TEXTE
32/2015

Future measures for fuel savings and GHG reduction of heavy-duty vehicles

Summary

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Future measures for fuel savings and GHG reduction of heavy-duty vehicles

by

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Kurzbeschreibung

Der Verkehrssektor ist heute für ca. 30 % des Endenergieverbrauchs und 20 % der Treibhausgasemissionen in Deutschland verantwortlich. Dabei hat der Straßenverkehr den größten Anteil. Schwere Nutzfahrzeuge sind heute für rund ein Viertel des Energieverbrauchs im Straßenverkehr verantwortlich. Aktuelle Prognosen erwarten auch für die Zukunft eine weitere deutliche Zunahme des Lkw-Verkehrs. Um die Energieverbrauchs- und Klimaschutzziele zu erreichen sind damit auch bei schweren Nutzfahrzeugen deutliche Minderungen des Kraftstoffverbrauchs notwendig. In der vorliegenden Studie wurden Energieeinspar- und Treibhausgasminderungspotenziale von bisher nicht serienmäßigen technologischen Effizienzmaßnahmen bei schweren Nutzfahrzeugen abgeschätzt sowie deren Kosteneffizienz zur Treibhausgasminderung untersucht.

Im ersten Arbeitsschwerpunkt wurden Potenziale zur Reduktion von Energieverbrauch und Treibhausgasemissionen ausgewählter Technologien am Antriebstrang, zur Verbesserung von Aerodynamik und Rollwiderstand sowie Optimierungen von Fahrzeuggewicht, Nebenverbrauchern und Fahrzeugregelung systematisch untersucht. Dabei wurde mit dem Simulationstool VECTO das neue Berechnungsverfahren zur CO_2-Zertifizierung von schweren Nutzfahrzeugen in der Europäischen Union eingesetzt.

Anschließend erfolgte die Analyse von mit dem Einsatz dieser Technologien verbundenen Änderungen der Fahrzeugkosten, insbesondere zusätzlicher Anschaffungskosten und möglicher Kraftstoffkosteneinsparungen. Einsparpotenziale und Kosten einzelner Technologien sowie von Maßnahmenpaketen wurden in einer Kosten-Nutzen-Matrix zusammengeführt und Auswertungen zur Potenzialhöhe und Kosteneffizienz zur Treibhausgasminderung über verschiedene Betrachtungszeiträume durchgeführt.

In einem zusätzlichen Schwerpunkt des Vorhabens wurden mögliche Maßnahmen und politische Strategien untersucht, welche die Einführung zusätzlicher treibhausgasmindernder Technologien bei schweren Nutzfahrzeugen unterstützen und ihre stärkere Verbreitung in Europa fördern können.

Abstract

The transport sector is currently responsible for approx. 30 % of final energy consumption and 20 % of greenhouse gas emissions in Germany. In this context, road transport accounts for the largest share. Heavy-duty vehicles (HDVs and buses >3.5 t GVW) account for about a quarter of the energy consumption in road transport at present. Current projections expect substantial increases of HDV transport in the future. Therefore, compliance with climate change mitigation goals and the minimisation of final energy consumption require a substantial reduction of the fuel consumption associated with heavy-duty vehicles. The objective of the present study is the estimation of energy and greenhouse gas emissions reduction potentials of technological efficiency measures that are not yet established in heavy-duty vehicles in Europe. The reduction potentials and associated costs are both identified and evaluated.

In the first work package, energy-saving and greenhouse gas reduction potentials of selected vehicle technologies in the fields of powertrain, aerodynamics, rolling resistance and optimisation of vehicle weight, engine auxiliaries and vehicle control systems were analysed. This was using VECTO the designated simulation-based approach for the standardised quantification of CO_2 emissions from heavy-duty vehicles in Europe.

The second work package included the analysis of changes in vehicle costs accompanying the use of these technologies, including primarily additional investment costs and fuel cost savings. GHG reduction potentials and cost changes of individual technologies as well as measure packages were consolidated in a cost-benefit matrix. On this basis, cost efficiency of the measures for GHG mitigation was assessed for different reference periods.

Many energy-saving and greenhouse gas-reducing technologies for heavy-duty vehicles already available on the market find limited application and are used by only a fraction of vehicle operators. In consequence, the scope of the present study included the discussion of political strategies to promote the introduction and establishment of such technologies

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1 Background and objective

The transport sector is currently responsible for approx. 30 % of final energy consumption and 20 % of greenhouse gas emissions in Germany. In this context, road transport accounts for the largest share. In recent years, road freight transport in particular has steadily increased. Transport services of heavy-duty vehicles rose by 26 % between 2000 and 2010. Heavy- duty vehicles (HDVs and buses >3.5 t GVW) account for about a quarter of the energy consumption in road transport at present. Current projections expect substantial increases of HDV transport in the future (2010 to 2030: +30 %) and distinctly slower growth for passenger cars (+10 %) [BMVI, 2014].

Compliance with climate change mitigation goals and the minimisation of final energy consumption require a substantial reduction of the fuel consumption associated with heavy-duty vehicles. The European Commission is devising strategies for the reduction of CO_2 emissions from heavy-duty vehicles in collaboration with its member states and published an initial Key Issues Paper in May 2014 [EC, 2014a]. One vital prerequisite for vehicle-related strategies is the standardised quantification of CO_2 emissions from heavy-duty vehicles. The EC is currently developing an appropriate test method. The designated simulation-based approach (VECTO) should be available for application for certain vehicle categories shortly [JRC, 2014].

The objective of the present study is the estimation of energy and greenhouse gas emissions reduction potentials of technological efficiency measures that are not yet established in heavy-duty vehicles in Europe. All calculations performed seek to comply with the EC test method. The reduction potentials and associated costs are both identified and evaluated. For this purpose,

- Important current or future efficiency technologies relevant for heavy-duty vehicles were selected;
- Technology-specific reduction potentials (energy consumption, greenhouse gas emissions) of individual technologies and their combinations were calculated with the CO_2 emission simulation tool (VECTO), the future tool for heavy-duty vehicle certification;
- An evaluation of the cost efficiency for vehicle operators as well as an analysis of specific greenhouse gas abatement costs for the selected technologies was performed;
- Existing impediments for the application of available technologies were analysed. Based on these results, political strategies for the future advance of fuel-efficient and greenhouse gas reducing technologies for heavy-duty vehicles were devised.

2 Energy saving and greenhouse gas reduction potentials

2.1 Vehicle categories under investigation

Specific reduction potentials (energy consumption and greenhouse gases) of selected technologies for heavy-duty vehicles were investigated for the following vehicle classes:

- **Semi-trailer truck 40 t**: This vehicle class is associated with about half of the overall CO_2 emissions of the commercial vehicle fleet in Europe. The simulation was carried out for both the options Long Haul Cycle and Regional Delivery Cycle.
- **Delivery truck 12 t**: At 2.6 %, the CO_2 share of this vehicle class is minor. However, the class may be seen as representative of the majority of 4x2 and 6x2 solo HDVs (approx. CO_2 share 22 %). The analyses were performed with the setting Urban Delivery Cycle.
- **City bus 18 t (rigid bus, length 12 m)**: This vehicle class is associated with 4.4 % of CO_2 emissions (including rigid and articulated buses, thus representing a minor proportion of the overall emissions. City buses are frequently purchased by public institutionsm and thus they are in the public eye, yet may be the focus of cost-cutting measures. Analyses were carried out with the City bus Urban Cycle.

There was no bias towards any manufacturer in the analyses. All vehicles in the models were based on assumptions for default vehicles equipped generic technology.

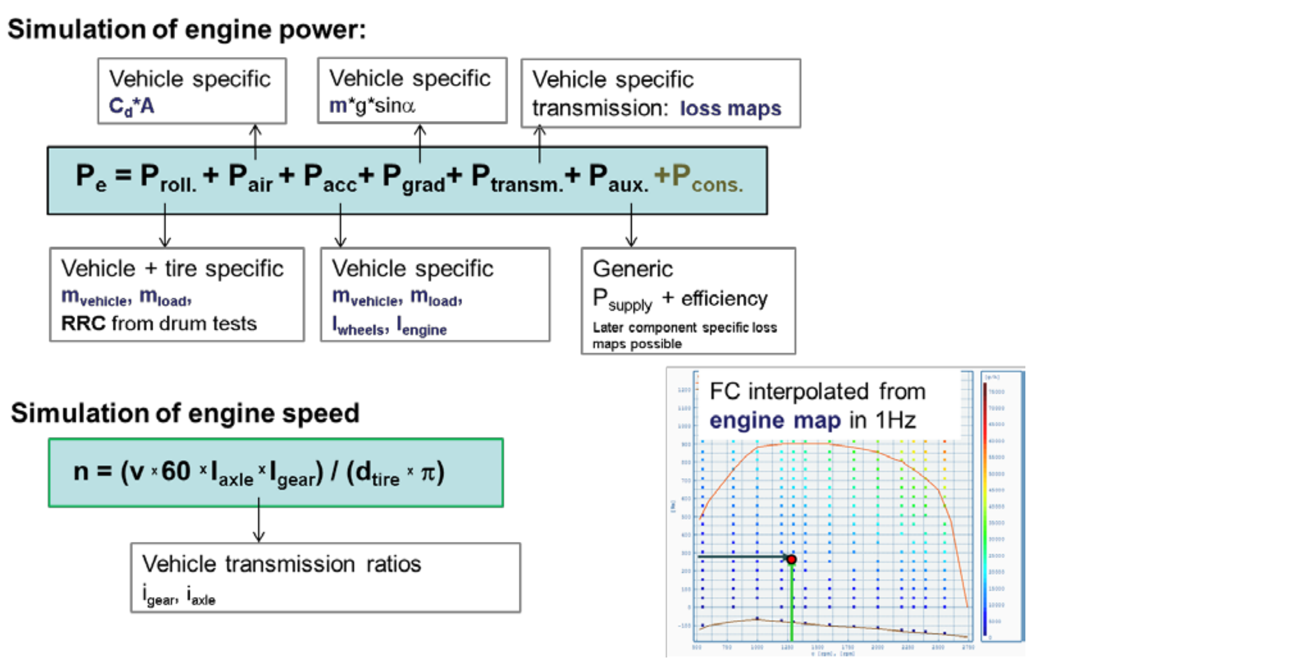
2.2 Vehicle Energy Consumption Calculation Tool (VECTO)

Due to the high number of models and variants on the heavy-duty vehicle market, the calculation of final energy consumption and direct CO_2 emissions for each individual model is both too elaborate and too expensive. For instance, there are more than 1000 different options for a 12 t delivery truck within one production series: engine size, wheel base, cabin size, type of suspension, additional tanks, air conditioning, speed control etc. may all be combined practically at random from a modular system. For these reasons, the European Commission in collaboration with the OEMs chose an approach that first tested all individual components separately. The total consumption of the vehicle then follows from the individual component test data. The simulation programme developed for the impending European CO_2 certification of heavy-duty vehicles is VECTO. Amongst others, the following input data

- engine fuel consumption map, gearbox loss map, curb weight, air drag coefficient, rolling resistance coefficient of the tyres according to EC 1222/2009, power consumption of engine auxiliaries (e.g. fan, compressor, alternator, steering pump, air conditioning), gear ratios gearbox and axle differential

are quantified with standardised methodology. Thus, energy consumption and direct CO_2 emissions of the respective vehicle model with an average load are simulated assuming standardised target speed cycles. An overview of the calculations scheme in VECTO may be found in the following figure.

Figure 1 Calculation of VECTO to determine the engine operation point and to interpolate the fuel consumption



[TU Graz, 2014]

C_d - Air drag coefficient, A - cross sectional area, m - vehicle mass, g - gravitational acceleration 9.81 m/s^2,α - road gradient angle, P_e - engine power, P_{roll} - rolling resistance power at wheels, P_{air} - air drag power at wheels, P_{acc} - acceleration power at wheels, P_{grad} - wheel power due to grade resistance, P_{trans} - power loss in drivetrain due to gearbox friction, P_{aux} - power consumption of auxiliary consumers, P_{cons} - power consumption at crankshaft of power take off (e. g. hydraulic pumps for waste presses, cranes ..., actual not depicted), $m_{vehicle}$ - vehicle curb weight, m_{load} - payload, RRC - rolling resistance coefficient of tires, I_{wheels} - rotational inertia of wheels, I_{engine} - rotational inertia of engine, P_{supply} - useful power output of auxiliaries, e. g. pressurized air, electrical power ..., n - engine speed, v - vehicle velocity, I_{axle} - axle ratio, I_{gear} - gearbox ratio, d_{tire} - dynamic tire diameter, FC - fuel consumption

2.3 Selection of energy-saving and greenhouse gas-reducing technologies

An elaborate literature search was performed to identify individual technologies that may already be available, or ready for market introduction in the coming years, yet not currently included in the European standard set of technologies applied in the relevant vehicle categories.

Based on the results of the literature survey, a selection of technologies for the different areas of application (powertrain, aerodynamics, rolling resistance, optimisation of vehicle weight, engine auxiliaries and vehicle control systems) was chosen for both in-depth potential analyses with VECTO and cost efficiency analyses. In this context, different technologies were selected for the respective vehicle categories, depending on the configuration of the reference vehicles and the availability and relevance of the individual technology for the specified mission profile (e.g. long-haul transport, urban delivery).

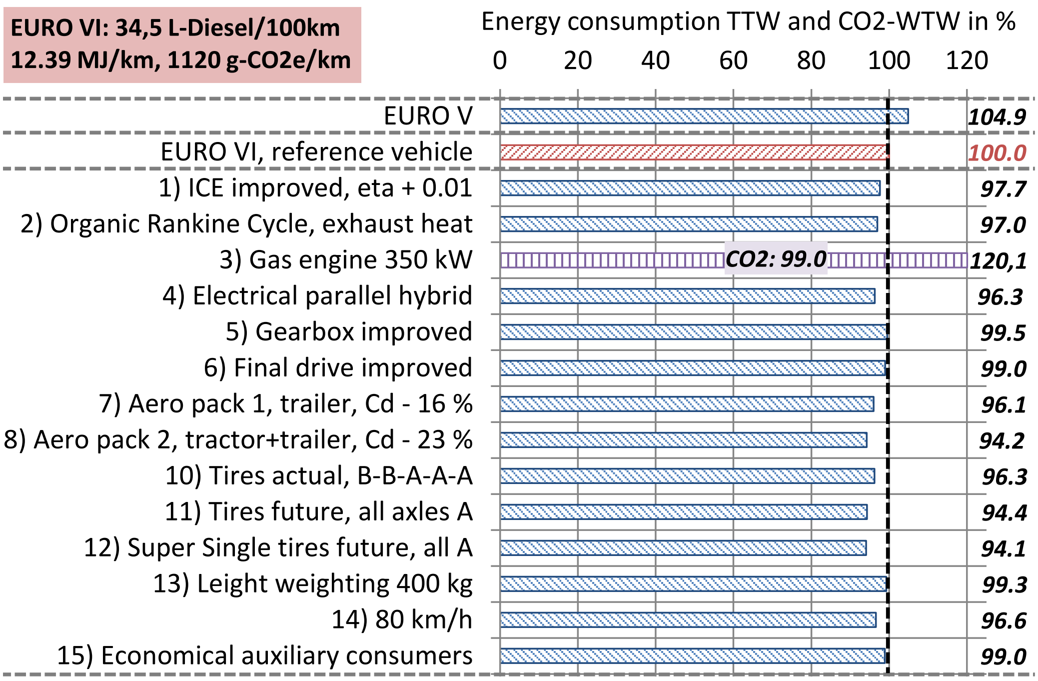
2.4 Energy-saving and greenhouse gas potentials of the technologies

The modelling process for the selected technological measures involved the simulation of standardised comparable final energy savings potentials based on current reference vehicle data (state of the art EURO V and EURO VI). The input data for the simulation of the energy consumption of reference vehicles and the potentials of energy saving measures were derived from own measurement data, industry data, generic standard data for VECTO from the industry, technical data sheets, product catalogues and expert consultation.

The final energy consumption potentials for most measures were directly simulated with VECTO. The options exhaust heat recovery (Organic Rankine Cycle - ORC), electric hybrid vehicles, battery-electric vehicles and start-stop-automatic were modelled with post-processing as these features were not (yet) available in the employed version of VECTO. Based on the final energy consumption levels, greenhouse gas reduction potentials in CO_2 equivalents (CO_2e) were calculated including the well-to-tank processes of fuel production and distribution. Well-to-wheel emission factors were applied according to DIN EN 16258 and [JEC, 2014].

The specific fuel-saving measures for the semi-trailer truck and the results of the Long Haul Cycle may be found in Figure 2.

Figure 2 semi-trailer truck on long haul cycle, single measures



The bars in the figure show the changed final energy consumption. Differing changes of GHG emissions (CO_2e wtw) for measures with alternative energy carriers instead of diesel are indicated separately.

The assumptions for the reference truck included tyre fuel-efficiency classes B-C-BBB and an aerodynamically non-optimised trailer. The simulation reveals that the measures available for immediate implementation

- 7) aero pack trailer (side- and underbody panels with boat tail 0.5 m)
- 10) best tyres on the market (B-B-AAA)
- 14) speed limiter of 80 km/h

would allow savings of approx. 10 % in comparison with the reference vehicle EURO VI.

The saving potential of the parallel hybrid is not primarily dependent on the structure of the powertrain (parallel or serial), but on the maximum generator power of the electrical machine (cf. Chapter 2.4.3.2).

In addition, selected single measures were combined into efficiency packages:

- **Efficiency Package A:** All measures proposed in this package are readily available on the market (state of the art mid 2014) and could in principle be implemented immediately.
- **Efficiency Package B:** In all likelihood, these measures will be technologically feasible in the foreseeable future. Development of components not yet available on the market is under way and market introduction is expected to be complete at the end of the current decade. In the case of the aero packages 2 for trucks, a change of EU legislation is necessary to accommodate vehicle length and rear view cameras.

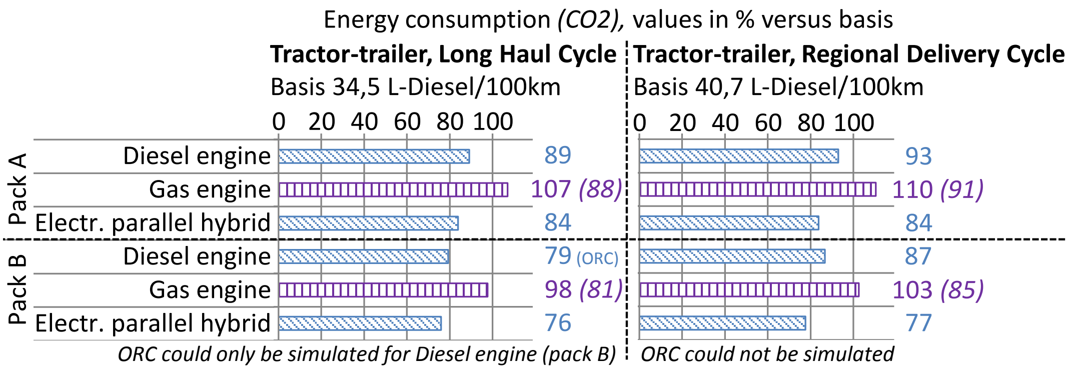
Appropriate efficiency packages were compiled for each of the drive concepts under investigation (diesel, gas, electric hybrid, battery-electric) in the relevant vehicle classes.

For the **semi-trailer truck 40 t,** packages for diesel, gas and parallel hybrid vehicles were defined:

- Efficiency Package A consists of single measures: 7) aero package 1 trailer, 10) best tyres on the market, 14) speed limiter 80 km/h, 15) efficient engine auxiliaries.
- In Efficiency Package B, the additional measures detailed in Figure 2 were included. (ORC could only be simulated for the diesel engine assuming the Long Haul Cycle).

The reduction potentials of the packages of measures are illustrated in Figure 3. Assuming state of the art technology (Package A), the semi-trailer truck could potentially achieve savings of up to 16 % of fuel consumption and greenhouse gas emissions. With a dedicated diesel powertrain, savings of approx. 11 % on the Long Haul Cycle are possible. The final energy consumption of the natural gas engine (LNG-tank) with a similar level of technology is approx. 7 % higher due to the lower energy conversion efficiency of this engine concept. However, the greenhouse gas emissions in this case are reduced by 12 % due to the lower emission factor of the fuel (75 vs. 90 g CO_2e/MJ_{therm} well-to-wheel, see [JEC, 2014]). For the parallel hybrid, the reduction potential with Efficiency Package A amounts to approx. 16 %.

Figure 3 semi-trailer truck on Long Haul and Regional Delivery Cycle, measure packages



The bars in the figure show the changed final energy consumption. Differing changes of GHG emissions (CO_2e wtw) for measures with alternative energy carriers instead of diesel are indicated separately.

The reduction potentials associated with the future Efficiency Package B are as follows: diesel engine (with ORC) approx. 21 % energy and greenhouse gas savings, a gas engine (without ORC) ca. 2 % energy and ca. 19 % greenhouse gases, and parallel hybrid (without ORC) approx. 24 %.

The semi-trailer truck model was also simulated on the Regional Delivery Cycle, without ORC, because its behaviour could not be calculated reliably due to the non-stationary engine operation. All reduction potentials are slightly lower in comparison with the Long Haul Cycle. One reason is the lower average speed of the Regional Delivery Cycle (58.6 km/h) in comparison with the Long Haul Cycle (73.2 km/h). Thus, the effect of the aerodynamic add-ons, which are particularly effective at high vehicle speeds, is attenuated.

The potentials of the Efficiency Packages A and B for delivery trucks and city buses are shown in Figure 4.

The investigated vehicle class **delivery truck 12 t GVW** is representative for rigid trucks from 7.5 t to 18 t. In addition to the diesel engine, gas engine with CNG tank (68 g CO_2e/MJ, see DIN EN 16258) and diesel engine with electric parallel hybrid, the measure packages were also modelled for a battery-electric vehicle.

- Efficiency Package A: aerodynamic improvement by partial fairings and a short boat tail of 0.5 m, current energy efficient tyres (B-D, reference vehicle C-D), start-stop-automatic, speed limiter 80 km/h, efficient auxiliary consumers.
- Additional measures of Efficiency Package B: improved engine efficiency, reduced gearbox and axle losses, rear view cameras, future energy efficient tires (A-A), light weighting 200 kg, LED headlights.

For HDVs with combustion engines, the measures detailed in Package A could achieve savings of 8 % fuel and greenhouse gases in dedicated diesel engines, whereas the savings of the parallel hybrid amount to 15 % in comparison with the reference vehicle EURO VI. The use of gas engines increases the energy consumption by 9 %, yet the emissions decrease by approx. 18 %.

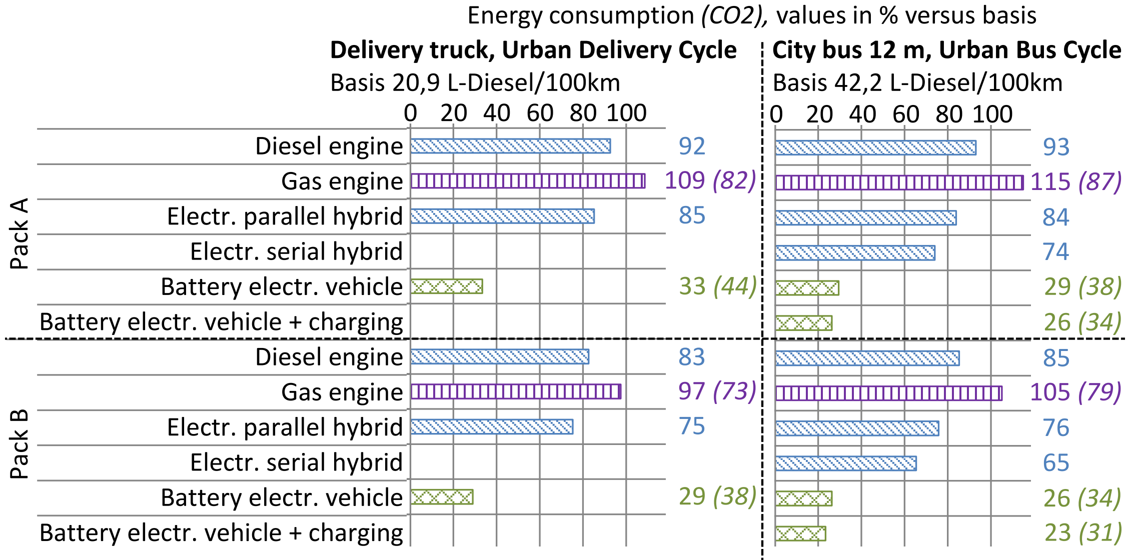
Substantially higher reduction potentials are associated with battery-electric engines, i.e. 67 % reduction of final energy consumption and 56 % greenhouse gas savings. The fundamental advantage of electric engines over combustion engines is revealed here. The conversion of fuel into kinetic energy in combustion engines is associated with process-related losses of 50 to 65 %, whereas the energy conversion efficiency of electric engines frequently exceeds 90 %. Thus, the final energy demand for the same kinetic energy is substantially lower. However, there are losses during conversion in the power plant depending on the electricity supply pathway (coal, gas, nuclear, wind, hydro, solar). The average greenhouse gas emission factor per final energy of 118 g CO_2e/MJ_{el} applied here (electricity mix of the EU27 member states according to DIN EN 16258) is distinctly higher than those of diesel or natural gas. Nonetheless, the approximately doubled conversion efficiency of electric engines in reference to combustion engines, as well as the option of energy recovery (regenerative brakes in vehicles), allows the saving of substantial quantities of greenhouse gases.

Implementation of the future measures of Package B further increases savings potentials. The GHG savings of thus improved diesel trucks amount to approx.17 %, whereas gas engines could save approx. 27 %. The electric parallel hybrid concept achieves a reduction of final energy and emissions of approx. 25 %, the savings of the battery-electric HDV amount to approx. 71 % final energy and approx. 62 % greenhouse gases.

For the **City bus 18 t (length 12 m)**, in addition to the HDV powertrains above (gas engine with CNG tank), the drive concepts electrical serial hybrid and battery-electric vehicle with intermediate charging were included in the analysis. In the case of the battery-electric bus with intermediate charging, the size of the battery was assumed to be substantially smaller than that of a dedicated battery-electric bus (cost and weight aspects). The charge of the smaller battery is sufficient to complete one run of a bus line (recharge is required at each final stop, i.e. twice per cycle, for approx. 10 minutes).

- Efficiency Package A consists of single measures: current energy efficient tyres (C-C, reference vehicle D-D), start-stop automatic, efficient auxiliary consumers;
- Additional measures of Package B: improved engine efficiency, reduced axle losses, future energy-efficient tyres (A-A), lightweighting 350 kg, LED headlights, partly insulated passenger compartment.

Figure 4 Delivery truck and city bus, measure packages



The bars in the figure show the changed final energy consumption. Differing changes of GHG emissions (CO_2e wtw) for measures with alternative energy carriers instead of diesel are indicated separately.

For the city bus, the measures of Efficiency Package A achieve savings of approx. 7 % energy and greenhouse gases for a conventional diesel engine. With a natural gas engine, the final energy demand is approx. 15 % higher, yet the greenhouse gas emissions are approx. 13 % lower. In comparison with the EURO VI reference bus, the hybrid drivetrains with implementation of Package A offer a reduction potential of approx. 16 % for a parallel hybrids and approx. 26 % for serial hybrids. The higher saving potential of the serial hybrid primarily results from the bigger electrical machine of the selected vehicle model, and *not* from differences in the powertrain structure, for further details see chapter 2.4.3.2. Overall, the reduction potentials for final energy and greenhouse gas emissions of the city bus reflect those of the delivery truck with the most substantial savings achieved by dedicated electric vehicles. The reduction potential of the battery bus without intermediate charge is slightly lower due to the increased vehicle weight in reference to the bus with frequent intermediate charge.

Implementation of the additional technologies summarised in Efficiency Package B is likely to result in further final energy and greenhouse gas savings for all drive concepts (see Figure 4). Both hybrid and electric buses are going to benefit from the decreased rolling resistance of future tyres due to the fact that these tyres will exert less of a ‘braking effect’, thus allowing improved energy recovery with regenerative brakes.

In conclusion, the analyses of reduction potentials reveal that the implementation of current technologies summarised in Efficiency Package A could achieve greenhouse gas reductions of 7 % to 11 % for dedicated diesel vehicles, depending on the vehicle category. The savings of hybrid vehicles range from 14 % (semi-trailer truck) to over 26 % (city bus). Vehicles with natural gas engines are associated with an increase of final energy consumption in comparison with the EURO VI reference vehicles, however, greenhouse gas emissions decrease by 13 to 19 %. Additional technologies that are feasible and will be available in the foreseeable future could reduce greenhouse gas emission by an additional 6 to 10 % depending on vehicle category, mission profile and powertrain. At present, the use of dedicated battery-electric vehicles could already cut greenhouse gas emissions (well-to-wheel) by half. With the additional implementation of soon-to-be-available technologies, greenhouse gas savings on 60 % to 79 % assuming the current average electricity mix of the EU27 member states are possible.

3 Costs of the investigated efficiency measures for the reduction of greenhouse gases

Among the key factors for the implementation of energy-efficient and greenhouse gas-saving technologies is the cost efficiency of the proposed measures. Thus, the analysis of vehicle cost differences is a pivotal aspect of the evaluation of the technologies under investigation.

- The use of novel technologies is only economically beneficial for the vehicle operators if the additional costs associated with technology implementation do not exceed the resulting fuel cost savings.
- From a socio-economic perspective, the question of currently feasible and future expected greenhouse gas savings and their associated costs arises.

In consequence, the single technologies investigated in the present study were subject to an analysis of business economics and GHG abatement costs. In addition, marginal abatement cost curves (MAC curves) and cumulative savings costs were estimated for the packages of efficiency measures proposed here.

3.1 Additional technology-specific costs for vehicle operators

The cost analysis estimated the level of current additional investment costs for the purchase of a vehicle equipped with the investigated additional fuel-saving technologies. The calculations were based on published information on pricing of technology measures already available on the market, e.g. manufacturer price lists and relevant technical journals.

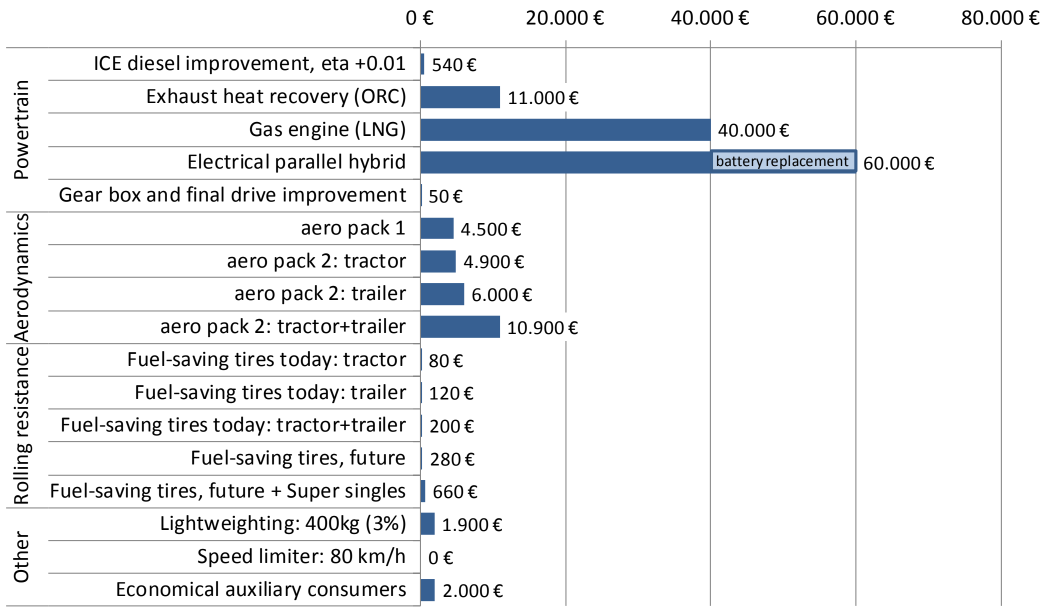
In the case of a **semi-trailer truck 40 t** GVW (see Figure 5), the average investment costs for the selected efficiency technologies range between 0 and approx. 60 000 €. In consequence, the total investment costs for the purchase of a tractor-trailer may increase by more than 50 %.

- A speed limiter restricting the vehicle speed to 80 km/h is not associated with any additional costs. The application of low rolling resistance tyres and measures for the optimisation of axle and transmission losses will not exceed 1000 € per vehicle.
- The costs for optimisation of aerodynamics and engine auxiliaries as well as limited lightweight retrofitting (curb weight reduction of 3 %) range between 2 000 and 8 000 €. The costs for exhaust heat recovery via ORC were estimated to result in additional average costs of 11 000 €.
- The most expensive measure is the purchase of vehicles with alternative drive concepts. Trucks with natural gas engines and LNG tanks are available on the market today. In contrast, no hybrid semi-trailer trucks are currently available on the market. The reported additional investment costs thus represent an estimate for the price upon market introduction, which could be substantially reduced in the future.

For **delivery trucks with 12 t** GVW, the additional investment costs for the selected technology packages currently range between 0 € (speed limiter) and approx. 25 000 € (parallel hybrid, not including extra costs for battery replacement). The battery-electric delivery truck represents an exception; the cost is tripled in reference to a diesel HDV.

A similar picture emerges for the **city bus with 18 t** GVW. In this case, the additional investment costs for the single optimisation measures under investigation range between averages of 300 to 4 000 €. However, investing in vehicles with alternative drive concepts is substantially more expensive. The additional costs for the purchase of a natural gas-fuelled bus amount to an average of 34 000 €, whereas a hybrid bus exceeds the cost of the reference vehicle by 70 000 to 100 000 €. The most expensive option is the battery-electric bus. Based on pricing for battery-electric buses sold in Germany, the current surcharge in reference to a diesel bus was calculated to range between 100 000 to 400 000 € independent of differences between dedicated battery-electric buses or models with intermediate charge option (overhead wire, induction).

Figure 5 Additional investment costs per vehicle – semi-trailer truck 40 t



The application of energy-efficient technologies may also affect a number of variable vehicle costs. In the context of some efficiency measures, the mileage-dependent additional costs may distinctly exceed the immediate additional investment costs. In consequence, the following mileage-dependent variable differences in vehicle costs were included in the cost analyses:

- Changes in the urea consumption for SCR facilities (improvement of diesel engine energy conversion efficiency, natural gas vehicle),
- Oil changes (low-friction oil for the improvement of the energy conversion efficiency of diesel engines, minimisation of axle and transmission losses),
- Tyre changes (energy-efficient tyres) as well as
- Increased maintenance costs (natural gas vehicles).

3.2 Changes to the overall vehicle costs with implementation of the measures

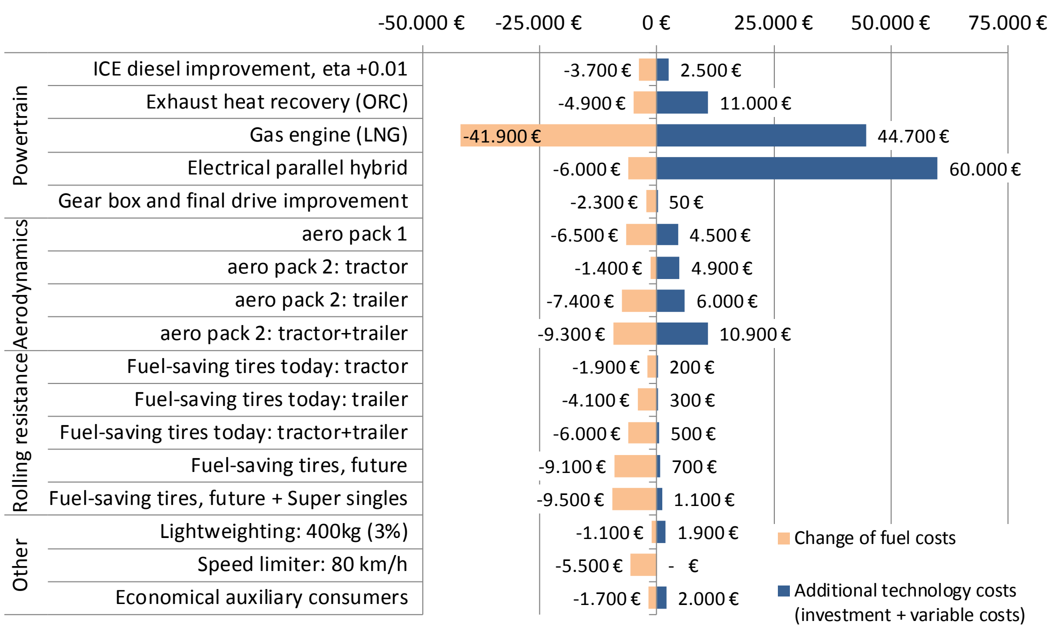
The analysed technological measures will not pay off from an economic point of view unless the technology-dependent fuel cost savings exceed the additional costs incurred through the technology application. Based on the energy savings potentials of the proposed measures for vehicles with medium annual mileage (per mission profile), a comparison between potential fuel cost savings and technology-specific additional costs was carried out assuming current fuel prices. Many vehicle operators, especially in long-haul transport strive for amortisation of additional vehicle technologies within a maximum of three years. In line with this, the comparison of fuel cost savings and additional costs in the present study applied the same time period. However, in other mission profiles (e.g. urban passenger transport) varying payback expectations are possible. Hence, in a second step, the question was reversed to examine the payback period, i.e. the time it would take for the measures to achieve full amortisation assuming current additional costs and constant fuel prices.

Semi-trailer trucks 40 t GVW are primarily operated in multi-day long-haul transport. However, vehicles of that size class are also frequently or even predominantly employed in regional delivery. In consequence, the present study examined both mission profiles. Figure 6 illustrates the results of the cost analysis for the long-haul transport. Many technologies are able to achieve fuel cost savings that exceed the additional investment into their implementation within the initial three years. This applies for measures with very low investment costs in particular. In contrast, the additional costs for alternative drive concepts (LNG, parallel hybrid), exhaust heat recovery, lightweighting and optimisation of engine auxiliaries are higher than the fuel cost savings achieved over the period of three years. In long-haul transport, the length of the payback period ranges between three to four years (LNG vehicle, engine auxiliaries) to about 30 years for the parallel hybrid. The payback periods for a truck regional delivery transport are generally longer in comparison with long-haul transport due to lower annual mileage.

For **delivery trucks 12 t** GVW, the potentials for fuel cost savings are distinctly lower in comparison with the tractor-trailer due to lower specific potentials and lower annual mileage. Most of the measures under investigation yield cost savings below 1000 € during the initial three years. Only alternative drive concepts (CNG, parallel hybrid, battery-electric) and tyres of efficiency category A were associated with higher savings. The highest energy costs savings of about 15,000 € within three years were achieved by the battery-electric delivery truck. Low-friction oil and low rolling resistance tyres will achieve amortisation within the first year, whereas the length of the payback period of diesel engine optimisation measures, vehicle regulation and the purchase of CNG trucks ranges between three and four years. The length of the payback period of all remaining measures distinctly exceeds ten years with current costs. Due to high additional investment costs, the payback periods of hybrid and battery-electric vehicles exceed the regular vehicle service life.

In the case of the **city bus 18 t** GVW, low rolling resistance tyres, optimisation measures for diesel engine energy conversion efficiency and axle losses all have a payback period of about one year. A 3 % reduction of curb weight is going to pay off after three year. Moreover, the optimisation of engine auxiliaries breaks even in less than five years. The use of natural gas buses also pays off within five years, as long as there is no need for additional supply infrastructure and the current energy tax benefits remain in place. In contrast, assuming current conditions, both hybrid and battery-electric buses are associated with higher additional investment costs than may be saved through reduced energy costs over the average service life. Only for battery-electric buses with intermediate charge, a payback within regular vehicle service life seems possible with current additional investment costs.

Figure 6 Change in costs per vehicle in the first 3 years (semi-trailer truck long-haul)



With increasing production, the production costs of alternative drive technologies are expected to fall due to learning and optimisation of production processes, thus resulting in lower investment costs for vehicle purchase. Simultaneously, current scenarios expect fuel prices to rise in the future due to inflation. An additional analysis was carried out to examine the effects of future learning resulting in optimised production and rising fuel prices on the overall cost efficiency of hybrid and battery-electric vehicles, thus influencing the length of future payback periods. Two scenarios modelled the reduction of additional investment costs by an annual rate of 5 and 10 %, respectively, while simultaneously assuming an annual increase of fuel and electricity prices driven by inflation of 2 %. For parallel-hybrid vehicles additional the case was analysed if future battery generations have a better durability and no battery replacement is required anymore within regular vehicle service life. The following table illustrates the changes in payback periods in the scenarios in comparison with current conditions.

A semi-trailer truck 40 t with parallel hybrid technology will not become economically viable in long-haul transport even with a reduction of additional investment costs by more than 60 % - unless an additional battery replacement can be avoided with future battery generations of longer durability. In regional delivery, a parallel hybrid semi-trailer truck could pay off within regular vehicle service life also including battery replacement. Also a delivery truck 12 t with parallel-hybrid or battery-electric technology could pay off in future with assumed strong reductions of additional investment costs – however still having payback periods beyond typical short-term expectations of vehicle operators. Urban buses with hybrid or electric technology could become economically viable in case of assumed cost reductions within 7-11 years (scenario A) resp. 4-6 years (scenario B) compared to a regular diesel bus. Electric buses with intermediate charge could pay off even one or two years earlier. According to the scenario results, hybrid and electric heavy-duty vehicles could become economically viable in future and generate cost savings for the vehicle operators. Indeed, this will only be achieved in case of substantial reductions of additional investment costs for such vehicles with alternative powertrain technologies.

Table 1 Average payback periods of hybrid and electric vehicles in different scenarios

Average payback periods in years			with today‘s costs	with future costs in 10 years	
				scenario A	scenario B
Semi-trailer truck 40 t long-haul	parallel hybrid	- with battery replacement	30.0	15.0	8.8
		- without battery replacement		10.0	5.8
Semi-trailer truck 40 t regional delivery	parallel hybrid	- with battery replacement	27.2	13.6	7.9
		- without battery replacement		9.1	5.3
Delivery truck 12 t	parallel hybrid	- with battery replacement	40.2	20.1	11.7
		- without battery replacement		14.4	8.4
	electric		25.7	12.8	7.5
Urban bus 18 t	parallel hybrid	- with battery replacement	22.0	11.0	6.4
		- without battery replacement		8.5	5.0
	serial hybrid		14.8	7.4	4.3
	electric		14.4	7.2	4.2
	electric with intermediate charge		10.7	5.3	3.1

Legend of payback periods	≤3 years	>3-6 years	>6 years, but within vehicle service life	Not within vehicle service life

3.3 Cost efficiency of the technological measures for GHG reduction

Greenhouse gas abatement costs are defined as the costs that allow the reduction of greenhouse gas emissions by 1 ton of CO_2 equivalents (€/ton CO_2e). In this way, a comparison of the cost efficiencies of different measures in transport, but also of measures and approaches in other areas is possible. The specific greenhouse gas reduction costs of vehicle-related measures is calculated from the quotient of the difference in vehicle costs divided by the overall achievable greenhouse gas reductions in a defined period of time.

Longer periods of time and thus, higher mileages, are associated with higher greenhouse gas reductions per vehicle and higher fuel cost savings.

$$GHG\ abatement\ costs\ \left(\frac{€}{tons\ CO2e}\right) = \frac{[additional\ technology\ costs\ (€)] - [fuel\ costs\ savings\ (€)]}{[GHG\ emission\ reduction\ (tons\ CO2e)]}$$

From a socio-economic perspective, the entire vehicle service life is relevant. In contrast, vehicle operators assess cost efficiency of technologies in reference to the period of use in their businesses and expectations towards the payback period on the additional investments. For these reasons, the calculation of specific greenhouse gas abatement costs for the measures included several different reference periods.

Single technological measures

The following figure exemplifies the greenhouse gas reduction measures for the semi-trailer truck 40 t in long-haul transport sorted according to their GHG abatement cost efficiency. The specific abatement costs range between -4 800 up to +3 300 €/t CO_2e. In the three-year assessment, the abatement costs are higher compared to an assessment based on the average vehicle service life of about eight years. Over three years, a number of measures cause additional costs although their specific GHG abatement costs are negative over longer periods of time. In fact, 10 out of 17 measures are associated with negative abatement costs over a period of three years. This number rises to 14 measures over a period of six years and totals at 15 measures with negative abatement costs over the entire vehicle service life.

Figure 7 Specific GHG abatement costs of technological measures for a semi-trailer truck in long-haul transport depending on the reference period

	3 years	Euro / t CO2e	6 years	Euro / t CO2e	vehicle service life (8 years)	Euro / t CO2e
1	Speed limiter 80 km/h	-370 €	Gas engine (LNG)	-3.756 €	Gas engine (LNG)	-4.849 €
2	Gearbox and final drive improved	-363 €	Speed limiter 80 km/h	-370 €	Speed limiter 80 km/h	-370 €
3	Fuel-saving tyres today: trailer	-342 €	Gearbox and final drive improved	-363 €	Gearbox and final drive improved	-363 €
4	Fuel-saving tyres future	-341 €	Fuel-saving tyres today: trailer	-342 €	Fuel-saving tyres today: trailer	-342 €
5	Fuel-saving tyres today: all axles	-338 €	Fuel-saving tyres future	-341 €	Fuel-saving tyres future	-341 €
6	Fuel-saving tyres today: tractor	-329 €	Fuel-saving tyres today: all axles	-338 €	Fuel-saving tyres today: all axles	-338 €
7	Fuel-saving tyres future + supersingles	-327 €	Fuel-saving tyres future + supersingles	-335 €	Fuel-saving tyres future + supersingles	-336 €
8	ICE diesel improved	-124 €	Fuel-saving tyres today: tractor	-329 €	Fuel-saving tyres today: tractor	-329 €
9	Aero pack 1	-115 €	Aero pack 1	-243 €	Aero pack 1	-275 €
10	Aero pack 2: trailer	-70 €	Aero pack 2: trailer	-220 €	Aero pack 2: trailer	-258 €
11	Aero pack 2: tractor+trailer	66 €	Aero pack 2: tractor+trailer	-152 €	Aero pack 2: tractor+trailer	-207 €
12	Economical auxiliary consumers	66 €	Economical auxiliary consumers	-152 €	Economical auxiliary consumers	-207 €
13	Lightweighting	276 €	ICE diesel improved	-147 €	ICE diesel improved	-153 €
14	Exhaust heat recovery with ORC	467 €	Lightweighting	-47 €	Lightweighting	-128 €
15	Gas engine (LNG)	617 €	Exhaust heat recovery with ORC	48 €	Exhaust heat recovery with ORC	-57 €
16	Aero pack 2: tractor	946 €	Aero pack 2: tractor	288 €	Aero pack 2: tractor	123 €
17	Electric parallel hybrid	3.340 €	Electric parallel hybrid	1.485 €	Electric parallel hybrid	1.021 €

The order of measures also changes according to the length of the reference period. For instance, the LNG semi-trailer truck is associated with positive GHG abatement costs in the first three years due to the high initial investment. In consequence, its rank is 15 out of 17. However, if the reference period is extended to six years, the reduction costs turn negative with increasing fuel savings and the LNG truck ranks first (with current energy prices including energy tax benefits for natural gas).

The cost efficiency analyses reveal negative abatement costs of most single technological measures under present conditions for the semi-trailer truck as well as for the other analysed vehicle classes. In particular, measures for the reduction of driving resistance can pay off often within the initial three years, thus within the economic expectations of many vehicle owners. If acceptance of longer payback periods was established by vehicle owners, a number of additional technologies would be rated cost efficient. In consequence, the temporal aspect, i.e. the reference period for cost efficiency of greenhouse gas reduction measures, is critically relevant for the assessment of the cost efficiency of individual technologies.

From a socio-economic perspective, i.e. across the average vehicle service life, most technologies incur negative abatement costs. Thus, the implementation is associated with an economic advantage. But this is not the case for hybrid and battery-electric vehicles. These technologies generate additional costs (= positive abatement costs) even over the entire service life due to the high technology costs at present. However, the scenario calculations revealed that these technologies may also achieve negative abatement costs in future given relevant reductions of technology costs (learning and economy of scale effects with increasing production).

Packages of measures

A number of cost analyses were carried out for the packages of measures defined in the potential analyses

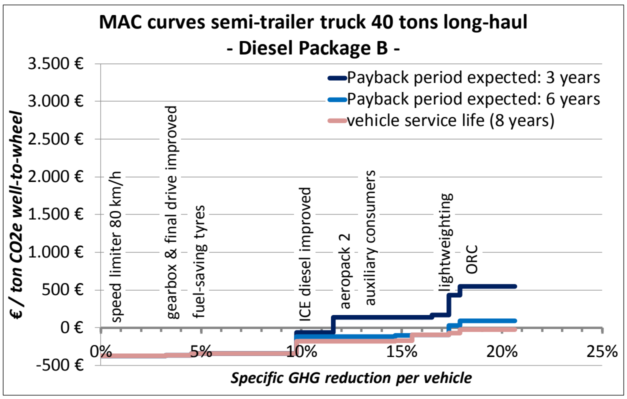
- Average greenhouse gas abatement costs of the efficiency packages were calculated based on combined greenhouse gas reduction potentials and vehicle cost changes of the measures included in the packages;
- Marginal abatement cost (MAC) curves were computed for all packages;
- Based on these MAC curves, the cumulative abatement costs per vehicle were calculated.

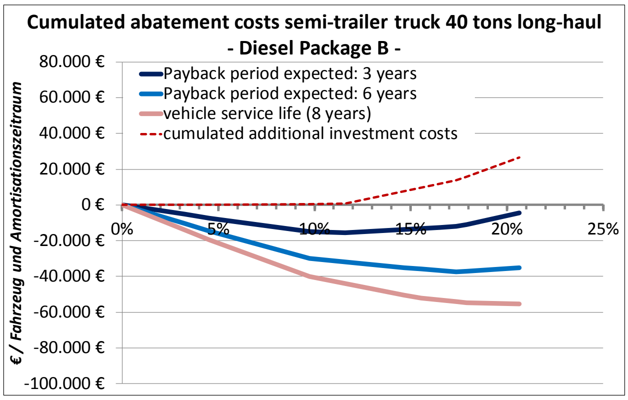
MAC curves reveal the marginal costs that allow additional emission reductions within a given system (e.g. truck measures). For this purpose, measures within the efficiency packages were sorted according to their individual cost efficiency (marginal cost in € / t CO_2e) and combined based on the most cost-efficient measure. For each additional measure, the additional greenhouse gas reduction potential and the specific costs of the additional reduction were calculated and applied.

Figure 8 exemplifies MAC curves (left) and cumulative greenhouse gas abatement costs per vehicle (right), i.e. the sum of the changes to vehicle costs with the incremental combination of single measures. The figure, thus, reveals which total cost changes per vehicle are associated with which GHG reductions. The maximum cost reduction is achieved with the combination of all measures with negative abatement costs alone. Further measures (with positive abatement costs) will in consequence result in decreased savings for the operator.

For the semi-trailer truck 40 t in long-haul transport, combination of analysed technologies in measure package Diesel B with negative GHG abatement costs can save 12 % with technologies that pay off within three years up to 21 % with all technologies that pay off within vehicle service life. The maximum cost reduction per vehicle is 15 000 Euro (3 years) up to 55 000 Euro (vehicle service life). Combining all technologies that pay off within vehicle service life (thus saving 21 % of GHG emissions) would reduce vehicle costs already within the first three years by about 4 000 Euro as cost savings from most cost-efficient technologies would offset the additional costs of those technologies, which pay off only after longer time periods.

Figure 8 MAC curves and cumulated GHG abatement costs of measure packages B for a semi-trailer truck 40 t in long-haul transport





Finally, the maximum cumulative GHG reduction potentials with negative marginal abatement costs of all efficiency packages were compared with the total potentials. The results show clearly that a restriction to measures with payback period of maximum three years will limit the exploitation of the full GHG reduction potential of the package. An extension of the payback period to six years or more distinctly broadens the scope for additional emission reductions due to the fact that the number of measures with negative abatement costs increases. Thus, the relevance of the expectations of vehicle operators towards payback periods for their assessment of measures is revealed. This in turn influences the likelihood and feasibility of reduction potentials through energy-saving and greenhouse gas reducing technologies. If vehicle operators could be won over to accept longer payback periods, a number of current and future technologies for greenhouse gas reduction in heavy-duty vehicles could be much more common and popular.

The use of hybrid and battery-electric vehicles is associated with additional costs for all vehicle classes under investigation, even across the entire vehicle service life, assuming present technology and fuel costs. In general, those positive abatement costs may not be compensated with other technologies having negative abatement costs. However, these alternative drive concepts have been recently introduced to the market, or may not even be available for some vehicle classes as yet. Relevant future cost reductions could render city buses viable within five to six years and shorten the payback period of delivery trucks to seven to eight years. Thus, considerable additional greenhouse gas reduction potentials could be exploited as soon as development and increased availability of alternative drive concepts effectively lower production costs.

Table 2 Total GHG mitigation potentials of the measure packages and partial mitigation potentials of measures in the packages with negative GHG abatement costs

Vehicle class and mission profile	Measure package	Combined GHG mitigation potential of the package	Partial GHG mitigation potentials of individual measures in the package with negative GHG abatement costs		
			After 3 years	After 6 years	Within vehicle service life
Semi-trailer truck 40 t, long haul cycle	Diesel A	11%	10%	+1%	+0%
	Natural gas (LNG) A	12%	10%	+2%	+0%
	Parallel hybrid A	16%	10%	+1%	+0%
	Diesel B	21%	12%	+6%	+3%
	Natural gas (LNG) B	19%	10%	+9%	+1%
	Parallel hybrid B	24%	12%	+6%	+1%
Semi-trailer truck 40 t, regional delivery cycle	Diesel A	7%	4%	+0%	+2%
	Natural gas (LNG) A	9%	4%	+0%	+4%
	Parallel hybrid A	16%	4%	+0%	+2%
	Diesel B	13%	9%	+0%	+1%
	Natural gas (LNG) B	15%	7%	+0%	+5%
	Parallel hybrid B	23%	9%	+0%	+1%
Delivery truck 12 t, urban delivery cycle	Diesel A	8%	4%	+2%	+0%
	Natural gas (CNG) A	18%	4%	+11%	+2%
	Parallel hybrid A	15%	4%	+2%	+0%
	Electric A	56%	2%	+0%	+2%
	Diesel B	17%	7%	+5%	+3%
	Natural gas (CNG) B	27%	7%	+14%	+3%
	Parallel hybrid B	25%	7%	+5%	+3%
	Electric A	62%	8%	+0%	+3%
City bus 18 t, city-bus urban cycle	Diesel A	7%	2%	+3%	+3%
	Natural gas (CNG) A	13%	2%	+3%	+9%
	Parallel hybrid A	16%	2%	+3%	+3%
	Serial hybrid A	26%	2%	+3%	+3%
	Electric A	62%	2%	+3%	+0%
	Electric with intermediate charging A	66%	2%	+3%	+61%
	Diesel B	15%	8%	+4%	+2%
	Natural gas (CNG) B	21%	6%	+12%	+2%
	Parallel hybrid B	24%	8%	+4%	+2%

Vehicle class and mission profile	Measure package	Combined GHG mitigation potential of the package	Partial GHG mitigation potentials of individual measures in the package with negative GHG abatement costs		
			After 3 years	After 6 years	Within vehicle service life
	Serial hybrid B	35%	8%	+4%	+2%
	Electric B	66%	6%	+4%	+0%
	Electricwith inter-mediate charging B	69%	6%	+4%	+59%

4 Strategies to promote the introduction and establishment of fuel-saving and GHG reducing technologies for heavy-duty vehicles

Many fuel-saving and greenhouse gas-reducing technologies for heavy-duty vehicles already available on the current market find limited application and are used by only a fraction of vehicle operators. In consequence, the scope of the present study included the discussion of political strategies to promote the introduction and establishment of such technologies.

The initial step included the analysis of prerequisites and barriers for a market introduction and establishment of greenhouse gas-reducing technologies beyond greenhouse gas reduction potentials and cost (reductions). These include legal and practical parameters as well as information deficits and other barriers to stakeholder acceptance in freight transport. Based on these results, the second step included the analysis of strategies to promote the introduction and establishment of energy-saving technologies for heavy-duty vehicles in Europe. Advantages and disadvantages of different strategies as well as their acceptance within the freight logistics sector were discussed. From these single strategies, a roadmap combining different strategies was developed.

4.1 Barriers for establishing fuel-saving and GHG reducing technologies

The analysis of prerequisites and barriers for the market introduction and establishment of energy-saving technologies included a literature search complemented by consultations with stakeholders in freight transport (truck manufacturers, haulage businesses and transport companies).

The introduction of energy-saving HDV technologies is hampered by a number of obstacles:

- **Technology-specific barriers** are related to characteristic features (e.g. dimensions, weight) of a specific technology or special prerequisites necessary for the application of a certain technology. Major technology-specific barriers are associated with
  - Reduced ease of use/ user friendliness (e.g. driver comfort, time-consuming routines)
  - Reduced economical use of the vehicle for compliance with legal requirements (e.g. construction changes) or reduced compatibility with international standards (e.g. craneability)
  - Non-existent supply infrastructure and service network (e.g. for natural gas, hybrid and battery-electric vehicles)
- **Financial barriers** result from absolute costs (e.g. high investment costs) or from the evaluation of the cost-benefit-ratios of a technology (e.g. assessment of outage probabilities, payback expectations, resale value). Smaller businesses in particular frequently lack the personnel to accurately assess cost reduction potentials and have both limited financial means at their disposal and limited access to loans.
- **Structural barriers** are caused by existing structures and established procedures in the logistics sector. The pivotal question in this context is the importance of fuel costs for vehicle operators. There are two aspects relevant to the question, the proportion of fuel costs in reference to the overall total of the business, and the 'fuel responsibility', i.e. which party effectively pays for the fuel consumed during transport. With a share of 20-30 %, fuel costs are particularly relevant in regional and long-haul transport. However, a number of mechanisms exist for hauliers to shift costs to clients (e.g. fuel escalation clauses). If the financial responsibility is shifted to the client to a large extent, the incentive for the establishment of efficiency measures among the fleet is low. Beyond that, a smaller transport client has only limited opportunities to induce the establishment of energy-saving technologies in a major haulage contractor.
- **Information deficits** arise due to the complexity of the topic, particularly with respect to the challenge of accurate calculation of reduction potentials and costs, and the adequate communication of results.

The assessment of barriers distinguishes between technology-specific barriers and others. The assessment of the relevance of technology-specific barriers strongly depends on the evaluation of the importance of a technology from political, economic and environmental angles. Moreover, barriers should be differentiated into those with a foreclosing and those with a delaying effect.

The additional barriers not related to individual technologies should be considered in context. According to survey data, there is a general awareness of energy-saving technologies within the freight transport sector. A pivotal barrier to widespread implementation may be found in the lack of reliable and credible information. Knowledge on reduction potentials of a given technology is fundamentally important for the calculation of cost-benefit-ratios. The absence of economic analyses in turn impedes the acquisition of funding for additional purchases. Small businesses are at a particular disadvantage to invest in novel technologies due to limited personnel and restricted financial resources. In addition, a limited reliability of novel technologies may act as a major deterrent in the view of vehicle operators.

4.2 Measures to promote technology introduction and establishment in heavy-duty vehicles

Based on the analysis of barriers, measures promoting the introduction of energy-saving HDV technologies and their widespread establishment throughout the vehicle fleet were examined. The focus was particularly on political incentives for the improvement of fuel efficiency in road freight transport. The resulting measures were grouped depending on their overall approach:

- **Information** involves measures for the supply and dissemination of information;
- **Funding** comprises measures that involve financial support;
- **Regulation** defines measures addressing changes in legislation.

Both the analysis of barriers and the analysis of measures revealed that a combination of different measures should be pursued to most effectively address the different barriers and stakeholders. A synthesis of the different aspects is attempted in the proposed roadmap (Figure 9).

Information: Potential buyers depend on reliable and transparent information on reduction potentials and costs of a technology to carry out realistic cost-benefit-analyses. To satisfy the demand for reliable and transparent information on cost-benefit-analyses of efficiency technologies, an initial requirement would be a standardised test methodology for the quantification of CO_2 emissions. These data are required both for entire vehicles and individual technologies. The VECTO simulation model of the European Commission is already pursuing this approach. However, due to the great diversity and complexity of technologies, it is not possible to model all technologies and combinations at present. Further development of VECTO or the development of supplementary methods for technologies currently not included in the VECTO model is required. The goal should be a model that includes all available and future technologies applying unequivocal standards.

Standardised test methodology acts as the foundation for a number of additional measures. This correlation is illustrated with a uniform blue colouring in the figure. One pivotal measure is the CO_2 certification of HDVs or single technologies for the purpose of publishing information on reduction potentials in a transparent and comprehensible way. Energy consumption and CO_2 certification should be mandatory for all new HDVs. As a complement to these general certificates, a voluntary certification for single technologies should be made available, particularly for technologies with retrofitting potential, thus providing manufacturers with proof of the efficiency effects of their technologies. Such certification allows the establishment of targeted incentives, which in turn alleviate the barrier of high investment costs for the purchase of new vehicles, or the retrofitting of the existing fleet with energy-saving and greenhouse gas-reducing technologies.

Even with appropriate information available, smaller businesses may struggle to compile such information and calculate payback periods adequately. Independent efficiency consultants could support hauliers during the purchase of vehicles with superior efficiency or supervise the retrofitting with efficiency technologies. Moreover, such consultants could be in charge of disseminating information on government incentives (e.g. funding programmes) and support the introduction of fuel-consumption monitoring. General information events (e.g. trade fairs, road shows) introducing successful examples of consumption reduction through available or newly developed efficiency technologies present an opportunity for stronger promotion of the entire topic of HDV energy efficiency and measures for energy savings.

Funding: Despite the general promise of economic benefits, high cost of purchase may act as a barrier preventing investment into additional energy-saving technologies when purchasing a new vehicle. Appropriate funding measures may help alleviate this obstacle. Among the incentives could be investment loans at reduced rates for certified technologies, or funding programmes for municipalities allowing the retrofitting of their fleets. Another conceivable option would be the establishment of environmental incentives in the form of a scrappage scheme for old HDVs with simultaneous purchase of a new vehicle. Funding programmes may target technologies that are currently not economical, but desired from a political point of view. Targeted funding may increase production numbers, which in turn generates knowledge and learning of optimal methods, thus reducing specific production costs and lowering prices for new vehicles. Moreover, research and development by technology manufacturers could be funded to accelerate market availability, functionality, reliability and economic pricing.

In addition to government funding, private fuel-saving-contracting should be considered. External investors bear the cost of purchase for efficiency technology (or part thereof) in return for a stake in the subsequent cost savings. The introduction of fuel consumption monitoring in the transport sector would be a prerequisite for such schemes.

Measures for the promotion of alternative drive concepts are seen as a separate group within the roadmap. The integration of alternative drives into the market requires extensive support, particularly with regard to the supply infrastructure. The development of the energy supply infrastructure including the extension of refuelling stations with natural gas supply (CNG, LNG) and electricity charging stations is indispensable for the establishment of alternative drives. A comprehensive service network for maintenance and repairs is equally important. As long as the number of vehicles with alternative engines remains low, garages are unlikely to invest in the education of their staff or the purchase of new equipment. Conversely, potential buyers may be reluctant to invest in new technology if the service network is underdeveloped and adequate service is scarce. Finally, the suitability of tax benefits such as the current energy tax benefit of natural gas should be examined for other alternative drive concepts.

Regulation: A number of technical measures are currently ignored due to the fact that these technologies are frequently larger or heavier than regular diesel engines, thus considerably decreasing the payload. Although future technical developments may optimise dimensions, it is recommended to consider adaptations of legal requirements for such technologies to provide manufacturers with more flexibility during the development of efficiency technologies.

Pressure to act may also be generated through mandatory efficiency classes for individual technologies, e.g. tighter restrictions for the rolling resistance of future tyres exceeding current EU standards. Such measures not only promote the equipment of vehicles with the most energy-efficient technology, they also prevent vehicle operators from letting standards slip during the maintenance with consumables (e.g. tyres, oil, lighting) and electing to use less efficient products.

In the case that information and funding measures fail to produce the desired effects in lowering greenhouse gas emission of HDVs, the introduction of a mandatory European CO_2 regulation for heavy-duty vehicles should be considered in analogy to the passenger car sector.

Figure 9 Roadmap of political measures to promote the establishment of energy-saving and GHG reducing technologies in the HDV fleet