

# THE CURIOUS CASE OF SELECTING AND RANKING GHG MITIGATION MEASURES IN TRANSPORT

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## Abstract

Marginal abatement cost curves and cost-effectiveness estimates for transport CO<sub>2</sub> emission mitigation measures are useful tools and widely accepted for policy-makers for displaying a range of available emissions reduction options, their cost-effectiveness and reduction potential. However there is a large variety in outcomes which consequently changes the prioritisation of policies and measures as well. This paper shows a wide range of cost-effectiveness estimates in different studies for the EU car CO<sub>2</sub> emission performance regulation caused by only a few but significant methodological differences. The uncertainty involved indicates that calculating abatement costs and prioritizing transport CO<sub>2</sub> emission mitigation policies and measures is a sensitive process. According to this paper it seems that not the cost curve itself or the price of abating one ton CO<sub>2</sub> matters most, but the underlying methodological choices, approaches and assumptions used to produce the results.

## 1 Introduction

According to the Intergovernmental Panel of Climate Change (IPCC, 2007) in its Fourth Assessment Report, “most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is very likely due to the observed increase in anthropogenic (human induced) GHG concentrations”. Particularly burning of fossil fuels has made the blanket of greenhouse gases around the earth ‘thicker’ and more of the sun’s energy is being trapped in the atmosphere. The transport sector is one of the major sources of greenhouse gas emission<sup>1</sup> as it accounts for about 25% of global CO<sub>2</sub> emissions of which cars and trucks represent the bulk (about 75% worldwide) of these emissions. Without strong global action, car ownership worldwide is set to triple to over two billion by 2050, according to IEA (2009). Trucking activity will double and air travel could increase four-fold. These trends will lead to a doubling of transport energy use by 2050 (IEA, 2009).

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<sup>1</sup> The primary greenhouse gases produced by the transport sector are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and hydrofluorocarbons (HFC).

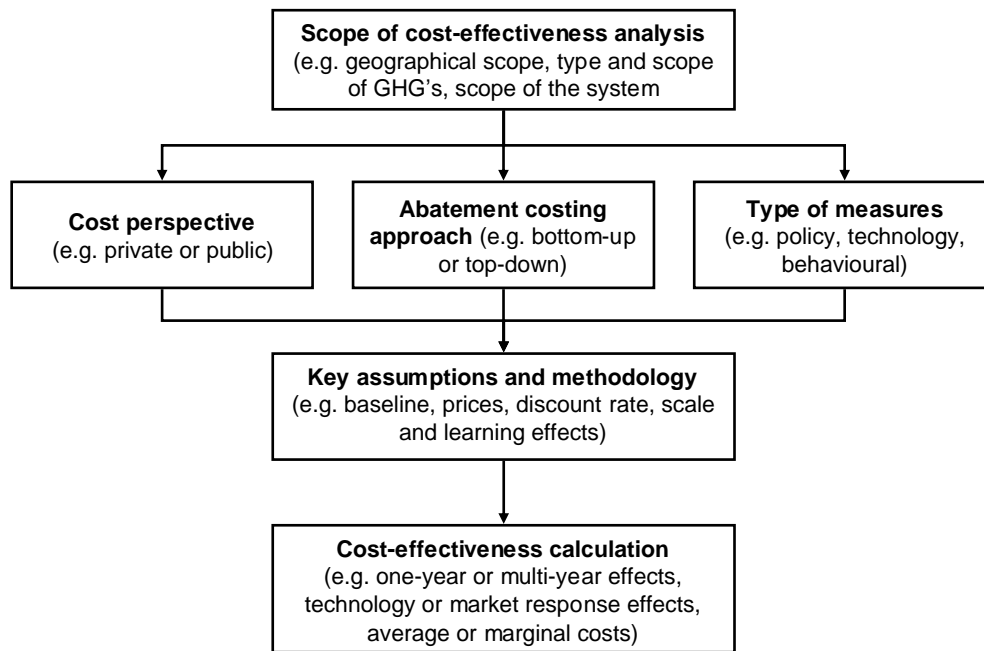
Policy makers are thus facing a huge challenge to decarbonize the transport sector. The desired reduction of CO<sub>2</sub> emissions in transport is not exclusively driven by environmental concerns with respect to global warming and climate change. Also energy security concerns or increasing transport operating costs as a result of increasing energy prices (e.g. oil price) motivate action to curb oil use in transport, and thus, CO<sub>2</sub> emissions. Policy makers aim for the best case of value (CO<sub>2</sub> reduction) for money (societal costs) towards reducing CO<sub>2</sub> emissions, but the process of ranking and selecting the most suitable policies and measures based on cost-effectiveness does not seem to be straightforward. The emission source – the vehicle – in road transport is relatively small and mobile, employs a large variety of technologies, and depends very much on traveller behaviour. Therefore, it is difficult to forecast CO<sub>2</sub> effects and costs of policy measures. There are many approaches to transport GHG policy appraisal and there appears to be a methodological chaos. Consequently, this results in cost-effectiveness estimates of policies and measures that are uncertain due to a.o. different calculation scope, cost perspectives, modelling approaches, assumptions, incomplete data and methodologies used.

This paper presents a framework for analysing key influential scope and methodology issues relevant for cost-effectiveness estimates of GHG mitigation in transport. Consequently, several cost-effectiveness studies on emission performance standards regulation for passenger cars in the EU are analysed and compared according to the framework. The paper continues with exploring the current practices and limitations of using cost-effectiveness estimates in marginal abatement costs (MAC) curves for selecting and prioritising different abatement policies and measures in transport. Finally, conclusions and a discussion reflecting on the curious case of selecting and ranking GHG mitigation measures in transport will be presented.

## **2 Scope and methodology issues**

In figure 1, a framework is introduced to conceptualize different steps that provide important aspects necessary to systematically analyse GHG abatement cost-effectiveness in the transport sector.

Figure 1: Framework for scope and methodological issues



The first step in the framework is the scope of the cost-effectiveness analysis (figure 1). The most important scope elements are the geographical scope (countries, world regions), the types of GHG emissions (CO<sub>2</sub> or CO<sub>2</sub> equivalents<sup>2</sup>), the scope of GHG emissions (direct combustion<sup>3</sup>, lifecycle, and/or embedded) and finally the scope of the system under consideration (vehicle level, transport sector level, multi-sector level or world economy level).

In the second step of the framework it is shown that the researcher carrying out a cost-effectiveness analysis has to consider three parallel issues related to the cost-perspective, the abatement costing approach and the type of measures:

1. First, there are two important cost perspectives in cost-effectiveness analyses: the financial-economic private perspective and the socio-economic public perspective. From a private perspective the price of an abatement measure would include the cost plus all taxes/subsidies and profits/losses. From a public perspective one would only be interested in the societal costs of GHG mitigation where profits/losses and taxes/subsidies are considered distribution effects that do not change the net costs to society. Other important elements that relate to the cost perspective in this second step are the discount rate and amortization period (which are different in a private perspective compared to a public

<sup>2</sup> CO<sub>2</sub>-eq or carbon dioxide equivalent is a standardized measure of GHG emissions designed to account for differing global warming potentials (GWP) of GHG's. The 100-year GWP's listed in the Intergovernmental Panel on Climate Change's (IPCC) assessment reports are often applied.

<sup>3</sup> Direct emissions are often referred to as Tank-to-Wheels (TTW), Pump-to-Wheels (PTW) or vehicle operating emissions. Indirect emissions are often referred to as Well-To-Tank (WTT), upstream emissions: from feedstock extraction and distribution to fuel production and distribution. Lifecycle emissions are direct + indirect emissions also known as Well-to-Wheels (WTW) emissions. Embedded CO<sub>2</sub> emissions are the emissions embedded in the production of the physical system (vehicle manufacturing, infrastructure construction).

perspective), accounting of co-benefits/external costs and accounting of rebound effects (both only taken into account in a public perspective).

2. Second, there are basically two different approaches to estimating the costs in cost-effectiveness studies. Economic costing approaches use "top-down" models, which analyze aggregated behaviour based on macro-economic relationship such as trade flows, GDP, price elasticity and often include multiple sectors, markets, countries or regions. Technology-oriented costing approaches use "bottom-up" engineering models, which focus on the integration of technology cost and performance data. The systematic difference in cost-effectiveness outcomes from bottom-up and top-down studies is explained by an optimism bias and pessimism bias in these approaches (see also Grubb et al, 1991; Grubb et al, 1993; Skea, 1993):
  - Optimism bias: bottom-up end-use modelling studies tend to overestimate the potential (and underestimate abatement costs) because they neglect various 'hidden' costs (transaction, rebounds) and constraints that limit the uptake of apparently cost-effective technologies. Technology studies and cost curves show that a large 'energy efficiency gap' (see section 4.3) exists between the apparent technical potential for energy savings and GHG reductions, and what is actually taken up in energy markets. Again, this highlights the non-optimality of the assumed adoption of energy efficient technology options in the baseline development in bottom-up studies.
  - Pessimism bias: top-down modelling studies tend to underestimate the potential for low-cost efficiency improvements (and overestimate abatement costs) since they ignore a whole category of gains that could result from non-price (regulatory, informative) policy changes. The economic principles in top-down models assume that markets function efficiently meaning that all new energy investments comprise the most energy efficient options consistent with cost-minimizing (or utility maximising) behaviour in response to the observed price signals.
3. Third, differences in cost-effectiveness studies can be found related to the conceptualisation of the GHG abatement policy, technology or behavioural change. Some studies analyze policy instruments: different types of governmental interventions that range from command-and-control type regulatory policies to market-based pricing instruments to education and information. The market response could either be technological change or behavioural change. Other studies analyze technologies ('electric vehicles') or behavioural changes (more people using public transport) without being clear how these new technologies or behavioural changes will be realized.

In the third step of the framework it is shown that key assumptions in the cost-effectiveness analysis have to be made. These assumptions relate to the assumed baseline reference development (e.g. autonomous energy efficiency improvement, changes in modal split or fuels used), as well as future oil price developments, discount rates, assumed lifetime of the reduction option, and others.

The last step of the analysis framework shows the importance of the formula used in the cost-effectiveness calculation. The main methodological issue in this step is the timing and timeframe of the cost-effectiveness calculation. There are six types identified in the literature:

1. Cumulated lifetime effects in a future year of implementation (e.g. cumulated 15 years lifetime effects of an option to be implemented in 2015)
2. Annualized lifetime effects in a future year of implementation (e.g. annualized effects of 15 year lifetime of an option to be implemented in 2015)
3. Weighted average of cumulated lifetime effects over a multi-year timeframe of implementation (e.g. weighted average of cumulated 15 years lifetime effects of an option to be implemented between 2015 and 2030)
4. Weighted average of annualized lifetime effects over a multi-year timeframe of implementation (e.g. weighted average of annualized effects of 15 year lifetime of an option to be implemented between 2015 and 2020)
5. One-year timeframe market penetration effects (e.g. effects of the actively adopted options in 2020)
6. Cumulated multiyear timeframe market penetration effects (e.g. effects of the actively adopted options between 2015 and 2030)

### **3 Cost-effectiveness of emissions performance standards for cars in the EU**

#### **3.1 Ex ante cost-effectiveness estimates**

The framework for scope and methodological issues (figure 1) shows that many assumptions and methodological choices have to be made in order to estimate the cost-effectiveness. To illustrate the importance of methodological choices on the outcomes, this paragraph shows the impact of different assessments with respect to the costs-effectiveness to reaching EU CO<sub>2</sub>-emissions performance standards<sup>4</sup> in 2012 (see table 1). These assessments assume that the 140 gCO<sub>2</sub>/km level of 2008 is maintained until 2012 in the reference baseline.

The following table 1 shows four policy scenarios with increasing stringency with respect to new sales averaged CO<sub>2</sub>-emissions performance for car manufacturers. The cost-effectiveness results are presented for five sources [A] to [E] employing various cost-effectiveness calculation formulas. All sources have only taken technological improvements into account. The sources [A] to [D] employ the TREMOVE model runs with second-order

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<sup>4</sup> Sales averaged type approval/test cycle CO<sub>2</sub> emissions of passenger cars in the EU by manufacturers, without trading between manufacturers.

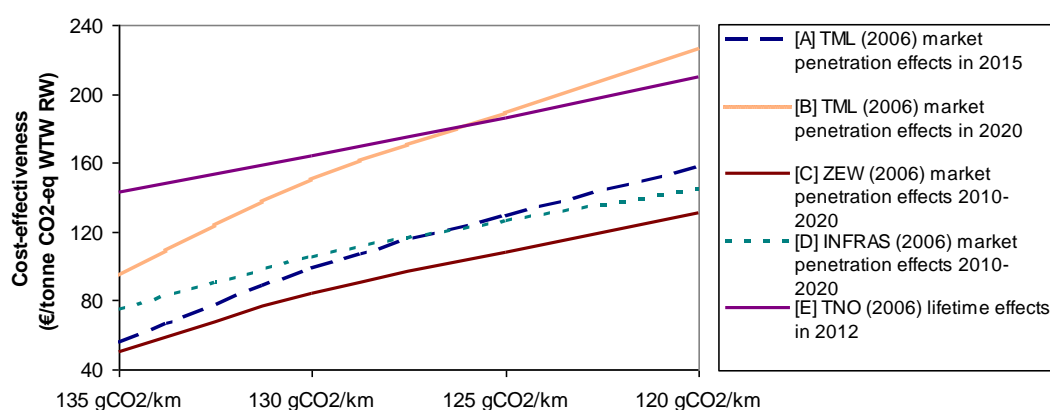
impacts (such as rebound effects), while source E employs a first-order impact assessment. Source E shows the smallest range of cost-effectiveness (factor 1.5) between the 135 gCO<sub>2</sub>/km and 120 gCO<sub>2</sub>/km targets. The min-max dispersion between the different sources is highest in the least stringent policy scenario (135 gCO<sub>2</sub>/km) showing a dispersion of €93 or 186%. Although the dispersion decreases with increasing stringency of the policy scenario, the min-max range is still a gap of €95 per tonne CO<sub>2</sub>-eq or 73% in the 120g CO<sub>2</sub>/km scenario.

Table 1: Cost-effectiveness (€/tonne CO<sub>2</sub>eq WTW)

Source:	A)	B)	C)	D)	E)	
Policy:	TML (2006) In 2015	TML (2006) In 2020	ZEW (2006) 2010-2020	INFRAS (2006) 2010-2020	TNO (2006)	Min-Max dispersion (€ and %)
Policy P1: From 140 gCO <sub>2</sub> /km in 2008/9 to 135 gCO <sub>2</sub> /km in 2012	56	94	50	75	143	€ 93 = 186%
Policy P2: From 140 gCO <sub>2</sub> /km in 2008/9 to 130 gCO <sub>2</sub> /km in 2012	99	150	84	105	164	€ 80 = 95%
Policy P3: From 140 gCO <sub>2</sub> /km in 2008/9 to 125 gCO <sub>2</sub> /km in 2012	129	189	108	126	186	€ 81 = 75%
Policy P4: From 140 gCO <sub>2</sub> /km in 2008/9 to 120 gCO <sub>2</sub> /km in 2012	157	226	131	145	210	€ 95 = 73%
Factor P4/P1	2.8	2.4	2.6	1.9	1.5	

The average abatement costs for reaching the 120gCO<sub>2</sub>/km by 2012 ranges from 131 to 226 € per ton CO<sub>2</sub>-eq WTW. The principal factors that affect these estimates are discussed in the following section 3.2.

Figure 2: Cost-effectiveness (Average Abatement Costs) of CO<sub>2</sub> emissions regulation using different methodologies



### 3.2 Scope and methodological differences

The main reasons (see figure 1) for these differences are determined by the 1) systems scope, 2) cost-perspective, 3) policy instrument or reduction option, 4) baseline reference development, 5) other assumptions and

relationships and 6) the calculation formula for the abatement cost for the cost-effectiveness analysis. Table 2 summarizes the main differences between the sources in [A] to [E]. Regarding the scope no substantial differences are found; all focus on the EU15 (or EU15 results extrapolated to EU25), CO<sub>2</sub> equivalent emissions using GWP factors, M1 passenger cars and use almost similar conversion factors for test cycles to real-world emissions and for tank-to-wheel to well-to-wheel emissions.

The main difference in scope relates to source [E] which employs a technology-engineering bottom-up system analysis, which could be characterised by employing a narrow system scope (limited to CO<sub>2</sub> reducing technical options) and a high level of disaggregation of system variables (detailed coverage of technical options). The other sources are based on the partial equilibrium model TREMOVE which could be characterised by employing a fairly broad system scope (vehicle technologies, fuels, mode choice, vehicle fleet evolution, emissions) and also a fairly high level of disaggregation (engine technologies, fuel types, size classes).

The cost-perspective is public / societal in all cases but nevertheless there are some important differences in the way tax revenues/losses and dealer cost/manufacture mark-up are treated. Changes in government tax revenues could be caused by changes in tax levels on vehicle purchase, insurance and maintenance/repair, changes in fuel consumption factors for diesel/petrol cars, overall decrease in transport demand and the substitution towards subsidised public transport modes. TML(2006) argues that as the government balances its revenues and expenses, changes in tax revenues from the transport sector will be compensated in one or another way and could lead to de/increased social security expenses, or also to in/decreases in labour taxes or in general taxes. Sources in [A] to [C] use this approach and apply it to general taxes. Source [D] excludes changes in tax revenues from the cost-effectiveness analysis. In source [E], the retail price of additional manufacturer cost minus taxes is employed, thus including mark-up of the manufacturer and dealer and additional dealer cost. It can be argued whether profits should or should not be a part of the costs to society. However, TNO(2006) argues that profits can to a large share be interpreted as mark-up for entrepreneurial risks (e.g. to cover losses in case of bankruptcy) and can thus be considered as real economical costs to be included in the calculation of CO<sub>2</sub>-abatement costs as perceived by society.

The next potential methodological difference is whether a policy instrument is being considered or a GHG reduction option. Clearly all sources listed in the table introduce a regulatory policy instrument that sets a sales averaged type approval CO<sub>2</sub>-emission limit value by manufacturer for new cars. The next question is how this target value is going to be achieved. All sources focus on the technical measures at the vehicle level where source [5] employs additional retail prices excluding taxes. In TREMOVE the technical changes are incorporated into the fixed (vehicle purchase) and variable (fuel consumption) resources cost changing the generalized costs (and utility) of transport, while the uptake of technical measures (fleet penetration) is

determined by the fleet renewal rate, scrappage functions and sales logit function. Since TREMOVE employs second-order impact assessment, there could be behavioural changes leading to people buying smaller cars or shifting from petrol to diesel or vice versa contributing to achieving the target limit value. The changes in market shares (size classes and fuel use) was analysed in TML(2006) and proved to be negligible. However, it is also noted that the sensitivity coefficient of the car market shares to price changes in TREMOVE is to be considered as a fairly low estimate.

Another important methodological issue is the definition of the baseline reference development and other assumptions and relationships. All five sources assume that the average vehicle sold in 2008 meets 140g CO<sub>2</sub>/km and that there are costs involved in maintaining this level between 2009-2012, compensating for autonomous mass increase (AMI<sup>5</sup>) of 1.5% per year. These costs are 16% lower in TREMOVE than in [5] because TREMOVE takes only additional manufacturer costs. Other important assumptions relate to the petrol/diesel market share and oil price scenarios which are slightly different. It should also be noted that changes in crude oil prices might lead to significant changes in transport patterns, car ownership and demand for transport. In principle, a forecast from an external transport forecast model (e.g. SCENES / TRANSTOOLS) is needed to assess these impacts, and to provide the necessary baseline data for TREMOVE. TREMOVE can only calculate small changes in transport demand (rebound effects). Price levels and discount rates are comparable between the sources (4% social discount rate, € 2000 and € 2002 real prices).

The last methodological issue is the formula used for the cost-effectiveness analysis. The table below shows the implications of the formulas being used. Source [A] calculates the cost-effectiveness for a single future year in the short term (5 years after first diversion from baseline development) for which the TREMOVE model is not ideally designed. Therefore, source [B] should provide a more reliable estimate of the cost-effectiveness of this regulation because in 2020 there will have been 8 years of fleet penetration of new cars meeting the 120 gCO<sub>2</sub>/km standard (and 10 years counted from 2010 when the baseline and policy scenario start diverging). Contrary to [A] and [B], source [C] calculates not a single future year but calculates the average cost-effectiveness over the 2010-2020 timeframe. The average cost-effectiveness in [C] proves to be a lower estimate than both [A] and [B]. In source [D] the same approach is used as in [C] but excludes tax revenues/losses. Apparently, the CO<sub>2</sub> regulation involves positive effects in the general tax revenues because [D] is more expensive or less cost-effective than [C]. Finally, in [E] the cost-effectiveness is calculated from a lifetime perspective of vehicles sold in 2012. Thus where [A] to [D] only consider the costs, savings and emission reduction in 2015, 2020 or 2010 to 2020, [E] calculated the full

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<sup>5</sup> Due to safety standards, Euro standards, bigger fleet average cars, higher performance of cars, luxury options like electric windows, DVD players, navigation, air conditioning etc. Autonomous mass increase results in additional fuel consumption and associated CO<sub>2</sub>-emissions which need to be compensated by additional CO<sub>2</sub>-reducing measures to keep absolute fuel efficiency (CO<sub>2</sub> emissions) at 140 gCO<sub>2</sub>/km in the 2009-2012 period.



lifetime impacts of new vehicles (from 2012 to 2025). None of the sources take into account potential secondary benefits such as energy security or other air pollutant emissions.

*Table 2: Definition of the scope, cost perspective and assumptions*

Source:	A) TML (2006) In 2015	B) TML (2006) In 2020	C) ZEW (2006) 2010-2020	D) INFRAS (2006) 2010-2020	E) TNO (2006)
Formula	[5]	[5]	[6]	[6]	[1]
Model/tool	TREMOVE	See [A]	See [A]	See [A]	Spreadsheet
Implications of formula	Short-term cost-effectiveness (5 years), tax revenues/losses counted	Long-term cost-effectiveness (10 years), tax revenues/losses counted	Average 10 year cost-effectiveness, tax revenues/losses counted	Average 10 year cost-effectiveness, tax revenues/losses not counted	Lifetime cost-effectiveness of car sales in 2012, tax revenues/losses not counted
Countries or regions	EU-15 + 4-NMS (CZ, HU, PL, SI)	EU-15 + 4-NMS (CZ, HU, PL, SI)	EU-15 + 4-NMS output (extended to EU-25)	EU-15 + 4-NMS output	EU-15
Types of GHG emissions	$CO_2\text{-eq} = CO_2 + 23 \times CH_4 + 296 \times N_2O$	See [A]	See [A]	See [A]	See [A]
Scope of GHG emissions	$RW = TA \times 1.15 + airco$ $WTW = TTW + 0.54 - 0.61 \times CO_2\text{-eq}$ per unit of fuel produced	See [A]	See [A]	See [A]	$RW = TA \times 1.195$ $WTW = TTW \times 1.183$
Sectoral scope	M1 passenger cars	See [A]	See [A]	See [A]	See [A]
Cost perspective	Public cost to society (additional manufacturer costs), € 2000 real prices	See [A]	See [A]	See [A], but tax revenues/losses not counted	Public cost to society (additional manufacturer costs x 1.16) € 2002 real prices
Discount rate	4%	See [A]	See [A]	See [A]	See [A]
Lifetime vehicle-km	Lifetime is based on scrappage functions, annual mileage decreases depending on age (avg. = 12 to 16,000 p.a. depending on size and fuel)	See [A]	See [A]	See [A]	208,000 (16,000 km x 13 years)
Oil price per barrel	\$ 36.8, \$ 37.1 and \$ 39.7 per barrel of oil in 2010, 2015 and 2020	See [A]	See [A]	See [A]	€ 36 per barrel = € 0.3 cost per litre petrol/diesel
Baseline – vehicle emissions	See [E]	See [E]	See [E]	See [E]	Average vehicle sold in 2008 meets 140g CO <sub>2</sub> /km
Baseline – petrol/diesel shift	Petrol/diesel 51/49 in 2008, 52/49 in 2012. Diesel share decreasing in policy scenarios due to higher abatement cost than petrol	See [A]	See [A]	See [A]	Petrol/diesel from 50/50 in 2008 to 45/55 in 2012
Baseline – sales volume	Not available	See [A]	See [A]	See [A]	Growth of 1% p.a.
Baseline – Autonomous Mass Increase (AMI)	1.5% AMI induced car cost increase to maintain the 140 gCO <sub>2</sub> /km level up to 2012 is calculated using add. manufacturer cost, no AMI and learning beyond 2012	See [A]	See [A]	See [A]	1.5% p.a.

## **4 Practices and limitations of MAC curves**

In paragraph 3 it is illustrated, with the case of CO<sub>2</sub> emission standards for cars, that methodological issues have great influence on cost-effectiveness results for the same policy option. Cost-effectiveness estimates for different options are often combined into a so-called abatement cost curve. This paragraph shows that methodological issues also play a major role in constructing and using abatement cost curves.

In abatement cost curves a selected set of measures for which the abatement cost has been calculated, is plotted into a graph which is horizontally arranged from the left to the right in function of increasing abatement cost (and thus declining cost-effectiveness). The resulting stepped curve from the bottom left to the upper right is then considered to be the marginal abatement cost curve (MAC-curve). Generally, the MAC curve gets increasingly steeper as one has to consider yet more expensive options with decreasing reduction potentials.

### **4.1 Mixing different studies**

A first methodological issue in constructing an abatement cost curve is related to the results of paragraphs 2 and 3. These paragraphs show clearly that mixing abatement cost estimates from different studies in one abatement curve could give a confusing picture. For example, a relative 'expensive' measure from one study may be only relatively expensive compared to other measures from other studies because of methodological issues. Therefore it is important to be aware of these issues in designing an abatement cost curve which should include cost-effectiveness estimates of abatement measures based on the same calculation methodology.

### **4.2 Average and marginal abatement cost curves**

A second methodological issue is related to average versus marginal abatement cost curves. In cost-effectiveness analysis from a societal perspective one should consider the marginal costs of a policy instrument or measure because once the marginal costs become larger than the marginal benefits, the society would be better off aiming at other policies or measures that do have lower marginal costs than marginal benefits. In case of emissions limit values for cars (see paragraph 3), the marginal abatement costs of reaching 120 gCO<sub>2</sub>/km are the additional costs and benefits (as compared to the baseline reference) of moving from 121 to 120gCO<sub>2</sub>/km divided by the additional CO<sub>2</sub> reduction of moving from 121 to 120 gCO<sub>2</sub>/km. The average abatement costs would comprise the total additional costs and benefits divided by the total CO<sub>2</sub> reduction of moving from 140 to 120 gCO<sub>2</sub>/km. Where average abatement costs take into account both fixed (FC) and variable (VC) costs divided by the total quantity (Q) produced (or emissions reduced),

marginal costs only take into account the difference in VC divided by the difference in Q. Consequently, the two formulas below show the concept of Average Abatement Costs (AAC) and Marginal Abatement Costs (MAC).

$$\text{Average Total Cost (ATC)} = \frac{FC + VC}{Q} = \frac{TC}{Q} = \text{Average Abatement Cost (AAC)}$$

$$\text{Marginal Cost (MC)} = \frac{d(FC + VC)}{dQ} = \frac{dVC}{dQ} = \text{Marginal Abatement Cost (MAC)}$$

Where:

FC = Fixed Costs

VC = Variable Costs

TC = Total Costs

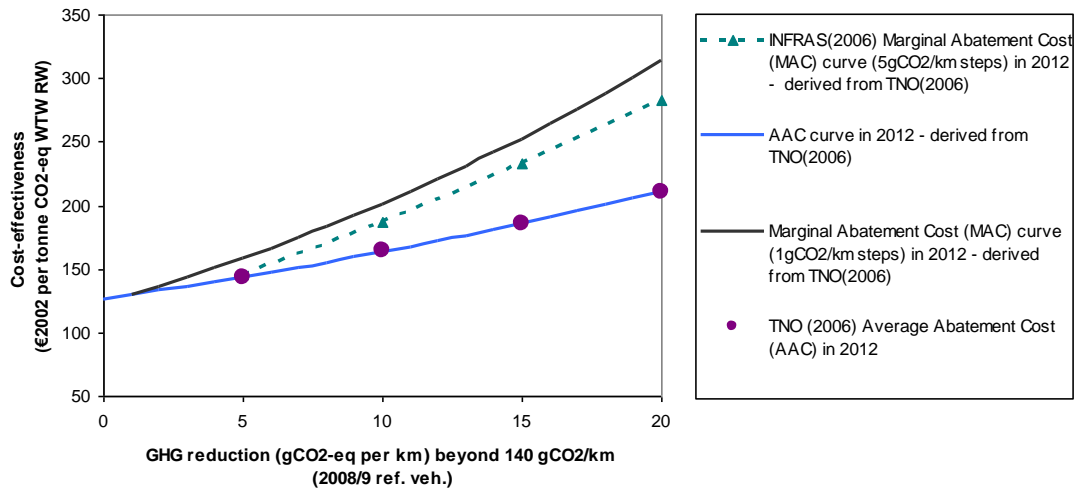
Q = Quantity of technical options produced or quantity emissions reduced

MC = the first derivative (d) of ATC and (by definition) fixed costs (FC) do not vary with production quantity (Q) and drops out of the equation when it is differentiated

Abatement costs are often not clearly defined, like in TNO (2006) where marginal costs are defined as the additional costs of applying CO<sub>2</sub>-reducing technologies to a baseline vehicle. As described above, it should rather be defined as the additional costs per additional unit of CO<sub>2</sub> reduction compared to a baseline vehicle. The following figure illustrates the difference between marginal- and average abatement costs for emissions regulation for cars. The abatement costs for the four target values (135 to 120 gCO<sub>2</sub>/km) calculated in TNO(2006) are plotted as well as an average abatement cost (AAC) curve. In INFRAS(2006), a marginal abatement cost curve (MAC-curve) was derived with unit steps of 5gCO<sub>2</sub>/km reduction per step. In addition, in this paper another MAC-curve is derived (by taking the first derivative of the AAC-curve) based on 1 gCO<sub>2</sub>/km reduction per step.

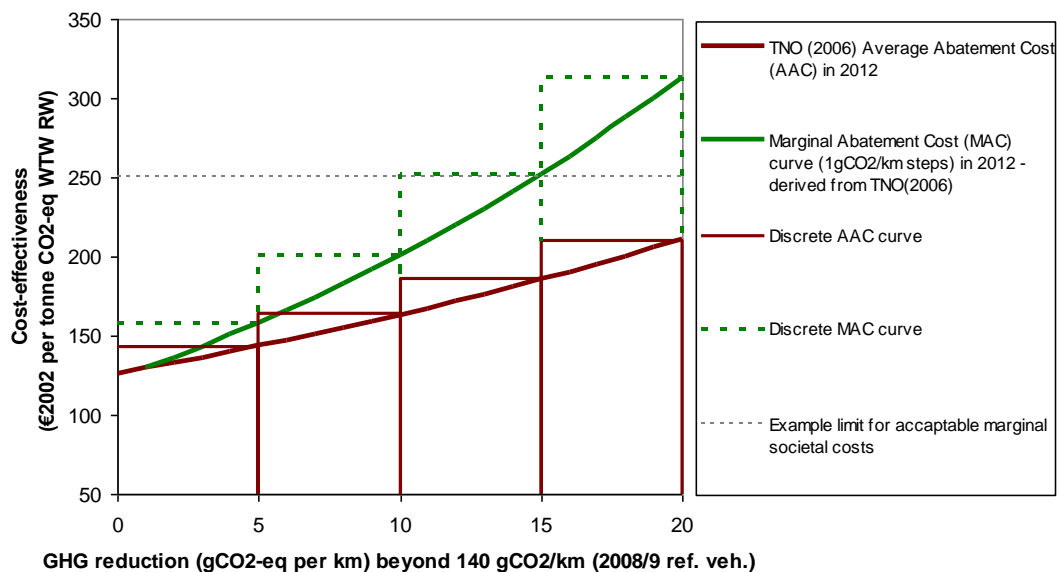
As shown in figure 3, the smaller the step size the more accurate and steeper the MAC-curve becomes. The magnitude of the difference between a MAC-curve and AAC-curve cannot be overlooked (50% in the 120 gCO<sub>2</sub>/km case) and highlights the importance of the ambiguity around these concepts found in many studies. Furthermore, as a MAC curve represents the abatement cost of the last ton (or percentage-point) of emissions abated, the total abatement cost of emission reductions can be determined by calculating the area under the MAC curve. In other words, a MAC curve can be used to calculate how much emissions can be abated according to a given budget.

Figure 3: Average and marginal abatement costs of CO<sub>2</sub> emission regulation for cars



A consecutive step in emission reduction, as depicted in a cost curve, can in itself already be a package of measures with differing marginal abatement costs. Let us consider for instance the four consecutive steps of 5 g CO<sub>2</sub>/km towards the target of 120 gCO<sub>2</sub>/km. All four steps comprise a package of technical measures and have equal emissions reduction potential, but the additional cost for each next step is increasing. The marginal abatement costs of the third package in the figure below is represented by the MAC curve between values 10 and 15 on the x-axis, while the marginal abatement cost to reach the full potential of the third package is represented by point x=15; y=252. The cost-effectiveness of a complete package/step is often expressed in terms of average abatement costs. The figure below shows a continuous as well as a discrete AAC- and MAC-curve. In some studies (e.g. TML, 2006) the AAC curve is plotted and referred to as MAC-curve.

Figure 4: Discrete versus continuous AAC- and MAC curves



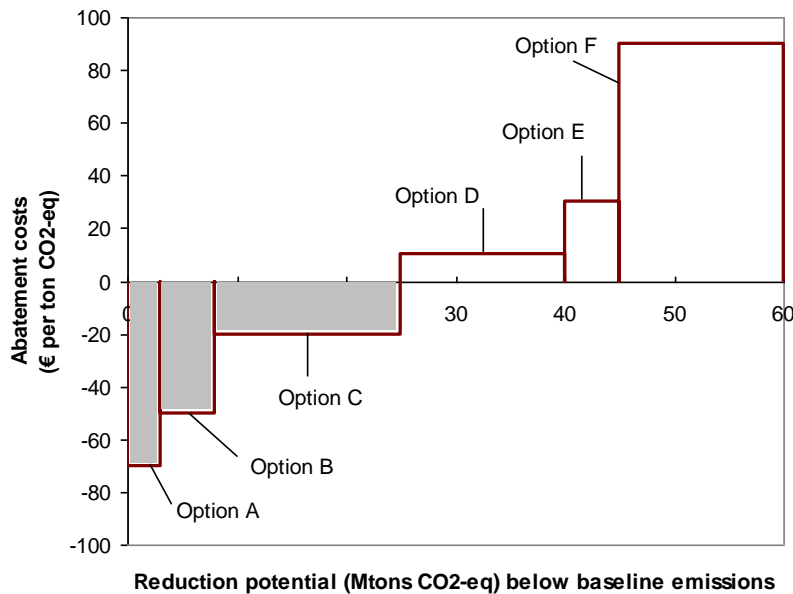
The potential risk of confusing MAC and AAC can be illustrated as follows. Let us consider a situation where policy makers want to know the cumulative or percentage reduction potential that can be obtained with measures that have GHG abatement costs below a given or desired level. An example of this level is plotted (horizontal dashed line) at €250 per tonne CO<sub>2</sub> but could also be chosen at the level determined by the price of CO<sub>2</sub> under a cap and trade system (e.g. EU ETS). Based on the AAC-curve one would conclude that the 120 gCO<sub>2</sub>/km target (more than 20 gCO<sub>2</sub>/km reduction in the graph) can be achieved below the €250 level, while based on the MAC-curve one would conclude that only the level of 125 g CO<sub>2</sub>/km can be achieved below this level (15 gCO<sub>2</sub>/km reduction).

#### **4.3 'No regret' options and the energy efficiency 'gap'**

A third issue is related to the existence or non-existence of so-called 'no regret' options. In bottom-up MAC curves often options are identified which result in CO<sub>2</sub> emission reduction and cost savings. Contrary in top-down approaches these 'no regret' options are non-existent, because they implicitly assume efficient markets and rational behaviour. Specifically, if consumers or companies can earn money with implementing a measure they will do that anyway.

In the economics literature a debate is ongoing about this topic. In bottom-up approaches it is argued or assumed that a significant proportion of the energy efficiency improvement potential is not realised due to the apparent failure of consumers and firms to take energy-saving measures that would actually save them money. These 'no regret' options are a result of barriers in the energy market which inhibit energy efficiency improvements. These barriers take many forms, ranging from inadequate access to capital, isolation from price signals, information asymmetry, split-incentives (or principal-agent problems), transactions costs, end-user preferences, non-priced costs (externalities) and bounded rationality (IEA, 2007; Grubb, 1993). The grey-shaded options in figure 5 depict the no regret options in a typical discrete bottom-up MAC curve.

Figure 5: a MAC curve including negative abatement cost options



## 5 Sensitivities of using cost-effectiveness estimates and MAC curves

Based on the analyses in chapters 3 and 4, the following list presents the methodological sensitivities related to using cost-effectiveness estimates and MAC curves for selection and prioritisation of GHG abatement measures in the transport sector, but may also apply to other sectors. The order of presenting the sensitivities is arbitrary.

- Unless they are developed iteratively<sup>6</sup> (using complex models or analysis taking into account potential overlaps), MAC curves may neglect interdependencies among abatement options and thus ‘double count’ some emissions reduction potentials (e.g. low carbon fuels diminishing the reduction potential of improved conventional engines, or improved conventional diesel engines diminishing the reduction potential of electric vehicles). Adding up the abatement potential of measures in a MAC curves does not necessarily mean that they are complementary; they could also be counterproductive. Policy makers should still carefully choose consistent policy packages.
- It is often not clear whether the abatement costs in cost-effectiveness studies refer to the 1) lifetime or annualized effects in one year, 2) lifetime or annualized effects weighted and averaged over multiple years, or 3) market penetration effects in one or multiple years.
- Technology-engineering bottom-up abatement costs assessments generally present the technical potential neglecting other important factors

<sup>6</sup> In TNO(2006) a ‘safety margin’ is applied in determining the cost curve for CO<sub>2</sub> emission reduction to correct for potential overlaps or interdependencies.

that determine what is realizable in practice. These factors (or potential barriers) include consumer preferences and resistance, hidden and transaction costs, rebound effects, and the policy changes that are required for take-up of options and determine the timescales needed for emission reduction.

- Prioritisation of options with negative abatement costs does not seem straightforward. At equal negative costs (e.g. option 1: €-1,000/20 tons CO<sub>2</sub> reduction = €-50 per ton, and option 2: €-1,000/40 tons CO<sub>2</sub> reduction = €-25 per ton) the option with the lowest reduction potential (here option 1) gets the highest priority. It would make more sense to select the no regret reduction option with the highest reduction potential first (here option 2).
- Taking account of rebound effects and co-benefits (from external costs) may substantially change the prioritisation and reduction potential of options in a MAC curve. One could argue that all options incur co-benefits and would lower the whole curve. However there could be large difference in co-benefits between options (e.g. speed limit reduction bringing about safety and noise benefits compared to for instance engine efficiency improvement).
- The static character of cost-effectiveness estimates and MAC curves with respect to their sensitivity to oil price changes and scale and learning effects indicates that the prioritization is very sensitive to exogenous shocks in time.
- Abatement costs are a very single-objective indicator, but could be extended by taking into account co-benefits. In some case the co-benefits could be the primary reason to take action in the first place and could be larger than the primary effects.
- The large width of options in discrete MAC curves shows that these steps do not reflect the marginal abatement costs of an additional ton or percent reduction.
- Choosing a policy focusing only on the early “free” no regret savings, could obstruct strategies needed to achieve the later more costly reductions that will require investment and technological innovation (e.g. transitional policies and measures land-use planning for higher density cities, transition to electric vehicles or hydrogen-fuel cell vehicles).
- Policies and measures aimed at non-technical and behavioural responses are underrepresented if not missing in MAC curves. Policy and decision makers should be aware of this and carefully consider other (‘harder to quantify’) measures as well.

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