Emissions Control Systems and Climate Change Emissions

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Introduction:

The effectiveness of emissions control technologies for reducing emissions of key air pollutants, especially oxides of nitrogen and particulate matter, is well known and is demonstrated by the overwhelming use of such systems to control emissions from cars, vans, trucks, buses, and motorcycles, and increasingly on construction machinery, tractors, ships, recreational boats, and railway locomotives and railcars.

The effect of engines, vehicles and machinery on emissions classed as relevant to climate change is now a significant element in their design. In Europe only CO_2 emissions have been considered in this respect, although the US is now looking at emissions of other climate-relevant emissions. Emissions control systems can have an effect on CO_2 emissions, depending on the engine, emissions system and calibration used – experience with cars shows that the average effect of an efficient diesel particulate filter on a new car is near-neutral, and experience with heavy-duty vehicles shows that use of SCR systems allows more fuel-efficient engine calibration with a consequent reduction in both CO_2 emissions and operating costs.

The effect of emissions control systems on other climate-relevant gases has not, so far, been fully considered. Measurements undertaken by AECC indicate that the potential for reduction of Black Carbon emissions may be particularly significant.

The Positive Impact of Emissions Control on Air Quality

Combustion engines emit reactive hydrocarbons, carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM) including ultrafine particles. They are a key contributor to local air pollutants. Toxic emissions from transport adversely affect air quality both in the immediate vicinity (‘at the kerbside’), in the local area and regionally. Modelling studies indicate that in many areas urban air quality will not meet standards for PM and NO_2 in the 2010-2015 timeframe, and this is borne out both by the numerous requests submitted to the European Commission for time extensions to meet the Air Quality Standards and by the European Environment Agency’s NEC Directive Status Report (European Environment Agency, 2009), which indicates that 12 Member States currently do not expect to meet their 2010 NOx target.

Emissions control systems produce major reductions in pollutants affecting air quality. Three-way catalysts are used to control CO, hydrocarbon (HC) and NOx emissions from petrol-engined vehicles. Oxidation catalysts control CO and HC from diesel engines. Selective Catalytic Reduction (SCR) is now widely used on new heavy-duty (truck/bus) diesel engines to control NOx emissions whilst allowing a benefit on fuel consumption and CO_2 emissions, and this technology is now starting to appear on cars. An alternative system (Lean NOx traps – LNT) is also in use on diesel and direct-injection petrol cars. Finally, new light-duty diesel vehicles are now fitted with particulate filters which very efficiently remove sooty particulate matter, including the ultrafine particles. Some buses are already using this technology, and it is expected that from 2014 all heavy-duty vehicles will need to use diesel particulate filters.

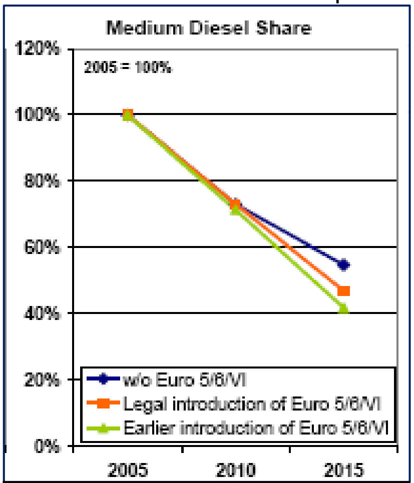

Figure 1: Future NOx emissions compared to 2005: *Source: Lambrecht (IFEU) 2007*

Effective legislation stimulates the use of emissions control technologies and so improves local air quality. Early implementation of these technologies, through incentives or implementation of Low Emission Zones, can assist in improving urban air quality to meet legislative targets for ambient air quality. Modelling by IFEU (Lambrecht, 2007) indicates that early implementation of the technologies needed to meet the future light-duty and heavy-duty emissions limits can give a significant boost to the rate of reduction in emissions (see Figure 1).

The Impact of Emissions Control on Climate Change Emissions

The United Nations Intergovernmental Panel on Climate Change (IPCC) says that global warming can be related to atmospheric levels of various emissions (Pachauri, 2007) of which CO_2, one of the main products of combustion, is the most prevalent. Engine and vehicle development trends are continually decreasing CO_2 emissions and this will be driven further through the new EU legislation setting CO_2 targets for cars (Official Journal of the European Union, 2009) and that proposed for light commercial vehicles (European Commission, 2009).

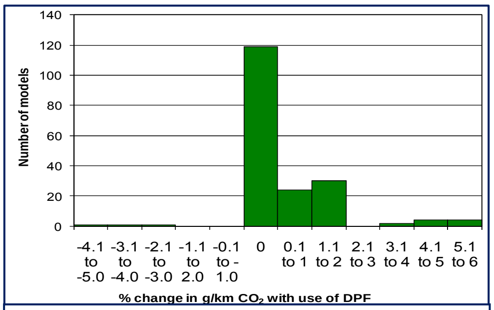

Figure 2: Change in CO_2 emissions with DPFs 184 Models paired in description, engine size, power, V_{max} manufacturer's engine code and Euro emissions standards.
Source: AECC analysis from KBA 2007 database.

For some types of emissions control systems, there may be a small CO_2 penalty due to, for instance, regeneration of particulate traps, but the system as a whole provides major benefits to improve local air quality as discussed above. Using German Type Approval data for 2007 (Kraftfahrt-Bundesamt, 2007) a comparison, shown in Figure 2, of the same cars that were available both with and without an optional Diesel Particulate Filter (DPF), shows an average CO2 increase of only 0.6% for fitment of a DPF. The modal value was 0.0% (119 models).

Other systems such as SCR allow the optimisation of the vehicle to provide improved fuel efficiency. Most European manufacturers of heavy-duty vehicles have selected SCR as their preferred technology to control NOx emissions for Euro IV, V and beyond. The European automobile manufacturers' association said (ACEA, 2003) that SCR technology would enable their members to comply with the Euro IV and V emission standards and, at the same time, achieve fuel consumption levels 5 to 6% lower than those of equivalent EU III engines. Diesel engines used in Non-Road Mobile Machinery such as construction equipment, tractors, railway locomotives and railcars should also benefit from this optimisation.

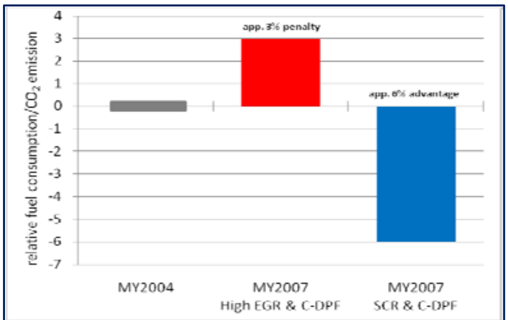

Figure 3: Fuel consumption and CO_2 emission of MY 07 emission strategies. *Source: (Schittler, 2003)DaimlerChrysler Powertrain; 9th Diesel Engine Emission Reduction Conference 2003.*

The contribution of motor vehicles to Global Warming is reported to be not only through CO_2 emissions but also (to a much lesser extent) emissions of N_2O (trace levels) and methane (typically ~10% of total HC). Both the emissions rate and the reported global warming potential of that emission over various timeframes need to be considered to understand the overall effect. These are shown in Table 1. Both methane and N_2O are classed as having a higher global warming potential than CO_2 but the net effect of their emissions from gasoline and diesel-fuelled engines, even taking into account their global warming potential, remains small. For a range of light-duty petrol and diesel vehicles tested by AECC in 2008, for instance, the global warming potential of their methane emissions ranged from 0.06% of that of the emitted CO_2 to 0.25% (measured on the European Driving Cycle, NEDC).

It is now also recognised that particulate matter plays a significant short-term role in climate change, but the effect of vehicle particulate matter is only just starting to be considered. Black Carbon (equivalent to the Elemental Carbon content of vehicle particulate emissions (Bahner, 2007) can be transported over very long distances. It has a direct effect on the scattering and absorption of radiation but also its deposition on snow can change the melting properties of snow. The UK's Meteorological Office Hadley Centre reports (Reddy, 2007) that the indirect GWP due to the BC effect on snow albedo is estimated to be largest for Europe (possibly as large as 1200), suggesting that BC emission reductions from this region are more efficient to mitigate climate change. Black Carbon is considered to have a high 100-year GWP figures by

Greenhouse Gas	Time Horizon	
	20 years	100 years
Carbon dioxide	1	1
Methane	72	25
Nitrous oxide	289	298
Black Carbon	2000 §	350 – 1500*

Table 1: Global Warming potentials
CO_2, methane and N_2O data from IPCC, 2007
§ Bond (2007)
* Jacobson (2007) reports 1500 - 2240

reputable authorities. Table 1 shows figures for the 20-year and 100-year global warming potential (GWP) of species found in vehicle exhaust emissions.

According to estimates by Prof. Mark Jacobson of Stanford University's (Jacobson, 2007), Black Carbon accounts for 16% of global warming, making it second only to CO_2 as a climate change emission. Estimates by the UN's Intergovernmental Panel on Climate Change (IPCC) in its 4th Assessment Report appear to corroborate this assumption.

Whilst transport is not the only source of Black Carbon, it is a significant one, especially in Europe and the US, where it forms a high proportion of the emitted Black Carbon (Streets, 2004), as shown in Figure 4. The authors of this assessment comment that Black Carbon emissions from the transport sector are expected to increase under most scenarios. They anticipate that the BC/OC (Black Carbon/Organic Carbon) emission ratio for energy sources would rise from 0.5 to as much as 0.8, signifying a shift toward net warming of the climate system due to carbonaceous aerosols. Measured Elemental Carbon (EC) is typically used as equivalent to Black Carbon for combustion engines. The US Environmental Protection Agency estimates (Somers, 2004) that EC accounts for some 50 to 80% of diesel particulate.

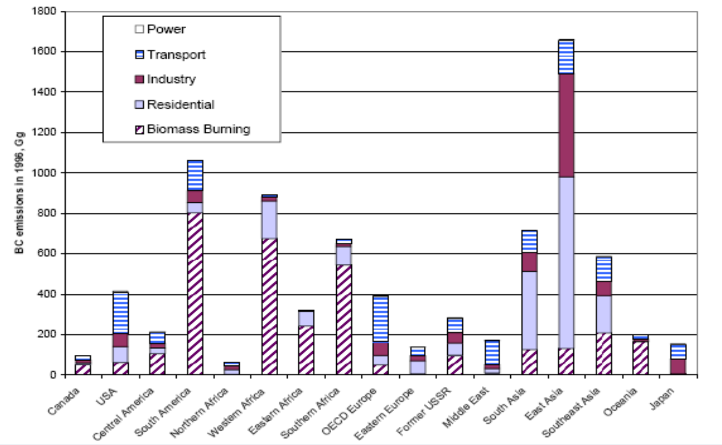

Figure 4: Worldwide BC emissions estimates (from Streets, 2004).

Figures 5, 6 and 7 show the Elemental Carbon content of particulate matter (PM) and the effects of Diesel Particulate Filters on both total particulate and Elemental Carbon. Figure 5 (Andersson, 2002) shows analyses of PM from a Euro III heavy-duty diesel engine fitted with an integrated emissions control system (ECS) of oxidation catalyst, particulate filter and SCR system. Samples were taken 'engine-out' (before the particulate filter) and at tailpipe, after the full ECS. Not only were the total particulate mass emissions substantially reduced, but the carbonaceous content of the remaining total particulate was also minimal.

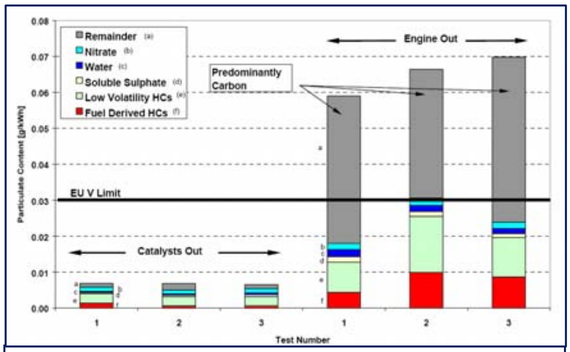

Figure 5: Particulate analyses from a Euro III engine with Integrated ECS, *Source: Ricardo/AEEC*

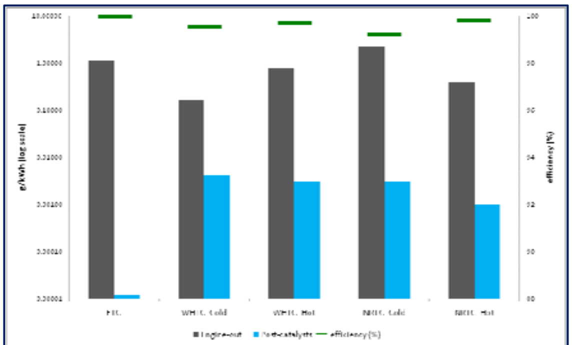
Figure 6: Elemental Carbon missions from Euro VI demonstration engine. *Source: AECC/Ricardo.*

A similar exercise in 2006 demonstrated the potential to meet the (then) proposed Euro VI emissions levels using a heavy-duty engine originally designed to meet the US 2007 emissions standards (May, 2007). The engine was again fitted with an integrated emissions control system including a diesel oxidation catalyst (DOC), wall-flow particulate filter and SCR system. Figure 6 shows the engine-out and tailpipe (post-ECS) emissions of Elemental Carbon and the related filtration efficiency for Elemental Carbon over three transient cycles – European (ETC), cold- and hot-start world-harmonised heavy-duty cycle (WHTC) and cold- and hot-start world-harmonised non-road cycle (NRTC).

The third graph, Figure 7 shows a comparison of the emissions over the NEDC (New European Driving Cycle) test from four cars; one petrol-engined, two different diesel-engined vehicles without particulate filters; and one diesel-engined vehicle with an original-equipment diesel particulate filter (DPF). The Elemental Carbon and Organic Carbon content of particulate matter from each vehicle was analysed by thermo-gravimetric analysis (Bosteels, 2006). The graph shows the near-elimination of Elemental Carbon on the vehicle with particulate filter, in addition to the substantial reduction in particulate matter, resulting in both particulate mass emissions and Elemental Carbon emissions comparable to those of the gasoline engine. Further tests confirmed that the low Elemental Carbon content of the particulate matter from the diesel with particulate filter was maintained over other duty cycles (The Artemis Suite of Urban, Extra-Urban and Highway cycles).

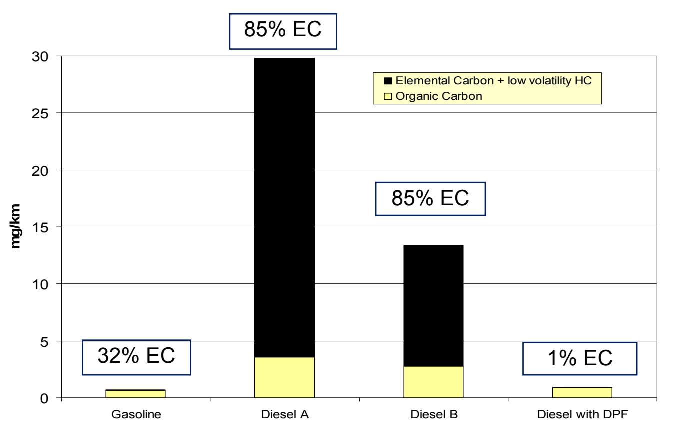

Figure 7: Elemental and Organic Carbon emissions of four cars
Source: AECC / AVL-MTC

To date, European legislation is only considering CO_2 in control tailpipe emissions of substances considered important for global warming. To consider the total effect of an emissions control system on such emissions, it is necessary to consider the mass emissions together with their respective global warming potentials (GWP) as discussed earlier. Total CO_2-equivalent emissions could thus obtained by multiplying the emissions of each climate change-relevant material by its Global Warming Potential for the given time horizon and then summing the CO_2-equivalent emissions of each gas. The Intergovernmental Panel on Climate Change (IPCC) uses the 100-year GWP figures, so the following calculations have been made using the 100-year figures shown in Table 1. There is still considerable debate on the appropriate GWP for Black Carbon. In testimony to the US EPA Hearing on Greenhouse Gases in May 2009 the 20-year Global Warming potential of Black Carbon was quoted as about 4500 and the 100-year figure as about 1500-2200 (Jacobson, 2009). Other sources quote figures as low as 350 for the 100-year GWP. Reddy & Boucher quote figures of 374 to 677, depending on region, but comment that the indirect GWP due to Black Carbon's albedo effect on snow may be as much as 1200. The following calculations, using measured emissions over cold-start and hot-start WHTC (World Harmonized Test Procedure) tests from AECC's heavy-duty Euro VI demonstration programme, use a typical figure of 1500 for the GWP but also show the effect of using the low figure of 350.

Table 2: CO_2-equivalent emissions (g/kWh); heavy-duty engine over hot-start WHTC test.

	CO_2 GWP = 1	CH_4* GWP = 25	N_2O $^{\Phi}$ GWP = 298	BC † (GWP = 1500)	Total (GWP = 1500)	BC (GWP = 350)	Total (GWP = 350))
Cold-start WHTC test							
Without emissions control system (ECS)	834.0	1.6	2.6	782.3	1620.5	182.5	1020.7
With emissions control system (ECS)	834.0	0.5	16.0	0.078	850.6	0.035	850.5
Difference	0	-1.1	13.4	-782.2	-769.9	-182.5	-170.2
Hot-start WHTC test							
Without emissions control system (ECS)	840.4	0.385	0.567	1006.9	1848.3	234.9	1076.3
With emissions control system (ECS)	840.4	0.792	14.9	0.077	856.2	0.018	856.1
Difference	0	0.407	14.3	-1006.8	-992.1	-234.9	-220.2

* methane emissions calculated from FTIR continuous measurements; 9.9% of THC without ECS, 13.8% with ECS.

$^{\Phi}$ N_2O emissions calculated from FTIR continuous measurements.

† measured EC was 87.8% of 0.594 g/kWh PM without ECS, 2.4% of 0.002 g/kWh PM with ECS.

Overall, the figures indicate that the global warming potential of the Black Carbon emissions removed by the Particulate Filter system amount to at least 22% of the engine's CO_2 emissions. Using the higher GWP for Black Carbon, the reduction in total Global Warming Potential could exceed the total CO_2 emissions during the test cycle.

In 2008 AECC conducted a further test programme on light-duty vehicles using petrol- and diesel-engined vehicles meeting the Euro 3, 4 and 5 standards. These vehicles had been used for various distances, from 3000 to 120 000 km, before testing. The data from these tests have been added to those from the previous light-duty test programme mentioned above, in which four vehicles (one petrol-engined, two diesels without DPF and one diesel with DPF) were tested at 4000km. In the earlier programme the diesel with DPF was also tested after durability running, at 160 000 km. As with the AECC heavy-duty Euro VI programme, measurements were made of the emissions of CO_2, methane, N_2O and particulate matter and the total CO_2-equivalent climate change emissions were calculated using a GWP of 1500 for Elemental Carbon (EC). As a number of different vehicle types were tested, with consequent differences in baseline fuel consumption and hence CO_2 emissions, the climate change-relevant emissions have been normalised in the following chart so that CO_2 emissions are set to an index of 100 for each vehicle and the CO_2-equivalents emissions are shown relative to this. For example, if the CO_2 emissions were 200 g/km and EC mass emissions were 0.005 g/km, then the CO_2-equivalent EC emissions are 0.005 x 1500 = 7.5 g/km. When the CO2 figure is normalised to 100, the EC CO_2-equivalent is (7.5/200) x 100 = 3.75.

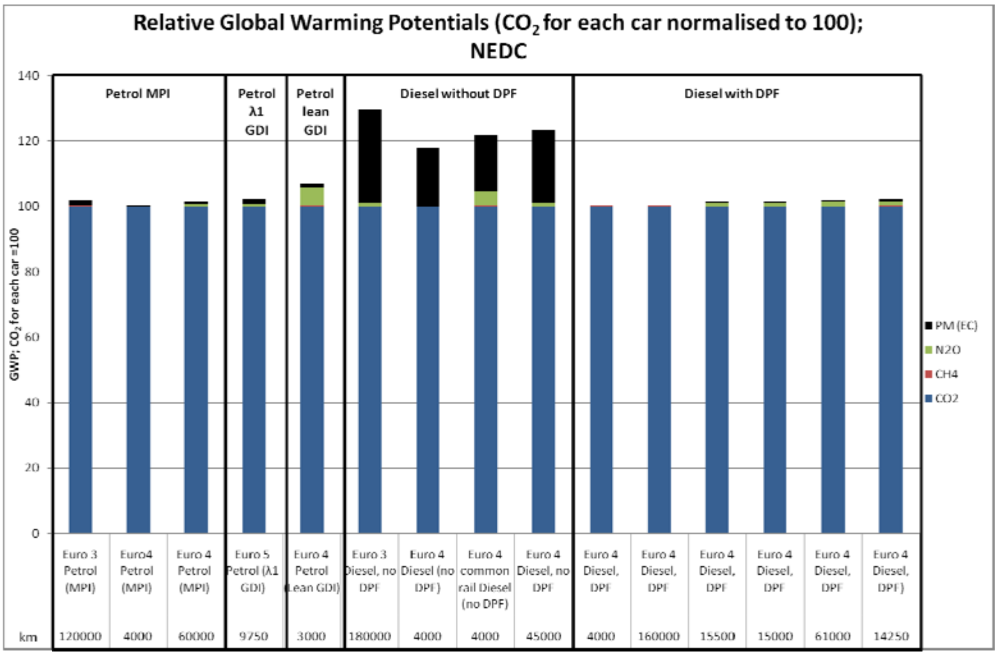

Figure 8: CO_2-equivalent emissions, light-duty vehicles over the NEDC test.

The significant effect on total emissions of materials reported to be relevant to climate change, including diesel particulate emissions and the effectiveness of the use of Diesel Particulate Filters on diesel engines can be seen.

Conclusions

There are increasing numbers of papers suggesting that emissions of Black Carbon have a significant short-term global warming potential, especially in Western Europe. There is debate over a figure for the Global Warming Potential (GWP) of Black Carbon, but the consensus appears to be that the 100-year figure is in the range of 350 to 1500 times that of CO_2.

Soot and particulate matter are measured in a number of ways. It is generally accepted that the Elemental Carbon (EC) content of engine and vehicle particulate matter (PM) emissions equates to Black Carbon. This Elemental Carbon can be measured by thermogravimetric analysis of collected PM.

Analysis of tests on light-duty vehicles and heavy-duty engines conducted by AECC shows that the use of particulate filters removes the majority of both the particulate matter and the Elemental Carbon emitted from engines. This indicates that the use of particulate filters could provide a substantial benefit in the overall reduction in emissions from motor vehicle of substances now considered to be of concern for climate change, in addition to the benefits to ambient air quality and health.

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