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Transport Impacts on Atmosphere and Climate: Land Transport

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1 **Abstract:**

2 Land transport emissions are dominated by road vehicles, but include also rail and inland
3 shipping. Among all transport modes land transport is the most relevant contributor to global
4 warming and its share is increasing, in absolute as well as in relative numbers. This assessment
5 gives an overview of past, present and potential future emissions, of impacts on atmospheric
6 composition, air quality, human health and climate change and on options for mitigation.
7 In the recent decades many measures successfully focussed on the reduction of short-lived
8 emissions like nitrogen oxides, carbon monoxide, volatile organic compounds and particulate
9 matter in order to improve air quality and reduce negative health impacts particularly in
10 industrialised countries. The concentration of health-affecting air pollutants and ozone peak
11 values have been decreasing in many countries and air quality has been improving. On the other
12 hand, due to growing urbanisation and less controlled and increasing emissions in developing
13 countries still many people are affected by air pollution and background ozone levels did not
14 decrease on a global scale. With respect to global warming, these pollutants have partially
15 opposite signs in the radiative forcing and their life-times of months to a couple of years are short.
16 Therefore, their long term global temperature potentials are low.
17 For climate change, the more challenging problems are the increasing emissions of long lived
18 greenhouse gases, first of all carbon dioxide and in the last decades also halocarbons from
19 mobile air conditioners. From trends of the global demand in mobility and comfort it can be
20 expected that the consumption of fossil fuels will grow also in the next decades until 2050 and so
21 far envisioned measures for mitigation and fuel replacement will not be sufficient to reverse this
22 development. Therefore, land transport will remain a key sector in climate change mitigation
23 during the next decades.

24

1	Table of contents:
2	1 Introduction
3	1.1 About this publication
4	1.2 Land transport from the past to the present
5	
6	2 Land transport emissions
7	2.1 Exhaust emissions from road transport
8	2.2 Emissions from rail transport
9	2.3 Emissions from Inland Shipping
10	2.4 Indirect Emissions
11	2.5 CFC and HFC emissions from road transport
12	
13	3 Impacts on Air Composition
14	3.1 Basics of atmospheric chemistry
15	3.2 Impacts on global atmospheric composition and chemistry
16	3.3 Impacts on and of aerosols
17	3.4 Impacts on visibility and clouds
18	3.5 Impacts on regional and local air quality
19	3.6 Impacts on health
20	
21	4 Impacts on Radiative Forcing and Climate
22	4.1 Impacts of Greenhouse gases
23	4.2 Impacts of Black carbon and sulphate
24	4.3 Climate Change and Future Impacts (6)
25	
26	5 Future developments
27	5.1 Standards and regulations
28	5.2 Vehicle technologies
29	5.3 Alternative fuels and well to wheel analysis
30	5.4 Mobility management and policy options
31	5.5 Scenarios of future exhaust emissions
32	
33	
34	6 Conclusions
35	Appendix 1
36	Acknowledgement
37	References
38	
39	

1

2 **1. Introduction**

3

4 **1.1 Scope and structure of this publication**

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

11

12 Emissions from land transport, coming primarily from road vehicles and to a smaller extent from
13 rail and inland shipping, dominate the release of long lived greenhouse gases from
14 transportation. They make a major and increasing contribution to the total anthropogenic
15 greenhouse effect. Furthermore, many short-lived gases and particles are emitted by land
16 transport, which have an impact on atmospheric composition and air quality. This report relies
17 on peer-reviewed literature, selected studies of the recent years and research carried out in the
18 European QUANTIFY project in order to assess what we know about this increasingly important
19 role of land transport. According to the concept of this publication, we give answers to the
20 questions: What is emitted? What are the impacts on the atmosphere? What are the impacts on
21 the radiation budget and climate change? Which responses and future developments are likely?
22 After an introduction and view back in chapter 1, we give in chapter 2 an overview of the
23 different types of direct and indirect emissions. This includes long-lived as well as short lived
24 emissions, released by land transport vehicles on a global scale and partially in comparison of
25 industrialied and developing regions. The briefly discussed chemistry of active species such as

1 nitrogen oxides (NO_x), carbon monoxide (CO) or non-methane volatile organic compounds
2 (NMVOC) have an impact on atmospheric composition which is presented as a result of global
3 models in chapter 3. These species or particles or both together have also an impact on visibility,
4 air quality and health which is summarised in the same section. In particular carbon dioxide and
5 ozone, but to a non-negligible extent also halocarbons have an influence on radiative forcing and
6 the climate system. This is discussed in chapter 4. Finally, we present in chapter 5 (future
7 developments) evolving trends in vehicle technology, alternative fuels and mobility management
8 and assess their potential to reduce emissions. In different emission scenarios we give an outlook
9 to the future, although the respective calculations of future climate impacts are still part of
10 ongoing research.

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

13 **1.2 Land transport from the past to the present**

14 Many people associate an increase in their personal mobility with an increase in life quality.
15 From the time of ancient civilizations up to about 250 years ago, the power to overcome long
16 distances came from horses, donkeys, cattle, camels or human muscles. Nowadays climate
17 science considers the period of the development of steam engines allowing to convert the energy
18 of fossil fuels into the movement of a wheel (e.g. by James Watt in 1769) as the end of the
19 preindustrial time and as the start of a significant human alteration of the natural greenhouse
20 effect. These engines, based on fossil fuels, did not only initialise the start of the industrial
21 revolution but also of modern transport. First they were applied in ships and trains. Between
22 1900 and 1930 it is likely that shipping was still the largest source of CO₂ emissions from the
23 transport sector (Fuglestvedt et al., 2008). **[previous paragraph slightly shortened]**
24 Since ships and rail were first the dominating emitters they still have a relatively higher
25 relevance in cumulative CO₂ than in present emissions as shown in **Table 1**. But after 1910 road

1 traffic gained soon more and more importance, overtaking all other transport modes. [moved
2 from 2.1] Figure 2 demonstrates the enormous increase in road vehicles, which are now
3 responsible for typically 75-80% of all CO₂ emissions from transport.

4 [Add here Table 1]

5 [Add here Figure 2]

6

7 The car fleet in the United States grew from about 140,000 vehicles in 1907 to more than 20
8 million in 1927. A similar development took place in Europe with a delay of about 30 years, i.e.
9 after the second world war. Still in 1960, there were less than 10 cars per 1000 inhabitants in
10 United Kingdom, growing up to about 400 and more within 40 years and boosting the usage of
11 oil. Now, again with a shift of 30 years, a similar evolution starts in East Asia. The permanently
12 increasing fuel consumption in road transport will soon generate more than one fifth of the
13 global CO₂ emissions.

14 Shorter-lived exhaust gases from dense road traffic had and have negative impacts on air quality.
15 Road vehicles are a major source of nitrogen oxides over land. The induced photochemical
16 smog, which is often mixed with particle emissions and was called 'ozone smog' or Los Angeles
17 smog. It was first discovered in Los Angeles and soon attributed to the dense road traffic in the
18 1940th and 1950th. Maximum concentration observed in L.A. was 580 ppb (1160 µg/m³) of
19 ozone. An answer to the problem was the regulation of car emissions which began with the U.S.
20 Clean Air Act of 1970. Mass production of catalytic converters started for the 1975 car
21 generation in the U.S. About one decade later it was introduced also in Europe.

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

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

3

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

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

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

19 [Add here Figure 1]

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

24 While the so far dominating European and North American regions could not yet achieve a
25 reduction of their fuel consumption, a very strong growth is observed in many developing

1 countries. Therefore land transport emissions continue to be a major burden for the environment.

2 The analysis of the present situation and the estimation of future developments are subject of
3 numerous scientific publications and several assessments. An overview of major studies and
4 recent research is also given in Appendix I.

5

6 **2 Land transport emissions**

7

8 **2.1 Exhaust emissions of road transport**

9

10 There are few recent estimates of road transport's global fuel consumption and related CO₂
11 emissions (IEA 2004, 2005; IEA/OECD, 2006; Turton, 2006) and a few estimates include non-
12 CO₂ exhaust emissions (Aardenne et al., 2005; Borken et al., 2007a, b; Fulton and Eads, 2004).

13 At the level of regions and countries more emission inventories are available and the level of
14 detail in both, approach and results, usually increases strongly. Here, we first discuss the global
15 emission totals and then briefly analyse emissions in North America, Western Europe and
16 developing Asia as the most relevant regions.

17 All global emission estimates take the road fuel consumption as given by the International
18 Energy Agency as a reference (e.g. IEA 2004, 2005: Entry Road transportation): Aardenne et al.
19 (2005) have taken the amount of fuel consumed as starting point and multiplied with fuel
20 specific emission factors (Tier 1 approach, cf. IPCC 2006). Fulton and Eads (2004) and Borken
21 et al. (2007a, b) have calibrated their vehicle mileage to the year 2000 fuel consumption (Tier 2
22 approach). Borken et al. (2007a, b) cross-checked with national data and calculated the fuel
23 consumption bottom-up notably for China, Iran, Saudi-Arabia, Russia and India as well as many
24 smaller countries in Africa and Latin America. They conclude on misallocation of the statistical
25 entries, under- or non-reporting notably of the diesel fuel consumption and derive a global diesel
26 fuel consumption of 550 Mtoe, about 6% higher than reported by IEA energy statistics for that

1 year. About 38% of the 1450 Mtoe total fuel consumed is diesel, 60% is gasoline, gaseous fuels
2 and liquid biofuels account for about 1% and 0.7% respectively. In consequence, all global
3 emission estimates assume about the same amount of fossil fuel and calculate about the same
4 global CO₂ emissions.

5 Differences are much stronger for the non-CO₂ emissions because of the different assumptions
6 how the mileage is distributed among the different vehicle categories and what the average
7 exhaust emission factors are. Both, Borcken et al. (2007a, b) and Fulton and Eads (2004) have
8 differentiated by 5 vehicle categories and several fuel types and the emission factors refer to the
9 transport activity of each vehicle fuel combination. All authors have aggregated countries to
10 about 11 to 13 world regions. Thus, the emission factors are assumed as regional averages and
11 differences between countries within one region are neglected.

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

17

18 *Emissions of road transportation worldwide in the year 2000*

19 Total exhaust emissions by road transportation worldwide are summarised in **Table 2**. As there is
20 largely agreement on the fuel types and their total amounts, the assumptions about emission
21 factors determine the overall results. They concur for CO₂ and NO_x emissions, but there are large
22 differences for all other compounds. To understand them, and hence to judge on the plausibility
23 of one or the other figure, we need to analyse results and emission factors on the regional level;
24 otherwise all will be dominated by the emissions of the OECD region. Emission factors from
25 Aardenne et al. (2005) are based on estimates for 1995 or 1990 in OECD or non-OECD regions.

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

3 [Add here Table 2]

4

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

6 The different world regions contribute in variable amounts to the global exhaust emissions.

7 Usually, North America, Europe and the highly populated Asian region contribute significant

8 amounts. However, vice versa, how well the road transport in the important regions has been

9 modelled determines how reliable the resulting global estimate can be considered. Therefore an

10 analysis of the regional emissions is mandatory and there are also further regional inventory data

11 to compare with, often produced with a much more detailed method. [Jens: are there references?]

12 For the purpose of this review we cannot go into the details of each approach, but already the

13 comparison of the final results is revealing.

14 [Add here Table 3]

15

16 *Carbon dioxide emissions*

17 All inventories concur for carbon dioxide emissions both globally and in the OECD regions. The

18 slightly higher value of Aardenne et al. (2005) for North America cannot be confirmed by

19 national (US-DoT 2006) or international fuel data (IEA 2004). The higher values of Borcken et al.

20 (2007a, b) for Asia and the Reforming Region are due to their corrections of the fuel data as

21 explained above.

22

23 *Non-carbon dioxide emissions*

24 Estimates for nitrogen oxide emissions agree within 30 percent across the different inventories,

25 both globally and in the regions. Emission factors of Borcken et al. (2007a, b) for OECD regions

1 are slightly higher: It has recently been found that real world emissions from heavy duty vehicles
2 in Western Europe are by about 30% higher than the limit values [What is a "limit value"?
3 according to EC regulations?] (Hausberger et al. 2003). For carbon monoxide the emission
4 estimates concur for the relative distribution among regions. However, absolute differences are
5 large: Borken et al. (2007a, b) use the lowest emission factors, the more detailed emission
6 inventories for the US and Western Europe (US-DoT 2006, US-EPA 2005, De Ceuster et al.
7 2006) have higher ones, while the emission factors assumed by Fulton and Eads (2004) appear
8 rather high. For sulphur dioxide emissions the lower totals of Borken et al. (2007a, b) reflect the
9 reductions in the fuel sulphur contents since 1995, the base year of Aardenne et al. (2005). The
10 emissions of volatile organic compounds are not directly comparable as Borken et al. (2007a, b)
11 calculated tail pipe emissions only, while the other inventories include evaporative emissions as
12 well. [Jens: Can evaporative emissions be estimated? The reviewers regard this as a non-
13 satisfying statement.]

14 For PM emissions the large differences can be traced back to the emission factors assumed for
15 gasoline vehicles. Emissions factors broadly concur for diesel vehicles between Borken et al.
16 (2007a, b) and Fulton and Eads (2004). However for gasoline powered vehicles Fulton and Eads
17 (2004) assume as much as 40-50% of the respective value of diesel vehicles without giving a
18 reference. Usually PM emissions of gasoline powered vehicles are about two orders of
19 magnitude smaller (Bond et al. 2004; US-EPA 2003; Zamaras et al. 2005).

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

22

23 *Uncertainties*

24 The biggest differences in values are for the region of developing Asia, comprising China, India
25 and the growing South East Asian economies. This region has undergone a very rapid

1 development in road transport volume and increase in vehicle stock. Therefore the state for the
2 year 2000 is difficult to estimate. Furthermore, vehicle exhaust emission control has not been as
3 stringent as in OECD countries and hence their variability is bigger.
4 Moreover, the inventories differ in the sophistication of the approach and in the quality of their
5 input data. Therefore the range of values rather reflects the outcome of various more or less well
6 controlled simplifications not the range of uncertainty.
7 To estimate the potential uncertainty we give the following expert judgement for the year 2000
8 based on the differentiated results of Borken et al. (2007a, b): The input data (vehicle stock
9 composition and their mileage, the emission factors and the overall fuel balance) are more
10 reliable and less variable in OECD countries. Our judgement goes for 5% uncertainty in the fuel
11 balance and related CO₂ emissions over an estimated 30% uncertainty for CO, NMVOC and
12 NO_x to about 50% uncertainty for PM emissions. For non-OECD countries the available data are
13 much less representative, less reliable and the variation in vehicle technology and operating
14 conditions is much larger. Consequently we have assumed about a two to three times higher
15 uncertainty for each species. Weighted with the respective region's share in emission we
16 estimated a cumulated uncertainty in the order of 10% for CO₂ emissions, about 30% for SO₂
17 and NO_x emissions, 40-50% for CO and NMVOC emissions and 66% for PM (Table 4).

18 [Add here Table 4]

19

20

21 **2.2 Emissions of rail transport**

22

23 In many countries railway plays an important role in transport of goods and passengers. Globally
24 rail transport's performance is 2.2 (±0.4) trillion passenger km and 8.6 (±1.7) trillion tonne km
25 per year [Kristin: What is the reference year? 2000?]. Approximately one third of this transport
26 takes place in Europe. Rail goods transport plays an important role in North America [Jens,

1 **Kristin: The reviewers request here concrete numbers for North America]** while ¼ of the global
2 rail passenger transport takes place in India and China, respectively (Community of European
3 Railway and Infrastructure Companies). In EU-25 rail contributes to 9% of total passenger
4 transport and 3% of the goods transport (EEA 2006). Approximately 30% of the global rail
5 network is currently electrified; this share is 50% in the European Union.

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

8

9 *Fuel consumption and carbon dioxide emissions*

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

14 European (EU-25) rail emissions have also been estimated by the EEA and TERM (2003). This
15 study shows that rail emissions in Europe make up for only 1-3% of the total transport emissions.
16 Rail fuel consumption data are available for all world regions at the country level from the IEA
17 for all years since 1971. Selected years are presented in **Table 7**. The table shows a large decline
18 in coal consumption, a 70% increase in electricity consumption and stable diesel consumption
19 from 1971 to 2004.

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

25 **[Add here Table 6]**

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

4

5 *Emissions of short lived pollutants*

6 European rail vehicles produced after 1990 emit substantially less NO_x and PM compared to
7 older vehicles. For example for mainline locomotives the reduction has been 30% in NO_x and
8 70% in PM emission factors, while for railcars the reduction has been even larger (UIC/CER
9 2006). We have estimated emissions using the EMEP/Corinair emission factors for diesel and
10 the IPCC emission factors for coal. The UIC/CER emission factors are only applicable for
11 Europe. The uncertainty margins are large for all emission data given the uncertainty in emission
12 factors and fuel consumption and the fact that independent studies are not available for
13 verification.

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

17

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

1 are more than 8 times as high as emissions from maritime shipping. These figures however mask
2 differences in average distance travelled and capacity utilisation. (Eionet, TRENDS, 2003)

3 [Add here Table 7]

4 [Add here Table 8]

5

6 **2.3 Inland Shipping**

7

8 Inland shipping, defined as shipping on rivers and lakes, is not important in terms of emissions at
9 the global level, but can play an important role for transport primarily of goods at the local level.
10 Emission estimates are not always comparable in different studies, since the differentiation
11 between ocean going ships and inland shipping is not always sharp. But emissions from shipping
12 on inland waterways is below 1% of all emissions from transport. For the EU 27 region the
13 IIASA Gains model reports CO₂ emissions of 5.73 Tg for 2000 and 7.41 Tg for 2005. This is
14 0.7% or 0.85% of the emissions from cars, trucks and buses. In Europe (EEA 30) inland shipping
15 is estimated to have a share of 5% in freight transport (EEA Report No 1 / 2007), but there is no
16 relevant passenger transport. Inland shipping will not affect the global climate to a measurable
17 extent.

18

19 **2.4 Indirect Emissions**

20

21 *Material related emissions*

22 Transport generates direct emissions when fuel is combusted in the engine of the vehicle.

23 However, when assessing the land transport impact on climate it is evidently relevant to consider
24 all emissions generated as a result of transport activities. Construction of transport infrastructure
25 (e.g. roads, rail-lines and harbour facilities) requires energy for construction work, maintenance
26 and production of materials (e.g. asphalt, concrete and steel). Production of transport equipment

1 requires energy, in particular for primary products (e.g. steel, aluminium and plastic). And,
2 finally, production of fuels generates emissions from extraction, refining and transportation.
3 **There are no comparable data on how much transport infrastructure contributes in terms of**
4 **global emissions. However, we note that despite their energy intensive production, generally the**
5 **life-time of such infrastructure is long – several decades. Furthermore, large variations between**
6 **regions are expected due to differences in emission intensity of production and use of human**
7 **labour vs. machinery. [Jens: These sentences should be removed and be replaced by a rough**
8 **estimation based on the available publications. Ask Jean-Pierre, Leonidas and Jens – Jens**
9 **assumes 10-15% for infrastructure and maintenance. However, not to be included in transport**
10 **emissions, because potential double counting with the construction sector.]**

11
12 For transport equipment, there are large differences in the life-time of vehicles between the
13 different modes, where typically rail and ships have a longer life-time (more than 20 years)
14 compared to road vehicles (less than 20 years). According to the Japanese institute for Lifecycle
15 Environmental assessment (<http://www.ilea.org>) emissions from production of a gasoline
16 conventional vehicle would be around 1/8 of the total CO₂ emissions from use over its life-cycle.
17 Also Jancovici reports that about 15% of the CO₂ emissions can be attributed to the production
18 and another 15% for the maintenance (Jancovici, 2004).* **In comparison**, a life cycle analysis for
19 a ferry concluded that 97% of CO₂ emissions are from operation, 1.4% from construction, 0.65%
20 from maintenance and 1.1% from scrapping. (Johnsen and Fet, 1999).

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

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

1

2 *Well-to-tank emissions*

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

10

11 The indirect emissions are at present most important for electricity production (power plants) for
12 use in railways and to a small extent for road transport. Indirect emissions from electricity
13 provision will depend on the technology used for producing the electricity and abatement level.
14 Due to increasing electrification of the railway network, indirect CO₂ emissions for rail are
15 nowadays approaching the same order of magnitude as direct emissions. It is important to
16 include this component in an assessment of future emission where more of the transport system
17 is being electrified. Future emissions per unit of electricity produced is, however, also expected
18 to change. For example, use of carbon capture and storage and more use of solar and wind power
19 will reduce emissions substantially. **[Kristin, Stephan: It would be nice to compare here the well-
20 to-wheel CO₂eq of an electric car and a diesel car and of an electric locomotive and a diesel
21 locomotive. Can this be done?]**

22

23 Also fossil fuels have a footprint from the extraction phase and refineries. Energy requirements
24 for extraction and processing/refining generate i.a. CO₂, NO_x and SO₂ emissions. In addition
25 there are fugitive emissions of methane and NMVOCs from the extraction, refining and transport

1 of fuels. Typically CO₂-equivalent emissions of direct greenhouse gases well-to-tank would
2 constitute 14 and 16 percent of well-to-wheel emissions for conventional gasoline and diesel
3 road vehicles, respectively (JRC/Concawe/EUCAR, 2006). It is not expected that similar figures
4 for fuels used in rail and inland shipping would be very different.

5
6 Gasoline used for road transport is a light and relatively volatile fuel. Therefore it is more easily
7 evaporated during handling and use compared to diesel fuels and heavy fuel oil. Gasoline
8 distribution and tanking is an important NMVOC source, depending on fuel properties, climate
9 and technologies. In Europe tighter standards for emissions from gasoline stations have resulted
10 in reduced emissions the last years. In addition to exhaust emissions, gasoline vehicles
11 themselves will result in evaporative emissions (EMEP/Corinair 2006). These emissions can be
12 classified as running losses, hot soak and diurnal (daily) emissions (ibid). Diurnal emissions are
13 associated with daily variations in ambient temperature that results in vapour expansion inside
14 the gasoline tank and contraction during nights with lower temperature. Hot soak emissions
15 occur when a hot engine is turned off and heat from the engine and the exhaust system increases
16 the temperature of the fuel in the system. Running losses are the result of vapour generated in
17 gasoline tanks during vehicle operations. Modern vehicles control these emissions by 90%
18 (EMEP/Corinair 2006) compared to older vehicles.

19
20 Unfortunately different inventories differ with respect to inclusion of NMVOC from gasoline
21 distribution and evaporative losses from use as part of transport emissions. The EDGAR
22 inventory attributes both sources to road transport emissions, while the Quantify inventory
23 excludes both. Standardised inventories (e.g. building on reporting standards to the LRTAP
24 Convention and the European inventory model COPERT IV) includes evaporative emissions
25 from the vehicle in the total road transport estimate, but excludes emissions from gasoline

1 distribution. [Kristin: The reviewers regard this statements as not satisfying. At least a rough
2 estimation of numbers would be helpful.]

3
4 In recent years and likely in the near future biofuels are increasing in importance for use in road
5 transportation and perhaps also in shipping. Emissions from the production of biofuels must be
6 added to the indirect emissions. This will include emissions from fertilization and fertilizer
7 production (N₂O and CO₂), fuel processing, transport of fuels and even CO₂ emissions from land
8 use change. Synthetic fuels, for example hydrogen, will shift most emissions to the production
9 stage. An overview of these well-to-tank emissions from alternative fuels is given in the well-to-
10 wheel analysis as described in section 5.3 (cf. JRC/Concawe/EUCAR (2005, 2003 and online:
11 <http://ies.jrc.ec.europa.eu/wtw.html> 2006))

12

13 **2.5 CFC and HFC Emissions**

14

15 Emissions from transport include emissions from mobile air-conditioners (MAC) in passenger
16 vehicles or cooling/freezing systems of goods transport. We do not discuss emissions from the
17 latter in this report. Air conditioning in cars became common in the United States since 1960.
18 However, mass production in Europe and in the developing countries started later, in about 1995.
19 In 2000 half of the worldwide automotive fleet of 720 million vehicles was equipped with air
20 conditioners (SROC, 2006). This number is increasing. Previously CFC-12 (CCl₂F₂) was used as
21 chemical in MAC, but in 2003 HFC-134a (CH₂FCF₃) was already used in 338 million road
22 vehicles. In the near future they are envisioned to be replaced by CO₂ or HFC-152a
23 (difluoroethan, CHF₂CH₃). The emissions of HFC-134a take place during accidents, through
24 leakage and servicing and at disposal. The recovery rates are low. A US model study estimates
25 the loss by leakage and service to be 10.9% and the loss during disposal to be 42.5% of the total
26 MAC charge in developed countries and 69% in developing countries (DeAngelo et al., 2006).

1 Indirect emissions arise from additional fuel use of the vehicle in which the MAC is installed.
2 This can amount to 2.5 – 7.5% of the total fuel consumption, depending on the operation time.
3 These emissions depend strongly on the local climate and can only be roughly estimated.
4 Systematic inventories for additional fuel consumption are not yet established. But the resulting
5 CO₂ emissions are included in the emission figures in section 2.1 to 2.3.

6
7 In 2002 about 110-130 ktonnes of CFC-12 were emitted. This is slightly more than a quarter of
8 the 1990 emissions (400-430 ktonnes). Half of the 2002 CFC-12 emissions were emitted from
9 MAC. 63 ktonnes are estimated for 2003 (SCROC, 2006). A typical air conditioner in a car
10 contains 1 kg of CFC-12 or 0.8 kg of HFC-134a (Atkinson, 2000). **Figure 5** shows that the total
11 amount of refrigerants emitted is constantly rising, but now mainly consisting of HFC-134a. In
12 2002, about two thirds of the 97 ktonnes emitted came from MAC. As can be seen from
13 estimations that were made in 1999 (**Figure 6**), much faster progress in the market integration of
14 CO₂ or HFC-152a based systems was assumed before. But alternatives to HFC-134a needed
15 longer development and test phases (SAE, 2003). Furthermore, the strong increase in the market
16 share of cars equipped with air conditions of up to more than half of the fleet at present was not
17 expected. Consequently, recent estimates for MAC refrigerant emissions in 2005, suggesting 140
18 ktonnes, are more than twice as high as projected in 1999. We can see that as one example how
19 difficult it is to project future developments if the introduction of new technologies is planned.

20 **[Add here Figure 5]**

21 **[Add here Figure 6]**

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

21 *“ATTICA”, WP3, Chapter no 4, version submitted to the editorial office on 14.07.2008*
LA08 - Assessment of Transport Impacts on Climate and Ozone: Land Transport

1

2

1

2 **3 Impacts on Air Composition**

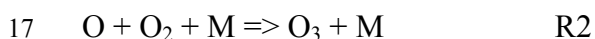
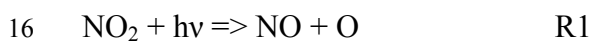
3 **3.1 Basics of atmospheric chemistry**

4

5 For atmospheric chemistry, the main concern related to land transport derives from emissions of
6 nitrogen oxides (mainly $\text{NO}_x = \text{NO} + \text{NO}_2$), non-methane hydrocarbons (NMVOC) and carbon
7 monoxide (CO), which are precursors of ozone and thus affect the oxidizing capacity of the
8 atmosphere. Through their impact on OH they also affect methane, constituting a secondary,
9 longer-lived effect on climate. In contrast to the impact from shipping and aviation, there have
10 been only few publications focusing on global chemical and climate effects of road emissions
11 (e.g. Granier and Brasseur, 2003; Grewe 2004; Niemeier et al., 2006, Matthes et al., 2007). The
12 main chemical mechanisms of relevance to road emission assessments are summarised in the
13 following paragraphs.

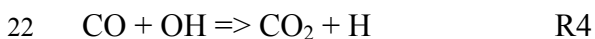
14

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



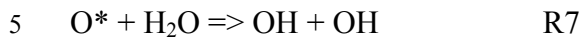
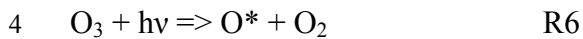
19

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



24

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



6 [Add here Figure 8]

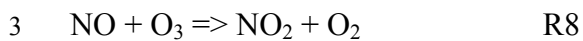
7

8 OH is the main oxidizing agent in the atmosphere, reducing the concentration of CO and CH₄ but
9 also of most other gaseous pollutants. OH can be enhanced by road transport not only due to the
10 ozone enhancement but also directly due to NO_x emissions that move the HO₂/OH balance
11 towards OH. Since CO and CH₄ have lifetimes of about 2 months and 10 years, respectively,
12 they constitute a longer-lived effect of road traffic emissions and can transport the signal over
13 large distances. Enhanced CO and CH₄ levels in turn can reduce OH in remote unpolluted areas.
14 As stated in Niemeier et al. (2005) the sign in the OH perturbation by road traffic is determined
15 by the ratio between the intensities of NO_x and CO perturbations. NO_x perturbations enhance
16 OH, while CO emissions reduce it. The absolute changes in the zonally averaged OH
17 concentration resulting from the extensive use of automobiles is thus relatively limited (Granier
18 and Brasseur, 2003).

19

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

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



4
5 which can lead to a local reduction of ozone in high NO emission areas. However, further
6 downwind from road traffic or in case of direct NO₂ emission from vehicles with particle filters
7 ozone is increased. Due to the dependence of reaction R1 on sunlight the ozone production from
8 road traffic is much larger during summer, while in winter ozone net reductions can occur
9 through ozone titration by the emitted NO.

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



14
15 This reaction can counteract the OH enhancement due to NO_x emissions from road traffic,
16 especially under low-sunlight conditions. According to Granier and Brasseur (2003) surface OH
17 decreases substantially in January in response to automobiles and trucks emissions in the highly
18 polluted regions of Europe and North America where the background nitrogen oxide level is so
19 high that additional NO_x tends to convert substantial quantities of HO_x into nitric acid.

20
21 Other minor effects of road traffic emissions exist with respect to heterogeneous chemistry
22 through emissions of particles and to stratospheric ozone depletion through the slowly expiring
23 emission of CFCs from MAC in vehicles. Long-lived CFCs are transported into the stratosphere
24 where they are decomposed by sunlight into inorganic chlorine, in part present as Cl and ClO
25 radicals that cause catalytic ozone depletion through

1



4

5 Most of the stratospheric inorganic chlorine is present as so-called reservoir species, HCl
6 (hydrochloric acid) and ClONO₂ (chlorine nitrate), which themselves do not destroy ozone.
7 However, heterogeneous processes, e.g. on Polar Stratospheric Clouds, which are present under
8 very cold conditions in the Arctic and Antarctic stratospheres, convert the reservoir species back
9 into less stable components that during spring are readily decomposed into Cl and ClO by
10 sunlight, leading to severe ozone depletion. Current research in regard to chlorine chemistry has
11 concentrated on the role of the ClO dimer (ClOOCI) which, according to a recent publication of
12 Pope et al. (2007), appears to be more stable than previously suggested, thus implying a smaller
13 role of chlorine for stratospheric ozone depletion as less ClO radicals are released.
14 HFC-134a, which has replaced CFC-12 in new MAC, has a much shorter lifetime (~14 years)
15 because it reacts with OH in the troposphere. Its effects in the stratosphere are thus much less
16 pronounced.

17

18

19 **3.2 Impacts on global atmospheric composition and chemistry**

20

21 *Key species and model approach*

22 Long-lived or longer-lived emissions like CO₂, methane and halocarbons as well as short-lived
23 species like carbon monoxide, nitrogen oxides and non-methane volatile organic compounds
24 (NMVOC) both can lead to changes in the global atmospheric composition. Here, we focus on
25 chemical impacts of short or medium lived gases. Radiative forcing impacts are discussed in

1 section 4. As we saw, their emission influences the formation of secondary pollutants and
2 oxidants like ozone, the hydroxyl radical (OH), the NO_x reservoir species PAN and methane.
3 Carbon monoxide and methane are depleted by OH but still have a relatively long life-time. The
4 background of the OH depleting carbon monoxide is enhanced by many fossil fuel related and
5 biomass burning sources. Therefore, CO emissions from land transport are less significant, on a
6 global scale although not negligible and clearly higher than for other transport sectors. Transport
7 emissions of NO_x and NMVOC have a substantial influence on O₃ and OH, and also on methane
8 through the reactions described in 3.1.

9
10 Since impacts of land transport add to or interact with impacts from other sources, they cannot be
11 directly measured in the real world but have to be estimated from models. Only few calculations
12 have been carried out so far (Niemeier et al., 2006; Matthes et al., 2007), the most recent in the
13 EC QUANTIFY project. We discuss QUANTIFY results being aware that **they are not based on**
14 **the most recent emission datasets presented in section 2, but on an older dataset shown in Table**
15 **10.**

16 [Add here Table 10]

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

21
22 In order to estimate the impacts of transport emissions against the background of all natural and
23 anthropogenic emissions, "base case" model runs have been carried out including all emissions.
24 The base case is compared with a "perturbed case" model run in which the transport emissions
25 are reduced by 5% (Hoor et al., 2009). For some estimations, the results from this 5%

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

7

8 **[shall the following paragraph be deleted?]**

9 The uncertainty of data for NO_x emissions is on average within the range of 30-40% depending
10 on the region. Uncertainties for CO can range from 30% in OECD countries to about 60% (this
11 publication, [table 4](#), non-OECD countries; Matthes, 2003).. **[changed for consistency with**
12 **uncertainty values in 2.1, reviewer remark LN]** The NO_x contribution from road traffic, which is
13 most pronounced in the Eastern US, central Europe and Far East Asia, is a globally important
14 factor for atmospheric chemistry. Emissions from ocean going ships, as explained in Eyring et al.
15 (2009), make a comparable contribution over the oceans. NO_x has a larger contribution relative
16 to CO for example in India and Eastern Europe. This is most likely due to a less established use
17 of catalysts and less pronounced NO_x reduction in these regions. **[The paragraph until here**
18 **does not describe impacts but is explanation of emissions. Please tell, if you regard deletion**
19 **as reasonable.]**

20

21 *Impacts on ozone*

22 The impact of transport emissions on global ozone is presented in [Figure 10](#) measured as the
23 difference in the concentrations between the base case and the perturbed case.

24 [\[Add here Figure 10\]](#)

25

1 Based on the 5% perturbation of road traffic emissions highest sensitivities in the northern
2 hemisphere can be up to 0.18 DU in summer and 0.07 DU in winter. If a linear scaling of this
3 modeling results to 100% would be applicable (this is questionable because of the non-linearity
4 of the chemistry) this would mean for the total road traffic contribution up to 3.5 Dobson Units
5 (DU) in summer and up to 1.4 DU in winter. The results are of a similar magnitude compared to
6 respective values of 5.2 DU and 2.1 DU found by *Matthes* (2003) based on emission data from
7 1990 with higher NO_x. Changes in the Southern Hemisphere are weak and probably due to
8 interhemispheric transport in phase with the Northern Hemisphere. On a global average land
9 transport contributes relatively strongest to the total ozone column in the NH summer in
10 industrialised regions with dense transport (Eastern US, Europe, Near East, Japan). The strongest
11 impact is seen in regions where at least two relevant factors come together: a large car fleet,
12 limited control of air pollution, dry and sunny weather conditions. Such regions are Italy, Eastern
13 Europe and the Near East. This is because ozone formation depends on photolysis and the OH
14 concentration. Both are higher in the NH summer. The chemistry of hydrocarbons has in many
15 cases an additive influence (*Matthes*, 2003). In the dark winter months, however, the
16 contribution of land transport to ozone formation is minor. The deviation between different
17 models is in the range of 15-30% for the most affected regions.

18
19 A remarkable result of the models shown in **Figure 11** is that the impacts of road traffic extend
20 from the boundary layer to the free troposphere and even to the Upper Troposphere - Lower
21 Stratosphere (UTLS) region. Although in the UTLS region (250 hPa layer, 11 km altitude)
22 aircraft emissions dominate the traffic impact, road emissions can reach a similar magnitude in
23 summer. Ship emission impacts, in contrast, are more strongly confined to the planetary
24 boundary layer (PBL) because of less vigorous convection, which is much stronger over land,
25 especially during summer. Ozone is transported from the source regions to the free troposphere

1 and UTLS region where its contribution to climate change is strongest. Therefore, it is more
2 meaningful for the illustration of the climate effect to show the total tropospheric ozone column
3 rather than ozone changes in the PBL.

4 [Add here Figure 11]

5

6 The relative contribution of road traffic emissions to atmospheric ozone, again if lineary scaled
7 from a 5% perturbation, reaches about 2-6% zonally averaged in the Northern Hemisphere
8 troposphere in July. Maxima are in the lower troposphere mid-latitudes. Matthes et al., 2007
9 found values twice as high (4-12%), but again based on emission data of the year 1990. They
10 also mention that calculated NO_x tends to be overestimated in their model compared to the
11 observed values in high NO_x regions. Differences between the model and observed values of the
12 NO_2 columns are 15-30%. Furthermore, we need to consider that during the period from 1990 to
13 2000 many relevant emissions (NO_x , CO and NMVOC) have been reduced in large parts of the
14 industrialised world due to the widespread use of catalytic converters.

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

22

23 *Impacts on OH*

24 As for OH concentration, moderate changes in the monthly average are modeled for a perturbed
25 system. While ozone is generally increased by transport the impact on OH can vary in sign. In

1 the NH winter road traffic emissions slightly decrease the OH concentration due to emissions of
2 CO and NMVOC. Both are direct sinks for OH. However, the difference between the perturbed
3 case and the base case is less than 1%.
4 In NH summer the OH concentration is clearly increased, in particular over high traffic regions.
5 This increase is 2-4% in the mid troposphere and close to the boundary layer between 20° and
6 60° North if scaled to 100% (reaching about 0.18% or $5 \cdot 10^3$ molecules/cm³ for a 5%
7 perturbation). The reason is that OH is more effectively recycled by NO_x due to the photolysis of
8 NO₂ and additional OH is formed from photochemically produced ozone, in particular in
9 summer. On the other hand, the OH production is less sensitive to perturbations at the high NO_x
10 levels in polluted regions, since the reaction of OH with NO₂ is also a sink for OH (Lelieveld et
11 al., 2002). Therefore, in the clean marine boundary layer emission from ship transport lead to
12 higher OH formation per molecule NO_x than road transport does. In summer, the reducing effect
13 of CO is relatively weak and minor compared to that of NO_x. Varying OH concentrations lead
14 also to changes in the methane lifetime as discussed in section 4.1. According to a simple
15 estimate ignoring feedbacks and non-linearities road transport could reduce the methane lifetime
16 by 1.6% (Hoor et al. 2009).

17
18

19 **3.3 Impacts on and of aerosols**

20

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

23 For black carbon (BC) and organic carbon, the contribution of road transportation to the global
24 burden of these aerosols was calculated in the Quantify project from yearly simulations using a
25 global aerosol/chemistry model INCA (Interactions of Chemistry and Aerosols) coupled with a
26 global simulations model LMDZ4. Black carbon and organic carbon are transported in the

1 accumulation mode, 20% of the black carbon is considered as soluble whereas 80% is treated as
2 insoluble upon emission. As the aerosol ages, the insoluble BC becomes soluble with an e-
3 folding lifetime of 1.1 day. Organic carbon is treated in the same way but the soluble and
4 insoluble fractions amount to 50% upon emission.

5 In order to analyze the fraction of the BC and particulate organic matter (POM) emitted from
6 road transportation two simulations were conducted by nudging ECMWF [this is not
7 understandable for non-experts] winds in the model for 14 months including the whole year
8 2000, the model was nudged to. The two first months of the simulation prior to 2000 were used
9 as the spin-up period for the aerosol fields and the results presented come from the 12 following
10 months.

11
12 Since sulphate is produced from sulphur dioxide oxidation and in-cloud chemistry, we also
13 present in addition to carbonaceous aerosols, the SO₂ budget in Table 11. A substantial fraction
14 (9%) of the total black carbon emitted is attributable to road transportation, from which 98.7% of
15 the BC produced comes from diesel from road and freight traffic whereas only the remaining,
16 1.3%, comes from gasoline. Figure 12 illustrates the area with maximum BC atmospheric
17 content which are contributing to the overall aerosol burden: Western Europe, Asia in particular
18 over India and Eastern Asia, Northeastern United States.

19 [Add here Table 11]

20 [Add here Figure 12]

21

22

23

24 **3.4 Effects on visibility, clouds and cloudiness**

25

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

8
9 In connection to the dramatic increase of vehicles in Chinese cities in the 1990s the deterioration
10 of visibility is analysed by Song et al. (2003a). Following Tang (2004), the number of vehicles
11 on roads increased in this period very rapidly, especially in medium-sized and large cities. In
12 Beijing it was by a factor of 4, from 0.5 million in 1990 to 2 million in 2002. Moreover, cars in
13 China have usually significantly higher emission factors than cars in developed countries,
14 because lower emissions standards for automobiles are applied. Direct inverse correlation
15 between visibility and concentrations of PM_{2.5} during the period 1999–2000 for every season is
16 shown in Song et al. (2003b) [Which concrete changes in visibility have been measured?] as well
17 as on an hourly basis for selected episodes by Bergin et al. (2001). Source apportionment of fine-
18 particle pollution based on a measurement campaign and a modelling study for selected sites in
19 Beijing (Zhang et al., 2004) provides evidence of road transport impacts: about 15% of PM_{2.5}
20 from mobile sources accompanied by about 21% of secondary road dust.

21
22 Faber (2002) identified visibility effects of emissions from road transport in addition to common
23 environmental impacts such as building soiling, material corrosion, crop damage and health
24 effects as major ones as well. The study attributed costs caused by air pollution assessing the
25 effects of the emissions on local and regional air concentrations and quantifying the resulting

1 health and environmental impacts in monetary terms. This approach suggests that the marginal
2 air pollution cost per vehicle kilometre is between three and eight times higher in urban areas,
3 when compared to rural areas (Faber, 2006). NPRI (2006) is addressing the issue of road dust
4 impact to the environment, with respect to the visibility problem emphasising the role of PM_{2.5},
5 which is close to the wavelength of the visible spectrum and thus affecting not only the visibility
6 range, but the colour, clarity and contrast of scenes (Malm, 2000, Malm et al., 2000).

7
8 Recently, the MILAGRO project has been studying extensively the environmental impact of a
9 megacity urban environment at regional scale. Many observational campaigns were performed
10 combining in situ measurements with flight and satellite observations with emphasis to Mexico
11 City and Veracruz covering the period of March 2006. The studies were concentrated mainly on
12 the air composition in urban plumes, chemical reactions affected by the solar radiation, aerosols
13 and their impact on radiative transfer etc. Detailed measurement of the aerosol composition with
14 its PM_{2.5} fraction is described by Moffet et al. (2007). Stone et al. (2007) provide source
15 apportionment analysis and conclude that during MILAGRO motor vehicles account for about
16 47% of the ambient organic carbon at the urban site and 31% at the peripheral site. Another
17 project for the Houston-Galveston-Brazoria area representing a coastal city of about 4 million
18 people is analysing similar effects in connection to the maritime environment (RSST, 2006).
19 Following Schwarz et al. (2007) the black carbon heating effect due to an about 25%
20 enhancement of BC absorption is not large enough to impact the tropospheric stability
21 significantly in the HGB area, but it might play some role in bigger megacities like Mexico City
22 or New York area. The simulation of the heating effects on life cycle of cumulus clouds was
23 performed by Zhao and Austin (2005) using LES techniques implying the impact of temperature
24 and vertical velocity changes on cloud elements depending on their height and saturation. The
25 real impact of aerosols included in similar computation by Jiang and Feingold (2006) for warm

1 convective clouds is shown to be different for the case of direct effects included or not. There is
2 negligible effect on cloud fraction and cloud depth when only indirect effects are taken into
3 account, but the optical depth of clouds is increasing with higher droplet concentration. When
4 direct effects and the dynamical coupling are included, the blocking of solar radiation, the further
5 cooling of the surface and heating of aerosols contribute to the stabilisation of the atmosphere.
6 This results in a decrease of the cloud fraction and cloud depth. These effects play a much more
7 significant role than aerosol-cloud processes themselves.

8

9

10 **3.5.3.5 Effects on regional and local air quality**

11

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

17

18 *Urban scale*

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

25

1 Particles: In urban conditions, the particle size distributions vary rapidly in shape and magnitude
2 following the instantaneous traffic variation and local meteorology.
3 The number size distribution is influenced by coagulation, condensational growth, plume
4 dilution, and vertical mixing during transport from the street to the urban background (Turco and
5 Fangqun, 1999). The total particle number measured in urban areas often correlates well with
6 NO_x and shows a distinct diurnal variation, indicating a common traffic source (Ketzler et al.,
7 2004; Hussein et al., 2004). Traffic emissions are able to affect submicron particle number
8 concentrations around major roads and may be a dominant source of ultrafine particles in the
9 urban atmosphere (Despiau and Croci, 2007; Rodriguez et al., 2007). For example, one hour
10 after a traffic peak at street level significant increases (bursts) in concentrations of particles
11 around 30 nm have been reported. Exhaust emissions affect mostly the particulate matter load in
12 the fine mode, while wear of the road surface is an important factor for the highest
13 concentrations in the coarse mode (Manoli et al., 2002). The contribution to particulate mass
14 ranges from place to place from a few percent up to 80% (Almeida et al., 2005; Johansson et al.,
15 2007). It was also found that the traffic contribution in the coarse size fraction (1.9-72 µm) was
16 approximately 80% up to 150 m from the road, it dropped abruptly by a factor of 2 over a
17 distance of 150-200 m and declined further to 20% at 1500 m from the road (Wrobel et al.,
18 2000).

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

23

24 Gaseous species: Gaseous species are often monitored in air quality networks and also
25 investigated in many single studies. Jimenez et al. (2003) demonstrated that the spatial and

1 temporal distribution of CO and NO_x follows that of the traffic, while Pfeffer (1994) and Perrino
2 et al. (2002) showed that the mean concentrations of gaseous pollutants at a very busy junctions
3 are considerably higher than those of areas that are not directly affected by road traffic. Ambient
4 volatile organic compound (VOC) levels are mainly affected by motor vehicle emissions where
5 high levels of aromatic hydrocarbons (toluene, benzene and xylenes) have been detected and
6 associated with diverse public transport systems (Velasco et al., 2007; Muezzinoglu et al., 2001).
7 Traffic-related hydrocarbons (m, p, o-xylenes, toluene, ethene, propene) were found to be
8 responsible for the generation of ozone impacts above 50 ppbv (Rappenglück et al., 2005).
9 Polycyclic Aromatic Hydrocarbons (PAHs) observed concentrations were found to be associated
10 predominantly with emissions from road traffic although other sources such as fuel oil, coal
11 combustion, and incineration contribute as well (Marr et al., 2006; Harrison et al. 1996). The
12 traffic contribution of PAHs to busy street air was estimated to be up to 90% on working days
13 and 60% during weekends and its contribution to the city background air was estimated to be
14 40% (Nielsen, 1996). In the same study, the PAHs contribution from diesel vehicles was about
15 2/3 of the total PAHs traffic contribution.

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

18

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

23 [Add here Figure 9]

24

1 Night and early morning depletion of ozone are explained by the increase of NO traffic
2 emissions. Hourly modelling using a simple constrained chemical model showed that the
3 NO₂/NO_x emissions ratio from road traffic has increased markedly from a mean of about 5–6
4 vol% in 1997 to about 17 vol% in 2003 (Carslaw, 2005). It was shown that besides from high
5 background ozone the increased use of continuous regeneration diesel particle filters (CRT)
6 contribute to the increasing trends in the NO₂/NO_x emissions ratio. Such filters require excess
7 NO₂ for regeneration and prevent at the moment that the NO_x problem and the particle problem
8 can be tackled in parallel.

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

14

15 *Regional scale*

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

1
2
3

4 **3.6 Impacts on health**

5

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

14 Humans are also indirectly affected by damages to soils, ecosystems, vegetation, crops and water
15 sources due to deposition of acidifying or eutrophying nitrogen species, as well as heavy metals
16 incorporated into PMs and/or by negative impacts of high tropospheric ozone levels. Finally, by
17 its capacity to induce climate change, traffic-related CO₂, O₃ and halocarbons are likely to affect
18 human health by climate change-related exposures. Such may be increases in heat waves, floods,
19 storms, fires and droughts, with the consequences of malnutrition as well as the migration of
20 some infectious diseases (IPCC AR4, 2007). Due to increasing knowledge about health effects of
21 air pollution, these effects are a bigger global issue today than they were in 20th century (Juda-
22 Rezler, 2006).

23 Evidence on health impacts has been gathered through numerous studies conducted by scientists
24 of various disciplines and published since the late 1980's (Pope, 1989, 2000; Pope et al., 1995,
25 2002; Brunekreef et al., 1995; Brunekreef & Holgate, 2002; Brunekreef & Forsberg, 2005;
26 Zmirou et al., 1998; Jędrychowski, 2000; Nyberg et al., 2000; Schwartz, 2000; Peters et al.,

1 2000, 2001; Katsouyanni et al., 2001; Hoek et al., 2002; Leikauf, 2002; Brook et al., 2004;
2 Boldo et al., 2006, Næss et al., 2006). The results of such studies have been condensed and
3 comprehensively evaluated in several WHO publications (WHO, 2000, 2002, 2005a+b) and in
4 relation to land transport impacts in WHO 2003; Krzyzanowski et al. (2005) and WHO 2006. It
5 is now possible to quantitatively assess and estimate the burden of the pollution both on a global
6 and on a continental scale (Medina et al., 2002). Furthermore, updated guidelines have been
7 released for PMs, O₃, NO₂ and SO₂ (WHO, 2005a). According to WHO estimates more than 2
8 million premature deaths each year are attributed to urban outdoor air pollution and indoor air
9 pollution from the burning of solid fuels. More than half of them are occurring in developing
10 countries (WHO, 2005b). A comparison with other leading risk factors is given in **Figure 15**.
11 **[Add here Figure 15]**

12
13 A large number of epidemiological studies demonstrated that the exposure to most of air
14 pollutants was related to respiratory and cardiovascular diseases. Some of them are also
15 carcinogenic. The observed symptoms range from modest temporary changes in the respiratory
16 tract and impaired pulmonary function, to illness requiring hospital admission and increased risk
17 of death from cardiovascular and respiratory diseases or lung cancer. The sensitivity in the
18 population varies. Most at risk are children, the elderly, and persons with respiratory, heart and
19 circulatory diseases. Asthma as well as chronic obstructive pulmonary disease (COPD) represent
20 nowadays a considerable health problem in industrialised countries. A recent study by Næss et
21 al. (2006) investigates the concentration-response relation between NO₂ and PMs and cause-
22 specific mortality in Norway. It shows that both pollutants effect cardiovascular causes, lung
23 cancer and COPD in different manner. Health impacts were particularly strong for COPD,
24 showing linear effects, while cardiovascular causes and lung cancer seemed to have threshold
25 effects. Moreover, controlled human exposure studies and animal experiments indicate, that

1 transport-related air pollution can increase the risk of intensified allergy reaction. The exact
2 components responsible for the allergic response remain still unknown, although NO₂ and O₃
3 have been linked to it (Krzyzanowski et al., 2005).

4 Many pollutants are of primarily local or regional importance. For example, CO affects human
5 health at relatively high concentrations in hot spots of urban centres. Impacts of benzene and
6 PAHs are also local, with the exception of PAHs bounded to PMs. The SO₂ emission from land
7 transport is now so low that it can be neglected. NO_x, can be transported for long distances via
8 carriers like PAN, but it has its most significant health impacts at urban to regional scale.

9
10 In contrast, particles and ozone can also be relevant for global scale health effects because of
11 high concentrations and relatively long residence time in the atmosphere. Furthermore, despite
12 substantial cuts in emissions across Europe, the PM and O₃ background values have not been
13 improving since 1997 (EEA 2007).

14
15 Particles: Out of all known air pollutants excluding dioxins, the strongest health effects are
16 currently assigned to PMs (e.g. Ibalid-Mulli et al., 2002; Pope et al., 2002; Kappos et al., 2004;
17 Dominici et al., 2006). PMs are generally monitored as PM₁₀. However the levels of the finer
18 fraction PM_{2.5}, if measured, give a better indication of the PMs health effects. Particulate matter
19 is a complex mixture of organic and inorganic components and differs in physical properties and
20 chemical composition. These properties as well as substances that adhere to PMs surface (as e.g.
21 PAHs) influence their harmfulness. PMs are directly emitted from fuel combustion in automobile
22 engines (primarily diesel engines) and from brake wear. They are also formed as secondary
23 products of combustion belong to the *fine* (PM_{2.5}) and *ultrafine* (PM_{1.0}) fractions. PMs generated
24 from road and tyre wear belong to the so-called *coarse PMs* (with a diameter between 2.5 and 10
25 μm – PM_{2.5-10}). PMs lifetime in the atmosphere differs significantly with their size. PM_{0.1} have

1 lifetimes from days to weeks and thus can be transported up to thousands of kilometres; the
2 lifetime of $PM_{0.1-2.5}$ is in the order of weeks to months - which allows them to travel over
3 continents. In consequence, $PM_{2.5}$ can affect people living far from their emission source. The
4 coarse PMs are more easily deposited by sedimentation and thus have rather local to regional
5 impacts. Primary $PM_{2.5}$, which have been found to have considerable inflammatory potency,
6 usually contain crustal material, fugitive suspended dust, organic and elemental carbon (soot),
7 inorganic ions (such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} and Cl^-), and heavy metals. Secondary $PM_{2.5}$ consist
8 mainly of SOA as well as sulphate and nitrate salts, which show lower toxic potency. Some PMs,
9 which contain As, Cr, Ni, Pb or those which bound specific PAHs (e.g. benzo-(α)-pyrene), are
10 carcinogenic. Nitrated polyaromatic hydrocarbons (nitro-PAH) include the most carcinogenic
11 substances known to man and can be found in diesel exhaust fumes.

12
13 Many European and US studies have shown that when the concentration of PMs rises, even from
14 low levels, there is a rise in mortalities from respiratory, cardiac and circulatory diseases as well
15 as a rise in the number of bronchitis and asthma attacks. Even exposure to low PMs levels for
16 long periods is considered harmful. $PM_{2.5}$ are believed to be the most harmful, because when
17 inhaled they can penetrate deep into the lungs. In particular, the effects of long-term PMs
18 exposure on mortality (life expectancy) seem to be attributable to $PM_{2.5}$ rather than to coarser
19 particles (Brunekreef & Forsberg, 2005; WHO, 2006). Relative risks (RR) for selected pollutants
20 estimated in meta-analysis studies prepared by WHO (Anderson et al., 2004) are presented in
21 **Figure 16**. Within the framework of the CAFE programme the loss of life expectancy due to
22 anthropogenic $PM_{2.5}$ has been assessed. For this purpose RR identified by Pope et al. (2002) for
23 500,000 individuals in the US have been transferred to the European situation and modelled
24 annual average $PM_{2.5}$ concentrations (Amann et al., 2004; WHO, 2006). The average loss of life
25 expectancy due to $PM_{2.5}$ in 2000 was estimated at 8.6 months in Europe, varying from around 3

1 months in Finland to 12-36 months in Benelux, Silesia and the Po Valley. The total number of
2 premature deaths was estimated to be 348,000 in the 25 EU countries.

3 [Add here Figure 16]

4

5 Ozone: Elevated levels of background ozone as well as high ozone levels in urban areas are
6 caused by precursor emissions from road traffic (Nilsson *et al.*, 2001a; Nilsson *et al.*, 2001b;
7 Mott *et al.*, 2005). Negative consequences for health are respiratory diseases. There are also
8 indications for increasing mortality, as well as premature mortality (*e.g.* Mudway and Kelly,
9 2000; Gryparis *et al.*, 2004; Bell *et al.*, 2005; Ito *et al.*, 2005; Levy *et al.*, 2005; Bell *et al.*, 2006).
10 Tropospheric O₃ causes eye irritations and irritations of the airways. The latter can lead to a
11 reduction in lung capacity, even at relatively low concentrations. Due to its low solubility in
12 water it can penetrate deep into the lungs. The exposure to O₃ is also linked with allergy
13 development as well as with aggravation of allergic reaction (Krzyzanowski *et al.*, 2005). As the
14 amount of O₃ an individual is exposed to depends on the time spent outdoors, children and
15 people working outside are most at risk. Although health impacts of ozone have been less
16 investigated than of PMs, existing European studies show convincing, though small, positive
17 associations between daily mortality and ozone levels, independent of the effects of PMs (see
18 [Figure 16](#)). Similar associations have been observed in North America as well (WHO, 2005).
19 Hemispheric background concentrations of tropospheric ozone vary in time and space but can
20 reach average levels of around 80 µg/m³. Based on time-series, the number of attributable deaths
21 brought forward can be estimated at 5-9% for daily exposures above the estimated background
22 (WHO, 2005). At concentrations exceeding 240 µg/m³ (EU alert threshold for O₃) both healthy
23 adults and asthmatics would experience significant reductions in lung function as well as airway
24 inflammation.

25

1

2 **4 Radiative forcing and impacts on climate**

3

4 **4.1 Greenhouse gases**

5

6 The different changes in greenhouse gases that are due to land transport are briefly reviewed in

7 this section and supplemented with results from recent literature and the QUANTIFY project.

8 Quantify estimates are based on 5 different models. For each of them land transport emissions

9 haven been decreased by 5% and results are obtained by an extrapolation to 100% (see also

10 section 3.3 of this report).

11

12 *Carbon dioxide*

13 The main impact of land transport on climate comes from carbon dioxide (CO₂). Due to its long

14 atmospheric residence time CO₂ is well-mixed throughout the troposphere and the stratosphere.

15 As the current emissions from land transport are almost three times as large as the emissions

16 from the aviation and shipping sectors combined (Eyring et al., 2005), its relative contribution to

17 radiative forcing is significant. The long residence time of CO₂ also requires that the historical

18 development of emissions be taken into account when calculating the contribution to CO₂

19 enhancement and thus the radiative forcing at a given point in time. The current radiative forcing

20 by CO₂ is estimated by IPCC (2007) to be 1.66 W/m², based on a total increase of nearly 100

21 ppmv since preindustrial times. Schultz et al. (2004) estimate that surface transport (including

22 maritime shipping) by the year 2000 had contributed 17.4 ppmv to the CO₂ increase, which

23 would translate into a radiative forcing of nearly 290 mW/m². In a recent study Fuglestedt et al.

24 (2008) calculated a value of 150(±17) mW/m² from road transport and 21(±3) mW/m² from rail

25 traffic. Indirect emissions related to rail traffic (production of electric power) add another 3.8(±1)

1 mW/m². In comparison, they obtain best estimates of 35 mW/m² and 21 mW/m² for the shipping
2 and aviation sectors, respectively.

3
4 Future radiative forcing for a given point in time will depend on the time evolution of emissions,
5 which in turn will reflect future policies, technologies, and economic growth. More accurate
6 statements can be made for the future impact of current emissions on a given time horizon.
7 Integration of the radiative forcing over a future time horizon for a one-year pulse of current
8 global emissions can be used to compare the impact of different climate gases in units of
9 (W/m²)·yr (see IPCC, 2007; their Fig. 2.22). The contribution of each climate gas depends on the
10 chosen time horizon and becomes relatively more important on longer time horizons in the case
11 of a long-lived gas such as CO₂. For a detailed discussion compare also ME08. Fuglestvedt et al.
12 (2008) use emissions from the EDGAR data base for 2000 and calculate that, on a 100-year time
13 horizon, the contribution from CO₂ is nearly 400 mW/m² yr for road transport, compared to
14 about 100 mW/m² yr for shipping and aviation combined. Their shipping emissions are based on
15 own calculations consistent with Endresen et al. (2007) and their aviation emissions from Eyers
16 et al. (2004).

17

18 *Ozone:*

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

1 Niemeier et al. (2006) applied a chemical transport model and emissions from the POET (Olivier
2 et al. 2003) and EDGAR-3 (Olivier et al., 2001) databases to calculate an ozone-related radiative
3 forcing of 50 mW/m². Fuglestvedt et al. (2008) obtain 54(±11) mW/m², compared to a best
4 estimate of 22 mW/m² from aviation and 32 mW/m² from shipping. The rail sector contributes
5 another 2 mW/m² according to their study. They also note that the radiative forcing per ozone
6 burden change is larger for land transport than for shipping, probably because of more efficient
7 vertical mixing occurring over land areas that extends the ozone increase towards higher
8 altitudes. (3.3 cross section [Figure 11](#))

9
10 In QUANTIFY, the perturbed ozone fields were provided for detailed radiative forcing
11 calculations (Myhre et al., 2008). [Table 12](#) shows results for the different models translated into
12 the effect of total road emissions, subdivided into long-wave, short-wave and net components.
13 Four models perturbed road emissions by a small amount to assure linearity and scaled the
14 modeled changes in ozone to a 100% change in road emissions. The E39C model (G. Myhre,
15 pers. Comm.) used an alternative method as described in Grewe (2007). The range of results
16 must be seen as a measure of uncertainty in current model studies of this kind.

17 [\[Add here Table 12\]](#)

18
19 For future radiative forcing from ozone change, Fuglestvedt et al. (2008) obtain about 50 mW/m²
20 yr for road emissions on a 100 year horizon, about as large a value as for aviation and shipping
21 combined. Given the relatively short lifetime and inhomogeneous distribution of ozone, future
22 changes in spatial emission distributions will alter the radiative forcing per ozone burden change,
23 as ozone production efficiency, ozone lifetime, and its radiative forcing efficiency vary in space.

24

25 [\[inserted from former 3.4\]](#)

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[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]

1 Moreover, modern air condition systems are in general expected better sealed than the older
2 ones, implying less need for refilling during the lifetime of the vehicle. Replacement of HFCs
3 with CO₂ in the next generation of cars implies reduced emissions in terms of CO₂-equivalents
4 due to the relatively lower GWP value of CO₂ compared to CFCs and HFCs. Comparable figures
5 are not available for road duty vehicles.

6
7 This means that the threat for the ozone layer derives primarily from banks of CFC-12. Banks
8 are the total amount of substances contained in existing equipment, chemical stockpiles, foams
9 and other products not yet released into the atmosphere. Because of the long atmospheric life
10 time (100 years) and high ozone depletion potential (0.82) of CFC-12 these banks and present
11 emissions will contribute to ozone depletion in the coming decades. CFC-12 makes the largest
12 contribution to stratospheric chlorine levels, about 28% estimated for 1998 (WMO, 1998) and is
13 just about to peak in the atmosphere.

14 [negative radiative forcing due to ozone depletion]

16 *Contribution of air conditioners to global warming*

17 The GWP of CFC-12 is 10900 on a 100-year time horizon, while HFC-134a has a global
18 warming potential of only 1430 (IPCC AR4, WG I, table TS.2) on a 100-year time horizon and a
19 lifetime of 14 years (WMO, 2002, Table 1-6). This is why annual emissions from MAC in CO₂
20 equivalents (CO₂-eq) are estimated to decrease and stabilise at about 280 Tg CO₂-eq per year in
21 2010. For 2003, 612 Tg CO₂-eq are estimated of which 514 Tg came still from CFC-12. These
22 amounts are clearly relevant for global warming. The 700 Tg CO₂-eq from mobile air
23 conditioning in 2002 constitute 17% of the 4300 Tg CO₂ estimated to be emitted by road
24 transport in 2000 (see section 2.2), or 2.7% of the 26.3 Pg CO₂ from anthropogenic fossil fuel
25 use and cement manufacture in 2002 (CDIAC website, Marland et al., 2007). Even when taking

1 into account the expected decrease in emissions, air conditioners would still contribute about
2 10% of the CO₂ equivalents that are due to global transport between 2010 and 2015.

3 [Add here Figure 14]

4

5 It is not sure how MAC are going to develop if there are strong changes in the powertrain
6 technology they are connected with and if Diesel and Otto engines are going to be completely
7 replaced. For the near future a US EPA model study estimates that the global HFC emissions,
8 replacing CFC and HCFC, are going to rise strongly from 117 Tg CO₂-eq in 2000 to 627 Tg
9 CO₂-eq in 2020, of which still more than two thirds are emitted in OECD countries. The MAC
10 shares of emissions in the US (and other Annex I countries) are going to decrease from 36%
11 (47%) in 2005 to 20% (37%) in 2020, but in China and India they are expected to increase from
12 41% to 66% (DeAngelo et al., 2006, section IV.2). Although there are high uncertainties in such
13 projections it seems clear that the impacts from mobile air conditioners remain to be relevant in
14 the future, primarily for climate change and to a much lesser extent for ozone depletion.

15 [merge with global warming and RF discussion from Michael]

16 *CFC/HFC*

17 CFC-12 and HFC-134a, used in mobile air conditioners, lead to radiative forcings of 170 mW/m²
18 and 5.5 mW/m² in 2005, respectively (IPCC, 2007). HFCs emissions will continue to increase
19 until the transition to CO₂ systems will mitigate the contribution from MAC. Therefore, the
20 impact of CFC/HFC from MAC on climate is relevant but will remain small compared to the
21 CO₂ and ozone forcings.

22 On the other hand, the stratospheric ozone depletion (about 3% since 1980) has led to a
23 stratospheric cooling of about 0.6 K per decade and a negative radiative forcing of about -150
24 W/m².

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

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

9

10

11 *Methane*

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

20 [\[Add here Table 13\]](#)

21

22 The models predict reductions in methane lifetime between one and two percent. This impact
23 compared to the total impact from transport is not as large as the fraction of road emissions
24 within the transport emissions. In particular, for road emissions the models calculate a much
25 smaller impact on methane lifetimes than for a corresponding reduction in ship emissions. This is

1 mainly due the high NO_x/CO and NO_x/NMVOC ratios in shipping emissions, and the generally
2 low NO_x levels in marine areas.

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

9

10 *Nitrous oxide*

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

16

17 **4.2 Black carbon, sulphate**

18

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

25 **[Add here Figure 17]**

26

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

9 The authors estimated a direct radiative forcing from preindustrial times of $+23 (\pm 9) \text{ mW/m}^2$ for
10 black carbon and $-12 (\pm 5) \text{ mW/m}^2$ for sulphate.

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

16 Black carbon also affects climate by changing ice and snow albedo. Forster et al. (2007) report
17 an estimate of this effect of $100 (\pm 100) \text{ mW/m}^2$ for all know black carbon emissions.

18

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

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

23

4.3 Climate change and Future Impacts

1
2
3 In 2004, road transport made up for 4.7 Pg CO₂, which is 17% of the global energy-related CO₂
4 emissions and about three quarters of the total transport emissions of 6.2 Pg CO₂ (IPCC AR4,
5 WG III, Chap.5). Current emissions from transport are responsible for 17% of the integrated net
6 forcing over 100 years from all current man-made emissions. Land transport gives a CO₂ forcing
7 of 150 (±17) mW/m² from road vehicles and 25 (±7) mW/m² from rail (direct + indirect), which
8 is together 12% of the total man-made CO₂ forcing since pre-industrial times. Furthermore, road
9 transport is responsible for 15% of the total man-made ozone forcing, about 54 (±11) mW/m²
10 (Fuglestvedt et al., 2008).

11

12 [Add here Figure 18]

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

17 The share in CO₂ emissions of non-OECD countries is 36% now and is expected to increase
18 rapidly to 46% by 2030 (IPCC AR 4, WG III, Chap.5). In Eastern Asia the NO_x and CO₂
19 emissions from road transport doubled from 1990 to 2000.

20 Due to the enormous dynamic in growth just in the recent years and diverse alternative
21 technologies discussed present projections do not dare to give an outlook beyond 2050. But,
22 unless there is a major shift away from current patterns of energy use, total transport energy use
23 and carbon emissions is projected to be about 80% higher by 2030 compared to 2004 values
24 (IPCC AR4, WGIII, Chap.5), most coming from land transport. In 2050, as much as 30–50% of
25 the total CO₂ emissions are projected to come from the transport sector
26 (JRC/CONCAWE/EUCAR, 2006).

1

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

7

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

23

24 It is hardly predictable, to what extent aerosol emissions from road transport will contribute to
25 the global energy balance as part of the direct or indirect aerosol effect. Since the major forcing

1 comes at the moment from black carbon, the present effect is positive. However, particle
2 emissions are highly undesirable due to their negative health impacts. They have already been
3 significantly reduced and will be more reduced according to more strict emission regulations in
4 the near future. The lifetime of particles is short. Therefore, particle impacts are not going to
5 make a large contribution to the long-term positive radiative forcing effects as shown in **Figure**
6 **19**.

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

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

1 GWP if a 100 year time scale is considered and are nearly negligible if the global temperature
2 potential is estimated. For the long term only very long lived GHG play a role: CO₂ and to some
3 extent CFC-12 from air conditioners.

4 [Add here Table 14 + 15]

5 [Add here Figure 19 a + b]

6

7

8 **5 Future developments**

9

10

11 **5.1 Present standards and regulations**

12

13 The European Union regulates land transport-related air emissions by automobile emissions
14 standards (Euro) and by automotive fuel quality standards. Emissions from road vehicles are
15 regulated individually for light-duty vehicles (LDV = cars and light vans) and for heavy-duty
16 vehicles (HDV), i.e. road vehicles heavier than 3.5 tonnes (trucks and buses). A whole series of
17 amendments have been issued to stepwise tighten the limit values. Also non-road vehicles and
18 machinery, as well as two- and three-wheeled vehicles haven been included. The first set of
19 modern European emission standards, Euro 1, entered into force in 1993. Euro standards regulate
20 the emissions of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO) and
21 particulate matter (PM) over a standardised drive cycle and are expressed in mg of pollutant per
22 km (LDV) or per kWh (HDV). All vehicle types must be tested in order to obtain a type
23 approval. At present, emissions of carbon dioxide (CO₂) are not regulated for any type of
24 vehicle.

25

1 For LDV, the emission standard currently in force is Euro 4 (from 2005) defined by Directive
2 98/70/EC. Diesel vehicles are allowed to emit around three times more NO_x than gasoline.
3 Emissions of PM from gasoline vehicles are not regulated since they are very low. For new Euro
4 5 and Euro 6 standards the implementing legislation is under preparation. Euro 5 will put
5 standards for PM, HC and NO_x from 2009 for new models with the main goal of a large
6 reduction of PM emission from diesel cars. Euro 6 is scheduled to enter into force in September
7 2014 and will probably further reduce the emissions of NO_x from diesel cars (Table 9). However,
8 recent studies have shown it might be difficult to comply with the air quality limit for NO₂ due to
9 a higher share of so called "direct NO₂ emissions" that have been observed for modern diesel
10 passenger cars and heavy duty vehicles using some particular technology of particle filter
11 systems (Palmgren et al., 2007). For comparison, the US state of California along with ten other
12 US states, has currently a much tougher NO_x standard of approximately 40 mg/km.

13 [Add here Table 9]

14

15 The current regulations for HDV are set in Directives 2005/55/EC and 2005/78/EC. Euro IV is in
16 force from 2006, Euro V will enter into force in October 2008. It also defines a non-binding
17 standard called Enhanced Environmentally-friendly Vehicle (EEV). In July 2007 the EU
18 Commission presented a proposal for the Euro VI standard and put forward four different
19 suggestions, considering different fuel types, for stakeholder consultation (Elvingson, 2007). The
20 proposed diesel engine standards (EU A to EU D) are compared to the Japanese and US
21 requirements for HDV in Figure 7. Scenario EU A represents the close global harmonisation
22 with forthcoming US and Japanese standards and would require a higher rate of cooled exhaust
23 gas recirculation (EGR) in addition to the use of a more efficient selective catalytic reduction
24 (SCR) system. Other scenarios are less strict and optimise either PM or NO_x or CO₂ emissions,
25 partially at the costs of higher other pollutants.

1 [Add here Figure 7]

2
3 As for fuel quality, common EU specifications for gasoline, diesel and gasoil used in road
4 vehicles, inland waterway barges and non-road mobile machinery have been set by the Fuel
5 Quality Directive 98/70/EC amended by 2003/17/EC Directive. They focus mainly on sulphur
6 and for gasoline on lead and aromatics. Since 1 January 2002 all gasoline sold in the EU is
7 unleaded, while the limit on the sulphur content of gasoline and diesel is 50 ppm since 1 January
8 2005. Recently the EC proposed that from 1 January 2009 maximum sulphur content for diesel
9 and petrol will be lowered to 10 ppm. Also the maximum permitted content of polyaromatic
10 hydrocarbons (PAHs) in diesel will be reduced by one-third, i.e. to 8% by mass.

11 CO₂ emissions are not regulated in the EU so far, but the EC intends to propose legislation
12 forcing car makers to limit average CO₂ emissions from all new cars sold in the EU to 120 g/km
13 by 2012 (EEA, 2007). Car manufacturers (the "ACEA agreement") settled that average CO₂
14 emissions of new passenger cars sold in 2008/2009 will be reduced to no more than 140 g/km.
15 But this goal will hardly be achieved.

18 **5.2 Vehicle technologies**

19

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

1 *Improving drivetrain efficiency*

2 Gasoline engines today are dominated by the homogenous charge stoichiometric combustion
3 process. They work well with a three-way catalyst to reduce air pollutant emissions (Eichlseder
4 and Blassnegger, 2006). Measures to reduce fuel consumption near to mid-term aim to (1)
5 improve part load efficiency (e.g. downsizing with turbocharging, cylinder deactivation), (2)
6 tackle throttle losses by direct injection of fuel and variable valve control, (3) improving high
7 pressure efficiency and (4) address power losses through e.g. friction or auxiliary units. Several
8 studies examined CO₂ reduction of individual measures (e.g. Austin et al., 1999; NRC, 2002,
9 Smokers et al., 2006). Fuel consumption improvements, related to the New European Drive
10 Cycle (NEDC), of up to 25% at the same driving performance for European middle class
11 vehicles have been demonstrated (Fraidl et al., 2007). Fuel economy of diesel engines in real
12 world driving however can not be reached due to thermodynamic reasons. Diesel engines have
13 already been improved in the past, e.g. by direct injection, and therefore offer a lower potential
14 for improvements. Still, downsizing with turbocharging and reduction of friction losses may
15 lower fuel consumption also in Diesel engines.

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

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

1 Hybrid vehicles are available since the 1990ies. In 2006 approximately 400,000 hybrid cars were
2 sold which is less than 1% of the world car production. For the future, an increasing number of
3 hybrid models are announced. The energy savings potential is reported for low hybridisation
4 (start-stop) and driving within cities between 3% and 12% (Japan) and for full hybrid vehicles
5 19% in US Highway cycle and 44% in the US City and NEDC cycle (Schmidt, 2006).

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

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

13 Recovery of waste energy is a way less well explored to improve engine efficiency. Only 25% to
14 35% of the chemical energy in the fuel is converted into mechanical energy by the engine. The
15 rest is lost as heat in the engine cooling system and the exhaust. 1 to 2% can be recovered today
16 e.g. through thermal electric generators (Thacher et al., 2006), fuel economy improvements of up
17 to 5% are projected (Friedrich et al., 2007).

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

20 Light weight construction to lessen vehicle mass is a prominent example, tackling power needs
21 to accelerate and to climb. 100 kg less weight leads to reductions of between 4 to 17 g CO₂/km
22 (Espig et al., 2006). Higher strength steels as well as lightweight materials as Aluminium,
23 Magnesium, glass fibre and carbon fibre reinforced plastics are already used to some extent in
24 vehicle structures today. Further potential to reduce 60 to 120 kg for a mid size car has been
25 shown with additional costs of 100 € to approx. 800 € (SLC, 2007).

1 Rolling resistance depends on the material of the tire, the construction of the tire and the radius,
2 tire pressure and driving speed. Studies indicate that tire pressure should be increased by 0.02 to
3 0.04 MPa which would lower fuel consumption by 1 to 2.5%. Tire industry has proposed new
4 concepts for wheels which are intended to lower rolling resistance until 2030 by 50%.
5 Aerodynamic resistance results from the product of aerodynamic drag (c_w) and frontal area (A).
6 While there is a continuous decrease in c_w , A shows an increase. Regarding average European
7 middle class vehicles, c_w has decreased from 0.35 in 1995 to 0.3 in 2006. Further potential is
8 given by optimising car underside and engine air flow. A c_w of 0.2 seems in reach in the mid
9 term (Schedel, 2007). Lowering of aerodynamic resistance by 10% is feasible at relative low
10 cost. At constant driving at 120 km/h, this would lower fuel consumption by 20%.

11

12 *Alternative drivetrains*

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

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

23 Fuel cell vehicles produce the electricity for propulsion by electrochemical reactions of hydrogen
24 with oxygen. They have their energy stored on board in form of hydrogen or materials to
25 produce hydrogen from. FCVs provide high efficiency for the production of electricity and

1 locally zero emission driving. But they shift emissions to the hydrogen production, depending on
2 the energy source (see also section 7.2). Polymer electrolyte membrane fuel cells (PEMFC) are
3 preferred for vehicle applications due to their high power density, which offers low weight, cost
4 and volume (Neburchilov, 2007; Zhang, 2006). Average drive cycle efficiencies have reached
5 36% equivalent to 4.3 l Diesel/100 km (EDC) (von Helmolt and Eberle, 2007). Major problems
6 to be addressed are durability with cycling of the fuel cell stack (status: 2000 h, target: 5000 h)
7 (Budd, 2006), operating temperature range (status: -20°C, target: -40°C) and cost reductions
8 (status: 120 \$/kWe, target: 25-35 \$/kWe)(DoE, 2007). Hydrogen onboard storage is a further
9 critical issue to provide sufficient driving range. A target of hydrogen storage of 6 wt% on a
10 system basis is generally considered hard to reach (Ross, 2006). Status today is 3-4 wt% (Chalk,
11 2006). Fuel cells can also be used for trains and ships.

12

13 **5.3 Alternative fuels and lifecycle analysis**

14

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

20

21 *Natural gas (CNG, GTL)*

22 Natural gas has about 20% lower CO₂-emissions per MJ fuel compared to gasoline due to its
23 higher content of hydrogen. While until recently average NG fleet vehicles in Europe could save
24 only up to 6% due to less well adopted engine technology (Umierski et al., 2004) more recent
25 vehicles can save up to 19% despite of approx. 200 kg more weight.

1 Conversion of natural gas to synthetic fuels like synthetic Diesel, Methanol, Dimethyl ether or
2 gasoline is another way to use it as an energy source for transport. This leads to very clean fuels,
3 generally lowering air pollutant emissions, but does not contribute to a CO₂ reduction compared
4 to the direct use of natural gas, as there is generally energy lost in the conversion step.

5 *Renewable fuels from biomass and waste*

6 Biofuels offer the benefit of a more or less balanced carbon cycle in contrast to fossil fuels. The
7 CO₂ of biofuels emitted as they are burned, was absorbed from the atmosphere by the plants in a
8 relative short period. However the production process lowers the net benefit, depending on
9 feedstock, production means (e.g. fertilizers etc.) and conversion technologies used.

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

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

17 Biodiesel from oil seeds represents almost 80% of the liquid biofuel produced in Europe in 2006
18 (EurObserv'ER, 2007). Rape seed, and to a lower extent sunflower, palm oil and animal fat is
19 used as feedstock. Since pure biodiesel use is not in agreement with emission regulations the
20 trend is towards blending with conventional diesel up to 5% by volume (EN 590). Best estimate
21 for net reduction in GHG emissions is 37% within a range of 10% to 66% (Edwards, et al.,
22 2007). The technology for more advanced, 2nd generation biodiesel with lower emissions is in
23 the demonstration stage (WSDA, 2007).

24 Biomethane (Biogas) can be produced from a variety of biomass e.g. maize, cereals, sunflower,
25 grass and waste by anaerobic digestion. Optimised methane yield from versatile crop rotations

1 that integrate production of food, feed and energy, are possible (Amon, et al., 2007). Biogas also
2 makes decentralised production possible, which is energy efficient due to saved transports.
3
4 Major barriers for biofuels are higher costs, compatibility with conventional fuels and
5 availability of technology for more advanced biofuels. Moreover, the combination of food, feed
6 and fuel in one crop raises concern on influences of food production and prices, which could be
7 observed already in the case of maize production in Mexico. Although land is available to some
8 extent due to overproduction in some areas, the economic influence is still given. Therefore
9 energy plants, which do not contribute to food production, seem to be better suited for fuel
10 production. Second, in order to improve crop yield, genetic engineering is and will be applied.
11 This however has met scepticism and regulatory hurdles in many countries (Torney et al., 2007).
12 The use of biomass for heat and power generation leads generally to higher GHG reductions than
13 the conversion to transport fuels. However, it has to be recognised that less options exist for
14 liquid alternative fuels for the transport sector.
15 Although biofuels tend to show a positive effect on GHG emissions, several authors warn of
16 hidden costs and adverse impacts on environment and society due to large scale production of
17 biofuels (e.g. Palmer et al., 2007). Many important environmental effects of biofuels seem not
18 well understood or taken into account, e.g. the influence of N₂O emissions (Crutzen et al., 2007).
19 For state-of-the-art life cycle analysis see e.g. Delucchi (2006) or Zah et al. (2007). An overview
20 of net CO₂-eq emissions of alternative fuels is given in **Figure 20**.

21 **[Add here Figure 20]**

22

23 *Hydrogen and electricity*

24 Hydrogen (H₂) as an alternative energy carrier has the advantage that it can be produced from a
25 wide variety of primary energy sources, fossil as well as renewable, e.g. wind, solar-thermal,

1 photovoltaic, tidal/wave energy, geothermal, and biomass and waste. Today, most of the world's
2 hydrogen is produced from natural gas. Hydrogen offers true zero emission at the tail pipe, if
3 combined with fuel cells. If burned in internal combustion engines, only NO_x remains as
4 significant air pollutant emission. Difficulties arise from the storage of hydrogen: energy density
5 of gaseous hydrogen is low by volume, and in liquid form, very low temperatures are needed,
6 which results in a lower overall efficiency and higher costs (Aceves et al., 2006). One of the
7 main obstacles for the broad use of H₂ for transport is the lack of an adequate infrastructure for
8 its distribution and the high costs for implementing it.

9 Electricity in battery electric vehicles is recently discussed as a true alternative to hydrogen. This
10 avoids the energy transformation cascade associate with the use of H₂. Advanced concepts of
11 storing fluctuating renewable electricity in batteries of vehicles connected to the grid are under
12 discussion, but the opportunities are not well assessed at the moment.

13

14 *Life cycle perspective*

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

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

23 'Well-to-wheel' analysis describe an important part of a complete LCA, focussing only on
24 propulsion system and fuel pathways. Several studies have been conducted for different
25 geographic regions and time horizons e.g by Edwards et al. (2007), Choudhury et al. (2002),

1 Mizuho (2004), Schäfer (2006) and Baba (2003). Exemplary results are presented in **Figure 21**
2 showing that potentially car technologies are conceivable which reduce CO₂-eq emissions by
3 about 50%, on the long run even more. However for most technologies their economic viability
4 on a large scale must still be proven.

5 Heavy goods road transport is less intensively assessed.

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

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

14 **[Add here Figure 21]**

15

16 **5.4 Mobility management and policy option**

17

18 *Transport policy and environmental assessment*

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

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

9 **[Add here Figure 22]**

10

11 To achieve a cohesive territory and a proper sustainable development, an interconnected
12 European transport system, based on multimodal corridors, high speed passenger networks and
13 improved traffic conditions, is needed. At the same time, roads must be safer, the transport costs
14 should be transparent, intermodal transport systems must be implemented, the rights and
15 obligation of users should be clearly defined and urban transports should be used in a rational
16 way. As an example, infrastructures should be taxed considering its real direct and indirect costs,
17 including externalities, i.e. indirect consequences for third parties, often for public goods., One
18 of the goals is usually to reduce road transport with its larger harmful externalities especially in
19 the freight sector. **Table 16** shows the cost levels generated by a heavy goods vehicle covering
20 100 km on a motorway in open country at off-peak times. Estimates are made for the costs of air
21 pollution (cost to health and damaged crops), climate change (floods and damaged crops),
22 infrastructure, noise (cost to health), accidents (medical costs) and congestion (loss of time).

23 **[Add here Table 16]**

24

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

7 The contribution of the Strategic Environmental Assessment (SEA), stated by Directive
8 2001/42/EC, should also be considered due to its potential to reduce transport emissions and
9 their impact on air quality and climate change. In transport, SEA is particularly useful in
10 assisting decisions on a multi-modal approach, comparing alternative planning and management
11 options in an integrated way and providing decision-makers with the relevant information to
12 enable them to take the most sustainable decision (European Commission, 1999). The most
13 updated guidance document specific for the transport sector (DG Energy and Transport, 2005) is
14 based on the results of BEACON project (Beacon, final report 2005). The integration of SEA in
15 transport planning was also a major issue of COST 350 (2006). An example of SEA applied to
16 Portuguese High-Speed Rail Network demonstrate that, despite its higher investment when
17 comparing with the traditional railway, it has positive effects such as the decrease of externalities
18 related to accidents, climate change and air quality.

19

20 *Land use and transport planning*

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

1 An integration of land use and transport planning is a key issue to reduce negative environmental
2 impacts from transportation. For example, sprawling of urban areas creates an inefficient land
3 use pattern, generates traffic and often disables public transport systems. Better community
4 planning and more compact development help people live within walking or bicycling distance
5 of some of the destinations they need to get to every day such as work, shops, schools. If they
6 choose to use a car, trips are short. One of the consequences of urban sprawl, intimately related
7 with atmospheric emissions and air quality, is the growing consumption of energy. **Figure 23**
8 presents data from a number of world cities, revealing that there is a consistent link between
9 population density and energy consumption: high energy consumption rates are associated with
10 lower population densities, characteristic of sprawling urban environments. Increased energy
11 consumption is in turn leading to the increase of CO₂ emissions to the atmosphere.

12

13 **[Add here Figure 23 + 24]**

14 **Figure 24** presents the relationship between CO₂ emissions and population density for several
15 European cities. It seems that emissions decrease progressively with the increase of urban
16 densities, although not as evidently as in the case of energy consumption, revealing that other
17 factors such as climate, fuel mix and industry activity are probably more important. A study
18 (Borrego et al., 2006) investigated the effects of different city structures in air quality through the
19 application of dispersion and photochemical models. In this study, in order to nullify the effects
20 from local meteorology and other uncontrolled variables, three cities with distinct urban
21 structures – dispersed, corridor and compact – were idealised. Result shows that the disperse city
22 has the lowest emissions per area and the compact city has the lowest absolute emissions.
23 Research conducted by the UK government has suggested that spatial planning policies could
24 reduce projected transport emissions by 16% over a 20-year period (European Sustainable Cities,
25 1996). Recent research published by the US Urban Land Institute (Ewing et al., 2007) identify

1 compact city development with mixed uses (housing, commercial and industrial developments)
2 as the best way in land pattern changes to reduce vehicle greenhouse gas emissions. It is reported
3 that compact development may reduce the need to drive between 20% and 40% and reduce total
4 transportation-related CO₂ emissions from current trends by 7% to 10% as of 2050.
5 The complexity of the interaction between transport and land-use makes it difficult to find how
6 the system affects human behaviour. The TRANSLAND study has concluded that land-use and
7 transport policies are only successful with respect to reduction of travel distances and travel time
8 and reduction of share of car travel if they make car travel less attractive, i.e. more expensive or
9 slower. On the other hand, transport policies to improve the attractiveness of public transport
10 have in general not led to a major reduction of car travel.(TRANSLAND, 2000)

11 *Mobility management*

12 Mobility management aiming to influence travel choice by encouraging changes in behaviour on
13 the part of organisations and individual travellers is one of the strategies to reduce the amount of
14 road traffic. The desired behavioural changes include more efficient use of vehicles, for example
15 through higher vehicle occupancies or less empty running, a switch to more sustainable transport
16 modes and even increasing teleworking to reduce daily travels where appropriate. Mobility
17 management is so far mainly being applied in a local and regional context focusing on the
18 everyday mobility, especially commuting to work or to school (EC DG Energy and Transport,
19 2004). The benefits of promotion range about a 10-20% decrease in car travel (MOST project,
20 2003).

21 The "Sustainable urban Transportation" project (SUTRA, 2003) developed a consistent and
22 comprehensive approach and planning methodology for the analysis of urban transportation
23 problems that helps to design strategies for sustainable cities. Combining an indicator based
24 approach with simulation models and scenario analysis, socio-economic and environmental
25 impact assessment, and a public information component, SUTRA includes awareness building

1 and educational aspects for citizens and stake-holders participating in urban decision making
2 processes. The effects of the measures included in the scenario definitions demonstrate that no
3 single measure can have a dramatic effects by itself. Only the combination of mobility
4 management and transport planning measures can lead to significant effects.
5 Although transport problems are well identified and their solutions are also known and accepted,
6 there is a lack of action on implementation. Most action plans are still at the pilot stage and are
7 locally applied. Although a precautionary approach is needed in order to avoid negative side
8 effects, e.g. due to increased exposure to air pollution in compact cities, the full implementation
9 of stated policies and measures at regional, supranational and even international scale is expected
10 to have a strong impact on emission reduction and will contribute to the mitigation of transport
11 impacts on climate and ozone.

12

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

16

17 **5.5 Scenarios of future road transport exhaust emissions**

18

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

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

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

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

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

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

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

23 **[Add here Table 5]**

24

25 *Global emission scenarios for road transportation*

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

3

4 [Add here Figure 3]

5 **Figure 3** summarises the global emission estimates for road transportation. Scenarios from
6 Fulton and Eads 2004, the US-DoE IEO (2006) and the IEA 2006 Baseline represent a frozen
7 policy under varying assumptions about global and regional economic and transport growth.
8 Scenarios developed within the QUANTIFY project (Borken-Kleefeld et al. 2008) represent
9 interpretations of the IPCC SRES storylines. The broad common features are as follows:
10 CO₂ emissions are expected to grow to the year 2050 according to all scenarios (**Figure 3a**). The
11 difference from the lowest to the highest value is about a factor of two in 2050, ranging from
12 about 6000 Tg to 11300 Tg CO₂. All scenarios assume a continued growth of the transport
13 volume that outweigh the improvements in vehicles' fuel efficiency and the introduction of
14 renewable fuels.

15 - In all scenarios CO₂ emissions up to 2050 stem predominantly from fossil fuels: Assumptions
16 reach from only 75% to 87% petroleum fuels in the extremely optimistic TECH plus scenario
17 or still optimistic ACT Map scenario (IEA 2006) or 80% petroleum fuels in a policy scenario
18 (B1) assuming very strong emphasis on renewable fuels and energy efficiency (Borken et al.
19 2007a) over 86% in a policy scenarios with much higher total fuel demand (A1B by Borken-
20 Kleefeld et al. 2008) to more than 97% fossil fuels in the scenarios without sustained
21 initiatives for alternative fuels nor petroleum fuel shortages or price increases (Fulton and Eads
22 2004; IEA 2006 'Baseline').

23 - The global emissions of the non-CO₂ exhaust compounds (NO_x, NMVOC, PM) are assumed
24 to be strongly decreased in the year 2050 according to all scenarios (**Figure 3b-d**). The
25 decrease relative to the year 2000 is between a factor of 5 and 60, depending on the assumed

1 policy and compound. Similar decreases are expected for global emissions of CO, SO₂,
2 PM10, BC and OC. Sooner or later the improvements in vehicle exhaust emission control
3 decouples the total emissions from the transport volume growth. The variation between
4 scenarios is about a factor of 2 in the year 2050, at the significantly lower levels.

5 - In general the change rates agree between Fulton and Eads (2004) and Borken-Kleefeld et al.
6 (2008), however the levels differ notably for NO_x and PM in the first decades. This results
7 from different assumptions on exhaust emission factors and the distribution of vehicle mileage
8 mainly between light and heavy duty vehicles notably outside the OECD region. These
9 differences are further explained in Borken-Kleefeld et al. (2008).

10 The span between the scenarios of the same source illustrates the influence of different
11 assumptions. In a way this range represent the impact of different pathways and policies as
12 assumed in the scenarios. Most notably, scenarios illustrate an apparent potential for either an
13 increasing or decreasing growth in CO₂ emissions globally.

14

15 *Regional differences in emission scenarios for road transportation*

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

20 [Add here Figure 4]

21

22 *CO₂ emissions from road transportation*

23 - In Europe CO₂ emissions grow only little, possibly stagnate at or decrease from high levels
24 from 2020 or 2030 onwards to 2050. The scenarios agree for a level of about 1000 ± 200 Tg
25 CO₂ emissions in the year 2020 and 2030. The trend scenarios by Fulton and Eads (2004) and

1 EC DG TREN (2004) are rather towards the high levels while IIASA 2007 seem to calculate
2 stagnating emissions. The span for various policy scenarios is about $\pm 20\%$ for EC DG TREN
3 2004, while the QUANTIFY scenarios assume less variation at tendentially lower levels
4 (Borken-Kleefeld et al. 2008).

- 5 - Scenarios with stagnating or decreasing emissions assume significant policy interventions in
6 the form of demand management, partial modal shift, strong improvements in vehicle fuel
7 economy as well as sizeable shares of biofuels, all in the face of continued transport growth.
- 8 - For developing Asia all scenarios assume a continuous and significant growth of CO₂
9 emissions. Policy interventions as described above only influence how much they may grow,
10 either to 1100 Tg or to 3800 Tg by the year 2050, up from about 500 to 600 Tg CO₂ emission
11 in the year 2000. The "frozen policy" scenario by Fulton and Eads (2004) calculates about
12 intermediate emissions by 2050.
- 13 - Consequently, the share of developing Asia in global road transport's CO₂ emissions grows
14 from about 12% in 2000 to between 20% and 33% in 2050. Over the same period the global
15 share of Europe may decline from about 20% in the year 2000 to 8% to 15% in the year 2050
16 (Borken-Kleefeld et al. 2008).

17

18 *Non-CO₂ emissions from road transportation*

19 In all scenarios the non-CO₂ emissions follow a similar pattern:

- 20 - In Europe, the so-called regulated exhaust compounds NO_x, CO, NMVOC and PM all
21 continue to decline strongly. All scenarios concur in the rates of change though the initial
22 values differ. In detail: NO_x emissions from (Borken et al. 2007a, Borken-Kleefeld 2008) are
23 highest as they incorporate latest emission measurements (Hausberger et al. 2003); NMVOC
24 emissions from Fulton and Eads (2004) are highest as they include evaporative emissions; PM
25 emissions from IIASA 2007 are highest as they assume only current legislation in the baseline

1 scenario; contrary to the other scenarios, they therefore do not include the use of diesel
2 particulate filters.

3 - All scenarios for Europe furthermore concur that future emission levels are lower by several
4 factors for all compounds. The continued tightening of vehicle exhaust emission standards in
5 the scenarios effectively decouples the non-CO₂ emissions from transport growth.

6 - For developing Asia the emission development is more complex: On the one hand the
7 transport growth drives emissions, though at very different rates across the scenarios. On the
8 other hand, fleet renewal and tightening of vehicle exhaust emission controls tend to contain
9 emissions. How quickly and how strongly these factors change determines whether the
10 resulting total emissions grow initially, as in some scenarios, or whether they decline
11 continuously, as in scenarios assuming very tight emission controls and lower transport
12 demand growth. QUANTIFY scenarios (Borken-Kleefeld et al. 2008) are characterised by a
13 delayed decrease in emission totals, as fleet renewal takes time and a significant transport
14 growth is assumed.

15 - All scenarios for developing Asia concur, that emission levels in the distant future will be very
16 much lower than today. Scenarios differ in the initial and current emission level and in the
17 speed of the reduction. The difference is highest for NO_x emissions, that might for some while
18 still be driven by a high growth in freight transport, i.e. an expansion of trucking.

19

20 *Regional pattern of emissions from road transportation*

21 The regional pattern illustrated above can be generalised as follows:

22 - In some policy scenarios the OECD region may see a stabilisation or even absolute decrease of
23 its high CO₂ emissions. In all developing regions emissions are set to grow significantly,
24 regardless of the scenario.

1 - The share of the OECD in global emissions might decline from two thirds in the year 2000 to
2 one quarter or two fifths in the year 2050. On the other hand, the strongly developing regions,
3 notably Asia, will more than double their shares over the same period (Borken-Kleefeld et al.
4 2008).

7 **6. Conclusion**

8
9 Land transport and in particular road traffic play an significant role in the atmospheric
10 composition and its importance for climate change is growing. The direct emissions from land
11 transport in CO₂-equivalents contribute more than one fifth to the total anthropogenic emissions
12 excluding land use change. In the year 2000 the share of OECD countries of land transport
13 emissions was about two thirds. Although the absolute amount may still increase until the year
14 2050, the fast growing non-OECD countries will emit at least twice as much by then.

15
16 The impacts on the atmosphere and climate are of different significance for different gases and
17 emitted species depending on the time scale considered. We distinguish three main categories:

18 1) Carbon dioxide

19 A long term and strong climate signal comes from increasing CO₂ emissions. The impact will
20 last for centuries. IPCC AR4 describes the consequences of global warming in detail. The
21 contribution by land transport is mixed with that of other emissions from ground-based fossil
22 fuel combustion and contributes according to its share within these emissions.

23 Road transport dominates with 4300 Tg CO₂ released in 2000, corresponding to 72% of the CO₂
24 emitted by transport and 17% of the global 25.6 Pg CO₂ emitted through anthropogenic fossil
25 fuel combustion and cement manufacture. The cumulative emissions since pre-industrial times

1 translate into a radiative forcing of about 150 mW/m² in 2000 for road traffic and 21 mW/m² for
2 direct rail emissions compared to a total CO₂ forcing of 1660 mW/m². Road traffic's contribution
3 is expected to grow significantly until the year 2050 in all scenarios. The future range of
4 emissions may be between 6000 Tg to 11300 Tg CO₂ per year, depending on the scenario
5 assumptions. In the near-future road transport will account for more than 20% of all annual
6 human-induced CO₂ emissions. Integrated over 100 years a one year pulse of the emissions in
7 2000 would translate into a radiative forcing of about 400 mW/m² yr.
8 Direct emissions from rail transport are relatively minor, approximately 120 Tg CO₂ in 2000. A
9 similar contribution comes from indirect emissions by electricity generation. Emissions from
10 inland shipping are negligible on a global scale.

11 2) Halogenated compounds

12 A mid-term impact on radiative forcing comes from halogenated compounds, in particular HFCs
13 and CFCs, released from mobile air conditioners (MAC). Presently, more than 50% of the
14 worldwide automotive fleet is equipped with MAC. The 700 Tg CO₂-equivalents emitted as
15 halocarbons in 2002 are of similar magnitude to the CO₂ emitted by aviation and constitute 17%
16 of road transport emissions in 2000. The radiative forcing will decrease with shrinking banks of
17 CFC-12, but it will remain to be relevant during the next decades. Existing CFC-12 banks and
18 already emitted gases from MAC will also continue to contribute to the decomposition of the
19 ozone layer in the next decades. Until recently, stratospheric ozone depletion has contributed to a
20 negative radiative forcing of climate (cooling tendency); however, this is expected to reverse in
21 the next decades due to the decreasing chlorine concentration in the stratosphere. Hence, the
22 positive radiative forcing in the troposphere by the growing use of the cooling agent HFC-134a
23 is of higher relevance for the climate system.

24 3) Short lived emissions

1 A smaller, short to mid-term climate impact comes from short lived non-CO₂ gases as well as
2 particles and particle precursors. These include nitrogen oxides (NO_x), carbon monoxide (CO),
3 non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO₂), particles (PMs) and
4 black carbon (BC). They affect air quality and climate warming through the formation of ozone,
5 peroxyacetyl nitrate (PAN), hydroxyl radicals (OH) and thereby the equilibrium concentration of
6 the greenhouse gas methane (CH₄). In particular emissions of NO_x and NMVOC from road
7 traffic contribute zonally averaged 2-6% to the formation of tropospheric ozone in the Northern
8 Hemisphere during summer. On a regional scale ozone may increase by 3-5 ppb whereas in
9 urban and industrial areas the impact may be larger. In parallel, OH can be increased by 2-4% in
10 dense traffic regions in NH summer. In winter, the change of O₃ and OH is small.

11 For the year 2000 an ozone-related radiative forcing in the range of 50 to 54 (±11) mW/m² has
12 been calculated. A one year pulse of the year 2000 emissions integrated over 100 years leads to
13 an RF of about 50 mW/m².

14 Since the contribution to radiative forcing per unit ozone change is relatively high in the free
15 troposphere, it is of relevance that road traffic induced O₃ can mix up to the tropopause in
16 summer. The impact is similar to the one of aviation. On the other hand, since ozone induces
17 also OH formation, the positive ozone forcing is partially offset by a reduced lifetime of
18 methane. A small positive radiative forcing comes from aerosols, primarily due to the effect of
19 black carbon (28 mW/m²).

20 In all world regions vehicle emission standards become stricter and fuel quality improves, with
21 respect to sulphur, lead and aromatics contents. In consequence the non-CO₂ emissions from
22 road traffic have been declining in most OECD countries. Non-OECD countries with high traffic
23 growth might experience increasing emissions in the next two decades. Nonetheless, the global
24 total emissions are assumed to decline significantly in all scenarios. Hence, one might conclude

1 that the radiative forcing from short-lived species may not increase. Conversely, attention on the
2 long-lived climate gases – expected to be increasing anyway – becomes even more important.

3
4 Short lived traffic-related primary and secondary pollutants affect substantially human health.
5 Concerning global-scale health effects those that should be considered because of high
6 concentrations and relatively long residence times in the atmosphere are particles (PMs) and O₃.
7 Concentrations of both PMs and O₃ in Europe have not improved since 1997 despite substantial
8 cuts in emissions. Increased O₃ and fine particulates (PM_{2.5}) concentrations from road traffic can
9 cause severe respiratory and cardiovascular diseases up to increased risk of death. Some
10 pollutants, in particular polycyclic aromatic hydrocarbons (PAHs), belonging to PM_{2.5}, are also
11 carcinogenic. NO₂ and O₃ can increase the risk of exacerbating allergy reactions.

12
13 In addition, indirect emissions must be considered. They include evaporation of NMVOC while
14 filling or driving a vehicle which is, depending on the inventory, also accounted for through the
15 direct emissions.

16 Indirect emissions arise also from the production of transport equipment, infrastructure and fuel
17 production, transformation and supply. About 1/8 of the life-cycle emissions of a mid-size car
18 can be attributed to its production. CO₂-equivalent emissions of direct greenhouse gases well-to-
19 tank, i.e. for the fuel production and transport, would constitute 14% and 16% of well-to-wheel
20 emissions for conventional gasoline and diesel road vehicles, respectively. For the first
21 generation biofuels, well-to-tank emissions will constitute a large share of total life-cycle
22 emissions. Second generation biofuels are expected to be more efficient. For electricity or
23 hydrogen as fuels, there are no tail pipe emissions. All relevant emissions relate to the production
24 phase. Unless produced from carbon free energy sources, for example from nuclear, solar or

1 wind energy or from hydrogen produced with carbon capture and storage, they usually result in
2 even higher CO₂ emissions per unit useful energy.

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

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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 emitting 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.

1

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

11

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

19

20 *Recent and ongoing research*

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

23 A significant improvement in our understanding of transport's impacts on climate and ozone is
24 expected from the EC FP6 integrated project QUANTIFY (www.pa.op.dlr.de/quantify/). This
25 project is dealing with quantifying impacts from individual transportation sectors like aviation,

1 shipping and road transport. It is the first comprehensive attempt not only to quantify these
2 impacts in global climate model (GCM) runs, but to account for the effects of chemical
3 nonlinearity in dilution of the emission behind the exhausts as well as to include metrics for
4 simpler emission reduction assessments.

5

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

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

18

19 A cluster of European projects focussed on the investigation of vehicles emissions: *ARTEMIS*
20 (Assessment And Reliability Of Transport Emissions And Inventory Systems), *COST 346*
21 (Emissions and Fuel Consumption from Heavy Duty Vehicles <http://www2.vito.be/cost346/>)
22 and *PARTICULATES* (Characterisation of Exhaust Particulate Emissions from Road Vehicles).
23 *ARTEMIS* computes emissions at a low spatial scale and investigates the behaviour of vehicles
24 in driving cycles. The results, which are implemented in a European emission model for light
25 vehicles, tell that different approaches in emissions inventories and the unstable behaviour of

1 vehicles with emission reduction devices (catalytic converters, particles filters) lead to a high
2 uncertainty about what a single car emits. ARTEMIS states for example that there is quite
3 contrasted behaviour between Diesel (rather sensitive to speed and stop parameters) and gasoline
4 cars (rather sensitive to accelerations).

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

10 PARTICULATES investigated the progress and potentials in the reduction of particulate matter.

11 A major step forward is seen in the control of automotive particulate emissions is through the
12 application of diesel particulate filters and sulphur-free fuels (10 mg/kg max Sulphur content).

13 PARTICULATES focussed mainly on diesel light duty and heavy duty vehicles, but emphasises
14 for example also that the role of two wheelers in less developed countries may be
15 underestimated.

16

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

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

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

4

5

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2
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TABLES LA08

Table 1: Emissions of CO₂ from transport in year 2000 and cumulative emissions 1900 to 2000.
Derived from calculations condensed in Fuglestvedt et al., 2008

	2000		Cumulative 1900-2000	
	Emissions Tg CO ₂	Share [%]	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

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2 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

3 a: Without evaporative emissions

4 b: Total VOC emissions

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6 References:

7 (1) Aardenne et al. (2005)

8 (2) Borken et al. (2007a, b)

9 (3) Fulton and Eads (2004)

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

Ref.	CO ₂ Tg	SO ₂ Tg S	CO Tg	NM VOC 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} (PM₁₀: 0.21 Tg). e) About 1514 Tg CO₂ 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

1

2 Table 4: Estimate of the uncertainty for road transport emission in the year 2000 (Borken et al.
3 2007a)

	CO ₂	SO ₂	CO	NM VOC	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%

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1 Table 5: Summary of scenario characteristics relevant for road transport's long-term fuel
 2 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.

1

2 Table 6: Rail emission factors

	NO _x	CO	NMVOC	PM _{2.5}	CH ₄	N ₂ O
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

3 () = coal

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3 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.

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3 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.

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3 Table 9: The new Euro standards [mg/km] for NO_x and PM from passenger cars (Acid News,
4 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

5 ¹ Diesel cars only.

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2 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

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2 Table 11: Total and road transportation emissions for BC, POM and SO₂.

	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 (<i>Borken et al., 2007b</i>)	0.72	0.31	0.95
Fraction (%) of emissions	9.0	0.9	1.3

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2 Table 12: Annual-mean long-wave, short-wave, and net radiative forcings due to road emissions
3 for the five models that participated in the first Quantify ozone impact calculation. Unit: mW/m².

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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

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2 Table 13: Methane lifetime in the base case (years), and reductions in methane lifetime in
3 percent due to road emissions (second row) or due to road, aviation, and shipping emissions
4 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

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Table 14: Emission metrics (GWP₁₀₀, GTP₂₀, GTP₅₀, GTP₁₀₀) and corresponding CO₂-equivalent emissions (in Gg (CO₂)/yr for all metrics) for the various components of road transport emissions.

	GWP₁₀₀	GTP₂₀	GTP₅₀	GTP₁₀₀	CO₂-eq emissions (GWP₁₀₀-based)	CO₂-eq emissions (GTP₂₀-based)	CO₂-eq emissions (GTP₅₀-based)	CO₂-eq emissions (GTP₁₀₀-based)
CO₂	1	1	1	1	4174	4174	4174	4174
NO_x	-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
NMVOG	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
SO_x 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

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Table 15: Emission metrics (GWP₁₀₀, GTP₂₀, GTP₅₀, GTP₁₀₀) and corresponding CO₂-equivalent emissions (in Gg (CO₂)/yr for all metrics) for the various components of rail emissions.

	GWP₁₀₀	GTP₂₀	GTP₅₀	GTP₁₀₀	CO₂-eq emissions (GWP₁₀₀-based)	CO₂-eq emissions (GTP₂₀-based)	CO₂-eq emissions (GTP₅₀-based)	CO₂-eq emissions (GTP₁₀₀-based)
CO₂	1	1	1	1	119.7	119.7	119.7	119.7
NO_x	-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
SO_x dir.	-44	-38	-6.3	-5.2	-24	-22.8	-3.8	-3.1

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4 Table 16: External and infrastructure costs of heavy goods vehicle travelling 100 km on a
5 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

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FIGURES LA08

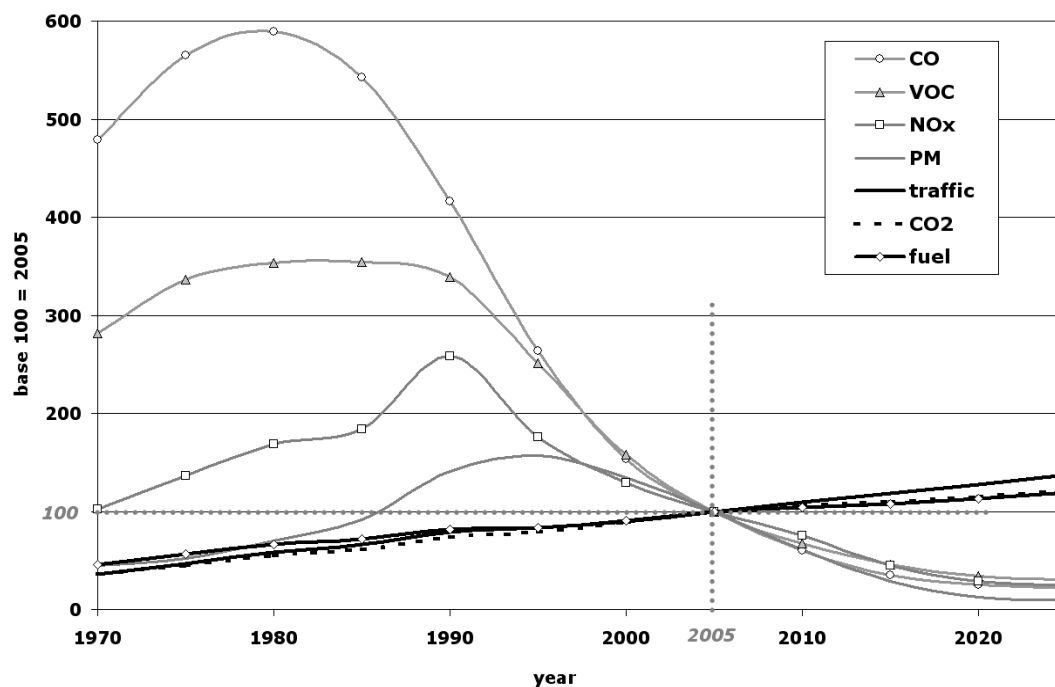


Figure 1: Relative evolution of mileage and emissions of French road traffic emissions from 1973 to 2020. Base 100 = year 2005. (Joumard, 2005)

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 Émissions des véhicules en France de 1970 à 2025. Rapport Inrets, n°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 @vol tr %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

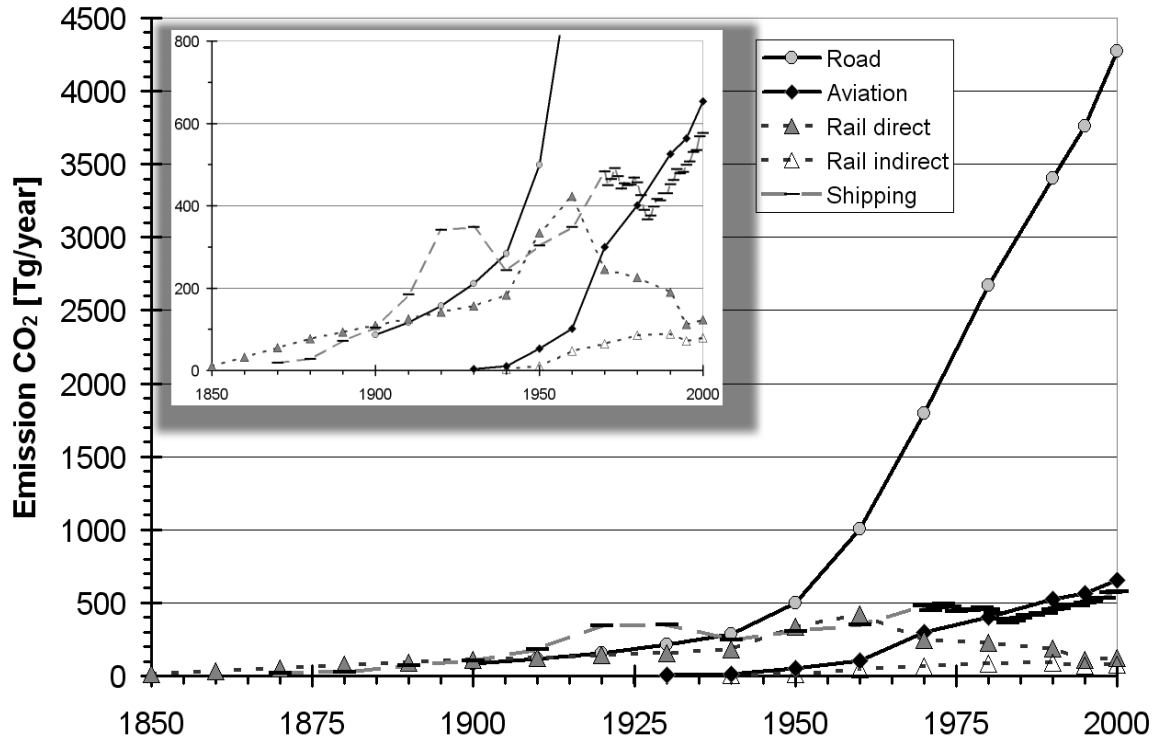
Directeur de Recherche / Senior researcher

INRETS - Laboratoire Transports Environnement

Institut National de Recherche sur les Transports et leur Sécurité /

French National Institute for Transport and Safety Research

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4 Figure 2: CO₂ emissions from the transport sector 1900 to 2000 (from Fuglestvedt et al., 2008).
5 The inset shows the lower values with a higher resolution of the y-axis.

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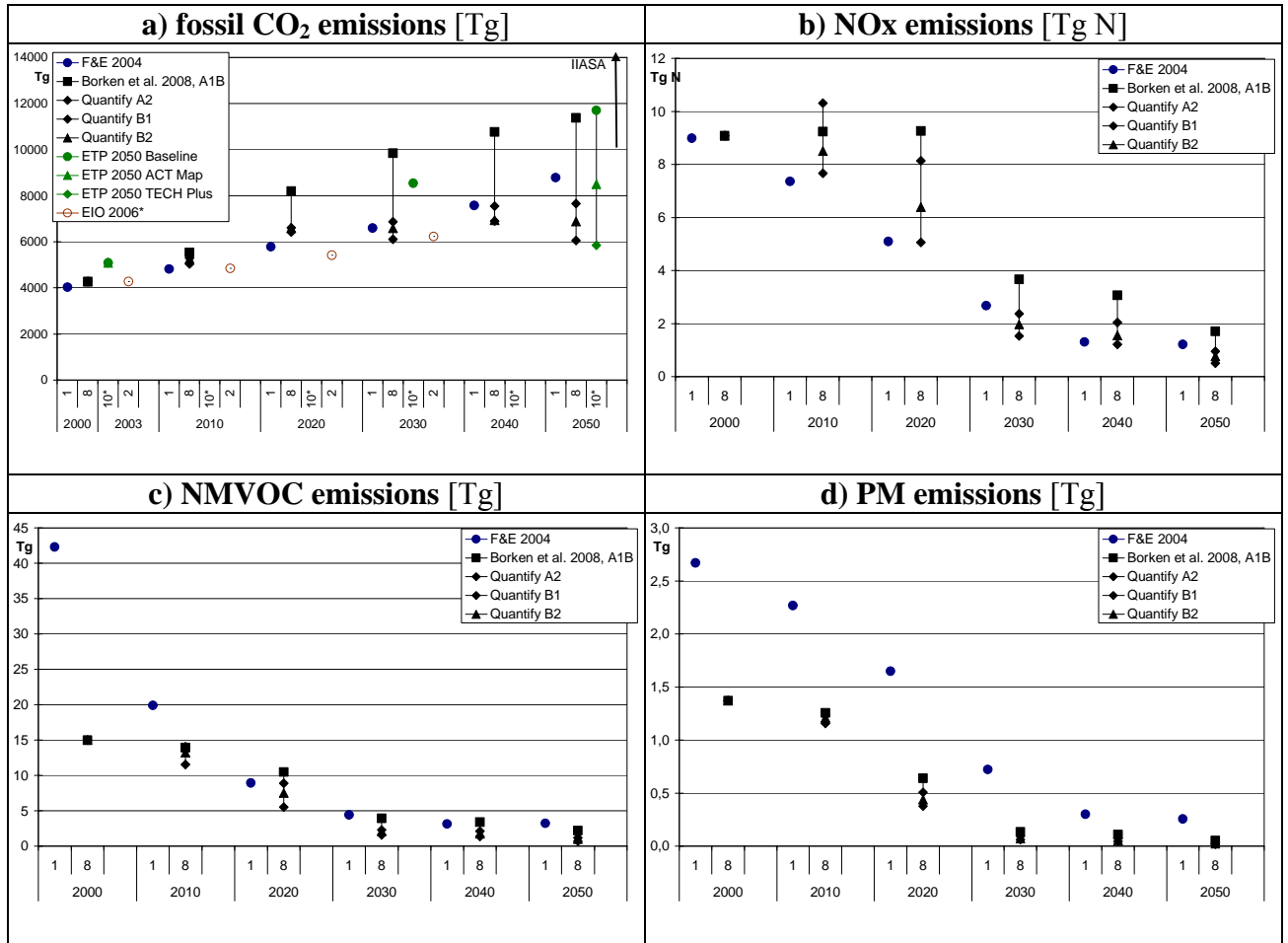
8 Notes for the editorial office

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

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2 Figure 3: Global total emissions for road transportation: a) CO₂ – (US-DoE, IEO 2006 covers all
 3 transport modes, i.e. approximately 20% more than just road transportation. IEO 2006 calculated
 4 from growth rate of fuel demand applied to QUANTIFY y2000 CO₂ emissions. b) NO_x, c) VOC
 5 including or NMVOC excluding evaporative emissions (Fulton and Eads 2004 / Borken et al.
 6 2007a), d) PM emissions.

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9 Notes for the editorial office

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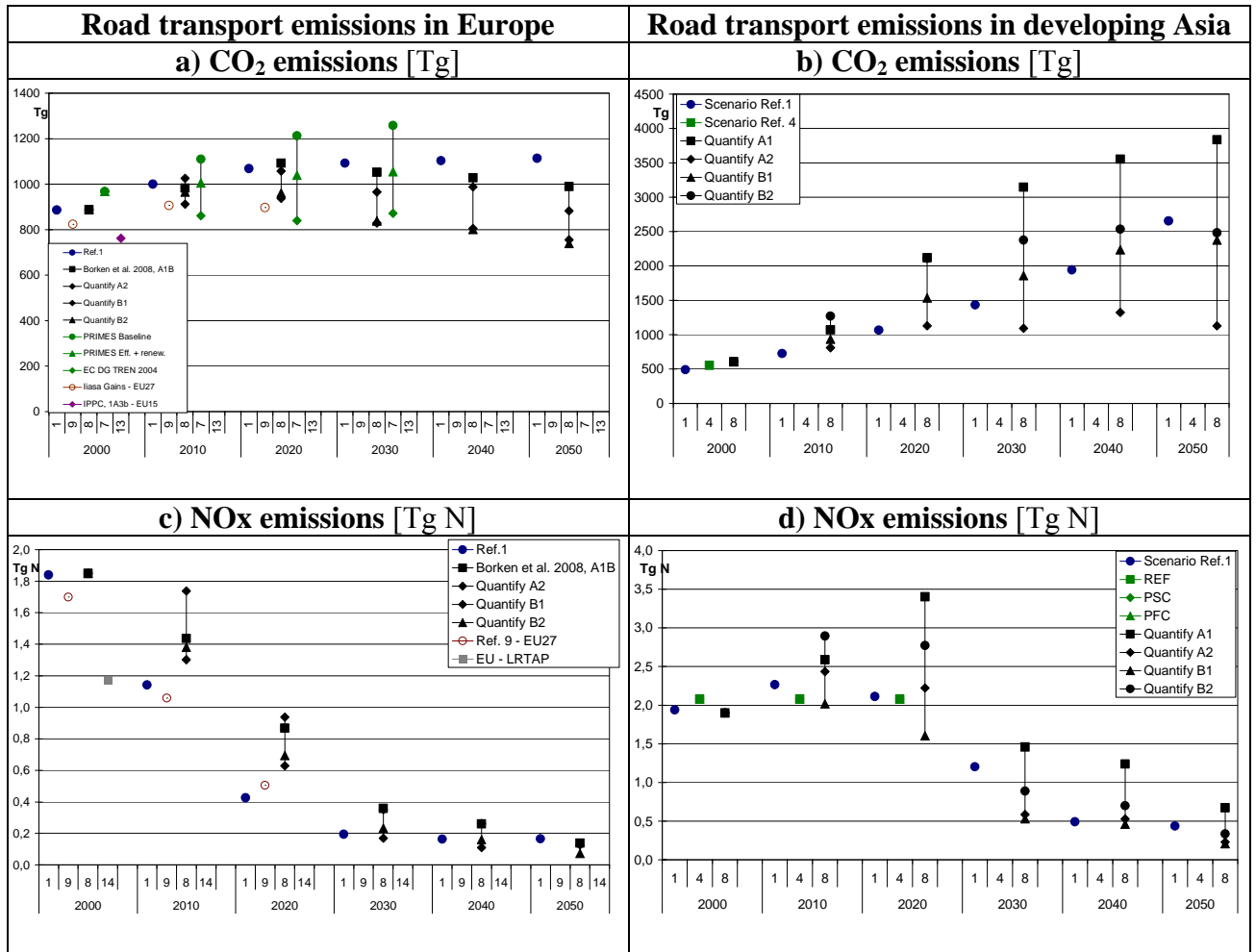
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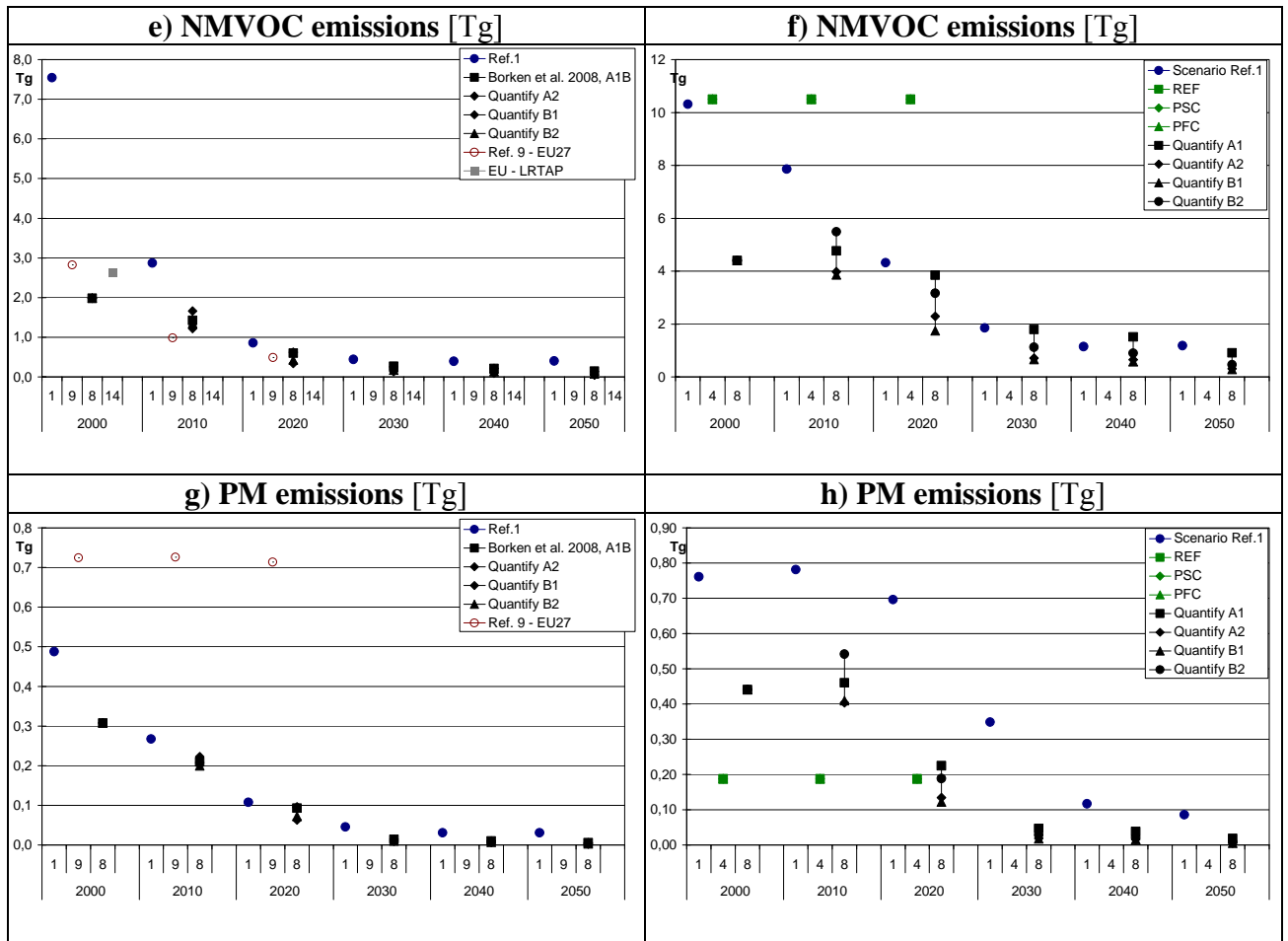
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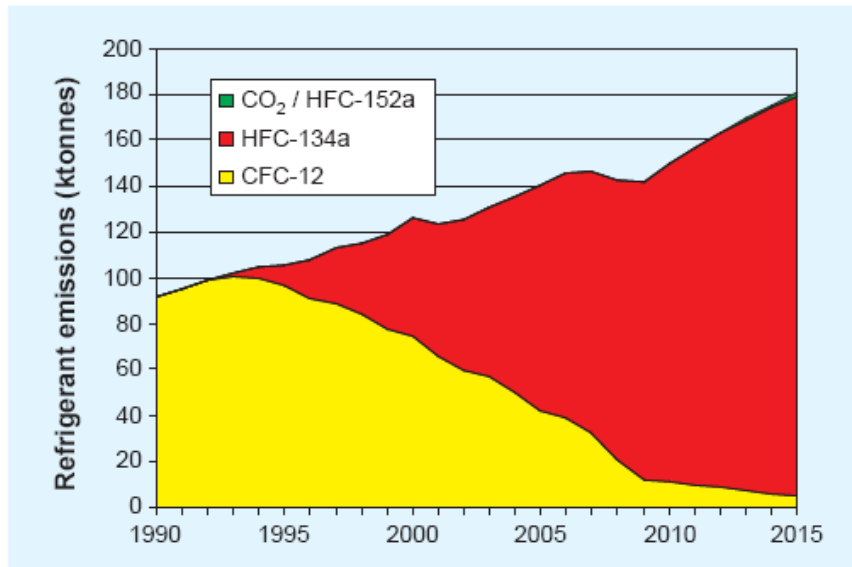
1
 2 Figure 4: Emission scenarios for road transportation in Europe and developing Asia. a-b) CO₂, c-
 3 d) NO_x, e-f) NMVOC, g-h) PM. They illustrate the developments in OECD regions and growing
 4 developing regions in general.

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 7 Notes for the editorial office

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

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3 Figure 5: SROC 2006, Figure 6a. MAC refrigerant emissions from 1990 to 2015 (Clodic et al.,
4 2004).

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Notes for the editorial office

8

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

11

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

13

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

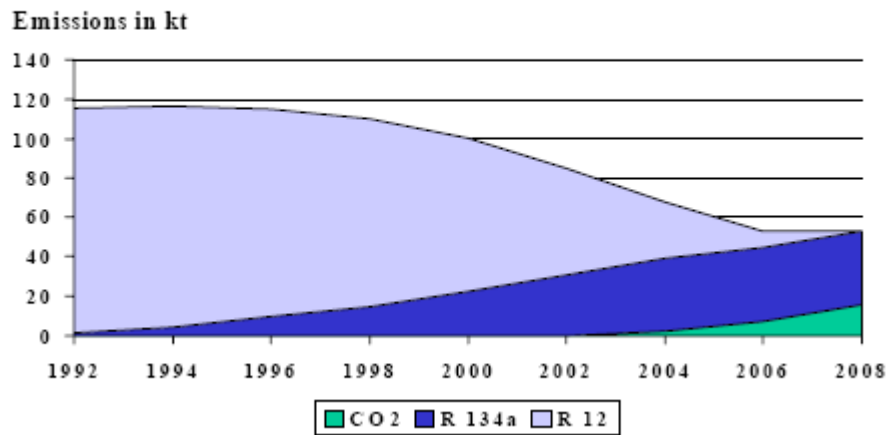
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Refrigerant emissions from the fleet of air conditioned cars in kt/a



2

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

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7 Notes for the editorial office

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9 The figure is available from:

10

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

13

14 Published on the IPCC website at:

15

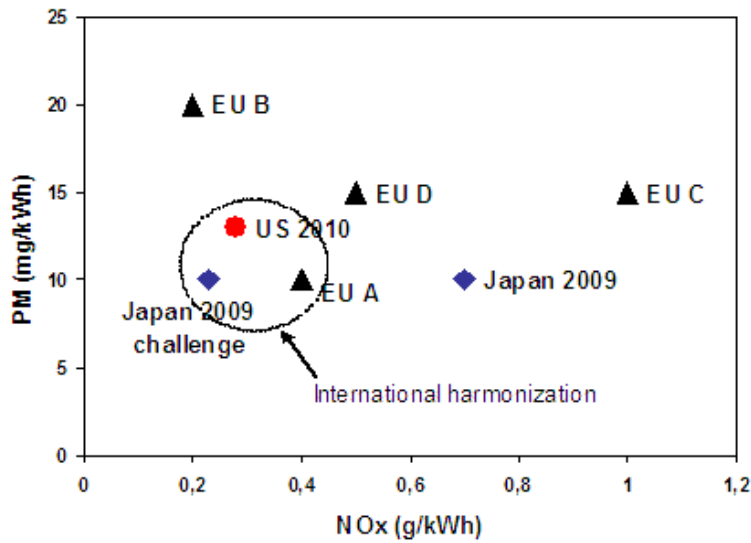
16 <http://arch.rivm.nl/env/int/ipcc/docs/IPCC-TEAP99/files/m99a3-12.pdf>

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

4

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6 Notes for the editorial office

7

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

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

10 Katarzyna gave me the following contact information:

11 Per Elvingson

12 The Swedish NGO Secretariat on Acid Rain, Box 7005, SE-402 31 Göteborg, Sweden.

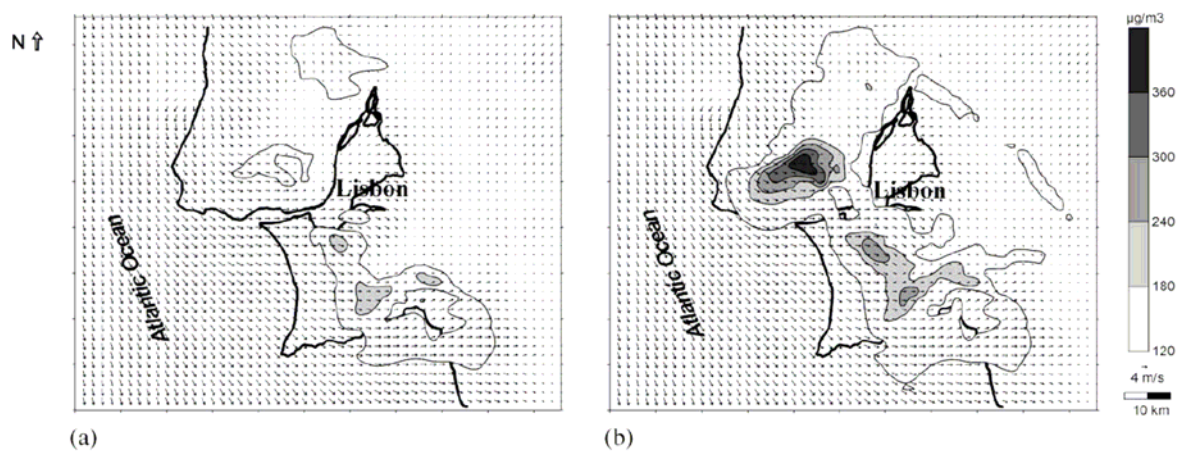
13 Phone. +46-31-711 45 15, Fax +46-31-711 46 20, info@acidrain.org

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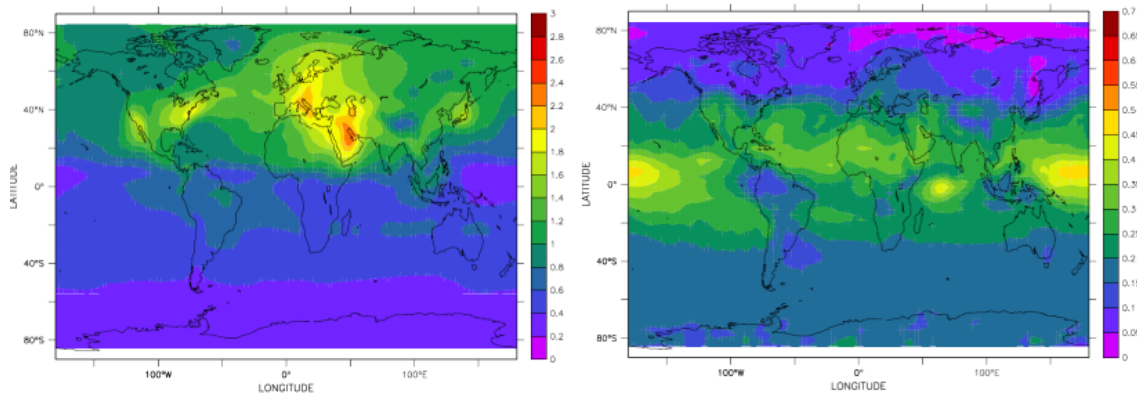
2
3 Figure 9. Simulation results of ozone peak values in July for two emissions scenarios at Lisboa:
4 (A) without traffic emissions; (B) with traffic emissions. (Borrego et al., 2000)

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7 Notes for the editorial office

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

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4 Figure 10:

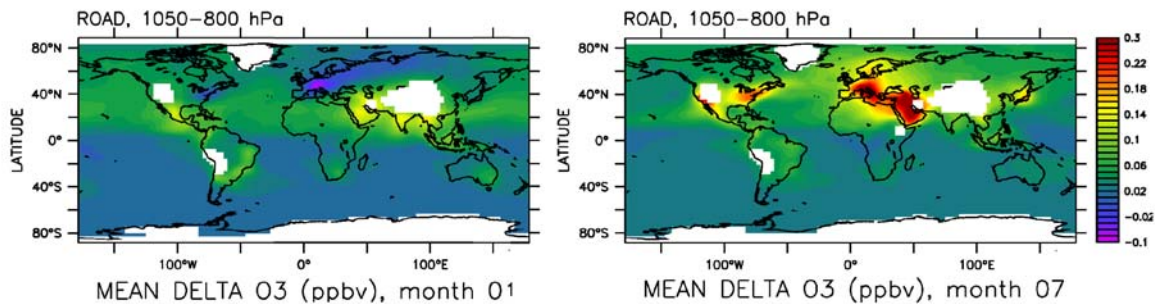
5 Left: Changes in the ozone column from 1000 to 40 hPa in DU, July, due to the effect of road
6 transport. The difference between base case and perturbed case is shown for an average over four
7 models and a 5% perturbation scaled up to 100%. [1 DU = 21.4 mg O₃ m⁻²]

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

10

11 *Alternative Figure 10 from Hoor et al., 2009:*

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

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20 Notes for the editorial office

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22

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

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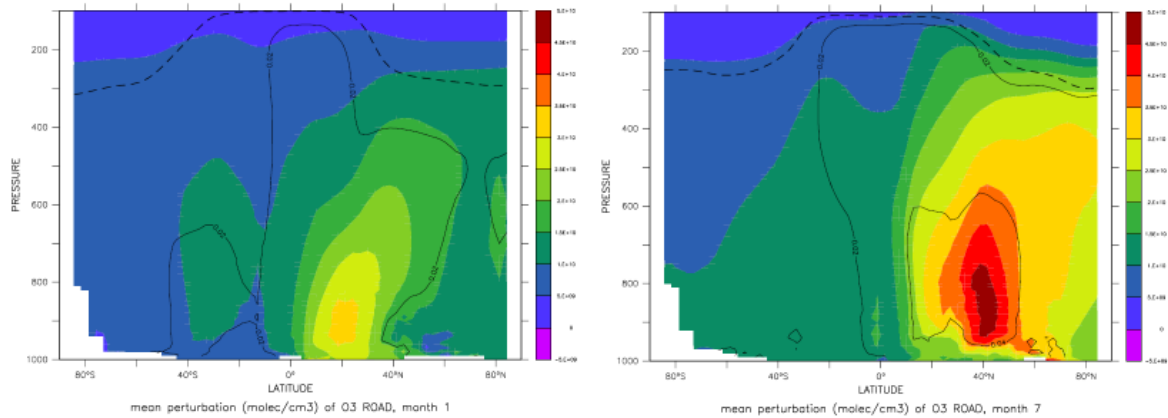
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3 Figure 11: Zonal mean contribution of road traffic to ozone in molecules per cm³ in January
4 (left) and July (right), average from four models. Isolines of 2% and 4% change and the
5 tropopause (dashed line) are shown in the graphs. Source: Hoor et al., Quantify

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9 Notes for the editorial office

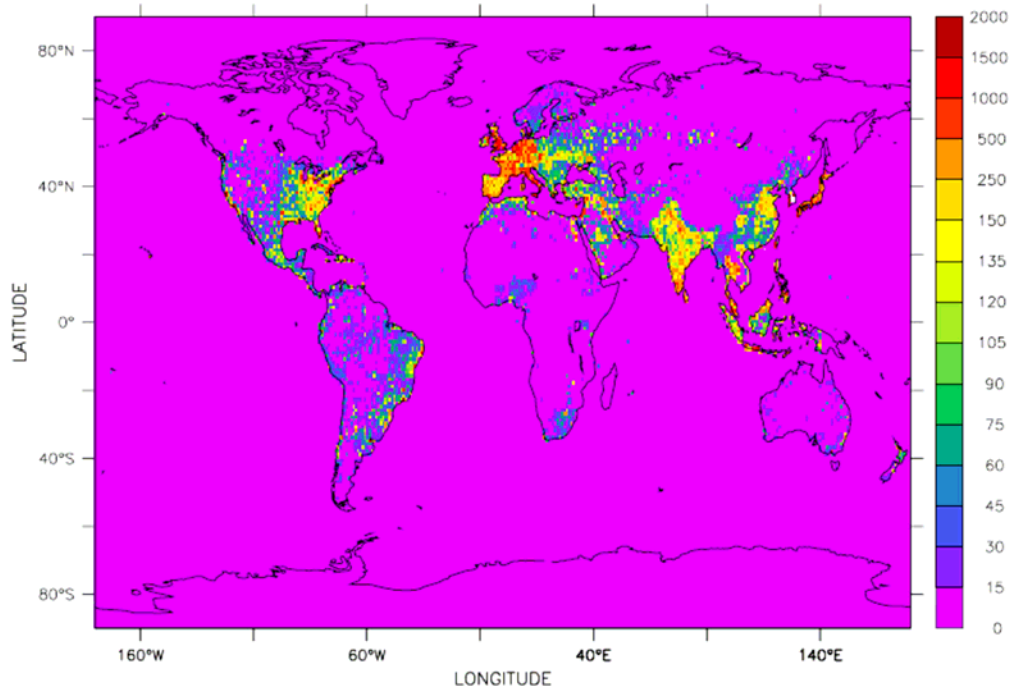
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11 The figures are based on Quantify calculations from Peter Hoor. He has the respective images in different formats
12 and the maximum available resolution. But I have also eps-figures from him.

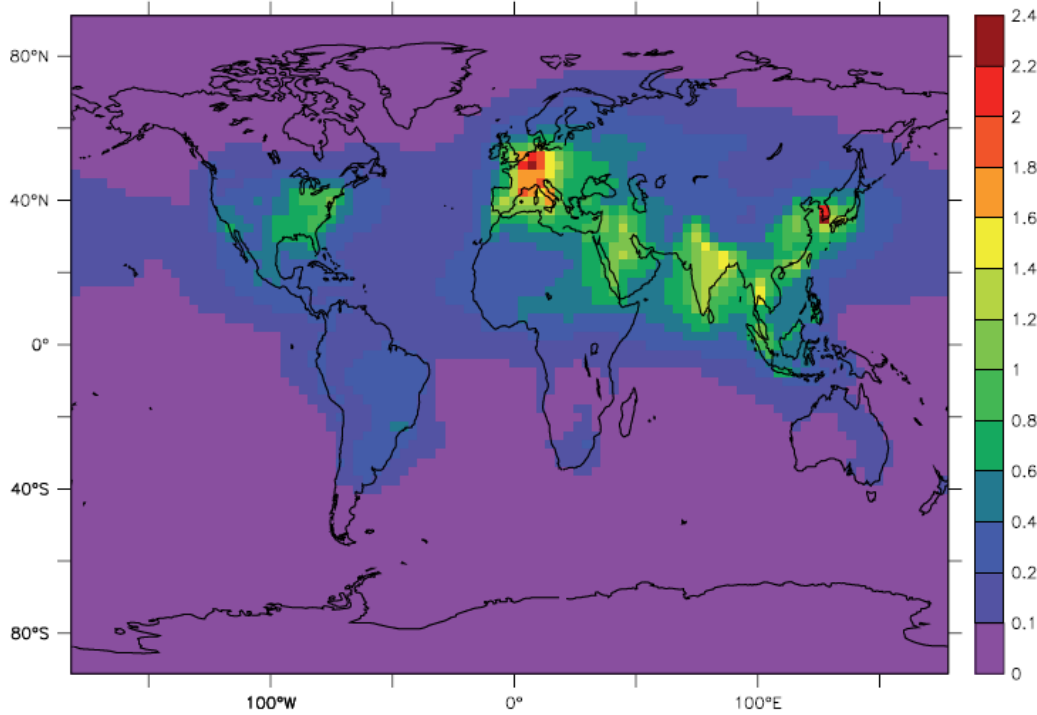
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5 Figure 12: Top Panel: Total amount of black carbon (tons carbon/yr) emitted from passenger and
6 freight transport (Gasoline+Diesel), Borken et al. (2007b)

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

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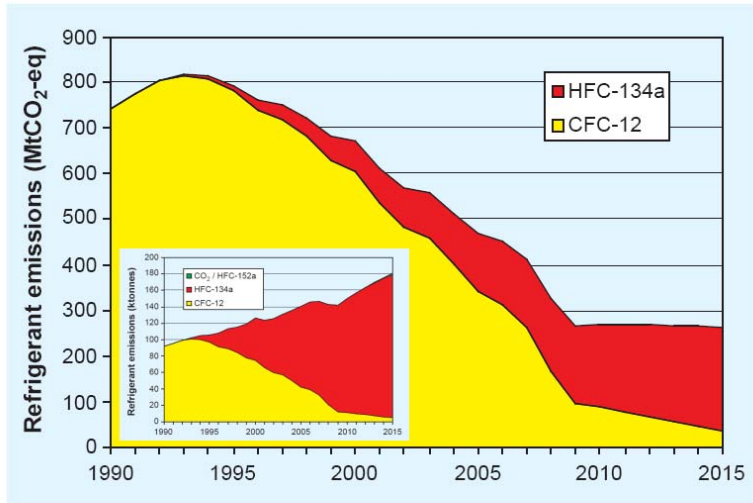
10 Notes for the editorial office

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

14

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2 **Figure 6b.** MAC refrigerant emissions in CO₂-eq from 1990 to 2015
(Clodic *et al.*, 2004).

2

3 Figure 13: SROC 2006, Figure 6b. MAC refrigerant emissions in CO₂-eq from 1990 to 2015.
4 CFC-12 and HFC-134a emissions are transformed into CO₂-eq based on their GWP, as given in
5 the IPCC Second Assessment Report (IPCC, 1996). (Clodic *et al.*, 2004).

6

7 Notes for the editorial office

8

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

11

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

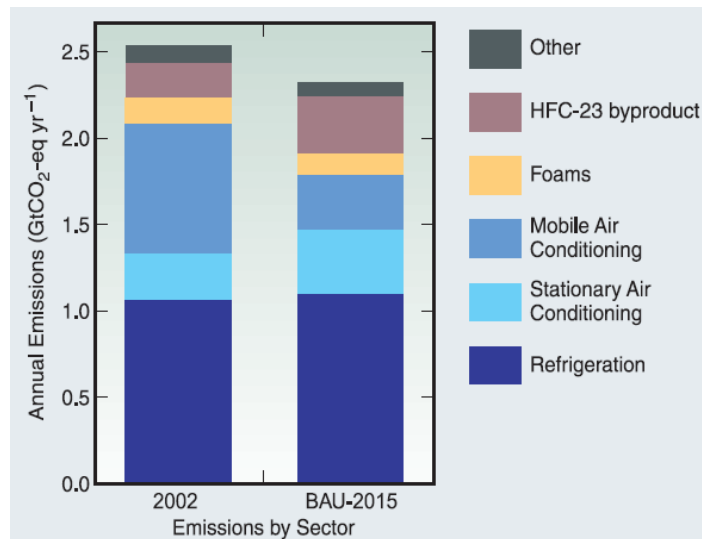
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14 I added a copy of figure 5 as inset.

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4 Figure 14: Historical data for 2002 and Business-As-Usual (BAU) projections for 2015 of
5 greenhouse gas CO₂-equivalent direct annual emissions, related to the use of CFCs, HCFCs and
6 HFCs. SROC 2006 fig. SPM-4.

7

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9 Notes for the editorial office

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11 This figure is taken from the IPCC SROC report, Part 6 on Mobile Air Conditioners, which is provided as PDF
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14 http://www.mnp.nl/ipcc/pages_media/SROC-final/SpecialReportSROC.html

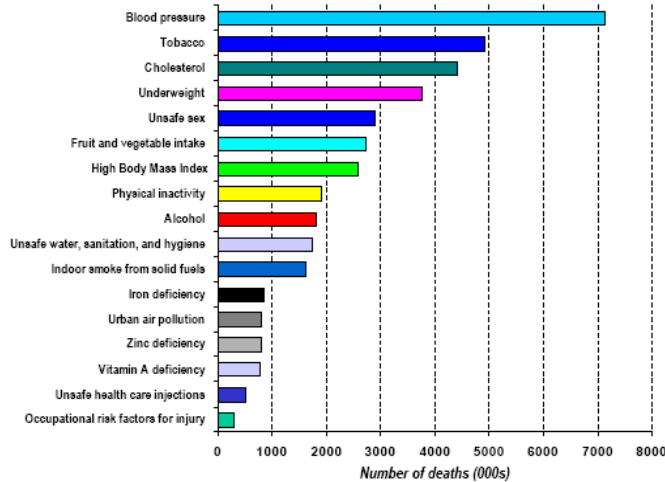
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World Deaths in 2000 attributable to selected leading risk factors



Source: WHR 2002

10  World Health Organization

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

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Notes for the editorial office

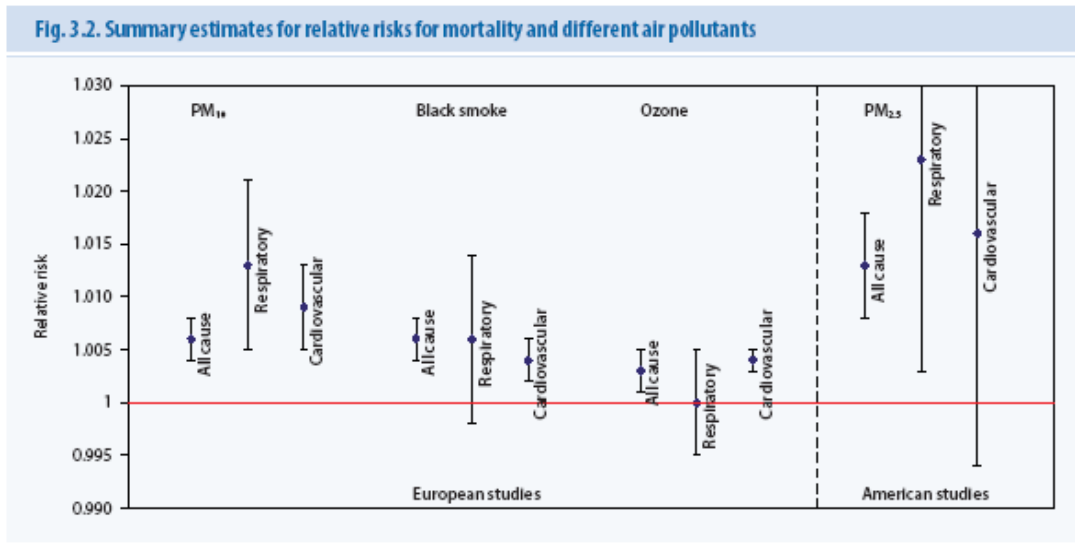
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The figure is available from the WHO website at:

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

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

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

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11 Notes for the editorial office

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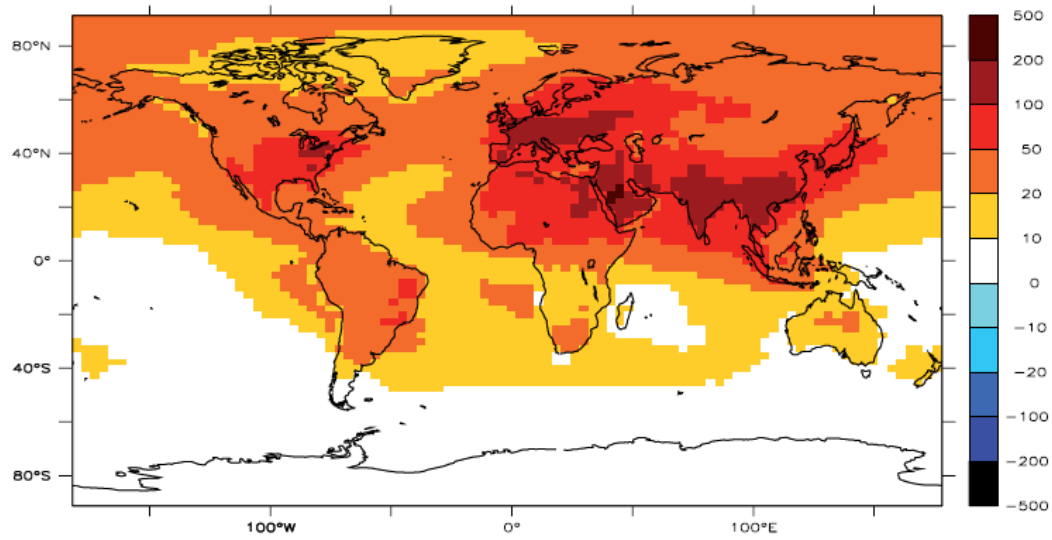
13 The figure has been sent to me by Katarzyna Juda-Rezler. I will contact her and ask from whom we have to request
14 the copyright. (e-mail to Katarzyna 10.2.)

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

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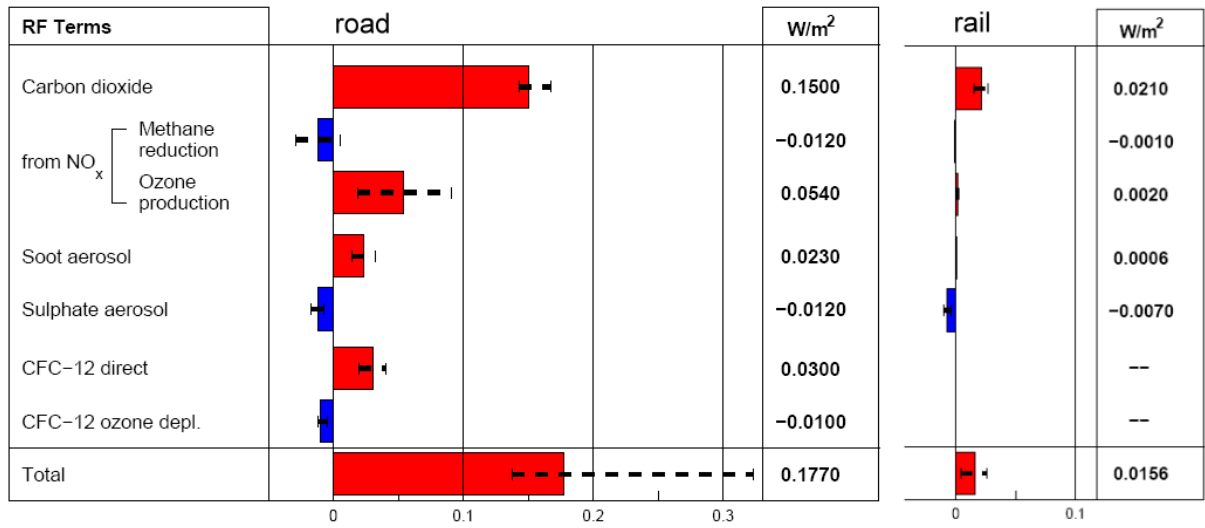
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8 The figure has been sent to me by Yves Balkanski. I will contact him and ask if its his work or if we have to
9 consider copyright issues. (e-mail to Yves, 10.2.)

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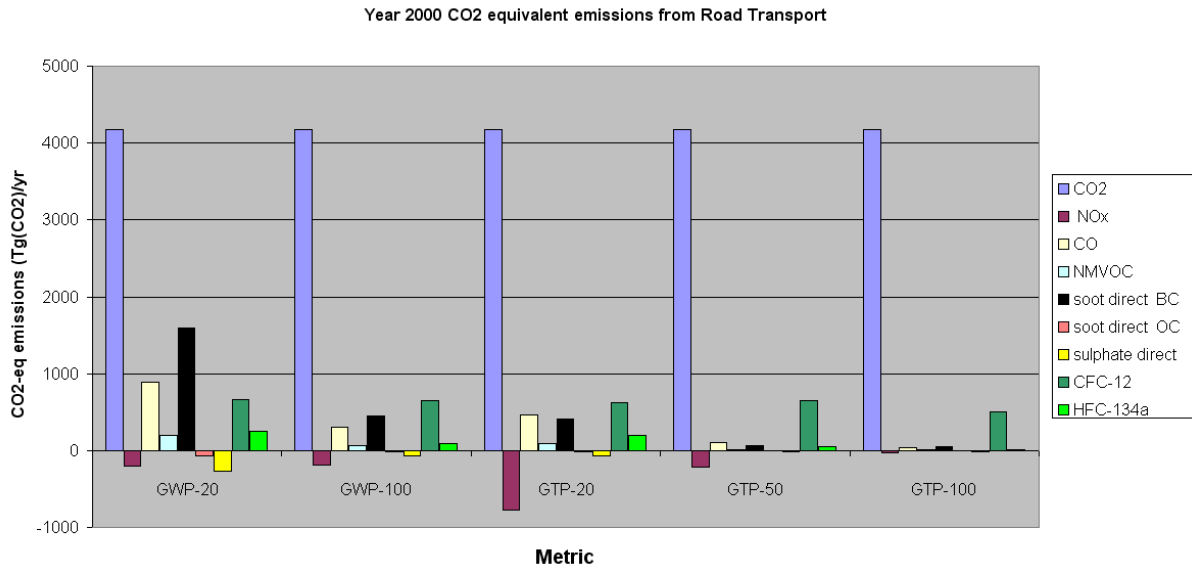


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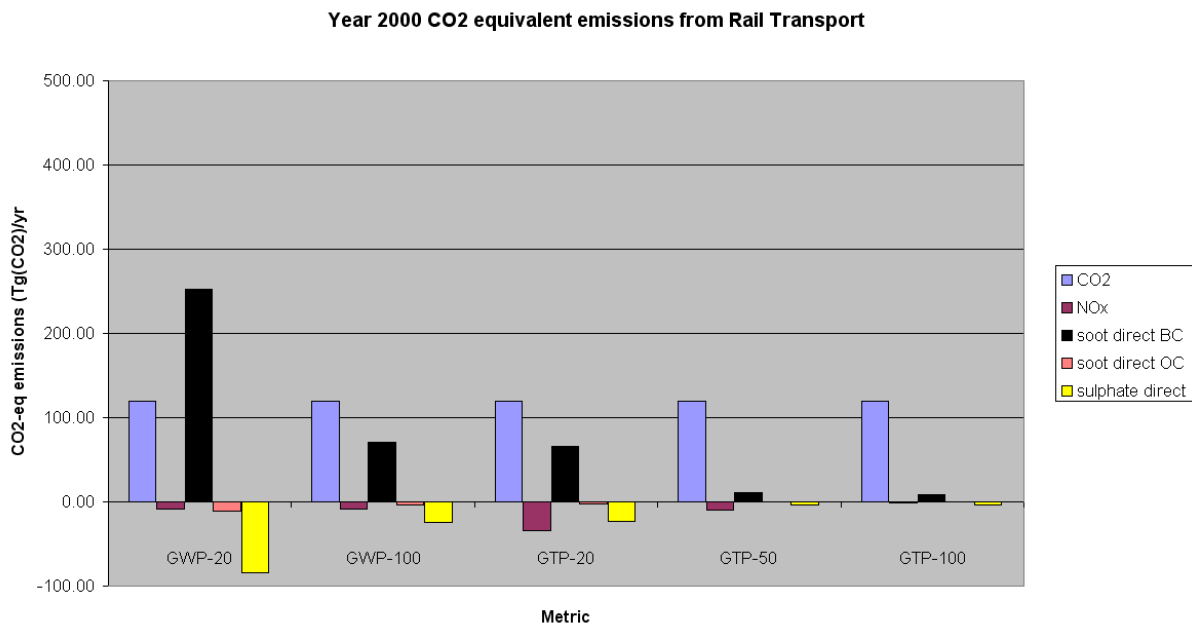
4 Figure 18: Radiative forcing for road and rail transport in 2000.

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

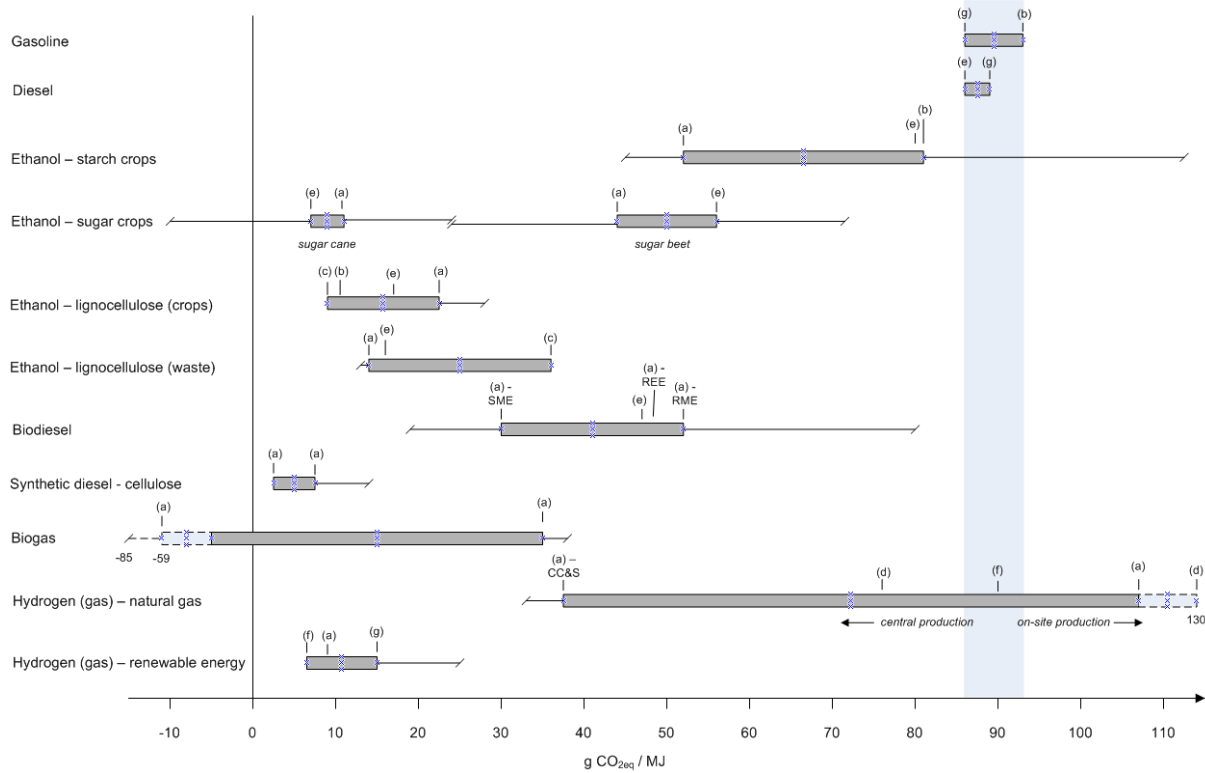
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11 Notes to the editorial office

12 Figure based on numbers in the metrics chapter. For the calculation I followed the process Terje Berntsen has
 13 chosen.

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Figure 20: Summary on net CO₂-eq emissions for some alternative fuels

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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.

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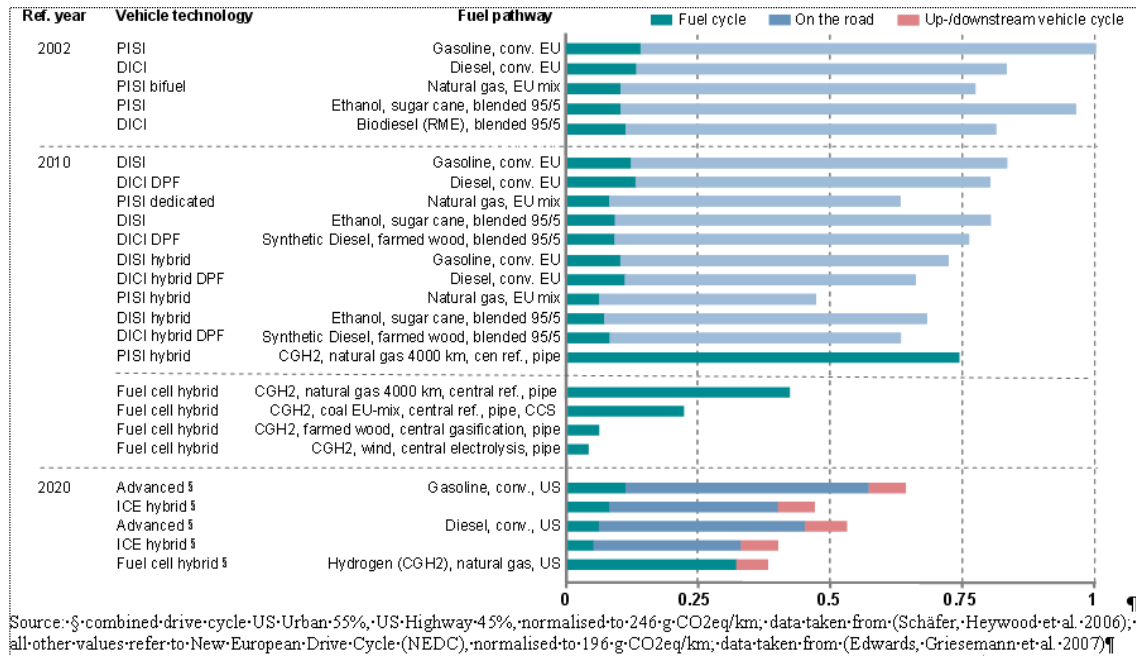
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3 Figure 21: Vehicle technologies and alternative fuels: CO₂-eq emissions well-to-wheels

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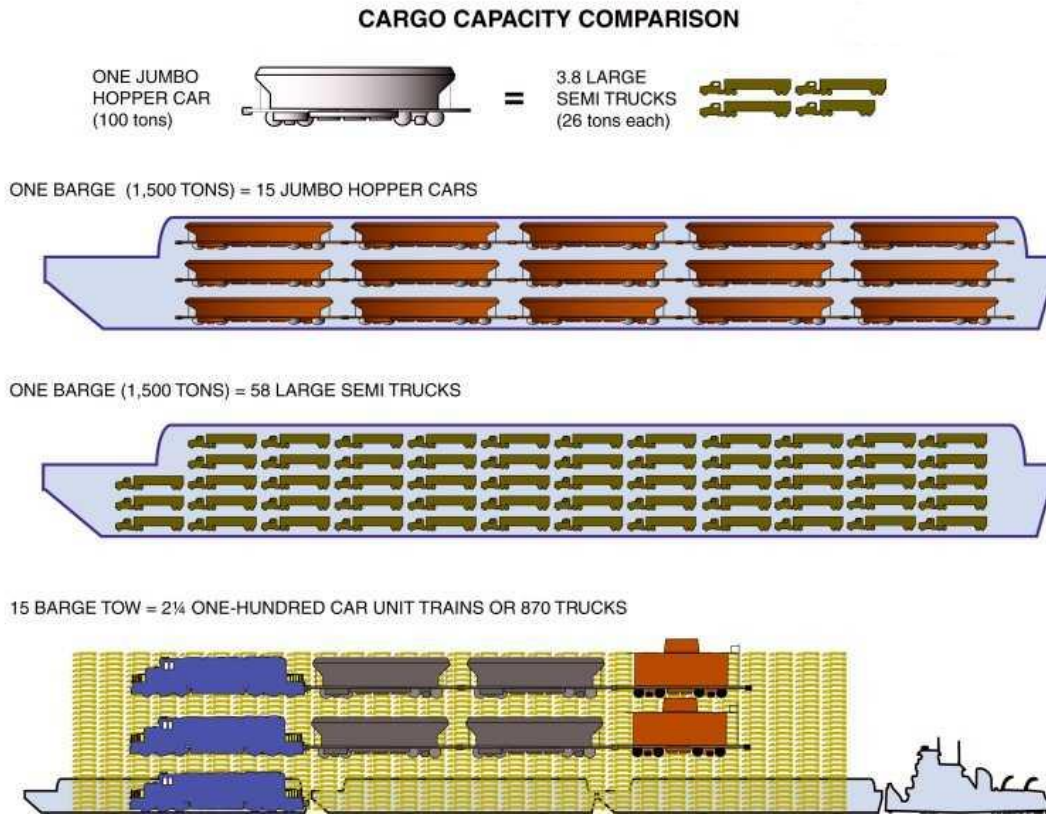
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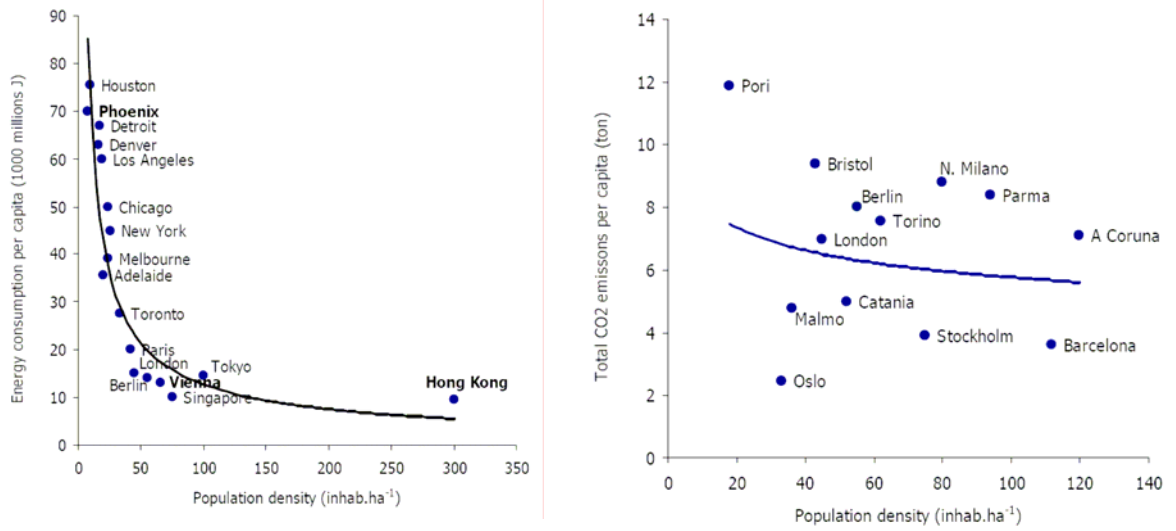
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Figure 22: Cargo Capacity Comparison (Source: www.ccpa-ohioriver.com)

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

6 Figure 24: CO₂ emissions per capita and population density for several world cities (adapted
7 from Ambiente Italia, 2003)

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