Marginal abatement cost curves for Heavy Duty Vehicles

Background report

Report
Delft, September 2012

Author(s):
Arno Schroten
Geert Warringa
Mart Bles

Publication Data

Bibliographical data:
Arno Schroten, Geert Warringa, Mart Bles
Marginal abatement cost curves for Heavy Duty Vehicles
Background report
Delft, CE Delft, September 2012

Publication code: 12.4726.63

CE publications are available from www.cedelft.eu

Commissioned by: European Commission, DG CLIMA
Further information on this study can be obtained from the contact person, Arno Schroten.

CE Delft
Committed to the Environment

CE Delft is an independent research and consultancy organisation specialised in developing structural and innovative solutions to environmental problems.
CE Delft's solutions are characterised in being politically feasible, technologically sound, economically prudent and socially equitable.

Contents

Summary

Background

In the Transport White Paper the European Commission presents a CO_2 reduction target of 60% in 2050 for transport. Improving the energy performance of vehicles is identified as one of the routes that should be followed to reach this objective. In this respect the Commission announced in its 2010 European Strategy on Clean and Energy Efficient Vehicles that it will propose a strategy targeting fuel consumption and CO_2 emissions from HDVs. In developing this strategy the abatement costs of technical measures is a key criterion. Since these kinds of measures could result in potentially high costs, minimising these costs is important to keep the EU transport sector competitive and to maximise welfare.

Objective

In order to provide insight in the abatement costs of technical reduction options for HDVs CE Delft developed marginal abatement cost (MAC) curves for these vehicles – at the vehicle level – for packages of technical CO_2 emission reduction measures. These cost curves are derived for eight different vehicle categories (service, urban delivery, municipal utility, regional delivery, long haul, construction, bus, coach) as well as for an ‘average’ truck and bus.

Since abatement costs depend heavily on the methodological assumptions and parameter values applied, the MACH (Marginal Abatement Costs of Heavy duty vehicles) model was developed which provide users the opportunity to apply detailed sensitivity analyses to determine the robustness of the results. Issues for which sensitivity analysed could be carried out by the model are:

- *Perspective applied*; the abatement costs could be estimated from both a social and an end-user perspective.
- *Discount rate*; various values for the discount rate could be chosen.
- *Fuel prices*; the MACH model provides the opportunity to choose between three fuel price scenarios (for the period 2012-2035). Additionally, users could also estimate abatement cost curves by using their own fuel price scenarios.
- *Time horizon;* considering a shorter time horizon results in higher abatement cost. The MACH model provides the opportunity to consider all time horizons between three years (which is often considered to be the maximum payback period HDV owners require) and the technical lifetime of the measure.
- *Investment costs;* for every individual technical reduction measure investment costs could be adjusted (within ranges based on cost estimates in the literature).

Methodology

The abatement costs of technical reduction options are calculated based on total costs (mainly investment costs) and benefits (fuel savings and CO_2 emission reductions) over the time period considered. As input for this assessment data from two detailed studies on technical abatement measures for HDVs are used: TIAX (2011) and AEA/Ricardo (2011). Both the baseline vehicles assumed as well as the reduction potentials of the various technical measures are taken from TIAX (2011). With respect to the investment costs of the various technologies large differences exist between TIAX (2011) and AEA/Ricardo (2011). In this project we tried to explain these differences by studying the reports in detail, interviewing the authors of both studies and compare their results with other cost estimations found in the literature. Based on this assessment default values for the investment costs were chosen as well as bandwidths to reflect the uncertainty in these values. These bandwidths are implemented in the MACH model and could be used to carry out detailed sensitivity analyses.

Output

The MACH model provides the opportunity to estimate the abatement costs of packages of technical CO_2 reduction measures under a wide range of assumptions. As an illustration the break-even abatement potentials (CO_2 reductions that could be realised by technologies with zero or negative abatement costs) for an 'average' truck and bus under various assumptions are shown in Table 1 and Table 2.

The results in Table 1 and Table 2 show that both for trucks and busses significant cost effective technical measures are available, particularly if a long time horizon is considered. For trucks a break-even abatement potential of ca. 30% could be realised, while for buses this potential is even ca. 36%. If a shorter time horizon of three years is considered still a significant break-even abatement potential is available; from a social perspective a reduction potential of 20% for trucks and 9% for buses could be realised in a cost effective way. From an end-user perspective even larger cost effective abatement potentials are available: ca. 23% for trucks and 12-30% (depending on the fuel price scenario assumed) for busses.

Table 1 Break-even abatement potential 'average truck' under various assumptions (%)

	Time horizon: three years	Time horizon: vehicle lifetime
Social perspective		
Low fuel price scenario	20%	29%
Reference fuel price scenario	20%	30%
High fuel price scenario	20%	30%
End-user perspective		
Low fuel price scenario	23%	30%
Reference fuel price scenario	23%	31%
High fuel price scenario	23%	31%

Table 2 Break-even abatement potential 'average bus' under various assumptions (%)

	Time horizon: three years	Time horizon: vehicle lifetime
Social perspective		
Low fuel price scenario	9%	36%
Reference fuel price scenario	9%	36%
High fuel price scenario	9%	36%
End-user perspective		
Low fuel price scenario	12%	36%
Reference fuel price scenario	30%	36%
High fuel price scenario	30%	36%

In addition to the sensitivity analyses carried out for the cost perspective, time horizon and fuel price scenario applied, we also checked the sensitivity of the results for changes in the discount rate and investment costs of technical reduction options. Compared to the reference case (social perspective, long time horizon, reference fuel price scenario) changes in these parameters only slightly affect the break-even abatement potentials for most of the vehicle categories considered.

1 Introduction

1.1 Background

Transport is responsible for around a quarter of EU greenhouse gas emissions. From the various transport sectors road transport is the biggest contributor to the emissions of greenhouse gas emissions: about two-third of EU transport-related greenhouse gas emissions are emitted by road transport (Hill et al., 2012). Passenger cars are responsible for the main part of these emissions, but also Heavy Duty Vehicles (HDVs) accounts for a significant part of the transport-related greenhouse gas emissions in the EU. According to AEA and Ricardo (2011) around 26% of all CO_2 emissions from road transport in the EU are from HDVs. Of this, over 85% is due to trucks, with the remainder due to buses and coaches.

While greenhouse gas emissions from other sectors are generally falling, decreasing 24% between 1990 and 2009, those from transport have increased by 29% in the same period. Also for the future years (till 2050) significant increases in total GHG emissions of transport – and in particular HDVs – are expected if no additional policies are implemented (Skinner et al., 2010).

In the Transport White Paper the European Commission presents their vision for the future of the EU transport system and defines a policy agenda for the next decade to begin to move towards 60% reduction in CO_2 emissions in 2050 (European Commission, 2011). Improving the energy performance of vehicles and developing and deploying sustainable fuels and propulsion systems are identified as one of the routes that should be followed to reach this objective.

With respect to HDVs the Commission announced in its 2010 European Strategy on Clean and Energy Efficient Vehicles that it will propose a strategy targeting fuel consumption and CO_2 emissions from HDVs. In developing this strategy, the abatement costs of technical measures is a key criterion. Since these kinds of measures could result in potentially high costs, minimising these costs is important to keep the EU transport sector competitive and to maximise welfare. For that reason the European Commission commissioned CE Delft to develop marginal abatement cost curves for technical measures for HDVs.

1.2 Objective of the project

The main objective of the study is to derive marginal abatement cost (MAC) curves for HDVs, at the vehicle level, for packages of technical CO_2 emission reduction measures. Therefore, a consistent data set of costs, fuel benefits and relative CO_2 reduction figures, is required. This dataset needs to be based on the most recent market and technology developments.

As was shown in the EU Transport GHG Routes to 2050 study (CE, 2012), the abatement costs of technical reduction options depends heavily on the methodological assumptions applied. Some important issues in this respect are:

- perspective applied; abatement costs based on an end-user perspective differ from ones based on a social perspective (see also Section 2.4);

- baseline scenario and technology assumed; both the baseline vehicle assumed as factors like fuel price (developments) significantly affect abatement cost estimations;
- amortization period assumed; shorter amortization periods results in higher abatement costs;
- discount rates applied.

To make the impact of some of these parameters (and some other variables, see Chapter 2) on the MAC curves more explicit, we developed the MACH (Marginal Abatement Costs of Heavy duty vehicles) model that makes it possible to adjust the values of some of the parameters/variables. Users of this tool are provided the opportunity to apply detailed sensitivity analyses to determine the robustness of the results.

1.3 Scope of the project

Desk research

A state-of-the-art overview of abatement technologies for HDVs, including an assessment of reduction potentials and investment costs, is provided by TIAX (2011) and AEA/Ricardo (2011)[1]. Therefore we decided, in consultation with the European Commission, to use the data from these studies to derive the abatement cost curves.[2]

However, there are significant differences in reduction potentials and investment costs of the various technological measures as presented by TIAX (2011) and AEA/Ricardo (2011). These differences may be the result of different underlying assumptions or they may reflect the uncertainty in the cost estimates of these (future) technologies. Based on a thorough review of the various studies (and particularly the assumptions applied by them) combined with some interviews (by phone) with the authors of these studies we tried to identify the reasons for the differences in cost estimates and eliminates (some of) the differences caused by using alternative assumptions. In this assessment of differences between TIAX (2011) and AEA/Ricardo (2011) we also took some other studies into account.

A full discussion of the way the data set for the cost curves is established can be found in Chapter 3.

Vehicle categories

As TIAX (2011) and AEA/Ricardo (2011) we distinguish the following vehicle categories:
- service/delivery (< 7.5 t);
- urban delivery/collection;
- municipal utility;
- regional delivery/collection;
- long haul;
- construction;
- bus;
- coach.

---

[1] These studies discuss all technologies available in the 2015 to 2020 timeframe.

[2] These studies have estimated potential savings and investment costs of the measures. However, no values have been estimated for maintenance/operational costs of the measures.

Next to abatement cost curves for these eight vehicle categories the MACH model also includes abatement costs curve for an average truck and an average bus. These costs curves are weighted averages of the cost curves of the various vehicle categories. GHG emissions by the various vehicle categories (from AEA/Ricardo, 2011) are used as weighting factors.

Alternative fuels

Next to technological measures to the vehicle also the use of alternative fuels (biofuels, natural gas, LPG) is a potential option to reduce the GHG emissions of HDVs. However, these options are not considered in this study for the following reasons:

- In this study we only consider reduction options at the vehicle level – tailpipe emissions – and hence alternative fuels are out of the scope of the study.
- Data availability on the abatement costs of alternative fuels is rather poor (CE, 2012). Particularly with respect to biofuels, little estimates of abatement costs are known that take Indirect Land Use Change (ILUC) effects into account[3]. As a consequence of the poor data availability on abatement costs of alternative fuels the reliability of the estimates that are available is significantly lower than for the technical abatement measures for HDVs.
- The scarce evidence available on the abatement costs of alternative fuels show that these are probably high, particularly for biofuels. For example, ICCT (2011) estimates the abatement costs of biofuels, based on UK DfT cost figures for 2020 and the most recent IFPRI MIRAGE modelling results, at ca. € 2,500 per tonne of CO_2. For natural gas and LPG the abatement cost estimates are probably lower (in the range of € 200-700 per tonne CO_2), but still significant higher than most of the technical solutions (CE, 2012). Due to the (very) high abatement costs the alternative fuels will show up at the right side of the cost curves and hence will probably not play a key role in most assessments with the cost curves. Additionally, by including the abatement costs of these fuels in the MAC curves would significantly stretch the vertical axis of the figures; as a consequence the differences in abatement costs between the other (technical) measures will not be visible anymore.

Base year

All costs and fuel benefits are expressed in €2012.

---

[3] ILUC effects refer to the emissions released when pristine lands are cleared and converted to new cropland, in order to produce the crops for feed and food that were diverted elsewhere due to biofuels production. These emissions may be very significant, depending on the type of crop used for the biofuel production, but they are more difficult to quantify than the direct emissions of biofuels (European Parliament, 2011; European Commission, 2011; IFPRI, 2011). To estimate the net GHG reduction potential of biofuels it is important to take these ILUC effects into account. Taking them into account, the net GHG emission reductions are found to differ significantly between biofuels; some of them achieve significant GHG savings, while others do not achieve any savings or cause more emissions than the fossil fuels that they replace (IFPRI, 2011; Smokers et al., 2012). Only for the former it is possible (and useful) to determine abatement costs, but as mentioned the evidence on abatement costs of these biofuels is rather scarce (CE, 2012).

1.4 Overview of this report

This document functions as a background document for the MACH model.
In Chapter 2 we discuss the methodological framework for deriving cost curves. Chapter 3 describes the input values of the MACH model.
In Chapter 4 we present the main output of the model: cost curves for the eight vehicle categories as well as average cost curves for trucks and busses. Additionally, the results of some sensitivity analyses carried out are presented.

2 Methodological framework

2.1 Introduction

In this chapter the methodology used to derive the abatement cost curves is discussed. First, in Section 2.2 the way the abatement costs are calculated is presented, while the actual derivation of abatement cost curves is discussed in Section 2.3. Finally, in Section 2.4 the opportunities to apply sensitivity analyses with the help of the MACH model are presented.

2.2 Calculation of abatement costs

The abatement costs of GHG reduction options are defined as the costs of an option divided by its greenhouse gas abatement potential. The abatement costs are expressed in € per ton of CO_2. Costs included are investments, operating costs and benefits due to reductions in fuel use. Broader welfare costs/benefits (co-benefits like increase vehicle safety, reduced emissions of air pollutants) are not taken into account[4].

Two general approaches to calculate cost effectiveness figures could be used. The first approach calculates cost effectiveness based on the CO_2 emission reduction and accompanying costs/benefits for a specific year (e.g. Blok, 2001; AEA, 2001; INFRAS, 2006). Therefore, the following formula is applied:

$$\text{(1) Cost effectiveness} = \frac{I^{an} + \Delta\text{O\&M} - \Delta\text{fuel costs}}{\text{annual } CO_2 \text{ emission abatement}}$$

In the formula I^{an} is the annuity of the total investment costs I:

$$I^{an} = I * \frac{(1+r)^{l} * r}{(1+r)^{l} - 1}$$

where l is the lifetime of the option, r the discount rate and I the total investment. ΔO&M represents the additional annual operating and maintenance costs and Δfuel costs the annual savings on fuel costs.

Another approach is to calculate the cost effectiveness based on total costs and benefits instead of annual costs and benefits (see e.g. TNO et al., 2006). In that case the following formula is used:

$$\text{(2) Cost effectiveness} = \frac{\text{I} - \text{NPV}\ (\Delta_{\text{lifetime}}\ \text{O\&M}) - \text{NPV}\ (\Delta_{\text{lifetime}}\ \text{fuel costs})}{\text{Lifetime } CO_2 \text{ emission reduction}}$$

The results from both approaches could not be directly compared, since the results from the first approach are expressed in future values, while the results from the second approach are expressed in present values. A fuel cost

---

[4] This could result in an over- or underestimation of the abatement costs of technical reduction options in case a social perspective is applied. However, no data is provided by TIAX (2011) or AEA/Ricardo (2011) on these kinds of effects. In general, we expect these effects to be small.

saving of € 400 in 2015 has in 2011 a lower value (i.e. € 342 if we assume a discount rate of 4%), since there are some foregone interest payments since people receive these benefits not in 2011 but in 2015. Hence, the present value (value in 2011) of fuel saving benefits is lower than their future value (value in 2015). By the same kind of reasoning it holds that the present value of costs is higher than the future value. If we correct for this, by taking the present values from the annual benefits and costs in the first approach, the average of the annual cost effectiveness figures are equal to the cost effectiveness figures found by applying the second approach (for more information, see CE, 2012).

Both approaches can be applied to determine the abatement costs of technical reduction options. As the results of the second approach are easier to interpret in terms of sensitivity to the amortization period (time horizon) applied we decided to apply this approach.

2.3 Derivation of cost curves

As mentioned in Section 1.2 in this project abatement cost curves for HDVs, at the vehicle level, for packages of technical CO_2 emission reduction measures are derived. On the horizontal axis the cumulative emission reduction (in %) is presented, while on the vertical axis the abatement costs (in €/ton CO_2) is shown. The cost curves will be derived for the most efficient package of abatement options (which is in line with the definition of cost curves), i.e. the package consisting of technologies with the lowest individual abatement costs.

The derivation of the abatement costs curves for the various vehicle categories consist of the following three steps:

- *Estimate abatement costs of all individual abatement technologies*; the approach discussed in Section 2.2 is used to estimate the abatement costs of the various technologies.
- *Rank all abatement technologies based on their abatement costs;* we started with the technology with the lowest abatement costs, followed by the technology with the second-lowest abatement costs, etc. In this way the most efficient package of abatement technologies was composed.
- *Estimate combined reduction potential of abatement technologies;* as a final step in the derivation of cost curves the combined reduction potential of the package of abatement technologies should be calculated. This should be done for every subset of the whole package, i.e. for the two most efficient abatement technologies, for the three most efficient abatement technologies, etc. In general, the estimation of combined reduction potentials will be done in the same way as TIAX (2011), i.e. by applying the following formula:

Combined reduction potential (%) = 100 x (1-(1-RC_1)/100) x (1-RC_2/100) x … x (1-RC_i)/100))

As mentioned in Section 1.3 also cost curves for an ‘average’ truck and bus are developed. These cost curves are weighted averages of the cost curves of the various vehicle categories. The following steps are applied to derive these curves:

- *Rank all abatement technologies of all relevant vehicle categories based on their abatement costs*; first all technologies for all relevant categories (all HGV categories or all bus categories) are taken together. Next these technologies are ranked based on their abatement costs as determined in the first step of the derivation approach of cost curves for every vehicle category separately.
- *Estimate the relative reduction potential of every individual technology in terms of % reductions in total CO_2 emissions of trucks or busses;* this could be realised by weighting the reduction potentials of the individual abatement options by the shares of the relevant vehicle category[5] in total GHG emissions of trucks (or busses).
- *Estimate combined reduction potential of abatement technologies;* with help of the results of the previous steps the combined reduction potentials could be estimated. The same approach as for the cost curves of individual vehicle categories is applied.

2.4 Sensitivity analyses

As mentioned in Section 1.2 the costs of abatement technologies depends heavily on the values chosen for some of the parameters (discount rate, fuel price, etc.). For that reason we have developed the MACH model that makes it possible to adjust the values of the main parameters. The user of this model has the opportunity to apply some sensitivity analyses themselves and – in this way – test the robustness of the results.

The model provides for the following parameters the opportunity to apply a sensitivity analysis:

- *Perspective of costs;* the costs of technical measures can be assessed from the perspective of the end-user or that of the society as a whole. These perspectives result in different abatement cost figures due to the fact that savings on fuel taxes (default value: € 0.45 per litre diesel; calculated based on oil bulletins of the European Commission) are taken into account by the end-user perspective but not by the social perspective[6]. The MACH curve model provides the user the opportunity to derive the costs curves for both types of perspectives.
- *Fuel prices*; fuel prices are collected from statistics from the Market Observatory for Energy. This body, created by the European Commission, presents net prices of petroleum products in EU member states each week, including weighted averages for the EU. We have calculated the average diesel price from week 1 till 21 in 2012. The fuel price scenarios are based on predictions of the International Energy Outlook 2011 of the US Energy Information Administration. This outlook presents three international oil price scenarios until 2035 (low, reference, high) (see Figure 1). We use these trends to estimate price developments of diesel, as oil and diesel

---

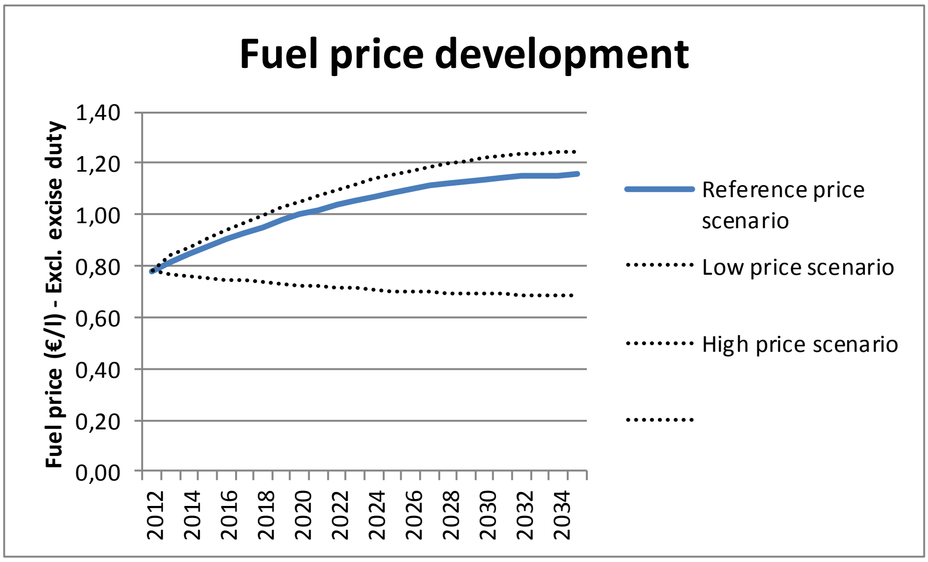
[5] The vehicle category on which the technology will be applied.

[6] Notice that the VAT on fuel is not taken into account by both the social and end-user perspective. Since taxes are no social costs VAT is excluded from cost calculations based on a social perspective. With respect to the end-user perspective, it should be considered that hauliers and bus transportation companies are excluded from VAT payments on fuel and hence these taxes shouldn’t be taken into account in the end-user perspective too.

prices are strongly correlated.[7] Next to these three price scenarios the MACH model provides users also the possibility to apply 'own' values for fuel prices for the period 2012-2035.

- *Time horizon*; as a default value the technical lifetime of the abatement technology is used (see Section 3.3). As alternative values a continuous range with three years as lower bound and the technical lifetime as upper bound is applied.
- *Discount rate;* the value of the discount rate to be applied depends, among other things, on the cost perspective applied. In general, an end-user perspective requires a higher discount rate (reflecting the expected rate of return of a company investing in the technology) than a societal perspective. With respect to an end-user perspective, a default discount rate of 7% is included in the MACH model (alternative values are a continuous range from 4 to 12%). With respect to a social perspective, a default discount rate of 4% is included in the model (alternative values are a continuous range from 2 to 7%).

Figure 1 **Fuel price scenarios**



Next to variations in some of the main parameters the MACH model provides also the opportunity to vary the reduction potential and investment costs of the various technologies. In this way the (rather large) uncertainties in the estimates of these variables could be explicitly taken into account.
In Chapter 3 the default and alternative values for both the reduction potentials and costs of the various technologies are extensively discussed.

---

[7] A calculation of Barrington Consulting of the US diesel price per gallon and the crude oil costs per gallon from 1994 to 2010 shows an R^2 of 0,97. This indicates a very high correlation. An R^2 lies typically between 0 and 1. An R^2 of 0 indicates no correlation, an R^2 of 1 indicates a perfect correlation, such as Celsius and Fahrenheit. An R^2 of 0,97 is close to 1 and indicates therefore a very strong correlation.

3 Input values

3.1 Introduction

In this chapter we discuss the input values for the MACH model. First, in Section 3.2 the baseline vehicles are described. Next, the abatement technologies and their reduction potentials are discussed for the various vehicle segments considered (Section 3.3). Finally, the costs of these technologies are discussed in Section 3.4.

3.2 Baseline vehicle

In this study we used the same baseline vehicles as the ones defined by TIAX (2011). These vehicles are assumed to be 2014 vehicles that meet Euro VI emissions standards, which are more appropriate to evaluate future CO_2 reduction options CO_2 reduction options than current baseline vehicles[8]. The main assumptions on the baseline vehicles on the baseline vehicles are summarized in

Table 3. A further discussion on the characteristics of the baseline vehicles can be found in TIAX (2011, Chapter 4).

Table 3 Assumptions on the baseline vehicles

Vehicle category	**Assumptions on baseline vehicles**
Baseline vehicles	– 2014 vehicles meeting Euro VI standards (EGR+DPF+SCR) – No aerodynamic trailers or fairings – Regular rolling resistance tires, no wide-base single tires – No engine turbo compound or waste heat recovery, engine specifications corresponding to those of US2010 engines – No hybridisation – No predictive cruise control
Additional segment-specific technologies incorporated	
Service	– Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)
Urban delivery	– Manual transmission – Integrated air dam, cab side edge turning vanes
Municipal utility	– Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)
Regional delivery	– Automated transmission (4 to 8% fuel consumption benefit over manual transmission) – Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector
Long haul	– Automated transmission (4 to 8% fuel consumption benefit over manual transmission) – Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector
Construction	– Manual transmission
Bus	– Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)

---

[8] The latter ones were used as baseline vehicles by AEA/Ricardo (2011).

Vehicle category	Assumptions on baseline vehicles
Coach	– Automated transmission (4 to 8% fuel consumption benefit over manual transmission)
Fuel economy projections	– No underlying fuel economy changes over time (i.e. all fuel economy increases result directly from application of specific technologies)

Source: TIAX, 2011.

Next to the technological characteristics of the baseline vehicles, Table 4 presents some other assumptions with respect the baseline vehicles, i.e. vehicle lifetimes, annual mileages and fuel consumption values. Vehicle lifetimes, fuel consumption and annual mileage are based on TIAX (2011).

Table 4 Some baseline assumptions

Vehicle segment	Vehicle lifetime	Annual mileage (kilometres)	Fuel consumption (l/100 km)
Service/delivery	10	35,000	16.0
Urban delivery/collection	19	40,000	21.0
Municipal utility	17	25,000	55.2
Regional delivery/collection	12	60,000	25.3
Long haul	8	130,000	30.6
Construction	19	50,000	26.8
Bus	14	50,000	36.0
Coach	12	52,000	27.7

Source: TIAX, 2011.

3.3 Technical measures

The technical abatement measures considered by TIAX (2011) and AEA/Ricardo (2011) are rather comparable. In both studies the technologies fall into seven broad categories:

- aerodynamics;
- lightweighting;
- tires and wheels;
- transmission and driveline;
- engine efficiency;
- hybridisation;
- management.

Although the type of measures is similar, specific measures differ. For instance, TIAX (2011) has, in contrast to AEA/Ricardo (2011), not adopted single wide tires and automatic tire pressure adjustment for all vehicles in the tires and wheels category. For aerodynamics and lightweighting category, the main difference between the studies is that measures in TIAX are more specified. For instance, TIAX (2011) has specified the weight savings while the saving is unknown in AEA/Ricardo (2011). In the transmission and driveline categories, measures differ due to different assumptions in the baseline vehicles. For instance, AEA/Ricardo assumes manual transmissions for the baseline vehicles, while TIAX (2011) assumes a mix of manual and automated transmissions. Therefore, automated transmissions are not included as a technological abatement option in TIAX (2011). For the management category,

the measures are more or less similar, although TIAX (2011) has added some extra measures for the long haul category (training and feedback).
For consistency reasons, we choose to select the specific measures of TIAX (2011) to create a coherent set of measures. Selecting measures of both studies has a risk of mixing oranges with apples, as there are differences between the specific features of the baseline vehicles in TIAX (2011) and AEA/Ricardo (2011). Furthermore, this approach makes sure that all measures are compatible with each other, as the OEM's have explicitly indicated that measures in TIAX (2011) are compatible with each other.[9]

By choosing the technology package of the TIAX study, we exclude some types of hybrid configurations (e.g. start-stop systems, flywheel hybrids) from the MAC curves. In the TIAX study only full hybrid vehicles are considered[10].
Since the abatement costs of some of these hybrid configurations may be (significantly) lower than the abatement costs of full hybrid vehicles, including them in the MAC curve may lower (part of) these curves. This would mean that at a certain set of assumptions the total percentage CO_2 reduction at below zero cost may be greater, in particular where full hybridisation does not appear to be cost effective. Further work would be required to expand the cost curves to include these kind of abatement technologies or others[11] that have not been included in the TIAX study. In view of this, it is likely that the cost curves represent a conservative view of the available below cost savings available.

The (relative) abatement potentials of the various technologies are based on the estimates provided by TIAX (2011) for the following reasons:

- The abatement potential of the technologies depends heavily on the baseline vehicles assumed. Since we applied the baseline vehicles from TIAX (2011), it seems appropriate to apply TIAX's estimations of the abatement potentials as well.
- Most of the large deviations in reduction potential estimations between TIAX (2011) and AEA/Ricardo (2011) can be explained by differences in the baseline applied (see TIAX, 2011). The remaining deviations are rather small and hence it seems appropriate to apply the abatement potential estimates of just one study.
- The definition of the technologies is based on TIAX (2011) and differs in some cases from the definitions used by AEA/Ricardo (2011). Hence, for these technologies it seems appropriate to apply reduction potential estimates from TIAX (2011).

In

---

[9] According to TIAX, the OEM's have indicated that the set of measures presented in TIAX (2011) are fully compatible.

[10] AEA/Ricardo (2011) does consider some alternative hybrid configurations for HDVs. However, as for the reasons mentioned above, the reduction potential and technology cost figures from this study couldn't be directly compared to the abatement cost estimates based on the TIAX study. Therefore, we didn't include these reduction technologies in our MAC curves.

[11] The TIAX study was not exhaustive on other technologies as well. For example, TPMS that is much cheaper than automated tyre inflation (and presently widely available on the market) is not considered by the TIAX study.

Table 5 the reduction potential of the various abatement technologies as used in this study are shown. For some of the technologies ranges of reductions potentials are presented by TIAX (2011). For these technologies the MACH model uses the central value of these ranges as default value. Additionally, the user is provided the opportunity to choose for the lower or upper bound of the range.

Table 5 Relative reduction potentials (%)

Technology		Vehicle category							
		Service/ delivery	Urban delivery/ collection	Municipal utility	Regional delivery\collection	Long haul	Construction	Bus	Coach
Aerodynamics	10% reduction in aerodynamic drag	2-3							
	Aft box taper		1.5-3						
	Boat tail				2-4	2-4			
	Box skirts		2-3						
	Cab side extension or cab/box gap fairings		0.5-1						
	Full gap fairing				1-2	1-2			
	Full skirts				2-3	2-3			
	Roof deflector		2-3						
	Streamlining								3-10
Lightweighting	Material substitution	1-1.5	3-5	0.7-1.2	2.2	2.2	0.3	5-7.5	1.1
Tires and wheels	Automatic tire inflation on vehicle/tractor				0.6	0.6	0.6		0.4
	Automatic tire inflation on trailer				0.6	0.6			
	Low rolling resistance tires	1-2	2.1-4.2	2.4-3				1-2	1-2
	Low rolling resistance wide-base single tires				9-12	9-12	9-12		
Transmission and driveline	Aggressive shift logic and early lockup	1.5-2.5		0.5-1					
	Increased transmission gears	2.7-4.1		2-3					
	Transmission friction reduction	0-1		1	1-1.5	1-1.5	1-1.5		1-1.5
Engine efficiency	Improved diesel engine	4-5	9.4-12	9.4-12	9.4-12	14.6-17.9	9.4-12	9.4-12	14.6-17.9
Hybridization	Dual-mode hybrid	20-30			8-12	8-12			
	Parallel hybrid		25-35				25-35		9-13
	Parallel hydraulic hybrid			20-25					
	Series hybrid							30-40	
Management	Predictive cruise control				1-2	1-2			1-2
	Route management					0-1			
	Training and feedback					1-4			

Source: TIAX, 2011.

3.4 Investment costs

While the reduction potentials are more or less in the same magnitude between AEA/Ricardo (2011) and TIAX (2011) the investment costs differ more significantly. Therefore, in the following sections we have a closer look at these costs, in order to explain differences and determine bandwidths of investment costs for the MAC curve model.

Before we compare the investment costs of the measures specifically, we note that an important observation for the comparison, is that the baseline vehicles in TIAX (2011) are more specified than in AEA/Ricardo (2011). For example, the Service segment in TIAX (2011), is represented by the US equivalent of a Class 2b vehicle (11,030 pounds or 5 tonnes), while the segment in AEA-Ricardo include all heavy duty vehicles 7,716 to 16,535 pounds (3.5 to 7.5 tonnes) GVWR. This may result in cost differences, as the baseline vehicles could differ.

For the investments, we assume that the lifetime of each of the measures is equal to the lifetime of the vehicle. The only exception is the category tires and wheels. For measures in this category, we assume a lifetime of 300.000 km. This value is based on RWS (2008) and Beukering et al. (2001). We have corrected for this lower lifetime in the input values by adding up reinvestments. Maintenance costs and operational costs are not considered in TIAX (2011) and AEA/Ricardo (2011) and therefore not taken into account in this study (see also scope Section 1.3). Further research is necessary to investigate the amount of these costs.

3.4.1 Aerodynamics

The measures for aerodynamics and cost estimates by TIAX and AEA/Ricardo are presented in Table 6. This information is based on tables 5-2 to 5-9 in TIAX (2011).

Table 6 **Cost differences aerodynamic measures**

	TIAX		AEA/Ricardo		
Category	**Measure**	**Costs**	**Measure**	**Costs**	**Cost difference**
Service	10% reduction in aerodynamic drag	77	Aerodynamic bodies	1,500	
			Spray reduction mud flaps	14	
	Total	77	Total	1,514	1866%
Urban delivery	Aft box taper	384	Aerodynamic bodies	1,500	
	Box skirts	576	Spray reduction mud flaps	14	
	Cab side extension or cab/box gap fairings	442			
	Roof deflector	500			
	Total	1,902	Total	1,514	-20%

	TIAX		AEA/Ricardo		
Category	Measure	Costs	Measure	Costs	Cost difference
Regional delivery	Boat tail	1,345	Aerodynamic trailers	3,500	
	Full gap fairing	961	Aerodynamic fairings	1,180	23%
	Full skirts	2,306	Spray reduction mud flaps	14	
	Total	4,612	Total	4,694	2%
Long haul	Boat tail	1,345	Aerodynamic trailers	3,500	
	Full gap fairing	961	Aerodynamic fairings	1,180	23%
	Full skirts	2,306	Spray reduction mud flaps	14	
	Total	4,612	Total	4,694	2%
Coach	Streamlining	2,114	Aerodynamic fairings	350	
			Spray reduction mud flaps	14	
			Vehicle improvements using improved aerodynamics	–	
	Total	2,114	Total	364	-83%

Table 6 shows that aerodynamics measures are applied for the categories service, urban delivery, regional delivery, long haul and coach. The cost estimates differ significantly for especially service (1,866%) and coach (83%). The differences are smaller for the categories urban delivery, regional delivery and long haul.

Some of the differences in cost estimates may be explained by the fact that the measures in the AEA/Ricardo study are more vaguely described. For instance, for urban delivery, AEA/Ricardo (2011) defines the measures as aerodynamic bodies and fairings (unspecified), while TIAX (2011) specifies aft box tapering, roof deflectors, box skirts, and cab side extensions or cab/box gap fairings. This implies that the specific measures could have different features (scope, size, definition), explaining at least part of the differences in cost estimates.

However, this will probably not explain the whole difference, especially for the service and coach segment. The differences in cost estimates for the service segment may be explained by a misinterpretation in TIAX (2011). Although in table 5-2 in TIAX (2011) is stated that aerodynamic bodies may cost € 1,500 for the service segment, we were not able to retrieve these costs in the AEA/Ricardo document.[12] However, after contacting TIAX on this issue, it appeared that the costs of AEA/Ricardo were provided to TIAX, and not presented in the report of AEA/Ricardo (2011).[13] As we have not been able to

---

[12] In AEA/Ricardo (2011) is stated that aerodynamic measures are not possible for the service segment (see table 4-22, it states that aerodynamic bodies are N/A).

[13] In table 4-21 of AEA/Ricardo (2011) is presented that aerodynamic bodies have a reduction potential of 1%. As no corresponding costs have been presented in table 4-22, TIAX has contacted AEA/Ricardo and received the cost information.

retrieve the specific information behind these cost estimates of AEA/Ricardo, we have not been able to explain this difference.

For the coach segment, in contrast to TIAX (2011), vehicle improvements using improved aerodynamics are not costed in AEA-Ricardo.[14] The differences in cost estimates for the coach segment may therefore be explained by differences in assumptions on the baseline vehicle. Possibly in AEA/Ricardo (2011) it is assumed that these measures already are adopted in the baseline vehicle.

For the other measures the total costs fall within margins of +/- 25% (see

---

[14] According to the authors of TIAX (2011), this explanation seems reasonable.

Table 5). These margins are not unexpected, as similar bandwidths are presented in TIAX/NAS (2009)[15] for aerodynamic measures, the source document of TIAX (2011). Based on the available information, we conclude that using the cost estimates of TIAX (2011) with margins of +/- 25% will be reasonable.

3.4.2 Lightweighting

The differences in costs for the lightweighting category measures are presented in Table 7.

Table 7 Cost differences lightweighting

	TIAX (2011)		AEA/Ricardo (2011)		
Category	**Measure**	**Costs**	**Measure**	**Costs**	**Cost difference**
Service	Material substitution - 5% weight reduction	480	Lightweighting	375	-22%
Urban delivery	Material substitution - 1,000 lb (454 kg)	3,666	Lightweighting	375	-90%
Municipal Utility	Material substitution - 500 lb (228 kg)	2,306	Lightweighting	5,650	145%
Regional delivery	Material substitution - 990 lb (450 kg)	2,283	Lightweighting	375	-84%
Long Haul	Material substitution - 990 lb (450 kg)	2,283	Lightweighting	1,600	-30%
Bus	Material substitution - 2,500 lb (1,134 kg)	11,760	Vehicle improvements using 5% weight reduction	-	
Coach	Material substitution - 1,500 lb (680 kg)	4,612	Vehicle improvements using weight reduction	-	

The table shows that the differences in cost estimates are substantial, especially for urban delivery, municipal utility, regional delivery, bus and coach. Some of the differences can be explained by the fact that weight reductions, in contrast to TIAX (2011), are not specified in AEA/Ricardo (2011). For example, in the Long Haul segment, the 990 lb (450 kg) material substitution weight in TIAX (2011) corresponds to specific weight savings in front, rear, and side bumpers, chassis, and accessories. In AEA/Ricardo (2011) the measures are not specified. This implies that the measures are not fully comparable, as it is not clear which weight reductions are achieved with the measures in AEA/Ricardo.

For bus and coach, the differences may be explained by assumptions on the baseline vehicle. In AEA-Ricardo lightweighting measures are not costed in contrast to TIAX (2011). This could imply that lightweighting is already assumed to be adopted in the baseline vehicle.

---

[15] See table 4-24, page 4-37. Kromer, M., W. Bockholt, M. Jackson. “Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles.” Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

For Urban delivery, municipal utility and regional delivery, the bandwidths are substantial. However, as the cost estimates in AEA/Ricardo (2011) are not tied to specific weight reductions, it is difficult to explain the differences.[16] The bandwidths of the service and long haul segment fall within the cost margins of the TIAX/NAS (2009), the source document of TIAX (2011).[17] We will use the cost estimates of TIAX (2011) with a margin of +/- 30% as input values for the MAC curve model.

3.4.3 Tires and wheels

The cost estimates in the category tires and wheels are presented in Table 8.

Table 8 **Cost differences tires and wheels**

	TIAX (2011)		AEA/Ricardo (2011)		
Category	**Measure**	**Costs**	**Measure**	**Costs**	**Cost difference**
Service	Low rolling resistance tires	8	Low rolling resistance tires	250	3025%
			Single wide tires	825	
			Automatic tire pressure adjustment	11,790	
Urban delivery	Low rolling resistance wide-base single tires with aluminum wheels (2)	346	Low rolling resistance tires	250	-28%
			Single wide tires	825	
			Automatic tire pressure adjustment	11,790	
Municipal utility	Low rolling resistance tires	231	Low rolling resistance tires	300	30%
			Single wide tires	825	
			Automatic tire pressure adjustment	11790	
Regional delivery	Next generation low rolling resistance wide-base single tires with aluminum wheels (2)	346	Low rolling resistance tires	350	1%
	Automatic tire inflation on trailer	269	Single wide tires	825	
	Automatic tire inflation on tractor	3,459	Automatic tire pressure adjustment	11,790	216%

---

[16] The authors of TIAX (2011) were not able to explain these differences as well, due to lack of specification of the measures in AEA/Ricardo (2011).

[17] See tables 4-39 to 4-42 (TIAX/NAS 2009). Margins in capital cots range from 11% (940 to 1,650 lbs) to 33% (0-470 lbs and 470 to 940 lbs).

	TIAX (2011)		AEA/Ricardo (2011)		
Category	Measure	Costs	Measure	Costs	Cost difference
Long haul	Next generation low rolling resistance wide-base single tires with aluminum wheels (2)	346	Low rolling resistance tires	350	1%
	Automatic tire inflation on trailer	269	Single wide tires	1,300	
	Automatic tire inflation on tractor	3,459	Automatic tire pressure adjustment	11,790	216%
Bus	Low rolling resistance tires	231	Low rolling resistance tires	350	52%
			Single wide tires	825	
			Automatic tire pressure adjustment	11,790	
Coach	Low rolling resistance tires	184	Low rolling resistance tires	350	90%
	Automatic tire inflation	269	Automatic tire pressure adjustment	11,790	4283%
			Single wide tires	825	

Table 8 shows that cost estimates diverge widely for some of the categories. Cost estimates for low rolling resistance differ most for the service segment (3,025%). For the bus and coach segment, differences are substantial as well (52 and 90% respectively). For the other segments, differences are smaller (1% - 30%).

According to TIAX (2011), these differences may be explained by the selected vehicles to represent each segment. The costs for low rolling resistance tires for the service category (€ 8) represent the lighter vehicles in the segment, whereas the costs in AEA/Ricardo (2011) (€ 250) may represent the heavier vehicles. As explained earlier, the baseline vehicles in AEA/Ricardo (2011) are not specified. It is therefore possible that the costs of low rolling resistance tires differ widely, based on the specification of the baseline vehicle.

Cost differences for the automatic tire inflation systems are not unexpected, as the TIAX/NAS study received wildly diverging cost estimates for automatic tire inflation systems (€ 230 to € 10,000). It seems that many systems are available on the market, and the sophistication of the systems differs widely.

To summarize, we can conclude that the investment costs of measures in the tires and wheels segment can differ widely based on assumptions of the specification of the baseline vehicle and sophistication of the measure. We therefore propose to use the TIAX (2011) estimates as lower band value, and the values in AEA-Ricardo to create upper bands, implying a very wide cost range for measures in this category.

3.4.4 Transmission and driveline and engine efficiency

The cost estimates in the categories engine efficiency and transmission and driveline are difficult to compare due to differences in assumptions between the studies on the baseline vehicles. In contrast to TIAX (2011), in AEA/Ricardo (2011) is assumed that engine improvements such as higher injection pressure or higher cylinder pressures are year-to-year product improvements and were not costed. For the transmission and drivelines category, the potential measures differ because of different assumptions on the baseline vehicle. AEA/Ricardo assumed that the baseline vehicle was equipped with a manual transmission. TIAX (2011) assumes a mix of automatic, manual, and automated manual transmissions.

As the measures differ, we have not compared cost estimates. We use the cost estimates of TIAX (2011) as base value for the MAC curve model and based on TIAX/NAS (2009), we estimate a bandwidth on the costs for engine efficiency, transmission and driveline measures of +/- 30%.

3.4.5 Hybridization

The costs for hybridization are presented in Table 9.

Table 9 Cost differences hybridization

	TIAX (2011)		AEA/Ricardo (2011)		
Category	**Measure**	**Costs**	**Measure**	**Costs**	**Cost difference**
Service	Dual-mode hybrid electric	22,290	Full hybrid (electric)	24,000	8%
Urban delivery	Parallel hybrid electric (engine-off at idle, electric accessories, optimized controls, lighter components)*	14,604	Full hybrid (electric)	24,000	64%
Municipal Utility	Parallel hydraulic hybrid*	23,059	Hydraulic hybrid	13,200	-43%
Regional delivery	Gen II dual hybrid with all electric capability, electrified accessories, overnight hotel loads, engine-off at idle	17,871	Full hybrid (electric)	24,000	34%
Long Haul	Gen II dual hybrid with all electric capability, electrified accessories, overnight hotel loads, engine-off at idle	21,137	Full hybrid (electric)	24,000	14%
Bus	Series hybrid electric	16,910	Full hybrid (electric)	24,000	42%
Coach	Gen II parallel hybrid electric	26,902	Full hybrid (electric)	24,000	-11%

Table 9 shows that costs for hybridization are not specified between the vehicle categories in AEA/Ricardo (2011). The costs of electric hybrids are estimated to be € 24,000 for all vehicle categories. This explains the major differences between the studies, as the costs for hybrids are specified for all categories in TIAX (2011). However, costs in AEA/Ricardo (2011) are higher for almost all categories. One of the explanations is the technology specification (full hybrid versus parallel, series, etc.). Furthermore, the cost estimates of series hybrid electrics for the bus and regional delivery segments may be (far) too low. According to Scania, investment costs of € 20,000-30,000 are more likely for the regional delivery segment and € 50,000-70,000 for the bus segment. Scania agrees with other cost estimates of TIAX (2011).

As we consider it unlikely that costs for hybridization are the same for each of the categories, we propose to use the TIAX (2011) estimates as base values. We estimate the bandwidths on the cost to be +/- 20% for each of the categories, based on estimates in (TIAX/NAS, 2009). Based on comments of

Scania, the upper bounds of regional delivery and bus segment are respectively € 30,000 and € 70,000.

3.4.6 Management

The cost of management measures are presented in Table 10.

Table 10 Cost differences management

	TIAX (2011)		AEA/Ricardo (2011)		
Category	**Measure**	**Costs**	**Measure**	**Costs**	**Cost difference**
Regional delivery	Predictive cruise control	77	predictive cruise control	1,400	1718%
Long haul	Predictive cruise control	77	Predictive cruise control	1,400	1718%
	Route management	461	Vehicle improvements using driver aids	–	
	Training and feedback	615			
	Total	1,153		1,400	21%
Coach	predictive cruise control	77	predictive cruise control	1,400	1718%

Table 10 shows that cost estimates differ widely. For the predictive cruise control, TIAX (2011) estimates costs as low as € 77, while AEA/Ricardo (2011) estimates costs of € 1,400. It's not immediately clear why the estimates would differ so much. It's possible that AEA-Ricardo relied on some older numbers in developing their cost estimates (e.g. some sources on page 141 of their report were from 2004/2005). The cost estimates in TIAX (2011) have been based on interviews with OEM's in 2009.

3.5 Conclusion

In this chapter the input parameters of the MACH model for the cost curves have been presented. For consistency reasons, we have selected the measures from TIAX (2011) to create a coherent set of measures. The fuel consumption benefits have been based on TIAX (2011), while ranges of the investment costs have been determined based on estimates of TIAX (2011), TIAX/NAS (2009), AEA/Ricardo (2011) and comments from Scania and Daimler on TIAX (2011).

4 Output

4.1 Introduction

In this chapter we present the main results of the MACH model. These are the cost curves (from a social perspective) for the different vehicles segments using the default parameters as presented in the previous chapters (Section 4.2 and 4.9). Additionally, the break-even abatement potentials (abatement potential realised by technologies with zero or negative costs) under various assumptions for the time period considered (life time of the vehicle or three years[18]) and fuel price scenarios (low, reference and high) are discussed (both for a social and an end-user perspective). Also the impact of the discount rate and the investment costs applied will be discussed. In Section 4.10 the results for the average bus and truck will be presented. Finally, the main conclusions are presented in Section 4.11.

4.2 Service

The cost curve for the service segment is presented in the Figure 2.

Figure 2 **Cost curve service segment**

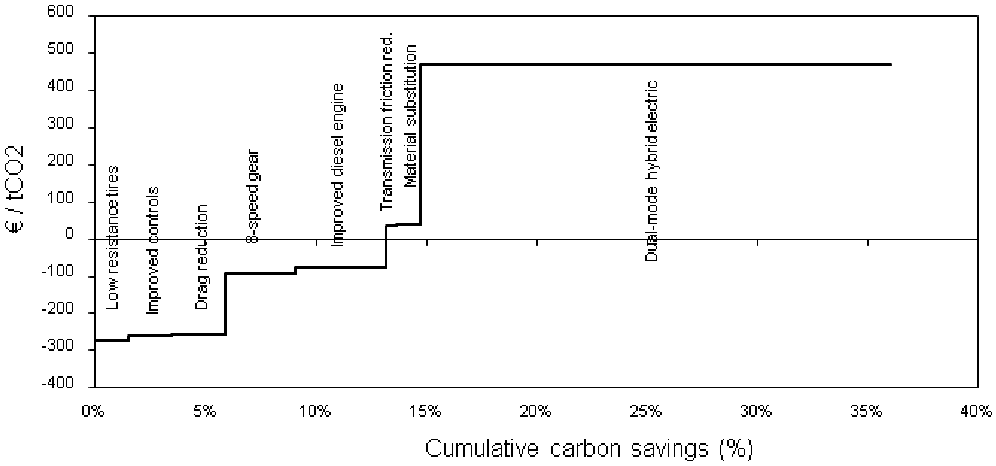


Figure 2 shows that from a social perspective most of the measures in the service segment have negative cost effectiveness when taking into account the complete lifetime of the measure. Transmission friction reduction, material substitution and dual mode hybrid electric are no cost effective measures, implying that benefits do not outweigh the costs over the lifetime of the measure. The dual mode hybrid electric has the largest reduction potential. However, it is by far the most cost ineffective measure as well. The break-even reduction potential is 13% under basic assumptions.

---

[18] Three years are often considered a payback period required by HDV owners in purchase decisions.

Sensitivity analyses time horizon, fuel price and cost perspective
In Table 11 the break-even abatement potentials for service trucks under various assumptions with respect to the time horizon, fuel price and cost perspective are presented. The results show that if a time horizon (payback period) of three years is applied, less technologies will be considered cost effective and hence the cost effective abatement potential will be lower. The impact of fuel prices on the cost effective abatement potential is rather small[19].

Table 11 **Break-even abatement potentials service trucks under various assumptions (%)**

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	6%	13%
Reference fuel price scenario	6%	13%
High fuel price scenario	6%	13%
End-user perspective		
Low fuel price scenario	6%	15%
Reference fuel price scenario	6%	15%
High fuel price scenario	6%	15%

Sensitivity analysis discount rate
Next to the sensitivity analyses presented above we also carried out a sensitivity analysis for the discount rate that is applied. Assuming a social perspective (as well a long time horizon and a reference fuel price scenario) we calculated the abatement costs for both a discount rate of 2 and 7%. In both situations the break-even abatement potential is equal to 13%, which is equal to the reference case.

Sensitivity analysis investment cost
Finally, sensitivity analyses for the investment costs were carried out. These analyses shows that if we apply the lower bound of the investment cost estimates as presented in Chapter 3, the break-even abatement potential increases from 13 to 15% (the same reference as in the sensitivity analysis for the discount rate was applied); this is due to the fact that material substitution becomes cost effective (zero or negative abatement costs) if the lower investment cost estimates are considered. Applying the higher investment cost estimates (see Chapter 3) doesn't affect the break-even abatement potential.

---

[19] Although it should be mentioned that the differences between the reference and high fuel price scenario are relatively small.

4.3 Urban delivery

The cost curve for the urban delivery segment is presented in Figure 3.

Figure 3 Cost curve urban delivery

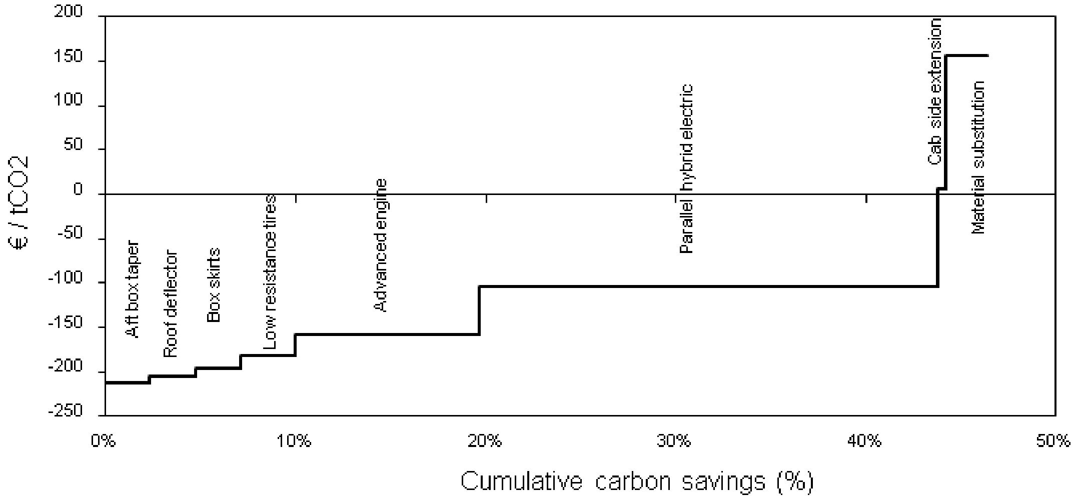


Figure 3 shows that from a social perspective most of the measures are cost effective taking into account the entire lifetime of the measure. Exceptions are the cab side extension and material substitution. The cost curve shows that there is a large reduction potential (44%) of cost effective measures, especially because of the advanced engine and parallel hybrid electric which are both cost effective measures under the default assumptions.

Sensitivity analyses time horizon, fuel price and cost perspective
In Table 12 the break-even abatement potentials of urban delivery trucks under various assumptions are shown. The break-even abatement potential depends heavily on the time horizon (payback period) applied. In case of a long time horizon hybridisation and advanced engine options are cost effective, while they aren't in most of the scenarios with a short time horizon (the only exception is a high fuel scenario from an end-user perspective in which case advanced engine options are cost effective). Next to the time horizon also the fuel price scenarios applied affects the break-even abatement potential. Finally, the break-even abatement potential is higher if an end-user perspective is applied in stead of a social perspective.

Table 12 Break-even abatement potentials urban delivery trucks under various assumptions (%)

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	3%	44%
Reference fuel price scenario	5%	44%
High fuel price scenario	5%	44%
End-user perspective		
Low fuel price scenario	10%	44%
Reference fuel price scenario	10%	44%
High fuel price scenario	20%	44%

Sensitivity analysis discount rate
As for the service trucks, the sensitivity analyses for the discount rate shows that the break-even abatement potential is – ceteris paribus - not affected by changes in the discount rate.

Sensitivity analysis investment cost
If we apply the low values of the investment costs (as presented in Chapter 3) the abatement cost of all technologies are negative. This implies that under these assumptions all technical options could be applied with negative costs. Compared to the reference case also material substitution and cab side extension could be applied with negative costs in this case. On the other hand, applying the high values of the investment costs doesn't affect the break-even abatement potential.

4.4 Municipal utility

The cost curve for the municipal utility segment is presented in Figure 4.

Figure 4 **Cost curve municipal utility**

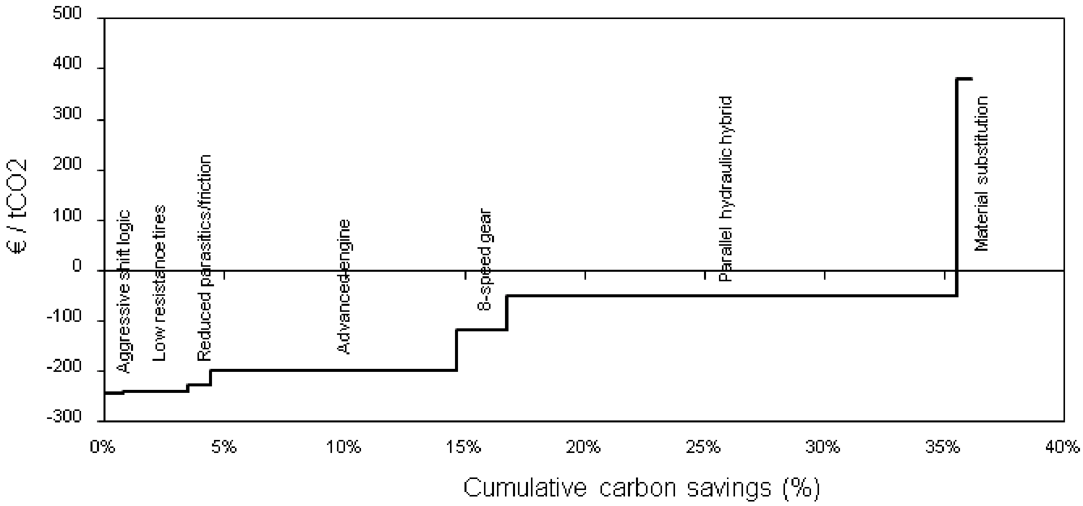


Figure 4 shows that from a social perspective the break-even abatement potential is 36% taking into account the entire lifetime of the measure. Only the material substitution measure is not cost effective under default assumptions.

Sensitivity analyses time horizon, fuel price and cost perspective
The break-even abatement potentials of municipal utility trucks under various assumptions are presented in Table 13. Again, the break-even abatement potentials are significantly lower if a time horizon of three years is applied instead of the lifetime of the measure (particularly since hybridisation is cost effective in most scenarios with a long time horizon, while it isn't on the short term). Particularly for the short time horizon of three years significant differences exist between the break-even abatement potential from a social and an end-user perspective (particularly due to the fact that advanced engine options are only cost effective from an end-user perspective).

Table 13 Break-even abatement potentials municipal utility trucks under various assumptions (%)

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	4%	17%
Reference fuel price scenario	4%	36%
High fuel price scenario	4%	36%
End-user perspective		
Low fuel price scenario	15%	36%
Reference fuel price scenario	15%	36%
High fuel price scenario	15%	36%

Sensitivity analysis discount rate

Applying a higher discount rate (7%) results in a break-even level of 17% instead of 36% in the reference case. This is due to the fact that in this case hybrid trucks are not cost effective anymore. Applying a lower discount rate (2%) doesn't affect the break-even abatement potential.

Sensitivity analysis investment cost

Compared to the reference case applying different investment costs (within the ranges determined in Chapter 3) doesn't affect the break-even abatement potential for municipal utility trucks.

4.5 Regional delivery

The cost curve for the regional delivery segment is presented in Figure 5.

Figure 5 Cost curve regional delivery

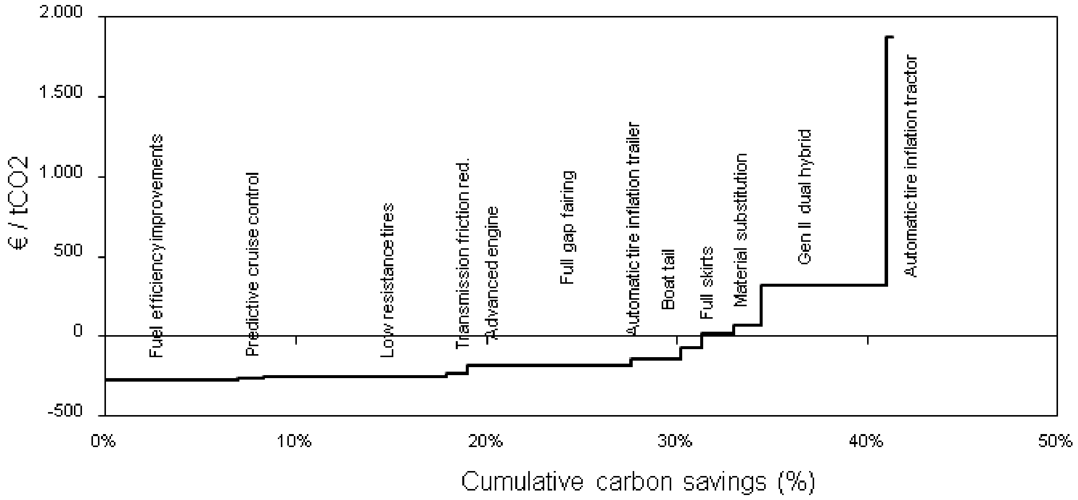


Figure 5 shows a break-even abatement potential of 31% (social perspective). The Y axis is stretched very much in this figure, because the automatic tire inflation system on the tractor is a very cost ineffective measure (abatement costs over € 1,500 per tonne CO_2).

Sensitivity analyses time horizon, fuel price and cost perspective
The break-even abatement potentials of regional delivery trucks under various assumptions are presented in Table 14. If a time horizon of three years is applied still significant cost effective abatement potentials are available (19% from a social perspective and 28% from an end-user perspective), although these potentials are considerably higher in case the time horizon of the lifetime of the measure is considered. As for most of the other segments, the abatement costs of technologies for regional delivery trucks are higher from an end-user perspective than from a social perspective.

Table 14 Break-even abatement potentials regional delivery with various assumptions (%)

	Time horizon: three years	**Time horizon: measure's lifetime**
Social perspective		
Low fuel price scenario	19%	31%
Reference fuel price scenario	19%	31%
High fuel price scenario	19%	31%
End-user perspective		
Low fuel price scenario	28%	33%
Reference fuel price scenario	28%	35%
High fuel price scenario	28%	35%

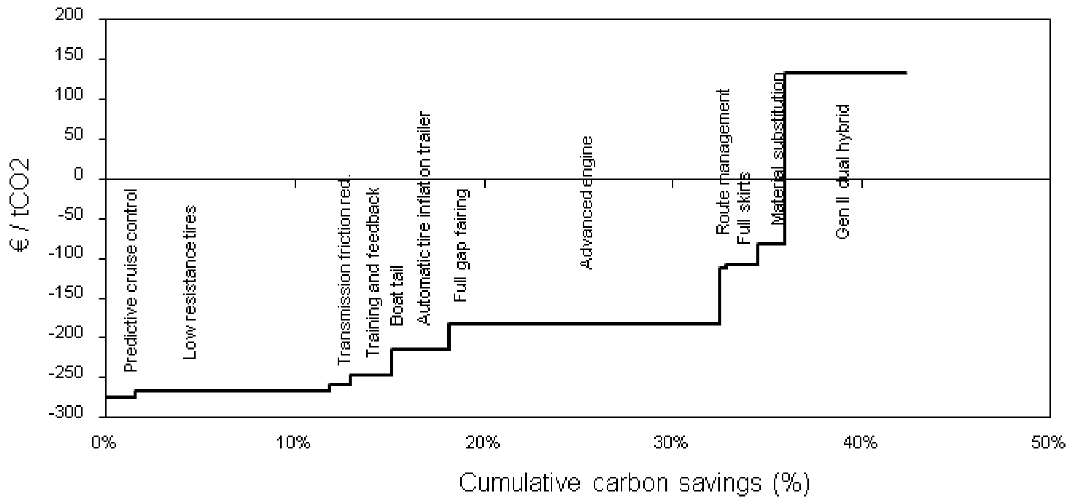
Sensitivity analysis discount rate
Applying a lower discount rate (e%) results in a break-even level of 33% instead of 31% in the reference case. This is due to the fact that in this case full skirts become cost effective. Applying a higher discount rate (7%) doesn't affect the break-even abatement potential.

Sensitivity analysis investment cost
Applying the lower bound of the investment costs determined in Chapter 3 results in an increase of the break-even abatement potential to 35% (compared to 31% in the reference case). This is due to the fact that full skirts, material substitution and automatic tire inflation for the trail become cost effective under these assumptions. Applying the higher bound of the investment costs doesn't affect the break-even abatement potential.

4.6 Long haul

The cost curve for the long haul segment shows that from a social perspective all measures are cost effective within the lifetime of the measure, except the gen II dual hybrid.

Figure 6 **Cost curve long haul**



Sensitivity analyses time horizon, fuel price and cost perspective

As is shown in Table 15 most technologies (with the exception of hybridisation for all scenarios and material substitution and full skirts for some scenarios) are cost effective under almost all assumptions. The cost effective reduction potential is ca. 33-36%.

Table 15 **Break-even abatement potentials long haul trucks under various assumptions (%)**

	Time horizon: three years	**Time horizon: measure's lifetime**
Social perspective		
Low fuel price scenario	33%	36%
Reference fuel price scenario	33%	36%
High fuel price scenario	33%	36%
End-user perspective		
Low fuel price scenario	33%	36%
Reference fuel price scenario	33%	36%
High fuel price scenario	33%	36%

Sensitivity analysis discount rate

Adjusting the discount rate (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

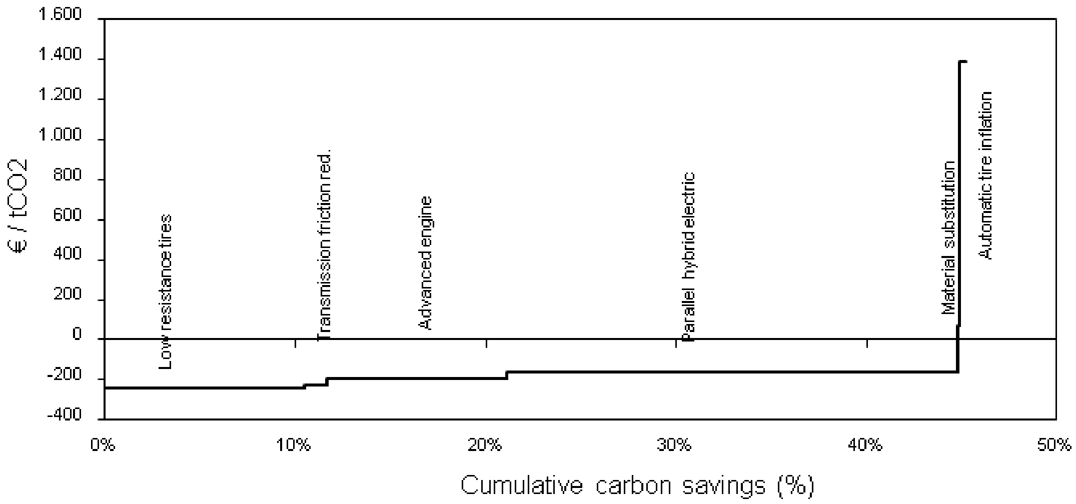
Sensitivity analysis investment cost

Adjusting the investment costs (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

4.7 Construction

For construction, the cost curve shows that from a social perspective a reduction potential of 45% is feasible taking into account the entire lifetime of measures. Only material substitution and automatic tire inflation are not cost effective, but the potential of these measures in small in comparison to the other measures.

Figure 7 Cost curve construction



Sensitivity analyses time horizon, fuel price and cost perspective

As is shown in Table 16 the break-even abatement potential differs significantly between a three years time horizon and a time horizon equal to the measure's lifetime: for a couple of technologies (hybridisation, advanced engine options) the (investment) costs will be paid back over the vehicle's lifetime, but not within a period of three year. For the short time horizon there are also significant differences between the cost effective abatement potentials from a social and an end-user perspective (12 vs. 21%).

Table 16 Break-even abatement potentials construction trucks under various assumptions (%)

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	12%	45%
Reference fuel price scenario	12%	45%
High fuel price scenario	12%	45%
End-user perspective		
Low fuel price scenario	21%	45%
Reference fuel price scenario	21%	45%
High fuel price scenario	21%	45%

Sensitivity analysis discount rate

Adjusting the discount rate (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

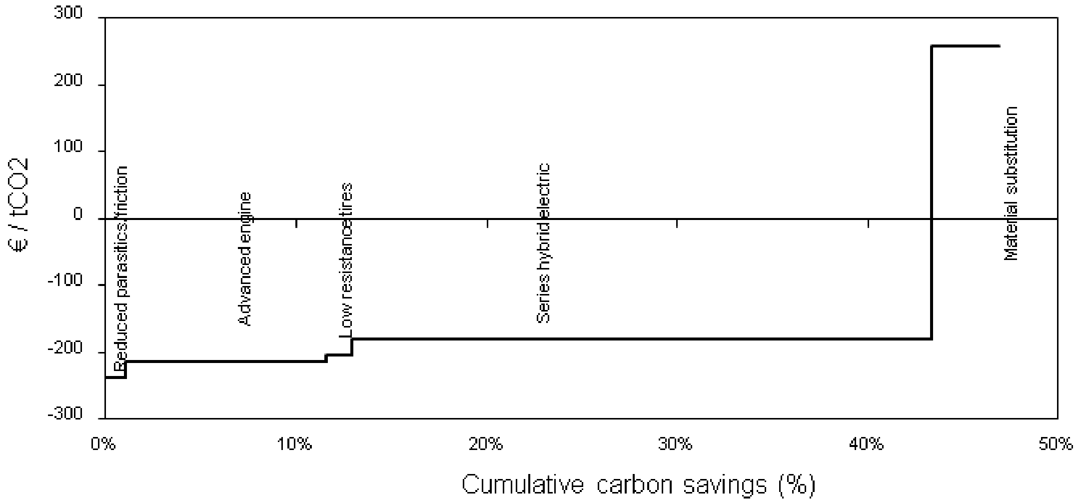
Sensitivity analysis investment cost

Adjusting the investment costs (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

4.8 Bus

Figure 8 shows that from a social perspective the break-even abatement potential for the bus segment is 43%. Only material substitution is not cost effective taking into account the entire lifetime.

Figure 8 Cost curve bus segment



Sensitivity analyses time horizon, fuel price and cost perspective

As is shown in Table 17 the cost effective abatement potentials of busses depends heavily on the time horizon considered, particularly if a social perspective is applied. This is mainly due to the fact that hybridisation is not a cost effective option on the short term from a social perspective. From an end-user perspective hybridisation is a cost effective options as fuel prices are relatively high (reference or high scenario).

Table 17 **Break-even abatement potentials busses under various assumptions (%)**

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	13%	43%
Reference fuel price scenario	13%	43%
High fuel price scenario	13%	43%
End-user perspective		
Low fuel price scenario	13%	43%
Reference fuel price scenario	43%	43%
High fuel price scenario	43%	43%

Sensitivity analysis discount rate

Adjusting the discount rate (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

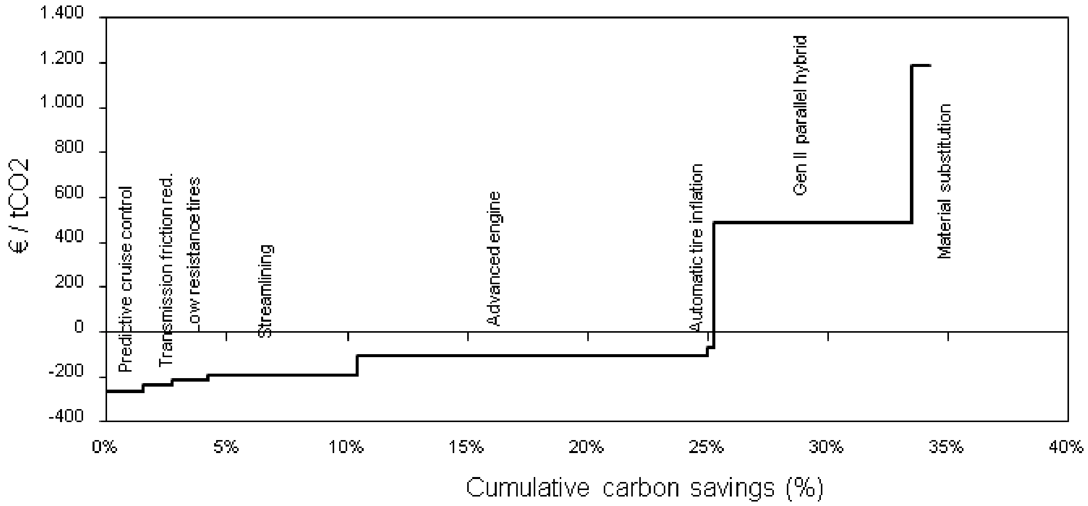
Sensitivity analysis investment cost

Applying the upper bound of the investment costs (as determined in Chapter 3) results in a decrease of the break-even abatement potential: from 43% to 13%. This rather large reduction could be explained by the fact that in this scenario hybrid busses are not cost effective anymore. Applying the lower bound of the investment cost doesn't affect the break-even abatement potential.

4.9 Coach

The cost curve for the coach sector is presented in Figure 9. The break-even abatement potential is 25% (social perspective). Only the gen II parallel hybrid and material substitution are no cost effective measures taking into account the entire lifetime.

Figure 9 **Cost curve coach segment**



Sensitivity analyses time horizon, fuel price and cost perspective

As is shown in Table 18 several abatement technologies (advanced engine options, automatic tire inflation (both social and end-user perspective), streamlining in case of a social perspective) for coaches are only cost effective if a long time horizon is considered.

Table 18 **Break-even abatement potentials coaches under various assumptions (%)**

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	4%	25%
Reference fuel price scenario	4%	25%
High fuel price scenario	4%	25%
End-user perspective		
Low fuel price scenario	10%	25%
Reference fuel price scenario	10%	25%
High fuel price scenario	10%	25%

Sensitivity analysis discount rate

Adjusting the discount rate (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

Sensitivity analysis investment cost

Adjusting the investment costs (within the range determined in Chapter 3) doesn't affect the break-even abatement potential (compared to the reference case).

4.10 Average cost curves

The cost curve for an 'average' truck from as social perspective is shown in Figure 10. It shows that from a social perspective a break-even abatement potential of about 30% exists for trucks (in case a long time horizon is applied). As is shown in Table 19 the cost effective abatement potential is lower if a short time horizon is considered: ca. 20–23%. Assuming a long time horizon, social perspective and reference fuel price scenario, adjusting the discount rate results in small change in the break-even abatement potential: 32-34%. Finally, also adjusting the investment costs within the ranges determined in Chapter 3 only results in small changes of the break-even abatement potential: 33-34%.

Figure 10 Cost curve average truck

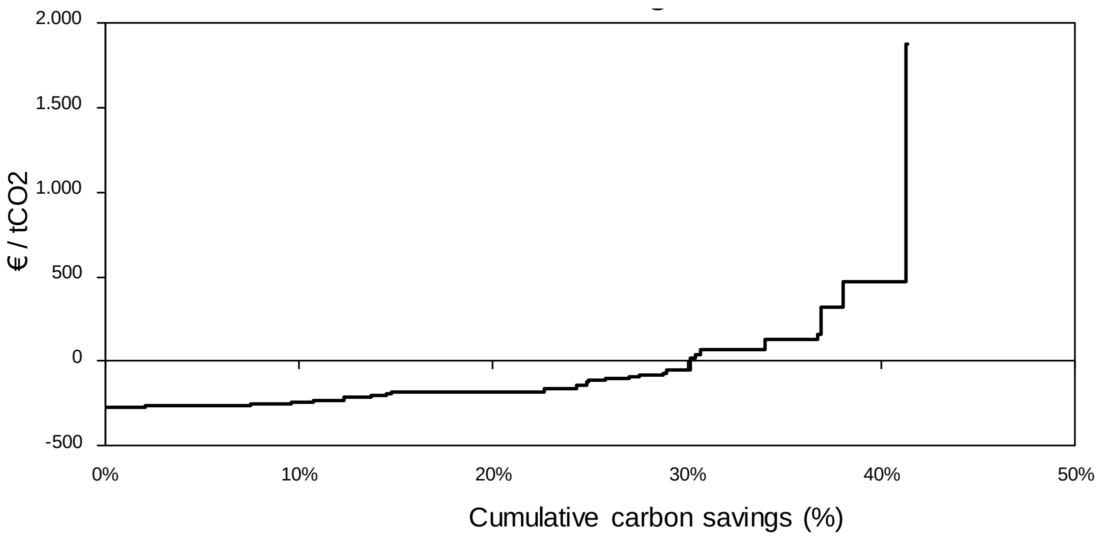


Table 19 Break-even abatement potential 'average truck' under various assumptions (%)

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	20%	29%
Reference fuel price scenario	20%	30%
High fuel price scenario	20%	30%
End-user perspective		
Low fuel price scenario	23%	30%
Reference fuel price scenario	23%	31%
High fuel price scenario	23%	31%

The cost curve of an 'average' bus from a social perspective is shown in Figure 11, while the break-even abatement potentials under various assumptions are shown in Table 20. If a long time horizon is applied a break-even abatement potential of ca. 36% could be realised. If a short time horizon is considered the break-even abatement potential is significantly lower; from a social perspective the potential is only 9%, while from an end-user perspective the potential ranges from 12 to 30% (depending on the fuel price scenario). In the latter case technical options like hybridisation for busses and streamlining for coaches become cost effective (thanks to higher fuel prices).

Compered to the reference case (social perspective, long time horizon, reference fuel price scenario) adjusting the discount rate (within the range of 2 to 7%) doesn't affect – ceteris paribus – the break-even abatement potential. However, adjusting the investment costs may result in a change of the break-even abatement potential. Applying the upper bound of the investment costs results in a reduction of the break-even abatement potential to 18%, which is particularly due to the fact that hybrid busses are not cost-effective anymore under these assumptions.

Figure 11 **Cost curve average bus**

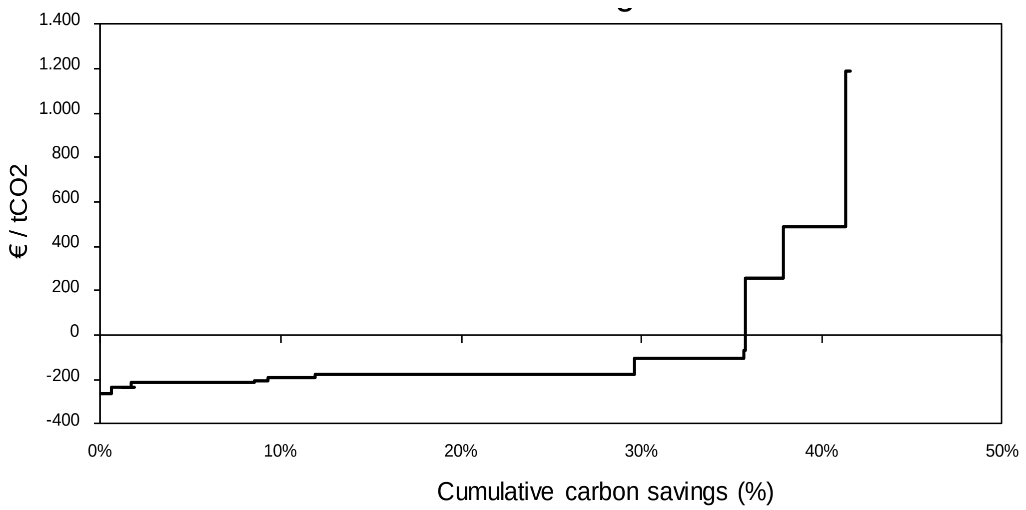


Table 20 **Break-even abatement potential 'average bus' under various assumptions (%)**

	Time horizon: three years	Time horizon: measure's lifetime
Social perspective		
Low fuel price scenario	9%	36%
Reference fuel price scenario	9%	36%
High fuel price scenario	9%	36%
End-user perspective		
Low fuel price scenario	12%	36%
Reference fuel price scenario	30%	36%
High fuel price scenario	30%	36%

4.11 Conclusion

The cost curves show that from a social perspective the break-even potential of reduction measures is significant when taking into account the entire lifetime of the measure. From an end-user perspective the potentials are equal or even larger. However, if a short time horizon (three years) is considered the cost effective abatement potential for all vehicle categories reduces. Since a smaller share of the financial benefits due to fuel savings are taken into account, technologies are judged less cost effective. In some cases also fuel prices significantly affect the cost effective abatement potential for the various vehicle categories.

Next to the sensitivity analyses applied with respect to the cost perspective, time horizon and fuel price scenario, we also carried out sensitivity analyses for the discount rate and the investment costs considered. Compared to the reference case (social perspective, long time horizon and reference fuel price scenario) the impacts of adjustments in the discount rate (within the range of 2–7%) on the break-even abatement potentials are rather small. Changes in investment costs (within the ranges determined in Chapter 3) have a larger but still rather small impact on the break-even abatement potentials (with the exceptions of busses).

Finally, it should be noticed that the MACH model provides the opportunity to combine the various sensitivity analyses discussed above. However, the results of these kinds of analyses are not presented in this report.

References

AEA/Ricardo, 2011
Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy
Oxfordshire : AEA, 2011

AEA, 2001
Economic evaluation of emissions reductions for the transport sector of the EU, Bottom up analysis
Oxfordshire : AEA, 2001

Blok et al., 2001
Economic evaluation of sectoral emission reduction objectives for climate change, bottom up analysis of emission reduction potentials and costs for GHG in the EU
Utrecht : Ecofys, 2001

CE, 2012
Schroten, A., Warringa, G., Van Essen, H., Bolech, M., Fraga, F., Smokers, R.
EU Transport GHG: Routes to 2050? Cost effectiveness of policies and options for decarboning transport
Delft : CE Delft, 2012

European Commission, 2010
R. Edwards, D. Mulligan and L. Marelli
Indirect Land Use Change from increased biofuels demand
Brussels : European Commission, Joint Research Centre Institute for Energy, 2010

European Commission, 2011
Transport White Paper: Roadmap to a single European transport area – Towards a competitive and resource efficient transport system
COM (2011) 144 final
Brussels : European Commission, 2011

European Parliament, 2011
R. Fritsche, K. Wiegmann
Indirect Land Use Change and Biofuels
This document is available on the Internet at:
http://www.europarl.europa.eu/activities/committees/studies.do?language=EN
Brussels : European Parliament, 2011

Hill et al., 2012
Hill, N., Brannigan, C., Smokers, R., Schroten, A., Van Essen, H., Skinner, I.
Developing a better understanding of the secondary impacts and key sensitivities for the decarbonisation of the EU's transport sector by 2050
Oxfordshire : AEA, 2012

ICCT, 2011
Indirect land use change in Europe – considering the policy options
Washington : ICCT, 2011

IFPRI, 2011
Assessing the land use change consequences of European biofuel policies

Washington : IFPRI, 2011

INFRAS, 2006
Cost-effectiveness of greenhouse gases emission reductions in various sectors, final report
Framework Service Contract No Entr/05/18
Zurich : INFRAS, 2006

RWS, 2008
Inventarisatie vrachtwagen banden. Een inventarisatie naar de wenselijkheid en noodzaak van het stellen van nadere eisen aan vrachtwagenbanden met bijzondere aandacht voor minimum profieldiepte.
Delft: RWS, 2008

Skinner et al., 2010
Skinner, I., Van Essen, H., Smokers, R., Hill, N.
EU Transport GHG: Routes to 2050? Towards the decarbonisation of the EU's transport sector by 2050
Oxfordshire : AEA, 2010

Smokers et al., 2012
Smokers, R., Fraga, F., Skinner, I., Kampman, B., Hill, N.
EU Transport GHG: Routes to 2050? Identification of the major risks/uncertainties associated with the achievability of considered policies and measures
Delft : TNO, 2012

TIAX/NAS, 2009
Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles
Cupertino : TIAX, 2009

TIAX, 2011
European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles
Cupertino : TIAX, 2011

TNO et al., 2006
R. Smokers, R. Vermeulen, R. van Mieghem, R. Gense (all TNO). I. Skinner, M. Fergusson, E. Mackay, P. ten Brink (all IEEP). G. Fontaras, Z. Samaras (both LAT)
Review and analysis of the reduction potential and costs of technological and other measures to reduce CO_2-emissions from Delft, passenger cars
Delft : TNO, 2006

US Energy Information Administration, 2011
International Energy outlook 2011

Van Beukering et al., 2001
Van Beukering, P.J.H., Janssen, M.A.
A Dynamic Integrated Analysis of Truck Tires in Western Europe
Journal of industrial ecology. 2001 by the Massachusetts Institute of Technology and Yale University Volume 4, Number 2