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Passenger car use and climate change:

Quantifying the impacts of technological innovations needed for substantial CO_2 emission reductions

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ABSTRACT

The purpose of the study is to model scenarios of technological innovations in the global passenger vehicle fleet, i.e. improvements in the energy economy of average regional vehicle fleets and blending of alternative fuels. This is to quantify the potential CO_2 emissions reductions that may stem from enhancing "business-as-usual technologies" in cars with respect to a set of baseline car stock projections.

The study adopts an international approach quantifying in total 11 world regions, thereby conceptualising regionally distinct growth patterns of average car stocks until 2050. Scenario analysis is used to analyze impacts of alternative futures in car technology, i.e. the adoption of efficiency improvements or the blending of low-carbon biofuels to overcome business-as-usual growth in car-related CO_2 emissions.

To facilitate the assessment the present study is based on a multi-model approach to car demand, applying two types of methodologies rooted in the economics of consumption, utility maximization and single equation models, to derived reference scenarios of car stock growth. They assume that preferences are the same throughout world regions, following the American lifestyle of individual passenger vehicle demand. The models are calibrated using empirical data that have been originally collated from international sources for the purpose of the study. Computation results show that given substantial growth in regional vehicle fleets under business-as-usual assumptions particularly in transition and developing regions, technological improvements in vehicle efficiency must be complemented by growing biofuel use with increasing mitigation potential in order to brake the trend of ever rising CO_2 emissions. We conclude that a necessary absolute reduction in emissions from the passenger car sector needs tremendous efficiency improvements in the passenger vehicle fleet accompanied by a growing share of biofuel use. However, lifestyle and behavioural changes in overall mobility patterns are imperative to mitigate emissions from the car sector.

Keywords: Global passenger car demand, sectoral CO_2 emission scenarios, mitigation policies,

JEL Code: Q42, Q47, Q54, Q55

1. PASSENGER CAR USE AND CLIMATE CHANGE

Passenger car use is a key sector of fossil fuel consumption and as such a contributor to anthropogenic greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2) - a relevant driver of climate change. Passenger transport predominantly operates on oil-based fuels (94% in 2006; IEA, 2008), although their overall share begins to fall slightly due to the growing use of biofuels. In 2006, global transportation energy use accounts for 23% of global energy-related carbon emissions (21.8% in 1990; IEA, 2008a). Recent trends in total aggregated GHG emissions of Annex I parties[1] state an overall decline from 1990 to 2006 in major energy consuming sectors except for the transport sector which was growing by 20.2% (IEA, 2008). On a worldwide basis, CO_2 emissions from the transport sector were even rising at a much higher rate, i.e. by 40.9% from 1990 to 2006, indicating the very dynamic growth in transport-related emissions from transition and developing regions. So far, attempts to reduce the emissions from transportation have failed.

And emissions from the transport sector are projected to increase further according to the reference scenario of the World Energy Outlook (WEO; IEA, 2008). Thereafter global transport contributes one fifth of the increase in global emissions to 2030, increasing from 6.4 Gt in 2006 to 8.9 Gt in 2030, remaining the second biggest emitting sector. The central drivers of this growth are increasing vehicle ownership and use in non-OECD countries and an increase in international travel by aviation and navigation in terms of marine freight.

On-road mobility contributes a majority share to transport related emissions, i.e. about 73% (2006; IEA, 2008) of total global transport-related CO_2 emissions are released on roads comprising passenger as well as freight transport. Improvements in energy efficiency and attempts to decarbonize the road sector hence will sign a substantial impact on transport energy demand and CO_2 emissions. The present study focuses on

[1] Annex I parties are industrialised countries that are included in Annex I to the United Nation Framework Convention on Climate Change (UNFCCC). They have pledged to reduce their GHG emissions by the year 2000 to 1990 levels. Annex I parties consist of countries belonging to the OECD and countries designated Economies-in-Transition.

the dynamics of passenger transport, i.e. on light-duty vehicles including cars, vans and light trucks that account for 65% of total road-fuel consumption.

Given the scope and dynamics of transport related emissions, this sector is essential for mitigation. While the power generation and the industrial sectors are covered by a cap-and-trade system (i.e. in the EU the Emissions Trading System), the transport sector offers a good opportunity for implementation of sector-specific energy efficiency standards (i.e. vehicle fuel efficiency standards and renewable fuel mandates as prosecuted by the USA and the EU). An essential step to the analysis of impacts from sectoral abatement strategies is to quantify long term reference and abatement scenarios of transport-related CO_2 emissions, here passenger car use. This is central in order to identify whether global CO_2 emissions from passenger vehicle use should be expected to be detrimental to the aim of climate protection. This question is of importance since other energy consuming sectors may not be able to bear the total burden of emissions reduction needed to stay within the 2°C target which the EU itself has committed to, nor to compensate for substantial emissions growth in the transport sector. In particular, reference scenarios are needed to systematically discuss impacts of alternative futures in car use, for example the adoption of efficiency technologies, the use of alternative fuels or altered modal splits in the transport sector.

Recently, sectoral approaches to emissions abatement are receiving attention in international/national climate policy debate, i.e. in the design of a post-Kyoto agreement (Baron, 2006; IEA, 2008). A sector wide approach to emissions mitigation may - in certain cases - be more successful than national approaches such as binding reduction targets because competitiveness risks and carbon leakage can be overcome. A sectoral approach is particularly interesting for internationally oriented sectors and their businesses given a fairly limited number of actors, as for example the car manufacturing industry.

The paper starts with a historical sketch of regional trends in car stock growth in section 2. It is demonstrated that regional car stock growth follows a stylized pattern known as Engel curve. Section 3 shortly presents regionalized reference vehicle stock demands derived from partial equilibrium demand models and single-equation models. Both methods are calibrated to the same historical data sets presented in section 2. Section 3 puts as well forward car related CO_2 emissions scenarios computed by involving behavioural and technological trend developments, i.e. distances driven per car (behavioral parameter) as well as average fuel economies of vehicle fleets in use (technological parameter). Section 4 embarks on quantified policy scenarios of technological innovations in passenger car stock and related CO_2 emissions mitigation that stem from 1) fuel efficiency improvements and 2) blending of biofuels. Given the model results, we conclude in section 5 that a portfolio of abatement strategies is needed in order to brake the current trend of ever rising CO_2 emissions form passenger car demand and use.

2. GLOBAL PATTERN OF HISTORIC CAR STOCK GROWTH

Aiming at calculating global but regionalized patterns of CO_2 emissions from passenger car use, the analysis considers eleven world regions representing clusters of regional proximity and comparable economic performance (see Figure 1). The spatial resolution is widely used in the literature allowing for convenient comparisons. Historical trends of per capita car stocks and GDP (gross domestic product) for the eleven world regions considered are shown in Figure 2.

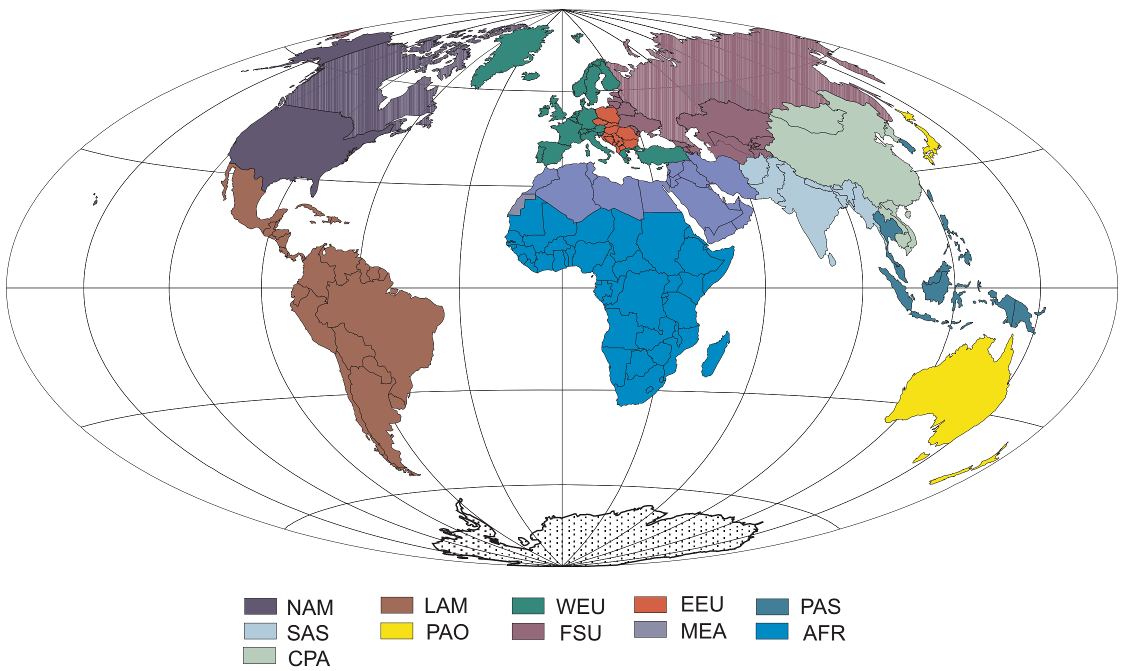

Figure 1: The eleven world regions considered

The data are collated from recognized international sources, i.e. the World Development Indicators published by the World Bank (2005, 2003) for population and GDP time series, the international source books by Mitchell (1995,1993,1992) and the International Road Federation (IRF, 2005, 1985-2001) for car stock data. Aggregated cluster specific time series of per capita car stock and per capita GDP are calculated by weighted average according to population figures of the representative countries of each cluster.[2]

Figure 2 shows NAM as the region with the worldwide highest per capita passenger car stock level of about 0.6, while WEU is slightly below at 0.5 followed by PAO at 0.45 at the end of 20th century. PAO denotes the leader at an average income level of more than US$ 40,000 per capita.[3] The three regions are followed by EEU, FSU, LAM with per capita car stocks between 0.12 and 0.28, the regions PAS, MEA, AFR, ranging from 0.02 to 0.05 and CPA and SAS ranging from 0.006 to 0.008 cars per capita. Figure 2 suggests that regional clusters together build a typical income-consumption curve - also known as Engel curve - of a stretched S-shape with each cluster representing a distinct development stage of car stock relative to per capita income within the temporal snapshot pictured. Thereafter a disproportionately high growth in car demand relative to income takes place when the market penetrations of the car and income levels are rather low. When car markets are ripe, notably when car endowments and income levels are gaining, growth in car demand slows below income growth. This is typically captured by income elasticities of greater or less than one. First, this derives from the empirical data, where every world region shows a particular income elasticity at a specific point in time and second, income elasticities vary with income growth following the pattern of a stylized S-shaped Engel curve. The conclusion from this analysis may be that preferences towards passenger cars are

[2] Countries that figure behind the regional clusters in terms of data are selected according to data availability and are listed in table 1 in the Appendix. Form the table it is apparent that the selected countries cannot fully reflect the geopgraphical scope in most cases. While some spatial clusters like NAM, WEU, PAO, CPA, and SAS are well represented by the data of the countries considered, other regions like AFR, LAM, MEA, EEU, FSU and PAS are under presented due to missing data.

[3] This high per capita income of PAO is due to Japan's high exchange rate measured in Purchasing Power Parity; the per capita income of PAO falls behind that of North America.

equal across time and space, i.e. across cultures, but they are restricted or determined by income patterns, transport infrastructure and media.[4]

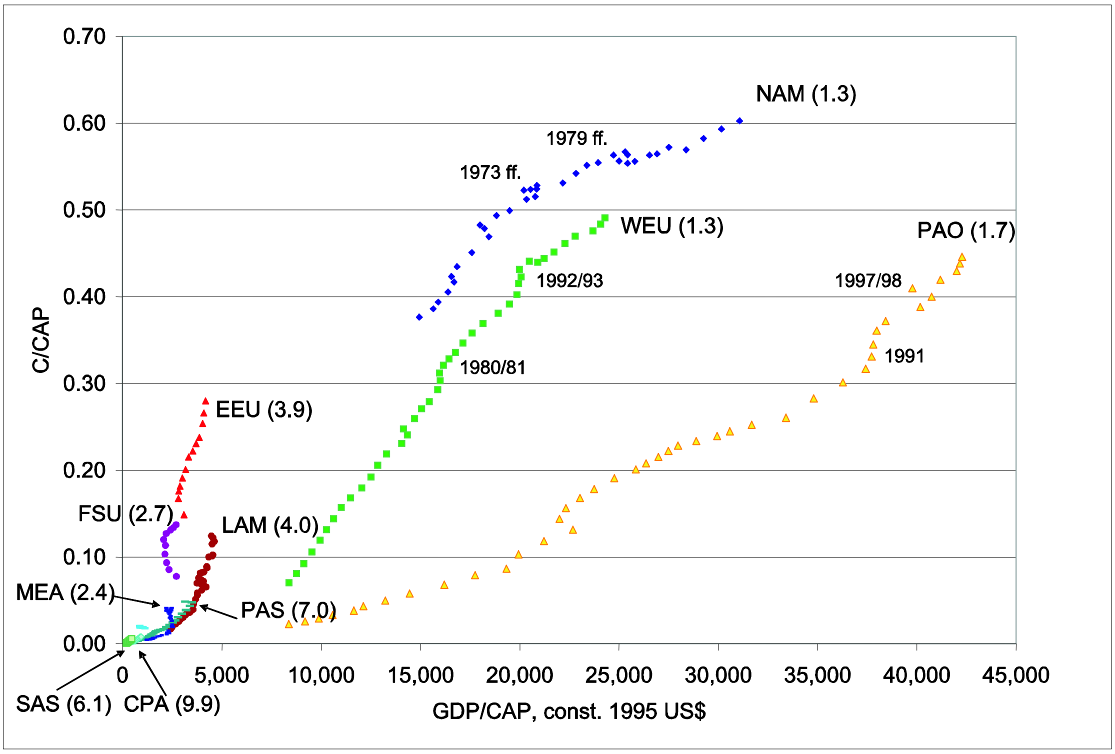

Figure 2: Income-consumption curves of car demand in eleven world regions 1960-2002

Also shown in the figure are average annual growth rates of average passenger car stocks during the last 5 years (figures in brackets). The Asian regions, among the lowest in car endowments, indeed show the highest growth rates of 9.94% in CPA, 6.14% in SAS and 6.95% in PAS. In contrast, industrialized countries exhibit low growth rates of 1.3% (WEU, NAM) and 1.7% (PAO) only, indicating maturing passenger car markets.

3. PASSENGER CAR FLEETS AND CO_2 EMISSIONS SCENARIOS

The computation of reference scenarios on car fleets and CO_2 emissions is based on drivers of high growth, i.e. world population is growing to 10.1 bn people in 2050 and economic growth leads to a five-fold increase in the global gross product by the year 2050 compared to 1990. Regional models of both methods, the utility maximization

[4] For an early analysis of transport demand patterns across different countries and cultures, see for instance Zahavi and Talvitie (1980). See also Stigler and Becker (1977) on equal preferences.

approach and the income-consumption models, have been calibrated to empirical data as shown in Figure 2. They are driven by region-specific income time series adopted from Leimbach and Tòth (2003) that have developed an optimal growth model operating with the same regional specifications and generating income time series through capital and trade flows. Price trajectories are defined as input with respect to the optimization approach, notably we consider a one percent real price increase for car use; c.f. Meyer et al. (2007) for further details on model specifications. Parameter values for preference functions are set for marginal budget shares concerning cars and generic goods demands (demand for all other consumer goods). A further parameter represents a subsistence level of demand that has to be satisfied before demand for cars takes off. The application of income-consumption models to car stock demand is based on the functional relationship between car stock demand and income alone as depicted in Figure 2. This can be represented in terms of Engel curves, notably by S-shaped or sigmoid functional forms. We use the Gompertz function as second method to estimate cluster specific car stock demands, see for instance Dargay and Gately (2001). The Gompertz model abstracts from marginal budget shares and price specifications. Parameters for saturation levels and starting levels are set equally across regions, i.e. 0.6 cars per capita for all regions. Regions-specific curvature parameters are estimated on the basis of empirical data shown in Figure 2.

Results for the utility-maximisation demand scenarios show that the global car fleet in use rises from around 640 million to about 1.5 bn. in 2050 and thus is more than doubling within a 50 years time span (see Fig. 3). While the industrialized regions NAM, WEU, PAO and EEU experience a slow absolute increase in car stock demand with an average annual growth rate of 0.8%, transition and developing regions together show a significant growth yielding an average annual growth rate of 3.3% in their vehicle fleet throughout the observation period. Average annual growth rates for these regions are slightly higher with respect to the year 2030, i.e. 0.9% for industrialized countries and 3.7% for transition and developing countries. The share of the industrialized countries vehicle fleet remains dominant throughout the observation period but is constantly decreasing from 77% in the year 2000 to 50% in mid 2040s.

Results from Gompertz models (c.f. to Fig. 4) show a more dynamic pattern of growth with the global vehicle fleet rising from around 600 million[5] to 2.7 bn. cars in 2050, thus the global vehicle fleet is more than quadrupling. Industrialized clusters yield average annual growth rates of 0.5%, i.e. lower than in Stone-Geary simulations, whereas transition and developing regions together show average annual growth rates of 6.4% within the simulated time span.

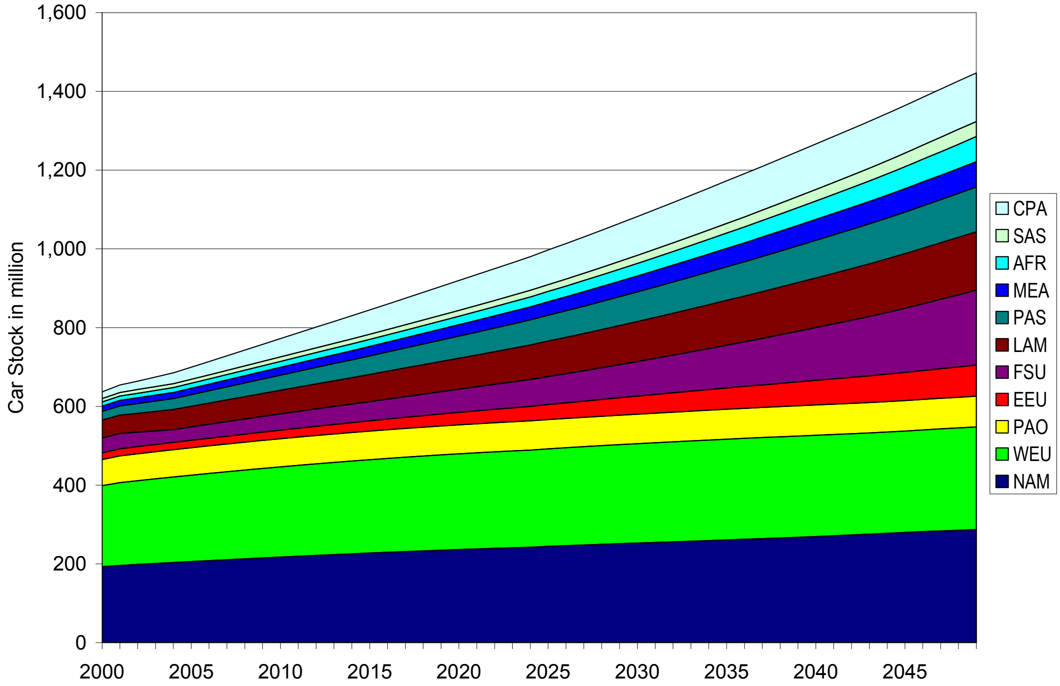

Figure 3: Car stock demand projections on the basis of utility-based approach to demand employing Stone-Geary utility functions 2000-2050

5 Differing starting values are due to the deviation of Gompertz regression models from empirical data.

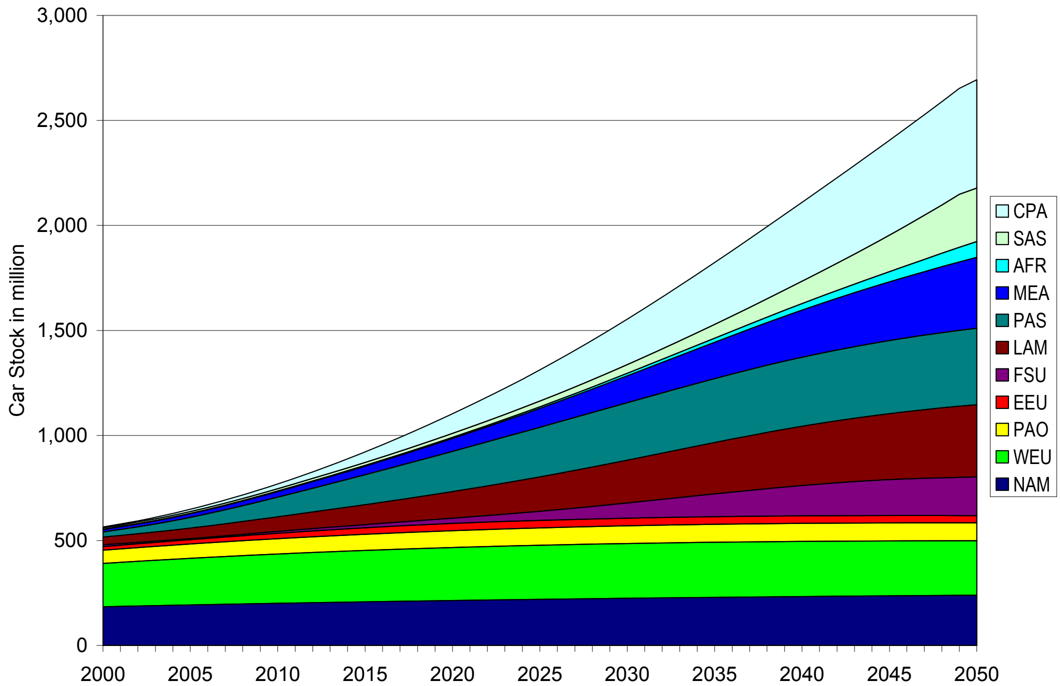

Figure 4: Car stock demand projections on the basis of income-consumption models employing Gompertz functions 2000-2050

Considering average annual growth rates until 2030, the vehicle fleet of the industrialised world is about to grow by 0.8% while the one of the transition and developing regions is at 8%. In the Gompertz case the share of industrialized car fleet falls from 83% to around 50% by 2022 already. Majorities in regional car fleet compositions are hence quickly shifting and car markets in Asia, Middle East, Latin America and Russia are rapidly gaining dynamics.

The variance in global passenger car fleets of the two scenario projections based on equal driving forces in population and income is widening over time. Main reasons are the assumptions behind the models that shall be briefly discussed, for details see Meyer et al. (2006). Modelling car stock demand by utility-maximization models incorporates the economical-modelling assumption that people's behaviour remains the same (constant preference assumption). So in each country people will continue to spend the same proportion of their salary on a car (constant marginal budget share). But as a rule and according to the historical example of industrialised countries, people start to spend a larger proportion of their earnings on a car (rising marginal budget shares) as they get richer. So projections of the utility-based approach are probably an underestimate, in particular with respect to transition and developing regions that experience high per capita income growth and thus have not reached their preferred share of budget spending on cars. Projections on the basis of Gompertz income-consumption functions, in contrast, may overestimate car demands as, first, contingencies from price developments and income restrictions are not incorporated in the model, and, second, the assumption that all regions will yield the same saturation level of 0.6 cars per capita as in the USA (NAM) is too simplified since most countries don't possess the wide-open spaces of North America but face high population densities and restricted road networks.

In order to base our subsequent calculations on a medium estimate, we use the average of the outcomes of the two methodologies applied, c.f. Figure 5 for results. Model refinements are subject to further research, i.e. income-dependent varying marginal budget shares, on the one hand, and country-specific saturation levels dependent on urbanisation and population densities, on the other hand (for the latter c.f. Dargay et al., 2007). Finally, the average projection of passenger car stocks from the two model approaches is validated in its range by similar projections from the literature, e.g. the WEO refers to a reference scenario of light-duty vehicle stock in the year 2030 of about 1.4 billion (IEA, 2008).

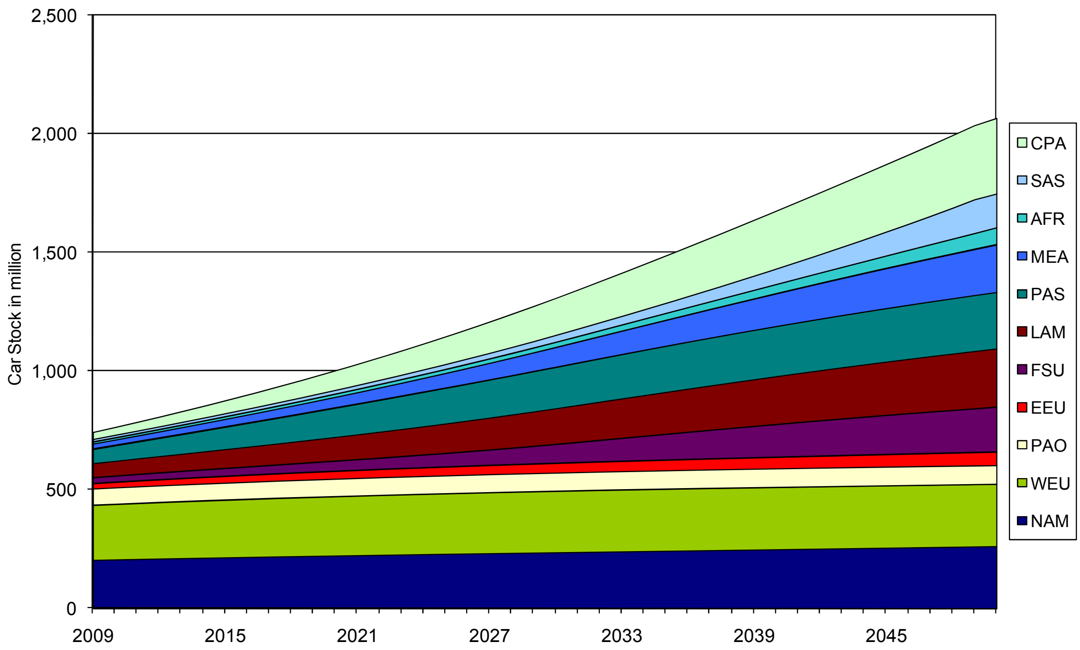

Figure 5: Car stock demand projections as average of optimization and income-consumption models (Figure 3 and Figure 4) 2000-2050.

We calculate associated CO_2 emissions scenarios on the basis of behavioral and technological assumptions. Behavioral scenarios encompass the total volume of transport activity from private car stocks in use, measured in kilometers as average annual distance driven per car. Converting activity volumes of the global car fleet in use into CO_2 emissions, we extrapolate the state-of-the-art fuel economy improvements using the example of Germany. Here, the average fuel economy of the vehicle fleet in use improved by one liter fuel per 100 kilometers driven within two decades (OECD, 2001). This development is applied uniformly to all regional vehicle fleets starting from regionally differentiated initial fuel use standards, however. In line with empirical data, NAM is modelled on the basis of 12 l/100 km while in WEU this level is at 9 l/100 km driven, for further details refer to Meyer et al. (2007).

CO_2 reference emissions scenario (BAU) is depicted in Figure 6. As demand for cars is increasing, so does the related fuel demand and the associated CO_2 emissions. We calculate the resulting CO_2 emissions on the basis of the IPCC standards regarding the carbon content of fuels. As we do not distinguish diesel and gasoline fuelled cars in the regional vehicle fleets due to fragmented data, we use the average carbon content of diesel and gasoline, i.e. 2.51 kg CO_2/l fuel. Compared with today's annual 3 gigatonnes (Gt) of CO_2, the global passenger car fleet may yield 7 Gt CO_2 within the next 50 years. Demand for passenger road transport is, thus, expected to increase strongly in the coming decades on the basis of a business-as-usual (BAU) development of fuel efficiency improvements from regional car fleets, especially in transition and developing regions. By 2030 CO_2 emissions from the global passenger car fleet in use are expected to be about 60% higher than in 2009. The counterfactual shows an emission path that would take place if the efficiency of the regional vehicle fleets is assumed to remain constant. This would yield additional CO_2 emissions of 11.5% in 2030 and 25% in 2050.

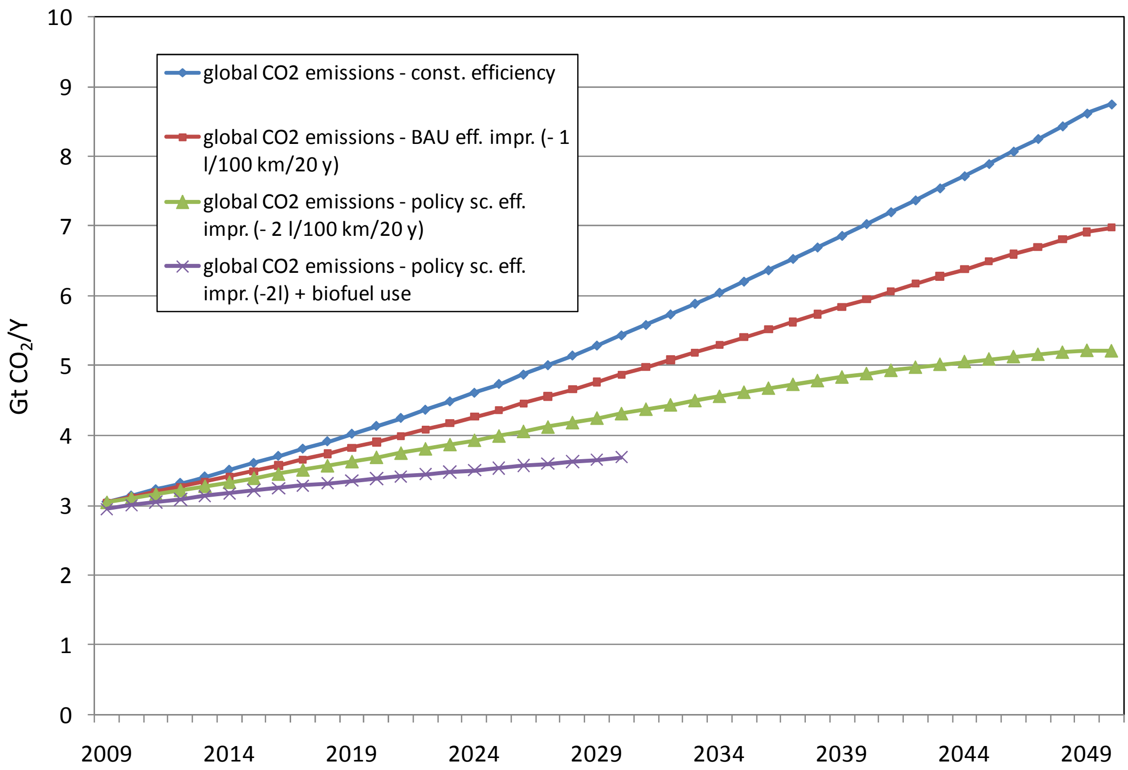

Figure 6: CO_2 emissions scenarios from global car fleet in use with const efficiency, BAU efficiency improvement, enhanced efficiency improvement and growing biofuel use with growing mitigation potential, own computation.

4. POLICY SCENARIOS OF ENERGY EFFICIENCY AND BIOFUELS

This section presents two alternative scenarios of CO_2 emissions based on the above reference scenario of passenger car fleets in use. We assume vehicle ownership to remain unchanged, i.e. follow a BAU-demand as laid down in the previous chapter, and employ this reference scenario as counterfactual to compute the impacts of 1) vehicle fuel efficiency improvements and 2) rising biofuel use. This implies that we consider measures that alter parameters of fuel consumption and associated CO_2 emissions but neither vehicle use nor vehicle demand.

4.1 SCENARIOS OF VEHICLE FUEL EFFICIENCY IMPROVEMENTS

The volume of CO_2 emissions released by the world car fleet in use reflects the combined influences of consumer car stock demand and use behavior as well as technological applications. The fuel efficiency is measured in liters fuel per hundred kilometers driven, or, in non-metric terms, in miles per gallon fuel use of passenger cars. Car manufacturers may dedicate technological advances in vehicle design to increase the power and performance of the vehicle or to increase its fuel efficiency. Generally, these aims conflict, with power improvements damaging fuel efficiency and vice versa. During the last decades, market forces supported a shift in demand towards heavier cars with greater engine size and higher power capacity (Meyer and Wessely, 2009). This trend was *inter alia* manifested in the growing demand for all-terrain vehicles (sports utility vehicles – SUVs). It counteracted substantially the scope of efficiency improvements that would have been realisable if average weight and power had not been increased. Although a trend towards heavier and more powerful cars occurred, the efficiency of the whole vehicle stock in most OECD countries nevertheless improved, since the fuel economy of new cars was better than that of the cars replaced. Taking the example of Austria, the diesel car fleet (about 54% of the total car fleet) showed an improvement in fuel efficiency of about 1% per year between 1990 and 2007 while the gasoline car fleet gained improvements of 1.6% on average per year. This amounts to a reduction in fuel consumption per 100 kilometers driven of 16% for diesels and 24% for gasoline cars since 1990 (the Kyoto reference year). For the total fleet, this results in a reduced diesel-equivalent fuel use of approximately 2 l/100 km within 17 years, being equal to an average annual reduction in fuel use of 1.7% considering the registration weighted car stock. This is a remarkable gain in fuel efficiency.

Takimg as an example the US American fuel economy of the combined car and light truck fleet since 1997, there was a rapid increase in the fuel efficiency of new cars from 1997 through the early 1980s, a slower increase until reaching its peak in 1987, a gradual decline until 2004, and an increase beginning in 2005 (EPA, 2008).

There are policy objectives to reduce the CO_2 emissions from new cars in the EU, i.e. improving the fuel efficiency of new cars sold in the EU. The EU regulation sets an EU-wide target for new car CO_2 emissions of 130 gCO_2/km by 2012 and a longer term target of 95gCO_2/km by 2020. How such an improvement will affect the on-road vehicle fleet efficiency depends on the share of new cars sold, old cars retired as well as the turn-over rate of cars. Finally, the fleet average fuel economy is more important than the new car sales weighted fuel economy regarding the related CO_2 emissions from passenger car use. The scrapping premiums that have recently been adopted in some European Countries (e.g. Germany and France) to stimulate car sales could, in theory, accelerate the improvements in the vehicle fleet fuel efficiency substantially if the promoted cars were those with ambitious energy efficiency improvements.

Given the fragmented international policy objectives (if any) towards vehicle fuel efficiency of new cars, we compute a policy efficiency scenario equal over all regional vehicle fleets. Our policy scenario assumes an improvement in the vehicle fleets fuel efficiency of 2 l/100 km driven within two decades. Results are depicted in Fig. 6. The difference in CO_2 emissions between the policy scenario of enhanced efficiency improvement and the BAU-efficiency scenario is again a reduction in emissions of about 11.5% in 2030 and 25% in 2050. What is striking with respect to regional growth patterns is that in NAM, WEU, PAO efficiency improvements are able to reduce emissions in absolute terms due to the slow growth in vehicle stock, while in the other world regions the growth in the passenger car stock outpaces efficiency improvements resulting in an absolute increase in CO_2 emissions in both regional as well as aggregated global emissions. In order to compensate for growing car demand and use, vehicle fleet fuel efficiency improvements consequently have to be enhanced tremendously above historical rates.

4.2 SCENARIO OF GROWING BIOFUEL USE WITH INCREASED MITIGATION CAPACITY

Recently, much attention has been directed to biofuels as a blend or substitute for conventional fuels, see for instance EEA (2006) and OECD/IEA (2004a). Biofuels can help curb GHG emissions, depending on how they are produced, and contribute to rural development. Higher oil prices have made biofuels more competitive with conventional oil-based fuels, but further cost reductions are needed for most biofuels to be able to compete effectively without subsidy (IEA 2006). There is considerable interest in the promotion of biofuels on both sides of the Atlantic for reasons of security in energy supply and agricultural support but also for reasons of CO_2 abatement and sustainable development in rural areas (Scheffran, 2009).[6]

There are several types of biofuels and many different ways of producing them. At present, almost all biofuels produced around the world are either ethanol or esters, referred to as biodiesel. Ethanol is usually produced from sugar and starchy crops, such as cereals, while biodiesel is produced mainly from oil-seed crops, including rapeseed, palm and sunflowers. Other crops and organic wastes can also be used (IEA 2006). Second-generation biofuels are made from any plant material such as waste from agriculture and forestry. They could significantly reduce CO_2 production, and do not compete with food crops. Second generation fuels are based on lignocellulose applying processing technologies such as gasification and Fischer-Tropsch technology, i.e. biomass-to-liquids (BTL). Producing ethanol made from trees, grasses and other types of biomass which contain a lot of cellulose, the energy balance could be much higher than from ethanol made from maize (The Economist, 2007).

The net impact on GHG emissions reduction from the substitution of conventional fuels through biofuels depends on several factors: These include the type of crop, the amount of energy that is embedded in the fertilizer used to grow the crop, emissions from fertilizer production, the resulting crop yield, the energy used in gathering and transporting the feedstock to the biorefinery, alternative land uses[7] and land use

[6] See for instance the EU Biofuel directive (Directive 2003/30/EC) for a legally binding target on biofuel use.

[7] For example, if crops are planted on land that would otherwise become a forest, then there is a significant emission of GHG associated with the loss of carbon sequestration.

changes, the energy intensity of the conversion process, emissions credits that can be attributed to the various by-products. CO_2 emissions from the point of use are assumed to be zero based on the fact that biomass feedstock is a renewable resource emitting as much carbon as was absorbed by the biomass (OECD/IEA 2006). But from the point of the full "fuel cycle", from biomass feedstock production to final fuel consumption, GHG emissions may vary substantially. In some cases, emissions may be as high as or even higher than the net GHG emissions from gasoline vehicles. On the other hand, some biofuel feedstock and conversion processes, such as enzymatic hydrolysis of cellulose to produce ethanol and increasing the use of biomass as the process fuel, can reduce well-to-wheels CO_2-equivalent emissions to near zero (OECD/IEA, 2004a). Estimating the net impacts of using biofuels on oil use and GHG emissions is, thus, a complex issue. A survey of studies conducted by the OECD/IEA (2004a) indicates a range of GHG emissions savings of specific biofuels as summarized in table 2.

Biofuels	**Well-to-wheels GHG emissions, compared to base gasoline/diesel vehicle**
Ethanol from starchy grains (corn/wheat)	-20% to -40%
Ethanol from sugar beets (European studies)	-35% to -56%
Ethanol from Sugar Cane (Brazil)	up to -92%
Ethanol from Cellulosic Feedstock (poplar trees, switchgrass) - enzymatic hydrolysis	-70% to -90 %
Biodiesel from FAME[8] or RME[9]	-40% to -60%
CNG[10] from local eucalyptus	-80%

Table 2: GHG impacts of alternative biofuels

However, the absolute potential of biofuels to abate CO_2 emissions is limited. Producing biofuels on a large scale requires large areas of land. At present about 1%

8 Fatty Acid Methyl Esters

9 Rapeseed Methyl Ester, i.e. biodiesel from oil-seed rape. In North America studies additionally look at soy-based biodiesel.

10 Compressed natural gas from gasification

of global road-transport fuels are derived from biomass. Increasing this share to a complete substitution is impossible unless fuel demand is reduced substantially, land productivity is increased dramatically, and large areas are converted to arable land, or biofueles are made from ligno-cellulosic biomass that requires less arable land.

We compute a biofuel scenario that is based on a September 2008 study by the U.S. Department of Energy (DoE) which estimates the worldwide potential to produce biofuels including biofuels for export (DoE, 2008). It was undertaken to improve understanding of the potential for imported biofuels to satisfy the requirements of Title II of the 2007 Energy Independence and Security Act (EISA) in the coming decades. The study modelled a detailed and up-to-date representation of the amount of biofuel feedstocks that are being and can be grown worldwide, current and future biofuels production capacity, and other factors relevant to the economic competitiveness of worldwide biofuels production, use, and trade. The baseline projection is given in the following table.

	2005	**2010**	**2015**	**2020**	**2025**	**2030**
USA	15.14	49.205	68.13	90.84	102.195	109.765
Brazil	18.925	22.71	34.065	45.42	56.775	60.56
West Europe	7.57	22.71	22.71	26.495	37.85	49.205
Rest of the World	3.785	7.57	18.925	41.635	68.13	94.625
Total	45.42	102.195	143.83	204.39	264.95	314.155

Table 3: Baseline scenario for biofuel production in USA, Brazil, Western Europe and rest of the world 2005-2030 (in billion liters ethanol equivalent). Source: DoE, 2008.

As a hypothetical reference case we assume that average emission reduction over all biofuels changes linearly from -30% in 2005 to -80% in 2030 compared to the fossil energy equivalents.

Results from computing a biofuel scenario of increasing biofuel use with steadily growing mitigation capacity on top of the enhanced efficiency scenario are depicted in Figure 6 until the year 2030. It is clear that with a growing capacity to mitigate CO_2 per liter of biofuel use the potential to reduce GHG emissions from the transport sector is improving. But this does not include indirect land use effects of feedstock production which could change the GHG balance of biofuels and is beyond the scope of this analysis. In total, these two approaches are not breaking the trend of rising emissions from the car sector. Hence, additional approaches towards changing mobility patterns are needed in order to reduce emissions in absolute terms.

5. PROSPECTS FOR ABATEMENT STRATEGIES IN THE PASSENGER CAR SECTOR

The above analysis illustrates that a displacement of oil by a growing share of biofuels that itself shows an increased potential to set-off GHG emissions together with an enhanced efficiency scenario have a potential to reduce passenger car-related CO_2 emissions with respect to the reference scenario. But these two approaches cannot reduce emissions in absolute terms.

The modelling exercise put as well forward that improvements in the fuel economy do not solve the problem of ever rising global CO_2 emission because gains from efficiency improvements are compensated by growing passenger car use, in particular in the economies in transition (BRICS). This leads us to the conclusion that 1) energy efficiency improvements and biofuel use must both be enhanced and 2) there is no silver bullet, no single technology to drive the scale of emissions reductions needed to break the trend of ever growing passenger car-related emissions. Therefore, we must prepare to rely on a portfolio of abatement strategies for the passenger transport sector in order to achieve CO_2 emissions savings. One of the main targets should be to ease growth in car demand and use because this could multiply the impacts from efficiency improvements and biofuel use.

As a final point we give an overview of strategic approaches that should be addressed in order to strive for a transformation of private mobility towards climate friendly mobility in the passenger car sector, see Figure 7. From the technological point of view a more ambitious approach to technically reducing the energy intensity of passenger cars is essential. This is considered to be a measure that can be implemented in the short to medium term. On the one hand, this addresses the motivation and responsibility of private car manufacturers around the world to act as innovators in decarbonizing passenger transport systems. On the other hand, public incentives for stimulating research and market deployment are necessary. Establishing price signals that pull new technologies at a sufficient rate and scale seems to be essential in order to make new technologies competitive with conventional ones. As vehicle manufacturing is highly concentrated - the world's 20 largest vehicle manufacturers account for 92% of global production (2003) - establishing a common technology standard would be a very effective way of realizing technically viable energy efficiency gains.

Behavioral Approach	**Technological Approach**
⇩	⇩
consumer choice towards efficient/advanced technology cars	enhance fuel efficiency of vehicles
shift in modal split	develop/deploy technological innovations of decarbonization
reduce transport activities and needs	alternative fuels/biofuels alternative propulsion systems (hybrid, electro, gas, hydrogen)
change preferences regarding spatial patterns of housing, working and leisure to prevent urban sprawl	optimize intermodality enhance quality of public transport
Set coherent political framework conditions (taxes, subsidies and standards)	

Figure 7: Approaches to decarbonize passenger car transport

The behavioral approach mainly addresses questions on how to shift individual preferences for passenger car demand and use towards efficient/advanced technology cars and/or how to consolidate passenger car demand in general. Preferences for cars as a mode of transport are manifold and range from the utility derived from using cars as a fast and comfortable way of being mobile, from the freedom from dependence on schedules and availability of public transport, to the car as being a luxury item with status-symbol significance. The choice of passenger transport is, hence, not only the result of individual preferences but is explained by socio-political preferences as well. Often, alternative public transport schemes and incentives to the car are lacking or public transport schemes are less attractive. For example, the length of road networks has been increasing constantly while the railway systems have been cut back. Thus preferences towards automobility and certain technological performance parameters are subject to a variety of boundary conditions of which price incentives, legislation, spatial planning and the quality and availability of public transport systems are among the most important factors. Besides setting the boundary conditions towards more efficient passenger transport it will be necessary to enhance the public understanding of the adverse environmental impacts from passenger transport on climate stability. Finally, a new culture of being mobile is needed.

APPENDIX

Region & Time Span of Series (Fig. 1)	Countries Considered due to Data Availability
AFR – Subsaharan Africa 1979-1996	Cameroon, Congo (GDP), Ethiopia (cars), Kenya, Nigeria, South Africa
CPA – Centrally Planned Asia 1985-2002	China
EEU – Eastern Europe 1990-2002	Hungary, Poland
FSU – Former Soviet Union 1993-2002	Russian Federation, Ukraine
LAM – Latin America 1964-2002	Argentina, Brazil, Chili, Mexico, Peru
MEA – Middle East, North Africa 1961-1995	Algeria, Egypt, Iran, Israel, Saudi Arabia
NAM – North America 1965-2000	Canada, United States
PAS – Pacific Asia 1960-1995	Indonesia, Malaysia, Singapore, South Korea, Thailand
PAO – Pacific OECD 1960-2002	Australia, Japan
SAS – South Asia 1961-2000	India
WEU – Western Europe 1960-2002	France, Germany (cars), Italy, Netherlands, Spain, Switzerland, United Kingdom

Table 1: Regions, countries, and time horizons of data considered

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