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GHG Mitigation Potentials and Costs in the Transport Sector of Annex I Countries: Methodology, Version 2

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Interim Report **IR-09-039**

GHG mitigation potentials and costs in the transport sector of Annex I countries

Methodology
Version 2

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Approved by
Markus Amann
Program Leader, APD
November 6, 2009

This report documents the specific methodology of IIASA's GAINS model for emissions from transport activities that has been used for comparing mitigation efforts across Annex I Parties.

The following additional information sources are available at http://gains.iiasa.ac.at/Annex1.html

- An interactive **GAINS GHG mitigation efforts calculator** that allows online-comparison of mitigation efforts across Annex I Parties. Free access is provided at http://gains.iiasa.ac.at/MEC.
- Access to all input data employed for the calculations for all countries via the on-line version of the GAINS model at http://gains.iiasa.ac.at.

The following report documents the basic methodology of IIASA's GAINS model that has been used for comparing mitigation efforts across Annex I Parties:

- Potential and costs for greenhouse ghas mitigation in Annex I countries. M. Amann et al., 2008

Other reports to document specific methodology details are:

- Estimating CO_2 mitigation potentials and costs from energy use and industrial sources. J. Cofala, P. Purohit, P.Rafaj. Z. Klimont, 2008
- Mitigation potentials from transportation in Annex I countries. J. Borken *et al.*, 2008
- Estimating GHG mitigation potentials from LULUCF in Annex I countries. H. Boettcher *et al.*, 2008

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Executive summary

It is consensus among the Parties of the Climate Convention to "achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system." This will require significant reductions in emissions. The efforts and investments over the next two to three decades will have a decisive impact on whether, how and when to achieve stabilisation levels of greenhouse gases. It will be a formidable challenge to negotiating Parties to arrive at an accepted scheme for sharing efforts ensuring the necessary emission reductions.

This report documents the GAINS methodology that has been developed to compare greenhouse gas mitigation potentials and costs for the transport sector in Annex I countries. The focus is on technologies for road transportation, the sub-sector with the biggest emissions. The same method could be applied in principle to the other transport modes.

In this report the International Institute for Applied Systems Analysis (IIASA) presents a coherent international comparison of greenhouse gas mitigation measures in the transport sector for Annex I Parties in 2020. In brief, the method (i) adopts exogenous trend projections of transport energy consumption, economic and population developments (the Word Energy Outlook 2008 of IEA) as starting point, (ii) develops a corresponding baseline projection of greenhouse gas emissions for 2020 with information derived from the national GHG inventories that have been reported by Parties to the UNFCCC for 2005, (iii) estimates bottom-up the potential emission reductions that could be achieved if new technologies would be applied as stringently as possible from 2010 onwards (maximum feasible potential scenario) and (iv) quantifies the associated extra costs that would emerge if these technologies would be applied under the specific national conditions. The method applies a detailed turn-over modelling of the technologies, using penetration rates for new technologies, and their associated extra costs relative to the baseline development.

Access to all input data that have been employed for the calculation is available over the Internet at http://gains.iiasa.ac.at/Annex1.html.

About the authors

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Glossary of terms used in this report

AT PZEV	Advanced technology partial zero emission vehicle (as defined by the Californian Air Resources Board. This corresponds to an HEV.)
BEV	Battery electric vehicles
Enhanced AT PZEV	AT PZEV using a ZEV fuel such as electricity or hydrogen. Examples include plug-in hybrids.
FAME	Fatty acid methyl ester, the general chemical name for “biodiesel” derived from plant oil by esterification, e.g. taking rape seed, soy beans or palm oil as feedstock
FCV	Fuel cell vehicle
GHG	Greenhouse gas
HEV	Hybrid electric vehicle (i.e. with an internal combustion engine as well as an electric engine)
ICE	Internal combustion engine
MAC	Mobile air conditioner
PHEV	Plug-in hybrid electric vehicle, i.e. with electric charging from the grid and all electric autonomy >50 km
PZEV	Partial zero emission vehicle (as defined by the Californian Air Resources Board. This corresponds to conventional vehicles certified to the most stringent tailpipe emission standards.)
TA	Type approval (relevant for choice of test cycle and its specifications)
WTT	Well-to-tank, meaning (here) energy demand and related emissions for the provision of final energy (here a transport fuel) to the vehicle tank.
WTW	Well-to-wheel, meaning (here) energy demand and related emissions for the propulsion of a vehicle including WTT demand/emissions.
ZEV	Zero emission vehicle (as defined by the Californian Air Resources Board. This corresponds to a FCV or BEV.)

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1 Modelling road transport's energy demand

This report documents the approach and key assumptions for modelling the energy demand and subsequent carbon dioxide emissions from road transportation. Emissions are calculated from fuel consumption by technology specific emission factors. Therefore, fuel consumption is the base variable. The modelling proceeds in the following steps:

1. Define the range of technologies considered,
2. Define the technology characteristics in terms of fuel efficiency and extra costs,
3. Model fuel consumption in a baseline development,
4. Model fuel consumption in alternative scenarios by higher application of more efficient technologies and determine the maximum feasible (technical) potential.
5. The best mix of technologies is then determined as that mix of technologies giving lowest fuel consumption at least total costs over the baseline. Costs are determined as the trade-off between extra investment for new technologies plus extra maintenance and running costs minus fuel savings over the lifetime of the technology.

The difference between the baseline development and the scenario shows fuel reduction potentials through **technical** measures. The extra positive or negative cost (above baseline) relative to the reduction potential defines the cost-effectiveness for each measure. The cost-effectiveness depends on the fuel price and can hence be influenced e.g. by a carbon tax. The least-cost optimisation is run for all technical measures available up to the target years (in our case 2020 and 2030) in all sectors. The results are finally ranked by their cost-effectiveness and presented as cost curves.

1.1 Mathematical formulation

1.1.1 FUEL CONSUMPTION IN BASE YEAR

The total national fuel consumption in a given year is calculated according to

(1) $$FC = \sum_{fc} (veh.no_{fc} * vkm_{fc} * sFC_{fc})$$

With:

FC: Total national consumption. [Unit: J]

veh.no: Number of active vehicles of category c and powered with fuel f. [Unit: numbers]

vkm: Annual mileage per vehicle of category c, powered with fuel f, averaged over all sizes and ages. [Unit: km per year per vehicle]

sFC: Specific fuel consumption of vehicle category c, powered with fuel f, averaged over all sizes, ages, driving regimes. [Unit: J per km]

The number of vehicles is usually taken from official national statistics, annual mileages from national vehicle use survey and specific fuel consumption is taken from technical reports and national transport models. For the base years 2000 and 2005 these factors are taken from or derived of given statistics. All parameters are calibrated to reproduce the total national fuel consumption in the years 2000 and 2005 for each fuel separately, as given by (IEA 2008).

1.1.2 FUEL CONSUMPTION IN BASELINE SCENARIO

The future fuel consumption depends on changes in vehicle stock, average mileage and fuel efficiency. These changes are different for the existing fleet and the newly added fleet. Furthermore technical options mostly address the "new vehicles". New vehicles are those added to the fleet in or after the year 2010. Thus the fuel consumption in a year T can be written as

(2) $$FC(T) = FC_{pre2010} + FC_{post2010}$$

The "old", i.e. pre2010-fleet is declining as vehicles drop-out and their average annual mileage decreases with age. Hence, their fuel consumption in year t can be calculated as

(3) $$FC_{pre2010} = \sum_{fc} (veh.no_{fc} * (1 - vtg_{fc}) * vkm_{fc} * (1 - a_{fc}) * sFC_{fc})$$

With, for each vehicle category c and fuel type f and year T:

vtg: Share of post-2010 vehicles in the fleet [Unit: %].

a: Deflator of mileage as a function of vehicle age [Unit: dimensionless].

The "vintage" share vtg is estimated as the number of pre2010 vehicles reduced by the vehicles retired from service in year T relative to the cumulated new registrations of vehicles of category c and fuel type f from 2010 onwards. Typical data are derived from national sales and registration statistics, scrappage probabilities and sales expectations.

The "new", i.e. post2010-vehicles have a higher than average annual mileage. Their specific fuel consumption is given by the sales shares of new technologies and their respective fuel efficiencies. Hence, their total fuel consumption can be calculated as

(4) $$FC_{post2010} = \sum_{fc} \left(veh.no_{fc} * vtg_{fc} * vkm_{fc} * (1 + b_{fc}) * \sum_{t} (p_t * sFC_t)_{fc} \right)$$

With, for each vehicle category c and fuel type f and year T:

vtg: Share of post-2010 vehicles in the fleet [Unit: %].

b: Inflator of mileage as a function of vehicle age [Unit: dimensionless].

p: The shares of each technology t [Unit: %]

sFC: The specific fuel consumption of technology t [Unit: J per km]

The mileage modifiers a and b are derived from vehicle use data differentiated by age; penetration shares p relate to expected sales shares of vehicle with new technologies; their specific fuel consumption is estimated from currently know specifications.

The vehicle stock and average vehicle mileage in year T can be expressed with growth rates relative to the base year 2005:

(5)
$$veh.no(T)_{fc} = veh.no(2005)_{fc} * \Delta N_{fc} \quad and$$
$$vkm(T)_{fc} = vkm(2005)_{fc} * \Delta K_{fc}$$

With, for each vehicle category c and fuel type f and year T:

ΔN: Change rate in vehicle stock veh.no relative to year 2005 [Unit: %],

ΔK: Change rate in vehicle mileage vkm relative to year 2005 [Unit: %].

The future fuel consumption can thus be calculated assuming changes in vehicle stock and average mileage, turnover of the fleet with an associated penetration of new technologies, and their respective fuel efficiencies. These parameters are adjusted such that a certain reference development for the fuel consumption in each country is reproduced from 2010 onwards. In our case we take this reference projection from the latest World Energy Outlook (IEA 2008). In this way, our baseline scenario is calibrated.

1.1.3 REDUCTION POTENTIAL IN ALTERNATIVE SCENARIOS

Alternative scenarios are determined by either a higher penetration of new technologies, or a higher efficiency of the same technology, or both. The reduction potential is the difference between the fuel consumption in the baseline and the fuel consumption in a scenario with a different technology package. The maximum is given when all feasible new technologies will have been implemented as much as possible from the year 2010 onwards:

(6)
$$\begin{aligned}\Delta FC_{\max}(T) &= FC^{BL}(T) - FC^{MFP}(T) \\ &= \left(FC^{BL}_{pre2010}(T) - FC^{MFP}_{pre2010}(T)\right) + \left(FC^{BL}_{post2010}(T) - FC^{MFP}_{post2010}(T)\right) \\ &= \sum_{fc}\left(veh.no_{fc} * vtg_{fc} * vkm_{fc} * (1+b_{fc}) * \sum_{t}((\underline{\underline{p_t - p_t^{\max}}}) * sFC_t)_{fc}\right)\end{aligned}$$

With, for each vehicle category c and fuel type f, and year T:

p_t^{max}: Maximal penetration share of new technology t [Unit: %]. (Underlined)

The maximal penetration shares p_t^{max} are determined as the upper limit for both production of the technology (or provision of the fuel) in the timeframe and an economical take-up in the market.

As long as we assume no change in behaviour, we assume the same growth in vehicle stock, the same fleet turnover (vtg) and the same vehicle mileage as in the baseline. Then the fuel consumption of the pre-2010 vehicles $FC_{pre2010}$ cancels out. The reduction potential is determined by the difference of the penetration rates of new technologies to their rates in the baseline scenario (cf. Figure 1). In addition, we include the option of retrofitting older (=pre2010) vehicles.

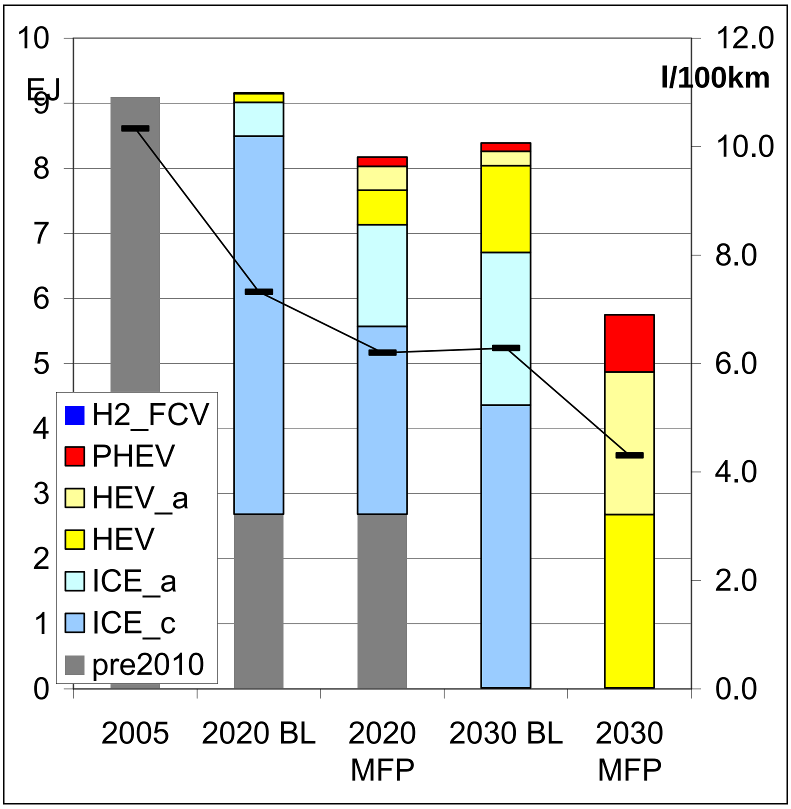

Figure 1: Fuel consumption by gasoline passenger cars in the USA in the 2005 base year and 2020 and 2030 scenarios, differentiated by vehicle technology (left axis). The fuel consumption in the MFP scenario is lower than in the BL scenario for each year as a larger share of more efficient vehicles has been introduced in the fleet. Consequently, the average fuel economy of the new fleet decreases (right axis).

1.1.4 CALCULATING CO_2 AND OTHER EMISSIONS

The CO_2 emissions are calculated from the fuel consumption and the carbon intensity of each fuel consumed. The (energy equivalent) blending share of biofuels is deducted as all carbon released by their combustion had been removed from the atmosphere before. However, emissions due to the production of biofuels are added. Exhaust emissions from CH_4 and N_2O are added with the respective emission factor by vehicle type and technology as well as emissions from F-gases.

1.1.5 SENSITIVITIES

The fuel consumption and hence the resulting CO_2 emission will be lower in an alternative scenario if

- growth in vehicle stock would be lower (parameter ΔN_{fc}),
- growth in vehicle mileage would be lower (parameter ΔK_{fc}),
- the turn-over of the fleet would be higher and consequently the share of new, more efficient vehicles was higher (parameter vtg_{fc}) or, vice versa, older vehicles would be phased out earlier (e.g. by an early or anticipated scrapping),
- new technologies would be phased-in earlier and/or more (parameters p_{t_fc}),
- the specific fuel consumption of new vehicles would be lower (parameters sFC_{t_fc}), or
- stricter measures on the existing fleet, e.g. through retrofit or changed maintenance.
- A higher share of fuels with lower carbon contents (over the life cycle) would further reduce CO_2 emissions at the same level of fuel consumption. (This could be modelled by changes in ΔN_{fc} and/or ΔK_{fc}).

1.1.6 COST-EFFICIENT RANKING OF REDUCTION OPTIONS

The implementation of new technologies is usually associated with extra investment costs and changed maintenance costs on the one hand. On the other hand a higher efficiency will provide saving on fuel costs over the lifetime of the technology. An optimisation routine determines when this trade-off becomes cost efficient. The break-even point strongly depends on the discount rate on the one hand, and the fuel price (including possible carbon increments) on the other hand. To capture this effect, discount rates as typical for an overall social consideration are chosen (4%) as well as from a private investors viewpoint (20%). The fuel price is varied simulating the impact of a carbon tax. The resulting series of cost-efficient measures as a function of total fuel price gives the so-called cost curve for road transport (cf. Figure 2).

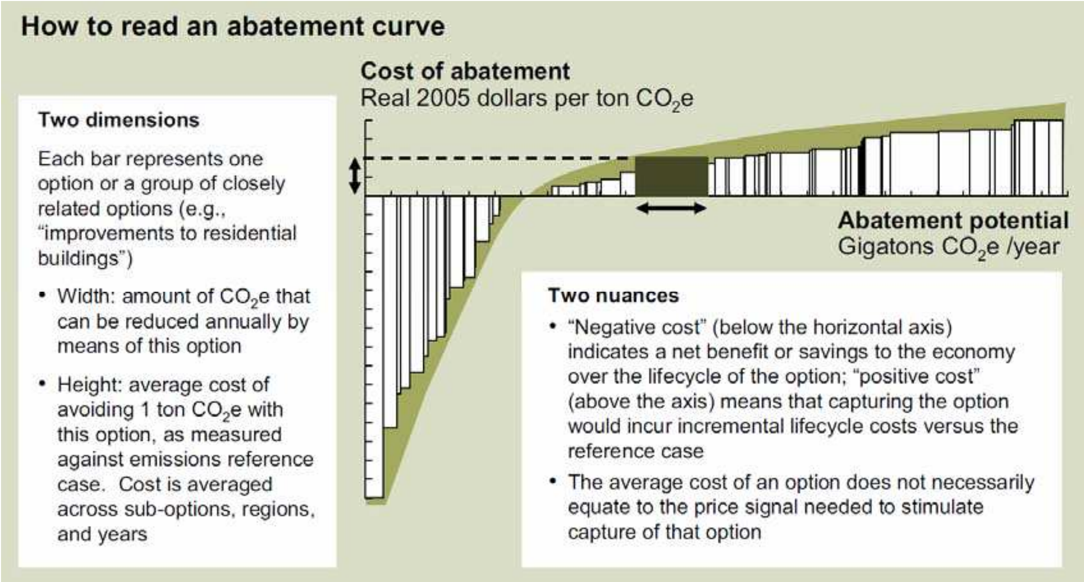

Figure 2: Schematic mitigation cost curve (Creyts, Derkach et al. 2007).

1.2 Technical scope

This report covers technical measures for road vehicles only. Non-road transport has been deliberately postponed to a later stage because of its smaller share in transport's CO2 emissions in the case of rail and inland shipping or because the majority of emissions occur in international areas outside a country as in the case of aviation and marine shipping[1].

Road vehicles are classified in six vehicle categories, distinct in their technical characteristics and transport use: Light duty passenger cars (LD4C), light duty trucks (LD4T), medium and heavy duty trucks (HDT), medium and heavy duty buses (HDB), two-stroke mopeds and scooters (LD2) and four-stroke motorcycles (M4).

As fuels we consider gasoline and diesel, refined from petroleum and potentially blended with biogenic fuels (ethanol and biodiesel), LPG and gas; for the technology scenario we also investigate the potential use of hydrogen as well as electricity (be it through electric traction e.g. as a trolley bus or stored in a battery charged from the electricity grid) as transportation fuel.

[1] The climate forcings from aviation and shipping are definitely not negligible as non-CO2 effects have to be included, cf. Fuglestvedt, J., T. Berntsen, et al. (2008). "Climate forcing from the transport sectors." PNAS 105: 454-458.

1.3 Geographical scope

This reports covers the following Annex-1 countries/regions:

- USA and Canada,
- Japan,
- the Annex-I parties of Europe (aggregated),
- Australia and New Zealand,
- Russia and Ukraine.

In 2000 these countries accounted together for two thirds of total global CO2 emissions from road transport globally (Figure 3).

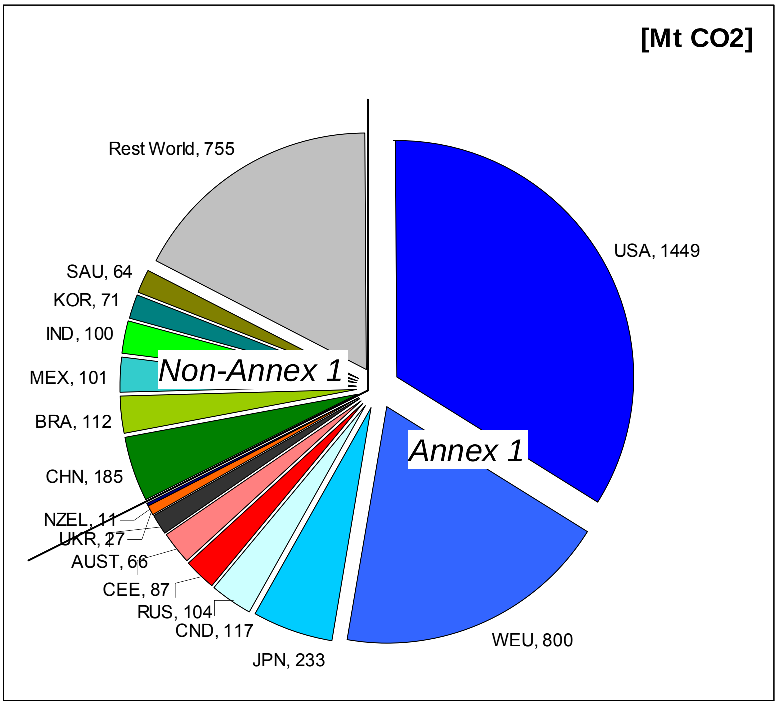

Figure 3: Distribution of CO_2 emissions from road transport in Annex-1 and non-Annex-1 countries in 2000 (Borken, Steller et al. 2007).

1.4 Temporal scope

Our modelling is calibrated to the years 2000 and 2005. The target year for the scenarios is 2020. The potential for the year 2030 as well as for every 5 years between 2000 and 2030 is also given, based on the estimates for the base and the target year.

2 Pool of technologies for the scenarios

This chapter argues which technologies should be considered in the baseline and the technology scenario. Broadly they are classified according to their propulsion system as the most prominent single characteristic. We've scanned the peer reviewed literature, conference proceedings, government and industry reports and spoken to numerous experts about vehicle technologies, potentials, costs, feasibilities.

The aim is to estimate a baseline technology mix and – relative to this – alternative features resulting from a "policy induced, recommended or forced" new, earlier, stricter and/or more widespread application of CO_2 emission reduction or fuel efficiency features. Hence we distinguish between baseline technologies and possible "add-on" technologies in case of policy forcing. For this purpose we broadly classify technologies by their current (as off December 2008) state of development relative to a mass market application, cp. (Frey and Kuo 2007):

The pool of potential baseline technologies for the target year 2020 comprises

- Current technologies, i.e., those used at this moment,
- Improved current technologies,
- New technologies that are commercially available today, even if not used to a large extent,
- All technologies necessary to comply with legal requirements in the year 2020, notably for exhaust emission control, safety standards, fuel economy, possibly control of GHG emissions.

The pool of potential "add-on" technologies for the target year 2020 comprises

- Technologies currently in a pilot phase and whose implementation is expected within 5 to 10 years,
- New concepts that still need research and development.

The "policy" scenario differs from the baseline in the following respects:

- The number and share of new technologies and/or vehicles applied; this is modelled by changing the penetration shares (comparable to sales shares).
- The performance of the new technologies and/or vehicles; this is modelled by the parameters on fuel efficiency, carbon contents, possibly filter or emission controls, etc.

In any scenario the activity or the transport demand remain unchanged; in other words we assume no change in behaviour but only changes in technologies applied. Furthermore, no change in utility is assumed, hence the model split, load factors, vehicle sizes etc. are not modified in any scenario. **The scenario presented is therefore constructed to answer the question: "Given a certain transport demand, what are the costs to reduce emissions and fuel consumption by technological means?"**

Non-technical measures or demand reductions are not considered in this work, though without doubt they can contribute significant reductions. Whether behavioural change however goes along with gains or costs is a matter of debate.

2.1 Conventional vehicles

First and foremost, vehicles with (conventional) internal combustion engine, both spark ignition and direct ignition, will remain the standard vehicles. Hence, this propulsion system is the backbone of the baseline scenario. Improvements address the engine, the powertrain, the body weight and aerodynamics, auxiliaries, tires and friction, etc. Most improvements will also be the basis for other propulsion systems.

2.1.1 MEASURES ON THE EXISTING FLEET

Technical improvements do not only concern new vehicles but also in-use vehicles. LDV fuel economy can be improved by a permanently maintained high tire pressure, low resistance tires, low friction lubricants, more efficient electrical appliances. For HDT aerodynamic retrofit appears an important option. Following (Smokers, Vermeulen et al. 2006; Lutsey 2008) we assume a certain retrofit potential for pre2010 vehicles. However, to the extent that old vehicles, i.e. vehicles introduced earlier than 2010, are phased out of service, the impact of retrofit decreases.

2.2 Hybrid electric vehicles

Hybrid electric vehicles (HEV) are vehicles with both, an electric and a thermal engine suitable for propulsion.[2] The electric engine has very low (thermal) losses and is intended to replace or complement the thermal engine when it would operate less efficiently, notably at low speeds and at transient power demand. Thus the electric engine can lead to overall efficiency gains, notably in urban driving. The electricity is generated on-board from the thermal engine. In addition, the electric powertrain can recuperate energy from braking, thus reducing losses. A battery stores the electric energy, generated by the thermal engine or recuperated from braking. In consequence the battery capacity in a HEV is larger than in a conventional ICE vehicle.

Plug-in hybrid electric vehicles (PHEV) can also charge their battery from the electric grid. The overall fuel economy of the vehicle, measured in energy demand per distance travelled, depends on how much is driven by the electric engine and how much of this energy has been supplied by the electric grid. Hence in essence, this can be regarded as a vehicle with similar features as a full HEV plus the option to charge the battery from the electric grid (e.g. cf. characteristics as summarised in (Lutsey 2008) and (Samaras and Meisterling 2008).

The extra battery capacity and extra electric engine in hybrid vehicle designs come with extra weight which is only partly compensated by the downsizing of the thermal engine. The extra weight results in a higher power demand and hence slightly reduces the fuel economy. Furthermore, the battery is the key single component responsible for extra costs of hybrid electric vehicles (Lipman and Delucchi 2006).

[2] For our purposes we deliberately exclude micro or mild hybrids where the electric engine is not designed to drive the vehicle for an important distance but works rather as a booster or small generation. These technologies (e.g. start-stop generator) are included as part of the conventional or advanced ICE vehicles and accounted in any improvements of fuel economy.

For both reasons the battery capacity and hence the vehicle's electric only range are constrained: The electric only range of HEV is (currently) below 10-15 km, while the design for PHEV is intended for a larger electric only range of about 40 km. In any case, the electric driving range will be much more limited than for a conventional vehicle. For a scenario year 2020 we stipulate significant improvements in the electric range; otherwise, and without invoking a drastic shift in consumer demand, these vehicles would only appear suitable for certain market segments/applications. With improvements in range they could be considered serious competitors.

Hybrid electric vehicles are as off Sept. 2008 produced and soled at a few 100'000 units globally, notably by Toyota and Honda. This technology is expected to develop further until the year 2020, hence it is part of the baseline scenario.

The application of hybrid technology is focused on cars and light duty vehicles with related/derived designs, not for heavy duty trucks. The application for urban buses will also be investigated.

2.3 Fuel cell vehicles

Opinions on a mass-market application of fuel cell vehicles and/or hydrogen in transportation are divided: Ambitions are high but actual progress and implementation has more often than not been postponed. Several obstacles are cited, that are partly interlinked (EC DG RES 2008):

- FC costs per kW are much higher than for ICE (EU target in 2020: <100 E/kW); by comparison, the cost target by the US DoE as well as European automotive manufacturers aims at 50 $ per kW by 2020 (Helmolt and Eberle 2007; NREL 2007). Otherwise, the fuel cell system is not considered competitive to conventional vehicles.
- A fuelling infrastructure is not readily available and very costly to set up (particular complication: who leads market and who follows?);
- "Indirect hydrogen through on-board autothermal reformers could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure. However, this offers little GHG benefit compared to advanced conventional powertrains or hybrids" (Edwards, Larivé et al. 2007).
- The new technology has to compete with established technologies that are continuously improved as well – hence the benchmark in terms of cost and fuel efficiency is nowadays moving towards a hybrid-diesel ICE.
- There is a performance difference compared to ICE as the fuel cell is slow in responding in high power demands, regardless of its nominal power.

These findings are further corroborated in a review of EU funded research on H2 and FC: The target for mass market application of 0.4 to 1.8 mio. vehicles in 2020 (cumulative 1-5 mio) is not supported by progress in research nor demonstration. This sales figure would correspond to about 1-3% of the expected total passenger car fleet. The focus is on LDV, APU and fleets (HyWays 2008).

In the US, hydrogen FC LDV are in development and demonstration phase. Possibly they meet customer acceptable criteria by 2015 (NREL 2007). Obstacles are the fuel production, its distribution and provision to the end user, its on-board storage (allowing suitable vehicle range), but also the vehicle range and durability of the FC system. Extrapolating from these demonstration results on LDV, it can be ruled out that H2 FC only vehicles will become commercially available by 2020 for long-distance transport (infrastructure not in place, range of vehicles not provided). Even an application in an urban context, e.g. for busses, appears questionable (and does not appear cost-effective relative to competing technology and fuels).

FCVs running on gasoline, methanol or ethanol have significantly lower vehicle fuel economy than H2 FCV. At even higher vehicle costs, as the **on-board reformer technology** adds to costs, and a higher complexity of the vehicle system, i.e. more concerns for durability, these vehicles cannot compete with H2 FCV and are therefore **not considered further in this analysis**[3] (Brinkman, Wang et al. 2005; Endo 2007). This statement applies to North America, Europe and Japan.

There are some demonstration **H2FC buses** in the EU, but capital investment is prohibitive, particularly in the case of strained public budgets. FC vehicles are best considered for LDV applications only. Even the most aggressive scenarios do not consider FC vehicles commercially viable by 2020, contrary to HEV (Gott, Linna et al. 2007)

Therefore it seems quite uncertain that FC vehicles will have a sizeable share in the baseline scenario. Their cost effectiveness will however be analysed in the technology scenario.

2.4 Hydrogen as transportation fuel

The prospects of hydrogen as a transportation fuel are assessed by (Edwards, Larivé et al. 2007) as follows:

> "In the short term, natural gas is the only viable and cheapest source of large scale hydrogen. WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles albeit at high costs. Hydrogen ICE vehicles will be available in the near-term at a lower cost than fuel cells. Their use would increase GHG emissions as long as hydrogen is produced from natural gas.
>
> Hydrogen from non-fossil sources (biomass, wind, nuclear) offers low overall GHG emissions. More efficient use of renewables may be achieved through direct use as electricity rather than road fuels applications.
>
> Indirect hydrogen through on-board autothermal reformers offers little GHG benefit compared to advanced conventional powertrains or hybrids. On-board reformers could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure.

[3] Caveat: The LCC including production of the fuel and infrastructure costs might be in favour of gasoline/methanol/ethanol compared to H2.

> The technical challenges in distribution, storage and use of hydrogen lead to high costs. Also the cost, availability, complexity and customer acceptance of vehicle technology utilizing hydrogen technology should not be underestimated.
>
> For hydrogen as a transportation fuel virtually all GHG emissions occur in the WTT portion, making it particularly attractive for CO_2 Capture & Storage."

For our purpose we conclude: For the time horizon 2020 there is little to no energy/GHG advantage in using H2 in an ICE compared to a conventional gasoline or diesel ICE. Using H2 in FC vehicles would offer considerable advantages, however at costs that are much higher than viable alternatives. Hence **H2 is not an important fuel for transportation in the baseline scenario.**

2.5 Fully electric vehicles

Fully electric vehicles are considered even less competitive than FCV as (Helmolt and Eberle 2007)

- Costs per kW much higher,
- Range more limited,
- Mass and volume requirements higher,
- Recharging time large.

These considerations are corroborated in a techno-economic analysis for future vehicle propulsion in Japan (Endo 2007): The efficiency improvements offered by fully electric vehicles are considered too costly compared to conventional improvements or alternative future concepts, notably HEV and FCV.

Nonetheless for applications in smaller vehicles and for a typical urban range there might be some niche markets developing. Hence BEV LDV are assumed to play some limited role in the baseline scenario and are part of the technology scenario options.

In the case of **buses** there might be a revival of trolleybuses. They will be considered in both, the baseline and the technology scenario. Because of their limitations a battery or fully electric drive is not considered for **HDT**.

2.6 Biofuel options

Biofuels are considered another option for mitigation of climate change. Almost all Annex I Parties have mandatory requirements for blending biofuels into gasoline and diesel. In the baseline scenario we assume the shares as derived from the WEO08 (IEA 2008) for non-European countries and from PRIMES 2008 (Capros, Mantzos et al. 2008) for European countries.

Biofuels reduce the emissions of carbon dioxide/GHG if and only if the emission per useful output (in the case of transport: per vehicle-kilometer) are lower over the whole provision chain relative to the fossil fuel that is replaced. Hence both, the emissions at the vehicle as well as the emissions related to the provision of the fuel have to considered. This demands a comparative life-cycle analysis.

The reduction potential for biofuels strongly depends on the feedstock (notably corn, grain or sugar-cane in the case of ethanol and oil seeds or palm oil in the case of fatty acid methyl esters (FAME), popularly termed biodiesel), its production conditions (notably yield and fertilizer use), how coupled products are allocated and what alternative land uses are substituted. For our purposes here we differentiate between biofuels derived from so-called 1st or 2nd generation production. The savings per vehicle kilometre compared to the fossil equivalent can be as low as -10% to -30% for corn-based ethanol in the USA, -40% to -60% for ethanol derived from sugar beet as well as rapeseed-derived biodiesel in Europe, and up to -80% to -90% for ethanol based on sugar cane in Brazil (IEA 2008). These values exclude land-use changes which however are so important that in cases they determine even the sign, i.e. whether there will be saving at all (Gibbs, Johnston et al. 2008). Currently about 90% of the biofuels consumed in Europe (and probably similarly in the USA) are produced locally (IEA 2008). But it is expected that global trade in biofuels increases given the large cost differentials notably between the tropics and the Northern latitudes.

For these reasons standards for so-called sustainable biofuels are discussed in Europe (EurActiv.com 2008). Indicative targets are a saving of at least 35% in GHG emissions per unit of final energy delivered, as calculated over the full life cycle, compared to the fossil substitute and applicable from 2013 onwards (with minor exemptions). The minimal GHG savings requirement for biofuels to be considered sustainable may be raised to 50% to 60% from 2017 onwards. A degradation of land rich in carbon, rich in biodiversity shall be prohibited and displacement effects on alternative land uses, notably food production, shall be minimised (EC 2008; EP 2008; EurActiv.com 2008). Similarly, recent legislation in the US stipulates a minimum of 20% savings of GHG-emissions over the life-cycle for 1st generation biofuels, and at least 50% to 60% savings of GHG-emissions over the life-cycle for 2nd generation biofuels (so-called “advanced) (Lutsey 2008).

For our purposes here we do not differentiate by feedstock, production place or production pathways. Relevant in our context is only the GHG saving associated with the use of an alternative fuel. As the discussion is still ongoing we apply a conservative savings potential of 35% reduction in GHG emissions per energy unit compared to the fossil fuel substituted for biofuels of 1st generation and 80% reductions in GHG emissions per energy unit for 2nd generation biofuels. Production shares are assumed 95% and 5% for 1st and 2nd generation biofuels in 2020 respectively, and 85% and 15% in 2030 in the baseline scenario, in line with the WEO2008 (IEA 2008). In total, the biofuels might represent about 6% to 10% of total road fuel demand in Annex I countries in 2020 and possibly up to 15% in 2030 (IEA 2008). These quantities might be 30% higher in a scenario with significantly higher prices for fossil fuels and significant progress in the cost reduction of 2nd generation biofuels.

We account for emissions from biofuels in two ways: First, CO_2 emissions from the tailpipe are deducted according to the biofuels’ share and carbon contents. Second, the emissions related to the production of the respective biofuel are accounted as upstream emissions. They are expressed as greenhouse gas equivalents per energy unit and added to the total emissions related to this energy use.

We assume the following blending shares (as share of energy) in the different countries.

Table 2.1: Shares of biofuels (as energy share) in the various countries.

COUNTRY	USA		CANA		AUTR		NZEL		JAPA		RUSS		UKRA	
YEAR	GSL	MD	GSL	MD	GSL	MD	GSL	MD	GSL	MD	GSL	MD	GSL	MD
2000	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2005	1.9	0.0	0.1	0.0	0.1	0.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
2010	4.5	0.0	1.0	0.3	4.5	0.3	3.0	0.6	1.0	0.3	0.3	0.3	0.5	0.3
2015	7.0	0.2	3.0	0.5	7.0	0.5	5.0	0.7	2.0	0.5	0.5	0.5	0.8	0.5
2020	8.0	0.5	7.0	0.6	8.0	0.6	7.5	0.8	3.5	0.6	0.6	0.6	1.0	0.6
2025	9.0	1.0	9.0	0.7	9.0	0.7	9.0	0.9	6.0	0.7	0.8	0.7	1.5	0.7
2030	10	1.2	10	0.8	10.0	0.8	10.0	1.0	8.0	0.8	1.0	0.8	2.0	0.8

2.7 Summary of technology packages

To estimate the reduction potential and its related costs we differentiate a number of technology packages for each vehicle category. These packages are characterised – for our modelling purposes here – by the resulting specific fuel consumption of the vehicle (measured in MJ/km to be comparable across different fuels) and the extra costs (both, investment as well as running costs) relative to base vehicle. The package applies to vehicle configurations as considered relevant in the baseline scenario and in a technology scenario in the target year 2020 (Table 2.2).

Table 2.2: Technological changes (“packages” or measures) of the vehicles in the target year 2020 relative to representative vehicles in the year 2005.

Vehicle category	Technology package (with reference technologies)	Fuels
Cars (LD4C)		
ICE_c	Moderate improvements: 10% mass reduction, drag reduction (aerodyn., friction), efficient VTEC engine.	GSL, MD (possibly with biofuels blended), LPG, GAS, H2
ICE_a	Advanced package: 20% mass reduction, more drag reduction (aerodyn., friction), efficient VTEC engine including starter generator	
HEV	Mild hybrid: Electric motor supplies about 15% of peak power, vehicle is based on the advanced package.	
HEV_a	Full hybrid: Electric motor supplies about 40% of peak power, vehicle is based on the advanced package.	
LDC_PHEV	Plug-in HEV with about 30 km electric only range. Based on HEV_a. Assumption: 20±5% of annual mileage is grid electric.	
LDC_H2_FCV	FCV with features as HEV_a, plus on-board H2 and FC	H2
LDC_BEV	Small EV with features of ICE_a (notably light, possibly relaxed acceleration), battery powered, with medium electric range	EL
LDC_BEV_a	Small EV with features of ICE_a (notably light, possibly relaxed acceleration), battery powered, with larger electric range	
Light duty trucks (LD4T)		
ICE_c	Moderate improvements: 20% mass reduction, drag reduction (aerodyn., friction), efficient VTEC engine.	GSL, MD (possibly with biofuels blended), LPG, GAS, H2
ICE_a	Advanced package: 33% mass reduction, more drag reduction (aerodyn., friction), efficient VTEC engine including starter generator	
HEV	Mild hybrid: Electric motor supplies about 15% of peak power, vehicle is based on the advanced package.	
HEV_a	Full hybrid: Electric motor supplies about 40% of peak power, vehicle is based on the advanced package.	
LDC_PHEV	Plug-in HEV with about 30 km electric only range. Based on HEV_a. Assumption: 20±5% of annual mileage is grid electric.	
LDC_H2_FCV	FCV with features as HEV_a, plus on-board H2 and FC	H2
LDC_BEV	Small EV (NiMH Gen4, MEV AC induction motor, MEV inverter) with features of ICE_a (notably light, possibly relaxed acceleration), battery powered, with medium electric range.	EL
LDC_BEV_a	Small EV (NiMH Gen4, MEV AC induction motor, MEV inverter) with features of ICE_a (notably light, possibly relaxed acceleration), battery powered, with larger electric range	
Heavy duty trucks (HDT)		
ICE_c	Anti-idling: Truck-board truck stop electrification Aerodynamic drag reduction: Cab top deflector, sloping hood and cab side flares Tire rolling resistance improvement: Low-rolling-resistance tires	GSL, MD (possibly with biofuels blended),

Vehicle category	Technology package (with reference technologies)	Fuels
ICE_i	Anti-idling and reducing accessory load: (1a) and improved electric auxiliaries	LPG, GAS
	Aerodynamic drag reduction: 2a and closing/covering tractor-trailer gap	
	Tire rolling resistance improvement: Wide-base tires (super singles)	
	Low viscosity lubricants for transmission and engine	
	Engine efficiency improvements: Increased peak cylinder pressures	
ICE_a	Anti-idling and reducing accessory load: (1a) and improved electric auxiliaries	
	Aerodynamic drag reduction: 2a and closing/covering tractor-trailer gap	
	Tire rolling resistance improvement: Wide-base tires (super singles)	
	Low viscosity lubricants for transmission and engine	
	Engine efficiency improvements: Increased peak cylinder pressures	
Bus/coach (HDB)		
ICE_c	Anti-idling: Coach-board coach stop electrification	GSL, MD (possibly with biofuels blended), LPG, GAS, H2, EL
	Aerodynamic drag reduction: Cab top deflector, sloping hood	
	Tire rolling resistance improvement: Low-rolling-resistance tires	
ICE_i	Anti-idling and reducing accessory load: (1a) and improved electric auxiliaries	
	Aerodynamic drag reduction: Cab top deflector, sloping hood	
	Tire rolling resistance improvement: Low-rolling-resistance tires	
	Low viscosity lubricants for transmission and engine	
	Engine efficiency improvements: Increased peak cylinder pressures.	
ICE_a	Anti-idling and reducing accessory load: (1a) and improved electric auxiliaries	
	Aerodynamic drag reduction: Cab top deflector, sloping hood	
	Tire rolling resistance improvement: Low-rolling-resistance tires and automatic tire inflation system	
	Low viscosity lubricants for transmission and engine	
	Engine efficiency improvements: 5a and improved fuel injectors	
	Hybrid propulsion for buses	
	Weight reduction: Lighter materials	

We estimate the share of each technology in each vehicle category and fuel type in the baseline scenario. Thus, the specific fuel consumption of a given vehicle category in the year 2020 is constructed as the weighted average over its constituent technologies.

$$sFC_{fc} = \sum_t p_{fct} * sFC_{fct}$$

With:
sFC: Specific fuel consumption of vehicle category c powered with fuel f and for each technology t [Unit: J per km].
p: Share of technology t in each vehicle category c powered with fuel f [Unit: %].

For the scenario with so-called maximal feasible (technological) potential, these shares increased under the assumption of a dedicated and consistent policy starting with an early and stringent phase-in of new technologies by 2010. Fuel efficiencies and costs as well as baseline penetration shares and maximal potential penetration shares differ between countries.

The impact of a certain technology on the total outcome depends on both, the difference in fuel economy compared to the baseline (standard) technology and its estimated penetration rate (or penetration potential). Limits and barriers to a quick or widespread take-up of new technologies are summarised in Table 2.3.

Table 2.3: Limits and barriers to the penetration of different technologies (with time horizon 2020).

Technology	Limits / barriers
For each vehicle category	Maximal turn-over with new vehicles. This is a function of the replacement of old and the augmentation with new vehicles.
HEV, PHEV, BEV	Battery capacity, costs, and durability
H2 FC	Costs for FC system and H2 storage at the vehicle side. Range and durability of the system. H2 is not supplied; fuel and supply infrastructure costly.
Gas, LPG	Fuel provision limited, advantages limited

3 Costs of technologies

We model extra costs per propulsion technology for each vehicle category-fuel combination. Costs are given in constant prices (Euro 2005) and estimated for conditions of a broad market penetration in 2020. The consumer price index is used to convert older cost estimates to year 2005 values.

3.1.1 LIGHT DUTY VEHICLES

We apply the following principles

- Some autonomous improvement of price, fuel efficiency;
- Reduction of 10% mass comes at no sizeable costs; further mass reductions however need a redesign or more expensive material (DeCicco, An et al. 2001) followed by (Lipman and Delucchi 2006).
- All vehicles have comparable characteristics in terms of safety, speed and acceleration. They can be considered alternatives for a lot of applications from the

customer's point of view. Battery electric and possibly fuel cell vehicles might compromise on space and range however, compared to conventional ICE powered vehicles.

- Battery and hence the vehicle costs grow strongly with higher range and power requirements. To contain costs it is therefore assumed, that hybrid and battery electric vehicles will be based on the already improved conventional vehicle (platform) (Delucchi and Lipman 2001; Lipman and Delucchi 2006) and references therein).

3.1.2 HEAVY DUTY VEHICLES

The fuel consumption of trucks is in all countries considered dominated by the fuel consumption from heavy duty trucks. These vehicles operate typically on long-haul, at speeds approaching 100 km/h (62 mph) – even if this is beyond the legal speed limit. Therefore, at speeds above 70 km/h (45 mph) the aerodynamic resistance dominates the energy consumption, e.g.(Bustnes 2006) , followed by the rolling resistance. Hence, measures to reduce aerodynamic resistance are important.

For city busses however, the biggest part of energy is consumed for the repeated accelerations in urban driving and after serving the bus stops. Therefore, efficiency options concentrate on a better energy management through electric auxiliaries and – possibly – hybrid propulsion. Coaches on the other could benefit from the same efficiency measures as heavy duty trucks, notably improved aerodynamics and lower rolling resistance, possibly coupled with weight reductions, and an improved energy management of auxiliaries.

Significant lifetime cost savings are calculated for many measures on HDT. This contradicts the understanding, that particularly businesses would use cost-effective measures quickly. Experts in the US from the DoE EIA[4], Argonne NatLab and TA Engineering gave the following reasons why the trucking industry does not take up efficiency measures even if they would pay back over the lifetime of the vehicles:

- First and foremost: The desired payback period is 1 to maximum 4 years!!! We however calculate the return over the lifetime of the vehicle, i.e. 15 years. With fuel costs of around 2.4 $ per gal each percent efficiency gain would save only about 200 $ => Hardly any measure economical within 4 years. Thus, in our lifetime perspective, we are bound to find a whole bunch of measures for improvement.
- Industry is risk averse: Anything that might compromise on durability or reliability of the vehicle is avoided (e.g. super-single tyres).
- Flexibility shall not be compromised, e.g. aerodynamic features might either limit the flexibility in loading, or in tractor-trailer combinations, or in overhead space,etc.
- Companies have only little investment capital. This is rather used for truck features or driver amenities or for extra mandatory exhaust emission control equipment

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[4] US DoE EIA, Washington/DC: John Maples. Argonne National Laboratory, Chicago: Anant Vyas. TA Engineering, Baltimore: James Moore.

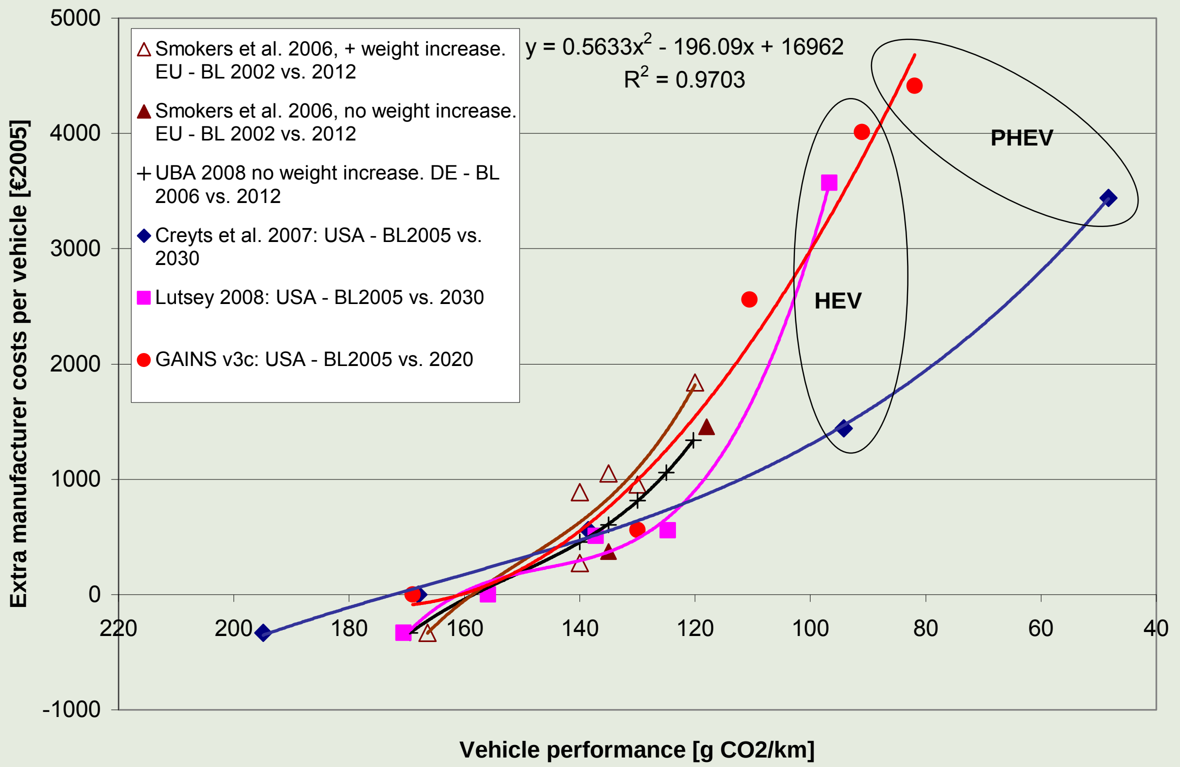
- Low fuel prices have provided no incentives so far.

3.2 Derivation of cost curves

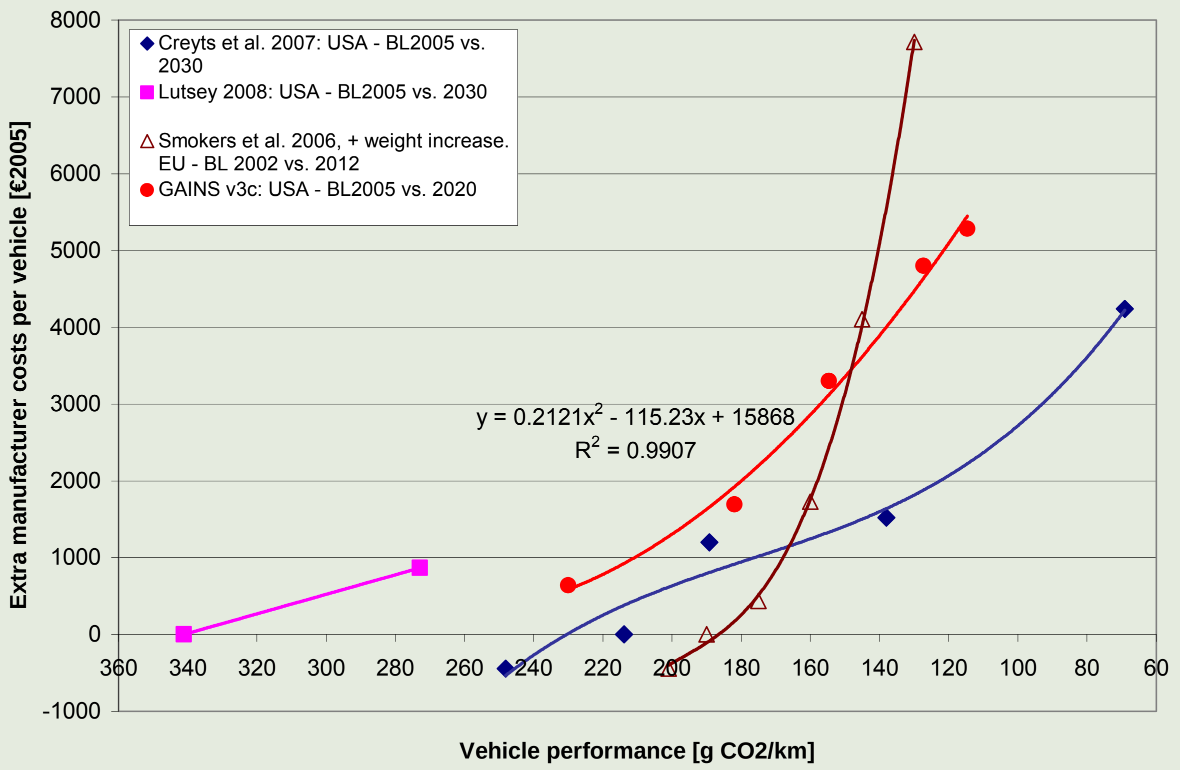
The data about incremental fuel efficiency improvements and incremental costs of the different technologies is summarised to three to five technology packages. These determine specific points for a specific combination of measure applied to certain base vehicles. For all possible other technical combinations, i.e. combinations of incremental efficiency versus extra manufacturer costs, we use an interpolation formula on the basis of the technologies/points determined above. Thus, the data on the incremental fuel efficiency improvements and incremental costs of the resulting vehicles are summarised as cost curves per vehicle (Figure 4).

Figure 4: Cost curves for extra vehicle manufacturer costs versus CO_2 emission per kilometre of a) cars, b) light duty trucks and c) trucks and buses. Each point represents a specific technology package. The interpolation graph and formula used for our calculation is given in each figure – and compared to other studies. Note: (Lutsey 2008) and (Creyts, Derkach et al. 2007) refer to vehicles in the USA in 2030. (Smokers, Vermeulen et al. 2006) and (Herbener, Jahn et al. 2008) refer to the cars in the EU and in Germany with target year 2012. Values at negative costs refer to base vehicles assumed in 2002 and 2005 respectively.

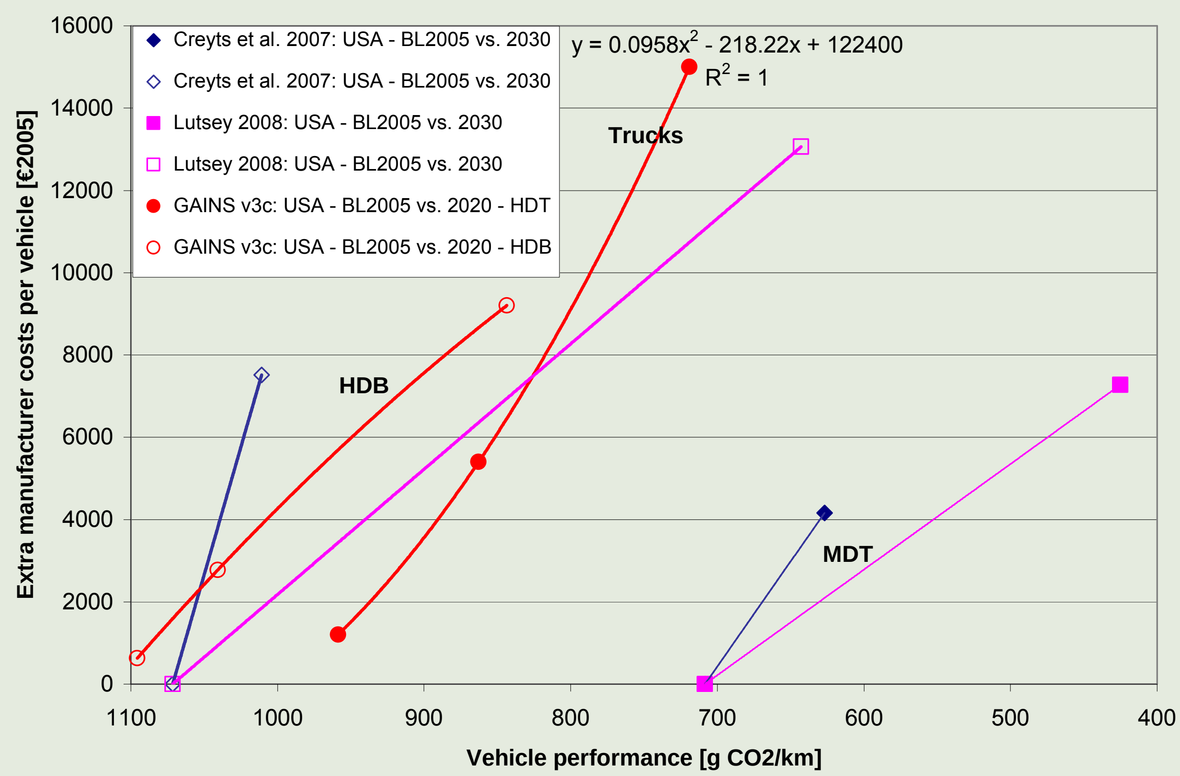
a) Cost curve for passenger cars



b) Cost curve for light duty trucks



c) Cost curve for trucks and buses



The same cost curve per technology is used to calculate the extra costs for incremental fuel efficiency improvement. Note, that all cost curves are concave, i.e. that marginal costs become higher or, in other words, that the same efficiency improvement is the more costly the more efficient the vehicle already is. The same formula per vehicle category is used for all countries, however individual countries have different efficiency levels – and thus the extra costs differ per vehicle technology.

3.2.1 COMPARISON WITH OTHER COST CURVES

A few studies permit a comparison of our cost curves: (Creyts, Derkach et al. 2007) are fully comparable to us in their approach, however their data sources are not documented and input data description is not fully transparent. The target year of their analysis is 2030. Thus, they assume twice as much time for the development of new technologies than we. Because of this extra learning we expect lower (=cheaper) cost curves. (Lutsey 2008) investigates consequences of a rather aggressive introduction of new technologies, also with target year 2030[5]. Thus again, we anticipate lower cost curves than for an introduction advanced vehicles ten years earlier in 2020, which is our target year.

Figure 4 includes the cost curves from these studies: For cars and light duty trucks (Creyts, Derkach et al. 2007) have the most optimistic assumptions, assuming the biggest efficiency improvements at the lowest extra manufacturer costs. The biggest discrepancy concerns the costs and final efficiency of full hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). (Lutsey 2008) assumes similar increments for all ICE technology, but is less optimist on costs for HEV and PHEV. Similar observations apply to the assumptions for LDT. These discrepancies becomes the more relevant the higher the assumed shares of HEV and PHEV will be. On the contrary, (Creyts, Derkach et al. 2007) assume the least potential for efficiency improvements of trucks at the highest costs. This is in stark contrast to the assumptions by (Lutsey 2008). Without knowing the primary data used by (Creyts, Derkach et al. 2007) we can however not go beyond this qualitative comparison. In the case of cars and light duty trucks, our assumptions are less optimist with respect to cost reductions, noting that we also have a shorter time horizon for technology developments. As far as reduction potentials in absolute figures are concerned, we are likewise conservative, as we do not assume technology that would not exist already today.

Two European studies have investigated potential and extra costs for efficiency improvements up to the year 2012. As their development time is much shorter we expect to see higher (=more expensive) cost curves for the same efficiency improvement. (Smokers, Vermeulen et al. 2006) have in parts referenced the same US studies as (Lutsey 2008)[6]. In contrast to the US data they assume that all efficiency measures have positive costs, i.e. no cost-free measure are assumed. Furthermore, they assume an ongoing weight increase of 1.5% p.a. assumed for all vehicles. Compensating this increases mitigation costs significantly! In a follow-up study (Herbener, Jahn et al. 2008) applied the same approach to

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[5] The retail costs given, i.e. including taxes, subsidies, profit mark-ups etc., are converted to manufacturer costs by dividing with 1.4 based on (Delucchi and Lipman 2001; Lipman and Delucchi 2006).

[6] It is unfortunately not transparent what sources Creyts et al. (2007) have used. However, there is little other peer-reviewed literature.

the German vehicle fleet. However, they did not assume an autonomous weight increase (no specific reason given) and several important technologies that increase efficiency at zero or low costs.

Figure 4 also includes the cost curves according to these European studies on light duty vehicles. The potential is lower because their limitation to achieving 140 g CO_2 per km and more costly because of the shorter time frame.

In conclusion, our cost estimates per vehicle category concur broadly with existing knowledge. Compared to other studies our curves keep a middle way neither assuming optimist cost reductions nor high efficiency improvements.

3.2.2 VEHICLE OPERATION AND MAINTENANCE COSTS

New technologies/vehicle might have different operation and maintenance costs compared to the alternative base vehicle. These annual costs are added to the annualised extra manufacturer costs. The following assumptions apply to the extra vehicle operation and maintenance costs for the different technologies and vehicle categories:

- No extra operation and maintenance costs for ICE vehicles (conventional and advanced). Their extra components are part the baseline developments.
- For hybrid and battery electric vehicles the battery and its lifetime is the most important single cost component. We assume conservatively that battery technology will have improved by 2020 such that only one replacement in 15 years is needed (i.e. a mean battery lifetime of 7.5 years) (Delucchi and Lipman 2001). Hence the costs with one battery replacement are extra costs for HEV and BEV. General maintenance costs for HEV and BEV are however only 75% of ICE vehicles because of much less mechanical wear[7].
- Assumption on battery costs, cp. (Delucchi and Lipman 2001; Lipman and Delucchi 2006): Battery replacement costs 80% of costs for a new battery for a BEV110: 80% * US$$_{2000}$ 5840 = US$$_{2000}$ 4670. Converted with 4% annual interest over 15 years life translates to 420 US$$_{2000}$ or 380 Euro2005 annual costs. Annual costs for BEV200: US$_{2000}$ 600 or Euro$_{2005}$ 540.
- Costs for FCV are taken from (Ogden, Williams et al. 2004).

3.2.3 COST EFFICIENCY

The importance of the different cost components is illustrated in Figure 5 for passenger cars: Fuel savings depend on the increment in fuel efficiency and fuel price, while (annual) extra expenses depend on extra operation and maintenance costs and discounted upfront investments costs. With increasing fuel price or decreasing discount rate investments become more economical.

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[7] Annualized maintenance costs for a Ford Taurus: 492 US$2000/a vs. 355 US$2000/a for a BEV (Delucchi, M. A. and T. E. Lipman (2001). "An analysis of the retail and lifecycle cost of battery-powered electric vehicles." Transportation Research Part D: Transport and Environment **6**(6): 371-404. Tab. 17), i.e. excluding battery replacement the maintenance of a BEV is about 125 Euro2005 cheaper.

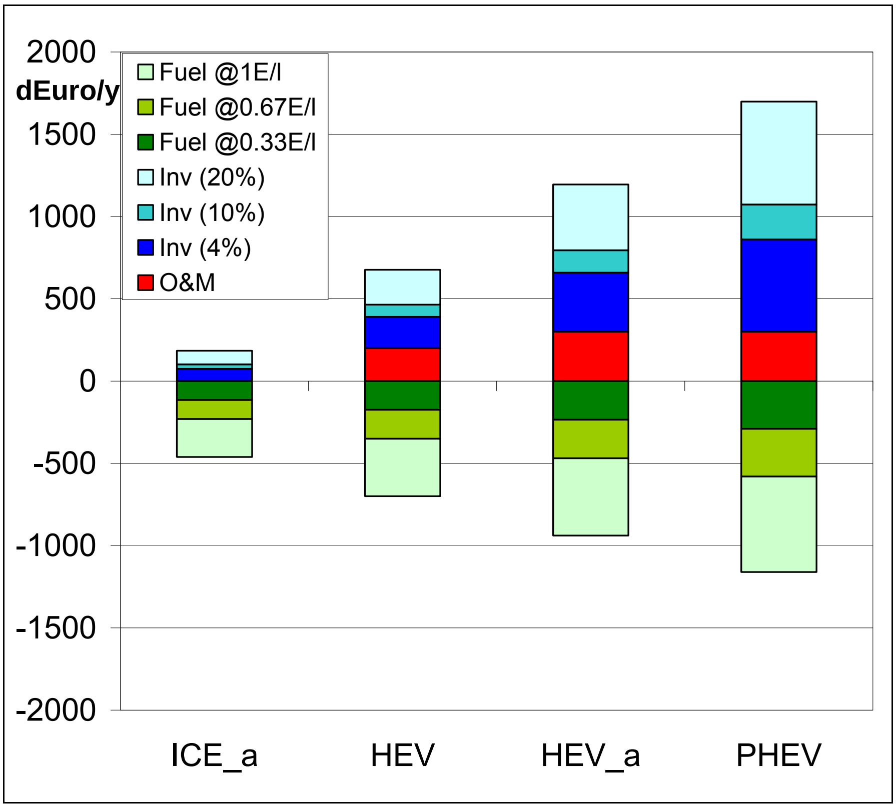

Figure 5: Costs components relative to baseline vehicles for different technology packages for the example of passenger cars in the USA in 2020, as a function of discount rate and fuel costs.

4 Autonomous technology trends in the baseline scenario

We assume by 2020 a globally homogenised vehicle market. Vehicle technology is determined by the big producers in North America, Asia (Japan and South Korea, later also China and possibly India) and Europe on the one hand and the market conditions in these regions on the other side. We here review main trends in the baseline scenario:

- Increase in comfort and safety features as well as increasing emission control has increased and is expected to increase still in the vehicle weight in all segments except the luxury cars. This trend leads to an autonomous increase in average and TA fuel consumption of new cars. On the other hand, aerodynamic efficiency increases, engine efficiency increases, less resistance from tyres and moving parts as well as advanced power and engine control (e.g. VGT, start-and-stop, break energy recuperation) will increase overall efficiency.
- In addition to added mass most appliances for (exhaust) emission control also lead to an increase in fuel consumption as they tend to increase the power demand.

- For HDT however the SCR for NOx control will actually decrease fuel consumption at Euro V level for HDVs by 2-3%. This will further reduce to Euro IV levels with Euro VI due to the higher NOx reductions required.
- The electrical efficiency of auxiliaries will be increased, e.g. by a switch to a higher on-board voltage and thus also more efficient components.
- In terms of driving there are trends to more vehicles per family. Though this results in a higher total mileage of all road transportation together, the mileage per vehicle usually decreases.
- The occupancy rate in passenger transport is declining, i.e. less persons per trip. This is true for passenger cars and – with a few exceptions [8] - also for public transportation.
- Likewise, the load factor of trucks vehicles has been declining, and less mass is transported per (freight) vehicle.

More specifically, the following developments apply for individual regions particularly. As we assume by 2020 a globally homogenised vehicle market, this developments determine the vehicle performance and specifications worldwide.

4.1 Light duty vehicles in Western Europe / European Union

The following features are considered part of the baseline of vehicles, cf. (Smokers, Vermeulen et al. 2006).

- The standard TA emission limit requirement for newly sold vehicles in 2012, i.e. between 140 and 120 g CO_2/km. This standard determines the base for any new vehicle by 2020! Note, that the long-term historic trend has been to increase the vehicle weight, defying in parts the efficiency improvement of the engine.
- Hybrid vehicles for S/M/L gasoline and for L diesel cars by 2008 – 2012.
- To meet requirement of 120 g CO_2/km in 2012 for sales weighted average of new cars sold in the EU (Smokers, Vermeulen et al. 2006). I.e. measures included under TA (contrary to those listed separately)!
- MAC with alternative refrigerant and/or improved energy efficiency by 2008-2014/15.

> "Ban on the high GWP R134a as a refrigerant for all mobile air conditioner systems as from 2011. As a result of this legislation, the auto industry is challenged to develop new systems which use low GWP refrigerants as an alternative to R134a. Parallel to these developments, the industry investigates possibilities to improve existing systems, as such legislation is not proposed for other parts of the world and as for the EU still some time has to be bridged before switching to alternatives. It is expected that CO2-based systems (R744) will be

[8] E.g. where a city toll has been established, with or without a simultaneous increase of the public transport offer. Or after a change in the fare system, some cities (or even long distance providers) have experienced an increase in ridership, e.g. Berlin public transportation (notably the S-Bahn) after the completion its the ring line.

the dominant alternative and that in response to existing policy these systems will gradually enter the market after 2008, reaching near 100% of new sales by 2014 or 2015. Both the existing R134a systems and the future R744 systems have room for improvement with respect to energy efficiency and the resulting indirect CO2-emissions associated with use of these aircos. In response to a possible EU policy promoting energy efficiency of MACs it is expected that improved systems will come to the market which have significantly lower energy consumption. The additional manufacturer costs for improved systems are estimated at €40 for R134a systems and €60 for R744 systems. Besides that further improvement of the average efficiency of R134a systems is expected to be achieved by an increased share of systems variable displacement compressors" (Smokers, Vermeulen et al. 2006).

- Low rolling resistance tyres, tyre pressure monitoring systems, low viscosity lubricants.

  "Various measures are proposed for supporting and accelerating the introduction of the aforementioned technologies in the market. Amongst them are the application of labelling schemes, creation of consumer support tools such as product databases, adoption of relevant standards for each technology and purchase incentive programs. All of these should be combined with a necessary update of the relevant legislative framework. Assuming a constructed scenario quantifying the effectiveness of policy measures promoting the application of low rolling resistance tyres, the total reduction potential associated with the increased use of low rolling resistance tyres is estimated for EU-15 at 2.4 Mtonne/y in 2012 growing to 5.3 Mtonne/y in 2020. Similarly for tyre pressure monitoring systems the overall potential is estimated at 2.0 resp. 9.6 Mtonne/y for 2012 and 202. The application of low-viscosity lubricants is estimated to result in an overall GHG reduction at EU-15 level of 2.0 Mtonne/y in 2012 increasing to 9.6 Mtonne/y in 2020. A more in-depth assessment of overall reduction potential, including possible effects of cost changes in consumer purchasing behaviour with respect to car size and fuel type, transport volume and model split, will be made outside this project using TREMOVE." (p.8)

- Note: No mentioning of H2, FC or full battery electric vehicles (Smokers, Vermeulen et al. 2006)!

4.2 Light duty vehicles in the US

The CAFE standards have been revised recently; this necessitates improvements in fuel efficiency important for the baseline: The combined PC and LDT standard for new models in 2020 is set to 35 mpg (TA). For the model year 2005 the combined fuel economy is estimated at 25.4 mpg, with 30.3 mpg for cars and 22.1 mpg for LDT (Davis et al. 2008, Tab. 4-17, Tab 4-18). This corresponds to an improvement in fuel economy of light vehicles of 27.5%.

We apply the following (linear) reduction rates.

Table 4.1: Calculated from Davis et al. 2008 (Tab. 4-1, 4-2, 4-17, 4-18). Note: These are type approval target values for fuel economy. Reduce by 18% to convert to real world fuel economy.

	Fuel economy (mpg)	*2005*	*2010*	*2015*	**2020**
PC	Fleet average	22.1	24.6	29.2	33.6
	New models	30.3	34.1	38.0	41.8
	Share new in fleet	30%	30%	30%	30%
	Change in fleet fuel consumption	100%	90%	76%	66%
LDT	Fleet average	17.1	19.2	22.1	25.0
	New models	22.1	24.9	27.7	30.5
	Share new in fleet	34%	34%	34%	34%
	Change in fleet fuel consumption	**100%**	**92%**	**80%**	**71%**

4.2.1 DEVELOPMENTS IN CALIFORNIA

Developments in California could be indicative of what can be achieved technologically in a relatively affluent market with customers open to change and a strong history of government support and control (always relative to US average or the federal level).

The ZEV regulations requires in the Base Path for Model Year 2009 as share of total vehicle sales in California: less than 1% ZEV, 5% AT PZEV, and 30% PZEV (CARB 2007). Manufacturers have responded to these requirements by some FCV as demonstration vehicles (160 up to 2006), and a larger number of HEV (110,000 by 2006). For the period 2012-2014 at least 7,500 to 25,000 FCV and up to 58,333 Enhanced AT PZEVs are required, corresponding to an estimated 1.8% and 4.7% of annual sales (CARB 2008). Targets aiming at ZEV or PZEV with annual sales numbers in the order of 100,000 vehicles annually have been deferred as it seems more than doubtful that the required technology would be available (CARB 2007). It is now expected (Walsh, Kalhammer et al. 2007) that

- HEV will continue to be commercialised paving the way also for PHEV,
- That FCV become technically available by 2015 to 2020, though it is not clear whether the costs can be reduced sufficiently and whether an adequate hydrogen fuelling infrastructure would support their market introduction,
- That BEV will only play a marginal role because of their limited range.

In conclusion: Not even as strong incentives and regulations as set in California will probably be sufficient for a widespread and costly market introduction of FCV or BEVs. Therefore, FCV or BEV are not considered important in the baseline scenario in 2020.

4.3 Light duty vehicles in Japan

Mandatory or indicative targets for vehicle fuel efficiency are part of the Baseline developments or the technology portfolio for its implementation.

Japan has issued ambitious targets to reduce the fuel consumption from automobiles (by 23% in 2015). However the best thinking about technologies and fuels in the future – at least in the automotive industry – does not differ from considerations in Western Europe or North America (Teratani, Mizutani et al. 2008). One notable exception is the high share of very small (mini) cars and LDT in the Japanese market and the high share of urban driving.

4.4 Heavy duty vehicles in the US

(Frey and Kuo 2007) have identified a large number of current, pilot and potential technologies for trucks. They estimate the potential for reductions in CO_2 emissions, fuel and refrigerant use as well as the associated costs for a target year 2025 in the US.

We assume that all technologies already commercially available today (as presented by (Frey and Kuo 2007) will have become part of the average truck fleet in the target 2020 (i.e. constitute the baseline). For the estimate of the maximal feasible (technical) potential we assume a certain additional degree of application/implementation of that commercial technology as well as and added amount of technology in the pilot phase and as new concepts (as presented by (Frey and Kuo 2007).

- Hybrids not considered for long-distance HDT but for MDT (i.e. with high share in local/urban mileage).
- FC only for auxiliary power, not for main power. Restrictions: Battery costs and durability.

Electric vehicles are not considered by 2020 as batteries/power supply inadequate. However, auxiliary power units and hybrid concepts, both for start-stop, idling and auxiliaries powering, are included as part of the standard and improved technology portfolio, cf. (Greszler 2007).

A big impact can be expected (Greszler 2007) from trailer aerodynamic features, tires and gap tractor-trailer on the one hand and drivetrain technologies, e.g. transmission and a hybrid drivetrain.

A few FC buses are in demonstration, but currently fuel costs only are three times more expensive than for the equivalent diesel bus and reliability seems reduced, let alone from capital and infrastructure costs (Chandler and Eudy 2007).

Similar developments are assumed for trucks in Europe.

4.5 Heavy duty vehicles in Japan

Japan has set targets to increase the fuel economy of heavy duty vehicles by 12.2% for trucks and busses from the 2002 model to the target year 2015 (Top-runner programme). The related technology are therefore part of the portfolio in the baseline scenario, and include (Walsh 2006):

- Improvements of the thermal efficiency of the diesel engine (notably DI, high turbo-charging pressures, intercooling),
- Reduction of engine losses (engine friction, idling, accessory power losses),
- Optimisation of the engine operation (transmission and torque converter)

Technologies/concepts that could be considered to go beyond this target and that actually exist in demonstration could include (Walsh 2006):

- DME trucks (similar FE as diesel trucks),
- CNG trucks (FE ~640 g/kWh),
- Series-hybrid bus (-50% FE compared to diesel bus),
- Parallel hybrid truck (-50% FE compared to diesel truck),
- Super-clean diesel engine (similar FE as base diesel truck).

Note, that neither fuel cell nor hydrogen nor fully electric concepts figure in this list. They might be too far from commercial applicability by the year 2020.

5 Caveats, limitations and uncertainties

5.1 Non-technical measures not considered

We have considered almost exclusively technical measures. We have not estimated impacts of behavioural change that could result in lower greenhouse gas emissions. Whether behavioural change is associated with costs to the consumer, no costs or actually savings/earnings is a contentious issue in economical valuation.

There savings in energy and/or greenhouse gas emissions due to some behavioural change can be significant. The following measures can serve as an illustration:

- Purchasing smaller, lighter, less powerful, … more efficient vehicles (e.g. compact instead of mid-size, a car instead of a van, …)
- Fuel shift, e.g. from gasoline to diesel powered cars.
- Lower vehicle mileage,
- Modal shift,
- Changing driving behaviour, e.g. through training or measures affecting the traffic flow (traffic management).
- Use pattern for auxiliaries, notably the mobile air conditioner.

5.2 Non-road transport modes

For this version we have not considered measures on other than road vehicles. However, in many Annex-I party countries aviation has a sizeable share in emissions and high growth rates. This would be one of the transport modes to treat, even if the high share of international aviation may complicate the political treatment.

Similarly, marine shipping is a global transport sector with growing importance. Its inclusion in international agreements appears tricky.

5.3 Uncertainties

The World Energy Outlook 2008 (IEA 2008) is our basis for the potential fuel demand in each sector including transportation. However, the data are not disaggregated by mode. From (IEA 2007) we take the demand shares for each mode and apply them to the future energy demand to derive future modal demand. This does not account for demand (or intensity) shifts between modes. Given, that growth rates for aviation (and maritime shipping) are expected to remain higher than for road transportation, our fuel allocation to road transport and hence the resulting emissions can be considered at the upper limit.

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