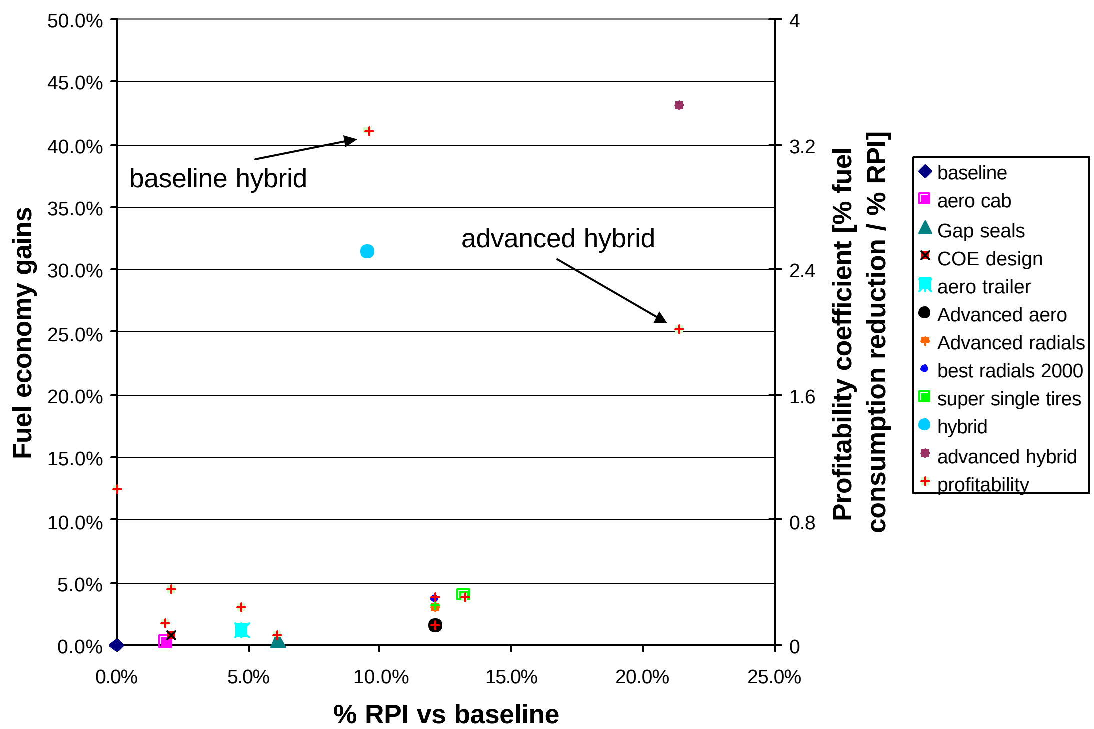

Figure 33: Fuel consumption reduction & profitability factor vs % RPI of baseline vehicle in urban case

The introduction of the hybrid technology adds some 9% price increase to the baseline vehicle. The resulting fuel savings are about 8.5% in the highway and 32% in the urban case. If the fuel consumption reductions are plotted against the corresponding RPIs, the picture is considerably different. A profitability ratio (as described in chapter 6; percentage of fuel consumption reduction compared to baseline divided by corresponding RPI percentage) represents the economic value of the investment into a certain technology. In the urban case, investments in aerodynamics and reduced rolling resistance "do not pay" and their profitability factor stays below 1. The best result is achieved with the introduction of a hybrid propulsion system into an existing baseline truck.

For the highway case, which has been defined typical for class 8 trucks, hybridization only is the worst "improvement" based on economic arguments. Money should instead be invested in measures reducing aerodynamic drag and rolling resistance.

7.6 Sources of errors and uncertainties

Several crucial characteristics are not exactly considered in the study due to simplifications for the simulation.

Simplified engine maps are used. They do not take into account that for the same torque requirement, low rpm modes are more efficient. As explained earlier, ecolomic driving can not be simulated for this reason. Implementation of precise engine maps with specific fuel consumption [g fuel/kWh] for each torque-rpm point would improve the modeling accuracy.

Tire RRCs are taken as average values, and speed dependence has not been considered due to lack of exact data. Trucks normally have different tires on drive and steer axles and on the trailer. For precise simulation these different tire types must be considered and axle load factors must be introduced. It cannot be the goal of this study to present precise data of fuel consumption, but to give an impression of possible gains for different measures.

C_d-values are well-described in the literature and therefore they present the data with lowest uncertainties. As described earlier, side wind effects are not considered and they can be of big importance for long vehicles [14]. The actual aerodynamic drag can more than double due to side wind, because the drag coefficient increases and the respective "frontal" area increases up to 26 m^2 for a vehicle of 16m in length and a wind yaw angle of 15 degrees.

8. Conclusions and proposals for further research

- This study shows that fuel efficiency improvements of heavy-duty trucks can be achieved by the three factors as described in section 2. These are resistance reductions, optimized propulsion systems and other factors such as driver skills.
- Some of the possible measures are "zero cost" and can be changed only by changing minds. The most obvious example is the idling of automatic transmissions in the "N" instead of the "D" mode. Ecolomic[45] driving is another example. Money spent on education for personnel has a very short payback time of under one year. Avoiding unnecessary idling is also a low cost means to reduce fuel consumption.
- Technological measures are larger investments. Aerodynamic drag reduction features can increase the purchase price of a vehicle by 12% for the lowest C_d of 0.4 considered in this study. As presented before, COE design can provide an aerodynamic improvement of about 12% in C_d and 7% in fuel consumption at a low RPI of 2%.
- Low resistance tires could improve fuel efficiency by 10% according to the findings of this study. Barriers to the introduction of super singles (improved single tires used for trucks) are not only higher price but safety considerations, since the redundancy of doubles is lost and therefore there is no second tire in the case of a tire blowout. However, super singles have been proven safe at present.
- Hybrid technology can improve heavy-duty truck fuel economy drastically depending on the driving cycle. For long haul highway driving this (expensive) solution could only be profitable to the purchaser if fuel prices were higher than today. With a retail price increase of $16,000 on the basis of $167,000 for the baseline vehicle, the payback period through fuel savings based on a constant fuel price of 0.4 $/L (1.5$/gal) and 100,000 km driven per year (4,000 L fuel saved per year) would be 10 years (not considering inflation and depreciation). If fuel prices are higher (in the EU for example), this number changes however, and could reach values of 4 years for fuel prices of 1$/L. Note that these assumptions are true for long haul trucking

[45] see section 5.1 for explanation

only. For delivery trucking, the hybrid configuration would be more attractive in any case. Making the same calculations with this $167,000 baseline truck and only 50000 km/year driven in an urban delivery truck, a fuel consumption reduction of 11420 L would result. With a fuel price of 0.4 $/L (1.5$/gal) the payback time would be 3.5 years, for fuel prices of 1$/L the breakeven point is reached after only 1.4 years. Diesel hybrids represent a viable alternative to conventional diesels not only regarding the vehicle itself, but also the existing fueling infrastructure.

- On the basis of the underlying knowledge, improvements in resistance reduction, especially COE design, for long haul trucks and implementation of hybrid technology for delivery trucks should be envisaged by trucking companies.
- In order to present a picture of all the propulsion technologies, further research should be performed in the area of fuel cell powered trucks, and compressed natural gas (CNG) powered Otto engines, which can provide very low NO_x emissions but have lower efficiency than the diesel. Simulation with these two propulsion technologies should be possible on the basis of the Matlab program. Thus, fuel economy behavior of FC and CNG-ICE technology in trucks could be assessed. In addition, series-type hybrids could be examined and the hybrid system optimized. In combination with the fuel cycle emissions, an overall fuel efficiency and cost “winner” might possibly be found among these technologies

9. Appendices

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9.2 Tables supporting figures shown

Table to Figure 2

Year	*Autos [trillion Btu]*	*Percent-age autos*	*Light trucks [trillion Btu]*	*Percent-age light trucks*	*Other trucks [trillion Btu]*	*Percent-age other trucks*	*Buses [trillion Btu]*	*Percent-age buses*	*Total highway [trillion Btu]*	*Total highway [EJ]*
1970	8527	73.0%	1540	13.2%	1503	12.9%	109	0.9%	11679	12.32
1971	8970	72.7%	1686	13.7%	1569	12.7%	108	0.9%	12333	13.01
1972	9547	71.9%	1895	14.3%	1722	13.0%	106	0.8%	13270	14.00
1973	9836	70.5%	2105	15.1%	1902	13.6%	109	0.8%	13952	14.72
1974	9332	69.5%	2083	15.5%	1904	14.2%	113	0.8%	13432	14.17
1975	9321	67.7%	2386	17.3%	1939	14.1%	119	0.9%	13765	14.52
1976	9844	67.3%	2605	17.8%	2046	14.0%	129	0.9%	14624	15.43
1977	9940	65.7%	2799	18.5%	2268	15.0%	132	0.9%	15139	15.97
1978	10140	64.0%	3022	19.1%	2539	16.0%	135	0.9%	15836	16.71
1979	9629	62.3%	3057	19.8%	2644	17.1%	137	0.9%	15467	16.32
1980	8798	60.4%	2976	20.4%	2651	18.2%	139	1.0%	14564	15.37
1981	8695	59.9%	2964	20.4%	2706	18.7%	143	1.0%	14508	15.31
1982	8695	60.4%	2839	19.7%	2707	18.8%	146	1.0%	14387	15.18
1983	8814	59.9%	2995	20.4%	2757	18.7%	145	1.0%	14711	15.52
1984	8857	58.8%	3202	21.3%	2846	18.9%	154	1.0%	15059	15.89
1985	8954	58.2%	3422	22.3%	2842	18.5%	161	1.0%	15379	16.22
1986	9162	57.8%	3636	22.9%	2903	18.3%	154	1.0%	15855	16.73
1987	9179	56.8%	3827	23.7%	2990	18.5%	157	1.0%	16153	17.04
1988	9180	55.5%	4096	24.7%	3117	18.8%	159	1.0%	16552	17.46
1989	9251	55.1%	4173	24.9%	3196	19.0%	163	1.0%	16783	17.71
1990	8707	52.2%	4467	26.8%	3329	20.0%	163	1.0%	16666	17.58
1991	8048	49.0%	4793	29.2%	3396	20.7%	174	1.1%	16411	17.31
1992	8188	48.3%	5134	30.3%	3460	20.4%	182	1.1%	16964	17.90
1993	8389	47.9%	5375	30.7%	3567	20.4%	192	1.1%	17523	18.49
1994	8494	47.2%	5530	30.7%	3772	21.0%	202	1.1%	17998	18.99
1995	8519	46.4%	5717	31.1%	3950	21.5%	179	1.0%	18365	19.38
1996	8622	45.9%	5936	31.6%	4033	21.5%	194	1.0%	18785	19.82
1997	8743	45.6%	6189	32.3%	4069	21.2%	184	1.0%	19185	20.24

Table to Figure 3

GVW class	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
pounds	0-6000	6001-10000	10001-14000	14001-16000	16001-19500	19501-26000	26001-33000	over 33000
year								
1977	66.0 %	17.9%	3.1%	1.3%	2.1%	3.4%	1.5%	4.6%
1982	77.8 %	11.6%	1.6%	0.9%	1.0%	2.4%	1.0%	3.8%
1987	85.4 %	6.5%	1.2%	0.5%	0.6%	1.7%	0.8%	3.3%
1992	85.4 %	7.9%	1.2%	0.5%	0.5%	1.2%	0.7%	2.8%

Table to Figure 4

GVW class (pounds)	*Number of trucks*	*Percentage of trucks*	*Average annual miles per truck*	*Average fuel economy (mi/gal)*	*Gallons of fuel use (millions)*	*Percentage of fuel use*
0-6000	37,068,163	62.61%	12,739	17.23	27,397	44.76%
6001-10000	17,519,216	29.59%	11,610	13	15,646	25.56%
10001-14000	349,301	0.59%	15,814	9.48	583	0.95%
14001-16000	127,219	0.21%	14,420	9.19	200	0.33%
16001-19500	209,158	0.35%	4,876	8.21	124	0.20%
19501-26000	1,859,529	3.14%	11,746	7.26	3,008	4.91%
26001-33000	197,985	0.33%	30,074	6.64	897	1.47%
more than 33000	1,870,183	3.16%	39,832	5.58	13,353	21.82%
Total	59,200,754	100%	13,282	10	61,208	100%

Table to Figure 10

Speed [mi/h]:	*Speed [km/h]:*	*Speed [m/s]:*	*F_B [N]*	*F_B [N]*	*F_B [N]*	*F_B [N]*	*1.5%*	*3.0%*	*4.5%*	*6.0%*
0	0	0	0	5186	10525	15865	0	0	0	0
10	16.1	4.47	0	5112	10452	15791	0	23	47	71
20	32.2	8.94	0	4891	10231	15570	0	44	91	139
25	40.25	11.175	0	4725	10065	15404	0	53	112	172
30	48.3	13.41	0	4522	9862	15202	0	61	132	204
35	56.35	15.645	0	4283	9622	14962	0	67	151	234
40	64.4	17.88	0	4006	9346	14686	0	72	167	263
45	72.45	20.115	0	3693	9033	14372	0	74	182	289
50	80.5	22.35	0	3343	8683	14022	0	75	194	313

Truck weight [lbs]:	80000
Truck weight [kg]:	36287
Frontal Area [m^2]:	10
C_D:	0.62
Grade1 [%]:	1.5%
Grade2 [%]:	3.0%
Grade3 [%]:	4.5%
Grade4 [%]:	6.0%
RRC:	0.007
Air density [kg/m^3]:	1.19
Grav. Cst [$kg*m/s^2$]:	9.81

F_{RR}: 5493.6

Needed storage capacity (batteries) for a certain downhill slope:

Speed [mi/h]:	50
Grade [%]:	6.0%
Time [min]:	2
Battery energy density [Wh/kg]:	35
Battery power density [W/kg]:	200
Percentage of energy stored [%]:	100%
Needed storage [kWh]:	10.4
Theoretical battery weight [kg]:	298.5
Battery peak power [kW]:	59.7

Table to Figure 15

rpm	*0-800*	*801-1000*	*1001-1200*	*1201-1300*	*1301-1400*	*1401-1500*	*1501-1600*	*1601-1700*	*1701-1800*	*1801-1925*	*sum*
0-10	6	0.2	0.2	0.1	0.1	4.4	0	0	0	0	11
11-20	0	0	0	0	0	1.3	0	0	0	0	1.3
21-30	0	0	0	0	0	2.6	0	0	0	0	2.6
31-40	0	0	0	0.9	0	2.1	0	0	0	0	3
41-50	0	0	0	0	0	26.9	0	0	0	0	26.9
51-60	0	0	0	0	0	40.7	0	0	0	0	40.7
61-70	0	0	0	0	0	2.7	0	0	0	0	2.7
71-80	0	0	0	0	0	2.3	0	0	0	0	2.3
81-90	0	0	0	0	0	1.3	0	0	0.1	0	1.4
91-100	0	0	0	0.1	1.5	4.5	0.4	0.6	1.1	0	8.2
Total	6	0.2	0.2	1.1	1.6	88.8	0.4	0.6	1.2	0	

Table to Figure 16

rpm	*0-800*	*801-1000*	*1001-1200*	*1201-1300*	*1301-1400*	*1401-1500*	*1501-1600*	*1601-1700*	*1701-1800*	*1801-1925*	*sum*
0-10	5.3	0.1	0.1	0.1	0.1	14.5	0	0	0	0	20.2
11-20	0	0	0	0	0	2.4	0	0	0	0	2.4
21-30	0	0	0	0	0	4.6	0	0	0	0	4.6
31-40	0	0	0	0	0	5.6	0	0	0	0	5.6
41-50	0	0	0	0	0	6.5	0	0	0	0	6.5
51-60	0	0	0	0	0	18.2	0	0	0	0	18.2
61-70	0	0	0	0	0	7.4	0	0	0	0	7.4
71-80	0	0	0	0	0	3.8	0	0	0	0	3.8
81-90	0	0	0	0	0	4.5	0	0	0	0	4.5
91-100	0	0	0	0.3	5.2	9	2.6	3.8	5.8	0.1	26.8
Total	5.3	0.1	0.1	0.4	5.3	76.5	2.6	3.8	5.8	0.1	

Truck load factors[46]

Payload percentage efficiency	*0-25%*	*25-50%*	*50-75%*	*75-100%*
Contribution	35%	11%	9%	45%

This yields an overall load efficiency of about 53% (all numbers taken as mean values)

[46] supplied by BFS

Table to Figure 31

Weight	*Fuel consumption diesel baseline*	*Fuel consumption diesel advanced*	*Fuel consumption hybrid advanced*
11000	28.31	20.56	18.37
30000	38.12	27.52	25.2
36287	41.31	29.78	27.13