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Article

Emissions of CO_2, CO, NO_x, HC, PM, HFC-134a, N_2O and CH_4 from the global light duty vehicle fleet

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Abstract

Vehicles emit carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), particulate matter (PM), hydrofluorocarbon 134a (HFC-134a), methane (CH_4), and nitrous oxide (N_2O). An understanding of these emissions is needed in discussions of climate change and local air pollution issues. To facilitate such discussions an overview of past, present, and likely future emissions from light duty vehicles is presented. Emission control technologies have reduced the emissions of CO, VOCs, PM, HFC-134a, CH_4, and N_2O from modern vehicles to very low levels.

Zusammenfassung

Fahrzeuge emittieren Kohlendioxid (CO_2), Kohlenmonoxid (CO), Stickoxide (NO_x), Kohlenwasserstoffe (HC), Ruß, (PM), Fluorkohlenwasserstoffe 134a (HFC-134a), Methan (CH_4) und Distickstoff-Monoxid (N_2O). Ein Verständnis dieser Emissionen wird im Hinblick auf die Diskussionen über Klimaänderung und lokale Luftverschmutzungen benötigt. Um solche Diskussionen zu erleichtern wird ein Überblick über historische, gegenwärtige und wahrscheinliche zukünftige Emissionen von Kraftwagen bis ca 4 Tonnen dargestellt. Effiziente Emissionskontrolltechnologien haben die CO, VOCs, PM, HFC-134a, CH_4 und N_2O Emissionen moderner Fahrzeuge auf ein sehr niedriges Niveau gesenkt.

1 Introduction

Recognition of the contribution of vehicle emissions to local air pollution and climate change has led to a considerable research effort at the Ford Motor Company and elsewhere focused on understanding the nature and quantity of vehicle emissions and developing control technologies to reduce these emissions. We present an overview of emissions from light duty (< 8,500 lbs) vehicles related to local air quality and/or global climate issues. Light duty vehicles are generally used as passenger vehicles (e.g., passenger cars, pickup trucks, vans, sports utility vehicles). Given their commercial importance, and the importance of their emissions into the atmosphere, it is surprising that there is no single report which provides an overview of CO_2, HC, CO, NO_x, PM, R-134a, N_2O, and CH_4 emissions from light duty vehicles. Our intent here is to provide such an overview with a focus on likely future trends. We discuss six aspects of vehicle emissions. First, we consider life-cycle CO_2 emissions from typical vehicles to provide perspective on the relative importance of CO_2 emissions associated with different aspects of the vehicle's life cycle. Second, we present historical data for emissions of HC, CO, and NO_x to illustrate the trends in emissions. Third, we describe the effectiveness of new diesel particulate filter technology to mitigate PM emissions. Fourth, we consider the magnitude and relative climatic impact of R-134a, N_2O, and CH_4 emissions from the global vehicle fleet. Fifth, we describe some projections of CO, VOC, NO_x, and PM emissions from the global light duty vehicle fleet up to 2050. Finally, we discuss some options to reduce vehicle CO_2 emissions.

2 Life cycle CO_2 emissions

The life cycle CO_2 emissions (SULLIVAN et al., 1998a; FORD MOTOR COMPANY 2006/7 Sustainability Report, 2007) for a typical mid-sized car and sports utility vehicle (SUV) in the USA are given in Table 1. As seen from the table, the "in-use" portion (fuel combustion) accounts for approximately 90 % of the life cycle CO_2 emissions. Reducing the life cycle CO_2 emissions requires careful attention to the in-use portion.

Figure 1 shows the regional distribution of fossil fuel CO_2 emissions in 2004 taken from the 2005 Annual Energy Review of the Energy Information Administration (EIA, 2006). In 2004 the total global emission of CO_2 from energy consumption was 27 Gt (EIA, 2006). The pie charts on the top of Figure 1 show (from left to right) a breakdown of USA emissions into end-use sectors, a breakdown of emissions from the USA transportation sector into different transportation modes, and finally a breakdown of emissions from passenger cars into those

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Table 1: Life cycle CO_2 impact for typical vehicles. ^{1}well to wheels analysis; ^{2}22.9 miles per USA gallon (10.3 litres per 100 km); ^{3}16.9 miles per USA gallon (14.0 litres per 100 km, assuming 10.51 kg WTW CO_2 per USA gallon gasoline (2.78 kg WTW CO_2 per litre gasoline).

	Mid-sized car		**Mid-sized SUV**	
	Tonnes of CO_2	**% of total**	**Tonnes of CO_2**	**% of total**
Raw material production (steel, aluminium, plastics, ...)	3.5	5.6 %	4.3	5.2 %
Manufacturing/assembly	2.6	4.2 %	2.6	3.2 %
Ford manufacturing logistics	0.3	0.5 %	0.3	0.4 %
Fuel (120,000 miles [192,000 km]) WTW^1	55.1^2	88.6 %	74.6^3	90.4 %
Maintenance and repair	0.6	1.0 %	0.6	0.7 %
End of life/recycling	0.1	0.2 %	0.1	0.1 %
Total Lifecycle	62.2	100 %	82.5	100 %

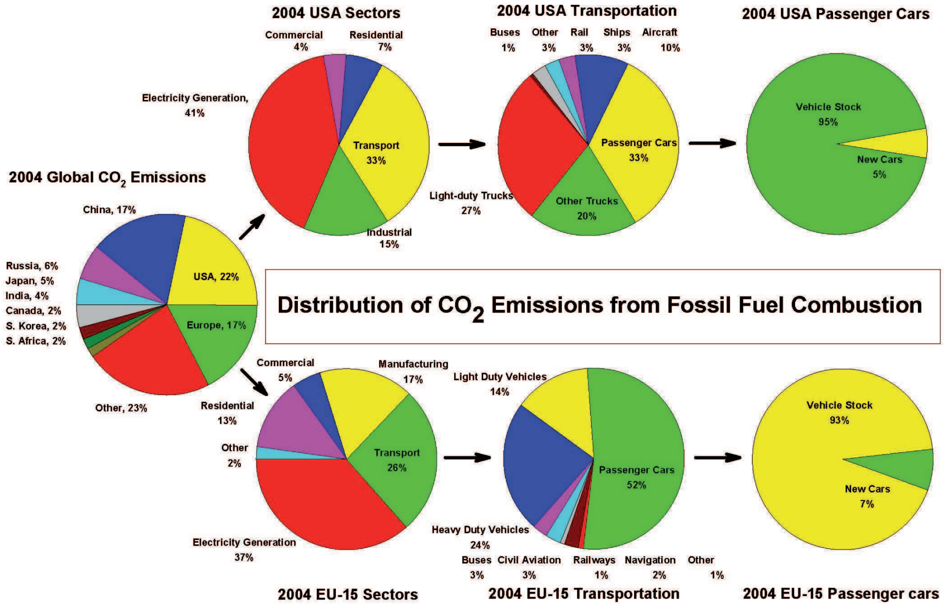

Figure 1: Distribution of CO_2 Emissions from Fossil Fuel Combustion.

from new cars versus those from cars older than 1 year. Data for the first two charts were taken from Tables 3–6 and 2–17 of the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks report (EPA, 2006). Data for the top right hand pie chart were taken from Tables 4.1 and 4.5 of the Oak Ridge National Energy Laboratory Transportation Energy Data Book (ORNL, 2006). The pie charts on the bottom of Figure 1 show comparable data from the EU. Data for the use sectors were taken from Table EU15-v1.3.xls in the European Environmental Agency's (EEA) Technical Report No 6/2006 (EEA, 2006a). Data for the transportation sector were taken from Figure 13 of EEA Technical Report 74 (EEA, 2006b). Data for the bottom right pie chart were taken from Tables 3.6.2 and 3.6.6 in the European Commission's European Union Energy & Transport in Figures 2005 report (EC 2006). As evident from Figure 1, passenger vehicles (cars and light duty trucks) in the USA and EU-15 are responsible for approximately 4.4 % and 2.9 % of global fossil fuel CO_2 emissions, respectively.

As illustrated by the pie charts on the right hand side of the figure, new cars represent rather small fractions of the vehicle stock (approximately 5 % in the USA and 7 % in the EU-15). The time taken for fleet turnover of approximately 10–15 years (ORNL, 2006) leads to a significant time lag between the adoption of new fuel efficient vehicle technology and its widespread penetration throughout the on-road vehicle fleet. Some options to reduce CO_2 emissions from vehicles are discussed in section 7. On a global basis, in 2004 light duty vehicles were responsible for approximately 3 Gt (SMP, 2004) which represents about 11 % of the total fossil fuel CO_2 emissions of approximately 27 Gt (EIA, 2006) (Gt = 10^9 tonnes = 1Pg).

3 HC, CO, and NO_x emissions

The chemistry leading to emissions of HC, CO, and NO_x from modern vehicles has been reviewed recently

Table 2: Historical perspective on vehicle HC, CO, and NO_x emissions.[1]from Table 3 in FEGRAUS et al., 1973; [2]gasoline; [3]80,000 km; [4]100,000 km; [5]Tier II bin 5 average requirement; [6]50,000 mile.

Year	HC (g/mile) [g/km]	CO (g/mile) [g/km]	NO_x (g/mile) [g/km]
1957–1962 USA Fleet[1]	8.8 [5.5]	81.6 [51]	3.7 [2.3]
1963–1967 USA Fleet[1]	9.1 [5.7]	92.8 [58]	3.5 [2.2]
1963–1967 USA Fleet[1]	4.7 [2.9]	58.7 [37]	4.9 [3.1]
1975/1976 USA Federal	1.5 [0.94]	15 [9.4]	3.1 [1.9]
1991 USA Federal	0.41 [0.26]	3.4 [2.1]	1.0 [0.6]
1994 USA Federal	0.41 [0.26]	3.4 [2.1]	0.4 [0.25]
2000 Europe Stage III[2,3]	0.32 [0.20]	3.8 [2.4]	0.24 [0.15]
2004 USA Federal	0.125 [0.08]	1.7 [1.1]	0.2 [0.13]
2005 Europe Stage IV[2,4]	0.16 [0.10]	1.6 [1.0]	0.13 [0.08]
2007 USA Federal[5,6]	0.075 [0.05]	3.4 [2.1]	0.05 [0.03]

(WALLINGTON et al., 2006), the details of engine operation are available in standard texts (HEYWOOD, 1988). Incomplete combustion leads to the presence of hydrocarbons (HC) and carbon monoxide (CO) in vehicle exhaust. Formation of NO in internal combustion engines occurs mainly as a result of the thermal dissociation of molecular oxygen to give oxygen atoms which then react with nitrogen molecules to give NO. This is known as the Zeldovich mechanism (ZELDOVICH, 1946). Recognition of the contribution of vehicle exhaust to the formation of photo-chemical smog in large urban areas such as Los Angeles in the 1950s led to the adoption of regulations controlling vehicle emissions starting in the 1960s in California. The development of vehicle emission control technology over the past 4 decades has led to large decreases in the emissions from new vehicles (per km driven) as illustrated in Table 2.

The data for the 1957–1967 fleet in Table 2 are averages from several hundred vehicles tested in the laboratory. The more recent data are regulatory standards which new vehicles must meet. Comparisons between regulatory standards for new vehicles and laboratory measurements of older vehicles in the on road fleet are complicated by the question of how closely the emissions from the on road fleet track those from new vehicles. However, it is clear from the increasing stringent regulatory standards and the magnitude of the difference between the latest standards and the measured emissions from the 1957–1967 fleet that on a per vehicle per km basis there have been major declines in HC, CO, and NO_x emissions over the past 40 years. It should be noted that because of increases in the vehicle fleet the reductions in the total emissions from the global vehicle fleet do not parallel those given in Table 2. However, as discussed in section 6, in spite of projected increases in the on-road vehicle fleet, the total emissions of “criteria” pollutants (i.e., HC, CO, NO_x, and PM) are projected to decline substantially in the coming decades. On a global basis, the emissions of HC, CO, NO_x in 2004 from light duty vehicles were approximately 27, 160, and 8 Mt, respectively (WBCSD, 2004) (Mt = 10^6 tonnes = 1Tg).

4 Particulate Matter (PM)

Combustion in diesel engines is initiated by the autoignition of diesel fuel sprayed into hot compressed air. Combustion in gasoline engines is initiated by a spark which ignites a homogeneous mixture of gasoline vapour and air. Diesel exhaust contains more PM (by a factor of approximately 50–100 on a mass basis) than gasoline exhaust. The higher particulate emissions arise from the incomplete combustion of liquid fuel droplets near the fuel injector. Although most of the particulates are burned by the excess O_2 in the cylinder before leaving the engine, some survive and leave in the engine-out exhaust as small particles (10–100 nm diameter). Control of particulate emissions is a significant issue for diesel engines. The recent development of diesel particulate filters (DPFs) that filter solid particles from the exhaust constitutes a significant advance in emissions control. As indicated in Figure 2, DPFs are effective at reducing exhaust PM to very low levels. DPFs have been introduced commercially and seem likely to become widely used in areas where PM emissions are a concern. As of July 2005 over 1 million DPF equipped vehicles had been sold by PSA Peugeot Citröen. The Ford Motor Company have been equip diesel vehicles with DPFs starting in 2007 in the USA and in 2005 in Europe. As discussed in section 6, the increased use of DPFs in the on-road vehicle fleet will contribute to the projected decline in PM emissions in the coming decades. On a global basis, the emissions of PM in 2004 from light duty vehicles were approximately 0.9 Mt, respectively (WBCSD, 2004).

5 Hydrofluorocarbon-134a (CF_3CH_2F), nitrous oxide (N_2O), methane (CH_4)

Hydrofluorocarbon-134a (also known as HFC-134a, R-134a, or CF_3CH_2F) is used as the replacement for CFC-

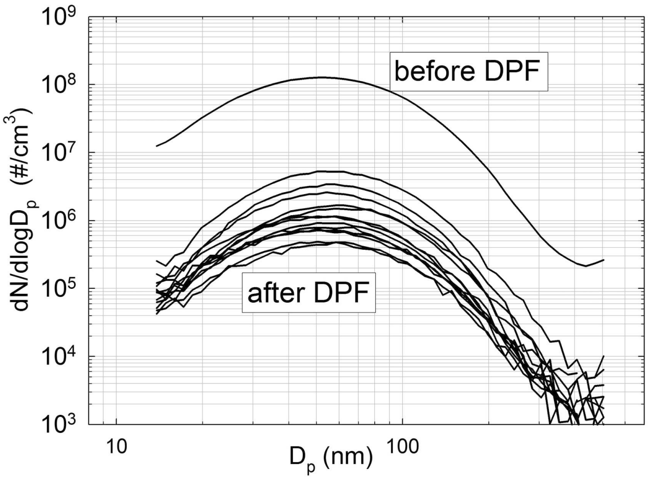

Figure 2: Illustration of Diesel Particulate Filter (DPF) effectiveness (adapted from GUO et al., 2003). The top trace shows the particle size distribution in exhaust before passing through the DPF. The lower traces show typical particle size distributions in exhaust after passing through the DPF.

12 (also known as R-12 or CF_2Cl_2) in vehicle air conditioning (AC) units. There are four emission modes of R-134a from vehicles; regular, irregular, servicing, and disposal. Regular loss refers to the slow leakage from hoses and seals. Irregular losses are caused by failures of the system. As their names suggest, servicing and disposal losses are incurred during servicing and disposal of the vehicle. The results from several studies of R-134a emission have been reported. SCHWARZ et al. (2001) give a total emission (i.e., from all modes) per vehicle of 0.24 ± 0.06 g/day. SIEGL et al. (2002) estimate a total emission rate of 0.41 ± 0.27 g/day. SCHWARZ and HARNISH (2003) reported the sum of regular and irregular emissions of be 0.19 g/day. STEMMLER et al. (2004) determined the sum of regular and irregular loss to be 0.336 g/day. Finally, VINCENT et al. (2004) estimate a total emission rate of 0.24 g/day. Within the likely experimental uncertainties, there is reasonable agreement between the results of the studies. Assuming 0.3 ± 0.1 g/day emission, 10000 miles (16,000 km) per year travelled, 25 miles per USA gallon fuel economy (9.5 litres per 100 km), and a global warming potential for R-134a of 1300 (100 year time horizon) SIEGL et al. (2002) estimated that the global warming impact of R-134a leakage from an AC equipped vehicle is approximately 3–5 % of that of the CO_2 emitted by the vehicle.

Nitrous oxide (N_2O) is produced as an intermediate during the reduction of NO_x in three way catalyst systems. Some N_2O escapes further reduction to N_2 and exits with the exhaust flow through the tailpipe into the atmosphere. N_2O has a global warming potential of 330 (100 year time horizon) and is an important greenhouse gas. Several studies of the emissions of N_2O from vehicles have been performed over the past 15 years. BERGES et al. (1993) reported emission factors (g of N_2O/g of CO_2) of (6 ± 3) x 10^{-5} and (14 ± 9) x 10^{-5} from tunnel studies in 1992 in Germany and Sweden, respectively. BECKER et al. (1999, 2000) reported emission factors of (6 ± 2) x 10^{-5} and (4.1 ± 1.2) x 10^{-5} from tunnel studies in Germany in 1997. JIMENEZ et al. (2000) used open path, cross road laser techniques to measure emission factors of (8.8 ± 2.8) x 10^{-5} and (12.8 ± 0.39) x 10^{-5} from on-road vehicles in California in 1996 and New Hampshire in 1998, respectively. BECKER et al. (2000) conducted a laboratory dynamometer study of 26 light duty cars and trucks and measured an average N_2O emission of 12 ± 8 mg/km. BEHRENTZ et al. (2004) conducted a similar test using 37 vehicles and found an emission rate of 20 ± 4 mg/km. HUAI et al. (2004) studied 60 vehicles, nearly half of which had N_2O emission rate $<$ 7 mg/km. Emission rates from the remaining vehicles varied significantly with the highest emissions being observed for older catalyst technologies. The results from all these studies are in broad agreement (within a factor of 2). The results reported by BERGES et al. (1993), BECKER et al. (1999, 2000), JIMENEZ et al. (2000), BEHRENTZ et al. (2004), and HUAI et al. (2004) are in broad agreement. BECKER et al. (1999) suggested that a good approximation of the average emission factor (g N_2O/ g CO_2) = (6∓2) x 10^{-5}. This corresponds to an emission rate of 16–8 mg N_2O /km for vehicles with fuel economies of 12–6 litres / 100 km (20–40 miles /U.S. gallon). Combining the (g N_2O/ g CO_2) = (6 ± 2) x 10^{-5} emission factor with a total CO_2 emission rate of 3Gt (see section 2) we estimate that the global vehicle fleet emits (0.18 ± 0.06) Tg yr^{-1} of N_2O (0.11 ± 0.04 Tg N yr^{-1}). Atmospheric levels of N_2O are increasing at a rate of 4.7 ∓ 0.9 Tg yr^{-1} (3.0 ± 0.6 Tg N yr^{-1}), BERGES et al. (1993). Hence, emissions from the global vehicle fleet represent approximately 2–6 % of the atmospheric growth rate of N_2O. The global warming potential of N_2O is 330 times that of CO_2. Using an emission factor (g N_2O/g CO_2) of (6 ± 2) x 10^{-5} it follows that N_2O emissions from light duty vehicles have a global warming impact which is 1–3 % of that of the CO_2 emitted from the vehicles.

Methane (CH_4) is produced in small quantities by combustion reactions occurring in internal combustion engines. NAM et al. (2004) analyzed CH_4 emissions from 30 different cars and trucks and recommended use of an emission factor (g of CH_4/g of CO_2) of (15 ± 4) x 10^{-5} for the USA on-road fleet. Using a global warming potential of 23, NAM et al. (2004) calculated that the global warming impact of CH_4 emissions from vehicles is 0.3–0.4 % of that of the CO_2 emissions from vehicles. The environmental impact of CH_4 emissions from vehicles is negligible and likely to remain so for the foreseeable future.

In the calculations above we have used the 100 year time horizon global warming potential, GWP, values of HFC-134a, N_2O, and CH_4 from the 2001 Intergovernmental Panel on Climate Change (IPCC) report, HOUGHTON et al. (2001). Global warming potential is defined as the ratio of the time integrated radiative forcing of a given mass of a well mixed greenhouse gas (HFC-134a, N_2O, and CH_4 for the calculations herein) relative to that of the same mass of another well mixed greenhouse gas (typically CO_2) over a specified time horizon. Global warming potential is a useful index to compare the radiative effects of different gases. The IPCC report provides an authoritative source of GWP values. Multiplication of the emission factor (g of X/g of CO_2) for a compound X (HFC-134a, N_2O, or CH_4 in the present work) by its GWP provides an estimate of the global warming impact of emissions of X from vehicles relative to that of CO_2. Uncertainties inherent in this approach include those associated with the emission factors (included above) and the global warming potential (difficult to estimate and not included in the analysis above, but includes typically approximately 10 % uncertainty in the measurement of IR cross sections, FORSTER et al. (2005), and approximately 20 % uncertainty in atmospheric lifetimes, RAVISHANKARA and LOVEJOY (1994)). This provides a useful method of placing the climate change impact of vehicle emissions of HFC-134a, N_2O, or CH_4 into perspective. Unfortunately, we can not use this approach to assess the climate impact of HC, NO_x and PM because these species have relatively short atmospheric lifetimes, do not become well mixed and hence do not have well defined global warming potentials.

6 Projections of future HC, CO, NO_X and PM emissions

The International Energy Agency (IEA) worked together with the World Business Council for Sustainable development (WBCSD) to develop a global transport spreadsheet model. The Sustainable Mobility Project (SMP) spreadsheet model is available from the WBCSD website (http://www.wbcsd.org) and provides a tool for projecting emissions associated with global transportation over the time period 2000–2050. Many of the world's leading automotive related companies were involved in developing the model: General Motors Corporation, Toyota Motor Corporation, Ford Motor Company, DaimlerChrysler AG, Honda Motor Company, Volkswagon AG, Nissan Motor Company, Renault SA, BP plc, Royal Dutch/Shell Group of Companies, Michelin, and Norsk Hydro ASA (WBCSD, 2004).

The reference case SMP model presents one possible set of future conditions, based on existing trends and including existing policies, population projections, income projections and expected availability of new technologies. In general, no major new policies are assumed to be implemented beyond those already implemented in 2003. An exception was when there was clear evidence of "policy trajectories" – future policy actions that are either explicit or implicit in other trends. For example, a clear trend was discernable in the developing world to adopt vehicle emissions standards similar to those already implemented in more developed nations. New DPF technology (see section 4) is projected to facilitate large decreases in PM emissions (down by a factor of approximately 10 and 3 from current levels by 2030 in OECD and non OECD countries, respectively).

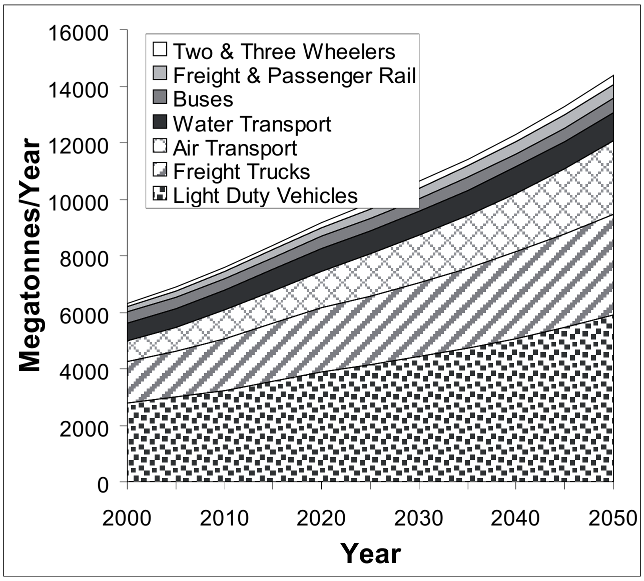

Figure 3: Projected transportation CO_2 emissions (in units of megatonnes of CO_2) in the SMP Reference Case (WBCSD, 2004).

Figure 3 shows the projected increase in CO_2 emissions in the SMP Reference Case (WBCSD, 2004). The main driver for the increase in CO_2 emissions shown in Figure 3 is the projected increase in demand for mobility by a factor of approximately 2 over the 2000–2050 time period. Figure 4 shows the projected decrease in NO_x emissions. The top panel give the emissions from Organization of Economic Cooperation and Development, OECD, countries (Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Mexico, The Netherlands, Norway, Japan, Korea, New Zealand, Poland, Portugal, Slovak Republic Sweden, Switzerland, United Kingdom, USA). The bottom panels give the projected emissions from non-OECD countries. Similar to the data for NO_x shown in Figure 4, the global emissions of CO, HC, and PM from light duty vehicles are projected decline by factors of approximately 10, 13, and 6, respectively (see Figures 2.16, 2.21, 2.17, 2.22, 2.18, and 2.23 in the SMT Report, (WBCSD, 2004)). Large reductions in the emissions of HC, CO, NO_x, and PM are anticipated from the on-road global vehicle fleet over the coming decades. The projected de-

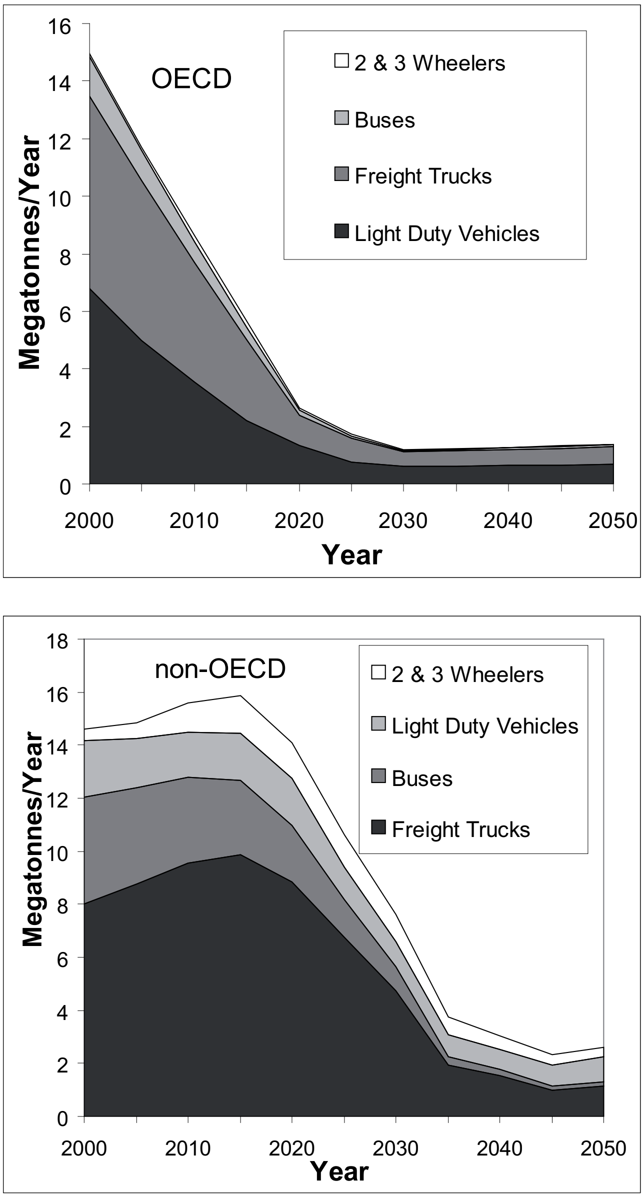

Figure 4: Projected NO_x emissions (in units of megatonnes of NO_2) from OECD (top panel) and non-OECD (bottom panel) countries in SMP Reference Case (WBCSD, 2004).

creases reflect both the continuing development of modern emission control technology (significantly more effective than older technology, see Table 2 and section 3) and its diffusion into the on-road fleet (10–15 year time lag, see section 2) and come despite a factor of approximately 2 increase in mobility delivered by light duty vehicles (1.5 x 10^{13} passenger km in 2000, 3.5 x 10^{13} passenger km in 2050) (WBCSD, 2004).

7 Options to reduce in-use cycle CO_2 emissions

Options to reduce vehicle CO_2 emissions include: (i) ecodriving, (ii) weight reduction, (iii), power reduction, (iv) dieselization, (v) hybrid technology, (vi) biomass derived fuels, (vii) electric vehicles, (viii) hydrogen internal combustion engine (H2ICE) vehicles, and (ix) hydrogen fuel cell vehicles. There are other options which may be important (e.g., use of low friction tyres, improved lubricants, tyre pressure monitors) but these options generally have a lower individual impact than the nine listed above and so are not discussed here. While the list of nine options above is not exhaustive, we believe that it is reasonably comprehensive. We provide a brief discussion of each of the nine options in turn below.

Ecodriving refers to driving in an ecological and economical fashion (driving at posted speed limits, accelerating smoothly, braking gradually, ensuring for proper tire pressure, replacing air filters as needed, using appropriate engine oils, etc.). Reducing the weight of the vehicle reduces its energy consumption, light weight magnesium and aluminium alloys are finding increased use in automotive applications. The life cycle CO_2 benefit associated with vehicle weight reduction by material substitution depends on the material (aluminium, magnesium, fibre composites, etc.) replacing the base case material (usually steel) and/or iron) and the efficiency of the powertrain efficiency. There is a trade-off between the extra energy almost always usually required to make an “alternative material” relative to its ferrous counterpart and the operational energy saved in reducing the vehicle inertial weight. As the energy efficiency of the powertrain increases, the life cycle energy and carbon dioxide emissions benefit of weight reduction decreases (SULLIVAN et al., 1995, 1998b). For today’s vehicles, weight reduction via material substitution is generally beneficial. Reducing the power of the engine reduces its energy requirement but also reduces the vehicle’s performance. Diesel engines are more efficient than gasoline engines for two main reasons. First, diesels do not suffer from the pumping losses associated with the throttling necessary in gasoline engines. Second, diesel engines operate at a higher compression ratio than gasoline engines (improved Carnot efficiency). Motivated by a desire to increase the fuel efficiency of their vehicles, automobile manufacturers are exploring new technologies which will make gasoline engines more diesel-like in their operation. SULLIVAN et al. (2004) have estimated that on a well-to-wheels per vehicle per km basis, the CO_2 reduction opportunity for replacing a gasoline vehicle with its equivalent diesel counterpart was 24–33 % in 2004 and will decrease to 14–27 % by 2015.

Hybrid vehicles are propelled down the road by a combination of an electric motor and an internal combustion engine (gasoline for all hybrids currently on the market). All the energy used to propel the vehicle comes from chemical energy in the gasoline in the fuel tank (although the battery alone can propel the vehicle, the energy in the battery comes from combustion of gasoline).

Regenerative braking is used to capture energy during braking and charge the battery. When there is little, or no load, on the engine (e.g. stopped at lights, travelling slowly in congested traffic) the gasoline engine shuts down to save fuel. Hybrid vehicles offer substantial fuel savings in city driving but offer more modest savings in highway driving. The 2.3 L Ford Hybrid Escape has city and highway fuel economies of 36 and 31 miles per USA gallon (6.6 and 7.6 litres per 100 km). The 2.3 L Ford Escape has city and highway fuel economies of 23 and 26 miles per USA gallon (10.2 and 9.1 litres per 100 km).

The use of biomass derived fuel such as ethanol or biodiesel can lead to a significant reduction in the well-to-wheels CO_2 emissions. In principal, if little, or no, fossil fuel is used in the production of the biofuel then the net CO_2 emissions associated with combustion of the fuel in the vehicle will approach zero. As seen from Table 1, fuel combustion accounts for approximately 90 % of the vehicle life cycle CO_2 emissions. Hence, in principle, the use of biofuels offers an opportunity to reduce the CO_2 emissions significantly. Given the fact that gasoline with up to 10 % ethanol (E10) can be used in vehicles currently on the road, biofuels could begin immediately reducing vehicle fleet fossil carbon emissions without waiting for significant penetration of more fuel efficient vehicles into the fleet. Ethanol can be made from corn (maize) or lignocellulosic feedstocks. Corn ethanol offers approximately a 20–30 % well-to-wheels greenhouse gas reduction per gallon of ethanol used to displace an energy equivalent amount of gasoline (WANG, 2005). Lignocellulosic ethanol offers an approximately 80–90 % well-to-wheels greenhouse gas reduction (WANG, 2005). At the present time it is unclear whether biofuels can be produced with sufficiently low fossil fuel inputs, in sufficient quantities, and at sufficiently low cost to make a major impact. Biofuels are an area of substantial current research interest.

Electric vehicles do not emit CO_2 and, if the electricity used to charge the battery has a low fossil fuel burden, then the use of electric vehicles would lead to a decrease in CO_2 emissions. The mass use of electric vehicles awaits the development of cheap, robust, high energy density, rapidly rechargeable batteries. Hydrogen can be burnt in internal combustion engines (H2ICE) or used in fuel cells. Hydrogen fuel cell vehicles have received considerable attention because of their potential to be much more efficient than gasoline vehicles on the road today. However, there are formidable technical challenges to be overcome before hydrogen will see mass use as a transportation fuel. These include: the high cost and environmental impacts associated with hydrogen production and distribution; low energy density, which makes storing sufficient hydrogen on a vehicle difficult; fuel cell cost; and fuel cell durability.

8 Conclusions

Vehicles emit carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), particulate matter (PM), hydrofluorocarbon-134a (HFC-134a), methane (CH_4), and nitrous oxide (N_2O). There has been substantial progress in reducing the emission of criteria pollutants (NO_x, CO, HC, and PM) linked to local photochemical air pollution and it seems likely that this progress will continue in the future. As a result of continued improvement in and more spread use of emissions control technology, the global emissions of NO_x, CO, HC, and PM from light duty vehicles are projected to decline by factors of approximately 6, 10, 13, and 6, respectively from 2000 to 2050 (WBCSD, 2004). With regard to climate change, the emissions of HFC-134a, CH_4, and N_2O from light duty vehicles have impacts which are approximately 3–5 %, 0.3–0.4 %, and 1–3 %, respectively, of that of CO_2 emissions from vehicles. Options to reduce vehicle CO_2 emissions include: (i) ecodriving, (ii) vehicle weight reduction, (iii) vehicle power reduction, (iv) increasing dieselization, (v) use of hybrid technology, (vi) use of biomass derived fuels, (vii) use of electric vehicles, (viii) use of hydrogen internal combustion engine (H2ICE) vehicles, and (ix) use of hydrogen fuel cell vehicles.

9 Acronyms

DFP – diesel particulate filter
EEA – European Environment Agency,
EIA – Energy Information Agency
EPA – Environmental Protection Agency,
G – giga (10^9)
H2ICE – hydrogen internal combustion engine
HC – hydrocarbons
HFC-134a – hydrofluorocarbon 134a (CF_3CFH_2)
M – mega (10^6)
ORNL – Oak Ridge National Laboratory
P – peta (10^{15})
PM – particulate matter
R-134a – refrigerant 134a (CF_3CFH_2)
SMP – Sustainable Mobility Project
T – tetra (10^{12})
WBCSD – World Business Council for Sustainable Development

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