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Abstract:

Land transport emissions are dominated by road vehicles, but include also rail and inland shipping. Among all transport modes land transport is the most relevant contributor to global warming and its share is increasing, in absolute as well as in relative numbers. This assessment gives an overview of past, present and potential future emissions, of impacts on atmospheric composition, air quality, human health and climate change and on options for mitigation.

In the recent decades many measures successfully focussed on the reduction of short-lived emissions like nitrogen oxides, carbon monoxide, volatile organic compounds and particulate matter in order to improve air quality and reduce negative health impacts particulary in industrialised countries. The concentration of health-affecting air pollutants and ozone peak values have been decreasing in many countries and air quality has been improving. On the other hand, due to growing urbanisation and less controlled and increasing emissions in developing countries still many people are affected by air pollution and background ozone levels did not decrease on a global scale. With respect to global warming, these pollutants have partially opposite signs in the radiative focing and their life-times of months to a couple of years are short. Therefore, their long term global temperature potentials are low.

For climate change, the more challenging problems are the increasing emissions of long lived greenhouse gases, first of all carbon dioxide and in the last decades also halocarbons from mobile air conditioners. From trends of the global demand in mobility and comfort it can be expected that the consumption of fossil fuels will grow also in the next decades until 2050 and so far envisioned measures for mitigation and fuel replacement will not be sufficient to reverse this development. Therefore, land transport will remain a key sector in climate change mitigation during the next decades.

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1. Introduction

1.1 Scope and structure of this publication

This is an international assessment of the impacts of land transport on climate and atmospheric composition within the European 6th Framework project 'ATTICA' publication series (Transport Impacts on Atmosphere and Climate). Further assessments give an overview of Metrics for estimating emission impacts at different time scales (Fuglestvedt, Shine et al., 2009), aviation impacts on atmosphere and climate (Lee, Pitari et al., 2009) and shipping impacts on atmosphere and climate (Eyring, Isaksen et al., 2009).

Emissions from land transport, coming primarily from road vehicles and to a smaller extent from rail and inland shipping, dominate the release of long lived greenhouse gases from transportation. They make a major and increasing contribution to the total anthropogenic greenhouse effect. Furthermore, many short-lived gases and particles are emitted by land transport, which have an impact on atmospheric composition and air quality. This report relies on peer-reviewed literature, selected studies of the recent years and research carried out in the European QUANTIFY project in order to assess what we know about this increasingly important role of land transport. According to the concept of this publication, we give answers to the questions: What is emitted? What are the impacts on the atmosphere? What are the impacts on the radiation budget and climate change? Which responses and future developments are likely? After an introduction and view back in chapter 1, we give in chapter 2 an overview of the different types of direct and indirect emissions. This includes long-lived as well as short lived emissions, released by land transport vehicles on a global scale and partially in comparison of industrialied and developing regions. The briefly discussed chemistry of active species such as nitrogen oxides (NO_x), carbon monoxide (CO) or non-methane volatile organic compounds (NMVOC) have an impact on atmospheric composition which is presented as a result of global models in chapter 3. These species or particles or both together have also an impact on visibility, air quality and health which is summarised in the same section. In particular carbon dioxide and ozone, but to a non-negligible extent also halocarbons have an influence on radiative forcing and the climate system. This is discussed in chapter 4. Finally, we present in chapter 5 (future developments) evolving trends in vehicle technology, alternative fuels and mobility management and assess their potential to reduce emissions. In different emission scenarios we give an outlook to the future, although the respective calculations of future climate impacts are still part of ongoing research.

[The section marked in blue above is a response to the request of the reviewers, to explain the scope and structure of the paper in the introduction.]

1.2 Land transport from the past to the present

Many people associate an increase in their personal mobility with an increase in life quality. From the time of ancient civilizations up to about 250 years ago, the power to overcome long distances came from horses, donkeys, cattle, camels or human muscles. Nowadays climate science considers the period of the development of steam engines allowing to convert the energy of fossil fuels into the movement of a wheel (e.g. by James Watt in 1769) as the end of the preindustrial time and as the start of a significant human alteration of the natural greenhouse effect. These engines, based on fossil fuels, did not only initialise the start of the industrial revolution but also of modern transport. First they were applied in ships and trains. Between 1900 and 1930 it is likely that shipping was still the largest source of CO_2 emissions from the transport sector (Fuglestvedt et al., 2008). [previous paragraph slightly shortened]

Since ships and rail were first the dominating emittors they still have a relatively higher relevance in cumulative CO_2 than in present emissions as shown in Table 1. But after 1910 road traffic gained soon more and more importance, overtaking all other transport modes. [moved from 2.1] Figure 2 demonstrates the enormous increase in road vehicles, which are now responsible for typically 75-80% of all CO2 emissions from transport.

[Add here Table 1]

[Add here Figure 2]

The car fleet in the United States grew from about 140,000 vehicles in 1907 to more than 20 million in 1927. A similar development took place in Europe with a delay of about 30 years, i.e. after the second world war. Still in 1960, there were less than 10 cars per 1000 inhabitants in United Kingdom, growing up to about 400 and more within 40 years and boosting the usage of oil. Now, again with a shift of 30 years, a similar evolution starts in East Asia. The permanently increasing fuel consumption in road transport will soon generate more than one fifth of the global CO_2 emissions.

Shorter-lived exhaust gases from dense road traffic had and have negative impacts on air quality. Road vehicles are a major source of nitrogen oxides over land. The induced photochemical smog, which is often mixed with particle emissions and was called 'ozone smog' or Los Angeles smog. It was first discovered in Los Angeles and soon attributed to the dense road traffic in the 1940th and 1950th. Maximum concentration observed in L.A. was 580 ppb (1160 $\mu g/m^3$) of ozone. An answer to the problem was the regulation of car emissions which began with the U.S. Clean Air Act of 1970. Mass production of catalytic converters started for the 1975 car generation in the U.S. About one decade later it was introduced also in Europe.

Road transport became more and more important not only for private passenger vehicles, but also in the cargo business. Vans were more flexible than trains or ships and the continuously improving state of the road infrastructure increased their mobility. The share of road transport in the European inland freight transport markets in tonne kilometers of freight reached 78% in 2004

(EEA member countries). The total freight volume increased by 43% between 1992 and 2005. (EEA report No. 1/2007)

Gradually, increasing attention has been paid to road transport as a health problem. Due to stricter legislation and improved reduction technologies emissions could be reduced in the recent two decades. Following near stagnation during the 1970s and 1980s, the emissions of carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) fell by a factor of two to three in 10 years in many European countries. Also nitrogen oxide (NO_x) and particulate matter (PM) emissions fell after a peak around 1990, although the problem of increasing NO2 emissions from diesel vehicles with particle filters still requires the improved technologies in order to achieve continued reductions.

[comment of the reviewers, that throughout the whole paper it should be clear, that the NOx problem is not yet solved.]

Carbon dioxide emissions continued to increase despite improved fuel efficiency. Increasing mileage and comfort (e.g. air conditioners) as well as larger and more powerful vehicles more than outweighed the progress made in engine technologies. The example in Figure 1 of the development in France, representative of many countries in Western Europe, illustrates this trend.

[Add here Figure 1]

The situation is slightly different for the United States, where large cars were already common in the past. Due to higher engine efficiency and smaller vehicles the fuel used per vehicle does not increase anymore. But the number of registered vehicles and the total amount of motor fuel consumed did not yet reach a saturation point.

While the so far dominating European and North American regions could not yet achieve a reduction of their fuel consumption, a very strong growth is observed in many developing countries. Therefore land transport emissions continue to be a major burden for the environment. The analysis of the present situation and the estimation of future developments are subject of numerous scientific publications and several assessments. An overview of major studies and recent research is also given in Appendix I.

2 Land transport emissions

2.1 Exhaust emissions of road transport

There are few recent estimates of road transport’s global fuel consumption and related CO_2 emissions (IEA 2004, 2005; IEA/OECD, 2006; Turton, 2006) and a few estimates include non-CO_2 exhaust emissions (Aardenne et al., 2005; Borken et al., 2007a, b; Fulton and Eads, 2004). At the level of regions and countries more emission inventories are available and the level of detail in both, approach and results, usually increases strongly. Here, we first discuss the global emission totals and then briefly analyse emissions in North America, Western Europe and developing Asia as the most relevant regions.

All global emission estimates take the road fuel consumption as given by the International Energy Agency as a reference (e.g. IEA 2004, 2005: Entry Road transportation): Aardenne et al. (2005) have taken the amount of fuel consumed as starting point and multiplied with fuel specific emission factors (Tier 1 approach, cf. IPCC 2006). Fulton and Eads (2004) and Borken et al. (2007a, b) have calibrated their vehicle mileage to the year 2000 fuel consumption (Tier 2 approach). Borken et al. (2007a, b) cross-checked with national data and calculated the fuel consumption bottom-up notably for China, Iran, Saudi-Arabia, Russia and India as well as many smaller countries in Africa and Latin America. They conclude on misallocation of the statistical entries, under- or non-reporting notably of the diesel fuel consumption and derive a global diesel fuel consumption of 550 Mtoe, about 6% higher than reported by IEA energy statistics for that year. About 38% of the 1450 Mtoe total fuel consumed is diesel, 60% is gasoline, gaseous fuels and liquid biofuels account for about 1% and 0.7% respectively. In consequence, all global emission estimates assume about the same amount of fossil fuel and calculate about the same global CO_2 emissions.

Differences are much stronger for the non-CO_2 emissions because of the different assumptions how the mileage is distributed among the different vehicle categories and what the average exhaust emission factors are. Both, Borken et al. (2007a, b) and Fulton and Eads (2004) have differentiated by 5 vehicle categories and several fuel types and the emission factors refer to the transport activity of each vehicle fuel combination. All authors have aggregated countries to about 11 to 13 world regions. Thus, the emission factors are assumed as regional averages and differences between countries within one region are neglected.

More than two thirds of the total global fuel is consumed in OECD countries, most of which in the US. Hence, the much higher data uncertainties in non-OECD regions and eventual corrections applied have not influenced much the global balance. However they will be important for the total exhaust emissions in the respective regions, as the emission level strongly depends on the vehicle technology.

Emissions of road transportation worldwide in the year 2000

Total exhaust emissions by road transportation worldwide are summarised in Table 2. As there is largely agreement on the fuel types and their total amounts, the assumptions about emission factors determine the overall results. They concur for CO_2 and NO_x emissions, but there are large differences for all other compounds. To understand them, and hence to judge on the plausibility of one or the other figure, we need to analyse results and emission factors on the regional level; otherwise all will be dominated by the emissions of the OECD region. Emission factors from Aardenne et al. (2005) are based on estimates for 1995 or 1990 in OECD or non-OECD regions.

Fulton and Eads (2004) underscore that their data for non-OECD regions are rough estimates only.

[Add here Table 2]

Emissions of road transportation in various world regions in the year 2000

The different world regions contribute in variable amounts to the global exhaust emissions. Usually, North America, Europe and the highly populated Asian region contribute significant amounts. However, vice versa, how well the road transport in the important regions has been modelled determines how reliable the resulting global estimate can be considered. Therefore an analysis of the regional emissions is mandatory and there are also further regional inventory data to compare with, often produced with a much more detailed method. [Jens: are there references?] For the purpose of this review we cannot go into the details of each approach, but already the comparison of the final results is revealing.

[Add here Table 3]

Carbon dioxide emissions

All inventories concur for carbon dioxide emissions both globally and in the OECD regions. The slightly higher value of Aardenne et al. (2005) for North America cannot be confirmed by national (US-DoT 2006) or international fuel data (IEA 2004). The higher values of Borken et al. (2007a, b) for Asia and the Reforming Region are due to their corrections of the fuel data as explained above.

Non-carbon dioxide emissions

Estimates for nitrogen oxide emissions agree within 30 percent across the different inventories, both globally and in the regions. Emission factors of Borken et al. (2007a, b) for OECD regions are slightly higher: It has recently been found that real world emissions from heavy duty vehicles in Western Europe are by about 30% higher than the limit values [What is a "limit value"? according to EC regulations?] (Hausberger et al. 2003). For carbon monoxide the emission estimates concur for the relative distribution among regions. However, absolute differences are large: Borken et al. (2007a, b) use the lowest emission factors, the more detailed emission inventories for the US and Western Europe (US-DoT 2006, US-EPA 2005, De Ceuster et al. 2006) have higher ones, while the emission factors assumed by Fulton and Eads (2004) appear rather high. For sulphur dioxide emissions the lower totals of Borken et al. (2007a, b) reflect the reductions in the fuel sulphur contents since 1995, the base year of Aardenne et al. (2005). The emissions of volatile organic compounds are not directly comparable as Borken et al. (2007a, b) calculated tail pipe emissions only, while the other inventories include evaporative emissions as well. [Jens: Can evaporative emissions be estimated? The reviewers regard this as a non-satisfying statement.]

For PM emissions the large differences can be traced back to the emission factors assumed for gasoline vehicles. Emissions factors broadly concur for diesel vehicles between Borken et al. (2007a, b) and Fulton and Eads (2004). However for gasoline powered vehicles Fulton and Eads (2004) assume as much as 40-50% of the respective value of diesel vehicles without giving a reference. Usually PM emissions of gasoline powered vehicles are about two orders of magnitude smaller (Bond et al. 2004; US-EPA 2003; Zamaras et al. 2005).

[Jens, Yves: the reviewers expect here a more detailed discussion on aerosol emissions, perhaps also a differentiation of the aerosol type.]

Uncertainties

The biggest differences in values are for the region of developing Asia, comprising China, India and the growing South East Asian economies. This region has undergone a very rapid development in road transport volume and increase in vehicle stock. Therefore the state for the year 2000 is difficult to estimate. Furthermore, vehicle exhaust emission control has not been as stringent as in OECD countries and hence their variability is bigger.

Moreover, the inventories differ in the sophistication of the approach and in the quality of their input data. Therefore the range of values rather reflects the outcome of various more or less well controlled simplifications not the range of uncertainty.

To estimate the potential uncertainty we give the following expert judgement for the year 2000 based on the differentiated results of Borken et al. (2007a, b): The input data (vehicle stock composition and their mileage, the emission factors and the overall fuel balance) are more reliable and less variable in OECD countries. Our judgement goes for 5% uncertainty in the fuel balance and related CO_2 emissions over an estimated 30% uncertainty for CO, NMVOC and NO_x to about 50% uncertainty for PM emissions. For non-OECD countries the available data are much less representative, less reliable and the variation in vehicle technology and operating conditions is much larger. Consequently we have assumed about a two to three times higher uncertainty for each species. Weighted with the respective region’s share in emission we estimated a cumulated uncertainty in the order of 10% for CO_2 emissions, about 30% for SO_2 and NO_x emissions, 40-50% for CO and NMVOC emissions and 66% for PM (Table 4).

[Add here Table 4]

2.2 Emissions of rail transport

In many countries railway plays an important role in transport of goods and passengers. Globally rail transport’s performance is 2.2 (±0.4) trillion passenger km and 8.6 (±1.7) trillion tonne km per year [Kristin: What is the reference year? 2000?]. Approximately one third of this transport takes place in Europe. Rail goods transport plays an important role in North America [Jens, Kristin: The reviewers request here concrete numbers for North America] while ¼ of the global rail passenger transport takes place in India and China, respectively (Community of European Railway and Infrastructure Companies). In EU-25 rail contributes to 9% of total passenger transport and 3% of the goods transport (EEA 2006). Approximately 30% of the global rail network is currently electrified; this share is 50% in the European Union.

The remaining railway network is using fossil fuels, namely diesel oil for propulsion. Due to large coal resources of the country coal driven trains are still common in China. (IEA).

Fuel consumption and carbon dioxide emissions

There is yet no global gridded rail inventory available. The global EDGAR inventory includes railways, but together with inland waterways and pipeline transport. EMEP prepares a gridded rail inventory for Europe based on data reported by the Parties to the Convention, which is however not fully complete (http://www.emep.int/index_data.html).

European (EU-25) rail emissions have also been estimated by the EEA and TERM (2003). This study shows that rail emissions in Europe make up for only 1-3% of the total transport emissions.

Rail fuel consumption data are available for all world regions at the country level from the IEA for all years since 1971. Selected years are presented in Table 7. The table shows a large decline in coal consumption, a 70% increase in electricity consumption and stable diesel consumption from 1971 to 2004.

The energy consumption can be used to estimate global carbon dioxide emissions. We address only direct emissions here excluding electricity generation and other indirect emissions which are discussed in section 2.4. Information about rail emission factors can be found in the EMEP/Corinair emission inventory guidebook, the IPCC 1996 inventory Guidelines and UIC/CER (2006).

[Add here Table 6]

[In table number 6 emission factors are given for rail. The table information says that coal is in brackets. I assume, the values without brackets are for diesel engines. For clarity it should be included in the table description.]

Emissions of short lived pollutants

European rail vehicles produced after 1990 emit substantially less NO_x and PM compared to older vehicles. For example for mainline locomotives the reduction has been 30% in NO_x and 70% in PM emission factors, while for railcars the reduction has been even larger (UIC/CER 2006). We have estimated emissions using the EMEP/Corinair emission factors for diesel and the IPCC emission factors for coal. The UIC/CER emission factors are only applicable for Europe. The uncertainty margins are large for all emission data given the uncertainty in emission factors and fuel consumption and the fact that independent studies are not available for verification.

[Kristin: For road emissions Jens made an expert guess due to the unavailability of reasonable uncertainty estimations. The reviewers generally stated, that a rough uncertainty estimate is better than no number at all. Can we give an expert guess for the emissions from rail?

The estimates shown in Table 8 illustrate that rail emission are small compared to the emissions from road transport.. Nevertheless, the mode is important as part of a transport inventory and assessment due to rails important role in current, and expected future transport policies. From a climate perspective rail transport will imply less emissions per passengers and freight transported (TERM, 2003), since per passenger emissions from road transport are more than twice as high as those from rail, while emissions from air transport are 10-20% higher than those from road (average figures for EU-15). [Kristin, Jens: Concrete numbers would be helpful.] For freight, on a tonne km basis, emissions from road are around five times as high as those from rail while they are more than 8 times as high as emissions from maritime shipping. These figures however mask differences in average distance travelled and capacity utilisation. (Eionet, TRENDS, 2003)

[Add here Table 7]

[Add here Table 8]

2.3 Inland Shipping

Inland shipping, defined as shipping on rivers and lakes, is not important in terms of emissions at the global level, but can play an important role for transport primarily of goods at the local level. Emission estimates are not always comparable in different studies, since the differentiation between ocean going ships and inland shipping is not always sharp. But emissions from shipping on inland waterways is below 1% of all emissions from transport. For the EU 27 region the IIASA Gains model reports CO_2 emissions of 5.73 Tg for 2000 and 7.41 Tg for 2005. This is 0.7% or 0.85% of the emissions from cars, trucks and buses. In Europe (EEA 30) inland shipping is estimated to have a share of 5% in freight transport (EEA Report No 1 / 2007), but there is no relevant passenger transport. Inland shipping will not affect the global climate to a measurable extent.

2.4 Indirect Emissions

Material related emissions

Transport generates direct emissions when fuel is combusted in the engine of the vehcicle. However, when assessing the land transport impact on climate it is evidently relevant to consider all emissions generated as a result of transport activities. Construction of transport infrastructure (e.g. roads, rail-lines and harbour facilities) requires energy for construction work, maintenance and production of materials (e.g. asphalt, concrete and steel). Production of transport equipment requires energy, in particular for primary products (e.g. steel, aluminium and plastic). And, finally, production of fuels generates emissions from extraction, refining and transportation. There are no comparable data on how much transport infrastructure contributes in terms of global emissions. However, we note that despite their energy intensive production, generally the life-time of such infrastructure is long – several decades. Furthermore, large variations between regions are expected due to differences in emission intensity of production and use of human labour vs. machinery. [Jens: These sentences should be removed and be replaced by a rough estimation based on the available publications. Ask Jean-Pierre, Leonidas and Jens – Jens assumes 10-15% for infrastructure and maintenance. However, not to be included in transport emissions, because potential double counting with the construction sector.]

For transport equipment, there are large differences in the life-time of vehicles betweeen the different modes, where typically rail and ships have a longer life-time (more than 20 years) compared to road vehicles (less than 20 years). According to the Japanese institute for Lifecycle Environmental assessment (http://www.ilea.org) emissions from production of a gasoline conventional vehicle would be around 1/8 of the total CO_2 emissions from use over its life-cycle. Also Jancovici reports that about 15% of the CO2 emissions can be attributed to the production and another 15% for the maintenance (Jancovici, 2004).* In comparison, a life cycle analysis for a ferry concluded that 97% of CO_2 emissions are from operation, 1.4% from construction, 0.65% from maintenance and 1.1% from scrapping. (Johnsen and Fet, 1999).

Road transport also generates emissions of particulate matter from road, tyre and brake wear. These emissions may have a large impact on local air quality and health.

* JANCOVICI J.-M., 2004, *Bilan carbone d'une activité industrielle ou tertiaire. Description de la méthode : objectifs, résultats exploitables, choix méthodologiques*. ADEME Report, 223p. http://www.ademe.fr/bilan-carbone [avril 2006].

Well-to-tank emissions

While material related emissions may be attributed to other sectors, we define in this assessment indirect emissions of the transport system to include emissions from the well to tank, bearing in mind that this can constitute an underestimate of the total impact of the transport system on climate. The well-to-tank emissions are relevant for all fuels used for transport and include emissions from extraction, processing and refining of evaporative emissions from fuel distribution. Combustion emissions from transportation of the fuels are already included in the datasets in section 2.1 to 2.. [Is this correct?]

The indirect emissions are at present most important for electricity production (power plants) for use in railways and to a small extent for road transport. Indirect emissions from electricity provision will depend on the technology used for producing the electricity and abatement level. Due to increasing electrification of the railway network, indirect CO_2 emissions for rail are nowadays approaching the same order of magnitude as direct emissions. It is important to include this component in an assessment of future emission where more of the transport system is being electrified. Future emissions per unit of electricity produced is, however, also expected to change. For example, use of carbon capture and storage and more use of solar and wind power will reduce emissions substantially. [Kristin, Stephan: It would be nice to compare here the well-to-wheel CO2eq of an electric car and a diesel car and of an electric locomotive and a diesel locomotive. Can this be done?]

Also fossil fuels have a footprint from the extraction phase and refineries. Energy requirements for extraction and processing/refining generate i.a. CO_2, NO_x and SO_2 emissions. In addition there are fugitive emissions of methane and NMVOCs from the extraction, refining and transport of fuels. Typically CO_2-equivalent emissions of direct greenhouse gases well-to-tank would constitute 14 and 16 percent of well-to-wheel emissions for conventional gasoline and diesel road vehicles, respectively (JRC/Concawe/EUCAR, 2006). It is not expected that similar figures for fuels used in rail and inland shipping would be very different.

Gasoline used for road transport is a light and relatively volatile fuel. Therefore it is more easily evaporated during handling and use compared to diesel fuels and heavy fuel oil. Gasoline distribution and tanking is an important NMVOC source, depending on fuel properties, climate and technologies. In Europe tighter standards for emissions from gasoline stations have resulted in reduced emissions the last years. In addition to exhaust emissions, gasoline vehicles themselves will result in evaporative emissions (EMEP/Corinair 2006). These emissions can be classified as running losses, hot soak and diurnal (daily) emissions (ibid). Diurnal emissions are associated with daily variations in ambient temperature that results in vapour expansion inside the gasoline tank and contraction during nights with lower temperature. Hot soak emissions occur when a hot engine is turned off and heat from the engine and the exhaust system increases the temperature of the fuel in the system. Running losses are the result of vapour generated in gasoline tanks during vehcicle operations. Modern vehicles control these emissions by 90% (EMEP/Corinair 2006) compared to older vehicles.

Unfortunately different inventories differ with respect to inclusion of NMVOC from gasoline distribution and evaporative losses from use as part of transport emissions. The EDGAR inventory attributes both sources to road transport emissions, while the Quantify inventory excludes both. Standardised inventories (e.g. building on reporting standards to the LRTAP Convention and the European inventory model COPERT IV) includes evaporative emissions from the vehicle in the total road transport estimate, but excludes emissions from gasoline distribution. [Kristin: The reviewers regard this statements as not satisfying. At least a rough estimation of numbers would be helpful.]

In recent years and likely in the near future biofuels are increasing in importance for use in road transportation and perhaps also in shipping. Emissions from the production of biofuels must be added to the indirect emissions. This will include emissions from fertilization and fertilizer production (N_2O and CO_2), fuel processing, transport of fuels and even CO_2 emissions from land use change. Synthetic fuels, for example hydrogen, will shift most emissions to the production stage. An overview of these well-to-tank emissions from alternative fuels is given in the well-to-wheel analysis as described in section 5.3 (cf. JRC/Concawe/EUCAR (2005, 2003 and online: http://ies.jrc.ec.europa.eu/wtw.html 2006))

2.5 CFC and HFC Emissions

Emissions from transport include emissions from mobile air-conditioners (MAC) in passenger vehicles or cooling/freezing systems of goods transport. We do not discuss emissions from the latter in this report. Air conditioning in cars became common in the United States since 1960. However, mass production in Europe and in the developing countries started later, in about 1995. In 2000 half of the worldwide automotive fleet of 720 million vehicles was equipped with air conditioners (SROC, 2006). This number is increasing. Previously CFC-12 (CCl_2F_2) was used as chemical in MAC, but in 2003 HFC-134a (CH_2FCF_3) was already used in 338 million road vehicles. In the near future they are envisioned to be replaced by CO_2 or HFC-152a (difluoroethan, CHF_2CH_3). The emissions of HFC-134a take place during accidents, through leackage and servicing and at disposal. The recovery rates are low. A US model study estimates the loss by leakage and service to be 10.9% and the loss during disposal to be 42.5% of the total MAC charge in developed countries and 69% in developing countries (DeAngelo et al., 2006).

Indirect emissions arise from additional fuel use of the vehicle in which the MAC is installed. This can amount to 2.5 – 7.5% of the total fuel consumption, depending on the operation time. These emissions depend strongly on the local climate and can only be roughly estimated. Systematic inventories for additional fuel consumption are not yet established. But the resulting CO_2 emissions are included in the emission figures in section 2.1 to 2.3.

In 2002 about 110-130 ktonnes of CFC-12 were emitted. This is slightly more than a quarter of the 1990 emissions (400-430 ktonnes). Half of the 2002 CFC-12 emissions were emitted from MAC. 63 ktonnes are estimated for 2003 (SCROC, 2006). A typical air conditioner in a car contains 1 kg of CFC-12 or 0.8 kg of HFC-134a (Atkinson, 2000). Figure 5 shows that the total amount of refrigerants emitted is constantly rising, but now mainly consisting of HFC-134a. In 2002, about two thirds of the 97 ktonnes emitted came from MAC. As can be seen from estimations that were made in 1999 (Figure 6), much faster progress in the market integration of CO_2 or HFC-152a based systems was assumed before. But alternatives to HFC-134a needed longer development and test phases (SAE, 2003). Furthermore, the strong increase in the market share of cars equipped with air conditions of up to more than half of the fleet at present was not expected. Consequently, recent estimates for MAC refrigerant emissions in 2005, suggesting 140 ktonnes, are more than twice as high as projected in 1999. We can see that as one example how difficult it is to project future developments if the introduction of new technologies is planned.

[Add here Figure 5]

[Add here Figure 6]

The introduction of HFC-134a led to a sudden and strong increase of this compound in the atmosphere, reaching mixing ratios of 25.5 to 30.6 ppt within the ten years after 1995. However, the atmospheric relevance of HFCs is clearly different from CFCs and will be discussed in section 4.1.

3 Impacts on Air Composition

3.1 Basics of atmospheric chemistry

For atmospheric chemistry, the main concern related to land transport derives from emissions of nitrogen oxides (mainly $NO_x = NO + NO_2$), non-methane hydrocarbons (NMVOC) and carbon monoxide (CO), which are precursors of ozone and thus affect the oxidizing capacity of the atmosphere. Through their impact on OH they also affect methane, constituting a secondary, longer-lived effect on climate. In contrast to the impact from shipping and aviation, there have been only few publications focusing on global chemical and climate effects of road emissions (e.g. Granier and Brasseur, 2003; Grewe 2004; Niemeier et al., 2006, Matthes et al., 2007). The main chemical mechanisms of relevance to road emission assessments are summarised in the following paragraphs.

Ozone production in the troposphere proceeds in the presence of NO_x and sunlight via

$NO_2 + h\nu \Rightarrow NO + O$ R1

$O + O_2 + M \Rightarrow O_3 + M$ R2

$NO + HO_2 \Rightarrow NO_2 + OH$ R3

The HO_2 radical that reconverts NO into NO_2 (reaction R3), can be produced from the oxidation of carbon monoxide or hydrocarbons, e.g.

$CO + OH \Rightarrow CO_2 + H$ R4

$H + O_2 + M \Rightarrow HO_2 + M$ R5

with similar reactions involving methane and other hydrocarbons. NO_x has a rather short chemical lifetime and its largest effects on ozone are confined to the vicinity of the emission sources. From ozone, the OH radical is formed in the presence of water vapor and sunlight:

$O_3 + h\nu \Rightarrow O^* + O_2$ R6

$O^* + H_2O \Rightarrow OH + OH$ R7

[Add here Figure 8]

OH is the main oxidizing agent in the atmosphere, reducing the concentration of CO and CH_4 but also of most other gaseous pollutants. OH can be enhanced by road transport not only due to the ozone enhancement but also directly due to NO_x emissions that move the HO_2/OH balance towards OH. Since CO and CH_4 have lifetimes of about 2 months and 10 years, respectively, they constitute a longer-lived effect of road traffic emissions and can transport the signal over large distances. Enhanced CO and CH_4 levels in turn can reduce OH in remote unpolluted areas. As stated in Niemeier et al. (2005) the sign in the OH perturbation by road traffic is determined by the ratio between the intensities of NO_x and CO perturbations. NO_x perturbations enhance OH, while CO emissions reduce it. The absolute changes in the zonally averaged OH concentration resulting from the extensive use of automobiles is thus relatively limited (Granier and Brasseur, 2003).

NO_x as such cannot be transportet over large distances due to its short lifetime. However, Matthes et al. (2007) found that the formation of relatively long-lived PAN species (peroxyacetyl nitrates) from NMVOC and NO_x has the potential to transport the signal of road traffic to remote areas such as the Arctic. PAN is decomposed in areas of subsidence, releasing NO_x and thus effectively enhancing ozone in remote unpolluted areas. This makes emissions of NMVOC from road traffic important even for remote regions. The ozone production efficiency per emitted NO_x

molecule decreases at higher NO_x levels. At very high NO_x concentrations ozone titration becomes important:

$NO + O_3 \Rightarrow NO_2 + O_2$ R8

which can lead to a local reduction of ozone in high NO emission areas. However, further downwind from road traffic or in case of direct NO_2 emisssion from vehicles with particle filters ozone is increased. Due to the dependence of reaction R1 on sunlight the ozone production from road traffic is much larger during summer, while in winter ozone net reductions can occur through ozone titration by the emitted NO.

Nitrogen deposition and acid rain are enhanced through road traffic emissions of NO_x, CO and sulfur components. E.g. NO_x from road traffic is converted into nitric acid, which is highly water soluble and washed out, leading to nitrogen deposition.

$NO_2 + OH \Rightarrow HNO_3$ R9

This reaction can counteract the OH enhancement due to NO_x emissions from road traffic, especially under low-sunlight conditions. According to Granier and Brasseur (2003) surface OH decreases substantially in January in response to automobiles and trucks emissions in the highly polluted regions of Europe and North America where the background nitrogen oxide level is so high that additional NO_x tends to convert substantial quantities of HO_x into nitric acid.

Other minor effects of road traffic emissions exist with respect to heterogeneous chemistry through emissions of particles and to stratospheric ozone depletion through the slowly expiring emission of CFCs from MAC in vehicles. Long-lived CFCs are transported into the stratosphere where they are decomposed by sunlight into inorganic chlorine, in part present as Cl and ClO radicals that cause catalytic ozone depletion through

$Cl + O_3 => ClO + O_2$ R10

$ClO + O => Cl + O_2$ R11

Most of the stratospheric inorganic chlorine is present as so-called reservoir species, HCl (hydrochloric acid) and $ClONO_2$ (chlorine nitrate), which themselves do not destroy ozone. However, heterogeneous processes, e.g. on Polar Stratospheric Clouds, which are present under very cold conditions in the Arctic and Antarctic stratospheres, convert the reservoir species back into less stable components that during spring are readily decomposed into Cl and ClO by sunlight, leading to severe ozone depletion. Current research in regard to chlorine chemistry has concentrated on the role of the ClO dimer (ClOOCl) which, according to a recent publication of Pope et al. (2007), appears to be more stable than previously suggested, thus implying a smaller role of chlorine for stratospheric ozone depletion as less ClO radicals are released.

HFC-134a, which has replaced CFC-12 in new MAC, has a much shorter lifetime (~14 years) because it reacts with OH in the troposphere. Its effects in the stratosphere are thus much less pronounced.

3.2 Impacts on global atmospheric composition and chemistry

Key species and model approach

Long-lived or longer-lived emissions like CO_2, methane and halocarbons as well as short- lived species like carbon monoxide, nitrogen oxides and non-methane volatile organic compounds (NMVOC) both can lead to changes in the global atmospheric composition. Here, we focus on chemical impacts of short or medium lived gases. Radiative forcing impacts are discussed in section 4. As we saw, their emission influences the formation of secondary pollutants and oxidants like ozone, the hydroxyl radical (OH), the NO_x reservoir species PAN and methane. Carbon monoxide and methane are depleted by OH but still have a relatively long life-time. The background of the OH depleting carbon monoxide is enhanced by many fossil fuel related and biomass burning sources. Therefore, CO emissions from land transport are less significant, on a global scale although not negligible and clearly higher than for other transport sectors. Transport emissions of NO_x and NMVOC have a substantial influence on O_3 and OH, and also on methane through the reactions described in 3.1.

Since impacts of land transport add to or interact with impacts from other sources, they cannot be directly measured in the real world but have to be estimated from models. Only few calculations have been carried out so far (Niemeier et al., 2006; Matthes et al., 2007), the most recent in the EC QUANTIFY project. We discuss QUANTIFY results being aware that they are not based on the most recent emission datasets presented in section 2, but on an older dataset shown in Table 10.

[Add here Table 10]

Newer calculations with more recent emission data are not available and a linear extrapolation might cause misleading results because of interdependencies described in Hoor et al. (2009). However, in general the impacts described below will be stronger for the emissions presented in section 2 of this article.

In order to estimate the impacts of transport emissions against the background of all natural and anthropogenic emissions, "base case" model runs have been carried out including all emissions. The base case is compared with a "perturbed case" model run in which the transport emissions are reduced by 5% (Hoor et al., 2009). For some estimations, the results from this 5%

perturbation are linearly extrapolated to a 100% reduction in order to estimate the full traffic contribution. This approach was chosen and preferred to a direct 100% reduction of the transport emissions, because the impacts may not be proportional to the contribution of each of the factors but arise from interactions of several factors. Such interactions would be switched off in a 100% reduction approach as applied in an earlier study (Matthes, 2003). In the QUANTIFY calculations all transport sectors were included.

[shall the following paragraph be deleted?]

The uncertainty of data for NOx emissions is on average within the range of 30-40% depending on the region. Uncertainties for CO can range from 30% in OECD countries to about 60% (this publication, table 4, non-OECD countries; Matthes, 2003).. [changed for consistency with uncertainty values in 2.1, reviewer remark LN] The NO_x contribution from road traffic, which is most pronounced in the Eastern US, central Europe and Far East Asia, is a globally important factor for atmospheric chemistry. Emissions from ocean going ships, as explained in Eyring et al. (2009), make a comparable contribution over the oceans. NO_x has a larger contribution relative to CO for example in India and Eastern Europe. This is most likely due to a less established use of catalysts and less pronounced NO_x reduction in these regions. **[The paragraph until here does not describe impacts but is explanation of emissions. Please tell, if you regard deletion as reasonable.]**

Impacts on ozone

The impact of transport emissions on global ozone is presented in Figure 10 measured as the difference in the concentrations between the base case and the perturbed case.

[Add here Figure 10]

Based on the 5% perturbation of road traffic emissions highest sensitivities in the northern hemisphere can be up to 0.18 DU in summer and 0.07 DU in winter. If a linear scaling of this modeling results to 100% would be applicable (this is questionable because of the non-linearity of the chemistry) this would mean for the total road traffic contribution up to 3.5 Dobson Units (DU) in summer and up to 1.4 DU in winter. The results are of a similar magnitude compared to respective values of 5.2 DU and 2.1 DU found by *Matthes* (2003) based on emission data from 1990 with higher NO_x. Changes in the Southern Hemisphere are weak and probably due to interhemisperic transport in phase with the Northern Hemisphere. On a global average land transport contributes relatively strongest to the total ozone column in the NH summer in industrialised regions with dense transport (Eastern US, Europe, Near East, Japan). The strongest impact is seen in regions where at least two relevant factors come together: a large car fleet, limited control of air pollution, dry and sunny weather conditions. Such regions are Italy, Eastern Europe and the Near East. This is because ozone formation depends on photolysis and the OH concentration. Both are higher in the NH summer. The chemistry of hydrocarbons has in many cases an additive influence (Matthes, 2003). In the dark winter months, however, the contribution of land transport to ozone formation is minor. The deviation between different models is in the range of 15-30% for the most affected regions.

A remarkable result of the models shown in Figure 11 is that the impacts of road traffic extend from the boundary layer to the free troposphere and even to the Upper Troposphere - Lower Stratosphere (UTLS) region. Although in the UTLS region (250 hPa layer, 11 km altitude) aircraft emissions dominate the traffic impact, road emissions can reach a similar magnitude in summer. Ship emission impacts, in contrast, are more strongly confined to the planetary boundary layer (PBL) because of less vigorous convection, which is much stronger over land, especially during summer. Ozone is transported from the source regions to the free troposphere and UTLS region where its contribution to climate change is strongest. Therefore, it is more meaningful for the illustration of the climate effect to show the total tropospheric ozone column rather than ozone changes in the PBL.

[Add here Figure 11]

The relative contribution of road traffic emissions to atmospheric ozone, again if lineary scaled from a 5% perturbation, reaches about 2-6% zonally averaged in the Northern Hemisphere troposphere in July. Maxima are in the lower troposphere mid-latitudes. Matthes et al., 2007 found values twice as high (4-12%), but again based on emission data of the year 1990. They also mention that calculated NO_x tends to be overestimated in their model compared to the observed values in high NO_x regions. Differences between the model and observed values of the NO_2 columns are 15-30%. Furthermore, we need to consider that during the period from 1990 to 2000 many relevant emissions (NO_x, CO and NMVOC) have been reduced in large parts of the industrialised world due to the widespread use of catalytic converters.

In the QUANTIFY results the globally averaged impact of road traffic on ozone in the PBL is only moderate with differences in the perturbed case of 1-2 ppb. In the mid latitudes it is most pronounced and shows a clear seasonality. The regional impact can be stronger and reaches for example 3 ppb in summer in the Eastern US and central Europe whereas Matthes et al. (2007) found even changes up to 5 ppb. It seems that in some cases the pollutants are transported downwind from the original region exhibiting a similar effect of ozone production in the downwind regions.

Impacts on OH

As for OH concentration, moderate changes in the monthly average are modeled for a perturbed system. While ozone is generally increased by transport the impact on OH can vary in sign. In the NH winter road traffic emissions slightly decrease the OH concentration due to emissions of CO and NMVOC. Both are direct sinks for OH. However, the difference between the perturbed case and the base case is less than 1%.

In NH summer the OH concentration is clearly increased, in particular over high traffic regions. This increase is 2-4% in the mid troposphere and close to the boundary layer between 20° and 60° North if scaled to 100% (reaching about 0.18% or $5 \cdot 10^3$ molecules/cm^3 for a 5% perturbation). The reason is that OH is more effectively recycled by NO_x due to the photolysis of NO_2 and additional OH is formed from photochemically produced ozone, in particular in summer. On the other hand, the OH production is less sensitive to perturbations at the high NO_x levels in polluted regions, since the reaction of OH with NO_2 is also a sink for OH (Lelieveld et al., 2002). Therefore, in the clean marine boundary layer emission from ship transport lead to higher OH formation per molecule NO_x than road transport does. In summer, the reducing effect of CO is relatively weak and minor compared to that of NO_x. Varying OH concentrations lead also to changes in the methane lifetime as discussed in section 4.1. According to a simple estimate ignoring feedbacks and non-linearities road transport could reduce the methane lifetime by 1.6% (Hoor et al. 2009).

3.3 *Impacts on and of aerosols*

[It should be discussed if this section is not primarily an emission section. The data in table 11 are emission data.]

For black carbon (BC) and organic carbon, the contribution of road transportation to the global burden of these aerosols was calculated in the Quantify project from yearly simulations using a global aerosol/chemistry model INCA (Interactions of Chemistry and Aerosols) coupled with a global simulations model LMDZ4. Black carbon and organic carbon are transported in the accumulation mode, 20% of the black carbon is considered as soluble whereas 80% is treated as insoluble upon emission. As the aerosol ages, the insoluble BC becomes soluble with an e-folding lifetime of 1.1 day. Organic carbon is treated in the same way but the soluble and insoluble fractions amount to 50% upon emission.

In order to analyze the fraction of the BC and particulate organic matter (POM) emitted from road transportation two simulations were conducted by nudging ECMWF [this is not understandable for non-experts] winds in the model for 14 months including the whole year 2000, the model was nudged to. The two first months of the simulation prior to 2000 where used as the spin-up period for the aerosol fields and the results presented come from the 12 following months.

Since sulphate is produced from sulphur dioxide oxidation and in-cloud chemistry, we also present in addition to carbonaceous aerosols, the SO_2 budget in Table 11. A substantial fraction (9%) of the total black carbon emitted is attributable to road transportation, from which 98.7% of the BC produced comes from diesel from road and freight traffic whereas only the remaining, 1.3%, comes from gasoline. Figure 12 illustrates the area with maximum BC atmospheric content which are contributing to the overall aerosol burden: Western Europe, Asia in particular over India and Eastern Asia, Northeastern United States.

[Add here Table 11]

[Add here Figure 12]

3.4 *Effects on visibility, clouds and cloudiness*

There is no evidence yet on direct impact of land transportation on low stratus clouds as it is found for ship transportation (Eyring, Isaksen et al., 2009), neither on high level cirrus clouds as from aviation (Lee, Pitari et al., 2009). Despite of the changes in the composition of the atmosphere mentioned in Sec. 3.2, the analysis of the impact of land transport on cloudiness from the QUANTIFY project are not yet available as well as there are no studies dealing with this topic recently. However, land transport has impacts on visibility at surface level which are mixed with impacts of other sources of pollutants.

In connection to the dramatic increase of vehicles in Chinese cities in the 1990s the deterioration of visibility is analysed by Song et al. (2003a). Following Tang (2004), the number of vehicles on roads increased in this period very rapidly, especially in medium-sized and large cities. In Beijing it was by a factor of 4, from 0.5 million in 1990 to 2 million in 2002. Moreover, cars in China have usually significantly higher emission factors than cars in developed countries, because lower emissions standards for automobiles are applied. Direct inverse correlation between visibility and concentrations of PM2.5 during the period 1999–2000 for every season is shown in Song et al. (2003b) [Which concrete changes in visibility have been measured?] as well as on an hourly basis for selected episodes by Bergin et al. (2001). Source apportionment of fine-particle pollution based on a measurement campaign and a modelling study for selected sites in Beijing (Zhang et al., 2004) provides evidence of road transport impacts: about 15% of PM2.5 from mobile sources accompannied by about 21% of secondary road dust.

Faber (2002) identified visibility effects of emissions from road transport in addition to common environmental impacts such as building soiling, material corrosion, crop damage and health effects as major ones as well. The study attributed costs caused by air pollution assessing the effects of the emissions on local and regional air concentrations and quantifying the resulting health and environmental impacts in monetary terms. This approach suggests that the marginal air pollution cost per vehicle kilometre is between three and eight times higher in urban areas, when compared to rural areas (Faber, 2006). NPRI (2006) is addressing the issue of road dust impact to the environment, with respect to the visibility problem emphasising the role of $PM_{2.5}$, which is close to the wavelength of the visible spectrum and thus affecting not only the visibility range, but the colour, clarity and contrast of scenes (Malm, 2000, Malm et al., 2000).

Recently, the MILAGRO project has been studying extensively the environmental impact of a megacity urban environment at regional scale. Many observational campaigns were performed combining in situ measurements with flight and satellite observations with emphasis to Mexico City and Veracruz covering the period of March 2006. The studies were concentrated mainly on the air composition in urban plumes, chemical reactions affected by the solar radiation, aerosols and their impact on radiative transfer etc. Detailed measurement of the aerosol composition with its $PM_{2.5}$ fraction is described by Moffet et al. (2007). Stone et al. (2007) provide source apportionment analysis and conclude that during MILAGRO motor vehicles account for about 47% of the ambient organic carbon at the urban site and 31% at the peripheral site. Another project for the Houston-Galveston-Brazoria area representing a coastal city of about 4 million people is analysing similar effects in connection to the maritime environment (RSST, 2006). Following Schwarz et al. (2007) the black carbon heating effect due to an about 25% enhancement of BC absorption is not large enough to impact the tropospheric stability significantly in the HGB area, but it might play some role in bigger megacities like Mexico City or New York area. The simulation of the heating effects on life cycle of cumulus clouds was performed by Zhao and Austin (2005) using LES techniques implying the impact of temperature and vertical velocity changes on cloud elements depending on their height and saturation. The real impact of aerosols included in similar computation by Jiang and Feingold (2006) for warm convective clouds is shown to be different for the case of direct effects included or not. There is negligible effect on cloud fraction and cloud depth when only indirect effects are taken into account, but the optical depth of clouds is increasing with higher droplet concentration. When direct effects and the dynamical coupling are included, the blocking of solar radiation, the further cooling of the surface and heating of aerosols contribute to the stabilisation of the atmosphere. This results in a decrease of the cloud fraction and cloud depth. These effects play a much more significant role than aerosol-cloud processes themselves.

3.5 *3.5 Effects on regional and local air quality*

Air quality in most European cities does not always meet the limit values set by European regulation, and still has major negative impacts on human health and welfare. Land transport effects can be categorized by scale in local and regional: “local” concerning urban air quality and health impacts and “regional” pertaining to the welfare losses from acid deposition and tropospheric ozone (Faiz, 1993).

Urban scale

Many regions in the world undergo increasing urbanisation and motorisation. Approximately 9% of the EU-25 population live closer than 200 meters from a road with more than 3 million vehicles per year, and as many as 25% live within 500 meters (EEA, 2007). Consequently, approximately 4 million life-years are lost each year due to high pollution levels. Problems arise from particles and gaseous species like nitrogen and sulfur oxides, ozone, hydrocarbons and ammonia.

Particles: In urban conditions, the particle size distributions vary rapidly in shape and magnitude following the instantaneous traffic variation and local meteorology.

The number size distribution is influenced by coagulation, condensational growth, plume dilution, and vertical mixing during transport from the street to the urban background (Turco and Fangqun, 1999). The total particle number measured in urban areas often correlates well with NO_x and shows a distinct diurnal variation, indicating a common traffic source (Ketzel et al., 2004; Hussein et al., 2004). Traffic emissions are able to affect submicron particle number concentrations around major roads and may be a dominant source of ultrafine particles in the urban atmosphere (Despiau and Croci, 2007; Rodriguez et al., 2007). For example, one hour after a traffic peak at street level significant increases (bursts) in concentrations of particles around 30 nm have been reported. Exhaust emissions affect mostly the particulate matter load in the fine mode, while wear of the road surface is an important factor for the highest concentrations in the coarse mode (Manoli et al., 2002). The contribution to particulate mass ranges from place to place from a few percent up to 80% (Almeida et al., 2005; Johansson et al., 2007). It was also found that the traffic contribution in the coarse size fraction (1.9-72 μm) was approximately 80% up to 150 m from the road, it dropped abruptly by a factor of 2 over a distance of 150-200 m and declined further to 20% at 1500 m from the road (Wrobel et al., 2000).

Particulate matter from traffic may contain diverse elements, as Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe, Cu, Zn and Pb (Wrobel et al., 2000). Several studies show that traffic is responsible for the emission of carbonaceous material (primary aerosol) as well as for the formation of Secondary Organic Aerosols (SOA) (Brook et al., 2007; Rappenglück et al., 2005)

Gaseous species: Gaseous species are often monitored in air quality networks and also investigated in many single studies. Jimenez et al. (2003) demonstrated that the spatial and temporal distribution of CO and NO_x follows that of the traffic, while Pfeffer (1994) and Perrino et al. (2002) showed that the mean concentrations of gaseous pollutants at a very busy junctions are considerably higher than those of areas that are not directly affected by road traffic. Ambient volatile organic compound (VOC) levels are mainly affected by motor vehicle emissions where high levels of aromatic hydrocarbons (toluene, benzene and xylenes) have been detected and associated with diverse public transport systems (Velasco et al., 2007; Muezzinoglu et al., 2001). Traffic-related hydrocarbons (m, p, o-xylenes, toluene, ethene, propene) were found to be responsible for the generation of ozone impacts above 50 ppbv (Rappenglück et al., 2005). Polycyclic Aromatic Hydrocarbons (PAHs) observed concentrations were found to be associated predominantly with emissions from road traffic although other sources such as fuel oil, coal combustion, and incineration contribute as well (Marr et al., 2006; Harrison et al. 1996). The traffic contribution of PAHs to busy street air was estimated to be up to 90% on working days and 60% during weekends and its contribution to the city background air was estimated to be 40% (Nielsen, 1996). In the same study, the PAHs contribution from diesel vehicles was about 2/3 of the total PAHs traffic contribution.

Ammonia emissions from traffic have their origin usually in gasoline-powered motor vehicles equipped with three-ways catalytic converters (Fraser and Cass, 1998; Moeckli et al.,1996).

Photochemical models are applied based on emission inventories in order to assess theoretically the impact of traffic emissions on air quality. Comparisons to simulations without traffic emissions show that for example ozone peak values can double due to the the traffic influence (Figure 9; Borrego et al., 2000).

[Add here Figure 9]

Night and early morning depletion of ozone are explained by the increase of NO traffic emissions. Hourly modelling using a simple constrained chemical model showed that the NO_2/NO_x emissions ratio from road traffic has increased markedly from a mean of about 5–6 vol% in 1997 to about 17 vol% in 2003 (Carslaw, 2005). It was shown that besides from high background ozone the increased use of continuous regeneration diesel particle filters (CRT) contribute to the increasing trends in the NO_2/NO_x emissions ratio. Such filters require excess NO_2 for regneration and prevent at the moment that the NO_x problem and the particle problem can be tackled in parallel.

A source apportionment study undertaken in a large urban conurbation in the northwest of England (Greater Manchester and Warrington) with the use of the ADMS Urban Gaussian dispersion model indicates that the areas most likely to exceed NO_x air quality objectives are typically close to main arterial routes and close to urban centres. The major culprits of road traffic related air pollution were goods vehicles and car journeys over 8 km (Peace et al., 2004).

Regional scale

The impact of land transport on regional air quality is primarily assessed with the help of models. The EMEP 3-D Eulerian oxidant model has been used to estimate the relative contribution of each of the main road traffic sectors to ozone concentrations across Europe. A 2010 emission scenario has been developed on the basis of adopted measures and feasible emission reductions. Exceedences of the accumulated exposure thresholds (AOT) of 40 and 60 ppb are substantially reduced from 1990 to 2010, but significant exceedances remain, especially in southern Europe. Reductions in road-traffic emissions beyond those included in the trend scenario could still make an appreciable contribution to reducing ozone levels towards guideline values. Heavy-duty vehicles and evaporative emissions are predicted to make the largest contributions, followed by passenger car exhaust (Reis et al., 2000).

3.6 *Impacts on health*

Land transport causes health effects by direct emissions of traffic-related primary pollutants and precursors of secondary pollutants. Harmful primary pollutants are carbon monoxide, nitrogen oxides, sulphur dioxide and non-methane volatile organic compounds (NMVOCs), such as benzene, most polycyclic aromatic hydrocarbons (PAHs) and particulate matter. Secondary traffic-related pollutants include gases such as ozone, peroxyacetyl nitrate (PAN), formaldehyde (HCHO) and secondary particles. The secondary organic aerosol (SOA) generally belongs to the $PM_{2.5}$ fraction and consists for example of sulphate aerosol or particulate nitrate organic compounds of low volatility.

Humans are also indirectly affected by damages to soils, ecosystems, vegetation, crops and water sources due to deposition of acidifying or eutrophying nitrogen species, as well as heavy metals incorporated into PMs and/or by negative impacts of high tropospheric ozone levels. Finally, by its capacity to induce climate change, traffic-related CO_2, O_3 and halocarbons are likely to affect human health by climate change-related exposures. Such may be increases in heat waves, floods, storms, fires and droughts, with the consequences of malnutrition as well as the migration of some infectious diseases (IPCC AR4, 2007). Due to increasing knowledge about health effects of air pollution, these effects are a bigger global issue today than they were in 20th century (Juda-Rezler, 2006).

Evidence on health impacts has been gathered through numerous studies conducted by scientists of various disciplines and published since the late 1980’s (Pope, 1989, 2000; Pope et al., 1995, 2002; Brunekreef et al., 1995; Brunekreef & Holgate, 2002; Brunekreef & Forsberg, 2005; Zmirou et al., 1998; Jędrychowski, 2000; Nyberg et al., 2000; Schwartz, 2000; Peters et al., 2000, 2001; Katsouyanni et al., 2001; Hoek et al., 2002; Leikauf, 2002; Brook et al., 2004; Boldo et al., 2006, Næss et al., 2006). The results of such studies have been condensed and comprehensively evaluated in several WHO publications (WHO, 2000, 2002, 2005a+b) and in relation to land transport impacts in WHO 2003; Krzyzanowski et al. (2005) and WHO 2006. It is now possible to quantitatively assess and estimate the burden of the pollution both on a global and on a continental scale (Medina et al., 2002). Furthermore, updated guidelines have been released for PMs, O_3, NO_2 and SO_2 (WHO, 2005a). According to WHO estimates more than 2 million premature deaths each year are attributed to urban outdoor air pollution and indoor air pollution from the burning of solid fuels. More than half of them are occurring in developing countries (WHO, 2005b). A comparison with other leading risk factors is given in Figure 15.

[Add here Figure 15]

A large number of epidemiological studies demonstrated that the exposure to most of air pollutants was related to respiratory and cardiovascular diseases. Some of them are also carcinogenic. The observed symptoms range from modest temporary changes in the respiratory tract and impaired pulmonary function, to illness requiring hospital admission and increased risk of death from cardiovascular and respiratory diseases or lung cancer. The sensitivity in the population varies. Most at risk are children, the elderly, and persons with respiratory, heart and circulatory diseases. Asthma as well as chronic obstructive pulmonary disease (COPD) represent nowadays a considerable health problem in industrialised countries. A recent study by Næss et al. (2006) investigates the concentration-response relation between NO_2 and PMs and cause-specific mortality in Norway. It shows that both pollutants effect cardiovascular causes, lung cancer and COPD in different manner. Health impacts were particularly strong for COPD, showing linear effects, while cardiovascular causes and lung cancer seemed to have threshold effects. Moreover, controlled human exposure studies and animal experiments indicate, that

transport-related air pollution can increase the risk of intensified allergy reaction. The exact components responsible for the allergic response remain still unknown, although NO_2 and O_3 have been linked to it (Krzyzanowski et al., 2005).
Many pollutants are of primarily local or regional importance. For example, CO affects human health at relatively high concentrations in hot spots of urban centres. Impacts of benzene and PAHs are also local, with the exception of PAHs bounded to PMs. The SO_2 emission from land transport is now so low that it can be neglected. NO_x, can be transported for long distances via carriers like PAN, but it has its most significant health impacts at urban to regional scale.

In contrast, particles and ozone can also be relevant for global scale health effects because of high concentrations and relatively long residence time in the atmosphere. Furthermore, despite substantial cuts in emissions across Europe, the PM and O_3 background values have not been improving since 1997 (EEA 2007).

Particles: Out of all known air pollutants excluding dioxins, the strongest health effects are currently assigned to PMs (e.g. Ibald-Mulli et al., 2002; Pope et al., 2002; Kappos et al., 2004; Dominici et al., 2006). PMs are generally monitored as PM_{10}. However the levels of the finer fraction $PM_{2.5}$, if measured, give a better indication of the PMs health effects. Particulate matter is a complex mixture of organic and inorganic components and differs in physical properties and chemical composition. These properties as well as substances that adhere to PMs surface (as e.g. PAHs) influence their harmfulness. PMs are directly emitted from fuel combustion in automobile engines (primarily diesel engines) and from brake wear. They are also formed as secondary products of combustion belong to the *fine* ($PM_{2.5}$) and *ultrafine* ($PM_{1.0}$) fractions. PMs generated from road and tyre wear belong to the so-called *coarse PMs* (with a diameter between 2.5 and 10 µm – $PM_{2.5-10}$). PMs lifetime in the atmosphere differs significantly with their size. $PM_{0.1}$ have lifetimes from days to weeks and thus can be transported up to thousands of kilometres; the lifetime of $PM_{0.1-2.5}$ is in the order of weeks to months - which allows them to travel over continents. In consequence, $PM_{2.5}$ can affect people living far from their emission source. The coarse PMs are more easily deposited by sedimentation and thus have rather local to regional impacts. Primary $PM_{2.5}$, which have been found to have considerable inflammatory potency, usually contain crustal material, fugitive suspended dust, organic and elemental carbon (soot), inorganic ions (such as Na^+, K^+, Ca^{2+}, Mg^{2+} and Cl^-), and heavy metals. Secondary $PM_{2.5}$ consist mainly of SOA as well as sulphate and nitrate salts, which show lower toxic potency. Some PMs, which contain As, Cr, Ni, Pb or those which bound specific PAHs (e.g. benzo-(α)-pyrene), are carcinogenic. Nitrated polyaromatic hydrocarbons (nitro-PAH) include the most carcinogenic substances known to man and can be found in diesel exhaust fumes.

Many European and US studies have shown that when the concentration of PMs rises, even from low levels, there is a rise in mortalities from respiratory, cardiac and circulatory diseases as well as a rise in the number of bronchitis and asthma attacks. Even exposure to low PMs levels for long periods is considered harmful. $PM_{2.5}$ are believed to be the most harmful, because when inhaled they can penetrate deep into the lungs. In particular, the effects of long-term PMs exposure on mortality (life expectancy) seem to be attributable to $PM_{2.5}$ rather than to coarser particles (Brunekreef & Forsberg, 2005; WHO, 2006). Relative risks (RR) for selected pollutants estimated in meta-analysis studies prepared by WHO (Anderson et al., 2004) are presented in Figure 16. Within the framework of the CAFE programme the loss of life expectancy due to anthropogenic $PM_{2.5}$ has been assessed. For this purpose RR identified by Pope et al. (2002) for 500,000 individuals in the US have been transferred to the European situation and modelled annual average $PM_{2.5}$ concentrations (Amann et al., 2004; WHO, 2006). The average loss of life expectancy due to $PM_{2.5}$ in 2000 was estimated at 8.6 months in Europe, varying from around 3 months in Finland to 12-36 months in Benelux, Silesia and the Po Valley. The total number of premature deaths was estimated to be 348,000 in the 25 EU countries.

[Add here Figure 16]

Ozone: Elevated levels of background ozone as well as high ozone levels in urban areas are caused by precursor emissions from road traffic (Nilsson *et al.*, 2001a; Nilsson *et al.*, 2001b; Mott *et al.*, 2005). Negative consequences for health are respiratory diseases. Thereare also indications for increasing mortality, as well as premature mortality (*e.g.* Mudway and Kelly, 2000; Gryparis *et al.*, 2004; Bell *et al.*, 2005; Ito *et al.*, 2005; Levy *et al.*, 2005; Bell *et al.*, 2006). Tropospheric O_3 causes eye irritations and irritations of the airways. The latter can lead to a reduction in lung capacity, even at relatively low concentrations. Due to its low solubility in water it can penetrate deep into the lungs. The exposure to O_3 is also linked with allergy development as well as with aggravation of allergic reaction (Krzyzanowski et al., 2005). As the amount of O_3 an individual is exposed to depends on the time spent outdoors, children and people working outside are most at risk. Although health impacts of ozone have been less investigated than of PMs, existing European studies show convincing, though small, positive associations between daily mortality and ozone levels, independent of the effects of PMs (see Figure 16). Similar associations have been observed in North America as well (WHO, 2005). Hemispheric background concentrations of tropospheric ozone vary in time and space but can reach average levels of around 80 $\mu g/m^3$. Based on time-series, the number of attributable deaths brought forward can be estimated at 5-9% for daily exposures above the estimated background (WHO, 2005). At concentrations exceeding 240 $\mu g/m^3$ (EU alert threshold for O_3) both healthy adults and asthmatics would experience significant reductions in lung function as well as airway inflammation.

4 Radiative forcing and impacts on climate

4.1 Greenhouse gases

The different changes in greenhouse gases that are due to land transport are briefly reviewed in this section and supplemented with results from recent literature and the QUANTIFY project. Quantify estimates are based on 5 different models. For each of them land transport emissions haven been decreased by 5% and results are obtained by an extrapolation to 100% (see also section 3.3 of this report).

Carbon dioxide

The main impact of land transport on climate comes from carbon dioxide (CO_2). Due to its long atmospheric residence time CO_2 is well-mixed throughout the troposphere and the stratosphere. As the current emissions from land transport are almost three times as large as the emissions from the aviation and shipping sectors combined (Eyring et al., 2005), its relative contribution to radiative forcing is significant. The long residence time of CO_2 also requires that the historical development of emissions be taken into account when calculating the contribution to CO_2 enhancement and thus the radiative forcing at a given point in time. The current radiative forcing by CO_2 is estimated by IPCC (2007) to be 1.66 W/m^2, based on a total increase of nearly 100 ppmv since preindustrial times. Schultz et al. (2004) estimate that surface transport (including maritime shipping) by the year 2000 had contributed 17.4 ppmv to the CO_2 increase, which would translate into a radiative forcing of nearly 290 mW/m^2. In a recent study Fuglestvedt et al. (2008) calculated a value of 150(±17) mW/m^2 from road transport and 21(±3) mW/m^2 from rail traffic. Indirect emissions related to rail traffic (production of electric power) add another 3.8(±1) mW/m^2. In comparison, they obtain best estimates of 35 mW/m^2 and 21 mW/m^2 for the shipping and aviation sectors, respectively.

Future radiative forcing for a given point in time will depend on the time evolution of emissions, which in turn will reflect future policies, technologies, and economic growth. More accurate statements can be made for the future impact of current emissions on a given time horizon. Integration of the radiative forcing over a future time horizon for a one-year pulse of current global emissions can be used to compare the impact of different climate gases in units of (W/m^2)·yr (see IPCC, 2007; their Fig. 2.22). The contribution of each climate gas depends on the chosen time horizon and becomes relatively more important on longer time horizons in the case of a long-lived gas such as CO_2. For a detailed discussion compare also ME08. Fuglestvedt et al. (2008) use emissions from the EDGAR data base for 2000 and calculate that, on a 100-year time horizon, the contribution from CO_2 is nearly 400 mW/m^2 yr for road transport, compared to about 100 mW/m^2 yr for shipping and aviation combined. Their shipping emissions are based on own calculations consistent with Endresen et al. (2007) and their aviation emissions from Eyers et al. (2004).

Ozone:

Ozone has a relatively short lifetime of only a few weeks in the lower troposphere and is thus non-homogeneously distributed, so that models are commonly used to calculate its global mean radiative forcing. Increases near the surface are known to have a smaller impact on radiative forcing than increases in the upper troposphere (Lacis et al., 1990; Hansen et al. 1997). Therefore, the contribution of land transport to ozone radiative forcing per kg of fuel burnt is assumed to be smaller than for aviation.

Niemeier et al. (2006) applied a chemical transport model and emissions from the POET (Olivier et al. 2003) and EDGAR-3 (Olivier et al., 2001) databases to calculate an ozone-related radiative forcing of 50 mW/m^2. Fuglestvedt et al. (2008) obtain 54(±11) mW/m^2, compared to a best estimate of 22 mW/m^2 from aviation and 32 mW/m^2 from shipping. The rail sector contributes another 2 mW/m^2 according to their study. They also note that the radiative forcing per ozone burden change is larger for land transport than for shipping, probably because of more efficient vertical mixing occurring over land areas that extends the ozone increase towards higher altitudes. (3.3 cross section Figure 11)

In QUANTIFY, the perturbed ozone fields were provided for detailed radiative forcing calculations (Myhre et al., 2008). Table 12 shows results for the different models translated into the effect of total road emissions, subdivided into long-wave, short-wave and net components. Four models perturbed road emissions by a small amount to assure linearity and scaled the modeled changes in ozone to a 100% change in road emissions. The E39C model (G. Myhre, pers. Comm.) used an alternative method as described in Grewe (2007). The range of results must be seen as a measure of uncertainty in current model studies of this kind.

[Add here Table 12]

For future radiative forcing from ozone change, Fuglestvedt et al. (2008) obtain about 50 mW/m^2 yr for road emissions on a 100 year horizon, about as large a value as for aviation and shipping combined. Given the relatively short lifetime and inhomogeneous distribution of ozone, future changes in spatial emission distributions will alter the radiative forcing per ozone burden change, as ozone production efficiency, ozone lifetime, and its radiative forcing efficiency vary in space.

[inserted from former 3.4]

[remove emissions, crosscheck emission part in 2, merge with RF part]

[moved from 2:

HFC-152a (difluoroethan, CHF_2CH_3), a halogenated compound with a global warming potential of 140, which is nearly 10 times lower than that of HFC-134a (1430). But at present and in the near future mobile air conditioners have a significant market share in the use of halogenated hydrocarbons, which are strong greenhouse gases.

The global warming contribution from mobile air conditioners has two origins. Direct emission dominate and come from the release of the refrigerants. They contribute to the forcing dependent on their global warming potentials (GWP).

Impacts of halogenated compounds

Impacts on ozone depletion

CFC and HFC emissions from mobile air conditioners affect climate. However, the transition from CFCs-12 to HFC-134a in the early 1990s, which is now completed also in developing countries, is a clear progress. HFC-134a is estimated not to have an ozone depleting potential. Furthermore, it has a lower, although still relevant global warming potential.

This implies a reduction of the climate impact per tonne of chemical used, and the burden for the atmosphere measured in CO_2 equivalents is decreasing (Figure 13), although the total amount of refrigerants produced is continuously increasing (see section 2.7, Figure 5 and inset in Figure 13).

[Add here Figure 13]

Moreover, modern air condition systems are in general expected better sealed than the older ones, implying less need for refilling during the lifetime of the vehicle. Replacement of HFCs with CO_2 in the next generation of cars implies reduced emissions in terms of CO_2-equivalents due to the relatively lower GWP value of CO_2 compared to CFCs and HFCs. Comparable figures are not available for road duty vehicles.

This means that the threat for the ozone layer derives primarily from banks of CFC-12. Banks are the total amount of substances contained in existing equipment, chemical stockpiles, foams and other products not yet released into the atmosphere. Because of the long atmospheric life time (100 years) and high ozone depletion potential (0.82) of CFC-12 these banks and present emissions will contribute to ozone depletion in the coming decades. CFC-12 makes the largest contribution to stratospheric chlorine levels, about 28% estimated for 1998 (WMO, 1998) and is just about to peak in the atmosphere.

[negative radiative forcing due to ozone depletion]

Contribution of air conditioners to global warming

The GWP of CFC-12 is 10900 on a 100-year time horizon, while HFC-134a has a global warming potential of only 1430 (IPCC AR4, WG I, table TS.2) on a 100-year time horizon and a lifetime of 14 years (WMO, 2002, Table 1-6). This is why annual emissions from MAC in CO_2 equivalents (CO_2-eq) are estimated to decrease and stablise at about 280 Tg CO_2–eq per year in 2010. For 2003, 612 Tg CO_2-eq are estimated of which 514 Tg came still from CFC-12. These amounts are clearly relevant for global warming. The 700 Tg CO_2-eq from mobile air conditioning in 2002 constitute 17% of the 4300 Tg CO_2 estimated to be emitted by road transport in 2000 (see section 2.2), or 2.7% of the 26.3 Pg CO_2 from anthropogenic fossil fuel use and cement manufacture in 2002 (CDIAC website, Marland et al., 2007). Even when taking into account the expected decrease in emissions, air conditioners would still contribute about 10% of the CO_2 equivalents that are due to global transport between 2010 and 2015.

[Add here Figure 14]

It is not sure how MAC are going to develop if there are strong changes in the powertrain technology they are connected with and if Diesel and Otto engines are going to be completely replaced. For the near future a US EPA model study estimates that the global HFC emissions, replacing CFC and HCFC, are going to rise strongly from 117 Tg CO_2–eq in 2000 to 627 Tg CO_2–eq in 2020, of which still more than two thirds are emitted in OECD countries. The MAC shares of emissions in the US (and other Annex I countries) are going to decrease from 36% (47%) in 2005 to 20% (37%) in 2020, but in China and India they are expected to increase from 41% to 66% (DeAngelo et al., 2006, section IV.2). Although there are high uncertainties in such projections it seems clear that the impacts from mobile air conditioners remain to be relevant in the future, primarily for climate change and to a much lesser extent for ozone depeletion.

[merge with global warming and RF discussion from Michael]

CFC/HFC

CFC-12 and HFC-134a, used in mobile air conditioners, lead to radiative forcings of 170 mW/m^2 and 5.5 mW/m^2 in 2005, respectively (IPCC, 2007). HFCs emissions will continue to increase until the transition to CO_2 systems will mitigate the contribution from MAC. Therefore, the impact of CFC/HFC from MAC on climate is relevant but will remain small compared to the CO_2 and ozone forcings.

On the other hand, the stratospheric ozone depletion (about 3% since 1980) has led to a stratospheric cooling of about 0.6 K per decade and a negative radiative forcing of about -150 W/m^2.

The CFC-12 indirect forcing contributes -34 mW/m^2 to this value for the time 1980-2000 (IPCC SROC 2006 Chapter 1). This compensates only for 25% of the 140 mW/m^2 due to the CFC-12 positive RF for the time 1970-2000. Therefore, the negative RF contribution from mobile air conditioners through ozone depletion is of less relevance than the contribution to global warming.

From 1990-2000 MAC contributed about one third to the total CFC-12 emissions, but in the decades before clearly less than one quarter. Therefore the negative radiative forcing can be estimated to be smaller than –10 mW/m^2 for the time 1980-2000.

Methane

Methane is not emitted from road transport in significant amounts, but is changed through the emission of ozone precursors. Depending on the NO_x/VOC and NO_x/CO ratios in the exhaust gases, NO_x emissions tend to increase OH as described in section 3.3. OH stands for the main loss of methane in the atmosphere. Also ozone produced from emissions of NO_x and other ozone precursors increases OH levels. Resulting reductions in the lifetime of methane in part offset the positive radiative forcing of ozone. The changes in methane lifetime, translated into the impact of total emissions from each transport sector, are shown in Table 13 for the road sector and all transport sectors combined as calculated in QUANTIFY.

[Add here Table 13]

The models predict reductions in methane lifetime between one and two percent. This impact compared to the total impact from transport is not as large as the fraction of road emissions within the transport emissions. In particular, for road emissions the models calculate a much smaller impact on methane lifetimes than for a corresponding reduction in ship emissions. This is mainly due the high NO_x/CO and NO_x/NMVOC ratios in shipping emissions, and the generally low NO_x levels in marine areas.

Fuglestvedt et al. (2008) calculated the radiative impact of methane change due to each transport sector and obtained negative radiative forcings of -12 mW/m^2 for road transport, -43 mW/m^2 from shipping and -10 mW/m^2 from aviation. Although uncertainties exist in terms of the exact magnitude of the impact all models agree on the partial offset of the positive ozone radiative forcing by the reduction in methane lifetime. This offset appears to be smaller in relative terms for the road sector than for the shipping and aviation sectors.

Nitrous oxide

The global warming potential of N_2O is larger than that of CO_2 and indirect emissions from biofuel production may increase in the future. Nevertheless, its impact on climate is estimated to remain small. According to Fuglestvedt et al. (2008) even on a 100-year time horizon the radiative forcing from current N_2O emissions from road transport will be less than 1 mW/m^2 and thus negligible compared to the other forcing agents [Fuglestvedt, pers. comm.].

4.2 ***Black carbon, sulphate***

The aerosol radiative forcing from road transportation is dominated by black carbon. Figure 17 shows its geographical distribution for January. Top of the Atmosphere forcing calculated for the year 2000 averages 28 mW/m^2 globally for black carbon. When the effect of sulphate aerosol is computed, the radiative forcing from sulphate aerosol is a negative contribution of only -4 mW/m^2 in this year. The overall effect of the aerosol produced from road transportation is therefore a positive effect, although sulphate has a longer life time.

[Add here Figure 17]

Fuglestvedt et al. (2008) computed the radiative forcing for both well-mixed greenhouse gases and aerosols emitted from the transport sector. Aerosol radiative forcings were estimated based upon a global 3D simulation from the Oslo-TM2 chemical transport model. The model was run for 18 months, the first 6 months were used to intitialise the aerosols fields and the last 12 months used to estimate this forcing. In addition an uncertainty range representing one standard deviation was estimated for these distributions. This uncertainty estimate take into account uncertainties in fuel consumption, emission factors, atmospheric transport and removal as well as radiative forcing.

The authors estimated a direct radiative forcing from preindustrial times of +23 (± 9) mW/m^2 for black carbon and -12 (± 5) mW/m^2 for sulphate.

These results can be put in perspective by comparison with the radiative forcing of total fossil fuel emissions. For black carbon, Forster et al. (2007) report in chapter 2 of IPCC 2007 report a direct black carbon radiative forcing estimate from fossil fuel of 200 (± 100) mW/m^2. We infer from the numbers reported here that road traffic constitutes 7 to 16% of the total fossil fuel radiative forcing.

Black carbon also affects climate by changing ice and snow albedo. Forster et al. (2007) report an estimate of this effect of 100 (± 100) mW/m^2 for all know black carbon emissions.

The role that sulphate from the transport sector plays in the first indirect effect or so-called cloud albedo effect has been studied by Fuglestvedt et al. (2008). The authors estimate a sulphate indirect effect from the transport sector of -17 (-11, +7) mW/m^2.

[ask for further information on organic carbon, ammonia and nitrate]

4.3 Climate change and Future Impacts

In 2004, road transport made up for 4.7 Pg CO_2, which is 17% of the global energy-related CO_2 emissions and about three quarters of the total transport emissions of 6.2 Pg CO_2 (IPCC AR4, WG III, Chap.5). Current emissions from transport are responsible for 17% of the integrated net forcing over 100 years from all current man-made emissions. Land transport gives a CO_2 forcing of 150 (±17) mW/m^2 from road vehicles and 25 (±7) mW/m^2 from rail (direct + indirect), which is together 12% of the total man-made CO_2 forcing since pre-industrial times. Furthermore, road transport is responsible for 15% of the total man-made ozone forcing, about 54 (±11) mW/m^2 (Fuglestvedt et al., 2008).

[Add here Figure 18]

The dominating amount from road transport accumulated during a relatively short high emission history of not much more than 50 years. Transport has at the moment the highest growth rate among all end-user sectors. Therefore, the relevance for climate change will increase, in particular in developing countries.

The share in CO_2 emissions of non-OECD countries is 36% now and is expected to increase rapidly to 46% by 2030 (IPCC AR 4, WG III, Chap.5). In Eastern Asia the NO_x and CO_2 emissions from road transport doubled from 1990 to 2000.

Due to the enormous dynamic in growth just in the recent years and diverse alternative technologies discussed present projections do not dare to give an outlook beyond 2050. But, unless there is a major shift away from current patterns of energy use, total transport energy use and carbon emissions is projected to be about 80% higher by 2030 compared to 2004 values (IPCC AR4, WGIII, Chap.5), most coming from land transport. In 2050, as much as 30–50% of the total CO_2 emissions are projected to come from the transport sector (JRC/CONCAWE/EUCAR, 2006).

From this it is clear that the climate impact of transport will be primarily based on long lived greenhouse gases, in particular carbon dioxide. Since mitigation is easier to realise for stationary energy consumers, the relative share of the road transport contribution to global warming is going to grow. Therefore, general climate impacts as described in the recent IPCC AR4 report's scientific basis will be soon attributable with a more than 20% fraction to road transport.

Expected impacts according to IPCC AR4's summary for policymakers are for example a temperature increase of about 0.2°C per decade in the global average. Land surface will warm stronger. The Arctic regions are most affected, changing in turn the conditions for land transport. Winter road conditions in higher latitudes could improve, with consequences in commercial activities (*see* ACIA 2004, www.acia.uaf.edu). Opposite, in permafrost zones negative effects might appear with higher temperatures shortenning the winter-road season (Instanes et al. 2005). A sea level rise between 18 and 59 cm until the end of the century is expected and an additional sea level rise due to rapid melting of glaciers in particular in the Arctic is possible, affecting coastal settlements and transport infrastructure. Sea ice is going to shrink and snow cover is projected to contract. This leads to reductions of the Earth albedo. The warming of the oceans favours stronger tropical cyclones leading to higher damage in coastal regions. Since warmer air holds more water the water cycle is going to intensify, leading to stronger rain events and higher evaporation. Since increases in rainfall will be unevenly distributed, some regions are going to experience more severe droughts. Extreme precipitation and storms could e.g. imply in traffic limitations, road and railroad closures, train delays and cancellation (O'Brien et al. 2004).

It is hardly predictable, to what extent aerosol emissions from road transport will contribute to the global energy balance as part of the direct or indirect aerosol effect. Since the major forcing comes at the moment from black carbon, the present effect is positive. However, particle emissions are highly undesirable due to their negative health impacts. They have already been significantly reduced and will be more reduced according to more strict emission regulations in the near future. The lifetime of particles is short. Therefore, particle impacts are not going to make a large contribution to the long-term positive radiative forcing effects as shown in Figure 19.

Radiative forcing values as shown in Figure 18 are useful to evaluate the impact of historical emissions on climate until present. However, they are not necessarily useful to evaluate impacts of present and future emissions on the future climate. Decision making for the future requires other metrics as discussed in *Fuglestvedt et al.* (2008). Their applicability depends on the purpose. UNFCCC decided to use the Global Warming Potential with a 100 year time horizon (GWP_{100}) in the Kyoto Protocol. *Shine et al.* (2005; 2007) have proposed the Global Temperature Potential (GTP) as an emission metric going one step further in the chain from emission values to concrete consequences of climate change. It is consistent with the policy target of constraining the global mean surface temperature increase below a threshold (e.g. the EU's target of keeping it below 2 °C above pre-industrial levels). Table 14 and 15 and Figure 19 a + b show the GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100} and CO_2-equivalent emissions for these metrics for the various components of the land transport emissions. Details on input data and how the metrics are calculated are given in *Fuglestvedt et al.* (2008).

Figure 19 demonstrates a clear difference between short term and long term impacts. In the short term, two factors play a major role additionally to the CO_2 effect: 1) Methane is increased by CO emissions and decreased by NO_x emissions via OH reduction or formation, resulting in warming or cooling impacts. 2) Aerosols can either cause a warming, if they consist of black carbon (BC), which is an important short term factor, or cause a cooling if they consist of sulphate, which is a less important opponent in land transport. Both effects become significantly weaker in their

GWP if a 100 year time scale is considered and are nearly negligible if the global temperature potential is estimated. For the long term only very long lived GHG play a role: CO_2 and to some extent CFC-12 from air conditioners.

[Add here Table 14 + 15]

[Add here Figure 19 a + b]

5 Future developments

5.1 Present standards and regulations

The European Union regulates land transport-related air emissions by automobile emissions standards (Euro) and by automotive fuel quality standards. Emissions from road vehicles are regulated individually for light-duty vehicles (LDV = cars and light vans) and for heavy-duty vehicles (HDV), i.e. road vehicles heavier than 3.5 tonnes (trucks and buses). A whole series of amendments have been issued to stepwise tighten the limit values. Also non-road vehicles and machinery, as well as two- and three-wheeled vehicles haven been included. The first set of modern European emission standards, Euro 1, entered into force in 1993. Euro standards regulate the emissions of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) over a standardised drive cycle and are expressed in mg of pollutant per km (LDV) or per kWh (HDV). All vehicle types must be tested in order to obtain a type approval. At present, emissions of carbon dioxide (CO_2) are not regulated for any type of vehicle.

For LDV, the emission standard currently in force is Euro 4 (from 2005) defined by Directive 98/70/EC. Diesel vehicles are allowed to emit around three times more NO_x than gasoline. Emissions of PM from gasoline vehicles are not regulated since they are very low. For new Euro 5 and Euro 6 standards the implementing legislation is under preparation. Euro 5 will put standards for PM, HC and NO_x from 2009 for new models with the main goal of a large reduction of PM emission from diesel cars. Euro 6 is scheduled to enter into force in September 2014 and will probably further reduce the emissions of NO_x from diesel cars (Table 9). However, recent studies have shown it might be difficult to comply with the air quality limit for NO_2 due to a higher share of so called "direct NO_2 emissions" that have been observed for modern diesel passenger cars and heavy duty vehicles using some particular technology of particle filter systems (Palmgren et al., 2007). For comparison, the US state of California along with ten other US states, has currently a much tougher NO_x standard of approximately 40 mg/km.

[Add here Table 9]

The current regulations for HDV are set in Directives 2005/55/EC and 2005/78/EC. Euro IV is in force from 2006, Euro V will enter into force in October 2008. It also defines a non-binding standard called Enhanced Environmentally-friendly Vehicle (EEV). In July 2007 the EU Commission presented a proposal for the Euro VI standard and put forward four different suggestions, considering different fuel types, for stakeholder consultation (Elvingson, 2007). The proposed diesel engine standards (EU A to EU D) are compared to the Japanese and US requirements for HDV in Figure 7. Scenario EU A represents the close global harmonisation with forthcoming US and Japanese standards and would require a higher rate of cooled exhaust gas recirculation (EGR) in addition to the use of a more efficient selective catalytic reduction (SCR) system. Other scenarios are less strict and optimise either PM or NO_x or CO_2 emissions, partially at the costs of higher other pollutants.

[Add here Figure 7]

As for fuel quality, common EU specifications for gasoline, diesel and gasoil used in road vehicles, inland waterway barges and non-road mobile machinery have been set by the Fuel Quality Directive 98/70/EC amended by 2003/17/EC Directive. They focus mainly on sulphur and for gasoline on lead and aromatics. Since 1 January 2002 all gasoline sold in the EU is unleaded, while the limit on the sulphur content of gasoline and diesel is 50 ppm since 1 January 2005. Recently the EC proposed that from 1 January 2009 maximum sulphur content for diesel and petrol will be lowered to 10 ppm. Also the maximum permitted content of polyaromatic hydrocarbons (PAHs) in diesel will be reduced by one-third, i.e. to 8% by mass.

CO_2 emissions are not regulated in the EU so far, but the EC intends to propose legislation forcing car makers to limit average CO_2 emissions from all new cars sold in the EU to 120 g/km by 2012 (EEA, 2007). Car manufacturers (the "ACEA agreement") settled that average CO_2 emissions of new passenger cars sold in 2008/2009 will be reduced to no more than 140 g/km. But this goal will hardly be achieved.

5.2 Vehicle technologies

Today, almost all road vehicles worldwide and to some extent trains as well are propelled by internal combustion engines which convert the chemical energy of the fuel into mechanical energy at the wheel. Greenhouse gas emissions result mainly from the combustion of carbon containing fuels. Reduction of GHG emissions is possible by (a) lowering energy consumption by improving the drivetrain efficiency, (b) by reducing vehicle energy demand and (c) using alternative drivetrains.

Improving drivetrain efficiency

Gasoline engines today are dominated by the homogenous charge stoichiometric combustion process. They work well with a three-way catalyst to reduce air pollutant emissions (Eichlseder and Blassnegger, 2006). Measures to reduce fuel consumption near to mid-term aim to (1) improve part load efficiency (e.g. downsizing with turbocharging, cylinder deactivation), (2) tackle throttle losses by direct injection of fuel and variable valve control, (3) improving high pressure efficiency and (4) address power losses through e.g. friction or auxiliary units. Several studies examined CO_2 reduction of individual measures (e.g. Austin et al., 1999; NRC, 2002, Smokers et al., 2006). Fuel consumption improvements, related to the New European Drive Cycle (NEDC), of up to 25% at the same driving performance for European middle class vehicles have been demonstrated (Fraidl et al., 2007). Fuel economy of diesel engines in real world driving however can not be reached due to thermodynamic reasons. Diesel engines have already been improved in the past, e.g. by direct injection, and therefore offer a lower potential for improvements. Still, downsizing with turbocharging and reduction of friction losses may lower fuel consumption also in Diesel engines.

Transmissions are inevitable for internal combustion engines (ICE). They operate at speeds higher and torques lower than those requested at the vehicles wheels (Kasseris, 2006). Optimised gearboxes and dual clutches can improve fuel economy by 1 to 5% (Smokers et al., 2006).

Hybrid drivetrains consist of at least two different energy converters and two energy storage components. There are several different hybrid architectures in combination with ICE and levels of hybridisation. The latter is distinguished by the power of the electric motor. Hybrid drivetrains make use of engine displacement downsizing and automated gearswitch. Advantages are recuperation of brake energy, enhanced driving performance and improvements in engine efficiency due to downsizing. Disadvantages are higher costs, added system complexity and increase of vehicle weight.

Hybrid vehicles are available since the 1990ies. In 2006 approximately 400,000 hybrid cars were sold which is less than 1% of the world car production. For the future, an increasing number of hybrid models are announced. The energy savings potential is reported for low hybridisation (start-stop) and driving within cities between 3% and 12% (Japan) and for full hybrid vehicles 19% in US Highway cycle and 44% in the US City and NEDC cycle (Schmidt, 2006).

Different hybrid architectures, omitting direct mechanical link of ICE and wheels by a pure electric drive are also proposed (series hybrid). This includes so called range-extender or plugin-hybrids where the ICE/ generator on board is used to recharge the battery at high efficiency while the battery can also be charged from the power grid.

Alternative concepts are combustion engines like free piston engines with linear alternators, which directly produce electricity without driving a conventional generator (Achten et al., 2000; Max, 2005; Pohl and Gräf, 2005).

Recovery of waste energy is a way less well explored to improve engine efficiency. Only 25% to 35% of the chemical energy in the fuel is converted into mechanical energy by the engine. The rest is lost as heat in the engine cooling system and the exhaust. 1 to 2% can be recovered today e.g. through thermal electric generators (Thacher et al., 2006), fuel economy improvements of up to 5% are projected (Friedrich et al., 2007).

Reductions of the vehicle energy demand is possible by influencing three factors: inertia weight, aerodynamic drag and rolling resistance.

Light weight construction to lessen vehicle mass is a prominent example, tackling power needs to accelerate and to climb. 100 kg less weight leads to reductions of between 4 to 17 g CO_2/km (Espig et al., 2006). Higher strength steels as well as lightweight materials as Aluminium, Magnesium, glass fibre and carbon fibre reinforced plastics are already used to some extent in vehicle structures today. Further potential to reduce 60 to 120 kg for a mid size car has been shown with additional costs of 100 € to approx. 800 € (SLC, 2007).

Rolling resistance depends on the material of the tire, the construction of the tire and the radius, tire pressure and driving speed. Studies indicate that tire pressure should be increased by 0.02 to 0.04 MPa which would lower fuel consumption by 1 to 2.5%. Tire industry has proposed new concepts for wheels which are intended to lower rolling resistance until 2030 by 50%.

Aerodynamic resistance results from the product of aerodynamic drag (c_w) and frontal area (A). While there is a continuous decrease in c_w, A shows an increase. Regarding average European middle class vehicles, c_w has decreased from 0.35 in 1995 to 0.3 in 2006. Further potential is given by optimising car underside and engine air flow. A c_w of 0.2 seems in reach in the mid term (Schedel, 2007). Lowering of aerodynamic resistance by 10% is feasible at relative low cost. At constant driving at 120 km/h, this would lower fuel consumption by 20%.

Alternative drivetrains

Alternative drivetrains have in theory a higher potential to reduce GHG emissions than the options discussed above. Electric vehicles offer true zero carbon and air pollution emissions on the road. Battery- and fuel cell electric vehicles are the most prominent alternatives to the internal combustion engine.

Battery-electric vehicles carry their energy along on-board in chemical form. However, the present nickel metal hydride (NiMH) batteries have the disadvantage of low energy density and high additional weight, clearly reducing the driving range. A NiMH battery allowing 100 km non-stop travel would weigh 340 kg (Van Mierlo, 2006) at high costs. More recent high-energy lithium-Ion batteries, which are still subject to safety concerns, reduce the weight to 180 kg (Van Mierlo, 2006) at even higher costs today.

Fuel cell vehicles produce the electricity for propulsion by electrochemical reactions of hydrogen with oxygen. They have their energy stored on board in form of hydrogen or materials to produce hydrogen from. FCVs provide high efficiency for the production of electricity and locally zero emission driving. But they shift emissions to the hydrogen production, depending on the energy source (see also section 7.2). Polymer electrolyte membrane fuel cells (PEMFC) are preferred for vehicle applications due to their high power density, which offers low weight, cost and volume (Neburchilov, 2007; Zhang, 2006). Average drive cycle efficiencies have reached 36% equivalent to 4.3 l Diesel/100 km (EDC) (von Helmolt and Eberle, 2007). Major problems to be addressed are durability with cycling of the fuel cell stack (status: 2000 h, target: 5000 h) (Budd, 2006), operating temperature range (status: -20°C, target: -40°C) and cost reductions (status: 120 $/kWe, target: 25-35 $/kWe)(DoE, 2007). Hydrogen onboard storage is a further critical issue to provide sufficient driving range. A target of hydrogen storage of 6 wt% on a system basis is generally considered hard to reach (Ross, 2006). Status today is 3-4 wt% (Chalk, 2006). Fuel cells can also be used for trains and ships.

5.3 Alternative fuels and lifecycle analysis

Alternative fuels constitute an option to lower GHG emissions apart from other motivations like lowering crude oil dependency, support of agriculture and local air pollution abatement. A considerable number of fuel options are suggested, characterised by varying carbon and hydrogen content and ranging up to zero carbon emissions at the time of energy conversion in the vehicle.

Natural gas (CNG, GTL)

Natural gas has about 20% lower CO_2-emissions per MJ fuel compared to gasoline due to its higher content of hydrogen. While until recently average NG fleet vehicles in Europe could save only up to 6% due to less well adopted engine technology (Umierski et al., 2004) more recent vehicles can save up to 19% despite of approx. 200 kg more weight.

Conversion of natural gas to synthetic fuels like synthetic Diesel, Methanol, Dimethyl ether or gasoline is another way to use it as an energy source for transport. This leads to very clean fuels, generally lowering air pollutant emissions, but does not contribute to a CO_2 reduction compared to the direct use of natural gas, as there is generally energy lost in the conversion step.

Renewable fuels from biomass and waste

Biofuels offer the benefit of a more or less balanced carbon cycle in contrast to fossil fuels. The CO_2 of biofuels emitted as they are burned, was absorbed from the atmosphere by the plants in a relative short period. However the production process lowers the net benefit, depending on feedstock, production means (e.g. fertilizers etc.) and conversion technologies used.

Today, bioethanol from sugar cane (Brazil) and corn (US) and biodiesel from rape seed and palm oil used in Europe are the dominant biofuels used in transport. Bioethanol is currently blended with gasoline, and biodiesel is blended with fossil diesel – both options are used in conventional ICE vehicles.

Bioethanol is produced from biomass which contains sugars or substances that can be converted into sugars such as starch or cellulose. GHG emissions are reduced today only moderately by about 13% (Farrell, 2006; US-context).

Biodiesel from oil seeds represents almost 80% of the liquid biofuel produced in Europe in 2006 (EurObserv'ER, 2007). Rape seed, and to a lower extent sunflower, palm oil and animal fat is used as feedstock. Since pure biodiesel use is not in agreement with emission regulations the trend is towards blending with conventional diesel up to 5% by volume (EN 590). Best estimate for net reduction in GHG emissions is 37% within a range of 10% to 66% (Edwards, et al., 2007). The technology for more advanced, 2nd generation biodiesel with lower emissions is in the demonstration stage (WSDA, 2007).

Biomethane (Biogas) can be produced from a variety of biomass e.g. maize, cereals, sunflower, grass and waste by anaerobic digestion. Optimised methane yield from versatile crop rotations that integrate production of food, feed and energy, are possible (Amon, et al., 2007). Biogas also makes decentralised production possible, which is energy efficient due to saved transports.

Major barriers for biofuels are higher costs, compatibility with conventional fuels and availability of technology for more advanced biofuels. Moreover, the combination of food, feed and fuel in one crop raises concern on influences of food production and prices, which could be observed already in the case of maize production in Mexico. Although land is available to some extent due to overproduction in some areas, the economic influence is still given. Therefore energy plants, which do not contribute to food production, seem to be better suited for fuel production. Second, in order to improve crop yield, genetic engineering is and will be applied. This however has met scepticism and regulatory hurdles in many countries (Torney et al., 2007). The use of biomass for heat and power generation leads generally to higher GHG reductions than the conversion to transport fuels. However, it has to be recognised that less options exist for liquid alternative fuels for the transport sector.

Although biofuels tend to show a positive effect on GHG emissions, several authors warn of hidden costs and adverse impacts on environment and society due to large scale production of biofuels (e.g. Palmer et al., 2007). Many important environmental effects of biofuels seem not well understood or taken into account, e.g. the influence of N_2O emissions (Crutzen et al., 2007). For state-of-the-art life cycle analysis see e.g. Delucchi (2006) or Zah et al. (2007). An overview of net CO_2-eq emissions of alternative fuels is given in Figure 20.

[Add here Figure 20]

Hydrogen and electricity

Hydrogen (H_2) as an alternative energy carrier has the advantage that it can be produced from a wide variety of primary energy sources, fossil as well as renewable, e.g. wind, solar-thermal, photovoltaic, tidal/wave energy, geothermal, and biomass and waste. Today, most of the world’s hydrogen is produced from natural gas. Hydrogen offers true zero emission at the tail pipe, if combined with fuel cells. If burned in internal combustion engines, only NO_x remains as significant air pollutant emission. Difficulties arise from the storage of hydrogen: energy density of gaseous hydrogen is low by volume, and in liquid form, very low temperatures are needed, which results in a lower overall efficiency and higher costs (Aceves et al., 2006). One of the main obstacles for the broad use of H_2 for transport is the lack of an adequate infrastructure for its distribution and the high costs for implementing it.

Electricity in battery electric vehicles is recently discussed as a true alternative to hydrogen. This avoids the energy transformation cascade associate with the use of H_2. Advanced concepts of storing fluctuating renewable electricity in batteries of vehicles connected to the grid are under discussion, but the opportunities are not well assessed at the moment.

Life cycle perspective

For the evaluation of the numerous technological options to mitigate greenhouse gas emissions of surface transport, the very complex, site dependent interrelations in ecology and economy have to be taken into account.

Life cycle analysis (LCA), outlined in ISO 14040 et seq (2006), offers a methodology to address the potential environmental impacts throughout a product’s life cycle in a consistent way. For transport, three life cycle stages of the vehicle, ‘upstream’ (materials processing, parts assembly and distribution), ‘on-the-road’ operation, and ‘downstream’ (scrapping and disposal/recycling) plus the fuel cycle stages (extraction, processing and transport) have to be considered.

‘Well-to-wheel’ analysis describe an important part of a complete LCA, focussing only on propulsion system and fuel pathways. Several studies have been conducted for different geographic regions and time horizons e.g by Edwards et al. (2007), Choudhury et al. (2002), Mizuho (2004), Schäfer (2006) and Baba (2003). Exemplary results are presented in Figure 21 showing that potentially car technologies are conceivable which reduce CO_2-eq emissions by about 50%, on the long run even more. However for most technologies their economic viability on a large scale must still be proven.

Heavy goods road transport is less intensively assessed.

Problems of well-to-wheel studies limiting the validity and comparability of studies are uncertainty of data, differences in system boundaries and major differences in giving credits to by-products (Delucchi, 2006; Farrell et al., 2006). Up- and downstream processes for building and disposal of the vehicle are rarely taken into account. They become however more important with increase of lightweight design, the use of alternative powertrains and low-carbon fuels (Schäfer, 2006).

Despite given uncertainties we can conclude that generally more different fuels and more vehicle technologies are seen in the future concurrently.

[Add here Figure 21]

5.4 Mobility management and policy option

Transport policy and environmental assessment

Transport regulation strategies in Europe, as expressed in the White Paper for European Transport policy (2001) aim at bringing about substantial improvements in the quality, sustainability and efficiency of transport. They also propose measures designed to gradually achieve a decoupling of constant transport increase and economic growth, in order to reduce the pressure on the environment. Major recommendations focused on balancing modes of transport, eliminating bottlenecks, placing users at the heart of transport policy and on managing the globalisation of transport.

The strong growth of road transport compared to other land transport modes disables a correct exploitation of rail and shipping systems and, also, leads to the infrastructure saturation generating traffic congestion and pollution. To solve these problems the White Paper's action plan suggests measures aiming for the improvement of quality in the road sector, a revitalisation of the railways, a controlled growth in air transport, an adaption of the maritime and inland waterway transport system and a link between modes of transport. Placed into action, these measures have the potential to reduce significantly the number of road based transportation as demonstrated in the Figure 22.

[Add here Figure 22]

To achieve a cohesive territory and a proper sustainable development, an interconnected European transport system, based on multimodal corridors, high speed passenger networks and improved traffic conditions, is needed. At the same time, roads must be safer, the transport costs should be transparent, intermodal transport systems must be implemented, the rights and obligation of users should be clearly defined and urban transports should be used in a rational way. As an example, infrastructures should be taxed considering its real direct and indirect costs, including externalities, i.e. indirect consequences for third parties, often for public goods., One of the goals is usually to reduce road transport with its larger harmful externalities especially in the freight sector. Table 16 shows the cost levels generated by a heavy goods vehicle covering 100 km on a motorway in open country at off-peak times. Estimates are made for the costs of air pollution (cost to health and damaged crops), climate change (floods and damaged crops), infrastructure, noise (cost to health), accidents (medical costs) and congestion (loss of time).

[Add here Table 16]

The management of transport globalisation faces a challenge since a large part of transport systems are regulated at international levels. These regulations are implemented to ensure easy trades and commerce overlooking, in many cases, issues related to the environment. To invert this tendency, measures promoting proper funding for well planned infrastructures, efficient alternative transport systems (railway and shipping) and the usage of new technologies not only in vehicles, but also in infrastructures and infrastructure planning, are needed.

The contribution of the Strategic Environmental Assessment (SEA), stated by Directive 2001/42/EC, should also be considered due to its potential to reduce transport emissions and their impact on air quality and climate change. In transport, SEA is particularly useful in assisting decisions on a multi-modal approach, comparing alternative planning and management options in an integrated way and providing decision-makers with the relevant information to enable them to take the most sustainable decision (European Commission, 1999). The most updated guidance document specific for the transport sector (DG Energy and Transport, 2005) is based on the results of BEACON project (Beacon, final report 2005). The integration of SEA in transport planning was also a major issue of COST 350 (2006). An example of SEA applied to Portuguese High-Speed Rail Network demonstrate that, despite its higher investment when comparing with the traditional railway, it has positive effects such as the decrease of externalities related to accidents, climate change and air quality.

Land use and transport planning

Two important elements required for the reduction of transport emission have been discussed in section 7.1 and 7.2: vehicle technology and fuel properties. Land use planning, related to the numbers of kilometres travelled, is another essential tool due to its impact on transport demand, particularly for road traffic.

An integration of land use and transport planning is a key issue to reduce negative environmental impacts from transportation. For example, sprawling of urban areas creates an inefficient land use pattern, generates traffic and often disables public transport systems. Better community planning and more compact development help people live within walking or bicycling distance of some of the destinations they need to get to every day such as work, shops, schools. If they choose to use a car, trips are short. One of the consequences of urban sprawl, intimately related with atmospheric emissions and air quality, is the growing consumption of energy. Figure 23 presents data from a number of world cities, revealing that there is a consistent link between population density and energy consumption: high energy consumption rates are associated with lower population densities, characteristic of sprawling urban environments. Increased energy consumption is in turn leading to the increase of CO_2 emissions to the atmosphere.

[Add here Figure 23 + 24]

Figure 24 presents the relationship between CO_2 emissions and population density for several European cities. It seems that emissions decrease progressively with the increase of urban densities, although not as evidently as in the case of energy consumption, revealing that other factors such as climate, fuel mix and industry activity are probably more important. A study (Borrego et al., 2006) investigated the effects of different city structures in air quality through the application of dispersion and photochemical models. In this study, in order to nullify the effects from local meteorology and other uncontrolled variables, three cities with distinct urban structures – dispersed, corridor and compact – were idealised. Result shows that the disperse city has the lowest emissions per area and the compact city has the lowest absolute emissions. Research conducted by the UK government has suggested that spatial planning policies could reduce projected transport emissions by 16% over a 20-year period (European Sustainable Cities, 1996). Recent research published by the US Urban Land Institute (Ewing et al., 2007) identify compact city development with mixed uses (housing, commercial and industrial developments) as the best way in land pattern changes to reduce vehicle greenhouse gas emissions. It is reported that compact development may reduce the need to drive between 20% and 40% and reduce total transportation-related CO_2 emissions from current trends by 7% to 10% as of 2050.

The complexity of the interaction between transport and land-use makes it difficult to find how the system affects human behaviour. The TRANSLAND study has concluded that land-use and transport policies are only successful with respect to reduction of travel distances and travel time and reduction of share of car travel if they make car travel less attractive, i.e. more expensive or slower. On the other hand, transport policies to improve the attractiveness of public transport have in general not led to a major reduction of car travel.(TRANSLAND, 2000)

Mobility management

Mobility management aiming to influence travel choice by encouraging changes in behaviour on the part of organisations and individual travellers is one of the strategies to reduce the amount of road traffic. The desired behavioural changes include more efficient use of vehicles, for example through higher vehicle occupancies or less empty running, a switch to more sustainable transport modes and even increasing teleworking to reduce daily travels where appropriate. Mobility management is so far mainly being applied in a local and regional context focusing on the everyday mobility, especially commuting to work or to school (EC DG Energy and Transport, 2004). The benefits of promotion range about a 10-20% decrease in car travel (MOST project, 2003).

The "Sustainable urban Transportation" project (SUTRA, 2003) developed a consistent and comprehensive approach and planning methodology for the analysis of urban transportation problems that helps to design strategies for sustainable cities. Combining an indicator based approach with simulation models and scenario analysis, socio-economic and environmental impact assessment, and a public information component, SUTRA includes awareness building and educational aspects for citizens and stake-holders participating in urban decision making processes. The effects of the measures included in the scenario definitions demonstrate that no single measure can have a dramatic effects by itself. Only the combination of mobility management and transport planning measures can lead to significant effects.

Although transport problems are well identified and their solutions are also known and accepted, there is a lack of action on implementation. Most action plans are still at the pilot stage and are locally applied. Although a precautionary approach is needed in order to avoid negative side effects, e.g. due to increased exposure to air pollution in compact cities, the full implementation of stated policies and measures at regional, supranational and even international scale is expected to have a strong impact on emission reduction and will contribute to the mitigation of transport impacts on climate and ozone.

The section 7.3 was written in close cooperation by Prof. Carlos Borrego, Prof. Myriam Lopes and Dr. Oxana Tchepel at University of Aveiro, Portugal. The lead authors would like to express their thanks for this contribution to the Land Transport Assessment.

5.5 Scenarios of future road transport exhaust emissions

There have been several scenarios on fuel consumption of road transportation regionally or globally; some of them have also quantified the resulting exhaust emissions. Of course, they differ in their assumptions, the degree of detail, the input data and their treatment, etc. according to the purpose they have been designed for. The purpose of relevant road transport emission scenarios can be classified as follows:

a) Scenarios that investigate the impact of policies implemented up to a certain point in time, sometimes called frozen or no further policy, current legislation or do-nothing scenarios.

They may serve to illustrate the outcome of autonomous developments without any further (external) action, measure or policy.

b) Some scenarios assume the continuation of certain trends observed in the past, in addition to very likely policies or measures to be implemented in the foreseeable future and on top of all policies or measures already implemented. Scenarios of this kind are often called trend, forecast or business-as-usual.

c) Some scenarios intend to analyse the consequences of dedicated policies that are not necessarily already scheduled for implementation. This kind may be termed policy scenarios.

All scenarios of the above kind are usually forecasting scenarios; they start from a given state and look into the future. Furthermore, for each of the above scenario kinds there can be sensitivity scenarios with the help of which the consequences of variations of input parameters are analysed. Often, this concerns different assumptions about the economic growth in certain regions and times.

Table 5 summarises important characteristics of scenarios on road transport's long-term fuel consumption (and sometimes exhaust emissions) to be considered in the following. When comparing the numbers, it is important to remember the principal differences in each approach: Scenarios of the same kind can inform about different knowledge, interpretation or indeed uncertainty in input data, future assumptions, concepts and relationships, etc. which all claim to apply to the same subject. Scenarios of different kinds represent more variability and their modelled differences are at least partly due to a different approach and input data. Nonetheless, in the best cases they serve to analyse the consequences of certain policies or measures, in particular relative to the incremental difference in assumptions.

[Add here Table 5]

Global emission scenarios for road transportation

There are only few global scenarios for road transportation and most focus on the fuel demand. We review global exhaust emissions first and then analyse regional differences.

[Add here Figure 3]

Figure 3 summarises the global emission estimates for road transportation. Scenarios from Fulton and Eads 2004, the US-DoE IEO (2006) and the IEA 2006 Baseline represent a frozen policy under varying assumptions about global and regional economic and transport growth. Scenarios developed within the QUANTIFY project (Borken-Kleefeld et al. 2008) represent interpretations of the IPCC SRES storylines. The broad common features are as follows:

CO_2 emissions are expected to grow to the year 2050 according to all scenarios (Figure 3a). The difference from the lowest to the highest value is about a factor of two in 2050, ranging from about 6000 Tg to 11300 Tg CO_2. All scenarios assume a continued growth of the transport volume that outweigh the improvements in vehicles' fuel efficiency and the introduction of renewable fuels.

- In all scenarios CO_2 emissions up to 2050 stem predominantly from fossil fuels: Assumptions reach from only 75% to 87% petroleum fuels in the extremely optimistic TECH plus scenario or still optimistic ACT Map scenario (IEA 2006) or 80% petroleum fuels in a policy scenario (B1) assuming very strong emphasis on renewable fuels and energy efficiency (Borken et al. 2007a) over 86% in a policy scenarios with much higher total fuel demand (A1B by Borken-Kleefeld et al. 2008) to more than 97% fossil fuels in the scenarios without sustained initiatives for alternative fuels nor petroleum fuel shortages or price increases (Fulton and Eads 2004; IEA 2006 'Baseline').
- The global emissions of the non-CO_2 exhaust compounds (NO_x, NMVOC, PM) are assumed to be strongly decreased in the year 2050 according to all scenarios (Figure 3b-d). The decrease relative to the year 2000 is between a factor of 5 and 60, depending on the assumed

policy and compound. Similar decreases are expected for global emissions of CO, SO_2 , PM10, BC and OC. Sooner or later the improvements in vehicle exhaust emission control decouples the total emissions from the transport volume growth. The variation between scenarios is about a factor of 2 in the year 2050, at the significantly lower levels.

- In general the change rates agree between Fulton and Eads (2004) and Borken-Kleefeld et al. (2008), however the levels differ notably for NO_x and PM in the first decades. This results from different assumptions on exhaust emission factors and the distribution of vehicle mileage mainly between light and heavy duty vehicles notably outside the OECD region. These differences are further explained in Borken-Kleefeld et al. (2008).

The span between the scenarios of the same source illustrates the influence of different assumptions. In a way this range represent the impact of different pathways and policies as assumed in the scenarios. Most notably, scenarios illustrate an apparent potential for either an increasing or decreasing growth in CO_2 emissions globally.

Regional differences in emission scenarios for road transportation

The developments vary considerably across world regions and countries: In the OECD, the dynamics is lower while developing regions have a broader span of potential pathways. We illustrate these differences by the example of emission scenarios for Europe (Western, Central and Eastern) and developing Asia (i.e. excluding Japan and Korea).

[Add here Figure 4]

CO_2 emissions from road transportation

- In Europe CO_2 emissions grow only little, possibly stagnate at or decrease from high levels from 2020 or 2030 onwards to 2050. The scenarios agree for a level of about 1000 ± 200 Tg CO_2 emissions in the year 2020 and 2030. The trend scenarios by Fulton and Eads (2004) and

EC DG TREN (2004) are rather towards the high levels while IIASA 2007 seem to calculate stagnating emissions. The span for various policy scenarios is about ±20% for EC DG TREN 2004, while the QUANTIFY scenarios assume less variation at tendentially lower levels (Borken-Kleefeld et al. 2008).

- Scenarios with stagnating or decreasing emissions assume significant policy interventions in the form of demand management, partial modal shift, strong improvements in vehicle fuel economy as well as sizeable shares of biofuels, all in the face of continued transport growth.
- For developing Asia all scenarios assume a continuous and significant growth of CO_2 emissions. Policy interventions as described above only influence how much they may grow, either to 1100 Tg or to 3800 Tg by the year 2050, up from about 500 to 600 Tg CO_2 emission in the year 2000. The “frozen policy” scenario by Fulton and Eads (2004) calculates about intermediate emissions by 2050.
- Consequently, the share of developing Asia in global road transport’s CO_2 emissions grows from about 12% in 2000 to between 20% and 33% in 2050. Over the same period the global share of Europe may decline from about 20% in the year 2000 to 8% to 15% in the year 2050 (Borken-Kleefeld et al. 2008).

Non-CO_2 emissions from road transportation

In all scenarios the non-CO_2 emissions follow a similar pattern:

- In Europe, the so-called regulated exhaust compounds NO_x, CO, NMVOC and PM all continue to decline strongly. All scenarios concur in the rates of change though the initial values differ. In detail: NO_x emissions from (Borken et al. 2007a, Borken-Kleefeld 2008) are highest as they incorporate latest emission measurements (Hausberger et al. 2003); NMVOC emissions from Fulton and Eads (2004) are highest as they include evaporative emissions; PM emissions from IIASA 2007 are highest as they assume only current legislation in the baseline scenario; contrary to the other scenarios, they therefore do not include the use of diesel particulate filters.

- All scenarios for Europe furthermore concur that future emission levels are lower by several factors for all compounds. The continued tightening of vehicle exhaust emission standards in the scenarios effectively decouples the non-CO_2 emissions from transport growth.
- For developing Asia the emission development is more complex: On the one hand the transport growth drives emissions, though at very different rates across the scenarios. On the other hand, fleet renewal and tightening of vehicle exhaust emission controls tend to contain emissions. How quickly and how strongly these factors change determines whether the resulting total emissions grow initially, as in some scenarios, or whether they decline continuously, as in scenarios assuming very tight emission controls and lower transport demand growth. QUANTIFY scenarios (Borken-Kleefeld et al. 2008) are characterised by a delayed decrease in emission totals, as fleet renewal takes time and a significant transport growth is assumed.
- All scenarios for developing Asia concur, that emission levels in the distant future will be very much lower than today. Scenarios differ in the initial and current emission level and in the speed of the reduction. The difference is highest for NO_x emissions, that might for some while still be driven by a high growth in freight transport, i.e. an expansion of trucking.

Regional pattern of emissions from road transportation

The regional pattern illustrated above can be generalised as follows:

- In some policy scenarios the OECD region may see a stabilisation or even absolute decrease of its high CO_2 emissions. In all developing regions emissions are set to grow significantly, regardless of the scenario.

- The share of the OECD in global emissions might decline from two thirds in the year 2000 to one quarter or two fithts in the year 2050. On the other hand, the strongly developing regions, notably Asia, will more than double their shares over the same period (Borken-Kleefeld et al. 2008).

6. Conclusion

Land transport and in particular road traffic play an significant role in the atmospheric composition and its importance for climate change is growing. The direct emissions from land transport in CO_2-equivalents contribute more than one fifth to the total anthropogenic emissions excluding land use change. In the year 2000 the share of OECD countries of land transport emissions was about two thirds. Although the absolute amount may still increase until the year 2050, the fast growing non-OECD countries will emit at least twice as much by then.

The impacts on the atmosphere and climate are of different significance for different gases and emitted species depending on the time scale considered. We distinguish three main categories:
1) Carbon dioxide
A long term and strong climate signal comes from increasing CO_2 emissions. The impact will last for centuries. IPCC AR4 describes the consequences of global warming in detail. The contribution by land transport is mixed with that of other emissions from ground-based fossil fuel combustion and contributes according to its share within these emissions.
Road transport dominates with 4300 Tg CO_2 released in 2000, corresponding to 72% of the CO_2 emitted by transport and 17% of the global 25.6 Pg CO_2 emitted through anthropogenic fossil fuel combustion and cement manufacture. The cumulative emissions since pre-industrial times

translate into a radiative forcing of about 150 mW/m^2 in 2000 for road traffic and 21 mW/m^2 for direct rail emissions compared to a total CO_2 forcing of 1660 mW/m^2. Road traffic's contribution is expected to grow significantly until the year 2050 in all scenarios. The future range of emissions may be between 6000 Tg to 11300 Tg CO_2 per year, depending on the scenario assumptions. In the near-future road transport will account for more than 20% of all annual human-induced CO_2 emissions. Integrated over 100 years a one year pulse of the emissions in 2000 would translate into a radiative forcing of about 400 mW/m^2 yr.

Direct emissions from rail transport are relatively minor, approximately 120 Tg CO_2 in 2000. A similar contribution comes from indirect emissions by electricity generation. Emissions from inland shipping are negligible on a global scale.

2) Halogenated compounds

A mid-term impact on radiative forcing comes from halogenated compounds, in particular HFCs and CFCs, released from mobile air conditioners (MAC). Presently, more than 50% of the worldwide automotive fleet is equipped with MAC. The 700 Tg CO_2-equivalents emitted as halocarbons in 2002 are of similar magnitude to the CO_2 emitted by aviation and constitute 17% of road transport emissions in 2000. The radiative forcing will decrease with shrinking banks of CFC-12, but it will remain to be relevant during the next decades. Existing CFC-12 banks and already emitted gases from MAC will also continue to contribute to the decomposition of the ozone layer in the next decades. Until recently, stratospheric ozone depletion has contributed to a negative radiative forcing of climate (cooling tendency); however, this is expected to reverse in the next decades due to the decreasing chlorine concentration in the stratosphere. Hence, the positive radiative forcing in the troposphere by the growing use of the cooling agent HFC-134a is of higher relevance for the climate system.

3) Short lived emissions

A smaller, short to mid-term climate impact comes from short lived non-CO_2 gases as well as particles and particle precursors. These include nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO_2), particles (PMs) and black carbon (BC). They affect air quality and climate warming through the formation of ozone, peroxyacetyl nitrate (PAN), hydroxyl radicals (OH) and thereby the equilibrium concentration of the greenhouse gas methane (CH_4). In particular emissions of NO_x and NMVOC from road traffic contribute zonally averaged 2-6% to the formation of tropospheric ozone in the Northern Hemisphere during summer. On a regional scale ozone may increase by 3-5 ppb whereas in urban and industrial areas the impact may be larger. In parallel, OH can be increased by 2-4% in dense traffic regions in NH summer. In winter, the change of O_3 and OH is small.

For the year 2000 an ozone-related radiative forcing in the range of 50 to 54 (±11) mW/m^2 has been calculated. A one year pulse of the year 2000 emissions integrated over 100 years leads to an RF of about 50 mW/m^2.

Since the contribution to radiative forcing per unit ozone change is relatively high in the free troposphere, it is of relevance that road traffic induced O_3 can mix up to the tropopause in summer. The impact is similar to the one of aviation. On the other hand, since ozone induces also OH formation, the positive ozone forcing is partially offset by a reduced lifetime of methane. A small positive radiative forcing comes from aerosols, primarily due to the effect of black carbon (28 mW/m^2).

In all world regions vehicle emission standards become stricter and fuel quality improves, with respect to sulphur, lead and aromatics contents. In consequence the non-CO_2 emissions from road traffic have been declining in most OECD countries. Non-OECD countries with high traffic growth might experience increasing emissions in the next two decades. Nonetheless, the global total emissions are assumed to decline significantly in all scenarios. Hence, one might conclude that the radiative forcing from short-lived species may not increase. Conversely, attention on the long-lived climate gases – expected to be increasing anyway – becomes even more important.

Short lived traffic-related primary and secondary pollutants affect substantially human health. Concerning global-scale health effects those that should be considered because of high concentrations and relatively long residence times in the atmosphere are particles (PMs) and O_3. Concentrations of both PMs and O_3 in Europe have not improved since 1997 despite substantial cuts in emissions. Increased O_3 and fine particulates ($PM_{2.5}$) concentrations from road traffic can cause severe respiratory and cardiovascular diseases up to increased risk of death. Some pollutants, in particular polycyclic aromatic hydrocarbons (PAHs), belonging to $PM_{2.5}$, are also carcinogenic. NO_2 and O_3 can increase the risk of exacerbating allergy reactions.

In addition, indirect emissions must be considered. They include evaporation of NMVOC while filling or driving a vehicle which is, depending on the inventory, also accounted for through the direct emissions.
Indirect emissions arise also from the production of transport equipment, infrastructure and fuel production, transformation and supply. About 1/8 of the life-cycle emissions of a mid-size car can be attributed to its production. CO_2-equivalent emissions of direct greenhouse gases well-to-tank, i.e. for the fuel production and transport, would constitute 14% and 16% of well-to-wheel emissions for conventional gasoline and diesel road vehicles, respectively. For the first generation biofuels, well-to-tank emissions will constitute a large share of total life-cycle emissions. Second generation biofuels are expected to be more efficient. For electricity or hydrogen as fuels, there are no tail pipe emissions. All relevant emissions relate to the production phase. Unless produced from carbon free energy sources, for example from nuclear, solar or

wind energy or from hydrogen produced with carbon capture and storage, they usually result in even higher CO_2 emissions per unit useful energy.

At present, the world is facing the dilemma of a growing desire for mobility on the one hand and limited and unsustainable fuels on the other hand. Saving potentials exist but will likely be more than outweighed by the increasing demand. An internationally common and generally accepted solution is not foreseeable. It is likely that a range of different fuel types and vehicle technologies will be applied in the near future. But, according to the so far observable trends in technology introduction, consumer behaviour and policy it is very unlikely that current efforts are sufficient to prevent that in the coming decades until 2050 annual greenhouse gas emissions from land transport will clearly exceed the present emissions.

Appendix I

Reports and Assessments

Up to now, there is no comprehensive scientific assessment of ground transport effects on climate change available, including emission inventories, climate impact modelling and mitigation options. Fuglestvedt et al. (2008) present the first comprehensive analysis of radiative forcing arising from the different transport modes, for today as well as in an cumulative overview of the past.

The private industry involved in road traffic published the study „Mobility 2030“ as final report of the Sustainable Mobility project of the World Business Council for Sustainable Development (http://www.wbcsd.org/). An overview of land transport challenges is presented and a forecast model has been developed in cooperation with IEA (SMP/IEA transport model, Fulton and Eads, 2004), discussed also in the emission part of this assessment.

IPCC AR4 does not discuss the role of emittting sectors in detail, but gives an analysis of mitigation options in the transport sector in the WG III report.

Transport issues in Europe are regularly investigated by the European Environment Agency in the EEA transport series (http://www.eea.europa.eu/themes/transport/), e.g. the recent EEA report No.1-2007 “Transport and environment: on the way to a new common transport policy”. EEA observed a general increase in transport in Europe, for passenger transport slightly less than the increase in the gross domestic product GDP, for freight clearly more. Road freight transport growth in the EU is projected to continue, resulting in an increase in energy demand of more than 15% between 2000 and 2020 (De Ceuster et al., 2005).Therefore, additional policy initiatives and instruments are demanded.

Policy options are discussed in the European Commission's 2001 White Paper on European transport policy (European Commission WP, 2001). This listed around 60 policy initiatives which were later endorsed by subsequent European Council meetings, including not only climate and health impacts, but also traffic management, economic and safety aspects. WP 2001 also links emissions and infrastructure measures and considers political mitigation measures as harmonisation of fuel taxation for commercial users and alignment of the principles for charging for infrastructure use. A mid-term review (MTR) of the White Paper has been presented in 2006 by the European Commission taking stock of what has been achieved over the past five years and proposes a number of new actions to further improve the European transport system.

The EC Impact Assessment of the Thematic Strategy on Air Pollution and the Directive on "Ambient Air Quality and Cleaner Air for Europe" (EC 2005) include legislative proposals related to transport. In the near future, they shall achieve the reduction of the transboundary component of urban background concentration of $PM_{2.5}$. These measures include reviewing emissions limits for light- and heavy-duty vehicles (e.g. to go beyond current Euro standards) and revision of the National Emission Ceilings for 2015 or 2020 in order to reduce urban background concentrations of $PM_{2.5}$.

Recent and ongoing research

The European Commission supports many activities, programmes and initiatives dealing with air quality and climate change.

A significant improvement in our understanding of transport's impacts on climate and ozon is expected from the EC FP6 integrated project QUANTIFY (www.pa.op.dlr.de/quantify/). This project is dealing with quantifying impacts from individual transportation sectors like aviation, shipping and road transport. It is the first comprehensive attempt not only to quantify these impacts in global climate model (GCM) runs, but to account for the effects of chemical nonlinearity in dilution of the emission behind the exhausts as well as to include metrics for simpler emission reduction assessments.

The European “Clean Air for Europe” Programme (CAFE, http://ec.europa.eu/environment/air/cafe) aims to develop a long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment. A new phase of CAFE, the implementation of the Thematic Strategy on Air Pollution, started in September 2005.

The Cooperative Programme on the Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe (EMEP) has already been running for a long time under the Convention on Long-range Transboundary Air Pollution (http://www.unece.org/env/lrtap/) in order to support international co-operation to solve transboundary air pollution problems. EMEP includes also Northern America and recently even addresses long range transport of the whole northern hemisphere through the Hemispheric Transport of Air Pollution (HTAP) Task Force (http://www.htap.org/).

A cluster of European projects focussed on the investigation of vehicles emissions: *ARTEMIS* (Assessment And Reliability Of Transport Emissions And Inventory Systems), *COST 346* (Emissions and Fuel Consumption from Heavy Duty Vehicles http://www2.vito.be/cost346/) and *PARTICULATES* (Characterisation of Exhaust Particulate Emissions from Road Vehicles). ARTEMIS computes emissions at a low spatial scale and investigates the behaviour of vehicles in driving cycles. The results, which are implemented in a European emission model for light vehicles, tell that different approaches in emissions inventories and the unstable behaviour of vehicles with emission reduction devices (catalytic converters, particles filters) lead to a high uncertainty about what a single car emits. ARTEMIS states for example that there is quite contrasted behaviour between Diesel (rather sensitive to speed and stop parameters) and gasoline cars (rather sensitive to accelerations).

COST 346 focused on similar work for heavy duty vehicles. It gave an overview of emission data, developed an engine map database, used the datasets in an emission model and estimates uncertainties. For the EURO 4 and 5 emission standards, COST 346 expects common test bed analysis to become less reliable, since the engine performance depends more and more strongly on the control system of the specific vehicle.

PARTICULATES investigated the progress and potentials in the reduction of particulate matter. A major step forward is seen in the control of automotive particulate emissions is through the application of diesel particulate filters and sulphur-free fuels (10 mg/kg max Sulphur content). PARTICULATES focussed mainly on diesel light duty and heavy duty vehicles, but emphasises for example also that the role of two wheelers in less developed countries may be underestimated.

The potential use of alternative fuels have been studied in European projects like *TRIAS* (TRIAS = Sustainability Impact Assessment of Strategies Integrating Transport, Technology and Energy Scenarios http://www.isi.fhg.de/trias/) and *HyWays* (HyWays A European Hydrogen Energy Roadmap http://www.hyways.de):

TRIAS presents different scenarios of fuel mixes for the future and discusses the potentials in particular of biofuel. HyWays states that strong policy support is needed in order to achieve a fleet of 15 million fuel cell driven vehicles in Europe by 2030, even extreme policy support for the upper limit of 50 million vehicles.

Since such estimates are very uncertain they are at present not yet reflected in climate impact modelling. Therefore, long term potentials for climate change mitigation thanks to sustainable mobility are still an unknown.

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TABLES LA08

Table 1: Emissions of CO_2 from transport in year 2000 and cumulative emissions 1900 to 2000. Derived from calculations condensed in Fuglestvedt et al., 2008

	2000 Emissions Tg CO_2	Share [%]	Cumulative 1900-2000 Emissions Tg CO_2	Share [%]
Road	4282	72,3	114494	55,1
Rail	124	2,1	20913	10,1
Maritime shipping	626	10,6	31940	15,4
Aviation	688	11,6	16890	8,1

Table 2. Road transportation's exhaust emissions worldwide in the year 2000.

Ref.	CO_2 Tg	SO_2 Tg S	CO Tg	NMVOC Tg	CH_4 Tg	NO_x Tg N	PM Tg
1	4276	1.83	186	33.8	n.a.	8.7	n.a.
2	4282	0.95	110	*15.8*[a]	*0.8*	9.1	1.37 BC: 0.72 OC: 0.31
3	4037	n.a.	272	42.3[b]	n.a.	9	2.7

a: Without evaporative emissions
b: Total VOC emissions

References:

(1) Aardenne et al. (2005)
(2) Borken et al. (2007a, b)
(3) Fulton and Eads (2004)

Table 3: Road transportation's exhaust emissions by region in the year 2000

Ref.	CO_2 Tg	SO_2 Tg S	CO Tg	NMVOC Tg	NO_x Tg N	PM Tg
	OECD					
1	2776	0.51	89	14.8	4.3	-
2	2678	0.165	60	6.2a	4.7	0.52
3	2919	-	158.2	21.3	4.6	1.1
	of which North America					
1	1639	0.165	64.1	8	2.3	-
2	1566	0.095	40.8	3.8 a	2.4	0.18
3	1611e	-	97	12.6	2.3	0.54
	of which Western Europe					
1	819	0.135	16.6	4.2	1,4	-
2	800	0.046	12.1	1.6a	1.6	0.28
3	869	-	44.4	6.2	1.6	0.41
4	842	0.05	20.8	3.7	1.3	0.20b
5		0.05	16.32	2.62	1.5	
8	750	0.05		2.4	1.5	0.65
	Developing Asia					
1	589	0.765	37	8.9	1.7	-
2	608	0.265	21	4.4 a	1.9	0.44
3	591	-	51.2	10.3	1.95	0.76
6	-	0.4	-	-	-	-
7	551	0.38	40	10.5	2.1	0.19[c]
	Reforming / Former Communist Countries					
1	153	0.095	11	1.8	0.46	-
2	247	0.04	9	1.35a	0.64	0.11
	Africa, Latin America and Middle East					
1	757	0.46	49	8.3	2.25	-
2	750	0.48	20	3.1a	1.9	0.3

Region proxies: OECD: North America, Western Europe and Japan; ASIA: South, South-East and East Asia excl. OECD countries South Korea and Japan; REF: Central and Eastern Europe, Former Soviet Union; ALM: Africa, Latin America and Middle East.

-: No data.
a) Without evaporative emissions. b) From diesel fuelled vehicles only. c) Derived from fuel consumption.
d) $PM_{2,5}$ (PM_{10}: 0.21 Tg). e) About 1514 Tg CO_2 without MEX, that accounts for about 6% of the total road fuel consumption in NAM+MEX.

References:
(1) Aardenne et al. (2005)
(2) Borken et al. (2007a, b)
(3) Fulton and Eads (2004)
(4) De Ceuster et al. 2006
(5) EEA 2006
(6) IIASA 2001: RAINS-ASIA
(7) Ohara et al. 2007
(8) IIASA 2007: GAINS EU15

Table 4: Estimate of the uncertainty for road transport emission in the year 2000 (Borken et al. 2007a)

	CO_2	SO_2	CO	NMVOC	NO_x	PM
OECD						
emission share	61%	16%	52%	40%	49%	36%
uncertainty	5%	13%	30%	30%	30%	50%
non-OECD						
emission share	39%	84%	48%	60%	51%	64%
uncertainty	20%	30%	60%	60%	40%	75%
cumulated uncertainty	11%	27%	44%	48%	35%	66%

Table 5: Summary of scenario characteristics relevant for road transport's long-term fuel consumption and/or exhaust emissions

Type	**'Original Name' and scenario characteristics**
International Energy Outlook 2006 (US-DoE 2006)	
Frozen GDP sensitivity	'Reference': Policies enacted by Jan. 2006 'High/Low economy': Variation of Reference scenario with higher/lower growth rates of GDP.
Sustainable Mobility 2030 Project (Fulton and Eads, 2004)	
Frozen	'Reference': Policies enacted by 2003 + policy trajectories: Same energy intensity developments as IEA's WEO 2002 'Reference Case', but about 10% higher transport activity, for both passenger and freight transport. (Further tightening of veh. exhaust em. standards in developing countries; no further reduction in LDV fuel economy. Otherwise historic trends and extra-polation from 2030 to 2050.)
Energy Technology Perspectives 2050 (IEA 2006)	
Trend	'Baseline': Equal to 'reference scenario' of the World Energy Outlook 2005, but extended from 2030 to 2050. Calculates effects of technology developments of policies already enacted.
Policy	'Accelerated Policy Scenario ACT Map' Analysis the impact of technologies and best practices aimed "at reducing energy demand and emissions, and diversifying energy sources. The focus is on technologies which exist today or are likely to become commercially available in the next two decades".
Policy	'TECH Plus' As above, but "more optimistic assumptions" about the rate of technological improvements.
QUANTIFY Road scenarios (Borken-Kleefeld et al. 2008)	
Policy	A1B: Interpretation of the IPCC SRES 2000 storyline A1B. GDP and population projections taken from marker scenario. Own assumptions/derivation of passenger and freight transport volume, vehicle efficiency improvements, exhaust emission control, fuel shares. Transport volumes and road transport's energy consumption calibrated to y2000 levels.
Policy	A2: Interpretation of the IPCC SRES 2000 storyline A2. Approach as above.
Policy	B1: Interpretation of the IPCC SRES 2000 storyline B1. Approach as above.
Policy	B2: Interpretation of the IPCC SRES 2000 storyline B2. Approach as above.
(Turton 2006)	
Policy	B2 transportation scenario: Own interpretation of SRES 2000 B2 marker scenario (Riahi and Roehrl, 2000); GDP and energy consumption calibrated to y2000 values, updated population projections. Car travel demand modelled from time-money budgets based on Schafer (2000); autonomous efficiency improvements for car of 2% per decade. Road freight transport energy demand scaled from 2000 levels with general transport energy development of original B2 scenario (Riahi and Roehrl, 2000).
European Energy and Transport Scenarios (EC DG TREN 2004)	
Frozen	'Baseline': Policies enacted or in implementation by end 2001. Including effects from the VA with ACEA/JAMA/KAMA on reduction of passenger car fuel consumption. Excluding policy forced implementation of Biofuels Directive.
Policy	'High-efficiency and renewables' ⇔ 'Energy policy': Active policies to promote higher vehicle fuel efficiency and full compliance with Biofuels Directive.
Policy	'Promoting rail and higher load factors': Active policy to increase modal share of rail and public road transport and higher capacity utilisation - corresponding to an implementation of the Transport White Paper Scenario C by 2010.
Policy	'Extended policy options' ⇔ 'Full policy options': Active policy combining the above scenarios 'High-efficiency and renewables' and 'Promoting rail and higher load factors', in other words: A full implementation of the

Type	**'Original Name' and scenario characteristics**
	Biofuels Directive and of the Transport White Paper Scenario C by 2010.

Table 6: Rail emission factors

	NO_x	CO	NMVOC	$PM_{2.5}$	CH_4	N_2O
IPCC (kg/TJ)	1200 (300)	1000 (150)	100 (20)	-	5 (10)	0.6 (1.4)
EMEP/Corinair (kg/TJ)	915	247	107	112	4	29

() = coal

Table 7: Energy consumption in railways for selected years and per world region. Coal and diesel (kt), electricity (GWh). (n.a. = no data available)

	1971			1980			1990			2004		
	Coal	Diesel	Electricity	Coal	Diesel	Electricity	Coal	Diesel	Electricity	Coal	Diesel	Electricity
World	..	28102	107346	48738	35166	154490	35432	34152	182253	8328	33076	184950
EU-25	..	n.a.	n.a.	n.a.	n.a.	n.a.	181	3877	48089	1	2518	58403
Non-OECD Europe	..	n.a.	567	20	n.a.	1936	14	103	2207	n.a.	308	2136
Africa	..	187	2771	2217	299	4446	280	217	4370	7	343	3911
Latin America	..	378	1126	80	612	1224	2	560	2015	1	596	2119
Asia Excl. China	..	622	1663	11950	979	2514	5265	1832	4700	n.a.	2907	12622
China	..	n.a.	n.a.	19344	n.a.	2650	20271	2047	5936	8194	7833	20016
Former USSR	..	8200	48800	12007	11300	76000	9423	11600	87000	125	4721	50674
Middle East	..	8	n.a.	n.a.	10	n.a.	n.a.	17	n.a.	n.a.	n.a.	n.a.

Table 8: Emissions from rail (n.a. = no data available)

	CO_2 [Tg/year]				NO_x [Gg N/year]			
	1980	1990	2000	2004	1980	1990	2000	2004
World	209.0	179.1	119.7	121.5	512.8	476.3	393.7	413.9
EU-25	n.a.	12.7	9.3	8.0	n.a.	47.1	35.5	30.3
Non-OECD Europe	n.a.	0.4	1.3	1.0	0	1.3	4.9	3.7
Africa	5.4	1.2	1.2	1.1	7.6	3.1	4.5	4.1
Latin America	2.1	1.8	1.4	1.9	7.5	6.8	5.3	7.2
Asia Excluding China	27.0	16.3	6.1	9.2	33.6	31.7	23.1	35
China	38.7	47.0	44.5	41.2	35.3	61.7	108.2	109.4
Former USSR	59.8	55.6	13.7	15.2	158.1	157	52	57.1
Middle East	n.a.	0.1	n.a.	n.a.	0.1	0.2	n.a.	n.a.

Table 9: The new Euro standards [mg/km] for NO_x and PM from passenger cars (Acid News, 2007).

	Euro 3	Euro 4	Euro 5	Euro 6
Obligatory for new cars:	2000	2005	Sept 2009	Sept 2014
NO_x – diesel cars	500	250	180	80
NO_x – petrol cars	150	80	60	60
PM – all cars	50	25[1]	5	5

[1] Diesel cars only.

Table 10: Emission data for the year 2000 as used in the first Quantify approach.

	NO_x		CO	
	TgN/year	%	Tg/year	%
Road	6.85	14.7	73	7.4
Ship	4.39	9.4	1.4	0.1
Air	0.67	1.4	0	0
Non-traffic	27.8	59.7	796	81
Biogenic	6.89	14.8	113	11.4
Total	46.6	100	983	100

Table 11: Total and road transportation emissions for BC, POM and SO_2.

	BC [Tg/y]	POM [Tg/y]	SO_2 [Tg S/y]
Emission total for reference year 1996	8.0 (Bond et al., 2004)	33 (Bond et al., 2004)	74.8 (Boucher et al.,)
Emission from road transportation for reference year 2000 (*Borken et al., 2007b)*	0.72	0.31	0.95
Fraction (%) of emissions	9.0	0.9	1.3

Table 12: Annual-mean long-wave, short-wave, and net radiative forcings due to road emissions for the five models that participated in the first Quantify ozone impact calculation. Unit: mW/m^2.

Model	RF	TM4	OsloCTM2	p-TOMCAT	LMDZINCA	E39C
Spectrum	LW	19.6	25.5	15.6	25.5	70.4
	SW	6.7	7.2	3.6	7.4	20.9
	Net	26.3	32.7	19.2	32.8	91.3

Table 13: Methane lifetime in the base case (years), and reductions in methane lifetime in percent due to road emissions (second row) or due to road, aviation, and shipping emissions combined (third row), calculated by the QUANTIFY models.

Case	TM4	Oslo CTM2	p-TOMCAT	LMDz-INCA
base	9.0924	7.5838	11.562	9.129
road	-1.9	-1.4	-1.6	-1.1
road+air+ship	-7.2	-5.8	-9.5	-4.6

Table 14**:** Emission metrics (GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100}) and corresponding CO_2-equivalent emissions (in Gg (CO_2)/yr for all metrics) for the various components of road transport emissions.

	GWP_{100}	**GTP_{20}**	**GTP_{50}**	**GTP_{100}**	**CO_2-eq emissions (GWP_{100}-based)**	**CO_2-eq emissions (GTP_{20}-based)**	**CO_2-eq emissions (GTP_{50}-based)**	**CO_2-eq emissions (GTP_{100}-based)**
CO_2	1	1	1	1	4174	4174	4174	4174
NOx	-21.4	-87.6	-23.9	-3.7	-190	-778	-212	-32
CO	2.8	4.3	1.0	0.4	306	464	110	43
NMVOC	4.4	6.3	1.3	0.6	60	86	18	8
Soot BC	650	600	99	82	450	415	69	57
Soot OC	-66	-60	-10	-8.3	-20	-18	-3	-3
SOx dir.	-44	-38	-6.3	-5.2	-75	-71	-12	-10
CFC-12	10900	10500	10900	8470	652	628	652	507
HFC-134a	1430	2890	732	207	94	191	48	14

Table 15: Emission metrics (GWP_{100}, GTP_{20}, GTP_{50}, GTP_{100}) and corresponding CO_2-equivalent emissions (in Gg (CO_2)/yr for all metrics) for the various components of rail emissions.

	GWP_{100}	**GTP_{20}**	**GTP_{50}**	**GTP_{100}**	**CO_2-eq emissions (GWP_{100}-based)**	**CO_2-eq emissions (GTP_{20}-based)**	**CO_2-eq emissions (GTP_{50}-based)**	**CO_2-eq emissions (GTP_{100}-based)**
CO_2	1	1	1	1	119.7	119.7	119.7	119.7
NOx	-21.4	-87.6	-23.9	-3.7	-8.4	-34.5	-9.4	-1.4
Soot BC	650	600	99	82	71.2	65.7	10.9	9.0
Soot OC	-66	-60	-10	-8.3	-3.2	-2.9	-0.5	-0.4
SOx dir.	-44	-38	-6.3	-5.2	-24	-22.8	-3.8	-3.1

Table 16: External and infrastructure costs of heavy goods vehicle travelling 100 km on a motorway with little traffic in Euro.

External and infrastructure costs	Average range [EUR]
Air pollution	2.3 - 15
Climate change	0.2 – 1.54
Infrastructure	2.1 – 3.3
Noise	0.7 - 4
Accidents	0.2 – 2.6
Congestion	2.7 – 9.3
Total	8 - 36

FIGURES LA08

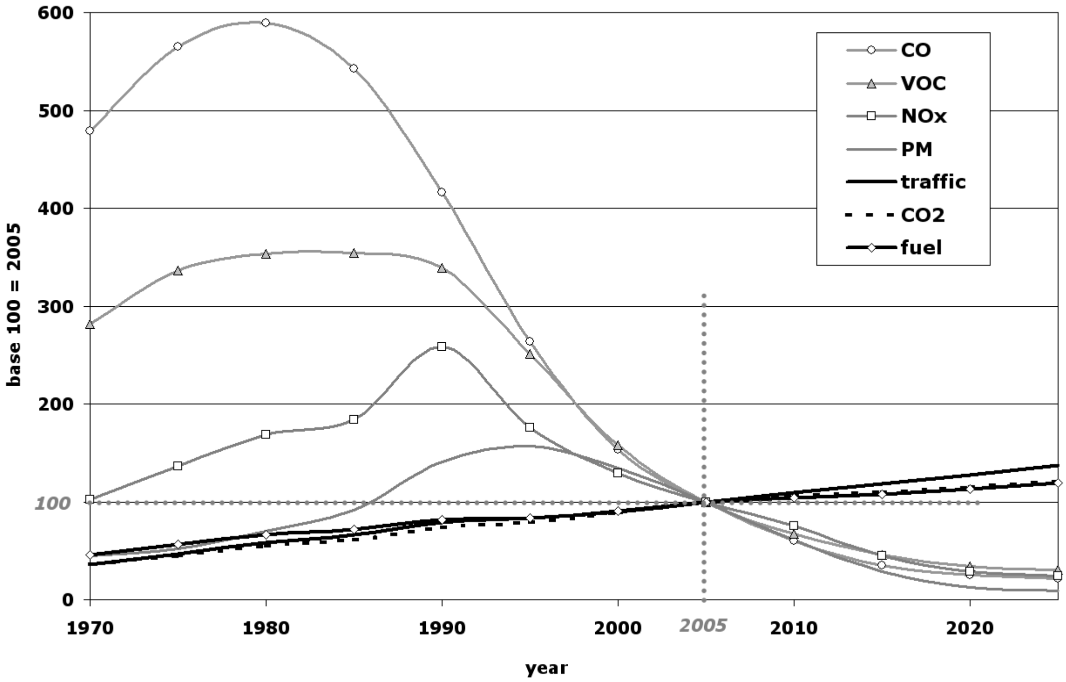


Figure 1: Relative evolution of mileage and emissions of French road traffic emissions from 1973 to 2020. Base 100 = year 2005. (Joumard, 2005)

Notes for the editorial office

The permission to use this figure has been given by Robert Joumard via E-mail. Raw data are available. I redraw the figure from these raw data provided by Robert Joumard:

Dear Dr Uherek,
We updated these calculations in the following report, with
calculation from 1970 to 2005:
Hugrel C. & R. Joumard (2004) : Transport routier - Parc, usage et
Ã©missions des vÃ©hicules en France de 1970 Ã 2025. Rapport Inrets, n Â°LTE 0420, Bron, France, 133 p.
available at http://www.inrets.fr/ur/ lte/publi-autresactions/notedesynthese/notehugrel.html
The data are in the attached Excel file, with the figure in the 3rd
sheet 'fig Ã©vol ttr %2005'. Therefore you can manage the figure as
you want.
Of course if you prefer an older version of the figure, I can send
you the corresponding file.
Regards
Robert JOUMARD
Directeur de Recherche / Senior researcher
INRETS - Laboratoire Transports Environnement
Institut National de Recherche sur les Transports et leur SÃ©curitÃ© /
French National Institute for Transport and Safety Research

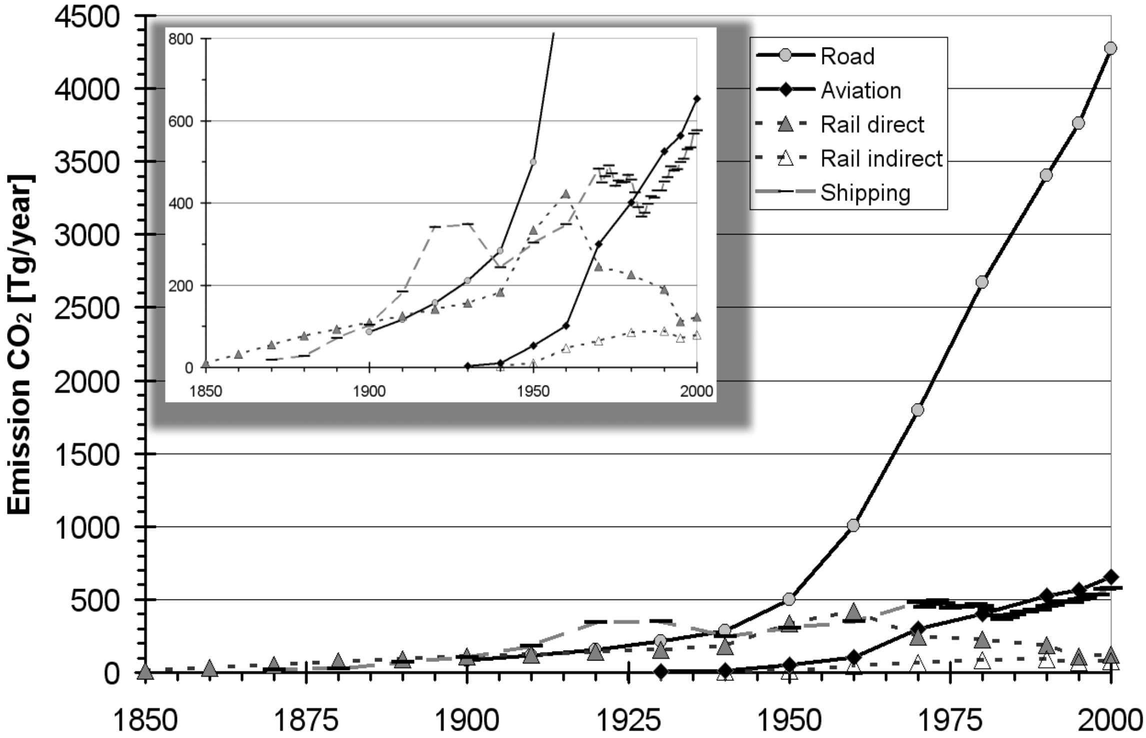


Figure 2: CO_2 emissions from the transport sector 1900 to 2000 (from Fuglestvedt et al., 2008). The inset shows the lower values with a higher resolution of the y-axis.

<u>Notes for the editorial office</u>

This figure has been generated based on raw data provided by Jan Fuglestvedt. In this way it is not published elsewhere.

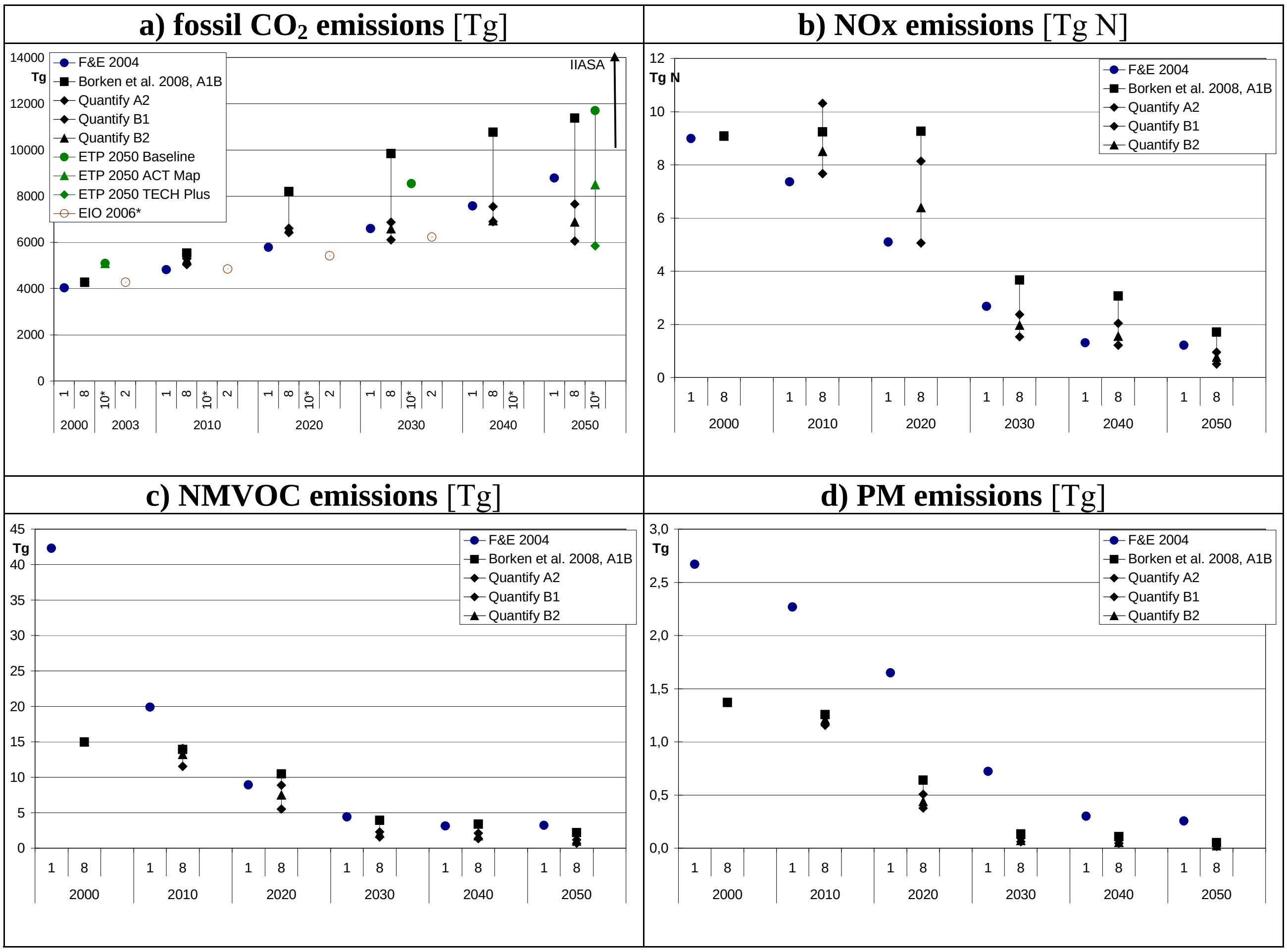


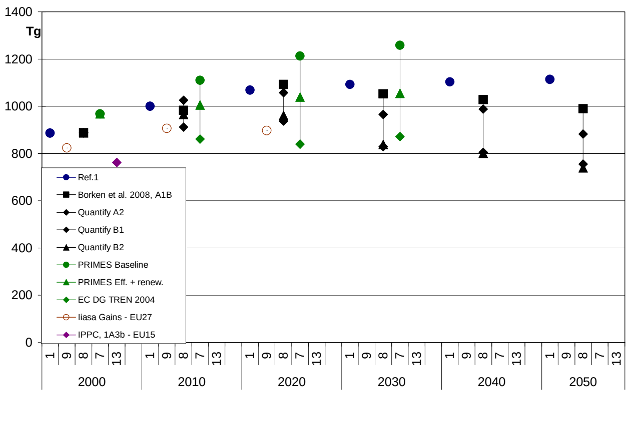
Figure 3: Global total emissions for road transportation: a) CO_2 – (US-DoE, IEO 2006 covers all transport modes, i.e. approximately 20% more than just road transportation. IEO 2006 calculated from growth rate of fuel demand applied to QUANTIFY y2000 CO_2 emissions. b) NOx, c) VOC including or NMVOC excluding evaporative emissions (Fulton and Eads 2004 / Borken et al. 2007a), d) PM emissions.

<u>Notes for the editorial office</u>

The figure has been drawn in the group of Jens Borken, based on raw data available in his group as well. The copyright is by Jens Borken and has been granted for the ATTICA report.

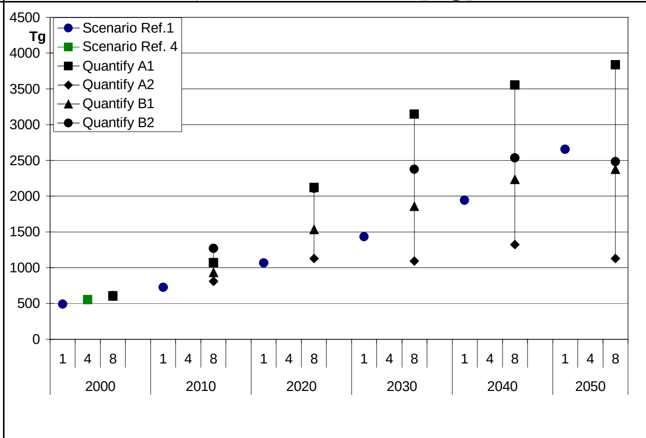
Road transport emissions in Europe

a) CO_2 emissions [Tg]

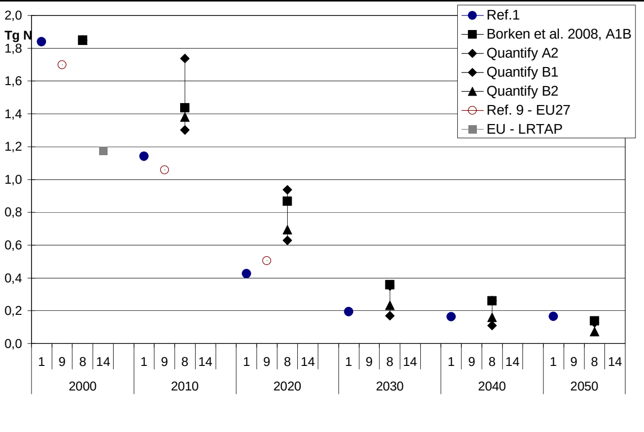


Road transport emissions in developing Asia

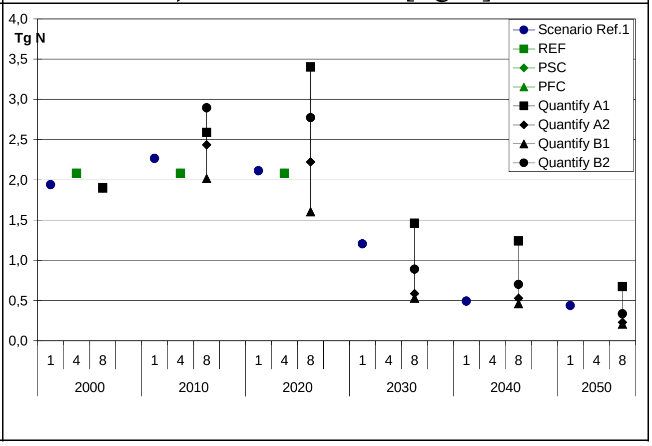
b) CO_2 emissions [Tg]



c) NOx emissions [Tg N]



d) NOx emissions [Tg N]



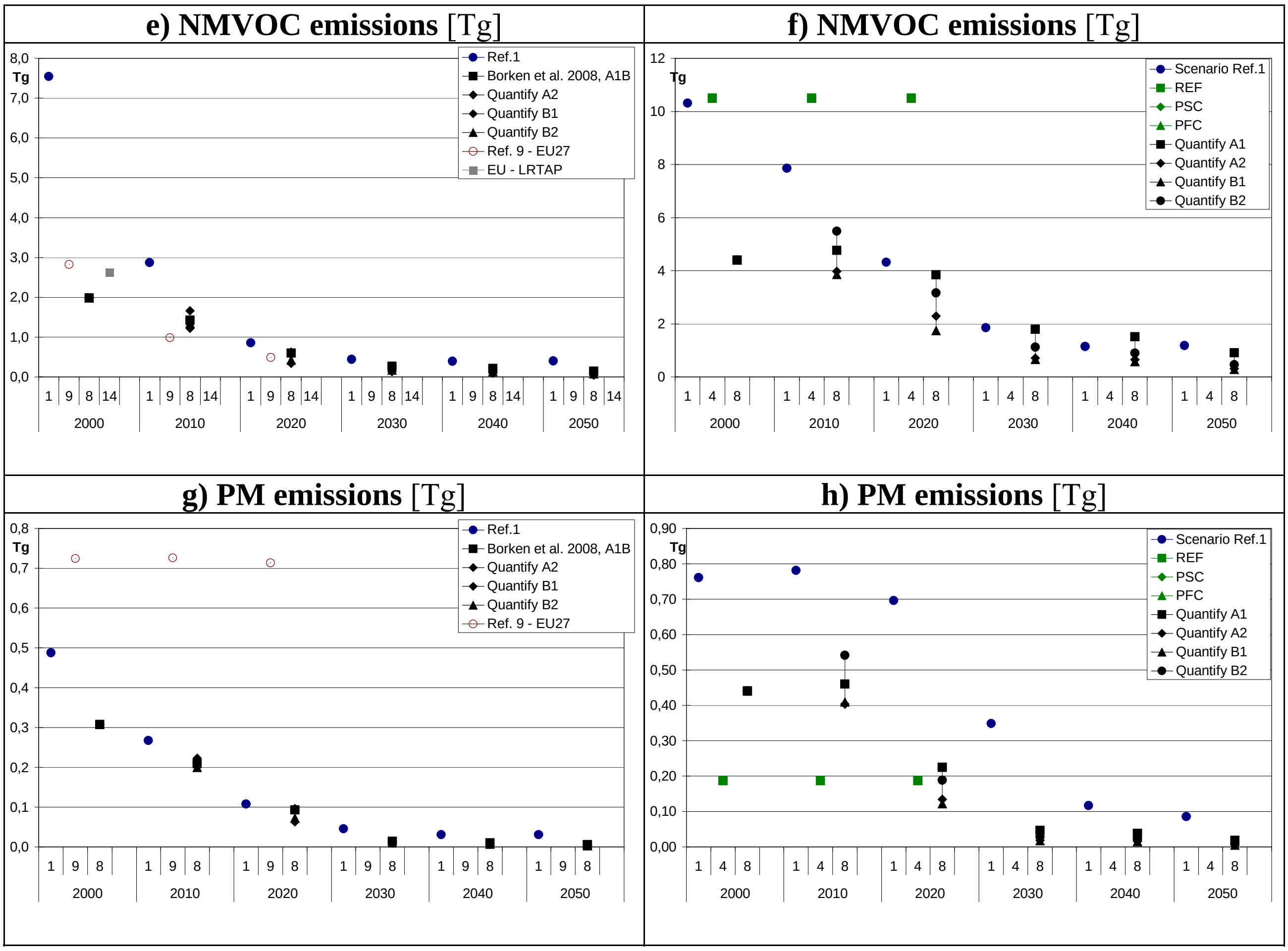


Figure 4: Emission scenarios for road transportation in Europe and developing Asia. a-b) CO_2, c-d) NOx, e-f) NMVOC, g-h) PM. They illustrate the developments in OECD regions and growing developing regions in general.

Notes for the editorial office

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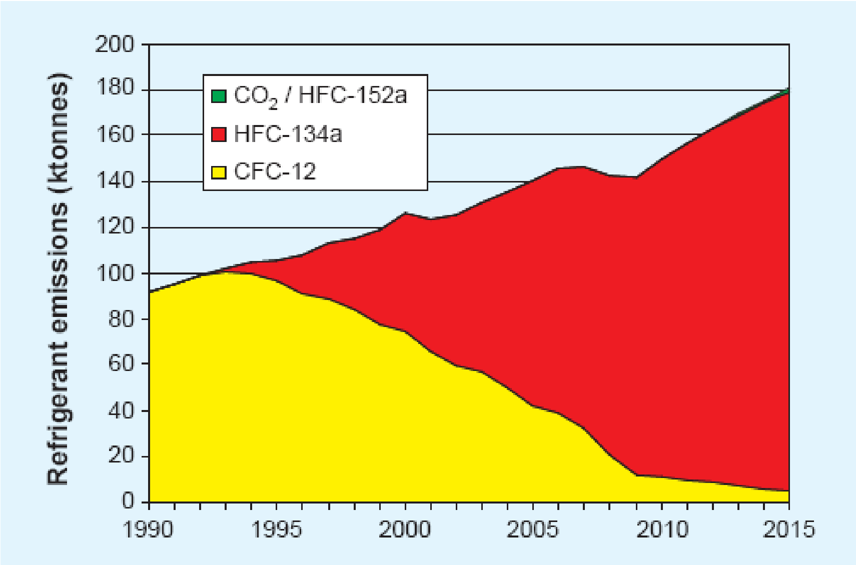


Figure 5: SROC 2006, Figure 6a. MAC refrigerant emissions from 1990 to 2015 (Clodic et al., 2004).

Notes for the editorial office

This figure is taken from the IPCC SROC report, Part 6 on Mobile Air Conditioners, which is provided as PDF version in the Internet at:

http://www.mnp.nl/ipcc/pages_media/SROC-final/SpecialReportSROC.html

Probably it could be redrawn in black and white. But we do not have the raw data. I tried to contact Mr. Clodic but did not get response via e-mail.

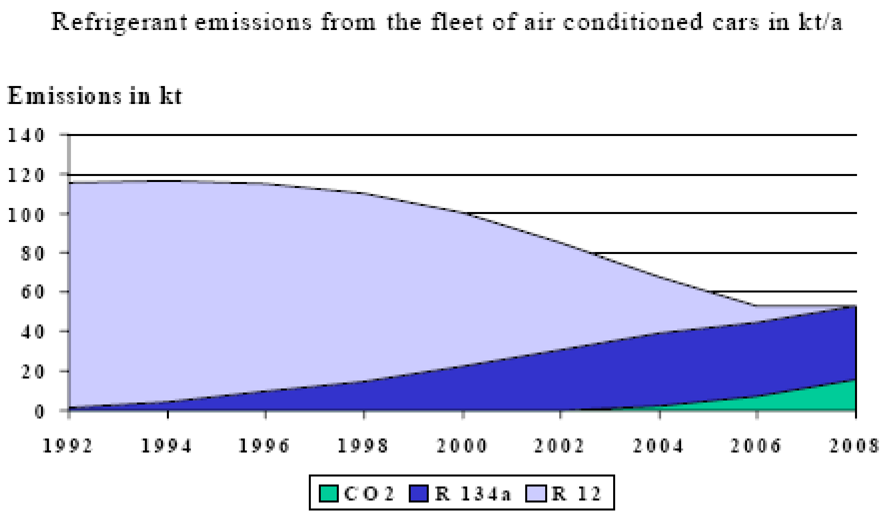


Figure 6: Refrigerant emissions from the fleet of air conditioned car in kt/a as estimated in 1999. Source: Preisegger E., Solvay Fluor und Derivate GmbH.

<u>Notes for the editorial office</u>

The figure is available from:

Preisegger, E., Automotive air conditioning impact of refrigerants on global warming, Solvay Fluor und Derivate GmbH.

Published on the IPCC website at:

http://arch.rivm.nl/env/int/ipcc/docs/IPCC-TEAP99/files/m99a3-12.pdf

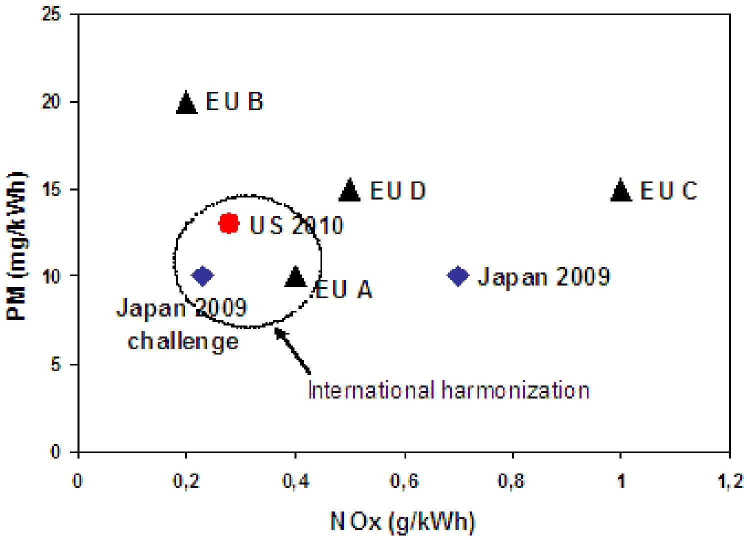


Figure 7: Current standards and proposed scenarios for HDV standards (Elvingson, 2007).

Notes for the editorial office

The figure has been sent by Katarzyna Juda-Rezler; It is published online at:

http://www.acidrain.org/pages/publications/acidnews/2007/documents/AN3-07.pdf

Katarzyna gave me the following contact information:

Per Elvingson
The Swedish NGO Secretariat on Acid Rain, Box 7005, SE-402 31 Göteborg, Sweden.
Phone. +46-31-711 45 15, Fax +46-31-711 46 20, info@acidrain.org

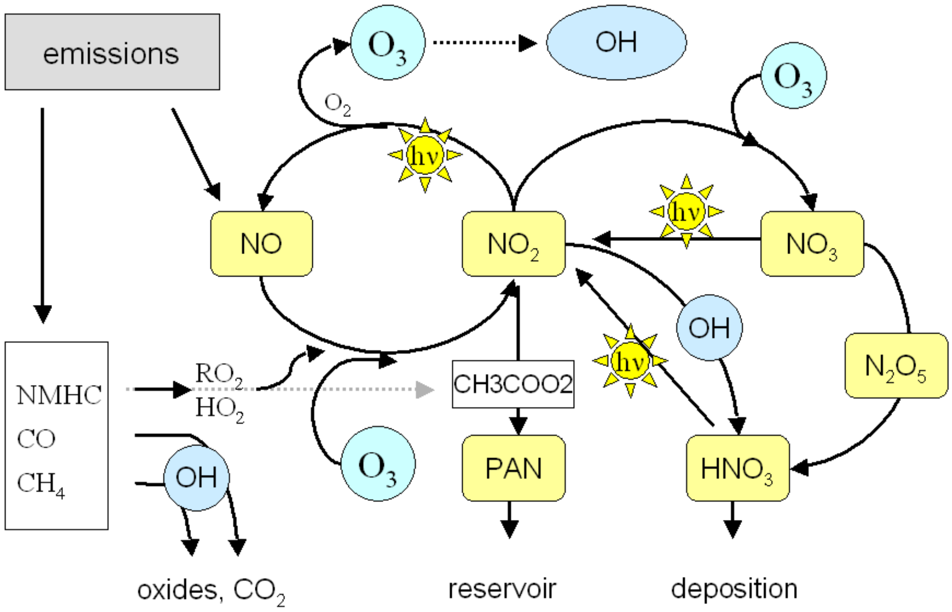


Figure 8: Basic processes in tropospheric chemistry

<u>Notes for the editorial office</u>

I draw this figure myself in Powerpoint.

It's available in this format and could be changed to greyscale.
ATTICA > Quantify WP 3 > Atmosphereschem.ppt

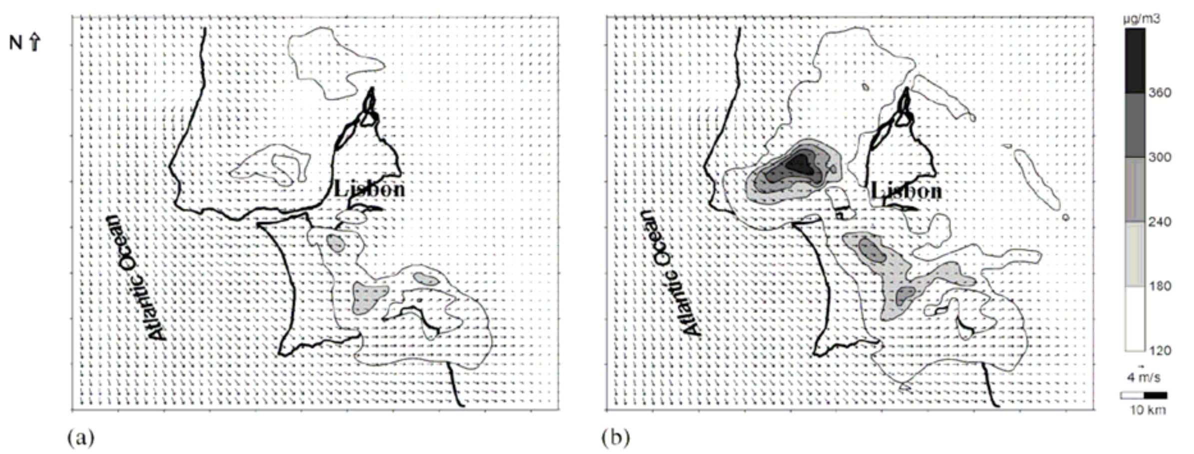


Figure 9. Simulation results of ozone peak values in July for two emissions scenarios at Lisboa: (A) without traffic emissions; (B) with traffic emissions. (Borrego at al, 2000)

Notes for the editorial office

The figure has been sent to me by Dimitris Melas. It should be from the publication Borrego et al., 2000. Permission from Carlos Borrego is given.

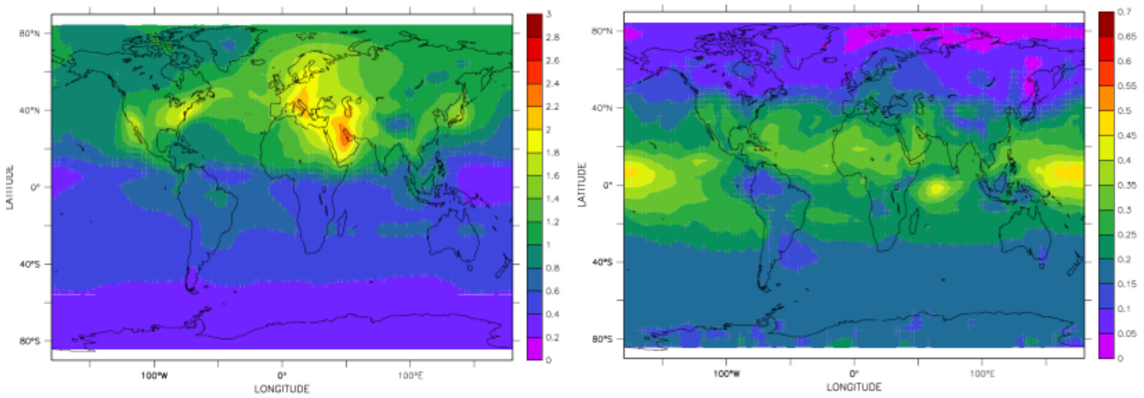
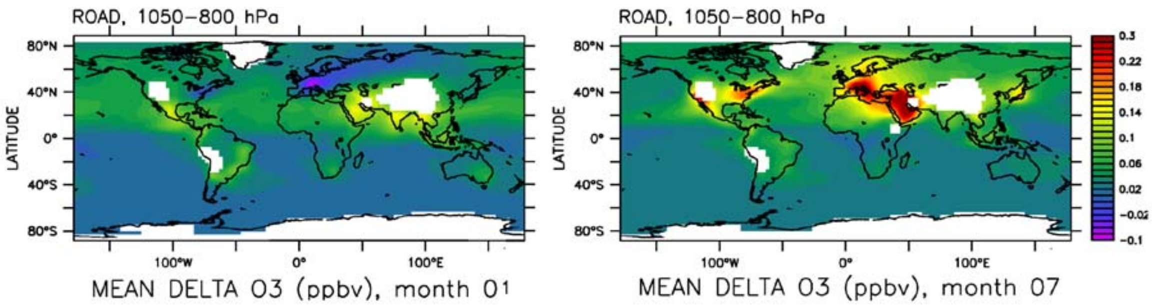


Figure 10:

Left: Changes in the ozone column from 1000 to 40 hPa in DU, July, due to the effect of road transport. The difference between base case and perturbed case is shown for an average over four models and a 5% perturbation scaled up to 100%. [1 DU = 21.4 mg O_3 m^{-2}]

Right: relative uncertainty among the models for the left hand map, calculated from the quotient of standard deviation and mean value for each grid cell. Source: Hoor et al., Quantify

Alternative Figure 10 from Hoor et al., 2009:



Mean perturbations of ozone (ppbv) in the lower troposphere (surfact – 800 hPa) during January (left) and July (right) applying a 5% emission reduction.

Notes for the editorial office

The figures are based on Quantify calculations from Peter Hoor. He has the respective images in different formats and the maximum available resolution. But I have also eps-figures from him.

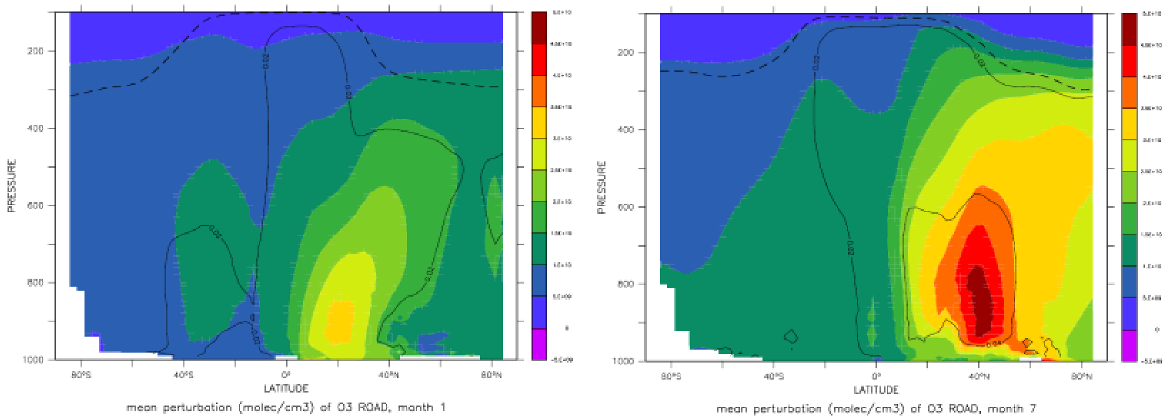


Figure 11: Zonal mean contribution of road traffic to ozone in molecules per cm^3 in January (left) and July (right), average from four models. Isolines of 2% and 4% change and the tropopause (dashed line) are shown in the graphs. Source: Hoor et al., Quantify

Notes for the editorial office

The figures are based on Quantify calculations from Peter Hoor. He has the respective images in different formats and the maximum available resolution. But I have also eps-figures from him.

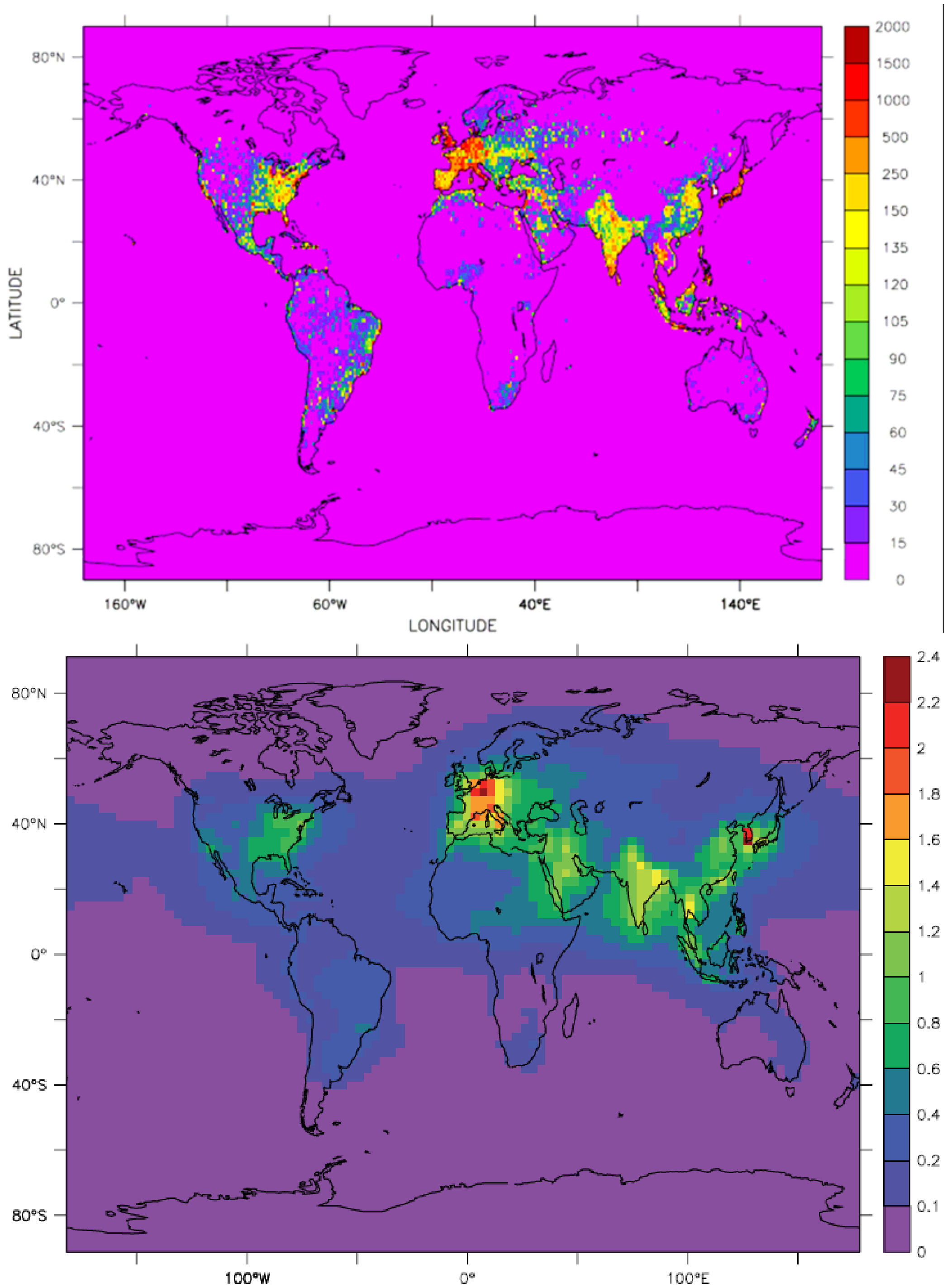


Figure 12: Top Panel: Total amount of black carbon (tons carbon/yr) emitted from passenger and freight transport (Gasoline+Diesel), Borken et al. (2007b)

Bottom Panel: black carbon optical depth (x1000) from passenger and freight transport (gasoline+diesel) global mean, ecmwf winds for 2000

Notes for the editorial office

The figure has been sent to me by Yves Balkanski for the ATTICA report. I think it is based on his Quantify calculations and copyright should not be a problem.

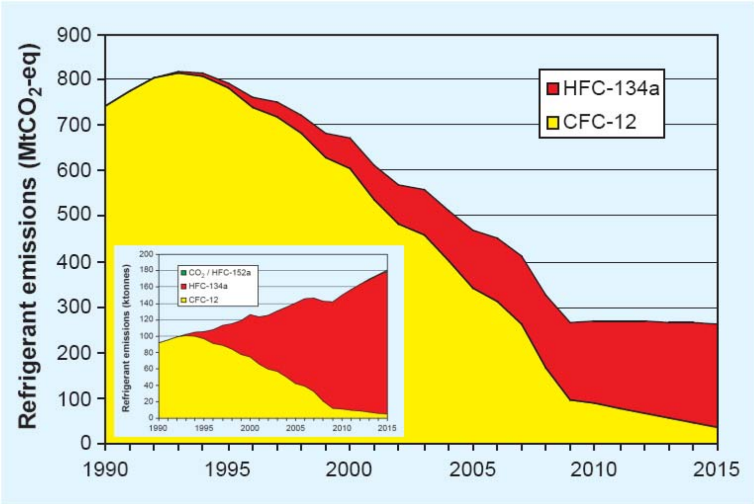


Figure 6b. MAC refrigerant emissions in CO_2-eq from 1990 to 2015 (Clodic *et al.*, 2004).

Figure 13: SROC 2006, Figure 6b. MAC refrigerant emissions in CO_2-eq from 1990 to 2015. CFC-12 and HFC-134a emissions are transformed into CO_2-eq based on their GWP, as given in the IPCC Second Assessment Report (IPCC, 1996). (Clodic et al., 2004).

<u>Notes for the editorial office</u>

This figure is taken from the IPCC SROC report, Part 6 on Mobile Air Conditioners, which is provided as PDF version in the Internet at:

http://www.mnp.nl/ipcc/pages_media/SROC-final/SpecialReportSROC.html

I added a copy of figure 5 as inset.

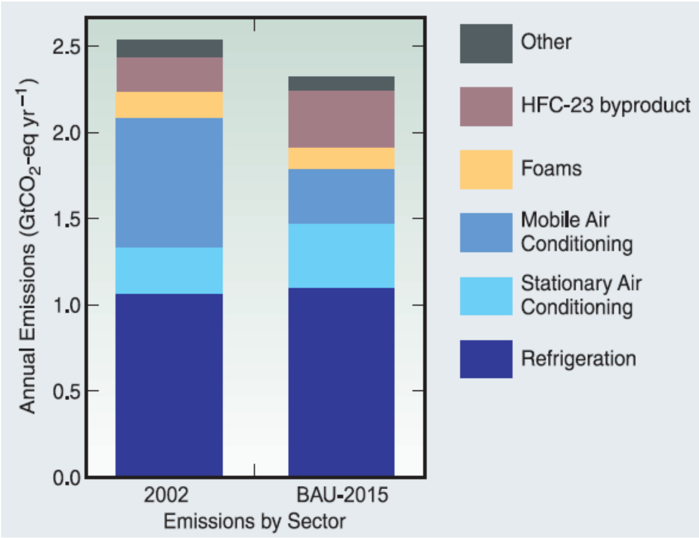


Figure 14: Historical data for 2002 and Business-As-Usual (BAU) projections for 2015 of greenhouse gas CO_2-equivalent direct annual emissions, related to the use of CFCs, HCFCs and HFCs. SROC 2006 fig. SPM-4.

Notes for the editorial office

This figure is taken from the IPCC SROC report, Part 6 on Mobile Air Conditioners, which is provided as PDF version in the Internet at:

http://www.mnp.nl/ipcc/pages_media/SROC-final/SpecialReportSROC.html

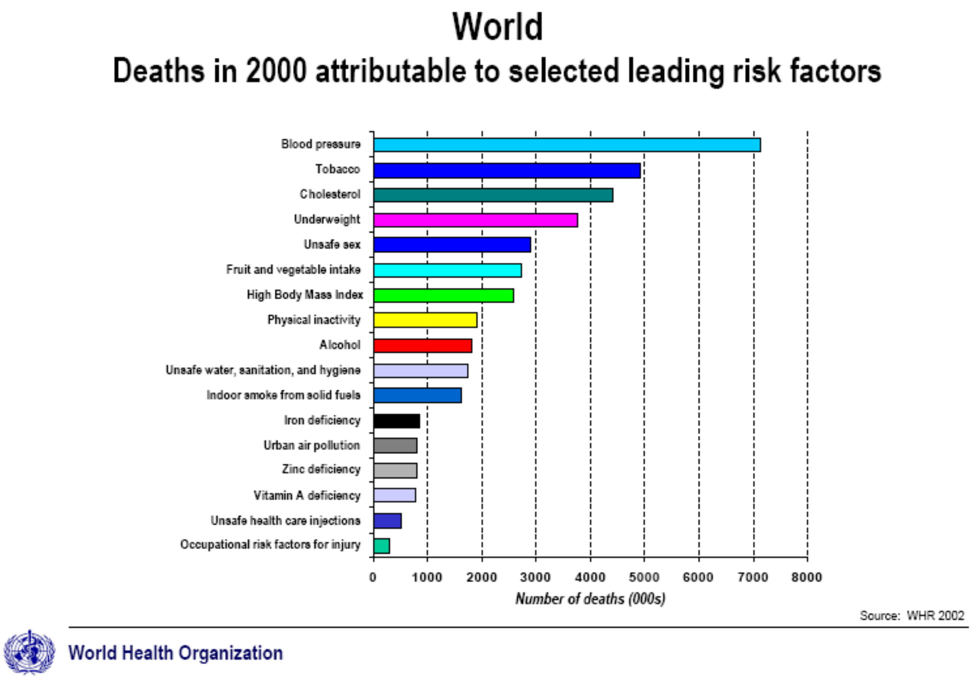


Figure 15: Deaths in 2000 attributable to selected leading risk factors (WHO, 2002)

Notes for the editorial office

The figure is available from the WHO website at:

http://www.who.int/dietphysicalactivity/publications/facts/en/gsfs_ppt_rf.pdf

Katarzyna thinks, it could be cited as WHO without permission.

Fig. 3.2. Summary estimates for relative risks for mortality and different air pollutants

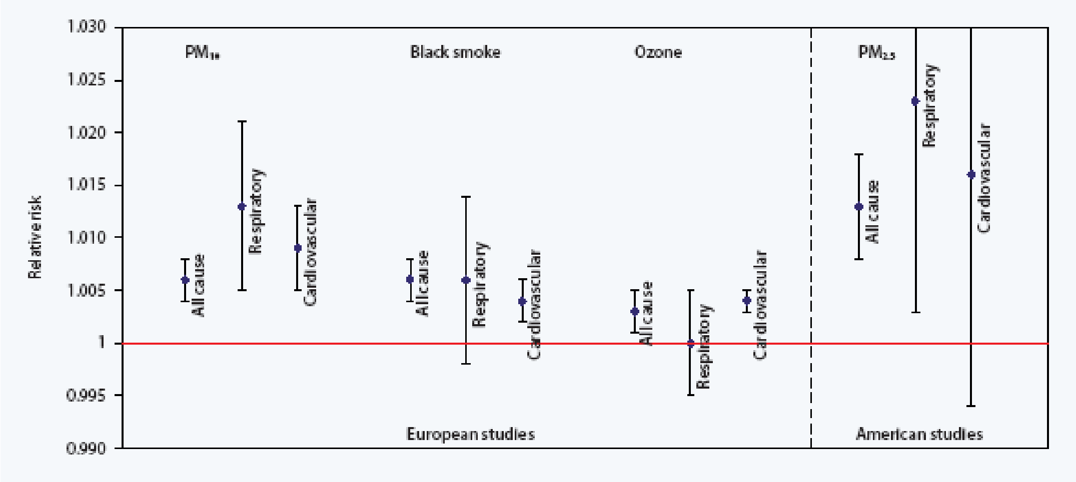


Figure 16: Summary estimates for relative risks (RR) for mortality and different air pollutants. RR is the risk of an event (or of developing a disease) relative to exposure and is calculated as a ratio of the probability of the event occurring in the exposed group versus the control (non-exposed) group. Note: There were not enough European results for a meta-analysis of effects of $PM_{2.5}$. The relative risk for this pollutant is from North American studies (WHO, 2006 after Anderson et al., 2004).

<u>Notes for the editorial office</u>

The figure has been sent to me by Katarzyna Juda-Rezler. I will contact her and ask from whom we have to request the copyright. (e-mail to Katarzyna 10.2.)

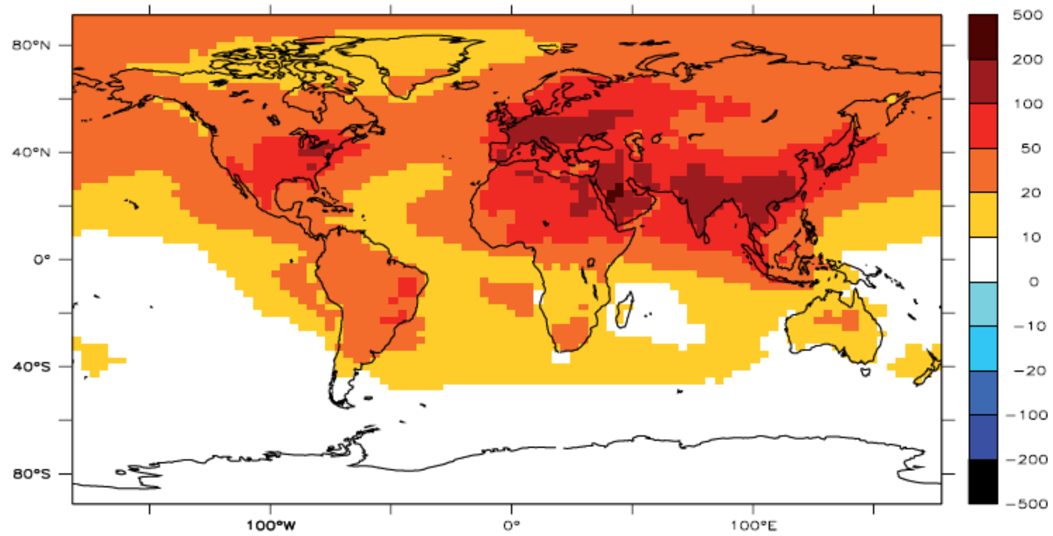


Figure 17: January top of the atmosphere radiative forcing (mW/m^2) due to black carbon emitted from road transportation.

Notes for the editorial office

The figure has been sent to me by Yves Balkanski. I will contact him and ask if its his work or if we have to consider copyright issues. (e-mail to Yves, 10.2.)

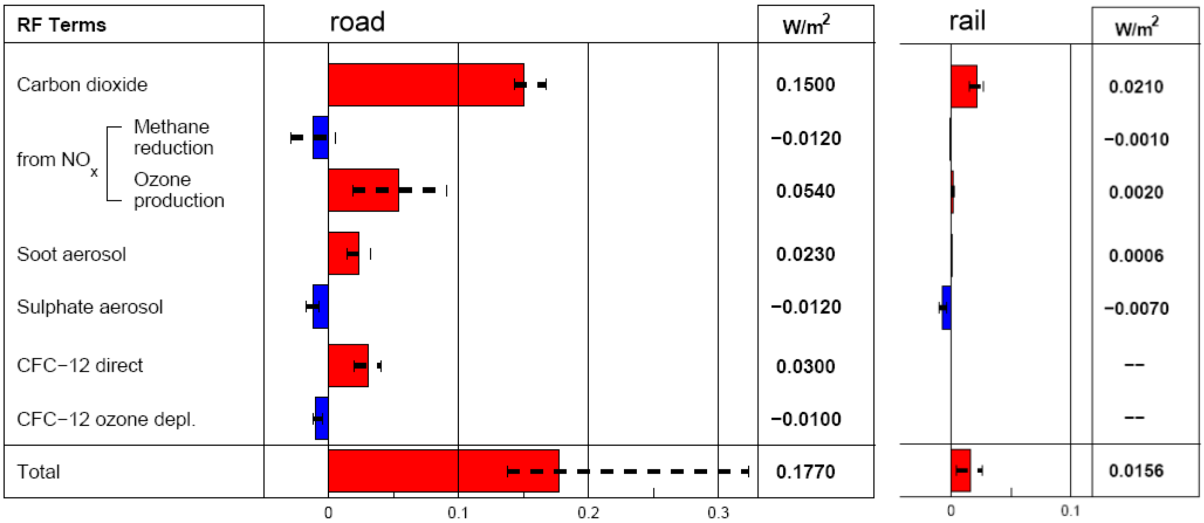
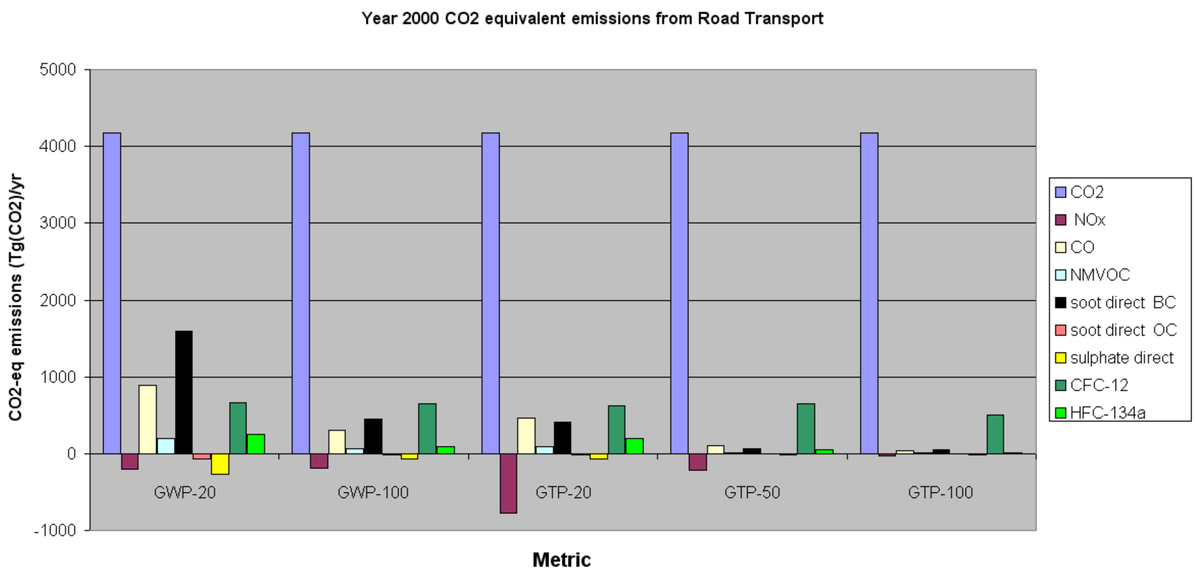


Figure 18: Radiative forcing for road and rail transport in 2000.



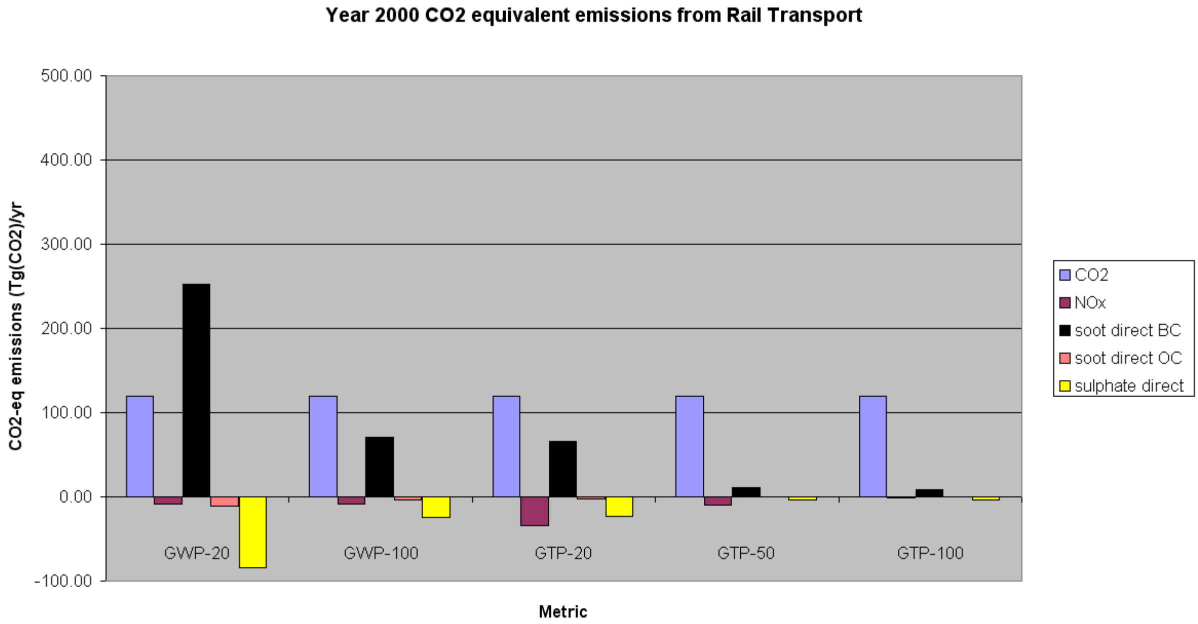


Figure 19 a + b: Short term and long term global warming potentials (GWP) and global temperature potentials (GTP) of emissions from road transport (above) and rail transport (below). The charts are based on data given in table 14 and 15.

<u>Notes to the editorial office</u>
Figure based on numbers in the metrics chapter. For the calculation I followed the process Terje Berntsen has chosen.

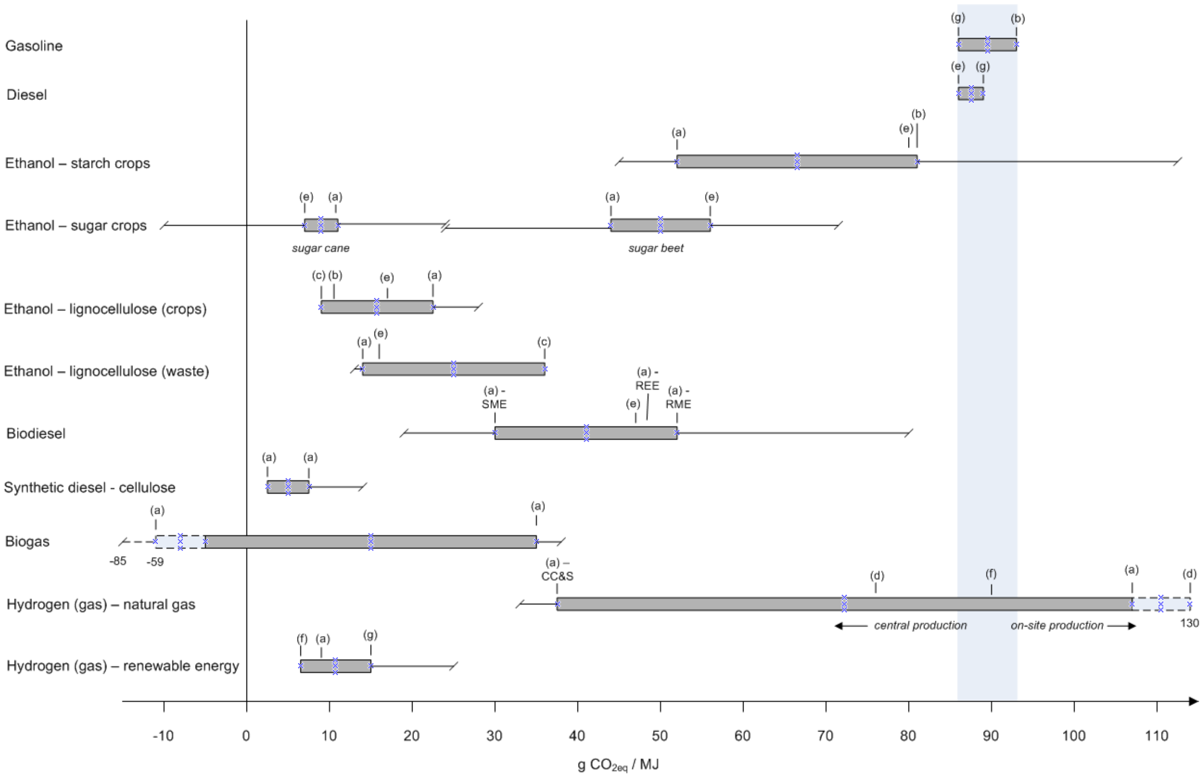


Figure 20: Summary on net CO2-eq emissions for some alternative fuels
Sources: (a) Edwards at al. (2007); (b) Farrell et al. (2006); (c) Kemppainen and Shonnard (2005); (d) MacLean and Lave (2003); (e) Ryan et al. (2006); (f) Wietschel et al. (2006); (g) own calculations.

<u>Notes for the editorial office</u>

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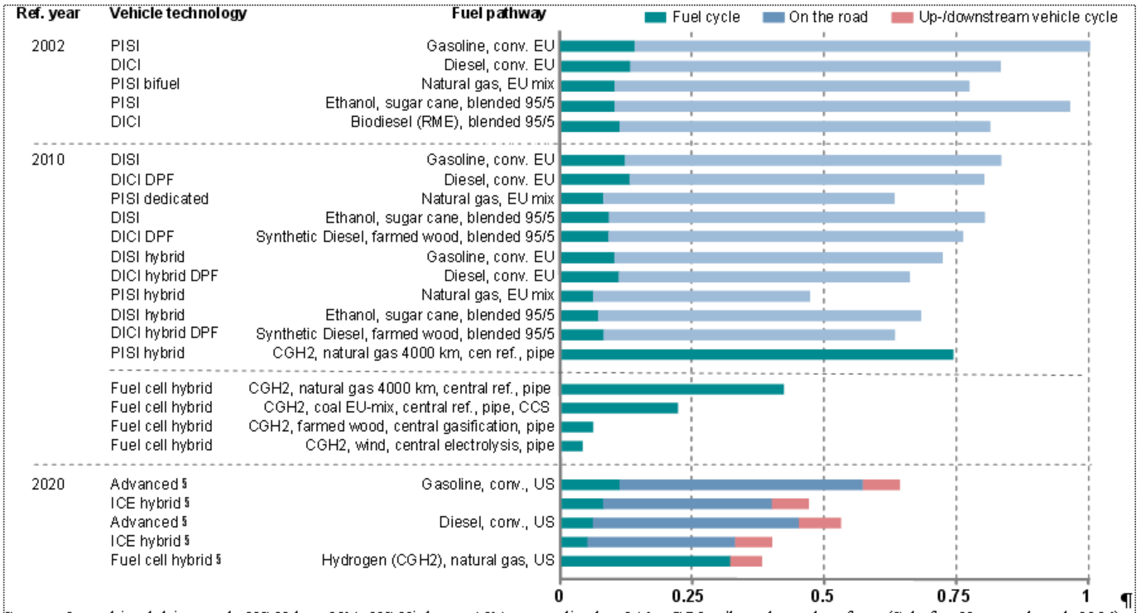

Source: § combined drive cycle US Urban 55%, US Highway 45%, normalised to 246 g CO2eq/km; data taken from (Schäfer, Heywood et al. 2006); all other values refer to New European Drive Cycle (NEDC), normalised to 196 g CO2eq/km; data taken from (Edwards, Griesemann et al. 2007)

Figure 21: Vehicle technologies and alternative fuels: CO_2–eq emissions well-to-wheels

<u>Notes for the editorial office</u>

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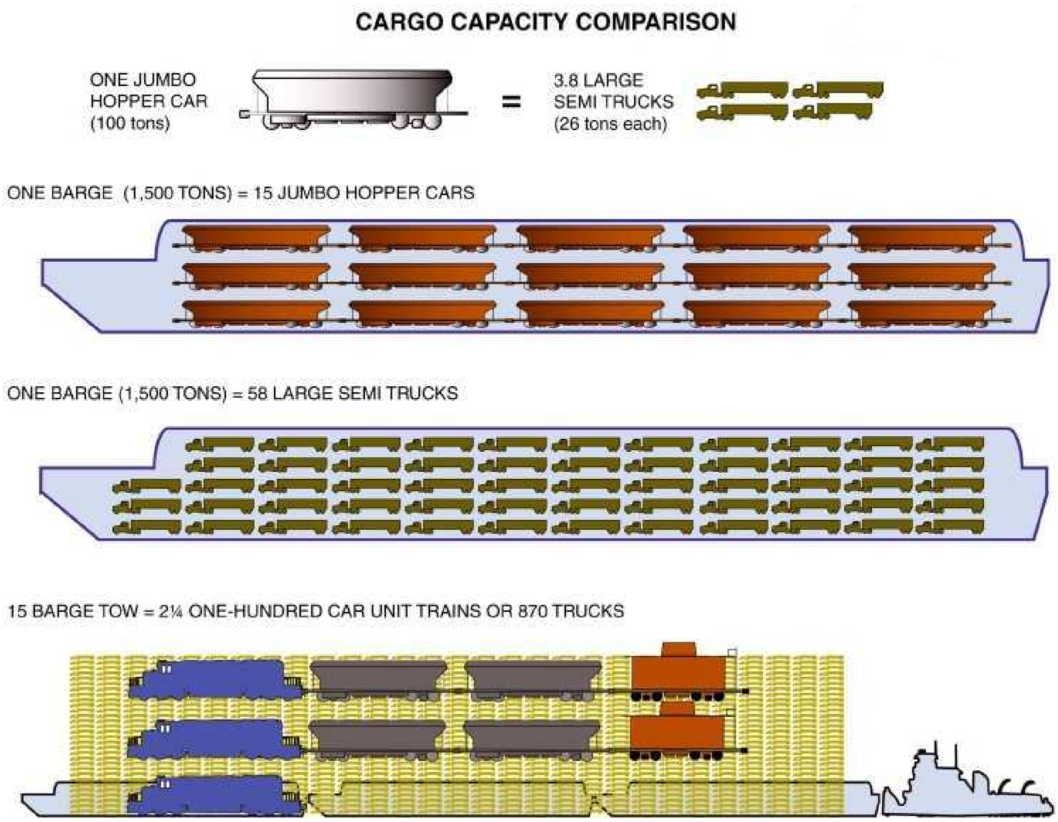
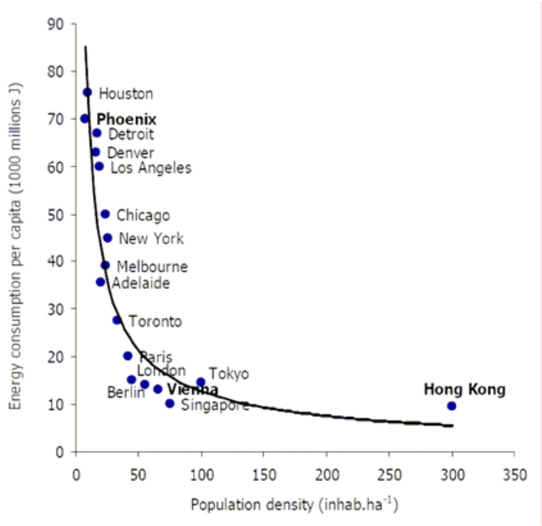


Figure 22: Cargo Capacity Comparison (Source: www.ccpa-ohioriver.com)



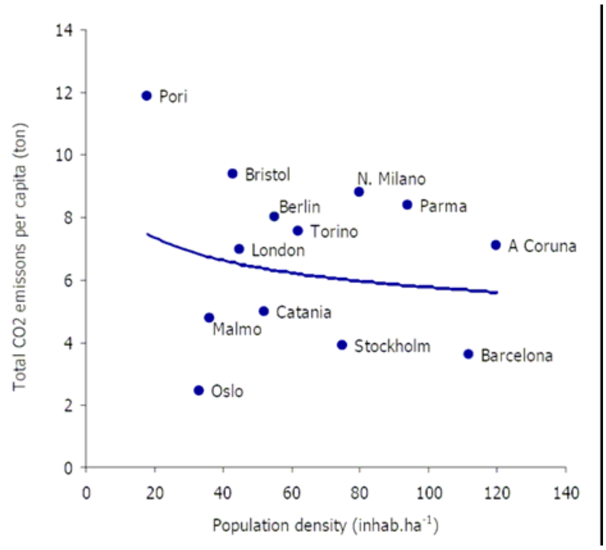


Figure 23: Energy consumption per capita and population density for several world cities (adapted from Newman and Kenworthy, 1999).

Figure 24: CO_2 emissions per capita and population density for several world cities (adapted from Ambiente Italia, 2003)