Extended Abstracts

Light Duty Vehicle Emissions

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ABSTRACT: Vehicles emit carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), 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 low levels.

1. INTRODUCTION

Recognition of the contribution of vehicle emissions to local air pollution and climate change has led to a considerable research effort focussed on understanding the nature and quantity of vehicle emissions and developing control technologies to reduce these emissions. We present an overview of six important aspects of light duty (< 8,500 lbs) vehicle emissions. First, the life-cycle CO_2 emissions from a typical vehicle. Second, the historical data for emissions of HC, CO, and NO_x. Third, the use of diesel particulate filter technology to mitigate PM emissions. Fourth, the magnitude of R-134a, N_2O, and CH_4 emissions from the global vehicle fleet. Fifth, the projections of CO, VOC, NOx, and PM emissions from the global vehicle fleet up till 2050. Finally, the options to reduce the vehicle life cycle CO_2 emissions.

2. LIFE CYCLE CO_2 EMISSIONS

The life cycle CO_2 emissions for a typical mid-sized car in the US are given in Table 1. 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.

Table 1: Life cycle CO_2 impact for typical mid-sized car

	Tonnes of CO_2	% of total
Raw material production (steel, aluminium, plastics, …)	3.5	5.7%
Ford manufacturing/assembly	2.5	4.0%
Manufacturing logistics	0.1	0.2%
Fuel (120,000 miles at 22.9 miles per US gallon) WTW [1]	55.1	88.9%
Maintenance and repair	0.6	1.0%
End of life/recycling	0.1	0.2%
Total Lifecycle	61.9	100%

[1] well to wheels analysis

3. HC, CO, AND NO_X EMISSIONS

Incomplete combustion leads to the presence of hydrocarbons (HC) and carbon monoxide (CO) in vehicle exhaust. Formation of NO by the Zeldovich mechanism (Zeldovich, 1946) leads to the

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emission of NO_x. Recognition of the contribution of vehicle exhaust to the formation of photochemical 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 mile driven) as illustrated in Table 2.

Table 2. Historical perspective on vehicle HC, CO, and NO_x emissions

Year	HC (g/mile)	CO (g/mile)	NO_x (g/mile)
1957-1962 US Fleet [1]	8.8	81.6	3.7
1963-1967 US Fleet [1]	9.1	92.8	3.5
1963-1967 US Fleet [1]	4.7	58.7	4.9
1975/1976 US Federal	1.5	15	3.1
1991 US Federal	0.41	3.4	1.0
1994 US Federal	0.41	3.4	0.4
2000 Europe Stage III [2,3]	0.32	3.8	0.24
2004 US Federal	0.125	1.7	0.2
2005 Europe Stage IV [2, 4]	0.16	1.6	0.13
2007 US Federal [5,6]	0.075	3.4	0.05

[1] from Table 3 in Fegraus et al., 1973;
[2] gasoline;
[3] 80 K km;
[4] 100 K km;
[5] Tier II bin 5 average requirement;
[6] 50 K mile

Data for the 1957-1967 fleet are averages from several hundred vehicles tested in the laboratory. The more recent data are regulatory standards which new vehicles must meet. As seen from Table 2, there has been major and continuing progress in reducing the emissions of HC, CO, and NO_x from new vehicles. Over the past 40 years the emissions (g/mile) of hydrocarbons and CO has declined by approximately 2 orders of magnitude. NO_x emissions have declined by a factor of forty. 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 (ie, HC, CO, NO_x, and PM) are projected to decline substantially in the coming decades.

4. PARTICULATE MATTER (PM)

Combustion in diesel engines is initiated by spraying liquid diesel fuel into the combustion cylinder. Combustion in gasoline engines is initiated by a spark which ignites a homogeneous mixture of gasoline vapor 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 1, DPFs are highly 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 will equip diesel vehicles with DPFs starting in 2007 in the US 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.

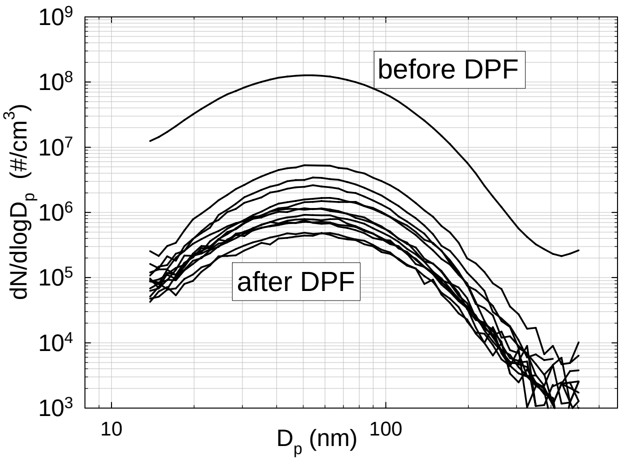

Figure 1: Illustration of Diesel Particulate Filter effectiveness (adapted from Guo et al., 2003).

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-12 (also known as R-12 or CF_2Cl_2) in vehicle air conditioning 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 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. 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 per year travelled, 25 miles per US gallon fuel economy, 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 < 10 mg/mile. 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). Becker et al. (1999) have estimated that N_2O emissions from vehicles have a global warming impact which is 1-3% of that of the CO_2 emissions from 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 US 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.

6. PROJECTIONS OF FUTURE HC, CO, NO_X AND PM EMISSIONS

The International Energy Agency (IEA) and World Business Council for Sustainable Development (WBCSD) have developed the Sustainable Mobility Project (SMP) spreadsheet model (http://www.wbcsd.org) which projects emissions from global transportation over the time period 2000-2050. Many of the world's leading automotive related companies were involved in developing the model (WBCSD, 2004).

Figure 2 shows the projected increase in CO_2 emissions in the SMP Reference Case (WBCSD, 2004). Figure 3 shows the projected decrease in NO_x emissions. The top panels give the emissions from Organization of Economic Cooperation and Development, (OECD) countries, the bottom panels give the projected emissions from non-OECD countries. Emissions reductions for CO, HC, and PM are projected to be comparable to those for NO_x . 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 decreases reflect the diffusion of modern emission control technology into the on-road fleet.

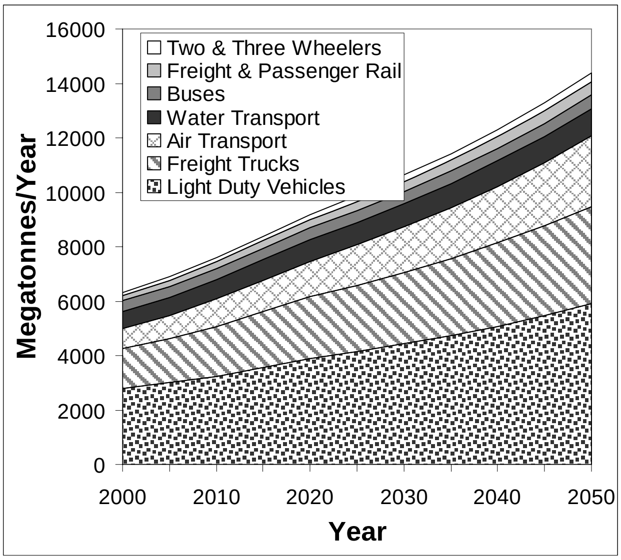

Figure 2: Projected transportation CO_2 emissions in the SMP Reference Case (WBCSD, 2004).

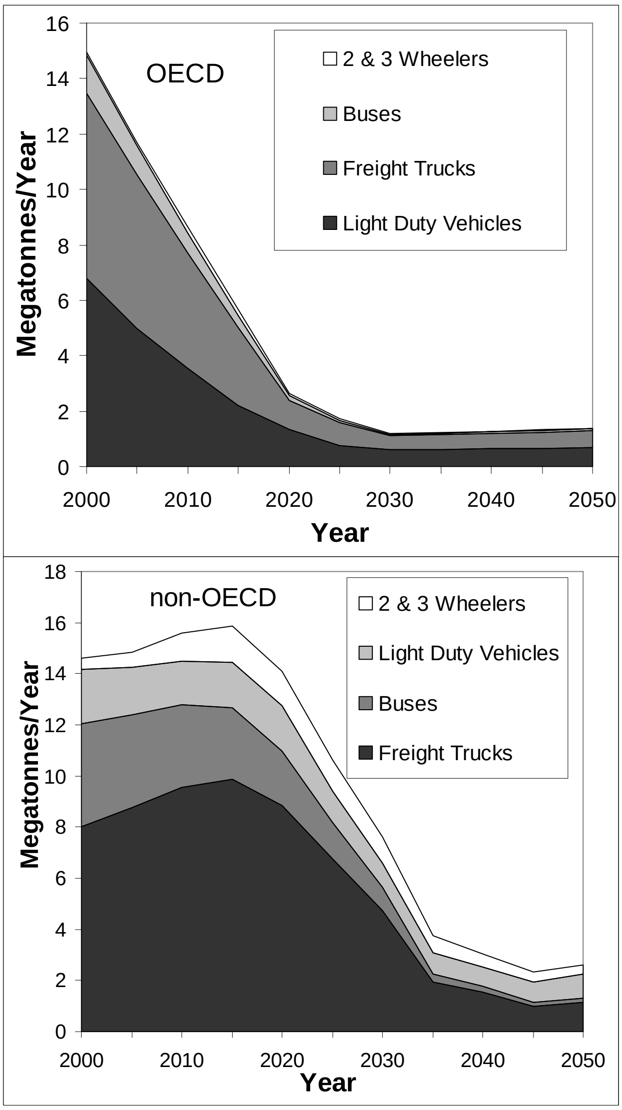

Figure 3: Projected NO_x emissions from OECD (top panel) and non-OECD (bottom panel) countries in SMP Reference Case (WBCSD, 2004).

7. OPTIONS TO REDUCE LIFE CYCLE CO_2 EMISSIONS

Options to reduce vehicle life-cycle 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.

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 (aluminum, magnesium, fiber composites, etc.) replacing the base case material (usually steel) and/or iron) and the efficiency of the powertrain efficiency. There is a tradeoff 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, 1998). 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 which is not desirable. 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. 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 mile 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 US gallon. The 2.3 L Ford Escape has city and highway fuel economies of 23 and 26 miles per US gallon.

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. 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 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 due to 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), hydrofluorocarbons-134a (HFC-134a), methane (CH_4), and nitrous oxide (N_2O). There has been substantial progress in reducing the emission of criteria pollutants (CO, NO_x, HC, PM) linked to photochemical air pollution. Emissions of CO, NO_x, HC, PM, HFC-134a, CH_4, and N_2O are small and/or short term issues. CO_2 is a large and long term issue.

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Physico-Chemical Characterization of Soot Emitted by a Commercial Aircraft Engine : Morphology, Size, Structure, and Elemental Composition

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ABSTRACT: We present here experimental studies performed on soot particles collected from a commercial aircraft engine. Electron microscopy techniques are used to determine the morphology, the microstructure, and the size distribution of primary soot particles. Their elemental composition is also determined as well as their vibrational characteristics by the mean of X-ray energy dispersive spectrometry and Fourier transform infrared spectroscopy.

1 INTRODUCTION

Nowadays, understanding the aviation's impact on the radiative forcing, climate change, air quality and human health is a challenging task (J.E. Penner *et al.*, 1999). Although only a few percent of the global fuel is used by air traffic, the major part of aircraft exhausts is emitted into sensitive atmospheric regions, namely the troposphere and lower stratosphere. Carbonaceous particles, such as aircraft engine soot, released in the upper troposphere are a major concern with regards to climate response impacts. Indeed, aviation-produced soot aerosols are suspected to enhance contrails and cirrus formation (Schumann *et al.*, 2002 ; Schumann, 2005), giving rise to a positive radiative forcing (Seinfeld, 1998). Numerous observations have shown that persistent contrails can evolve into extensive artificial cirrus clouds (Seinfeld, 1998 ; Schröder *et al.*, 2000) and the potential modification of natural cirrus caused by aircraft-produced carbonaceous particles via heterogeneous ice nucleation (Lohmann *et al.*, 2004) have been estimated with general circulation models. However, results obtained with these models largely depend on their ability to represent the sources, transport pathways, and sinks of various aerosol types in the atmosphere. Recent climate models with sophisticated aerosol modules have been developed (Stier *et al.*, 2005 ; Lauer *et al.*, 2005) but they need to be complemented by field and laboratory measurements with regard to the physico-chemical properties of atmospheric aerosols as well as their ice nucleation properties. In spite of many efforts undertaken to date by the scientific community, there is still a lack of knowledge about the structure, the morphology, the composition, and the reactivity of aircraft engine soot particles. In order to contribute to this effort, we present here an experimental study of the physico-chemical properties of soot particles emitted by a commercial aircraft engine.

2 EXPERIMENTS

The soot sampling is made on a civil aero-engine bench at SNECMA Villaroche center (France) during Landing/Take-Off (LTO) cycles. Jet A1 fuel containing 0.15 wt% of sulfur is used during the engine runs. Soot particles are collected by direct impaction on polycarbonate membranes (Nu-

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cleopore® Isopore), silicon windows (UQG Ltd, Cambridge), and electron microscope grids (Holey carbon film, Oxford Instruments) that are located in the exhaust flux axis at 27 m behind the commercial aircraft engine. Size and morphology of the particles are determined by using a high resolution scanning electron microscope (SEM) JSM-6320F (Jeol) having a spatial resolution of 1.2×10^{-9} m at 15 kV and a transmission electron microscope (TEM) JEM 2000FX (Jeol) having a spatial resolution of 0.28×10^{-9} m at 200 kV. Both microscopes are equipped with a X-ray energy dispersive spectrometer (EDS, TRACOR series II) that enables to determine the elemental chemical composition of our samples. Chemical elements having atomic number larger than 5 are detectable by this technique at concentrations > 0.1 wt%. Soot particles that impact the TEM grids are imaged by using the phase contrast imaging method and their microstructure is determined by electron diffraction. Polycarbonate membranes, which are not conductive, are coated with an amorphous thin carbon film that makes them conductive prior to SEM investigations. The Image J software package, which is freely available (http://rsb.info.nih.gov/ij/), is used for analyzing both SEM and TEM images. Soot samples collected onto silicon windows are studied by Fourier transform infrared spectrometry (FTIR) (Equinox 55, BRUKER) in transmission mode in order to characterize the surface functional groups.

3 RESULTS

3.1 *Morphology and size distribution of soot primary particles*

A typical SEM micrograph of a soot sample collected on a polycarbonate membrane and coated with an amorphous carbon film is shown in figure 1a. Small aggregates made of a few spherical soot primary particles are sparsely deposited but clearly visible near the black disk that corresponds to a pore of the membrane. The spherical shape of soot primary particles is also observed in figure 1b that shows a chain of primary particles recorded during a TEM experiment.

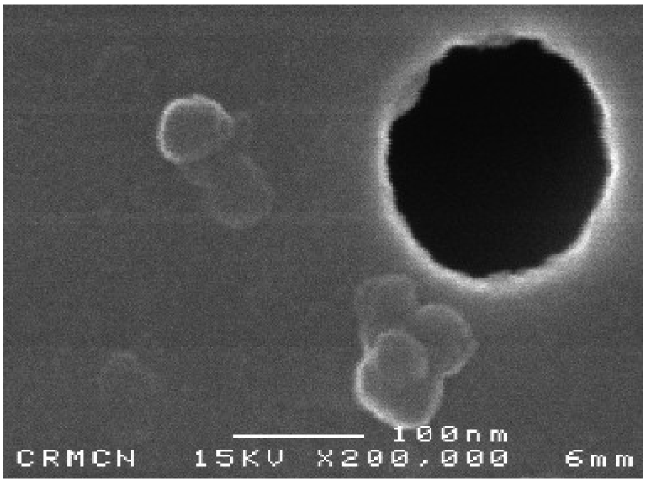

Figure 1a. SEM image recorded at 15 kV and a magnification of 200,000. The black disc corresponds to a pore of the membrane. Small aggregates of aircraft engine soot are located near the pore.

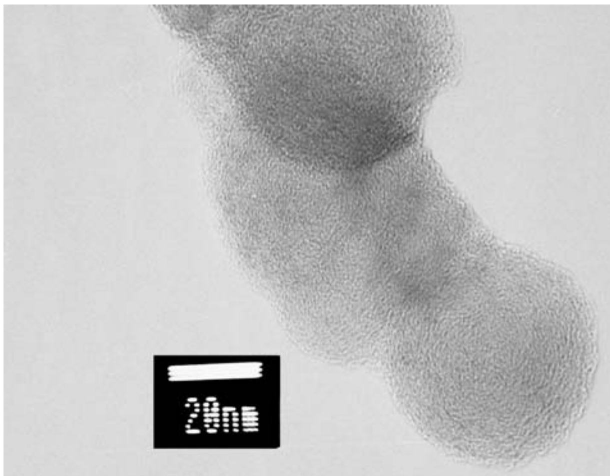

Figure 1b. TEM image of a chain of spherical soot primary particles recorded at 200 kV and a magnification of 300,000.

We rarely observe primary particles as single discrete spherules among our numerous SEM and TEM images. They mainly appear as small asymmetric aggregates or elongated chains with a limited number of particles, like diesel soot particles (Van Poppel, 2005). The size distribution, fractal dimension, and the number of primary particles of these aggregates and chains will be presented in a forthcoming
paper. We present here in figure 2 the primary particles size distributions derived from SEM and TEM analyses. The diameter of over 10,007 and 13,494 primary particles is measured respectively on TEM and SEM images.

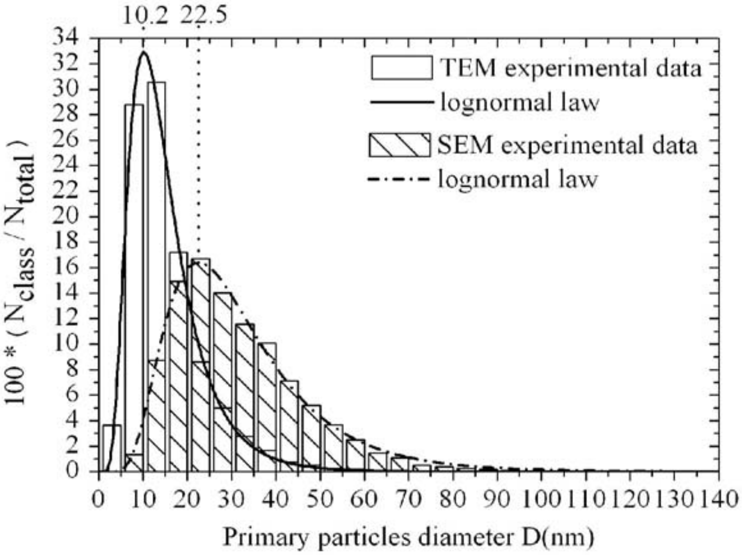

Figure 2. Primary particles size distributions derived from SEM and TEM images. N_{class} is the number of primary particles of a given class and N_{total} is the total number of particles which is equal to 10,007 and 13,494 respectively for the TEM and SEM analyses.

Although both size distributions follow a lognormal law, their maxima are centered at (10.2 ± 0.1) $\times 10^{-9}$ m and (22.5 ± 0.2) $\times 10^{-9}$ m when derived from TEM and SEM images respectively. Keeping in mind that soot samples deposited on polycarbonate membranes are coated with an amorphous carbon film prior to the SEM analysis, we attribute the difference in the maxima positions to the amorphous carbon film thickness. We conclude from several set of measurements that TEM is a more suitable technique for determining the primary particles size distribution since, unlike SEM, it does not require a sample preparation which strongly shifts the maximum of the size distribution towards higher values. This latter point will be discussed in another paper. The primary soot particles mean diameter of (10.2 ± 0.1) $\times 10^{-9}$ m obtained from our TEM measurements is lower than values available in the literature, which are in the range 25 to 50 $\times 10^{-9}$ m for various types of soot (Petzold, 1998 ; Popovicheva *et al*., 2000 . Popovicheva *et al*., 2003) but it has to be noted that this work is the first to have been conducted with a commercial aircraft engine in a civil aero-engine bench.

3.2 *Microstructure and elemental composition*

A TEM image of a soot primary particle is shown in figure 3a. It clearly exhibits a spherical shape made out of concentric, size-limited, graphene layers arranged in an “onion-like” structure. Such structures have already been observed in premixed flames (Grieco *et al*., 2000) as well as in combustor soot (Popovicheva *et al*., 2000).

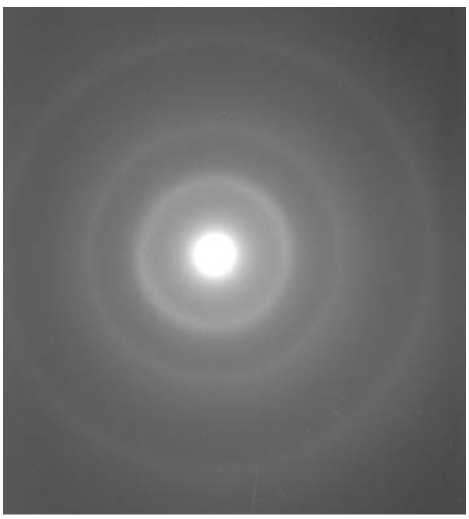

Figure 3a. “Onion-like” structure of a soot primary particle observed by TEM at 200 kV.

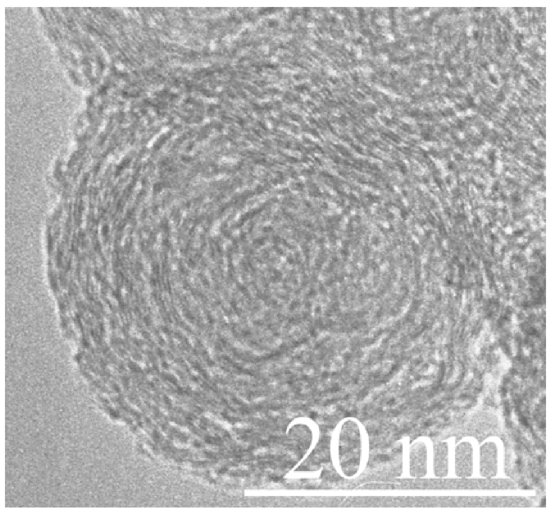

Figure 3b. Diffraction pattern of soot primary particles having an “onion-like” structure.

In addition to the specular reflection, diffraction patterns associated to the observed “onion-like” structures do not exhibit bright diffraction spots but three distinct diffuse rings, as shown in figure 3b, which correspond to real-space values of $d_{(002)} = (\ 3.82 \pm 0.17\ ) \times 10^{-10}$ m, $d_{(10.)} = (\ 2.15 \pm 0.07\ ) \times 10^{-10}$ m, and $d_{(11.)} = (\ 1.25 \pm 0.02\ ) \times 10^{-10}$ m. These diffuse rings are typical of turbostratic structures and thus support the real-space TEM observations. Numerous EDS analyses on such particles also allow us to determine their mean elemental composition. We find that they are mainly constituted of carbon atoms, 98.3 ± 2.5 % at., with a few oxygen atoms, 1.5 ± 0.4 % at., and traces of sulfur atoms, 0.12 ± 0.05 % at. This elemental composition do not really differ from that determined by Popovicheva *et al.* (2004).

3.3 *Infrared spectrum of aircraft engine soot*

Soot particles may have surface functional groups that cannot be evidenced by EDS experiments. Thus we have performed FTIR experiments in transmission mode on soot particles deposited onto silicon windows. An infrared spectrum recorded at room temperature and with a resolution of 4 cm^{-1} is shown in figure 4.

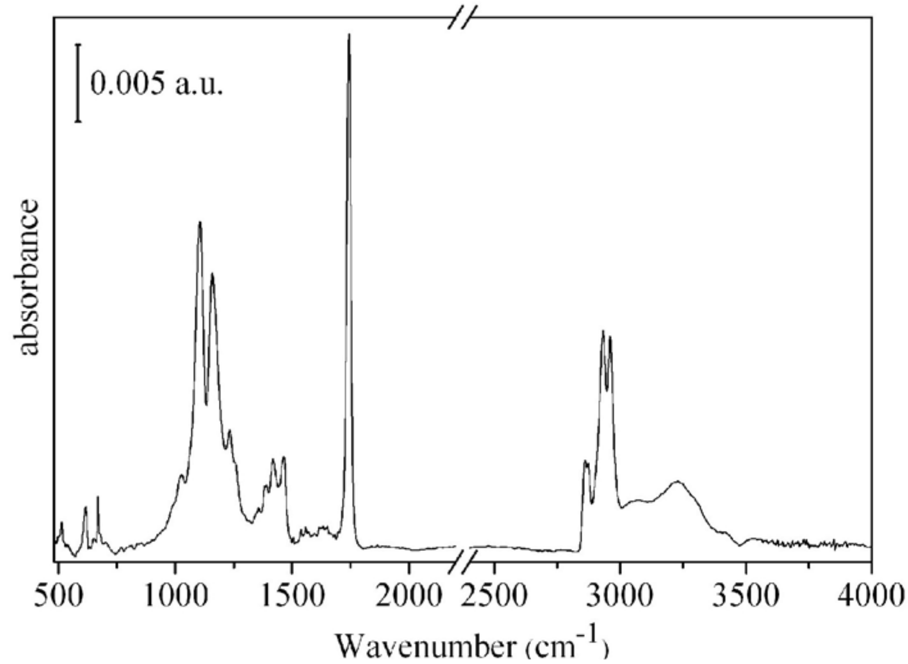

Figure 4. FTIR spectrum of aircraft engine soot recorded at 4 cm^{-1} resolution.

This spectrum is relatively complicated and at this stage, we can not unambiguously assess all the various peaks. The most intense contribution at 1730 cm^{-1} is due to C=O carbonyl groups. Bands between 3000 and 3600 cm^{-1} are attributed to free hydroxyl OH groups and also to associated OH groups such as alcohol and carboxylic functions. The carbon skeleton (-C-C- and -C=C- groups) results in many absorption bands between 1000 and 1600 cm^{-1} whereas CH_2 and CH_3 vibrational modes are detected in the range 2800 – 3000 cm^{-1}. We also note the presence of sulfur and disulfur bands around 500 cm^{-1}. The assessment of several other spectral features is still under investigation and a more detailed analysis will be presented in a forthcoming paper. However, the detected functional groups are consistent with our EDS analyses.

4 CONCLUSION

We have presented here an experimental characterization of the physico-chemical properties of soot particles collected from a commercial aircraft engine. We have performed TEM and SEM experiments that show the spherical morphology of the primary soot particles and allow the determination of their size distribution, which follows a lognormal law centered at (10.2 ± 0.1) × 10^{-9} m. The elemental composition indicates that these particles are mainly composed of carbon, with a few oxygen and traces of sulfur. Various surface functional groups have also been evidenced at the surface of soot particles through FTIR experiments. However, further experiments combining complementary experimental techniques are needed to investigate the reactivity of soot particles in order to reach a better understanding of their ice nucleating properties.

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Development of an Emissions Database to Inform Comparisons of Various Transportation Modes

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Keywords: intermodal comparison, transportation emissions, aircraft, on-road, locomotive, shipping

ABSTRACT: While comparison of emissions within a transportation mode (i.e. comparing Car A to Car B) is fairly straightforward using existing data sources, comparison across modes (i.e. comparing Car A to Aircraft B) is more difficult. Appropriate comparisons are challenging because duty cycles, emissions metrics, measurement instrumentation, and other factors differ among transportation modes. In response, a Comparative Emissions DataBase (CEDB) is being designed and implemented to inform comparisons of various transportation modes in terms of potential impact on global climate change. The transportation modes being considered are commercial aircraft, light-duty cars, heavy-duty diesel trucks/buses, locomotives, and marine vessels. Emissions data are being drawn from regulatory certification measurements and research-grade measurements, both from literature and our own studies. While the focus of this project is compiling and organizing measured emissions data rather than inventory development or policy analysis, some basic examples of the modal comparisons facilitated by the CEDB have also been performed.

1. MOTIVATION AND OVERVIEW

Often there are several options for the mode of transportation used by passengers or freight companies. For example, a passenger wishing to travel from Boston to New York can choose to travel by car, airplane, bus, or train. Freight companies make similar choices among heavy-duty diesel trucks, freight trains, cargo ships, and freight aircraft. These decisions are usually based on factors such as cost, travel time, safety, and convenience. However, various modes of transportation also present trade-offs in terms of environmental impact. The objective of this work is to build a database tool, incorporating data from our own measurements, literature and certification sources, that enables a comparison of the potential environmental impact (especially for climate change) of moving passengers and freight via various transportation modes. This tool could potentially be used by policy-makers or urban planners to devise incentives or other programs that would minimize environmental impact by encouraging the use of certain transportation modes for certain routes.

The pollutants considered in the database include traditional long-lived greenhouse gases (CO_2, CH_4, N_2O) that effect climate change directly and shorter-lived urban air pollutants (CO, NO_X, hydrocarbons) that can have an indirect effect on the climate in addition to contributing to smog formation and other environmental effects. In addition, formaldehyde (HCHO) is also included because it is an important air toxic and a major component of the total hydrocarbon emissions from many combustion sources.

The sources of data for the CEDB include measurements performed by Aerodyne Research (ARI) during various measurement campaigns, literature data, and certification data. The individual data sources are too numerous to list, but major sources for each mode include: on-road vehicles (Becker et al. 2000; Shorter et al. 2001; Nam et al. 2004; Davis and Diegel 2006), aircraft (Spicer et al. 1994; Herndon et al. 2004; Anderson et al. 2006; Herndon et al. 2006; ICAO 2006; Wey et al. 2006), locomotives (Fritz and Cataldi 1991; Fritz 1994; U.S. EPA 1998), and marine ships (Corbett and Koehler 2003; Endresen et al. 2003; Eyring et al. 2005; Williams et al. 2005).

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2. CHALLENGES OF INTERMODAL COMPARISON

Comparing emissions performance among transportation modes is challenging for several reasons. First, the metrics used by government agencies to regulate emissions from various modes are often different. The metrics used in the USA to regulate gas-phase pollutants and particulate matter or "smoke" are listed in Table 1. The gas-phase certification metrics are based on mass of pollutant per distance travelled for light-duty vehicles or mass of pollutant per unit of work for the other modes. To, for example, compare emissions performance of a car and bus, a conversion to a common metric must first be done. Comparing particulate matter emissions among modes is even more challenging. On-road compression-ignition vehicles are regulated based on a mass-based $PM_{2.5}$ measurement. In addition, buses, heavy-duty trucks, and locomotives are subject to a measurement of percent opacity of the exhaust plume. Aircraft are certified based on smoke number, which measures the amount of light reflected by filter paper that has been exposed to the exhaust. Large marine ships (C3) currently are not regulated for particulate matter or smoke. Some correlations exist for estimating PM emissions from the smoke measurements, but these correlations often involve considerable uncertainty.

Table 1. U.S. Transportation Emission Regulation Metrics

Mode	Basis for Certification (gas-phase)	Measure of particles (or smoke)
Light-duty vehicles	g/mi	PM2.5 (CI)
Buses	g/bhp-hr	PM2.5 and % opacity (CI)
HDD trucks	g/bhp-hr	PM2.5 and % opacity (CI)
Freight locomotives	g/bhp-hr	PM2.5 and % opacity
Ships	g/bhp-hr	None (for C3 engines)
Aircraft	g/kN (also report g/kg fuel)	smoke number

bhp = brake horsepower, CI = compression ignition, C3 = Category 3 (displacement/cylinder > 30 L)

Another complication arises because different modes of transportation use different drive cycles (or duty cycles) for emissions testing. In the USA, new light-duty vehicles are measured based on three drive cycles: the FTP drive cycle for emissions, the UDDS drive cycle for "city" fuel economy, and the HWFET cycle for "highway" fuel economy. Heavy-duty vehicles, such as buses, trains, trucks, and ships, have their own duty cycles. Aircraft are regulated based on the ICAO duty cycle, which does not include any emissions above 3000 ft (914 m). As a result of this variability, care must be taken to ensure that the duty cycle used for the emission measurements are representative of the "trip" that was envisioned for the comparison. This issue of duty cycle is somewhat less important for comparison within a single mode because, even if the cycle does not perfectly represent real-world use, the same cycle is used for all measurements in the comparison.

3. CALCULATION OF COMPARATIVE METRICS

The choice of an appropriate comparative metric is necessary to ensure that the intermodal comparisons are meaningful, so several alternatives were considered. The emission index, EI, (mass pollutant per mass of fuel burned) is attractive because it is widely used in the literature. However, the EI only describes how cleanly fuel is consumed and does not address how efficiently that fuel is used to transport passengers or freight. Ultimately, the emission intensity, defined as the mass of pollutant per passenger per distance travelled for passenger travel or the mass of pollutant per tonne per distance travelled for freight, was chosen as the comparative metric. The emission intensity of a passenger vehicle at maximum capacity (units of g/seat-km) is related to the emission intensity of a partially loaded vehicle (units of g/passenger-mi) by the load factor, which is the fraction of seats that are occupied. For passenger cars, the emission intensity of pollutant i, m_i, can be calculated from available data very easily:

$$m_{i,car}[\mathrm{g}_i/\text{seat-km}] = \frac{EF[\mathrm{g/km}]}{c[\mathrm{seats}]} \quad (1)$$

where EF is the emission factor and c is the number of seats in the car. For locomotives, literature data for emissions are typically available for each notch, or discrete locomotive power setting. The emission intensity, m_i, can be calculated by summing the product of the emission factor, EF, and the power, P, weighted by the fraction of time spent in each notch and dividing by the number of seats, c, and the average speed (d/t):

$$m_{i,locomotive}[\mathrm{g}_i/\text{seat-km}] = \frac{t[\text{hr}]}{100\% \cdot c[\text{seats}] \cdot d[\text{km}]} \sum_{n=1}^{modes} EF_{i,n}[\text{g/kW-hr}] \cdot P_n[\text{kW}] \cdot t_{mode,n}[\%] \qquad (2)$$

Note that the emission factor for the locomotive is defined based on the power for a particular notch and not the rated power of the engine. For aircraft, ICAO requires measurement of emission indices and fuel flow at four modes: idle, climb-out, approach, and take-off. Using these data and an estimate of emissions at cruise, the emission intensity can be calculated using:

$$m_{i,aircraft}[\mathrm{g}_i/\text{seat-km}] = \frac{n_{engines}}{c[\text{seats}] \cdot d[\text{km}]} \sum_{n=1}^{modes} EI_{i,n}[\text{g/kg fuel}] \cdot f_{fuel,n}[\text{kg fuel/min}] \cdot t_{mode,n}[\text{min}] \qquad (3)$$

where $n_{engines}$ = number of engines per aircraft, c = number of seats, d = trip distance, EI = emission index, f_{fuel} = fuel flow per engine, and t_{mode} = time in mode. Equations 1-3 can be multiplied by load factors to calculate g_i/passenger-mi and similar expressions can be used to calculate emission intensities for freight in g_i/tonne-mi.

4. IMPLEMENTATION OF THE DATABASE

The comparative emissions database (CEDB) was implemented using a relational database structure. Relational databases are linked groups of entities (tables) made up of attributes (columns) and records (rows). The tables are related to each other by use of unique columns called keys. The advantage of using a relational structure over a flat-file structure, such as a spreadsheet, is that the relational database removes the need for entering redundant information and thereby minimizes data entry errors. For example, the data presented in the ICAO emissions databank can be organized into four entities: 1) the engine, which has attributes such as manufacturer and bypass ratio; 2) the measurement, which has attributes such as test date and ambient temperature; 3) power cycle data, which contains the power setting and the emission indices; and 4) landing/take-off (LTO) data, which contains characteristic emissions of each pollutant averaged over the LTO cycle. The four entities are associated through "has one" or "has many" relationships. For example, the Engine entity has one Measurement in the ICAO databank (although in principle an engine could be measured on multiple occasions), and a Measurement has many PowerCycleData (one for each power setting) and LTOData (one for each species). The relational database structure used by the CEDB was implemented using the MySQL database management software. MySQL is a popular, open-source, well-documented relational database software package that is capable of efficiently handling large datasets. Queries to the database are performed using the structured query language (SQL), which is a flexible and powerful way to extract useful information from the database.

5. EXAMPLE CASE USING THE CEDB

The focus of this project is compiling and organizing measured emissions data rather than inventory development or policy analysis, yet in order to insure that the CEDB is a useful tool for enabling those types of analyses, its design and scope need to consider the range of queries that may be posed. Thus basic examples of modal comparisons facilitated by the CEDB have been performed.

Figure 1 shows a comparison of the emissions intensity from a light-duty car (2005 Toyota Camry, 4 cylinder, automatic transmission), a passenger locomotive (GM EMD F59PH engine, Amtrak Pacific Surfliner trainset), and a wide-body aircraft (Airbus A320-200) with modern turbofan engines (IAE V2527-A5). Figure 1 compares the emission intensities for the vehicles at full passenger capacity, while Figure 2 shows the comparison for typical passenger load factors (U.S. DOT BTS 2005a; Amtrak 2006; Davis and Diegel 2006). The emission intensities of CO_2, CO, HC, and PM are fairly comparable among modes, and the trend for CO_2 is to be expected. However, certain observations are immediately obvious from this type of comparison; for example, the fact that the automobile is the only mode using NO_X aftertreatment is evident.

The CO, NO_X and hydrocarbons (HC) data for the Toyota Camry were taken from the EPA Annual Certification Test Data (U.S. EPA OTAQ 2005) for model year 2005. The CO_2 emissions were estimated assuming complete combustion and using the combined city/highway fuel economy (11.9 km/L) reported in the 2005 DOE Fuel Economy Guide. The emission intensities for the EMD locomotive were calculated based on the emission factors and fuel flows reported by Fritz et al. (Fritz 1994) and the passenger locomotive duty cycle given in (U.S. EPA 1998). This locomotive engine uses a separate diesel generator to produce "head end power" for the cabin, and the figures presented here include emissions for that generator operating at 60% capacity (300 kW). The emission intensities for the A320 aircraft were calculated from emission indices and fuel flows from the ICAO emissions databank (ICAO 2006). Since ICAO does not include measurements of emissions at cruise, the Boeing Fuel Flow Method 2 (BFFM2) (Baughcum et al. 1996) was used to estimate cruise emissions. The fuel flow at cruise inputted to the BFFM2 was taken from the Eurocontrol Base of Aircraft Data (BADA) (Eurocontrol 2004). The PM emissions from the aircraft were estimated using the smoke number (SN) reported in the ICAO database and the FAA first-order approximation. This calculation overestimates PM for two reasons: 1) only the maximum SN was reported in the ICAO databank for this aircraft engine, and this SN was used for the entire flight, and 2) the FAA first-order approximation is intended to give a conservative overestimate of PM emissions. The aircraft emissions depend on the length of the trip because it affects the percent of time the aircraft spends at cruise compared to landing and take-off. A trip length of 440 mi (708 km) was chosen for this comparison, the approximate distance from Boston, MA to Washington, DC. The CO_2 emission intensity calculation used typical values for the C/H ratio of gasoline, diesel, and jet fuel, and assumed complete combustion for all modes.

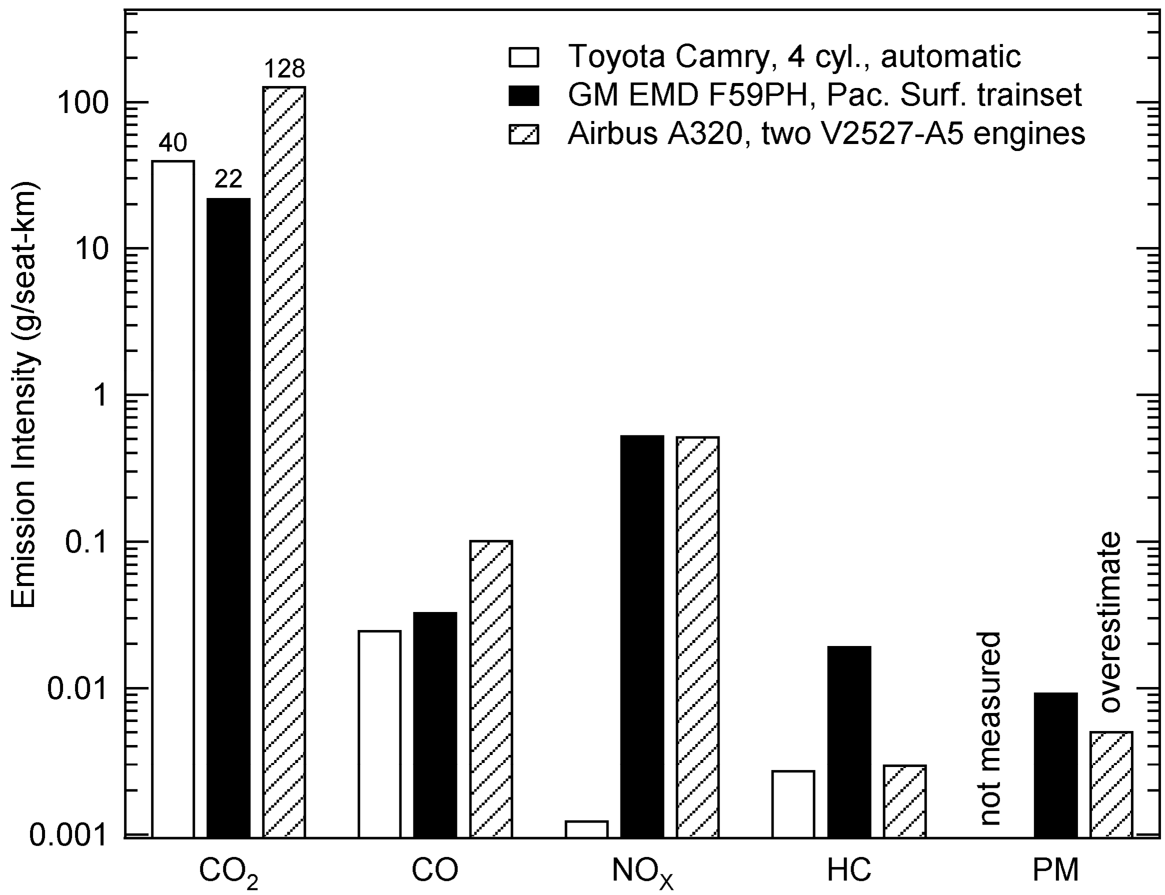

Figure 1. Comparison of emissions from a locomotive, automobile and airplane at full passenger capacity.

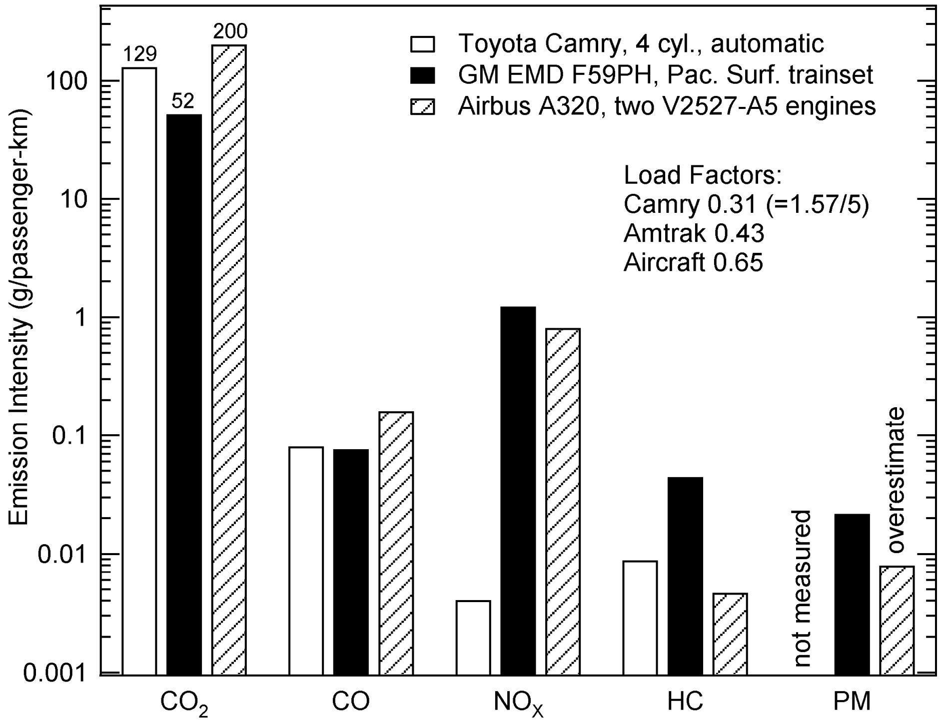

Figure 2. Comparison of emissions from a locomotive, automobile and airplane using typical passenger load factors.

It is important to remember that the vehicles compared in this example case are not necessarily representative of the fleet average emission intensities. This point is demonstrated in Figure 3, which compares the energy intensity (related to m_{CO2}) of the three vehicles in this example case to the 2001 fleet average (U.S. DOT BTS 2005b). The energy intensity of the A320/V2527 aircraft is quite close to the fleet average although slightly higher, while the energy intensity of the Toyota Camry and EMD locomotive are somewhat lower than their respective fleet averages. The data in the CEDB could easily be used to extend this example case to other vehicles and thereby account for fleet variability.

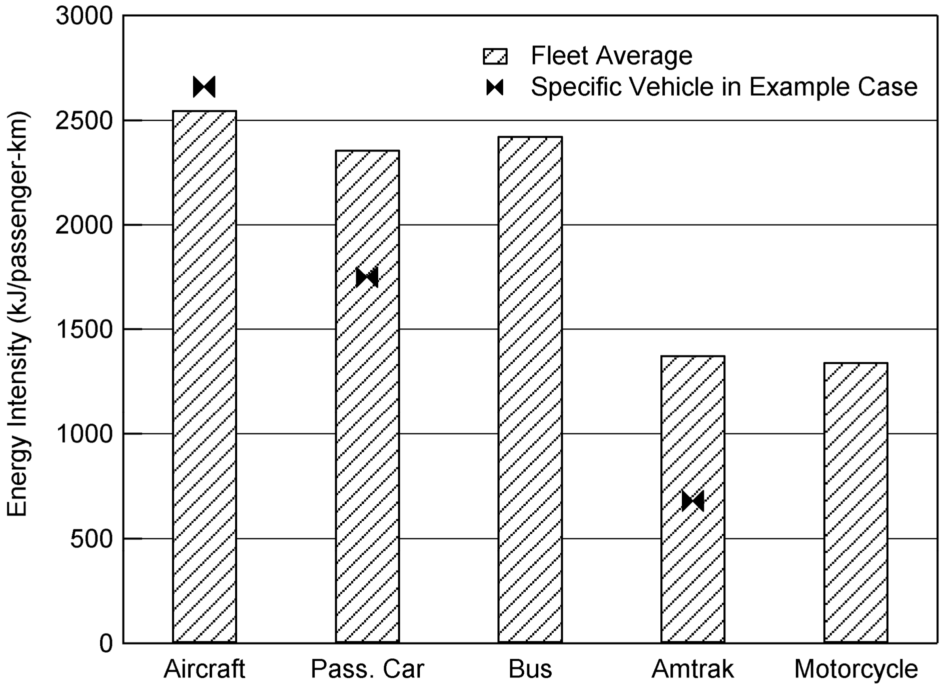

Figure 3. Comparison of energy intensity of specific vehicles used in this example case to fleet average values.

6. SUMMARY

A Comparative Emissions DataBase (CEDB) is being developed to enable comparisons of emissions of greenhouse gases and other pollutants from various modes of transportation. Potential end users of this tool would be policymakers and transportation policy researchers wishing to understand the environmental trade-offs of moving people and goods via different modes. This project is a work-in-progress, so improvements and expansion of the database are ongoing. Planned improvements include, for example, the inclusion of estimated uncertainties for the emissions data to allow propagation of uncertainty through to the final emission intensities.

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In-Situ Microphysical Measurements In Rocket Plumes With The Cloud And Aerosol Spectrometer (CAS)

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Keywords: rocket emissions, plume particle properties, particle shape analysis

ABSTRACT: High resolution, single particle measurements have been made in rocket plumes using an optical particle spectrometer that measures diameters from 0.5 to 44 μm. The diameter, shape and composition is derived from bi-directional scattering. The CAS was mounted on the NASA WB-57F aircraft as part of the Plume Ultrafast Measurements Acquisition (PUMA) project to study the chemistry and microphysics of rocket plumes. Measurements were made in plumes generated by an Atlas IIAS rocket and the booster of the space shuttle Discovery. The microstructure of the two plumes and the characteristics of their particles were distinctly different. The Atlas particles were on average larger and more irregular in shape. The composition of the Shuttle particles suggests hydrates of nitric acid whereas the Atlas particles were more representative of ice.

1 BACKGROUND

Solid-fueled rockets emit chlorine and alumina particles directly into the stratosphere, thus contributing to the depletion of the ozone layer [Prather et al., 1990; Jackman et al. 1998; Danilin et al, 2003]. Recent analysis of solid-fueled rocket plumes shows almost complete depletion of ozone locally [e.g., Ross et al., 2000]; however, global implications of such sharp local ozone reductions are predicted to be small [Danilin et al., 2001]. On the other hand, the heterogeneous reactions on alumina particles may be important on the global scale by converting emitted and background HCl into short-lived Cl_2, resulting in ozone depletion depending on the location of emissions and the size distribution and surface area of alumina particles. Previous measurements in rocket plumes have documented the emissions of gases and the average total concentrations of the particles, but were limited to the smallest particle sizes, < 1 μm. More recent measurements have been made that document the size distribution of particles > 1 μm at much higher spatial resolutions than previously possible. In addition, the instrument that made these measurements also provides information from which the shape and composition are derived. These measurements were made as part of the *Plume Ultrafast Measurements Acquisition (PUMA)* project. Instruments were mounted on the

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NASA WB57F to measure water vapor, ozone, CO_2 and particles. The objectives of the particle measurements were to characterize the size, shape and composition of fresh particles found in the rocket exhausts.

2 MEASUREMENT TECHNIQUE

The cloud, aerosol and precipitation spectrometer (CAPS), shown in figure 1, is a combination of three sensors for particle size and liquid water content (LWC) measurements. The cloud and aerosol spectrometer (CAS), circled in white, derives size distributions from the light scattered by individual particles that pass through a focused beam from a diode laser (*Baumgardner et al.*, 2001). Two cones of light, 4 to 12° and 168° to 176°, are measured by separate detectors and the peak amplitudes are classified into size bins to create two frequency histograms, forward and backward, every second. Figure 2 is a schematic diagram of the optical configuration of the CAS. The peak amplitudes of the forward and backward scattering signals are recorded for individual particles. In addition, the time of arrival, i.e. the time between successive particles that arrive in the laser beam, is recorded.

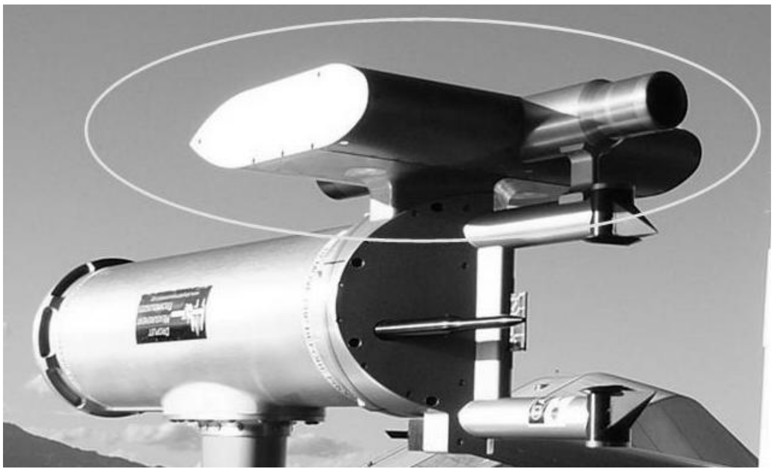

Figure 1. The CAPS probe, mounted on the wing the NASA WB57 F is shown here. The CAS portion of the CAPS is circled in white.

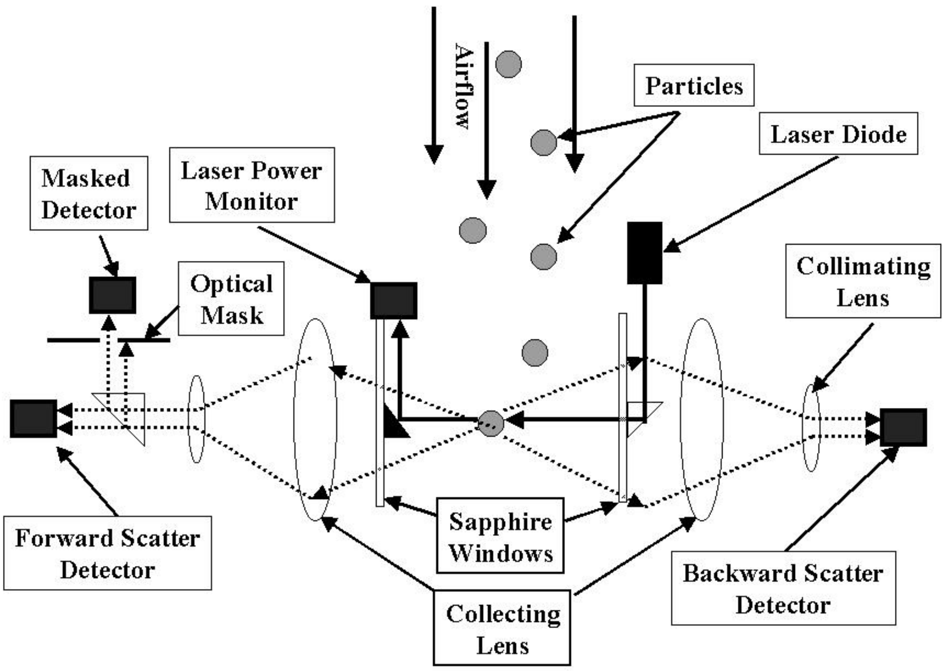

Figure 2. This block diagram is a schematic representation of the optical configuration of the CAS

The relationship between the forward and backward scattered light is a function of the particle size, refractive index and shape. This relationship is exploited in the CAS to derive a refractive index or shape factor from the ratio of forward and back scattered signals (*Baumgardner et al.*, 1996; *Baumgardner et al.*, 2005; *Chepfer et al.*, 2005). Figure 3 illustrates the relationship between refractive index and shape in relation to the forward to back ratio (F2BR) as measured by the CAS. The shape is expressed as an aspect ratio of spheroids, calculated using T-matrix scattering theory (Mischenko and Travis, 1998). As shown by the dashed line box, there is a range of F2BR in which the refractive index and aspect ratio cannot be resolved unambiguously.

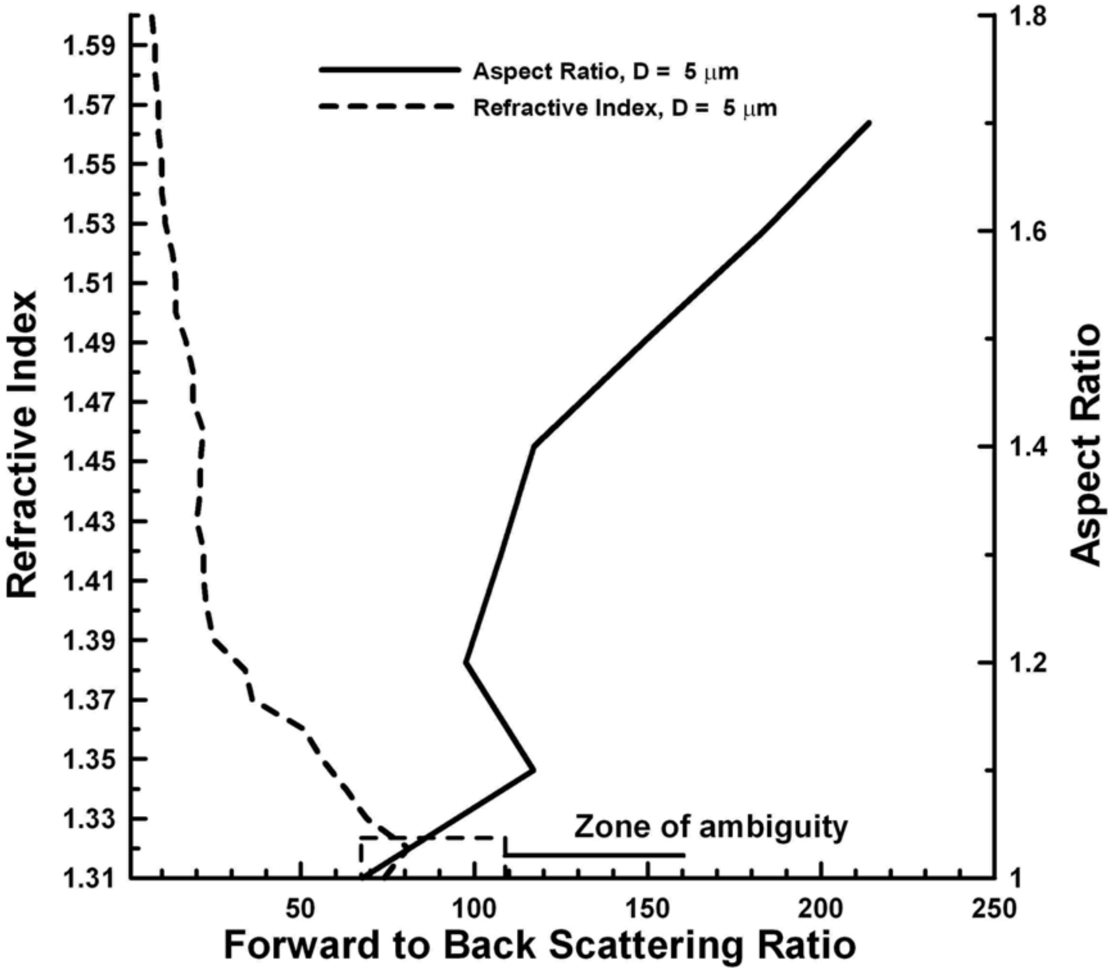

Figure 3. The ratio of light scattered forward and backward from a particle depends on the refractive index (dashed curve) and the shape (solid curve).

3 RESULTS

Measurements were made in the plume from an Atlas IIAS rocket on May 19, 2004 and from the first stage booster rocket of the Space shuttle Discovery on July 26, 2005, both launched from Cape Kennedy Space Center, USA The Atlas plume was intersected at 18 km, 16.2 km, 14.2 km and 13.6 km, at an environmental temperature of -67°C. The shuttle plume was sampled four times at an altitude of 18 km and a temperature of -67°C. Figure 4 compares the size distributions of the particles in the two plumes. The majority of the particles are less than 5 μm in equivalent optical diameter; however, the size distribution of the Atlas plume is broader than that of the space shuttle, although neither plume has particles larger than 8 μm.

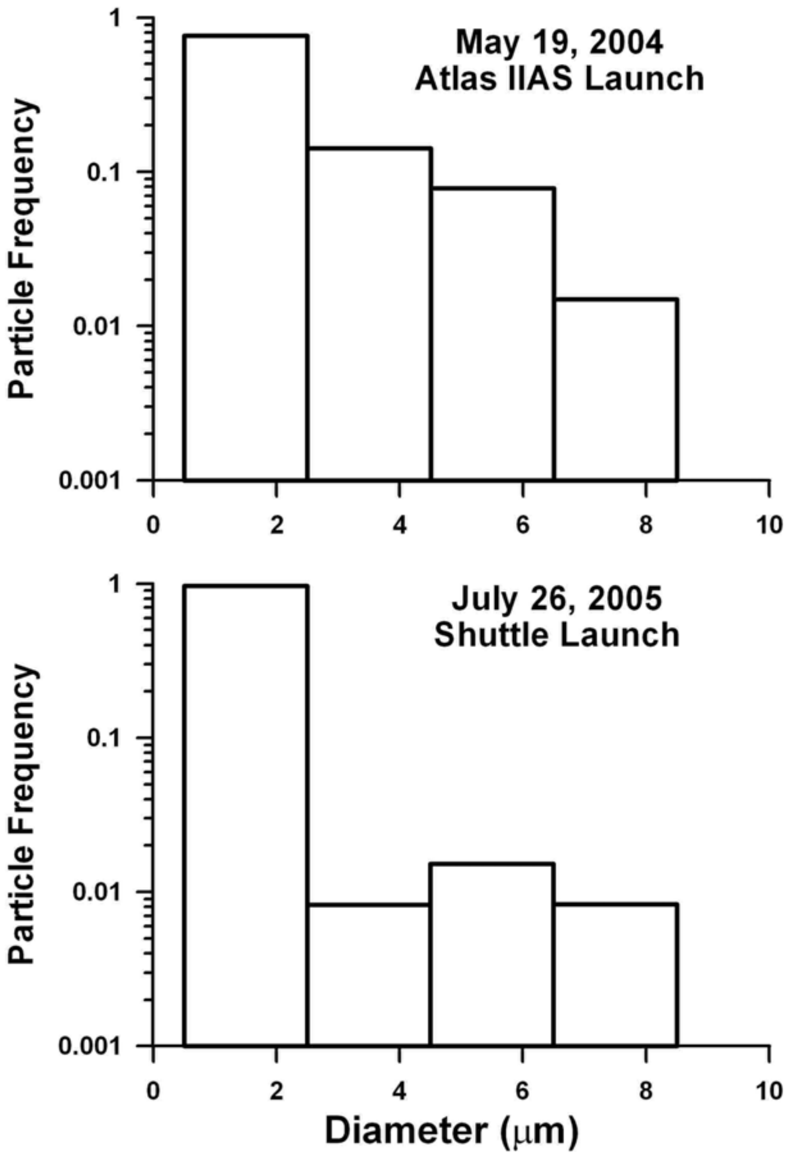

Figure 4. Size distributions of the Atlas and Shuttle particles.

The shape factors are given here in terms of as aspect ratios for equivalent spheroids using the model for oblate spheroids as described in Section 3. The frequency distributions of particle aspect ratios, shown in Figure 5, compare the plumes of the Atlas and Space shuttle. In this figure we see that 35% of the particles in the Atlas plume were spherical and the remainder had a variety of shapes with aspect ratios between 1.2 and 1.6. A larger percentage of the Shuttle particles were spherical, 45%, with the remainder between 1.2 and 1.4 aspect ratios.

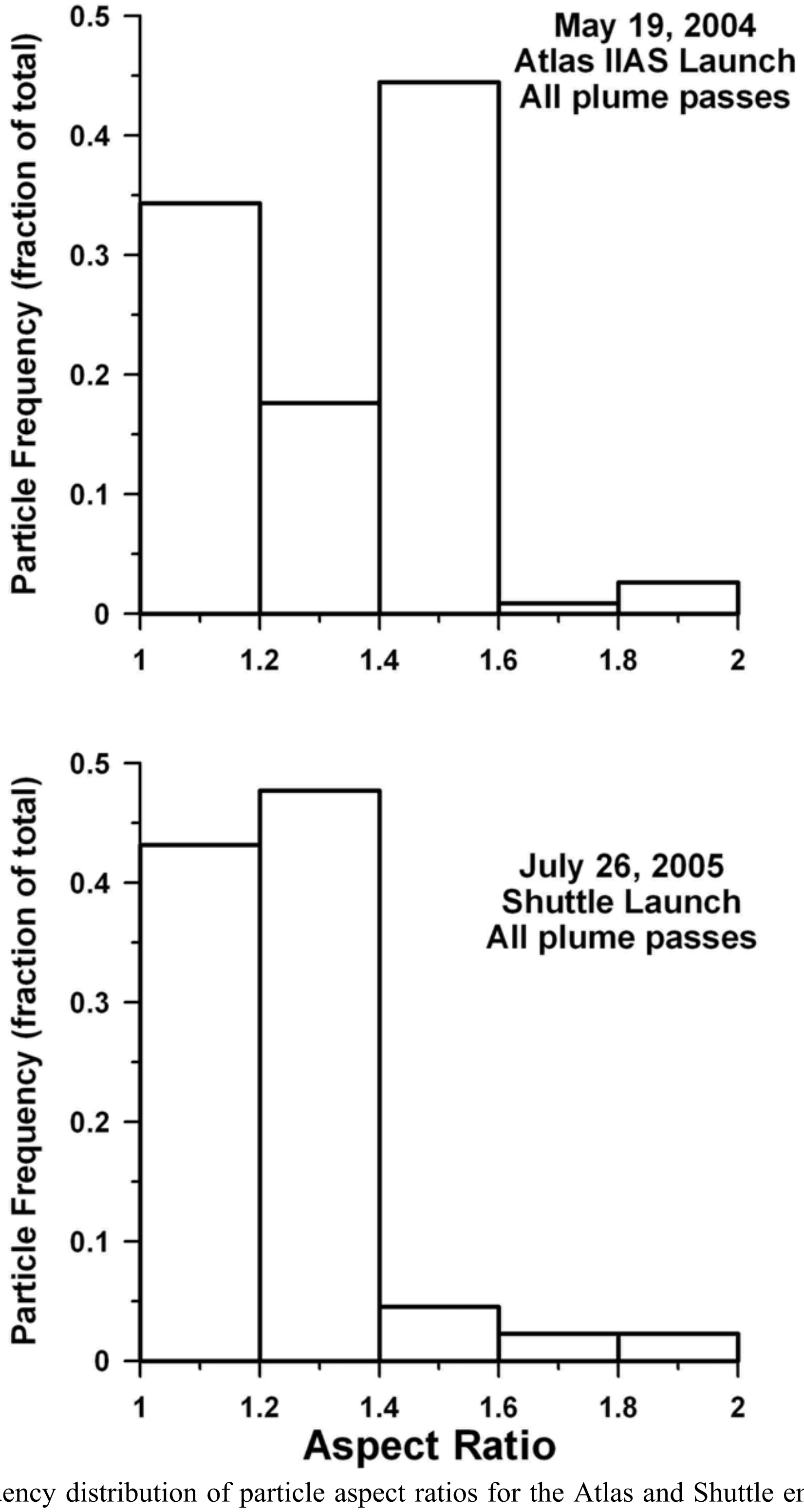

Figure 5. The frequency distribution of particle aspect ratios for the Atlas and Shuttle emissions are plotted in this figure

The composition of the particles, as indicated by the derived refractive indices, was very different, as shown in the frequency distributions in Figure 6. The 35% of particles in the Atlas plume that were near spherical had refractive indices between 1.30 and 1.35, indicative of ice. The majority of the spherical particles in the plume of the shuttle had refractive indices between 1.5 and 1.55. Ice particles with a coating of nitric acid or hydrates of nitric acid have refractive indices in this range.

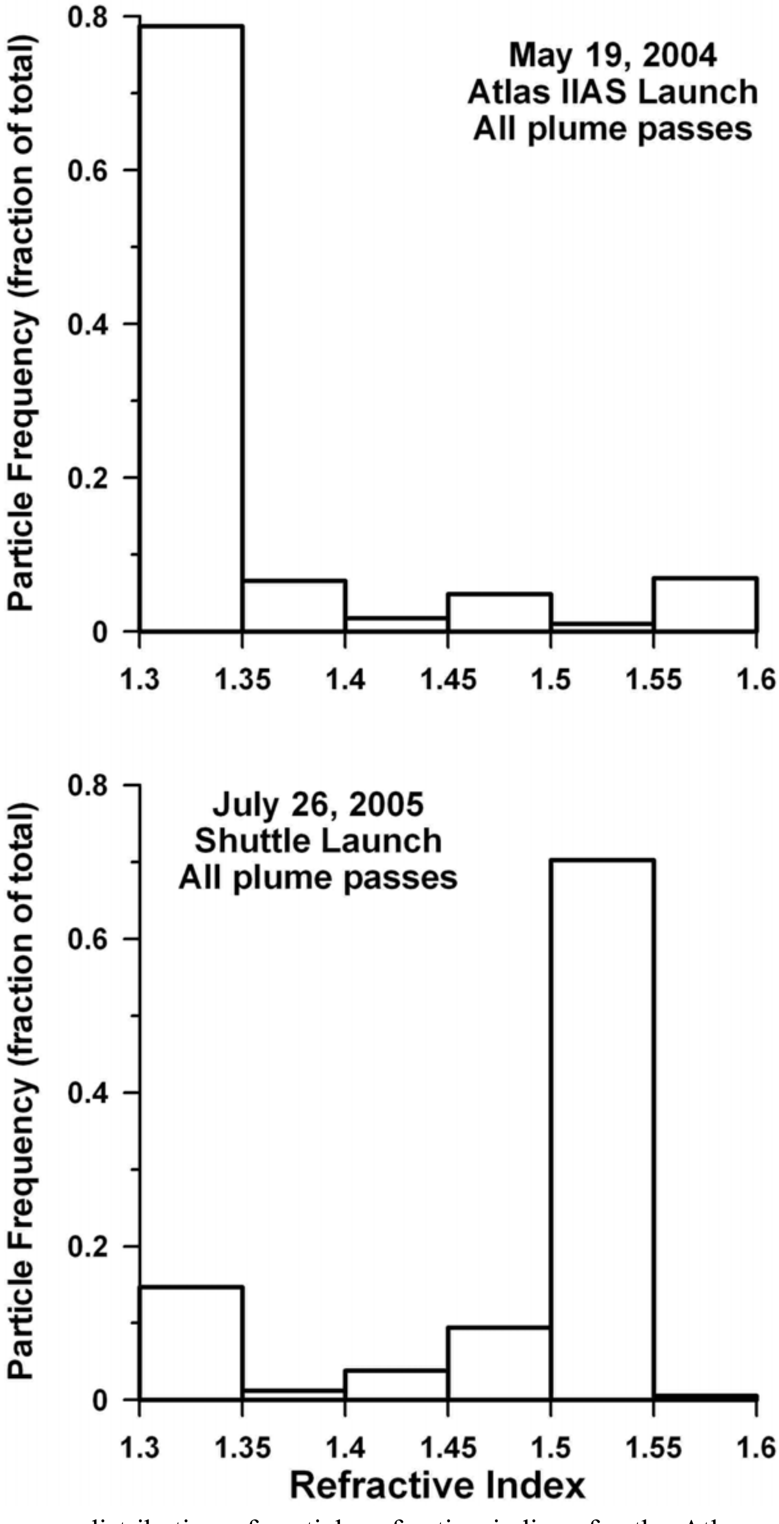

Figure 6. The frequency distribution of particle refractive indices for the Atlas and Shuttle emissions are shown here..

The dispersion of the plumes, as indicated by the spatial distribution of the individual particles, differs between the Atlas and the Shuttle exhausts. Figure 7 shows the frequency of spatial distances between the particles, measured in millimetres. The dashed lines on the figures are the spatial distributions predicted for uniformly, random spacing of particles with different number concentrations. These predicted curves assume Poisson probability distributions to predict the expected frequency of separations. The measured distributions of both plumes indicate that the exhausts are mixtures of high and low concentrations, as indicated by the dashed curves with steep (high concentration) and shallow (low concentration) slopes. The high concentrations were in the central parts of plumes where little dilution by mixing with environmental air has occurred and the low concentrations are at the plume edges where entrainment has diluted the concentrations.

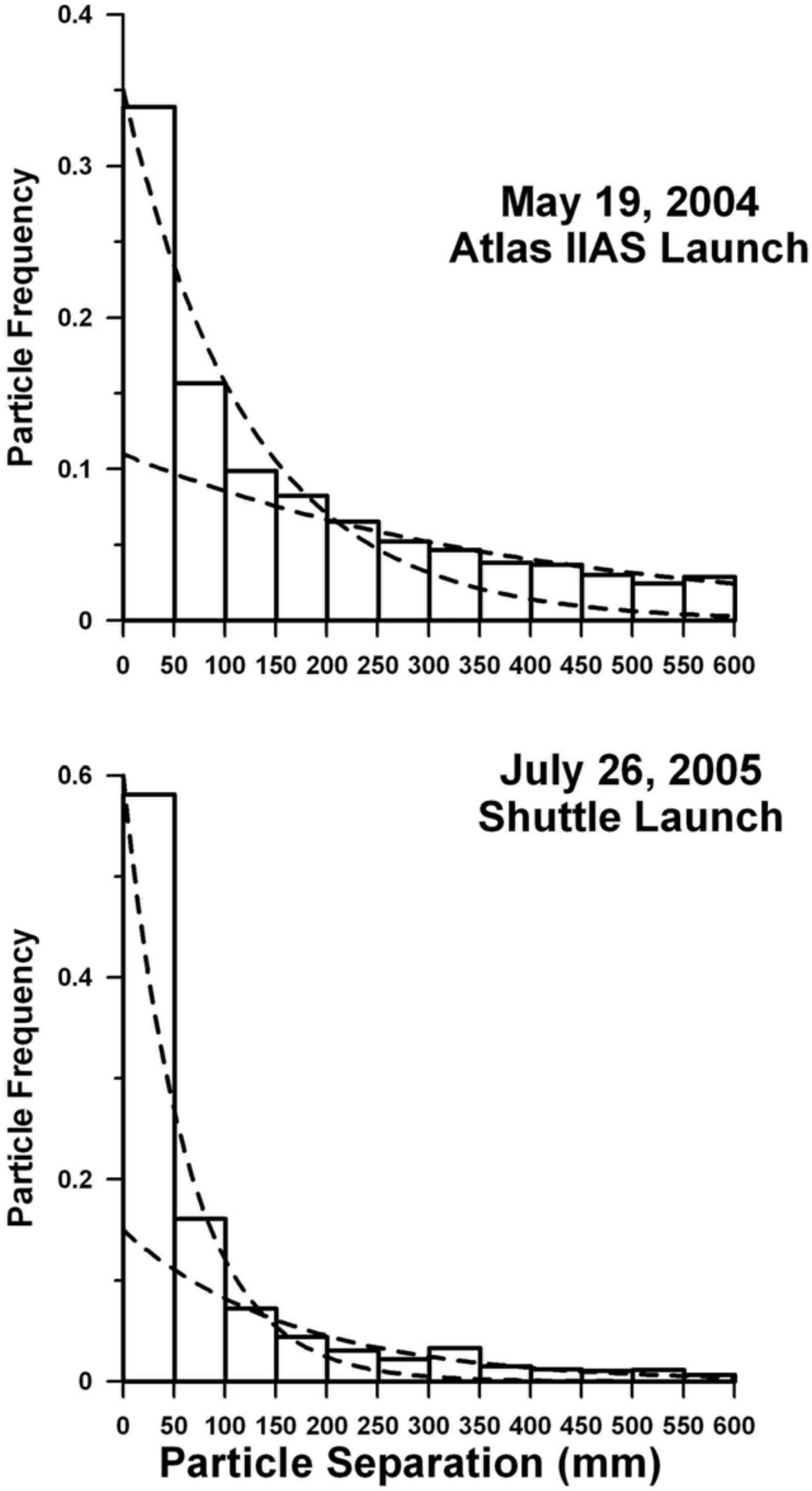

Figure 7. These are frequency distributions of the interarrival times of the particles in the Atlas and shuttle plumes

4 CONCLUSIONS

Measurements of particle size, shape, refractive index and spatial distribution indicate fundamental differences between characteristics of exhaust particles in an Atlas rocket plume and Shuttle booster rocket plume. These differences are related primarily to the type of fuel used in the two systems. The major characteristics that were detected were:

- The majority of particles were < 5 µm in both plumes.
- The particle refractive indices suggest ice as the dominant particle composition in the Atlas plume whereas hydrates of HNO3 nitric acid coated ice was dominate in the Shuttle plume.
- The particles in the Atlas plume were more aspherical than those in the Shuttle plume but 35% and 45% of the particles were spherical, respectively.
- These results can contribute to the improvement of chemical transport models of rocket plumes with better estimates of particle surface area and dynamics.

ACKNOWLEDGEMENTS

Thanks to NASA JSC, in particular, Andy Roberts, Joe Gerky, Shelley Baccus, Brian Barnett and the WB-57F crew for logistical support, to Anne-Marie Schmoltner and NSF for project funding and to Bruce Doddridge and Chris Cantrell for their early encouragement.

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Historical and future development of air transport fuel efficiency

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Keywords: air transport, fuel efficiency, piston engines, jet engines, history

ABSTRACT: The historical developments of the average fuel efficiency of both piston and jet powered aircraft are reviewed with the objective to find ways to better forecast future developments. It is argued that the current methods of a constant percentage efficiency improvement per year cannot satisfactorily represent the historical time series. A sigmoidal model is suggested for better fits and more reliable prognoses, leading to less optimistic fuel efficiency gains for 2040 than suggested in current literature.

1 INTRODUCTION TO HISTORICAL ANALYSIS OF FUEL EFFICIENCY

A recent study on the development of energy efficiency of individual new civil aircraft and for the USA fleet shows that the Intergovernmental Panel on Climate Change (IPCC) efficiency assumptions yield too optimistic fuel reductions if extrapolated towards the future (Peeters et al., 2005). Like IPCC, most air transport greenhouse gas emission scenarios assume a constant percentage energy efficiency increase (leading to a near-zero fuel consumption in the long term). The IPCC special Report on aviation and the global atmosphere assumes values between 1.2% and 2.2% efficiency increase per annum (Penner et al., 1999). Also several other authors propose constant percentages, though often assumed to differ between different time periods to fit the result better to the available data (see for example Green, 2003; Lee, 2003; Lee et al., 2001; Pulles et al., 2002). As will be shown in this paper, a constant reduction percentage approach might not be the best model for forecasting purposes.

Operational impacts have not been explicitly included in the analysis. Load factors, efficient routing, holding, weather impacts and delays depend (more) on the efficiency of deployment of the aircraft rather than the aircraft technical characteristics themselves.

2 MATHEMATICAL ANALYSIS OF FUEL EFFICIENCY DEVELOPMENT

Lee et al. (2001) introduced the term Energy Intensity (E_I), the energy consumption per available seat-kilometre (MJ/ASK), as a measure for the technological (transport) performance of individual aircraft or an aircraft fleet. This E_I typically depends on aircraft (technology) parameters:

- Aerodynamic efficiency, specifically the lift-to-drag ratio during climb and cruise.
- Weight efficiency, the ratio of payload to the Maximum Take-off Weight (MTOW) and the ratio between Operating Empty Weight (OEW) and MTOW.
- Engine efficiency in terms of fuel consumption per unit thrust (Specific Fuel Consumption, SFC). The number of seats; Cabin layout has a significant impact on the number of seats, hence seat-kilometres. Seating density may vary by a factor of two between a typical mixed-class lay-out and single-class high-density layout, while having approximately the same fuel burn per air-craft-kilometre.

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Many studies present technological trends in terms of a constant annual percentage efficiency gain, as observed from history. Lee et al. (2001), for instance, assert that this ratio will be between 1.2% and 2.2% a year in the future, while Penner et al. (1999) use 1.4% for most future scenarios. This approach can be modelled with the form:

$$E_I = E_{I_b} \cdot (1 - c_a)^{(Y - Y_{ref})} \tag{1}$$

where E_I is the Energy Intensity (unit MJ/ASK) and (Y-Y_{ref}) the number of years since a base year Y_{ref}. E_{I_b} is the Energy Intensity at the base year and c_a the annual (fractional) reduction of the Energy Intensity.

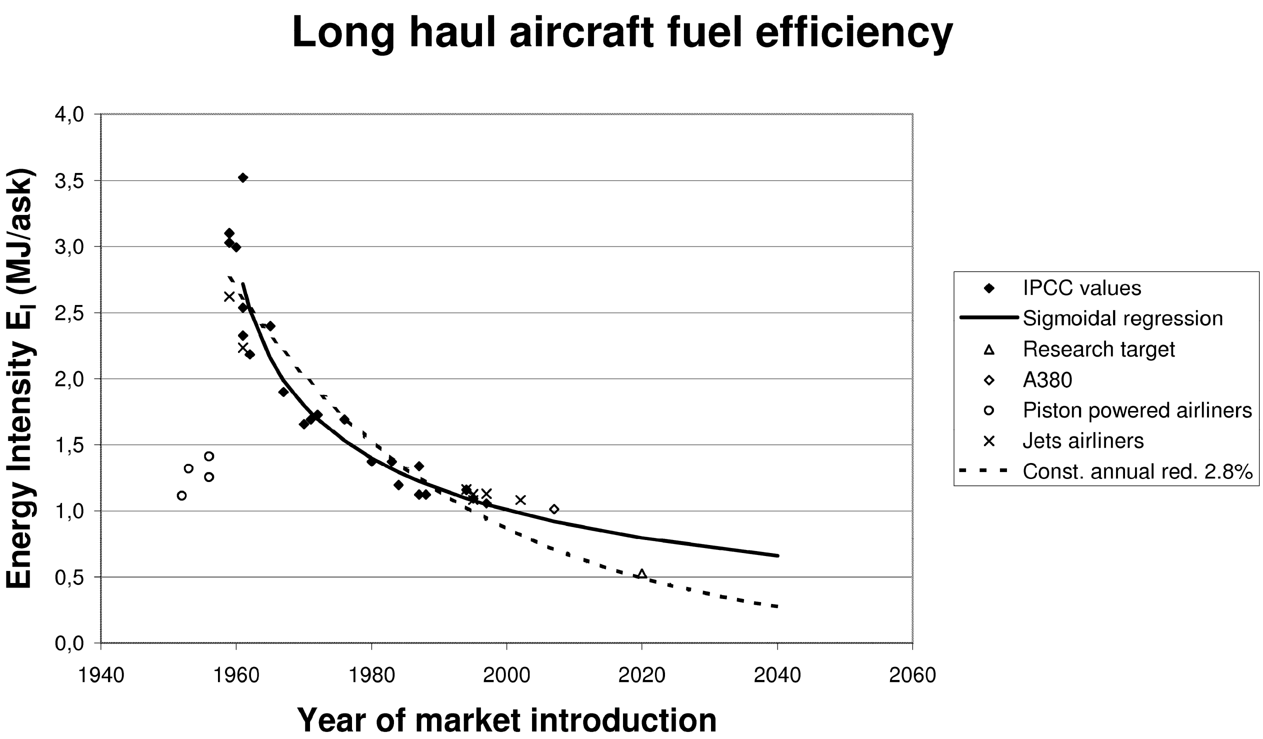

Figure 1: IPCC graph with additional data (see text for references).

The historical data presented in this paper show clearly that the reduction percentage itself is not a constant, but reduces with time (Fig. 1). Hence, the percent-wise fuel reductions observed in the past cannot directly be used for future fuel reduction assumptions. Implicitly, scenarios using this approach neglect several technology limits. Amongst others, these concern the limited energy content per kg fuel and minimum obtainable levels of aircraft drag and weight. Moreover, immediately after market introduction of technology, opportunities for improvement are numerous and relatively cheap, causing improvements initially to be implemented at a high rate. When the technology becomes mature, these opportunities for improvement reduce.

Therefore, this paper proposes an approach that allows strong improvements in the first years after introduction and continuously decreasing improvements over time. Several tests with GraphFirst (Vasilyev, 2002) showed the 'sigmoidal (logistic 5)' regression curve resulted in the best fit within the requirements. This curve has been developed to represent biological processes with rapidly slowing down growth rates (see Gottschalk and Dunn, 2005). The curve has the form:

$$E_I = E_{I_0} + \frac{C_{E_I}}{1 + \left(\frac{(Y - Y_{ref}) - C_1}{C_2} \right)^{\gamma}} \tag{2}$$

where E_I is the Energy Intensity (MJ/ASK) and (Y-Y_{ref}) the number of years since a base year Y_{ref} (i.e. the year of introduction of a new technology or the starting year of the data base), E_{I_0} is a theoretical minimum energy intensity and C_{E_I}, C_1, C_2 γ are constants defining the initial (maximum) energy intensity and the rate at which the annual gain of Energy Intensity reduces.

The E_I data of individual civil airliners, are taken from two sources (Penner et al., 1999 (IPCC), and Lee et al., 2001). These sources contain only data on jet aircraft since 1957. To complement the history of fuel efficiency, E_I of piston airliners, roughly since the introduction of all-metal fuselages with the DC-2, are added. The exact construction method of the data points by Penner et al., 1999 and Lee et al., 2001 are not published. Therefore we checked the data by first calculating the Energy Intensities for four piston airliners (the L-1049, L1049H and L-1649G version of the Lockheed Super Constellation and the DC-7C), two early jets (Boeing B707-120B B707-320) and five new jets (Boeing B737-800, B777-200 and B777-200IGW and Airbus A330-300 and A340-300). Then we fitted the results using the two early and seven modern jets to fit the same models to the IPCC data. The fuel consumption per ASK of individual aircraft is derived from the harmonic flight distance given by the aircraft's payload-range diagram (assuming still air, ICAO standard takeoff and landing procedures and flying an optimal flight profile). The harmonic flight distance indicates the maximum flight stage length at maximum payload and therefore describes the aircraft best fuel efficiency performance.

Figure 1 shows the data given by IPCC (Penner et al., 1999) plus the results of the sigmoidal model analysis for jets and piston engine airliners. Based on these the sigmoidal regression model has been applied (for parameters see Table 1). The dotted line represents a regression for the best fit of an evolutionary model with constant efficiency improvement of 2.8% per year. The E_I of the new Airbus A380 is based on the 12% reduction with respect to the B747-400, cited by Bickerstaff (2005). Finally the 'typical research target' as mentioned by ATAG (2005) is shown.

3 HISTORIC E_I DEVELOPMENTS OF THE US FLEET

Parallel to the analysis of individual aircraft types, the overall average energy efficiency E_I of a representative fleet of commercial aircraft is investigated as well. Though world-wide aviation traffic statistics are available from several sources (e.g. IATA, 1957-2004; Mitchell, 1999), specific data on world-wide fuel consumption for commercial aviation are not. Only for the US consistent data on both transport volume and fuel consumption could be found from several editions of three sources of data (ATA, 1940; ATA, 1950; ATA, 1980; ATA, 2005, Bureau of Transport Statistics, 2005a; Bureau of Transport Statistics, 2005b and Lerner, 1975). It is presumed that the development in the US is representative for world aviation as historically US originating commercial aircraft and engine technology has dominated the world fleet.

The databases cover various time-periods, definitions, units and parameters. All payload including mail, express and freight, is converted from ton-kilometres to hypothetically available seat-kilometres assuming 160 kg per seat. In this way a E_I time series was created for the period 1930-2005. For further details on the method used see Peeters et al. (2005).

The results are plotted in Figure 2, which clearly shows two general trends of energy intensity (E_I) decrease: one before 1955, the other after 1970. The "discontinuity" coincides neatly with the fast replacement of pistons with jet aircraft between 1957 and 1968 (also shown in the figure marked with **x**). Medium speed, low flying piston-engined aircraft, using (expensive) avgas as energy source, are replaced with high speed, high altitude jet powered aircraft, using (cheap) kerosene. As a result the overall air-transport productivity increased. In terms of transport capacity, energy consumption and energy efficiency, the transition from piston-engined aircraft to jets must have developed at an even higher rate, as the average jet aircraft has a much larger transport productivity as the average piston airliner replaced by the aircraft. Figure 2 also shows the fit of the two fleet sigmoidal (logistic 5) curves for piston and jet.

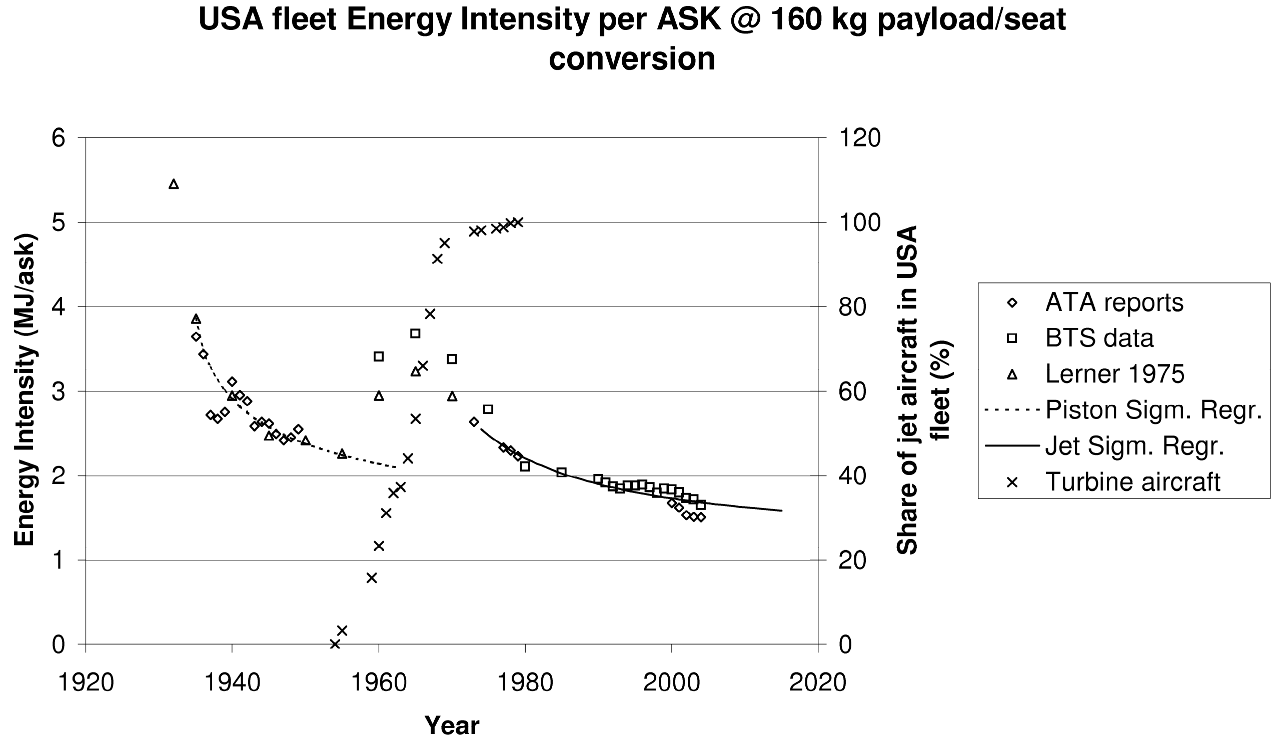

Figure 2: Overall results of the fleet analysis, (data series based on ATA, 1940; ATA, 1950; ATA, 1980; ATA, 2005; Bureau of Transport Statistics, 2005a; Bureau of Transport Statistics, 2005b; Lerner, 1975).

4 FUEL EFFICIENCY FORECASTS

Using the model presented in section 2, the sigmoidal (logistic 5) curve parameters for both individual aircraft types and fleet averaged data sets are obtained. Table 1 and Figures 1 and 2 show the results. The parameters of the graphs are relatively similar, with the exception of the parameters for the jet aircraft fleet data. Figure 2 shows these jet aircraft fleet data to be rather irregular, specifically after 1980. Speculatively this may be caused by an irregular fleet renewal rate by US airlines between 1970 and 2000 and by undefined changes in the measuring method of the data published by ATA.

Table 1: parameters as estimated with FindGraph (Vasilyev, 2002) for equation (2) and the four available time series.

Case	E_{I_0}	C_{E_I}	C_1	C_2	γ	Y_{ref}
IPCC individual long haul aircraft dataset (Albritton et al., 1997; Penner et al., 1999)	-0.2010	3.207	2.214	19.69	0.7183	1958
Lee individual long and short haul aircraft dataset (Lee et al., 2001)	0.0446	2.855	2.213	19.69	0.7183	1958
Piston fleet (ATA, 1940; ATA, 1950)	1.195	2.746	3.916	10.22	0.7186	1931
Jet fleet (ATA, 1980; ATA, 2005; Bureau of Transport Statistics, 2005a; Bureau of Transport Statistics, 2005b)	1.160	1.465	4.051	17.15	0.9976	1969

Using the parameters from Table 1 in the sigmoidal model for the IPCC data (long haul only) yields a 2040 EI of 0.658 MJ/ASK (35% reduction with respect to IPCC value in 2000), the Lee data (short and long haul) yields 0.810 MJ/ASK (28% reduction with respect to the Lee value in 2000) and for the USA jet fleet 1.460 MJ/ASK (16% reduction with respect to the jet fleet value in 2000).

These data contrast with the often cited constant percentage reduction per year 'best' fit on the IPCC data yielding 2.8% and E_{I_b} = 2.84 MJ/ASK. Extrapolation of "constant percentage reduction approach" results in 0.280 MJ/ASK and a reduction of 72% between 2000 and 2040. A moderate reduction of 1.4% proposed by Penner et al., 1999 would yield a reduction of 43% in 40 years, which is still significantly higher than the result with the sigmoidal model for the IPCC data.

5 DISCUSSION AND CONCLUSIONS

Figure 1 shows clearly that the common practice of a constant percentage reduction of energy consumption per year is less suitable for prognoses as it probably does not very well represent the economic and physical processes causing the evolutionary development. In many studies this shortcoming is countered by using different ‘constants’ for different periods of time. This method leaves us with rather arbitrary choices, introducing some extra uncertainty for prognoses. Therefore, one model able to represent the whole historical development with one set of parameters would help to reduce this uncertainty. The proposed sigmoidal model represents such a model.

The main message from the above is the notion that current fuel efficiency forecasts tend to be too optimistic.

The presented data support the idea that most aviation technology developments are clearly driven by cost savings, and productivity increases, safety improvements, increased range and take-off and landing performance. Fuel burn is only one - and commonly not the main – of cost components. The transition from piston engines to gas turbines illustrates this clearly as it was made predominantly to increase aircraft speed and altitude and to some extent range. The transition increased transport efficiency in terms of revenue ton kilometres per year as well as passenger appeal and comfort. As kerosene was much cheaper than avgas, the transition did not significantly raise fuel *cost*. The overall effect at the outset of this transition was higher energy intensity.

Comparing the performance of jet- and piston-powered aircraft in the transition phase between the fifties and the seventies of last century, implies comparing immature, early adoption of gas turbine technology with mature piston engine technology. In general, aircraft size, speed, range and (payload) weight all influence fuel consumption. Today’s aircraft differ significantly in these respects from aircraft in the past. Furthermore, load factors do have some influence on fuel consumption per seat-kilometre: extra payload costs extra fuel. As load factors increased between 1970 and 2000, this means that energy consumption per ASK has also been increasing, by several percent. However, this applies only for the jet fleet data, as the individual arcraft data are based on full payload. Finally the introduction of jet engines implied a significant reduction in complexity of the engine, hence, reduced maintenance costs and increased reliability.

In relation to aviation and environment and the piston-jet transition, there is more than just Energy Intensity. From a life-cycle perspective, kerosene is less pollutant to the environment and less costly to produce than avgas (of the fifties). The two fuel types have different fuel combustion quality requirements, due to fundamental differences between the respective engines. Leaded avgas is a high-grade fuel that (in the fifties) included dopes with highly toxic substances such as ethylene bromide. In those years, the use of avgas probably caused significant more damage to the local air quality (and may be even some to radiative forcing) than kerosene.

The following conclusions may be drawn from the study:

- The development of technical fuel efficiency – in terms of fuel consumption per ASK - of civil aircraft shows an S-curve due to the transition from the last fuel efficient piston powered airliners to the less fuel efficient first jets.
- The fuel efficiency development of a time series of a typical aircraft layout is in most studies represented by a model based on one or just a few time periods with a constant increase in fuel efficiency per year. However, a sigmoidal (logistic) model better represents with one set of parameters per dataset the full time series.
- Forecasts on fuel consumption, using the constant percent fuel consumption reductions per year tend to over-predict future gains, compared to the sigmoidal (logistic) model.

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Contracting UK carbon emissions: implications for UK aviation

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Keywords: carbon, aviation, energy consumption, UK, emissions

ABSTRACT: Stabilising atmospheric CO_2 concentrations at or below 550ppmv is widely believed to be necessary to avoid 'dangerous climate change'. However, the latest science suggests that a 450ppmv stabilisation is more likely to achieve the desired goal of ensuring that global mean surface temperatures do not increase by 2°C above pre-industrial levels. Achieving such levels demands industrialised nations make significant emissions cuts, whilst emerging economies adopt low-carbon pathways. This paper focuses on the UK as a typical Annex 1 nation, and demonstrates the severe consequences in meeting its obligations to reduce carbon emissions under the apportionment rules informing both the RCEP's 22nd report, Energy the Changing Climate, and the 2003 Energy White, if the UK Government continues to permit the current high levels of growth within its aviation sector.

1 INTRODUCTION

European nations are in broad agreement that individual States, and the EU as a whole, must tackle the problem of rising CO_2 emissions. In response, some nations have set carbon reduction targets. In theory, many of these targets are chosen to correspond with stabilising CO_2 concentrations at levels that are likely to avoid 'dangerous climate change'. Although there is no scientific consensus for what is considered to be 'dangerous' in relation to climate change, it has been broadly accepted by the policy community that this relates to global mean surface temperatures rising less than 2ºC above pre-industrial levels. However, many of the chosen carbon reduction targets omit emissions from the aviation industry. By choosing targets related to global CO_2 concentrations, governments have, often without due consideration or recognition, accepted that such targets must include all CO_2-producing sectors. In this regard, the UK is a clear example, and, as a typical OECD nation with a 'mature' aviation industry, it will provide the focus of this paper which addresses the conflict between the UK's energy and aviation policies. The UK Government set a carbon reduction target in 2003. Its basis for this target was a Royal Commission on Environmental Pollution's report (RCEP, 2000), which calculated that, for the UK to make its 'fair' contribution to stabilising global CO_2 concentrations at 550ppmv, it must cut its carbon emissions by 60% from 1990 levels by 2050. Their calculation used a Contraction & Convergence regime to apportion emissions between nations. However, the UK Government stated that this target does not include emissions from either international aviation or shipping. Furthermore, in the same year that it chose its carbon target, it published a White Paper proposing how the UK could meet the rising demand for air travel.

Selecting which sectors to include and which to omit to meet a particular carbon target essentially negates the choice of basing it on global CO_2 concentrations, unless those sectors contribute negligible amounts of CO_2. This paper clearly demonstrates that this is not the case for the UK's aviation sector, and illustrates that this sector's emissions are growing rapidly. The implications for such rapid growth in relation to the UK's carbon reduction target are highlighted using carbon profiles for stabilising CO_2 concentrations at both 550ppmv and 450ppmv.

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2 BACKGROUND

Although the UK's national emissions inventory does not include emissions generated by the UK's international aviation or shipping industries, data for these sectors are collected and submitted separately as a memo to the United Nations Framework Conventional on Climate Change (UNFCCC). To estimate the emissions generated by the UK's aviation sector, the National Environment Technology Centre (NETCEN), employ a methodology that takes into account aircraft movements, distances travelled, deliveries of aviation spirit and turbine fuel and the consumption of aviation turbine fuel by the military (Watterson et al., 2004). The data includes both passengers and freight and is plotted in Figure 1. Uncertainties analysis can be found in the Watterson paper.

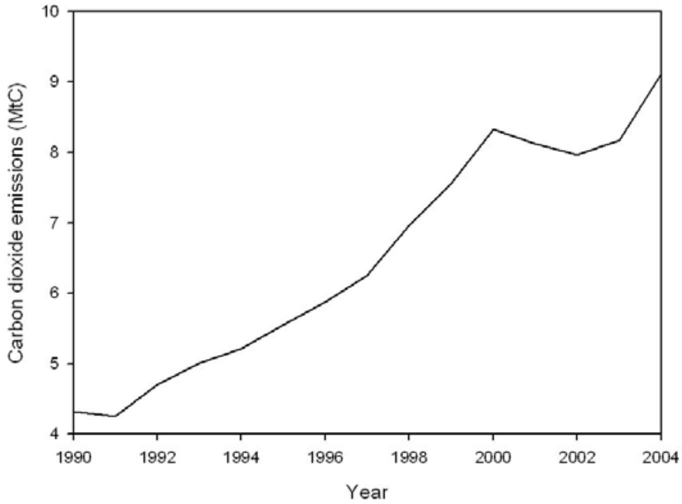

Figure 1. CO_2 emissions from the UK's international aviation industry measured in million tonnes of carbon.

The data indicates that CO_2 emissions from the UK's international aviation industry have increased rapidly since 1991, apart from during the two years following the events of September 11th 2001. On average, emissions increased at an annual rate of 7% between 1990 and 2000. According to these estimates, between 2003 and 2004, CO_2 emissions generated by international aviation increased by 11.7%, and those from domestic aviation increased by 3.8%. Not surprisingly, the figures for the number of passengers passing through UK airports collected by the Civil Aviation Authority follow a similar trend (CAA, 2005). The annual average growth rate between 1990 and 2001 was 7% per year. However, the increase in passenger numbers between 2003 and 2004 was much smaller than the growth in emissions, around 8% compared with 11%. The difference between these two figures has not been explored in detail, but could be due to a range of factors. For example, if there is a larger growth in number of passengers flying long-haul than short-haul, the emissions per passenger averaged over all flights will increase.

To assess whether or not future emissions from the aviation industry will be significant in relation to the UK Government's proposed contracting carbon profile, a combination of Government aviation forecasts, and 'what if' scenarios for the aviation industry are compared with UK CO_2 trajectories for the UK's 60% target trajectory relating to 550ppmv, and for 450ppmv, as it relates more closely to the 2°C temperature threshold.

3 DISCUSSION

3.1 *Current and historical CO_2 emissions*

Figure 2 illustrates the UK's domestic CO_2 emissions. According to these NETCEN estimates (Eggleston et al., 1998), emissions have been reducing on average at 0.36% per year. However, the period between 1991 and 1995 was significantly affected by a switch from coal to gas, and a relocation of energy intensive industry overseas. Both contributed to the biggest reduction in carbon emissions seen between 1990 and 2004, and are likely to be one-off events that can not be repeated.

CO_2 emissions have not been declining since 1995. When the estimates for CO_2 emissions from international aviation and shipping are added to this profile, it is clear that CO_2 emissions have not shown the same level of reduction since 1990. [Emissions for shipping submitted to the UNFCCC are currently based on UK marine bunker sales. However, unlike aviation, the tax on shipping fuel allows for large discrepancies in price from nation to nation, resulting in a significant amount of 'bunkering'. Assuming that the proportion of total marine bunker fuel is related to a nation's GDP is a crude but more realistic method of apportioning shipping emissions and is employed here. This method will be refined in the future. The uncertainty associated with this method has not been quantified, but will be affected by uncertainty in the global marine bunker fuels sold, for which no figure could be obtained. Assuming this figure, provided by the International Energy Agency, to be appropriate, the fact that the UK is an island state suggests that any apportionment of shipping emissions based on national GDP is more likely to be an underestimate than an overestimate]. The gap between emissions that do not include aviation and shipping, and those that do include these sectors, is widening. This indicates that international aviation and shipping emissions are becoming larger portions of the overall total as time progresses.

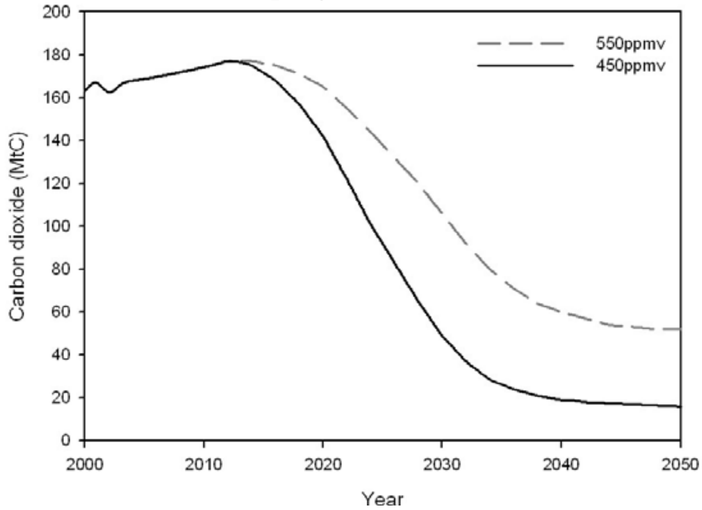

Figure 2. UK domestic CO_2 emissions estimates and those including international aviation and shipping.

3.2 *Carbon emission trajectories*

To produce total economy future emission trajectories for the UK, the Global Commons Institute (GCI) Contraction & Convergence model was used to reproduce the results of the RCEP report (RCEP, 2000), in line with the UK Government's 60% target. The GCI model, *CCOptions*, essentially calculates a global carbon trajectory based on stabilising atmospheric CO_2 concentrations at a particular level. This global carbon budget is then apportioned between nations as they move towards equal per capita emissions. However, the *CCOptions* model does not include emissions from international aviation and shipping.

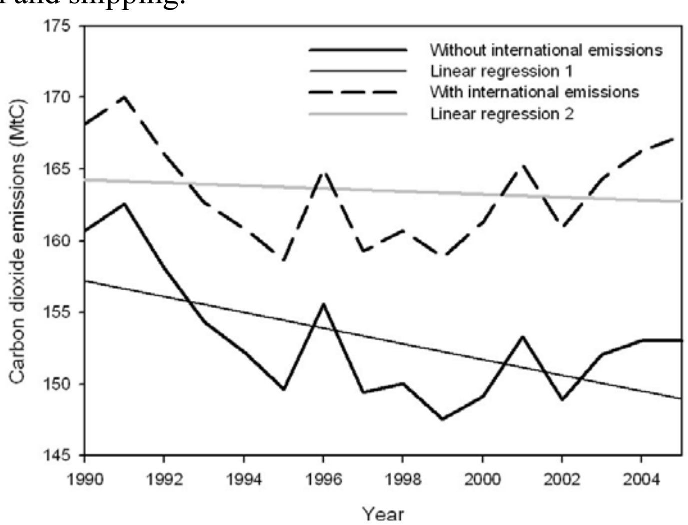

Figure 3. 450ppmv and 550ppmv profiles for UK carbon emissions.

To estimate the impact of including these emissions, the model was modified to incorporate global bunker fuel data available from the CDIAC database (CDIAC, 2005). A trajectory is generated for the UK based on the output of the *CCOptions* model, but modified to produce a scenario reflecting the historical emissions between 2000 and 2004, and their likely trends up until 2012. The resultant trajectory is illustrated in Figure 3. If a similar method is applied to the 450ppmv level, the second profile illustrated in Figure 3, is produced. To investigate the implications of these trajectories for the aviation sector, UK Government aviation forecasts and Tyndall scenarios are compared with the emissions profiles illustrated in Figure 3.

3.3 *Future aviation emissions*

In 2003, the UK Government published a White Paper (DfT, 2005) including 3 forecasts for aviation industry CO_2 emissions (DfT, 2005) from domestic, international and freight aviation (Table 1).

Table 1: UK Government aviation emission forecasts

Year	DEFRA Worst Case	DEFRA Central Case	DEFRA Best Case
		MtC	
2000	8.8	8.8	8.8
2010	11.4	10.8	10.3
2020	16.5	14.9	13.4
2030	20.9	17.7	15.9
2040	25.1	18.2	16.4
2050	29.1	17.4	15.7

The data for these forecasts begin in the year 2000, but data for 2004 is now available. Furthermore, the methodology used by the NETCEN to estimate emissions has been revised recently and historical figures re-evaluated (Watterson et al., 2004). Comparing the new estimates for 2000 to 2004 (Table 2) with these figures illustrates that the figure for 2004 is already close to the forecasted values for 2010. Emissions would therefore have to grow at extremely low rates between 2004 and 2010 to remain within the upper bound of the 'worst' case estimate by 2010.

Table 2. NETCEN aviation emissions data as submitted to the UNFCCC

Year	NETCEN data MtC
2000	9.0
2001	8.8
2002	8.6
2003	8.8
2004	9.8

The very high growth rates experienced by the aviation industry during the past few years have already rendered these UK Government's forecasts out-of-date. This is a significant limitation when attempting to assess this industry's impact on the climate. To illustrate how emissions are more likely to evolve if growth rates continue at close to current rates in the short term, two very simple scenarios are presented here.

The first assumes that the average annual rate of growth in emissions of 7% per year, seen between 1993 and 2001, continues from a baseline 2004 figure of 9.8MtC, until the year 2012. This growth rate is somewhat lower than the latest confirmed rate available indicating that emissions from international aviation increased by ~12% between 2003 and 2004. Between 2013 and 2050, emissions are assumed to grow at a much lower rate of 3% per year – similar to the figure suggested by the UK Government forecasts. Assumptions underlying this scenario for 2004 and 2012 include:

no new policies to address growth within the aviation sector; oil prices continue to have a very limited impact on growth; the success of the low-cost airlines continues and grows; fuel efficiency improves at around 1% per year across the fleet

For the period post-2012, it is assumed that: radical policies either in the form of quotas or fiscal measures, are introduced; fuel efficiency improvements are more significant

The second scenario, assumes:rates of growth in emissions seen historically, continue until 2030; fares remain affordable and there is little to no tax on kerosene; airport capacity is increased to adapt to this growth; fuel efficiency of the fleet increases by ~1% per year

Table 3: Aviation emission scenarios

Year	Scenario 1	Scenario 2
	MtC	
2000	9.0	9.0
2010	14.7	14.7
2020	21.4	29.0
2030	28.7	57.0
2040	38.6	76.7
2050	51.9	103.0

3.3.1 *Implications of a growing aviation for UK climate policy*

To assess the implications of a growing aviation industry within a UK striving to cut emissions, the UK Government aviation forecasts and the Tyndall aviation scenarios are compared with the Contraction & Convergence profiles illustrated in Figure 3. Figure 4 presents the comparison between the UK Government's aviation forecasts and the UK carbon budget. Despite these forecasts being unrepresentative of the true scale of aviation emissions, the results show that for all of the DfT's forecasts, carbon emissions from the aviation industry are accounting for more than the total carbon budget for the 450ppmv profile by 2050. Furthermore, the UK Government's 'worst' case scenario exceeds the 450ppmv profile during the 2030s. This is particularly worrying as recent scientific research (Elzen and Meinshausen, 2006) indicates that stabilising CO_2 concentrations at levels lower than 450ppmv, will be necessary if there is to be a reasonable likelihood of avoiding so-called 'dangerous climate change'. In other words, it will be virtually impossible to reconcile the levels of aviation growth forecast by the UK Government with a 450ppmv stabilisation level, unless dramatic changes are made to the way aircraft consume fuel or indeed the nature of the fuel source itself. This disproportionate allocation of emissions to one sector will inevitably have significant consequences for all other carbon-emitting sectors of the economy (Anderson et al., 2005).

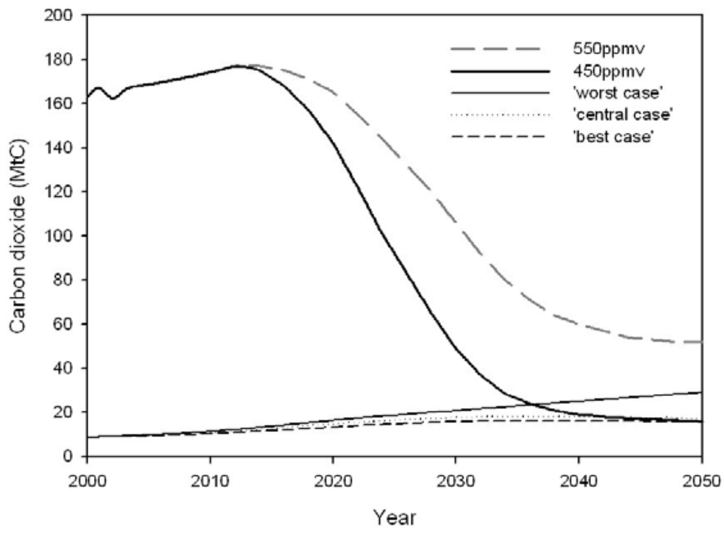

Figure 4. UK carbon emission trajectories vs UK Government aviation forecasts

Considering now the 550ppmv profiles, the DfT's forecasts show aviation emissions representing between 15% and 20% of the carbon budget by 2030, and between 30% and 56% by 2050. For comparison, in 2004, aviation accounted for 7% of the UK's carbon budget (Anderson et al., 2005). The likely shift from a 7% share to these much higher proportions would indicate that other sectors need to decarbonise substantially to compensate for air travel, either through significant reductions in energy consumption or the large-scale adoption of low-carbon energy supply. Consequently, the UK Government's forecasts predict the aviation industry accounting for over 50% of the UK's total carbon budget by 2050 if 550ppmv is the stabilisation target, and exceeding the UK's total 2050 carbon budget for 450ppmv. Whilst it may be argued that the Hadley Centre model, upon which the Contraction & Convergence profiles are based, generates slightly larger carbon-cycle feedbacks than other similar models (Zeng et al., 2004), the forecasts nevertheless clearly highlight the substantial contradictions between the UK Government's Energy White Paper targets for carbon emissions and the same government's Aviation White Paper's airport expansion proposals.

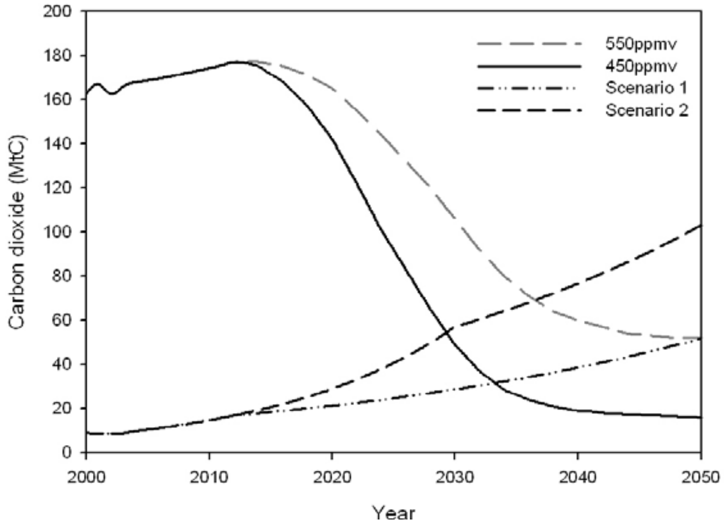

Figure 5. UK carbon trajectories vs aviation scenarios

The aviation scenarios presented in Table 3, and in graphical form in Figure 5 clearly illustrate the outcome of the arguably more realistic growth scenarios for the aviation industry, and what this means for the UK's total carbon budget. Both scenarios exceed the UK's carbon budget under the 450ppmv regime by the early 2030s, with scenario 2 exceeding it prior to 2030. If 550ppmv is the chosen trajectory, only scenario 1 remains within budget by 2050. The rapidly increasing emissions being generated by the aviation industry will likely leave the industry with extremely difficult choices in the future. If the current high rates of growth continue, even for a short period, then emissions growth will need to be curbed to less than 3% per year within the next 6 years, if the UK is to remain within the budget necessary to meet 550ppmv. However, the latest science is suggesting that to have a reasonable chance of avoiding 'dangerous climate change', a 450ppmv target is more appropriate. The corresponding budget would require growth in passenger-kilometres to closely match fuel efficiency per passenger-kilometre over the short to medium-term. In other words, growth in the region of 1 to 2% per year.

The silver bullet for the aviation industry is often cited as its swift incorporation into the EU Emissions Trading Scheme (EU ETS). However, as all of the EU nations are industrialised, they too will be looking to significantly reduce their carbon emissions from all of their sectors year-on-year. The EU Commission intends to include international aviation in the EU ETS by or before 2012 (COMM, 2005). The Commission is also intending for the scheme to include all flights taking off from EU nations, as opposed to a scheme incorporating just intra-EU flights in the first instance; the latter being preferred generally by the aviation industry (Bows et al., 2006). However, given the logistics of incorporating this international sector within the current EU ETS, it is highly unlikely that trading between the aviation industry and other sectors will begin prior to 2010-12.

4 CONCLUSION

By focussing on the UK as an exemplar nation, this paper illustrates a number of key points in relation its aviation industry and climate change targets. Firstly, UK Government forecasts for aviation emissions have quickly become outdated due to the very high rates of growth being seen within the industry. Consequently, these forecasts must be revisited as a matter of urgency. Secondly, that even using these outdated forecasts, this paper illustrates the conflict between the UK Government's Aviation White Paper, which lays out measures to meet the demand for flights, and the UK's Energy White Paper of the same year. Indeed, the UK typifies the EU in actively planning and thereby encouraging continued high levels of growth in aviation, whilst simultaneously asserting that they are committed to a policy of substantially reducing carbon emissions. Thirdly, using aviation emission scenarios that reflect the recent trends in emissions, the conflict between the UK Government's target and this growing industry has serious consequences for other sectors.

If the aviation sector is to be given a larger quota of emissions compared with other sectors, then these other sectors will need to decarbonise to compensate. This could be a reasonable solution to the limitations on technology and alternative fuels unique to the aviation sector, if the room for manoeuvre for other sectors were significant. However, these aviation scenarios suggest that if 450ppmv becomes the new climate target stabilisation level, then aviation emission can not be sustained at current levels, even with significant compensation from other sectors. If 550ppmv is chosen, then it is still possible that the total carbon budget will be exceeded by this one industry by 2050. Furthermore, if the industry were to take up 90% of the carbon budget, the pressure on other industries to decarbonise to 10% of their current levels would likely be too great. Ultimately, the UK and the EU face a stark choice: to permit high levels of aviation growth whilst continuing with their climate change rhetoric; or to convert the rhetoric into reality and substantially curtail aviation growth until it can be balanced by fuel efficiency gains.

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Estimates of UK CO_2 Emissions from Aviation Using Air Traffic Data

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Keywords: CO_2 Emissions, Aviation

ABSTRACT: The allocation of CO_2 emissions to specific sources is a major policy issue for international aviation. This paper addresses this problem by recommending a possible methodology for calculating air transport carbon dioxide (CO_2) emissions using detailed air traffic data. The basis for the calculations is an air traffic sample for one full-day of traffic for the UK. The results are compared with two of the most widely-used aviation CO_2 emission estimates to have been made for the UK: the SERAS study and NETCEN estimate. Their estimates for the year 2000 are 26.1 Mt and 31.4 Mt, respectively. Our estimate of total aviation CO_2 emissions, using detailed simulations and real air traffic data, is 34.7 Mt for the year 2004. Different methodologies and their implications are also discussed.

1 INTRODUCTION

Carbon dioxide (CO_2) is one of the main causes of climate change and air transport is the fastest growing source. Commercial air transport currently contributes a small but growing share of global anthropogenic CO_2 emissions. This share was estimated at 2% of the worldwide total in 1992 (Intergovernmental Panel on Climate Change (IPCC), 1999). In the UK, reported CO_2 from sales of fuel for international aviation was 2.8% of all CO_2 emissions in 1992 (which includes all international bunker fuels, which are sometimes ignored in assessments of CO_2 emissions). By 2003, this had risen to over 5% (UNFCCC, 2006). With estimated world wide growth in air transport as high as 5% per year, the air transport sector will account for a growing percentage of total CO_2 emissions, despite improvements in efficiency.

In the Kyoto Protocol, anthropogenic greenhouse gas emissions are attributed to individual countries to set targets and monitor performance. Currently, countries only have to include domestic air traffic in the calculation of total national emissions. Total international aviation fuel sales in each country are reported separately (as bunker fuels), but there is no agreed allocation procedure to attribute the associated CO_2 emissions to national totals and bring them within targets for emission reduction. In the context of national progress towards Kyoto targets, it is important to have a clear understanding of the total contribution of aviation, not just domestic flights, to ensure that policy priorities can be fairly assessed.

Several air transport CO_2 emission estimates have been provided for the UK in the past few years. The National Environmental Technology Centre (NETCEN) estimated that in 2000, UK air transport accounted for 31.4 million tonnes (Mt) of CO_2 emissions (DfT, 2003). Figures produced by Halcrow for the UK Department for Transport (DfT) in the South East and East of England Regional Air Services Study (SERAS) estimated total air transport related CO_2 emissions for 2000 at 26.1 Mt (DfT, 2003). Both studies had their limitations and assumptions. Here, in this study, we assess their findings using real air traffic data for one day to develop a new CO_2 emissions estimate.

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2 METHODOLOGY

2.1 *Scenario Definition*

The Reorganized Air Traffic Control Mathematical Simulator (RAMS Plus) and the Advanced Emission Model (AEM III) were used to analyse fuel burn use and hence CO_2 emissions. The RAMS Plus model simulates the four dimensional profile of each flight, describing the operation of the aircraft at each point, such that the fuel burn for each element of the journey can be calculated. This allows calculation of the emitted CO_2. The AEM has been developed at the EUROCONTROL Experimental Centre to estimate aviation emissions and fuel burn using flight profile information (AEM, 2003).

Simulations were conducted using traffic, route network and sector data provided by National Air Traffic Services in the UK (NATS). A 24-hour air traffic sample for Friday, 3rd September, 2004 was used with 7074 flights, each with specified departure and destination airports and simulation entry times. The simulation area covers the UK airspace. For the region simulated, data describing the location of sector boundaries, airports and navigation aids (navaids), are specified. The ATC sectors are specified in four dimensions and the routes are defined according to the sequence of navaids to be used.

2.2 *CO_2 Emissions Calculations*

The fuel burn rate, and hence the rate of CO_2 emission, varies with mode of flight. Two flight phases can be considered for emissions calculations: the Landing and Take Off cycle (LTO) which includes all activities below 3000 feet (1000 m) and the Climb, Cruise and Descent cycle (CCD) which is defined as all activities that take place at altitudes above 3000 feet.

Additional emissions occur due to fuelling and fuel handling in general, maintenance of aircraft engines and fuel jettisoning to avoid accidents. These emissions are, however, not included in this analysis. Also, CO_2 emissions from surface access to airports were not within the scope of this estimate.

To calculate the total fuel burn for the traffic sample, fuel burn rates from the performance tables of the Eurocontrol Experimental Centre (EEC) Base of Aircraft Data (BADA) Revision 3.6 were incorporated into RAMS Plus. Flight speed and rate of climb/descent were also defined according to the BADA performance tables.

The configuration of RAMS Plus with the UK air traffic sample has two limitations. Firstly, it only has the capability to calculate emissions above 3000 ft (CCD cycle), as detailed data on airport configurations and ground movements was not available. Secondly, given the limitations of the available air traffic sample and the specific sectors, navaids, and routes as defined for UK airspace, as required by RAMS Plus, it was possible to only calculate emissions within UK airspace. Since one of the objectives of this research was to estimate UK CO_2 emissions which can be allocated to the UK CO_2 budget, using a Flight Schedule Approach (meaning all domestic and traffic departing from UK airports), it was necessary to perform additional calculations using the AEM tool.

The air traffic sample available had detailed information only on flights within UK airspace. For international departures, the AEM completes the flight profile assuming that the aircraft uses the shortest (great circle) distance between the point of departure from UK airspace and the destination airport. On average, journeys are about 10% longer than this great circle route because of airspace constraints and meteorological factors (IPCC, 1999). In addition, the AEM completes the whole flight profile by adding missing LTO legs from departure and arrival airports as well as joining these legs with the first and last known position of the aircraft according to the flight file from RAMS.

3 UK CO_2 EMISSIONS ESTIMATE

The AEM uses flight profile information from the RAMS Plus output to calculate fuel consumption and emissions. Summing the emissions from all flights it was possible to derive total CO_2 emissions for the 24 hr traffic sample. Traffic was separated into three categories: domestic, UK departures to the EU, and UK departures to other international airports. All other traffic, including fly-over flights and flights arriving to the UK are omitted; emissions are calculated only for departures. This Flight Schedule approach gives a total fuel estimate consistent with the recorded deliveries of aviation fuel to the UK and prevents double counting of emissions allocated to international aviation. Just over half (55.19%) of the UK's total daily traffic movements are domestic (21.11% of total air traffic) or EU departures (22.78%) and international departures (11.30%) and they are used for estimation of the CO_2 emissions inventory.

The daily CO_2 estimates are adjusted to correct for underestimation due to the assumption that the flight trajectory follows the shortest (great circle) route outside of UK airspace. Previous studies (IPCC, 1999; Howell et all., 2003) have estimated that the distance flown is typically 10% longer than the great circle route. As this additional distance occurs in the cruise phase, and only outside UK airspace, the underestimation of the total CO_2 will be less than 10%. Assuming that the great circle portion of the flight underestimates distance flown by 10%, and that the additional CO_2 for the route as flown is proportional to the additional distance, the mean underestimation is 4.9% for EU departures and 6% for other international departures (expressed as a percentage of the total CO_2 for the full flight trajectory). Total daily CO_2 estimates are adjusted accordingly. CO_2 for domestic flights is not adjusted as there is no section outside of UK airspace.

In the absence of detailed data for each day, monthly total estimates for September were obtained by multiplying daily values by 30.

To reflect seasonal variation in air traffic volumes, monthly CO_2 emissions for the three categories of air traffic for the rest of the year were calculated using the reference values for September and weighting for the monthly number of air traffic movements using Civil Aviation Authority statistics for 2004 (CAA, 2004a). CAA monthly airport statistics tables for 2004 do not include records for accession countries admitted into the European Union in May 2004.

Air travel is greater during the week than on weekends and fairly uniform across individual days of the week. For scheduled traffic, a 20% difference between a weekday and a weekend day is not unusual (EUROCONTROL, 2006). Converting from a single weekday to an annual figure overestimates total traffic movements, partly by failing to account for the reduction in traffic at weekends. To correct for this, we assumed that the overestimation can be described by the difference between the number of air transport movements in our sample and those reported by the CAA and that this overestimation of traffic movements corresponds to a proportional overestimation of CO_2 emissions. For domestic traffic, the overestimation of traffic movements is 13.6%; for international (EU and other international departures), it is 9.7%. The annual CO_2 estimates are adjusted to correct for this.

Annual CO_2 emissions estimates for 2004 for the three traffic categories are shown in Table 1. It is assumed that the emissions in each category follow the annual cycle of movements, that is, the mix of aircraft types and route lengths remains constant and changes in frequency of service occur uniformly across the traffic fleet (within each traffic category).

Table 1. UK CO2 Emissions - 2004

2004 UK CO_2 Emissions Estimate	CO_2 (Mt)
Domestic	1.94 – 3.14
EU Departures	7.98 – 9.73
International Departures	16.54 – 22.97
Total	26.46 – 35.85

For domestic traffic, the monthly variation in movements is small and the distribution of routes shows little seasonal variability (CAA, 2004b). EU and International traffic are more variable. Most destinations for EU-bound traffic have a uniform pattern throughout the year, but traffic (in terms of carried passengers) to vacation destinations like Spain and Greece almost doubles during the summer. Within the International (non-EU) routes the largest variation is again for summer vacation destinations, such as Cyprus and Turkey, and for long haul flights to North America and the Far East (CAA, 2004c).

The assumption that the pattern of routes does not show seasonal variability overestimates stage lengths by about four percent for international scheduled services and by 7.5% for non-scheduled services within the 25 EU states. This is based on an analysis of CAA data (CAA, 2004d). There is a further underestimate of the stage lengths of international non-scheduled, non-charter traffic by 18.3%; however these flights represent only 2.3% of annual UK airlines flights for 2004.

Figure 1 shows the estimated annual cycle of the UK's CO_2 emissions from aircraft. As expected, the biggest polluter group comprises International Departure flights; although the number of movements is roughly half that for domestic or intra-EU flights. Aircraft are typically larger and the average route is much longer for these flights. EU and international departures have similar annual cycles; both groups have the highest emissions occurring in July and August. CO_2 emissions from domestic traffic have only minor variations throughout the year.

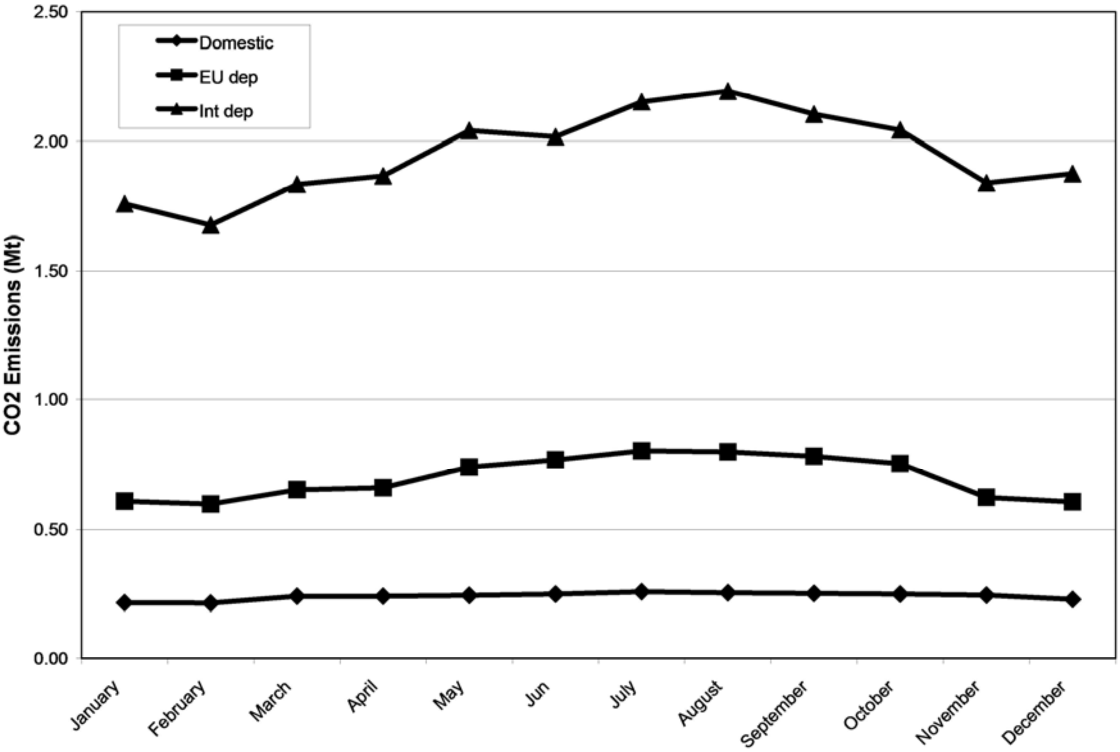

Figure 1. UK's CO_2 Emissions Annual Cycle

In addition to providing a national CO_2 emission estimate, this method allows analysis of those flights and aircraft within the sample that are the largest emitters. This provides an assessment of which flights and associated aircraft account for the bulk of emissions. More detailed analysis can be found in Pejovic *et al.* (in prep).

4 COMPARISON WITH OTHER CO_2 EMISSION ESTIMATES

Findings from this analysis are compared with the NETCEN and SERAS CO_2 estimates for the year 2000 taken from the report *Aviation and the Environment: Using Economic Instruments* (DfT, 2003). Despite the fact that estimates were made using different methodologies and data, there is some consistency between them (Table 2). Our estimate includes the uncertainty associated with the BADA performance data and fuel burn rates and uncertainties in the corrections for the great circle approximation and the overestimation of traffic. More detailed information can be found in Pejovic *et al.* (in prep).

Table 2. Aviation-related CO2 Emissions, Year 2000 (million tonnes)

Type of traffic	SERAS (2000)	NETCEN (2000 old)	NETCEN (2000 new)	NETCEN (2004 new)	This analysis (2004)
Domestic	1.5	2.9	1.97	2.30	1.94 - 3.14
International	24.6	28.5	30.24	33.12	24.52 – 32.71
Total	26.1	31.4	32.21	35.42	26.46 – 35.85

NETCEN estimated that in 2000, UK air transport accounted for 31.4 Mt of CO_2 emissions, of which 2.9 Mt CO_2 were emitted by domestic flights (DfT, 2003). In addition, NETCEN's updated UK Greenhouse Gas Inventory 1990 to 2003, records that the UK aviation sector, including all domestic flights plus international passenger departures and freight air traffic movements produced 32.2 Mt of CO_2. Of this total, UK civil passenger aviation produced 30 Mt of CO_2 (Baggot et al, 2005). Using a new methodology, their just released UK Greenhouse Gas Inventory 1990 to 2004, suggests that CO_2 emission estimates for international traffic in 2000 and 2004 were 30.2 and 33.1 Mt respectively (Baggott et al, 2006).

The NETCEN figures take into account the fact that international and domestic flights have a different proportion of emissions at altitude and in the LTO cycle. However, NETCEN calculates estimates of aviation CO_2 emissions at cruise altitudes based on aviation fuel sales data. Therefore NETCEN's estimate of the UK's CO_2 emissions is an approximation since NETCEN estimates the total fuel uplifted by aircraft in the UK as the UK's CO_2 emissions from aviation. In practice, part of the uplifted fuel could be used on flights not departing from the UK but used, for example, on a return flight back to the UK from a different country (or vice versa).

The SERAS study gave slightly different results. In the SERAS study total air transport related CO_2 emissions were estimated at 26.1 Mt for the year 2000 (DfT, 2003). SERAS produced estimates, which are over 10% lower than those estimated by NETCEN, assuming that aircraft use "great circle" routes. In addition, the SERAS estimates were based on the assumption that the UK's share of international flights is one-half of the total traffic. Apart from smaller coverage of UK airports by SERAS (29 UK airports), the likeliest reason for the discrepancy is that the modelling for the SERAS estimate assumed that all aircraft fly great circle distances. Our use of the RAMS simulation with real air traffic data allows actual flight paths to be modelled.

5 DISCUSSION AND CONCLUSIONS

The international air traffic emissions, calculated in this study (31.8Mt), appear to be slightly higher then those given by NETCEN for 2000 (30.2 Mt). However, looking at the NETCEN figures for the CO_2 emissions of international traffic in 2004 (33.1 Mt) and with respect to traffic growth between 2000 and 2004 which is in the range of 2-6% per year (CAA, 2004e), these estimates match well. Moreover, the latest UNFCCC records show that the UK's reported emissions resulting from fuel use for aircraft engaged in international transport were 30.24 Mt and 29.66 Mt in 2000 and 2003 respectively (UNFCCC, 2006).

There is a possibility, though, that NETCEN figures for emissions of international traffic are overestimated, since the metric used by NETCEN to measure the CO_2 emissions in cruise phase is an approximation. Furthermore, the high uncertainty in NETCEN's aviation fuel consumption reflects the uncertainty in the split between domestic and international aviation fuel consumption taken from DUKES. On the other hand, the SERAS study produces under-estimates and their approach uses assumptions which do not represent realistic assumptions about air traffic in the UK.

Nevertheless, both the NETCEN and the SERAS study provide a good basis for evaluation of our results. The results presented here indicate that by using real traffic profiles to calculate CO_2 emissions, by means of the Flight Schedule Approach, and applying different emission factors for each different mode of flight, it is possible to calculate a CO_2 emissions inventory consistent with other estimates. This approach also allows better disaggregation of domestic and international flights and their emissions as well as disaggregation into aircraft groups and route profiles that can serve as a basis for analysis of various policy effects, which the other estimates cannot provide.

Understanding of the total contribution of aviation, not just domestic flights, can ensure that policy priorities can be fairly assessed. Even if national targets for CO_2 emission reduction are met, a very small proportion of international departures can consume a large amount of the national allowances. This has implications for how the associated CO_2 emissions of international aviation can be brought within national targets for emission reduction.

Overall, this method for calculating a CO_2 emissions inventory based on actual flight paths, allows a better disaggregation of domestic and international flights and their emissions. CO_2 emissions of international traffic are calculated using real traffic profiles within UK airspace, and applying different emission factors for each different mode of flight, which results in a higher accuracy of the method. This approach also provides an assessment of which flights and associated aircraft account for the bulk of emissions. Furthermore, with availability of different traffic samples, to reflect seasonal and weekend traffic changes, it is evident that this approach can give us even more realistic and accurate estimates.

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Global road transport's emission inventory for the year 2000

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Keywords: emission inventory, road transport, gridding

ABSTRACT: Emission inventories are needed to determine the impact of different sectors and trace species on environment and health. We have calculated a highly differentiated emission inventory for road passenger and freight transportation worldwide, with a resolution of 1°x1° longitude/latitude, for CO_2, CO, NMVOC, CH_4, NO_x, primary PM and SO_2. Our bottom-up country by country calculation agrees to 2% with global fuel sales. We compare our results to other inventories, which have used a less differentiated approach or only cover certain world regions.

1 INTRODUCTION

Atmospheric research needs emission inventories to determine the impact of different sectors and trace species on the atmospheric composition and consequently on environmental and health impacts, among others climate change. Transportation has received increasing attention because it contributes about 15 to 20% of global anthropogenic emissions of carbon dioxide, carbon monoxide, nitrogen oxides, volatile organic hydrocarbons and primary particulate matter (EDGAR 32FT2000 Emission data, 2005). Furthermore, road transportation runs almost exclusively on oil products and combustion engines. With high growth rates for the transport volume in most parts of the world it is set to stay a major emitter of atmospheric pollutants, even if exhaust emission standards become more tightened and fuel quality improves.

This paper presents an inventory of road transport's fuel consumption and emissions of air pollutants on a 1°x1° grid for the whole world for the year 2000. We differentiate by vehicle category and fuel type on a country by country level. With this differentiation and scope of pollutants we go substantially beyond current knowledge (EDGAR 32FT2000 Emission data, 2005; Olivier et al., 2002; Schafer and Victor, 1999). Such a technology based approach is necessary for a more accurate estimate of current pollutant emissions.

Section 2 summarizes system boundaries and explains our calculation method, section 3 discusses validation, section 4 presents the emission results, and section 5 gives conclusions.

2 APPROACH

For the purposes of this inventory, road transport is any movement with motorized vehicles on public roads, for passenger or freight transportation. Excluded are movements by agricultural, forestry, building or construction machinery and with sports, pleasure or museum vehicles. Road vehicles are split up in five categories: mopeds, motor-cycles and three-wheelers (later referred to simply as two-wheelers); passenger cars; busses and coaches (later referred to simply as busses); light duty trucks below 3.5 tons gross weight; heavy duty trucks above 3.5 tons gross weight.

We consider consumption of motor gasoline, diesel, ethanol, biodiesel, LPG and CNG (the last four only for cars). We calculate exhaust emissions of CO_2 (from fossil fuels and non-fossil fuels separately), CO, NMVOC, CH_4, NO_x, primary PM and SO_2. Not included are evaporative losses, brake, tyre or clutch wear, resuspension, or discharges during maintenance, accidents or at the end-of-life.

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All emissions and the fuel consumption are calculated separately for 216 countries and territories, which are grouped in twelve world regions. For each country and vehicle-fuel combination, transport volumes (expressed as vehicle-kilometers) were estimated as described in Vanhove and Franckx (2006) and Borken et al. (submitted). Specific fuel consumption and exhaust emission factors (in g emitted substance per vehicle-kilometer) were estimated for each world region (Merétei, 2006; Borken et al., submitted). The sum-product of specific fuel consumption and transport volumes gives the total fuel consumption in a region. This calculated fuel consumption is compared to fuel sales data in road transport (IEA/OECD, 2003). The comparison is made separately for gasoline and diesel in each world region. Comparing on the level of world regions instead of countries has the advantage that fuel tourism does not distort the picture.

Our transport volumes are scaled such that the resulting fuel consumption matches the fuel sales data. Emissions are then calculated as the product of emission factor and transport volume, per vehicle-fuel combination and country.

2.1 *Uncertainties*

Emission factors have a high uncertainty even for OECD countries. This is because of the large number of factors influencing emissions, about which little data are available. Emission regulations provide some help, but they vary even between countries belonging to the same world region. Measurement data are often not representative of the fleet average. Also, so-called super-emitters have a high share in the overall emissions, despite their small number, and little data are available on them.

Inaccuracies in the mileage distribution over vehicle types affect both the overall level of emissions and the relative amount of particular substances. Especially uncertain is the distribution of freight vehicle mileage over light duty trucks and heavy duty trucks, as often only total ton-kilometers are given in statistics.

It is also known that some fuel is misallocated in the IEA data (e.g. fuel consumed in road transport is reported as fuel consumed in agriculture), notably in non-OECD countries. After comparison with other sources, we assumed different fuel sales for road transport than IEA in China, South Korea and India. This uncertainty affects the overall level of emissions in the respective world region.

3 VALIDATION

3.1 *Comparison of calculated fuel consumption with fuel sales data*

A first plausibility check for transport volumes, fuel consumption factors and fuel sales data is given by the comparison of our calculated fuel consumption with the fuel sales data (mostly IEA data). Globally, they are in good agreement; the total calculated gasoline consumption is lower than the sales data by 3% and the total calculated diesel consumption by 1%. In individual world regions, the discrepancy is sometimes much higher, but usually where gasoline consumption is underestimated, diesel consumption is overestimated, which means the discrepancy of total fuel sales is lower and the problem is partly due to difficulties with the distribution of mileage over fuel types (probably mostly freight mileage). The notable exception is the Middle East, where we underestimate both gasoline and diesel consumption by more than 40% compared to IEA sales data. We are therefore in the process of revising our transport volumes for this region and have also identified problems with the IEA sales data.

As discussed above, our raw data are adjusted according to the fuel sales data for each region and fuel separately. The following presents adjusted data only.

3.2 *Comparison with global and regional emission inventories*

As measurements of real world emissions are so far limited either in driving conditions or in the representativeness of the fleet, our best possibility of comparison are other global or regional emission inventories. Here we compare road transport's emissions globally, for North America, Western Europe and Asia. Comparison data are taken from one global, but regionally disaggregated inventory (EDGAR 32FT2000 Emission data, 2005) and one region specific inventory each (National Transportation Statistics 2004, 2005; De Ceuster et al., 2006; RAINS ASIA, 2001).

Table 1. Comparison of inventory data for road transport's emissions in the year 2000 globally, in North America, Western Europe and Asia; percentages denote differences to this work.

	CO_2 [Mt]	CO [Mt]	VOC [Mt]	NO_x [Mt]	PM [Mt]	SO_2 [Mt]
World						
this work	4223	111	15.6 [1]	29.2	1.33	1.79
EDGAR	4276 [+1%]	186 [+68%]	35.4 [+127%]	28.5 [-2%]		3.66 [+104%]
North America						
this work	1570	41	4.0 [1]	7.9	0.18	0.19
EDGAR	1639 [+4%]	64 [+56%]	8.4 [+110%]	7.5 [-5%]		0.33 [+74%]
NTS (only USA)	1407 [-10%] [2]	62 [+51%]	4.8 [+20%]	7.6 [-4%]	0.21 [+17%] [3]	0.24 [+26%]
Western Europe						
this work	800	12	1.7 [1]	5.4	0.28	0.09
EDGAR	819 [+2%]	17 [+42%]	4.4 [+159%]	4.6 [-15%]		0.27 [+200%]
TREMOVE	842 [+5%]	21 [+75%]	3.7 [+118%]	4.4 [-19%]	0.20 [-29%]	0.10 [+11%]
Asia						
this work	608	21	4.7 [1]	6.2	0.45	0.53
EDGAR	589 [-3%]	37 [+76%]	9.4 [+100%]	5.6 [-10%]		1.53 [+189%]
RAINS ASIA						0.78 [+47%]

[1] without evaporative emissions
[2] derived from fuel consumption
[3] PM_{10} ($PM_{2.5}$: 0.15 Mt)

The variation is small for CO_2 emissions, which means that the assumptions for road transport's fuel consumption are in close agreement. Therefore, differences in the other pollutants must result from different fleet average emission factors, i.e. due to different assumptions about the shares of the various vehicle-fuel combinations and the respective vehicle emission factors. E.g. EDGAR 32FT2000 values are calculated with emission factors for the year 1995. These do not capture the subsequent reductions in specific vehicle emissions and hence EDGAR has higher total emissions throughout than our work. One notable exception is the emission factor for NO_x: It has recently been discovered in EU15 that real world emissions from heavy duty vehicles are about 30% higher than the limit values (Hausberger et. al, 2003). This is already reflected in our emission factors, contrary to all other data.

Concerning VOC emissions it must be noted that we calculated tail pipe emissions only, and therefore our data are not directly comparable to other inventories which include evaporative emissions as well.

4 RESULTS

4.1 *Total global and regional pollutant emissions from road transport*

Road transportation emits about 4223 Mt CO_2, 111 Mt CO, 15 Mt NMVOC, 0.8 Mt CH_4, 29 Mt NO_x, 1.33 Mt primary PM and 1.8 Mt SO_2 worldwide in the year 2000 (Table 2).

The OECD regions (North America, Western Europe, Japan, Oceania) emit almost two-thirds of fossil CO_2, more than half of which is from North America. Asia and the Middle East account for one fifth of CO_2 emissions. Road transportation in the Former Soviet Union and in Central and Eastern Europe accounts for about 5% of CO_2 emissions, while Africa's share is about 3%. This reflects the regional shares in fuel consumption.

The shares are different for the other exhaust gases due to the regional differences in the vehicle fleet composition, fuel usages, in exhaust emission controls and technology: The OECD regions, which have started to implement vehicle exhaust emission controls long before the year 2000, account for 54% of CO, 41% of NMVOC, 38% of CH_4, 52% of NO_x, 39% of primary PM and only 18% of SO_2 emissions globally, with the US again providing the lion's share except for PM. Vice versa, all Asian regions have higher shares of exhaust pollutants than their respective share in fuel consumption. There, an exhaust emission control began only recently and many two-wheelers were still powered by two-stroke engines. Due to the high sulphur contents in their fuels, Africa, Latin America and the Middle East account for about half of global sulphur dioxide emissions.

Table 2. Emissions from road transportation in the year 2000 differentiated by region, in decreasing order of fuel consumption and CO_2 emissions, in absolute numbers and as shares of the global total.

	Fuel [Mtoe]	CO_2 [Mt]	CO [Mt]	NMVOC [Mt]	CH_4 [Mt]	NO_x [Mt]	PM [Mt]	SO_2 [Mt]
NAM	533 [37%]	1570 [37%]	40.9 [37%]	3.85 [26%]	0.18 [23%]	7.87 [27%]	0.18 [14%]	0.19 [11%]
EU15	268 [19%]	800 [19%]	12.2 [11%]	1.66 [11%]	0.08 [10%]	5.35 [18%]	0.28 [21%]	0.09 [5%]
LAM	130 [9%]	369 [9%]	9.3 [8%]	1.16 [8%]	0.06 [8%]	2.89 [10%]	0.13 [10%]	0.46 [26%]
EAS	101 [7%]	301 [7%]	10.1 [9%]	1.85 [12%]	0.11 [14%]	2.81 [10%]	0.15 [11%]	0.15 [8%]
JPN	78 [5%]	233 [6%]	4.6 [4%]	0.47 [3%]	0.03 [4%]	1.53 [5%]	0.04 [3%]	0.02 [1%]
MEA	71 [5%]	211 [5%]	8.5 [8%]	1.33 [9%]	0.07 [9%]	1.95 [7%]	0.10 [8%]	0.22 [12%]
SEA	59 [4%]	175 [4%]	7.1 [6%]	1.39 [9%]	0.08 [10%]	1.68 [6%]	0.15 [11%]	0.21 [12%]
CIS	47 [3%]	140 [3%]	6.6 [6%]	0.92 [6%]	0.04 [5%]	1.15 [4%]	0.06 [5%]	0.05 [3%]
AFR	44 [3%]	131 [3%]	3.3 [3%]	0.48 [3%]	0.02 [3%]	1.01 [3%]	0.05 [4%]	0.19 [11%]
SAS	43 [3%]	131 [3%]	4.0 [4%]	1.19 [8%]	0.08 [10%]	1.75 [6%]	0.14 [11%]	0.17 [9%]
CEC	29 [2%]	87 [2%]	2.2 [2%]	0.34 [2%]	0.02 [3%]	0.71 [2%]	0.03 [2%]	0.02 [1%]
OCN	25 [2%]	73 [2%]	2.2 [2%]	0.22 [1%]	0.01 [1%]	0.53 [2%]	0.01 [1%]	0.02 [1%]
World	1429	4223	110.9	14.86	0.78	29.23	1.33	1.79

NAM: North America; EU15: Western Europe; LAM: Latin America; EAS: East Asia; JPN: Japan; MEA: Middle East; SEA: South East Asia; SAS: South Asia; CIS: Commonwealth of Independent States; AFR: Africa; CEC: Central and Eastern Europe; OCN: Oceania

4.2 *Gridded pollutant emissions from road transport*

Emissions are distributed from a country level to a 1°x1° grid using rural and urban population densities, which are available for 1990 from EDGAR (Olivier et al., 2002). Depending on the vehicle category and world region, urban and rural populations are weighted differently in the gridding. The emissions of every vehicle category are split in two shares: one is distributed according to the density of the rural population, the other according to the density of the urban population. The shares are detailed in Table 3. This approach is a better approximation than distributing the traffic volumes according to the total population, because it takes into account the differences in the transport structure of rural and urban areas, e.g. individual motorized passenger transport in developing countries is available primarily in urban areas and heavy duty trucks drive more in rural areas compared to light duty trucks.

Figures 1 and 2 show as examples maps for emissions of CO_2 and NMVOC. Remarkable are especially the high NMVOC emissions in parts of India, China and South East Asia. These are due to the relatively low emission control standards and high share of two-wheelers, often still with two-stroke engines.

Table 3. Weighting of rural and urban population for gridding of emissions per vehicle category and region.

	Car		Bus		Two-wheelers		Light duty truck		Heavy duty truck	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
AFR+MEA	10%	90%	30%	70%	20%	80%	50%	50%	50%	50%
CEC	61%	39%	57%	43%	60%	40%	63%	37%	66%	34%
CIS	20%	80%	30%	70%	10%	90%	50%	50%	75%	25%
EAS+SAS+SEA	25%	75%	75%	25%	10%	90%	20%	80%	90%	10%
EU15+JPN	50%	50%	49%	51%	53%	47%	59%	41%	64%	36%
LAM	20%	80%	50%	50%	10%	90%	25%	75%	90%	10%
NAM+OCN	37%	63%	61%	39%	42%	58%	39%	61%	58%	42%

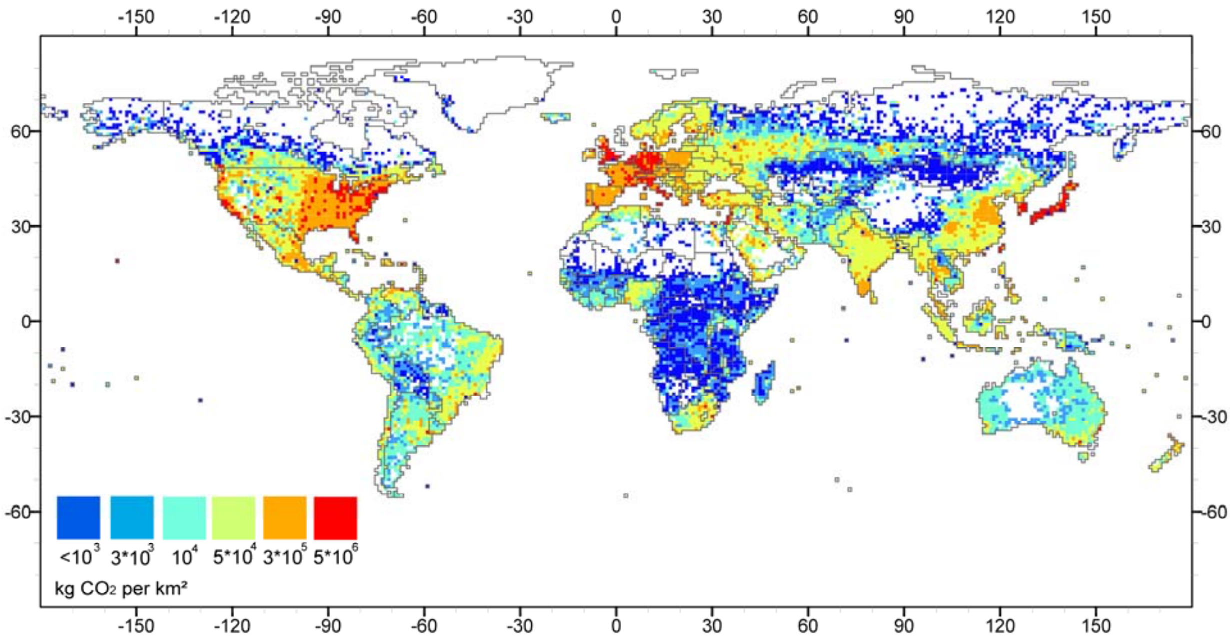

Figure 1. CO_2 emissions from road transportation in the year 2000

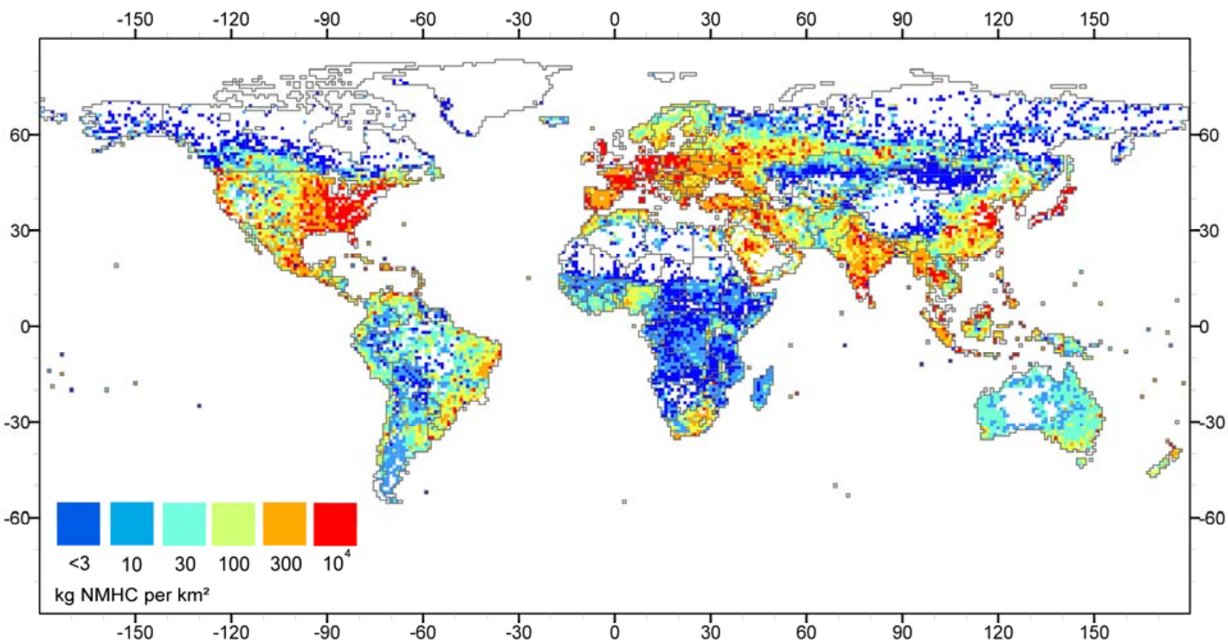

Figure 2. NMVOC emissions from road transportation in the year 2000

5 CONCLUSIONS

The work presented here is a major step towards a detailed and consistent global emission inventory for transportation (cf. QUANTIFY Homepage: http://www.pa.op.dlr.de/quantify/). Emissions of road passenger and freight transport are available separately, and if needed, emissions by vehicle category and by fuel type can be provided. Road transport's exhaust emissions have been calculated for the first time for many non-OECD regions at this level of detail. Fuel sales data have been cross-checked for some important non-OECD countries, which improves the reliability of the emission estimates for those countries.

The largest source of uncertainty remain the emission factors, especially in non-OECD regions. Also important are the uncertainties resulting from the lack of knowledge about the distribution of total ton-kms over the different vehicle and fuel types, and the associated load factors. A sensitivity analysis is planned to estimate the magnitude of the uncertainties. We also develop scenarios for future emissions from road transportation, analyzing the potential of different mitigation measures.

Similar inventories are being prepared for rail and inland waterways emissions. Together with the maritime shipping emission inventory produced by Det Norske Veritas and the aviation emission inventory produced by the Manchester Metropolitan University, the whole transport sector will be covered in much detail.

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Forecasted Maritime Shipping Emissions for Belgium with an Activity Based Emission Model

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Keywords: sea-going vessels, emission model, activity based, technological improvements, scenarios

ABSTRACT: In this paper we demonstrate the forecasting of maritime shipping emissions for Belgium with an activity based emission model. The activity based emission model made it possible to forecast the emissions from maritime shipping for the near future (2010). Emissions for the year 2010 are calculated by using activity growth factors, fleet evolution, existing legislation and detailed data from a statistical year (2004). To compute the effect of the existing IMO and EU legislation, we defined on the one hand an autonomous growth scenario and on the other hand a current legislation scenario. The IMO regulation decreases the NO_X emissions of the main engines with merely 1 % in 2010. The IMO and EU regulation on the sulphur content in maritime fuels has a large effect on the SO_2 emissions (decrease of 50 - 53 %).

1 INTRODUCTION

As in many other countries, the current emission estimation methodology for maritime shipping in Belgium is based on bunker fuels allocated to the country. VITO developed an alternative approach based on traffic related data. The activity based emission model for maritime shipping calculates the carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) emissions from sea-going vessels within Belgian jurisdiction. The activity based emission model made it possible to forecast the emissions from maritime shipping for the near future (2010), taking into account the effect of the current IMO and EU legislation.

2 OBJECTIVES

In this paper we want to demonstrate an activity based emission model to map historical emissions from maritime shipping and to make emission projections for the near future (2010). Therefore, we have defined the following subsidiary aims:

- To present briefly the activity based bottom-up approach for the calculation of an emission inventory of maritime shipping within Belgian jurisdiction.
- To describe the methodology used for forecasting maritime shipping emissions for Belgium, taking into account the IMO and EU legislation.
- To forecast the CO2, SO2, NOX, CO, HC and PM emissions from maritime shipping in Belgium for the year 2010 under a well-defined current legislation scenario.
- To analyse the effect of the current IMO en EU legislation on the emissions of sea-going vessels in the year 2010.

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3 ACTIVITY BASED MARITIME SHIPPING EMISSION MODEL

We have evaluated different European activity based methodologies MEET (1999), ENTEC (2002), ENTEC (2005), EMS (2003) and TRENDS (2003) used to estimate emissions for maritime transport. We screened the utility of the different methodologies for mapping emissions from sea-going vessels in Belgium on the basis of a list of strengths and weaknesses. Transparency, reproducibility, the integration of technical aspects of the sea-going vessels and the amount of detail were important selection criteria for the methodology. Therefore, we finally decided upon an approach similar to the one used in EMS (2003), but with specific adaptations to the Belgian situation.

We developed an activity based maritime shipping emission model for six different geographical areas in Belgium: four harbours, the river Scheldt and the North sea (12 mile zone). The model contains data on all shipping activities of sea-going vessels for the year 2004, originated from:

- each of the Belgian harbours (Antwerp, Ghent, Ostend and Zeebrugge) for the activities in the different harbours and the Belgian part of the river Scheldt;
- the Belgian/Dutch Vessel Traffic System for the activities in the Belgian jurisdiction of the North Sea (12 mile zone).

The information systems where the activity data for the year 2004 were extracted from are not modelled for the emission inventory purpose. It was a time consuming job to transform the information into appropriate input files.

We extracted for the year 2004 all Lloyd's numbers for sea-going vessels that called in at a Belgian harbour (or travelled in the 12 mile zone of the North sea). VITO then purchased the following characteristics of those sea-going vessels from Lloyd's Register Fairplay:

Ship Type	RPM
Length	TEU
Date of building	Refrigerated containers
Main engine type	Speed
Power main engine	Flag

The model determines CO_2, SO_2, NO_X, CO, HC and PM exhaust emissions through the energy use (power and fuel consumption), taking into account the length, building year and other technical aspects (e.g. engine type, RPM, fuel type, …) of the sea-going vessels, and the power use during each stage of navigation (cruise speed, reduced speed, manoeuvring, hotelling and anchoring). A distinction is made between the exhaust emissions of auxiliaries (e.g. for on board electricity production) and the main propulsion engines. For the latter, we distinguish three types of main engines, namely 2-stroke engines, 4-stroke engines and steam turbines.

The model is provided with technology-related emission factors from EMS (2003) to compute the NO_X, CO, HC and PM emissions. These emission factors depend on the building year of the vessel and the percentage of the maximum continuous rate. The emission factors for CO_2 correspond with the IPCC (1997) CO_2 emission factors for the different maritime fuels. The model also takes into account the EC (2002, 2005) and IMO (2005) regulations for the sulphur content of maritime fuels (Table 1).

Table 1. Overview of the CO_2 and SO_2 emission factors (kg/ton fuel).

Emission Factor [kg/ton]		Heavy fuel oil	Diesel & gas oil	Gas boil off
CO_2	-	3110	3100	2930
SO_2	(… – 18/05/2006)	54	4	~0
SO_2	(19/05/2006 – 2009)	30	4	~0
SO_2	(2010 - …)	30	4 or 2[1]	~0

[1] 2 kg SO_2/ton diesel or gas oil at berth (minimum duration of 2 hours)

Energy for loading and unloading can either be supplied from the vessel engines or from the harbour energy facilities. Currently, the energy consumption and the emissions resulting from it for loading and unloading are not included into the model.

4 FORECASTS

The activity based emission model made it possible to forecast the emissions from sea-going vessels for the near future. To compute the effect of the current IMO and EU legislation, we defined on the one hand an autonomous growth scenario and on the other hand a current legislation scenario.

4.1 *The autonomous growth scenario*

In the autonomous growth scenario, we only take into account the traffic and fleet evolution, based on activity growth rates per harbour and techno-economic improvements (fuel, ship size, engine management). So, no environmentally-friendly legislation was included.

The determination of the activity growth factors is exogenous to the model. We use economic growth rates to model future activities. The bases for the merchant vessels are the transported freight tonnes by sea-going vessels per harbour in the year 2004 and projected tonnages for the year 2010 according to a low and high autonomous growth scenario. From 2004 until the year 2010 and for each harbour, we implemented for passenger ships an annual growth rate of 1 % in a low autonomous scenario and 2 % in a high autonomous scenario (DG Environment, 2005).

In consultation with an expert committee, we assumed that the increase in traffic of merchant vessels will be filled in by newly built sea-going vessels. The extra tonnages have to be transported to the different harbours with those new ships. We determined how many extra visits the new ships will have to make by taking into account the gross tonnage of the new ships. For passenger ships and negative growth of merchant vessels, we assumed that the growths between the year 2004 and 2010 will have an effect on all ship categories (lengths). Therefore, we decreased the activity data of the different ship types with accumulated growth rates over 6 years.

We made the following assumptions to define the ship characteristics of the new sea-going vessels and this for each harbour and each ship type to take into account geometry of the harbours and the docks:

- new ships have the length of the largest ship visiting in 2004;
- the characteristics of a new ship are based on average ship characteristic from all available ships in the Lloyd's Register Fairplay database with the corresponding length that were built from 2000 on.

4.2 *The current legislation scenario*

We implemented extra measures in the current legislation scenario compared to the autonomous growth scenario to meet the IMO and EU regulations.

On the 19th of May 2005, the MARPOL Annex VI convention came into force. The NO_X Technical Code, developed by IMO, defines mandatory procedures for the testing, survey and certification of marine diesel engines to ensure that all applicable engines comply with the NO_X emission limits defined in it. The requirements for the control of emissions apply to all engines > 130 kW installed on ships constructed after 1st of January 2000 and all engines that undergo a major conversion after 1st of January 2000 (Table 2).

Table 2. NOX-standard for sea-going vessels according to Annex VI of MARPOL.

Engine speed - n [rpm]	n < 130	130 ≤ n < 2000	n ≥ 2000
Limit Value [g/kWh]	17.0	$45 * n^{-0.2}$	9.8

Apart from standards for NO_X, Annex VI also includes limit values for SO_2. In the Annex, a global upper limit of 4.5 mass % on the sulphur content of fuel oil for sea-going vessels is set as well as two emission control areas (SO_X Emission Control Areas – SO_XECA's) with more stringent controls on sulphur emissions. Ships in these areas can only use fuel oil with a sulphur content lower then 1.5 mass %. Alternatively, ships must fit an exhaust gas cleaning system or use any other technological method to limit SO_X emissions. In the original protocol, the Baltic Sea area has been designated as SO_XECA, the North Sea and the English Channel have been appointed in 2000 after negotiations with the EU-member states. This required the implementation of:

- a NOX correction factor in the emission model for all vessels built from 2000 on;

- a sulphur content of 1.5 mass % for heavy fuel oil.

The sulphur content of 1.5 mass % for heavy fuel oil is also prescribed by the 2005/33/EC Directive. This Directive also imposes the use of 0,1 mass % sulphur for vessels at berth with a minimum berth duration of 2 hours. We assumed the use of diesel oil with a sulphur content of 0.1 mass % for all vessels at berth because the duration at berth is in most cases (> 97 %) longer than two hours.

5 EMISSION RESULTS

Table 3 presents the emission results for the historical year 2004 and the future year 2010 in the low and high current legislation scenario.

Table 3. Emissions of sea-going vessels in the historical year 2004 and the future year 2010 (Belgium) in a low and high current legislation scenario.

Emission [kton]	2004	2010 (low)	2010 (high)
CO_2	720	735	783
SO_2	10.9	5.16	5.48
NO_X	16.9	17.1	18.1
PM	1.28	1.25	1.34
CO	2.77	2.89	3.11
HC	0.569	0.579	0.614

Depending on a low or high economic growth, the CO_2 emissions increase with respectively 2 % and 9 % in the current legislation scenario over the period 2004-2010 due to an increase in activity.

The NO_X emissions rise slightly (1 %) in the low current legislation scenario, the increase in activity offsets the reductions of the IMO and EU regulations. An increase of 8 % of the NO_X emissions takes place in the high current legislation scenario between the years 2004 and 2010.

The IMO and EU regulations are most effective for the reduction in SO_2 emissions. A decrease of 53 % (low) and 50 % (high) in SO_2 emissions is accomplished despite to the increase in activity between the years 2004 and 2010.

6 THE EFFECT OF THE IMO AND EU LEGISLATION

Figure 1 shows the regulated emissions SO_2 and NO_X of sea-going vessels in Belgium for the years 2004 and 2010 in the autonomous growth and current legislation scenarios.

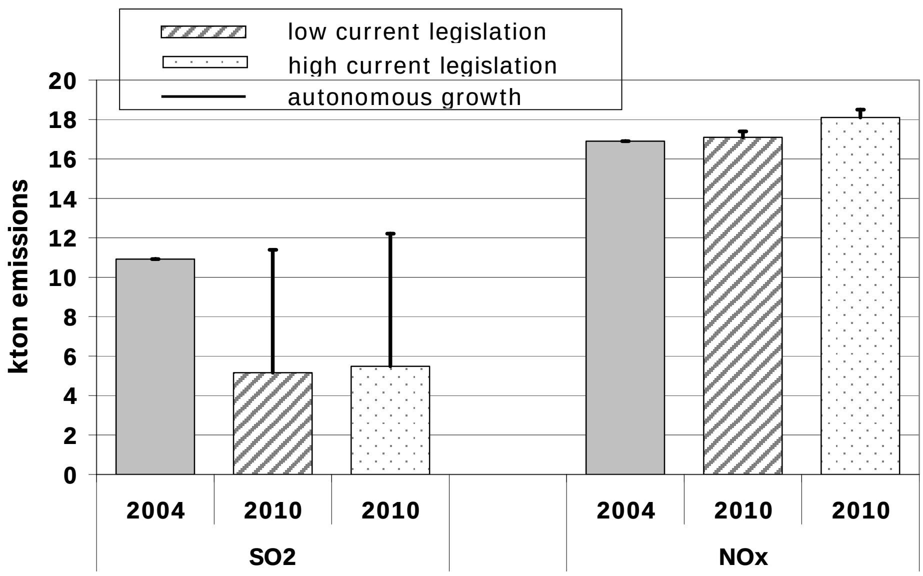

Figure 1. SO_2 and NO_X emissions of sea-going vessels in the reference and baseline scenarios.

The IMO regulation results in a reduction of merely 1 % of the NO_X emissions of main engines in the year 2010. The total reduction of 55 % in SO_2 emissions is due to both the IMO and EU regulations:

- a decrease of the sulphur content for heavy fuel oil;
- a decrease of the sulphur content for fuels used at berth, which also implies a switch from heavy fuel oil to diesel oil for vessels at berth built after 1984.

The switch form heavy fuel oil to diesel oil for vessels at berth results for the auxiliaries in a large emission reduction (33 %) for PM and small emission reductions for CO_2 (5 %), NO_X (5 %), CO (4 %) and HC (4 %).

7 CONCLUSIONS

The transformation of the activity data for historical years into the activity based emission model for maritime shipping is a time consuming job. The activity based emission model however, makes is possible to forecast the emissions from sea-going vessels for the near future by taking into account various legislations.

The technological evolution of sea-going vessels is slower than that of other transport modes. An increase in activity between 2004 and 2010 offsets the technological improvements for most pollutants. CO_2 emissions increase with 2 - 9 % between 2004 and 2010. The IMO and EU legislation have the largest effect on the SO_2 emissions. A decrease of 50 -53 % between 2004 and 2010 was calculated in the current legislation scenario. The IMO regulation has only a small reducing effect on the total NO_X emissions of sea-going vessels in the year 2010.

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