Diesel Vehicle Emissions and Urban Air Quality

December 1993

Second Report of the

Quality of Urban Air Review Group

Prepared at the request of the

Department of the Environment

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Executive Summary

In the First Report of this Review Group, attention was drawn to the major impact of motor vehicle emissions upon urban air quality. In this Second Report, the Review Group seeks to refine its analysis of vehicular impacts by comparing petrol and diesel vehicle emissions and examining the likely future consequences of an increased market penetration of diesel cars.

The introduction of three-way catalytic converters to new petrol cars since January 1993 has led to a substantial improvement in the emissions per vehicle with respect to the three most important locally-acting pollutants generated by this type of vehicle, carbon monoxide, oxides of nitrogen and hydrocarbons. Because of the different operating characteristics of diesel engines, it is not possible to use the same catalyst technology to clean up diesel exhaust gases. Consequently, diesel emissions will play a proportionately greater role in urban air pollution in the coming years.

It is not possible to make a simple direct comparison of the "environmental friendliness" of petrol and diesel vehicles. However, comparing near-equivalent diesel and catalyst-equipped petrol cars reveals that whilst the diesel is superior in relation to carbon monoxide and hydrocarbons, it has larger emissions of nitrogen oxides (by a factor of around two) and, most importantly, far larger emissions of particulate matter and black smoke. Although not a matter of direct concern to this Review Group, the diesel has lower emissions of three greenhouse gases, carbon dioxide, methane and nitrous oxide. This should not, however, necessarily be taken to imply a lesser impact of diesels on global warming as the carbonaceous particle emissions from diesels may also act to warm the lower atmosphere by reducing the predicted cooling effect of sulphate particles.

There is a general scarcity of on-road emissions measurements from diesel vehicles, which is most acute in relation to the heavy duty vehicles which are currently responsible for the major proportion of urban diesel emissions. Given the range of vehicle types and engine technologies used in this category, and the very wide range of measured emissions, this creates a major uncertainty in compiling inventories of emissions. New European Community emissions limits applicable to heavy duty diesel engines from 1996 are likely to lead to the wider use of turbocharging and intercooling. This development will give least benefit during stop-start driving so the impact upon urban air quality may be limited, but other technologies such as electronic engine management systems and improved fuel delivery systems can be expected to produce benefits in all driving conditions. In the longer term, the use of particulate traps to control smoke emissions, and of alternative fuels such as compressed natural gas may in future provide a means of further reducing pollution from heavy duty vehicles, but such technologies are still at a developmental stage.

Emissions inventories demonstrate the major impact of vehicle emissions on urban air quality and the greater proportionate influence of vehicles in the urban environment relative to the national inventory. Currently, road vehicles account for 74% of nitrogen oxides and 94% of black smoke emissions in London. On their own, diesels account for 32% and 87% of total emissions (43% and 92% of vehicle emissions) for these two pollutants respectively. Projections of future emissions, taking account of both anticipated traffic growth and stricter emission controls indicate that an increased market penetration of diesel cars at the expense of three-way catalyst petrol cars will on balance have a deleterious effect on urban air quality. Whilst diesel cars currently comprise 6% of the national total, recent sales of new cars have run at about 20%. The increased proportion of diesel cars is associated with an improvement in hydrocarbons and carbon monoxide and a worsening of emissions of nitrogen oxides and some carcinogens, relative to the situation where road traffic increases but the proportion of diesel cars stays close to that at present. The major difference is in emissions of particulate matter. If the proportion of diesel cars stays close to that represented by sales at present, by the year 2005 road transport particulate matter emissions will have approximately halved from their present level. If on the other hand, the proportion of diesel cars were to increase to 50% by 2005, emissions of particulate matter would improve only very marginally from those at present. Thus substantially increased market penetration by diesel cars could almost totally eliminate potential improvements in air quality with respect to particulates resulting from tightening of emission controls.

Studies carried out in Vienna using a tracer of diesel particles, at a time when the diesel population was slightly below that now existing in the UK, demonstrated a background concentration of diesel particles in the atmosphere of 11 $\mu g/m^3$ which was increased by 5.5 $\mu g/m^3$ per 500 diesel vehicles per hour passing near a sampling location. Equivalent measurements have not been made in the UK, but a similar situation is expected to prevail. With annual average concentrations of fine particulate matter (PM_{10}) in UK cities averaging 25-35 $\mu g/m^3$, this represents a major proportion of the airborne particle loading.

Taking into account trends occasioned by present and future emission controls, the two urban air pollutants which will be of greatest future concern are nitrogen dioxide and fine particulate matter (PM_{10}). It is estimated that to achieve an elimination of episodes of severe nitrogen dioxide pollution such as that which afflicted London in December 1991, will require a halving of nitrogen oxide emissions from low-level sources (mainly motor vehicles). This can be achieved by a strategy including widespread adoption of three-way catalyst cars, but will take longer if the market penetration of diesels is substantially increased. The black smoke component of particulate matter, which in most urban areas is almost wholly due to diesel emissions, is responsible for the soiling of buildings. Fine particulate matter is also associated with visibility degradation and has been linked with a range of adverse health effects, for which there appears to be a continuous dose-response relationship without a no-effect threshold. In this context, any development which leads to a lessening of progress towards lower particulate matter concentrations is most undesirable.

In the view of the Review Group, the impact of diesel vehicles on urban air quality is a serious one. Any increase in the proportion of diesel vehicles on our urban streets is to be viewed with considerable concern unless problems of particulate matter and nitrogen oxides emissions are effectively addressed.

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1 Introduction

The First Report of the Quality of Urban Air Review Group (QUARG, 1993) concluded that road transport was a major source of urban air pollution and that the proportional contribution to emissions in towns and cities from the transport sector had increased in recent years due to its rapid growth and the decline of other major pollution sources.

Both petrol and diesel engined vehicles play their part. It is expected, however, that in future, and even assuming no change in the current proportion of diesel vehicles in the fleet, emissions of some pollutants from diesels will become relatively more significant as strict emission controls bite on the petrol driven fleet. Expected changes in fleet composition, with a rise in the proportion of light duty diesel vehicles, will serve to exacerbate this trend.

The changing pattern of urban pollution has also affected the relative contribution from diesel pollution, such that diesels, in particular heavy duty vehicles, are now the single major urban source of black smoke. Declining emissions from other sources, notably domestic and light industrial coal burning, have resulted in diesel now contributing over 85% to levels of black smoke in Greater London.

Recent European Community (EC) legislation has provided new standards for both light and heavy duty vehicles. For the heavy duty fleet, which is almost entirely diesel, the first stage of these standards will make little impact on the in-service emissions of new vehicles and future emissions from this part of the fleet will be dominated by growth until the second stage comes into effect in 1995. This is anticipated to result in a significant reduction in particulate matter emissions from new vehicles but is unlikely to be sufficient to counter the effect of growth in the longer term.

In the case of light duty vehicles, the provision of a combined hydrocarbon (HC) and nitrogen oxides (NO_X) standard means that vehicle manufacturers have options in the relative proportions of NO_X and HC emitted in designing to meet type approval emissions levels. For diesels, present technology for NO_X emission reduction gives limited benefit and certainly does not approach the performance of three-way catalysts. It is not likely to be applied at this stage and the combined NO_X and HC standard will be met mainly through reductions in HCs. It is expected, therefore, that the future in-service NO_X emissions from each light diesel will be considerably higher than from an equivalent catalyst-equipped petrol vehicle. Both carbon monoxide (CO) and gaseous hydrocarbon emissions from light duty diesels in service are, however, expected to be lower than for petrol vehicles.

Within the light duty fleet the high turnover rate and the steady decrease in annual mileage as age increases ensure that new emission standards act quickly to produce lower fleet emissions. Diesel engines are expected to have a longer life, however, and with growth in the fleet proportion of diesels, new standards cannot be expected to act so rapidly in future.

On the other hand, however, there are attractions to diesel. It is a more efficient fuel than petrol. Consequently, increasing the proportion of diesel vehicles in this part of the fleet is a potential strategy to reduce emissions of carbon dioxide, the principal greenhouse gas, from the road transport sector as a whole.

The Government announced in its Environmental White Paper, “This Common Inheritance”, that it proposes to base action on air pollution increasingly on Air Quality Standards. Since the publication of the White Paper, an expert group, the Expert Panel on Air Quality Standards (EPAQS), has been set up to advise on standards for the protection of human health. The 15th report of the Royal Commission on Environmental Pollution (RCEP), “Emissions from Heavy Duty Diesel Vehicles”, recommends that the Government consider setting diesel emission standards on “guide values” for air quality, and include action on the fleet in service. The information in this report will give valuable guidance to policy makers in taking forward the aim of the Environmental White Paper and the recommendations of the RCEP.

Against this background, a full study of the emissions from diesels and of their impacts is timely. Policy makers are bound to consider the balance of diesel and petrol in the context of policy development on greenhouse gas emissions, and fiscal regimes to encourage diesel growth may seem attractive. They will require guidance on the broader consequences of growth in diesel to the urban environment.

In a recent initiative, the motor industry itself has been conducting a vigorous campaign to promote diesel as an environmentally desirable alternative to the petrol engine. Such claims, however, have conspicuously failed to take into account the full impact of diesel emissions. This report will provide a more complete picture of the overall contribution of diesel to urban environmental problems to remedy the omission.

Clearly, further policy to reduce emissions from diesels must take into account the cost and performance of measures to reduce emissions. It is accepted that future standards will impose costs on the manufacturers and operators of diesels and measures to reduce current fleet emissions are costly.

Emissions of particular concern are NO_X and particulates. NO_X emissions arise primarily as nitric oxide (NO) which is rapidly oxidised to nitrogen dioxide (NO_2). At high ambient concentration levels, NO_2 has health impacts on sensitive people and an EC Directive provides limit and guide values.

At present emissions in our larger cities give rise to NO_2 levels closely approaching limit values, and frequently exceeding guide levels, provided in the EC Directive. Any increase in NO_X emissions in the urban environment would be of considerable concern and policy makers would wish to consider options for reducing urban NO_X should analysis show that future emissions may lead to breaches of the EC Directive limit values.

In addition to the guide and limit levels provided in the EC Directive, the UK Government's Expert Panel on Air Quality Standards will be considering air quality standards for nitrogen dioxide. In this context, a report on NO_2 is expected in the Autumn of 1993 from the Department of Health's independent Advisory Group on the Medical Aspects of Air Pollution Episodes.

Particulates arise from diesel vehicles and contain a mixture of soot, unburned fuel and hydrocarbon compounds produced during incomplete combustion. They are now the major source of grime in towns and cities throughout the UK. Costs of cleaning buildings in London alone are calculated to be in excess of £35 million annually.

Diesel particulate emissions are also a potential health hazard: they contain compounds known to be carcinogenic and may also cause impairment of respiratory functions. There is evidence that an increase in mortality and morbidity may be associated with an increased concentration of particulate matter in urban air. The Government's Committee on Medical Effects of Air Pollutants (COMEAP) will be reporting on health impacts of particulates in 1994.

Levels of smoke are controlled by the EC Smoke and Sulphur Dioxide (SO_2) Directive. At present emissions levels, the areas where there remain difficulties in meeting the limit values in this Directive are where coal burning is the predominant source of urban smoke. However, the impact of a radical shift in the proportion of diesel vehicles in the urban vehicle fleet will require careful consideration to ensure that it will not raise emissions to levels that will place further sites at risk of breaching the limit values in the Directive.

Particulate matter, then, poses both amenity and health problems. Present EC emissions legislation, however, is not expected to reduce emissions per vehicle substantially below current levels. Technology to trap and destroy particulate emissions is under development, but is considered costly at present. A clear understanding of impacts of all kinds is needed in weighing the case for further control.

The remaining emissions from diesels are CO, SO_2 and gaseous hydrocarbons. Diesels are not regarded as high emitters of CO or HCs, although their relative contribution to emissions will increase as the new EC emission standards impact on petrol driven vehicles. Diesel fuel contributes about 1% to the national SO_2 total but emissions will decrease in 1996 in response to lower fuel sulphur levels set in EC legislation. The issue for this report is the assessment of the impact of emissions of SO_2 from diesel before levels fall in the latter half of this decade.

Health guidelines for CO are not generally exceeded at present and exceedences are not expected in future. The impact of HCs is dependent upon the species emitted. Certain species, such as the carcinogen 1,3-butadiene, will be the subject of reports from EPAQS, and Air Quality Standards might be set for them at some time in the future. Little information has been published on HCs in diesel exhaust, however, and this report reflects the lack of data on this important topic.

Diesel is a less volatile fuel than petrol, and diesel cars give rise to lower evaporative emissions than current petrol cars. The new EC car emission Directive provides standards for evaporative emissions, following which petrol car evaporative emissions will fall to a level closer to that of diesel cars.

Evaporative emissions from the petrol stored in cars, both parked and moving, petrol station forecourts, from petrol storage depots and oil refineries are a major source of hydrocarbons in ambient air in the UK and in the rest of Europe. Much of these evaporative emissions occur as n- and i-butane and n- and i-pentane. The main environmental significance of these hydrocabons is their contribution to regional scale photochemical ozone formation and its long range transport. Controls of evaporative emissions from petrol are being promulgated within the framework of the Commission of the European Communities with the long-term aim of controlling losses at each point in the petrol distribution chain. Additional measures to control evaporative emissions include the reduction of petrol volatility to reduce the incidence of vapour lock. Also all new petrol cars are required to have canisters fitted to provide partial control of evaporative emissions. Clearly all these evaporative emissions would be obviated if the entire car fleet were to be diesel-powered. For the large part, however, the influence of petrol evaporative emissions on urban air quality has little direct human health significance. However, petrol contains small quantities of benzene, a known human carcinogen. Evaporative emissions of benzene therefore do have some significance for urban air quality because they add to the urban levels which arise primarily from car exhausts. The benzene content of petrol is controlled at source through an EC Directive and this appears to be the most effective means of controlling urban benzene levels from evaporating petrol.

For the pollutants of most concern in the urban air, NO_X and particulates, the effects of changes in vehicle emission standards and the pattern of fleet turnover combine to suggest that the significance of diesel in urban air pollution will grow.

A number of strategies could be adopted to reduce the impact of diesel emissions upon urban air quality. These include the use of new technologies such as particulate traps, the switching to alternative fuels like natural gas or electric traction, ensuring better in-service emissions as well as the reduction in the volume of traffic. Particulate traps are not yet commercially available but have been widely tested in Europe and North America and are likely to be particularly suitable for vehicles operating from depots such as buses and dustcarts. They appear to have the advantage of being suitable for fitment to some vehicles already in service. Gas and electric traction are used in urban public transport systems elsewhere in the world, at least partly due to concern about the health impacts of diesel. In the UK electric traction has been widely used for milk delivery services for decades, though for reasons other than concern about emissions, and this could be extended to other urban delivery services, although careful consideration would have to be given to the impact of emissions from electricity generation.

The current emissions legislation largely relates to new vehicles. As drivers of motor vehicles are often unaware when there has been a failure of the pollution abatement system, techniques to reduce in-service emissions such as on-board diagnostics are to be introduced in parts of the United States. Similarly, technology to measure exhaust emissions at the road-side has been developed and widely applied. Backed up by good inspection and maintenance programmes these systems could identify and ensure the repair of the 'gross' polluters which contribute a disproportionate amount of the emissions. However, while these 'technical fixes' can go some way to reducing the contribution currently made by vehicles to urban air pollution, consideration also needs to be given to methods of reducing traffic volumes in urban areas.

These options carry costs, but ones which policy makers may wish to consider in the light of information contained in this report on the benefits to be expected from further reductions in the urban pollution burden due to diesel vehicles.

REFERENCES

Quality of Urban Air Review Group (1993) **Urban Air Quality in the United Kingdom**. QUARG, London

2 Comparison of Emissions from Diesel and Petrol Cars

2.1 INTRODUCTION

In recent years diesel cars have become increasingly popular as the gap with petrol cars in terms of performance, noise levels and purchase price has narrowed. The extra cost of installing closed loop three-way catalysts on petrol cars has meant that diesel models are now often the same price as the equivalent petrol version. The greater fuel economy and reduced maintenance requirements make diesel cars cheaper to run. They have also been promoted as cleaner than petrol cars by the motor industry.

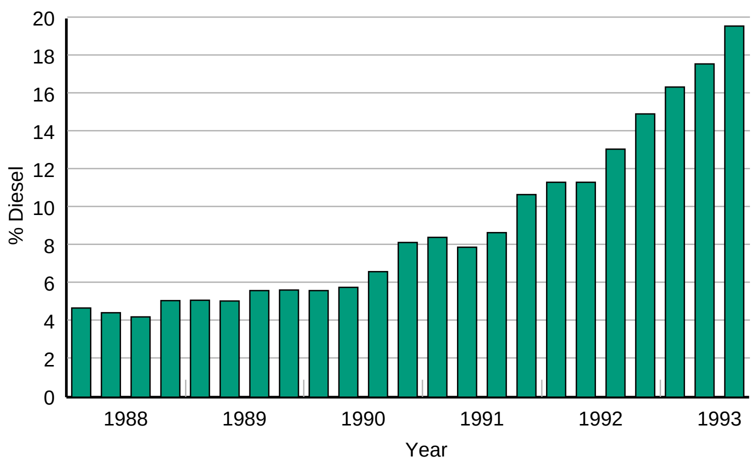
Figure 2.1 shows the increase in market penetration of diesel cars over the last five years. It is very difficult to predict whether this trend will continue. Future emissions regulations are likely to require expensive electronic equipment for diesel cars that may result in the price differential with petrol cars being re-introduced, with the result that the popularity of diesel cars may decline. As diesel and petrol cars have very different emission characteristics, increasing the proportion of diesel cars at the expense of petrol ones could have important implications for urban air quality, as well as for acid deposition, photochemical ozone formation and global warming.

In this chapter the emissions characteristic of diesel and petrol cars are described and compared.

It should be noted that relatively few measurements of on-road emissions from in-service three-way catalyst (TWC) petrol and diesel cars have been undertaken in the UK. Results from on-road measurements have been used in preference to those from dynamometer tests as they probably give a better indication of what actually happens in service. However, as the driving conditions vary from one journey to the next, the on-road measurements are not reproducible. Given the large variation in emissions, even from a single vehicle (see Figure 3.1, in Chapter 3), and the small number of cars tested, the values given in this chapter are subject to some uncertainty. However, they provide a useful indication of the emissions characteristics of different technology cars.

Much of the emissions data given in this chapter is based on a recent survey undertaken by the Warren Spring Laboratory for the Department of the Environment (DoE) and the Department of Transport (DoT). Each car was tested both on the road and using a chassis dynamometer. As this report is primarily concerned with the localised effect of emissions in urban areas, comparisons between

Figure 2.1 Growth in New Car Market Penetration of Diesel Cars 1988 to 1993.



Source: Society of Motor Manufacturers and Traders, 1993.

different technology vehicles have been largely based on urban driving.

2.2 COMPARISON OF REGULATED EXHAUST EMISSIONS FROM PETROL AND DIESEL CARS

Table 2.1 shows the average emissions when driving a car with a warmed up engine (and catalyst) on urban roads. Obviously many cars driving on these roads will not be fully warmed up and the effect of cold starts is discussed in a later section (Section 2.4). Diesel cars have lower emissions of the gaseous regulated pollutants - carbon monoxide (CO), nitrogen oxides (NO_X) and total hydrocarbons (THC) - than standard petrol cars (without catalysts). However, for particulate matter (PM) the reverse occurs, where emissions from diesel cars are considerably higher than from petrol cars.

Emissions from petrol engines can be dramatically reduced using a three way catalytic converter. Comparisons between TWC and diesel cars show that the emissions of the gaseous regulated pollutants are more similar.

Carbon monoxide and hydrocarbon emissions from diesel vehicles can be reduced using an oxidation catalyst. In addition, these catalysts can remove some of the hydrocarbons associated with the exhaust particulate matter, thus reducing the overall mass emitted.

It should be noted that the evaporation of petrol is another source of hydrocarbon emissions. Although new TWC cars are fitted with a small canister, this is not adequate to collect all the evaporative emissions, especially those arising during refuelling and running losses. Evaporative losses are not significant from diesel cars.

Typically, particulate emissions from petrol cars are so low that they are not routinely measured. However, a number of studies have shown that emissions from cars using leaded petrol are greater than those running on unleaded petrol. This is due to the presence of lead compounds in the particulate matter. Emissions from diesel cars may be as much as an order of magnitude higher than those from petrol cars with catalysts (which have to run on unleaded petrol).

It appears that the chemical composition of the particulates from the two different types of engine are different. An Australian study has shown that the major components of leaded petrol particulates are carbon, together with lead and bromide from the anti-knock and scavenging agents respectively added to the petrol. The carbon is generally organic rather than elemental in nature. The diesel particulate matter

Table 2.1 Urban Emissions of Regulated Pollutants from Current Technology Cars.

Vehicle Type	Average On-Road Emissions (g/km)			
	CO	THC	NO_X	PM
Standard (petrol without catalyst)	27.0	2.8	1.7	-
Petrol with catalyst	2.0	0.2	0.4	-
Diesel	0.9	0.3	0.8	0.4

Notes:

Based on the results of on-road tests conducted with 'as received' cars with hot engines.

The diesel car sample consisted of two with indirect injection diesel (IDI) engines and one with a direct injection diesel (DI) engine. Emissions from the IDI engines were significantly lower than from the DI engine, with average on-road emissions of 0.6 g/km NO_X and 0.2 g/km PM. Most diesel cars have IDI engines.

Of the TWC cars two had an engine capacity of 2.0 litres and one a capacity of 1.4 litres. The two indirect diesel engines had a capacity of 1.8 and 1.7 litres, and the direct injection diesel had a capacity of 2.0 litres.

- means that particulate matter was not measured.

Source: Farrow et al 1993a, 1993b, 1993c mainly consists of carbon, with approximately two thirds being elemental carbon and one third organic carbon (Williams et al, 1989a and 1989b). The different chemical composition of the particulates has an important bearing on their relative soiling characteristics, with diesel particulates having a soiling factor per unit mass approximately 7 times greater than that of petrol particulates.

2.3 COMPARISON OF UNREGULATED EXHAUST EMISSIONS FROM PETROL AND DIESEL CARS

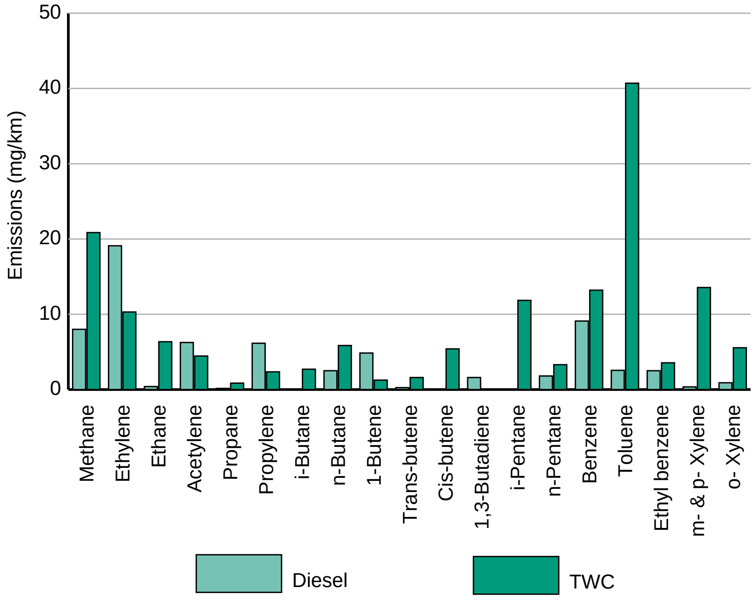
Many different hydrocarbons are emitted from car exhausts, and each exhibits a different toxicity and photochemical ozone creation potential. Figure 2.2 shows the results of a recent Warren Spring Laboratory survey of C_1 to C_6 hydrocarbon emissions from a selection of petrol and diesel cars, measured under simulated urban driving conditions (Bailey and Parkes, 1993). These data must be viewed with some caution as there is great variability in emissions amongst seemingly similar vehicles and few vehicles were tested. In addition, the diesel vehicles tested were quite different, one being a turbocharged indirect injection diesel with an oxidation catalyst, the other a direct injection diesel.

In general the emissions of individual hydrocarbon species appear to be lower from the diesel cars than petrol cars with three-way catalysts with some notable exceptions. At first sight this appears contrary to the emission rates presented in Table 2.1. This table refers to total hydrocarbon emissions whilst Figure 2.2 is restricted to the lighter hydrocarbons. Diesel exhaust tends to contain more higher molecular weight hydrocarbons than petrol exhaust.

Those light hydrocarbons which are emitted in greater amounts by diesel engines include a number of alkenes such as ethylene, propylene and 1-butene which are among the more important species for ozone formation. It should be noted, however, that the emissions of these reactive hydrocarbons were low from the diesel car with the oxidation catalyst. For ethylene and propylene they were below the detection limit. Also, compared with a petrol car without a catalyst the emissions of the diesel cars were very low. For example, the diesel emissions of ethylene and propylene were approximately 20-30% of those from a standard car.

Aromatic compounds are among the most photochemically important hydrocarbons emitted from car exhausts and some are also of more direct

Figure 2.2 Urban Emissions of Individual C_1 to C_6 Hydrocarbons from Diesel and Three-Way Catalyst Petrol Cars.



Note: Tested using the European Urban Test Cycle.

local significance because of their potential carcinogenicity. It appears that in urban areas the 'hot' emissions of these compounds are higher from TWC cars than from diesel cars. For example, urban emissions of benzene, a known carcinogen, are about three times higher from three-way catalyst cars than diesel cars. For toluene the difference in emissions is an order of magnitude. A number of important aromatic compounds, such as the xylenes, could not be detected in the diesel car exhaust. In contrast, the carcinogen 1,3-butadiene is present at higher concentrations in diesel vehicle exhaust than from catalyst-equipped petrol cars.

Emissions of the light alkanes (eg butane, pentane) are also low from diesel cars compared with three-way catalyst cars. These compounds are not found in diesel fuel but can be present in significant quantities in petrol. Butane, a cheap by-product of the refining process, for example, has been extensively blended into petrol.

Tests conducted at lower temperatures using a different test cycle designed to simulate congested traffic suggest that the hydrocarbon profiles are, in general, similar irrespective of ambient temperature and operating conditions, although these factors influence the absolute emission levels. These factors are discussed in the following sections.

Emissions of higher molecular weight hydrocarbons are more important for diesel than petrol cars. For example, emissions of polycyclic aromatic hydrocarbons (PAH) are highest from diesel cars, followed by non-catalyst petrol cars and then TWC petrol cars. The major PAH species present in car exhaust are fluoranthene and pyrene. For the known human PAH carcinogen benzo(a)pyrene, urban emissions from diesel cars are 50% greater than current petrol cars without catalysts. None of the diesel vehicles tested had an oxidation catalyst. It is likely that concentrations of these species will be reduced significantly by the use of an oxidation catalyst, which is likely to become standard for diesel cars meeting the proposed 1996 emission limits.

Another group of organic compounds found in car exhausts are aldehydes. Emissions from standard petrol cars (without catalysts) are the highest, followed by diesel cars, with those from TWC petrol cars the lowest. Emissions of total aldehydes may be an order of magnitude higher from a non-catalyst petrol car compared to one with a catalyst. In both petrol and diesel exhaust formaldehyde is the most important individual aldehyde, followed by acetaldehyde.

Many aldehydes have a low odour threshold and may contribute to the unpleasant smell associated with road traffic. However, due to the complex chemical nature of vehicle exhaust it has not been possible to identify all the odourants present. Traditionally, road traffic odour has been attributed to diesel rather than petrol exhaust gases. However, the introduction of catalyst cars has brought with it a new odour problem, namely emissions of hydrogen sulphide. Under certain driving conditions the sulphur in the petrol can be converted into hydrogen sulphide by the catalyst, and released into the exhaust gases. The problem is exacerbated in cars with open loop catalysts, and when the catalyst is new.

2.4 COLD START EMISSIONS

Emissions from cars are greatest when the engine is cold. On a hot day a petrol car may have to be driven for about 10 kilometres in an urban area before the engine is fully warmed and operating efficiently. In similar conditions a diesel car may warm up after about 5 kilometres. On a cold day both types of cars will take even longer to warm up (Martin and Shock, 1989).

It is the emissions of the products of incomplete combustion such as carbon monoxide and hydrocarbons that are particularly high during cold starts as the engine has to run richer (ie has a lower air to fuel ratio) under these conditions. Earth Resources Research have estimated that cold start emissions contributed approximately one third of the total volatile organic compound (VOC) and CO emissions from passenger cars in 1990 (Holman et al, 1993). Cold starts are relatively unimportant for nitrogen oxides, their contribution being less than 5% of the total emissions in 1990. Most of the cold start emissions will occur in urban areas where their impact on air quality will be greatest.

Cold start emissions are relatively more important for cars fitted with catalytic converters because it also takes a few minutes for the catalyst to reach its operational temperature. Thus during those early minutes of a journey when emissions from the engine are highest, the catalyst does not work.

Emissions have been measured during an urban drive around Stevenage by Warren Spring Laboratory with both cold and warmed up vehicles. Table 2.2 shows that the urban cold start emissions penalty for standard petrol and diesel cars are similar but for TWC cars the CO and HCs cold start emissions are about an order of magnitude higher than the hot emissions.

Table 2.2 Cold Start Emissions Penalty under Real Urban Driving Conditions.

	Ratio Cold:Hot			
	CO	**THC**	**NO_X**	**PM**
Car				
Standard petrol	1.6	2.0	1.0	-
TWC	9.6	11.0	1.3	-
Diesel	1.6	1.0	1.2	1.2

Note: This table gives the ratio of average emissions (expressed in g/km) when a car with a cold engine is driven on an urban trip to when a car with a hot engine is driven over the same trip.

The Transport Research Laboratory has investigated the effect of ambient temperature on emissions from different types of car over a temperature range -10˚C to +30˚C. For both petrol and diesel cars emissions of CO and HCs were substantially higher at the lower temperatures. As Figure 2.3 shows, emissions of carbon monoxide from TWC cars are particularly high during the first kilometre or so of the driving cycle when started from cold. For diesel cars the influence of ambient temperature on CO emissions is less marked. Figure 2.4 shows that the emissions of nitrogen oxides from both TWC and diesel cars are less affected by ambient temperature, and that the cold start penalty is less marked.

Most journeys in the UK are short with about 40% being less than 3 miles (5 kilometres). For journeys of one kilometre emissions of CO from a three-way catalyst petrol car may be fourteen times higher than those from a diesel car (Table 2.3). On the other hand, assuming the car is driven at moderate speeds and accelerations, the NO_X emissions from the TWC car will typically be about half of those from a diesel car. However, if the car is rapidly accelerated and driven at high speed during the period before the catalyst has lit up emissions from the petrol car will be higher than from the diesel one (Holman et al, 1993).

New technologies are being developed to reduce the cold start emissions penalty of TWC cars. Essentially these involve reducing the period of time it takes to reach the catalyst's operational temperature and include placing the catalyst closer to the engine (close coupled catalyst), the use of electronically heated catalysts and a British technology, exhaust gas ignition (where a carefully metered quantity of fuel is ignited on the front face of the catalyst).

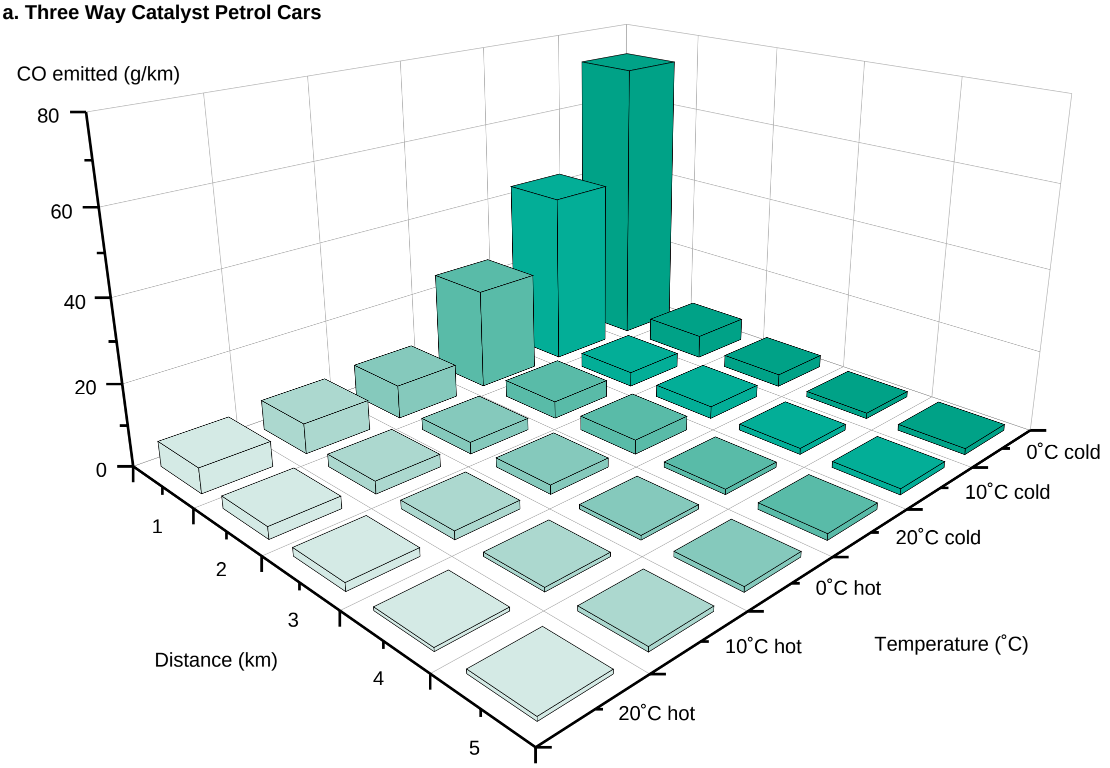
Table 2.3 Average Gaseous Emissions from Three Way Catalyst and Diesel Cars for Journeys of Different Lengths.

Temperature (˚C)	**Fuel**	**Journey Length (km)**	Emissions (g/km)		
			CO	**VOC**	**NO_X**
0	**TWC**	**1**	72.9	10.0	1.0
		5	17.0	2.2	0.3
		10	9.2	1.2	0.2
	Diesel	**1**	5.3	1.9	1.8
		5	2.6	1.1	1.2
		10	1.9	0.9	1.0
10	**TWC**	**1**	43.4	4.2	1.1
		5	10.6	1.0	0.4
		10	6.0	0.6	0.2
	Diesel	**1**	4.6	1.9	1.6
		5	2.3	1.2	1.1
		10	1.7	1.0	0.9

Source: Holman, Wade and Fergusson, 1993

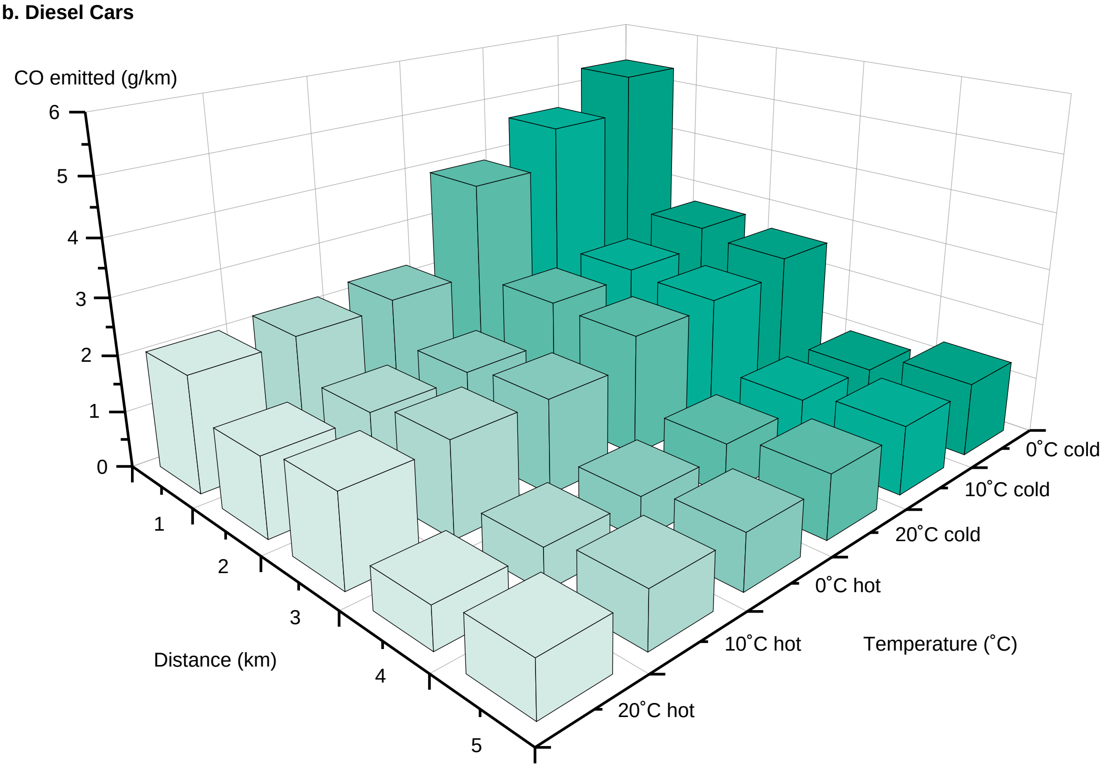
Figure 2.3 Emissions of Carbon Monoxide with Distance for Hot and Cold Starts in Ambient Temperatures of 0˚C, 10˚C and 20˚C.

a. Three Way Catalyst Petrol Cars



Note: Average emissions from 6 TWC cars tested over a TRL driving cycle designed to simulate the "commute to work" journey.
Source: TRL, Personal communication.

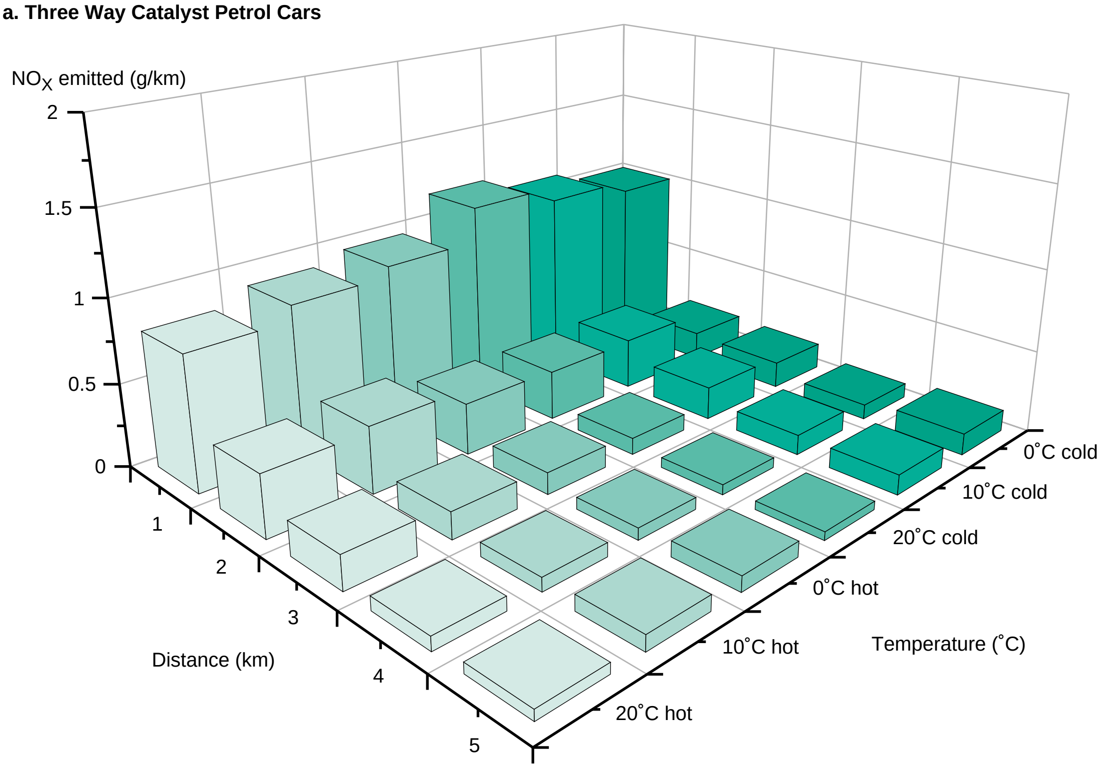
b. Diesel Cars



Note: Average emissions from 3 diesel cars tested over a TRL driving cycle designed to simulate the "commute to work" journey.
Source: TRL, Personal communication.

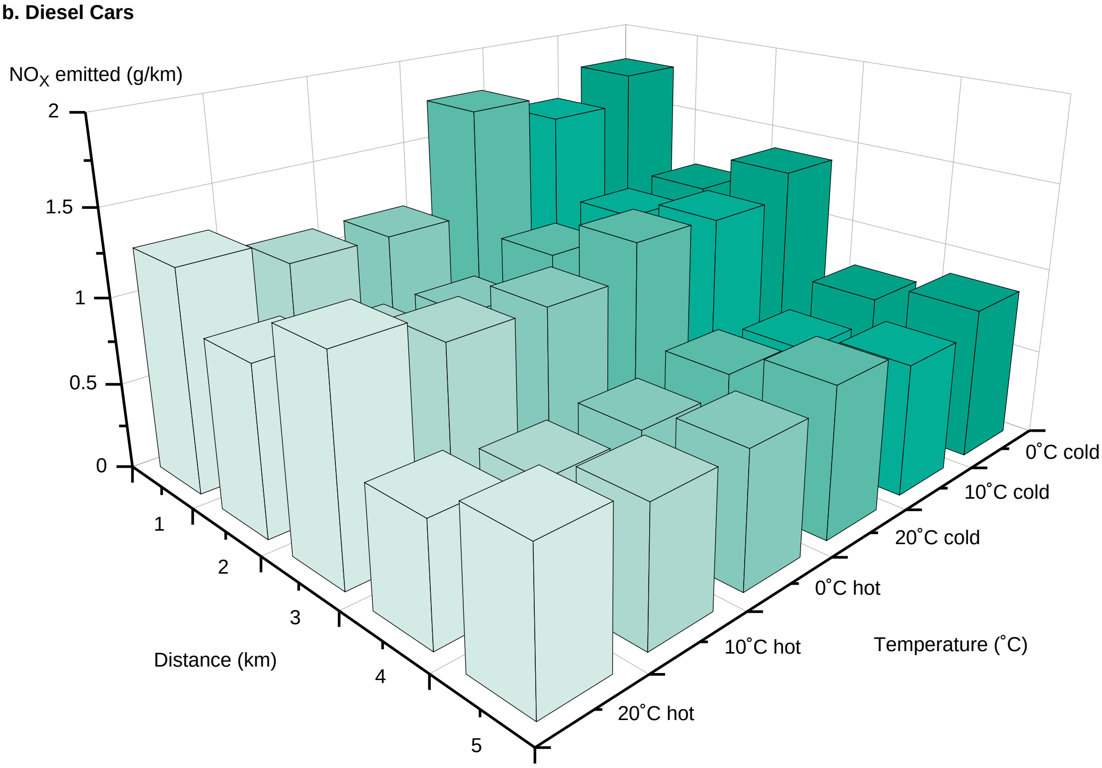
Figure 2.4 Emissions of Nitrogen Oxides with Distance for Hot and Cold Starts in Ambient Temperatures of 0˚C, 10˚C and 20˚C.

a. Three Way Catalyst Petrol Cars



Note: Average emissions from 6 TWC cars tested over a TRL driving cycle designed to simulate the "commute to work" journey.
Source: TRL, Personal communication.

b. Diesel Cars



Note: Average emissions from 3 diesel cars tested over a TRL driving cycle designed to simulate the "commute to work" journey.
Source: TRL, Personal communication.

2.5 CONGESTED TRAFFIC

A recent study by the Warren Spring Laboratory has compared emissions over two simulated urban test cycles - the European urban cycle and a 'congested traffic' cycle. The results suggest that the effects of congestion on emissions are typically greater than the effect of cold start for the same simulated trip. However, the cold start emissions penalty is much more widespread in that all cars are affected whereas congestion is generally more localised and occurs mainly in the peak traffic hours.

Emissions of carbon monoxide and hydrocarbons from both standard and TWC petrol cars increase with congestion while those from diesel cars remain very low. Under congested conditions diesels emit significantly lower amounts of carbon monoxide and hydrocarbons.

However, the standard petrol car, without a catalyst, appears to have lower nitrogen oxides emissions in congested traffic than in more typical urban driving conditions. Emissions of NO_X from both TWC and diesel cars appear to increase in congestion. In congested traffic, emissions of NO_X from diesel cars are similar to those from standard petrol cars and much higher than those from TWC cars.

2.6 EFFECT OF MAINTENANCE

Poorly maintained vehicles consume more fuel and emit higher levels of carbon monoxide and hydrocarbons than a regularly serviced one. Factors such as running over-rich, poorly adjusted ignition timing and worn spark plugs can all affect emissions. A Dutch study of over 1200 in-service cars has shown that a significant number of cars are being driven on the roads that require tuning and/or servicing. Nearly 80% of the standard petrol cars needed adjustment, compared with about one third of the TWC cars and just 6% of the diesel cars (Dutch Ministry of Housing, Physical Planning and Environment, 1992). It is unlikely that the situation is different in the UK.

The effect of correct tuning is particularly important. A number of studies have shown that tuning, in general, results in a reduction in emissions of CO, HCs and particulates. On the other hand there is an increase in NO_X emissions, particularly under urban driving conditions, although this increase is likely to be small, because changing the idle tuning mainly affects emissions at low engine loads, when NO_X emissions are typically low.

Studies of in-service emissions undertaken by Professor Don Stedman from the University of Denver in many different countries around the world suggest that approximately 80% of CO and HC pollution comes from about 20% of the vehicles. A poorly maintained but relatively new car with a catalyst can emit higher levels of carbon monoxide and hydrocarbons than a well maintained older car without a catalyst.

The disadvantage of using exhaust catalysts rather than optimising engine design to reduce emissions is that if the catalyst fails, emissions of all pollutants will increase dramatically. Equally, if the lambda sensor that is used to control the air to fuel ratio at stoichiometric fails, the engine may run rich and increase CO and HC emissions, or run lean and increase NO_X emissions. According to Swedish studies the most common reasons for high emissions from TWC cars are firstly failure of the lambda sensor, and secondly failure of the catalyst itself.

Unlike many car components the failure of the pollution abatement system does not affect the operation of the vehicle and thus the driver may be unaware that it is malfunctioning. In the future, on-board diagnostics are likely to become mandatory to warn the driver of catalyst failure.

Catalysts gradually degrade with use, making them less efficient at cleaning up exhaust pollution. Old catalysts tend to take longer to reach the light off temperature, and deposits may build up on the surface of the catalyst (Dutch Ministry of Housing, Physical Planning and Environment, 1992).

As a result of all these factors which affect emissions from petrol cars - going out of tune, requiring more maintenance, the use of 'add-on' pollution abatement equipment, catalyst deterioration - emissions from diesel cars are likely to remain more constant over the life of the vehicle than those from petrol cars.

2.7 EVAPORATIVE EMISSIONS

Spark ignition engines need a volatile fuel to operate. Evaporation of petrol can give rise to significant emissions of hydrocarbons, although these are controlled under an EC Directive using a range of technologies to achieve the regulated levels. Diesel fuel is much less volatile and therefore gives rise to insignificant evaporative emissions.

2.8 IMPLICATIONS FOR URBAN AIR

Currently only 6% of cars on the road are diesel cars. While this number remains small these vehicles are unlikely to make a significant contribution to ambient pollution levels in urban areas. However, if current sales of diesel cars are maintained, within ten years the diesel car population could increase to around 20% and become a significant source of urban emissions.

A switch from standard petrol cars to diesel cars would lead to a reduction in all pollutants with the exception of particulate matter. However, the choice nowadays is between diesel and three-way catalysts cars. Thus, the emission characteristics of these types of cars should be compared.

In comparison with the situation that will arise from the use of three-way catalyst cars, an increasing diesel car population will lead to an increase in emissions of both NO_X and particulates. However, the implications for air quality are complex as both particulate matter and nitrogen dioxide are both primary and secondary pollutants. As emissions of particulates are low from petrol cars increasing the proportion of diesel cars will give rise to higher emissions of particulate matter. This may be offset, to some extent, by cleaner buses and lorries being introduced as the result of new legislation. However, the net result is that in urban areas where road transport is the principal source of airborne particulates concentrations are likely to remain similar to the levels found today, despite an improvement in abatement technology.

Emissions of nitrogen oxides from both TWC and diesel cars are much lower than from non-catalyst cars and therefore total emissions are forecast to decline in future years in urban areas where there is limited capacity for traffic growth. However, there is not a linear relationship between nitrogen oxide emissions and ambient nitrogen dioxide concentrations. Recent analysis of NO_2 concentrations in London (see Section 6.3) suggests that emissions of nitrogen oxides in the capital will have to be cut by half to ensure that one hour average concentrations never exceed 100ppb (DoE's threshold for its 'poor' air quality bulletin category). Increasing the proportion of diesel cars will slightly increase the time it takes to reach this air quality objective.

Ambient concentrations of carbon monoxide and many hydrocarbons, including benzene, are likely to be significantly lower and 1,3-butadiene and benzo(a)pyrene slightly higher if the proportion of diesel cars increases. The fitting of oxidation catalysts to diesel cars to meet future emission requirements would however lead to an improvement in diesel emissions of these hydrocarbons.

In congested areas emissions of carbon monoxide and hydrocarbons are likely to be lower from a diesel car than a TWC car. On the other hand, emissions of nitrogen oxides from a diesel car are similar to that from a standard petrol car but much higher than from a TWC car, under these conditions. Predicting the effect of congestion at a time of changing technology and a growing car population on emissions and air quality is difficult. No such studies have been undertaken for any UK city to date.

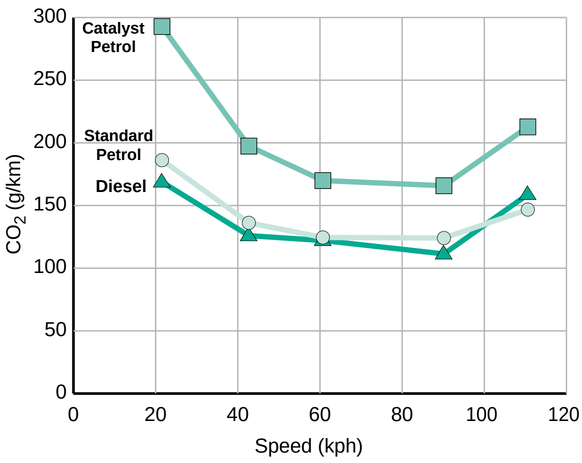
2.9 IMPLICATIONS FOR REGIONAL AND GLOBAL POLLUTION

Road traffic contributes to two important regional scale pollution problems - acid deposition and photochemical ozone. Nitrogen oxides are an important precursor of both acid rain and ozone while certain hydrocarbons play a vital role in the formation of tropospheric ozone. Increasing the proportion of diesel cars is likely to slightly offset the large reduction in NO_X emissions predicted as a result of the introduction of TWC cars (see chapter 6) but is unlikely to have a large effect on acid deposition.

It is more difficult to predict the effect of an increased proportion of diesel cars on the magnitude and frequency of ozone pollution episodes. Increasing NO_X emissions is likely to reduce urban ozone concentrations, but increase concentrations downwind. However, assuming that oxidation catalysts are required on all new diesel cars in the relatively near future (probably from 1996) the emissions of the reactive hydrocarbons are likely to be much lower with an increasing diesel car population. This will be beneficial as reducing the ambient concentrations of these compounds is likely to reduce ozone formation. However, the net effect is likely to be adverse (see Section 6.4).

Road traffic also contributes to global warming. The main greenhouse gas is carbon dioxide (CO_2), which arises from the combustion of all fossil fuels. Emissions are directly related to the carbon content of the fuel and the amount of fuel burnt. Diesel cars, particularly those with direct injection engines, are much more fuel efficient than petrol cars. However, as diesel is a denser fuel than petrol more CO_2 is emitted for every litre burnt. A diesel car has to be more than 11% more fuel efficient than a petrol car for there to be a net benefit in terms of CO_2 emissions.

Figure 2.5 Carbon Dioxide Emissions from Different Types of Cars.



Note: On-road emissions measured from in-service vehicles "as received" (ie not re-tuned).
Source: Farrow et al, 1993a, 1993b, 1993c.

Figure 2.5 shows the speed emissions curves for CO_2 as measured by Warren Spring Laboratory in their recent survey of on-road emissions. This shows that emissions of CO_2 are typically lowest from diesel cars, although at higher speeds they may be higher than from standard petrol cars. Average emissions from TWC cars are considerably higher, especially under urban driving conditions, than those from diesel cars. It should be noted that the cars were not matched for similar performance or engine capacity. The average engine capacity of the non-catalyst petrol cars was 1.5 litres; while that of the TWC and diesel cars was 1.8 litres. As the specific power output of petrol cars is greater than diesel cars (see Chapter 3), the average performance of the TWC cars would have been greater. Therefore the CO_2 emissions are not strictly comparable with those of the diesel cars.

Other studies that have tried to compare equivalent petrol and diesel cars have also found that under a range of driving conditions the diesel cars emit less CO_2 than petrol cars with catalysts. For example, in a study undertaken by UTAC in France for Lucas (Lucas Diesel, undated), emissions from the equivalent petrol and diesel models (ie with the same power output) were compared under several different driving cycles. The results suggest that average emissions of CO_2 were typically about 16% higher from the petrol cars over a range of driving cycles designed to represent urban and suburban driving conditions. However, for short urban driving cycles, when the cars were started from cold, there appears to be less difference in the CO_2 emissions (approximately 11 to 14%).

A recent study undertaken by Earth Resources Research for the World Wide Fund for Nature (WWF) has compared the total global warming effect of emissions from three-way catalyst petrol cars and diesel cars (Wade et al, 1993). It concludes that, while average emissions of carbon dioxide are about 10% lower from the diesel car, the total global warming potential, per kilometre travelled, is about 20% lower. This is because emissions of other greenhouse gases such as methane and nitrous oxide are also lower. This comparison ignored the potential climatic impact of diesel particles, which because of their high elemental carbon content may contribute to global warming (see Chapter 4). Such a contribution is however very difficult to quantify.

To make a proper comparison of CO_2 emissions from petrol and diesel cars it is necessary to carry out a life cycle analysis that takes account of the emissions from the production of the fuel at the refinery, and its distribution, as well as those from its use. Such a study is being carried out by the Energy Technology Support Unit (ETSU) for the Department of Transport but the results were not available in time for this report.

2.10 KEY POINTS

- *There has been much debate over recent years over the relative environmental benefits of petrol and diesel engines, especially in relation to whether the use of diesel engines in passenger cars should be encouraged. However, weighing up the relative advantages and disadvantages is not easy, and there is no unequivocal answer.*

- *The environmental benefits of diesel cars relative to three-way catalyst cars are that they typically produce little carbon monoxide, give rise to little evaporative and exhaust emissions of hydrocarbons and are intrinsically more fuel efficient. Emissions of the greenhouse gases carbon dioxide, nitrous oxide and methane are all lower from diesel cars, but emissions of climatically-active carbon particles are much greater.*

- *The main disadvantages of diesel cars are their higher emissions of nitrogen oxides and particulate matter relative to petrol cars with catalysts. These are particular problems with direct injection diesel engines, which are significantly more polluting than indirect injection diesel engines.*

- *The different nature of the particulates from diesel is also of concern. They have a greater soiling capacity than particulates from petrol vehicles and the amount of polycyclic aromatic hydrocarbons associated with the particles is greater. However, the widespread use of oxidation catalysts, which are likely to be needed to meet the proposed 1996 emission limits, are likely to substantially reduce emissions of PAHs.*

- *The emissions characteristics of different technology cars are shown in Table 2.4.*

REFERENCES

Bailey J C and Parkes S N (1993) **Speciated Hydrocarbon Emissions from the UK Large Scale Survey**, Report No LR979, Warren Spring Laboratory, Stevenage.

Table 2.4 Comparison of Emissions From Petrol Cars with Three Way Catalysts and Diesel Cars.

Pollutant	Petrol Without Catalyst	Petrol With Three Way Catalyst	Diesel Without Catalyst	Diesel With Oxidation Catalyst
Nitrogen Oxides (NO_X)	****	*	**	**
Hydrocarbons (HC)	****	**	***	*
Carbon Monoxide (CO)	****	***	**	*
Particulate Matter (PM)	**	*	****	***
Aldehydes	****	**	***	*
Benzene	****	***	**	*
1,3-Butadiene	****	**	***	*
Polycyclic Aromatic Hydrocarbons (PAH)	***	*	****	**
Sulphur Dioxide (SO_2)	*	*	****	****
Carbon Dioxide (CO_2)	***	****	*	**

Key: Asterisks indicates which type of car has typically the highest emissions
* Lowest emissions **/ *** intermediate ****Highest emissions

Note: This table only indicates the relative order of emissions between the different types of vehicle. No attempt has been made to quantify the emissions. The difference in emissions between, say, **** and *** may be an order of magnitude, or much smaller.

Department of Transport (1988) **National Travel Survey,** HMSO, London.

Dutch Ministry of Housing, Physical Planning and Environment (1992) **Project In Use Compliance: Air Pollution by Cars in Use: Annual Report 1991-1992 Including Data Over the Last Five Years,** The Hague.

Farrow I K, Kisenyi J M, Simmonds A C, Savage C A and Cudworth R S (1993a) **Legislated Emissions from the Seven Diesel Vehicles from the Large Scale Survey,** Report No LR 931, Warren Spring Laboratory, Stevenage.

Farrow I K, Cudworth R S, Savage C A and Simmonds C (1993b) **Regulated Emissions from the Forty Gasoline Vehicles without Catalysts from the Large Scale Survey,** Report No LR 933, Warren Spring Laboratory, Stevenage.

Farrow I K, Cudworth R S, Savage C A and Simmonds A C (1993c) **Regulated Emissions from the Three Gasoline Vehicles with Catalysts From the Large Scale Survey,** Report No LR 932, Warren Spring Laboratory, Stevenage.

Holman C, Wade J, and Fergusson M (1993) **Future Emissions from Cars 1990 to 2025: The Importance of the Cold Start Emissions Penalty,** World Wide Fund for Nature UK, Godalming.

Lucas Diesel, undated, **Pollution and Consumption: Comparison of the Performance of Gasoline and Diesel Cars,** Blois Cedex, France.

Martin D J and Shock R A W (1989) **Energy Use and Energy Efficiency in UK Transport Up to the Year 2010,** No 10 Energy Efficiency Series, Energy Technology Support Unit, Department of Energy, HMSO, London.

Society of Motor Manufacturers and Traders (1993) Personal Communication

Wade J, Holman C and Fergusson M (1993) **Current and Projected Global Warming Potential of Passenger Cars in the UK,** A Report for WWF UK, Earth Resources Research, London.

Williams D J, Milne J W, Roberts D B and Kimberlee M C (1989a) **Particulate Emissions from 'In-use' Motor Vehicles - 1. Spark Ignition Vehicles,** Atmospheric Environment, **23**, 2639-2645.

Williams D J, Milne J W, Roberts D B and Kimberlee M C (1989b) **Particulate Emissions from 'In-use' Motor Vehicles - 2. Diesel Vehicles**, Atmospheric Environment, **23**, 2647-2661.

3 Factors Influencing Emissions from Diesel Vehicles

3.1 INTRODUCTION

Two types of internal combustion engine - spark ignition and compression ignition - have been developed for use in road vehicles. These engines use petrol and diesel respectively and have traditionally been used in different types of vehicles. Petrol engines are typically used in motor cycles, passenger cars and small to medium sized vans, while diesel engines have a much wider range of on-road applications. They can be found in cars, vans, heavy goods vehicles and buses. Each type of engine has its own emission characteristics.

In this chapter the influence of the different types of engine, the main methods of pollution abatement and the effect of different operating conditions on emissions are briefly described. A more detailed comparison of petrol and diesel cars is given in Chapter 2 of this report.

It is important to note that for many of these vehicles very little is known about their on-road emissions, which can differ significantly from those measured on dynamometers. This is particularly the case for heavy duty vehicles where most of the emissions testing has been carried out on engines as opposed to vehicles. This is because a heavy duty engine can be used in a variety of different types of vehicles, and the final application is generally unknown at the time of manufacture. Often the engine, transmission and chassis manufacturers and bodybuilder are different companies. Therefore the legislation only requires tests to be carried out using engines on bench dynamometers.

3.2 AVAILABILITY OF EMISSIONS DATA

The emission factors used in this chapter are based on those obtained from in-service, on-road tests undertaken in the UK. Motor manufacturers, oil companies and others undertake numerous emission tests, generally using bench or chassis dynamometers. However, little of this data is published and it may not be representative of the range of vehicles that are being driven on the road, as the emphasis is on emissions testing for future vehicles.

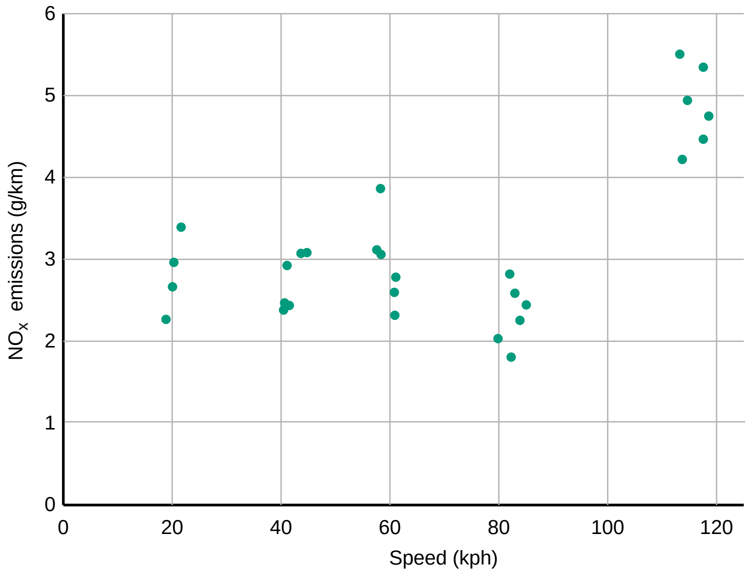
To obtain typical emission factors it is necessary to measure emissions from a range of vehicles that are in-service. Tests on new vehicles do not provide information about the effect of age/use of the vehicles, nor the effect of poor maintenance on emissions. Measuring emissions as vehicles are being driven along public roads provides a test of the real emissions. The disadvantage of this approach is that there is little information on emissions from vehicles using the latest technology.

On-road emissions from in-service vehicles have been measured for a number of years in the UK and a considerable database now exists for non-catalyst petrol cars. However, for other types of car, vans, trucks and buses, emissions have only been measured on a relatively small number of vehicles. In total, the on-road emissions from about 40 light diesel vehicles (cars and vans), and a similar number of heavy duty vehicles (mainly trucks), have been measured. The results from these studies have not yet been fully analysed and published.

Almost no measurements of emissions from diesel buses have been undertaken and much of the information available for these vehicles has been derived from measurements and estimates of emissions from lorries.

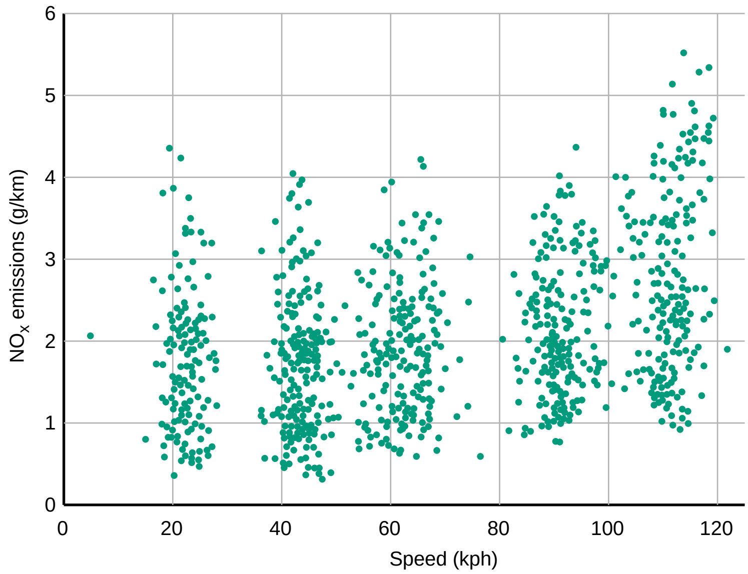
Recent analysis of on-road emission rates for standard petrol cars, measured by Warren Spring Laboratory, suggests that there is a large variation in emissions for any one type of vehicle (Eggleston, 1993). In the test programme emissions were measured four or five times for each vehicle. The scatter of data for one non-catalyst petrol car is illustrated in Figure 3.1 for nitrogen oxides. Figure 3.2 shows the scatter of data for all 40 cars tested in the programme. There is reason to suppose that the scatter will be less for diesel vehicles, however, due to their better control of combustion. Until such time as more data becomes available, emission rates derived from measurements on a small number of diesel vehicle tests must be treated with caution.

Figure 3.1 Variations in On-Road NO_X Emissions from One Non-Catalyst Petrol Car.



Source: Eggleston, Personal Communication.

Figure 3.2 Variation in On-Road NO_x Emissions from 40 Non-Catalyst Petrol Cars.



Source: Eggleston, Personal Communication.

Table 3.1 Specific Power Output for Different Types of Engine.

Engine Type	Technology	Specific Power Output (kW/litre)
Spark Ignition (petrol)	4 valves	45 to 60
	2 valves	30 to 45
Compression Ignition (diesel)	Naturally Aspirated	20 to 28
	Turbocharged	Up to 38
	Turbocharged and Intercooled	Up to 40

Source: Adapted from Martin and Shock, 1989

3.3 ENGINE TECHNOLOGY

Spark ignition engines have traditionally been used for cars where a high specific power output is required (see Table 3.1). They are cheaper to manufacture and offer better performance in terms of acceleration than equivalent compression ignition engines. For larger vehicles, such as lorries and buses, compression ignition engines are now almost exclusively used because they have better fuel economy and greater durability. In recent years, as smaller compression ignition engines have been developed and the price differential has been reduced, there has been a move towards diesel cars and vans. Many of these light duty vehicles have turbocharged engines to increase the specific power output.

The spark ignition engine requires a relatively volatile fuel that does not ignite spontaneously during compression, and enables progressive combustion. It is restricted to operating relatively close to the stoichiometric air to fuel ratio. Compression ignition engines do not need a fuel as volatile as petrol, but the fuel must ignite easily and burn progressively. It can use much leaner air/fuel mixtures than a spark ignition engine. A spark ignition engine can nominally operate in the range 10 to 1 up to 20 to 1, while a compression ignition engine can operate in the range 20 to 1 up to about 100 to 1. A petrol car with a three-way catalyst has to operate close to the stoichiometric air to fuel ratio for much of its operation (ie 14.7 to 1).

In compression ignition engines, air in the cylinder is compressed, the fuel injected and ignition results. This contrasts with a petrol engine, where the air and fuel are mixed, and ignition occurs as a result of a spark. In direct injection diesel engines the fuel is injected and burnt directly in the cylinder, while in indirect injection engines the fuel is injected into the compressed air in a pre-chamber (swirl chamber) where it ignites and combustion begins. The burning mixture then flows into the main combustion chamber and completes its combustion there.

Until fairly recently the higher noise from direct injection diesel engines and their limited operable speed range precluded their use in passenger cars, and nearly all diesel cars and small vans used indirect injection engines. However, the development of improved fuel injection technology, such as high pressure rotary pumps, has allowed direct injection technology to be applied to smaller vehicles.

These two diesel technologies have different fuel consumption, noise and emissions characteristics. In a direct injection engine there is a very rapid rise in pressure in the cylinder which gives rise to the additional engine noise associated with direct injection diesel engines. Indirect injection diesel engines are quieter because the cylinder pressure increases less rapidly. Another advantage of the indirect injection engine is that less nitrogen oxides (NO_X) and particulate matter are formed. However, heat losses occur when the burning mixture flows from the pre-chamber to the main combustion chamber. Cars with direct injection diesel engines may be up to 20% more fuel efficient than those with indirect injection diesel engines, and up to 40% more than those with petrol engines. Although some large cars on the market have direct injection engines, diesel cars are, in general, fitted with indirect injection engines. Vans which are based on car designs are also likely to have indirect injection engines, whilst larger vans are likely to have direct injection engines. All heavy duty vehicles use direct injection engines.

3.4 EMISSION CONTROL TECHNOLOGY

Three-way catalysts cannot be used with diesel engines as they operate with lean air/fuel mixtures. However, oxidation catalysts, which remove carbon monoxide and volatile organic compounds are used on some diesel cars. These catalysts can remove some of the hydrocarbons associated with diesel particulate matter, slightly reducing the weight of particles emitted. For heavy duty applications particulate traps have been developed, but are not currently suitable for smaller vehicles.

Currently there is no catalyst technology to reduce nitrogen oxides emissions from diesel engines. Although motor and catalyst manufacturers have been developing a lean burn de-NO_X catalyst for a number of years, it remains several years away from commercial production. Emissions, therefore, have to be reduced by modifying the engine design. Nitrogen oxides emissions can be reduced using exhaust gas recirculation (EGR), where a proportion of the exhaust gas is returned to the combustion chamber replacing some of the air. This lowers the peak combustion temperature and hence reduces the amount of NO_X produced. Electronic management of exhaust gas recirculation can enable direct injection diesel engines to equal the NO_X emissions of indirect injection diesel engines without increasing particulate emissions.

Most of the focus for reducing emissions from diesel engines has been on improving the combustion process. The greatest advances have been achieved by redesigning the combustion chamber, improving the injection of fuel, and increasing the charge of air by means of turbocharging and aftercooling.

Further improvements are likely to result from a combination of technologies but particularly the more precise control of the combustion process using on-board computers and improved fuel injection. However, there may be limits to what can be achieved as there is a trade-off between the combustion conditions that give rise to low particulate emissions and those that give rise to low NO_X emissions. Reducing emissions of one will typically increase emissions of the other. Although the evolution of new technology has reduced these trade-offs, in the future exhaust after-treatment devices may be required to reduce emissions. These may be used either to reduce the NO_X emissions, allowing engine design to be optimised to reduce particulates, or more likely, to reduce the levels of exhaust particulate matter allowing the engine to be optimised for low NO_X operation. The technologies likely to be used are particulate traps and oxidation catalysts.

Particulate traps can be fitted to new vehicles or, in some situations, retro-fitted to in-service vehicles. Unlike the catalysts fitted to petrol cars, these are filter systems. However, a ‘simple’ filter would rapidly become blocked and eventually exert an unacceptably high back pressure on the engine, adversely affecting engine performance (ultimately causing it to stall), and increasing fuel consumption and emissions. It is therefore necessary to clear the trap of particulates as it becomes blocked. This can be done by oxidising or burning the particulate matter and is known as trap regeneration. It does, however, give rise to a small fuel penalty (and hence increased carbon dioxide emissions) of up to about 2%, depending on the system used.

A number of different filter systems have been developed. The most common is the extruded ceramic monolith (often referred to as the wall flow monolith) which can trap over 80% of the exhaust particulates. There is also a range of different methods for regenerating the trap including directly burning off the particulates using electric heaters or fuel burners, and the use of catalysts either on the filter or as a fuel additive. The use of catalysts can eliminate the need for expensive regeneration equipment. Various metallic compounds have been tested based on cerium, copper, iron and manganese. All appear to work, but some are more effective than others. The use of metallic catalysts is likely to change the nature of the exhaust emissions and it is important that they are assessed for any possible toxic and carcinogenic nature before being used extensively.

Trials of particulate traps have been undertaken in North America and in a number of European countries. In general they have been fitted to urban buses, as these vehicles are widely used in areas close to the public, with the aim of improving urban air quality with respect to particulate matter. In general these field trials have been successful. However, there still remains some concern over their durability in service.

Oxidation catalysts can also be used to reduce the particulate emissions from diesel vehicles. The reduction in particulate matter is mainly related to the amount of hydrocarbons present - often referred to as the soluble organic fraction - which may range from 30% for an indirect injection diesel engine to up to 70% for a direct injection diesel engine. This is in addition to the reduction of some 10-40% in gaseous hydrocarbons in the exhaust which are not associated with the particulate matter. The high temperature of the catalyst also results in the burning of some of the carbon in the particulate matter.

Ideally the catalyst should operate at high enough temperature to ensure that the hydrocarbons are oxidised but not high enough to encourage the oxidation of the sulphur in the fuel to sulphur trioxide. If the design of the catalyst system is not optimised a diesel vehicle with an oxidation catalyst could emit higher levels of particulate matter, albeit of very different chemical composition, than one without a catalyst. Therefore the reduction of sulphur in the fuel is of paramount importance to the effective use of catalytic converters.

It is generally considered within the motor industry that the heavy duty emission limit values agreed by the European Community for 1996 (see Annex A) will, for most engines, be met using a package of improvements in engine design. In addition, low sulphur fuel will be required, as sulphur in the fuel contributes to the particulate matter.

However, it appears unlikely that motor manufacturers will be able to meet the proposed diesel car emission limits for the European Community for 1996 without the use of exhaust after-treatment. The limit values are likely to require the fitting of oxidation catalysts to these cars.

Some vehicles, such as urban buses and local authority utility vehicles (eg dustcarts), may be ideally suited to either retro-fitting of particulate traps (they can be recharged at the bus depot) or conversion to run on alternative fuels (until there is a refuelling infrastructure, the use of new fuels will be restricted to centrally refuelled vehicles). Urban buses tend to have a long average lifetime, and therefore the introduction of cleaner vehicles takes a long time to take effect. Of all the alternative fuels under consideration world-wide, compressed natural gas (CNG) appears to offer the most benefits in terms of clean combustion, and diesel engines can run on it with relatively few alterations.

For further information on pollution abatement technology for diesel vehicles the reader is referred to the Royal Commission on Environmental Pollution's fifteenth report (Royal Commission on Environmental Pollution, 1991).

3.5 OPERATIONAL FACTORS

3.5.1 Introduction

The way a vehicle is driven has a large effect on emissions. This is influenced by the type of road being driven on, the level of congestion, traffic management and driver attitude and behaviour. In urban areas the traffic is dominated by cars, with vans and buses playing a smaller but still significant role. Large trucks and coaches are generally driven on inter-city roads - motorways and primary trunk roads - and thus will have less impact on urban air pollution.

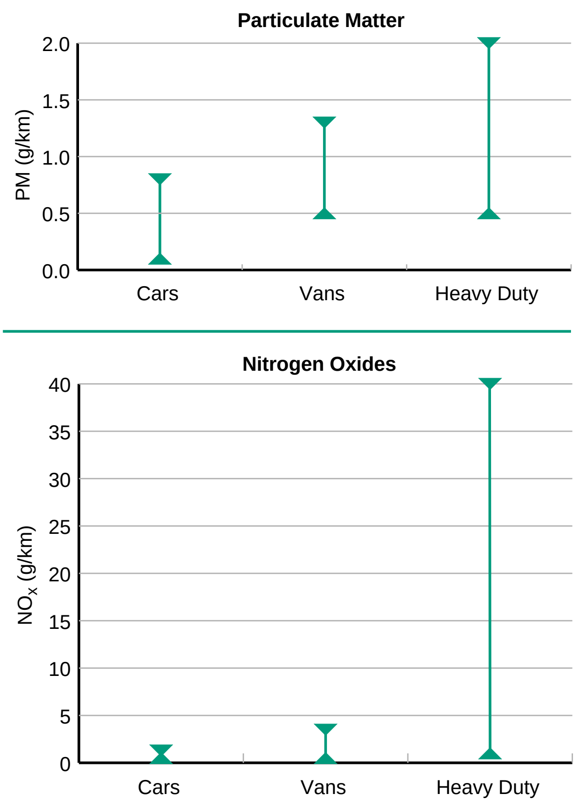
In general terms, when an engine is operating under load, emissions of hydrocarbons are low, whilst NO_X emissions are high as a result of the efficient combustion taking place. The engine may be running under load when the vehicle is accelerating, driving up hills or travelling at high speeds or when it is laden.

In diesel engines, high emissions of hydrocarbons can occur when an engine is started from cold, and under these conditions will generally appear as 'white smoke' from the exhaust. They can also occur when idling or under part load conditions when poor mixing of the fuel and air may result in late and/or incomplete combustion. At low loads emissions of NO_x are very low.

The formation of particulate matter is complex with several different processes contributing, and thus it is more difficult to relate emissions to operating conditions. However, it is known that the composition of the particulate matter varies with operating conditions. When the engine is operating at high loads the carbon fraction (black smoke) is predominantly produced whilst at low loads the hydrocarbon fraction, from unburnt fuel and unburnt lubricating oil, becomes more important. Emissions of carbon monoxide should be low from all diesel engines.

Figure 3.3 shows the range of emissions measured during recent on-road emissions tests of a range of different types of in-service vehicles. Emissions increase with increasing vehicle weight, thus

Figure 3.3 Range of Urban Emissions for Different Types of Diesel Vehicle.



Note: The large range of emissions for heavy duty vehicles reflects the wide range of vehicle types, sizes and technology in this category and the effect of laden weight on emissions, particularly of NO_x.

emissions of both particulate matter and NO_x per kilometre driven are typically lowest from diesel cars, and highest from heavy duty vehicles. The range of emissions from heavy duty vehicles, particularly of NO_x, is very large. This is because of the wide range of different types of vehicles and engine technologies included in this category.

3.5.2 Cars

Cars are driven quite differently from larger vehicles. One reason for this is that more power is available to the car driver than is strictly required. Thus, it is easier to accelerate rapidly and to drive at high speed. For example, the average motorway speed for cars is typically about 5% higher than that for vans and 20% higher than that for the heaviest lorries (Department of Transport, 1992).

Figure 3.4a shows speed emission curves for particulates and NO_x derived from average on-road emissions of three diesel cars (two with indirect injection engines and one with a direct injection diesel engine). Emissions of all pollutants, including carbon monoxide (CO) and hydrocarbons which are not shown, are at their lowest at moderate speeds and at their highest at low and high speeds. To some extent this reflects the load on the engine which can be high during stop-start driving conditions and at high motorway speeds. It should be noted that the low average speeds are not measured under constant speed but under urban driving conditions, and will therefore be the result of successive accelerations and decelerations. Results of other tests undertaken at lower speeds than in these on-road tests suggests that at very low speeds emissions increase markedly (Jost et al, 1992).

Recent Dutch studies have shown that emissions from petrol cars with catalysts increase significantly when driven ‘aggressively’ compared to those arising when driven ‘normally’ over the same driving cycle (Heaton et al, 1992). The average emissions of CO increased by a factor of about 3.5 and the NO_x by a factor of about 2. Under the same conditions emissions from diesel cars are also likely to increase.

3.5.3 Light Goods Vehicles (Vans)

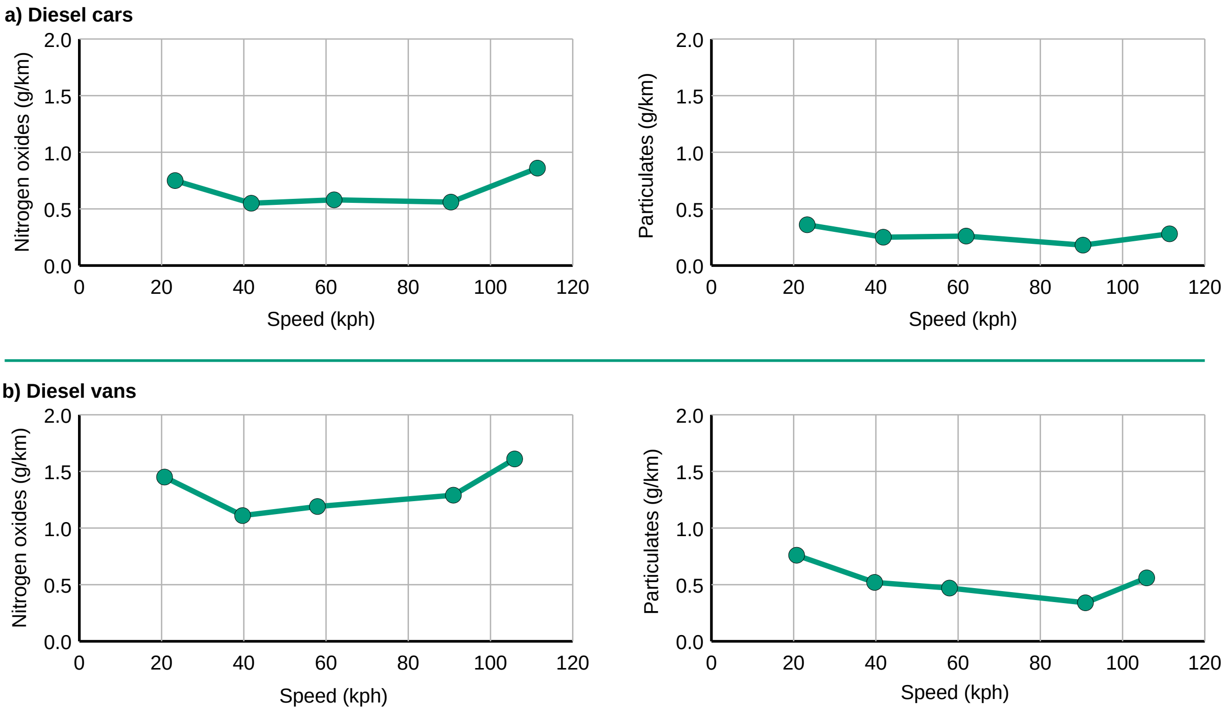
Again there is very little information on emissions from light duty commercial vehicles. One of the problems with this category of vehicle is that it encompasses a wide range of vehicle types. Many small vans are based on car designs but will not necessarily have the same emission characteristics as they may have a different power train (engine and transmission). Some medium sized vans, whilst not looking like a car, may also have power trains common to the motor car. Most van engines will be 'calibrated' to reflect the different operating conditions and they will typically be lower geared (ie have a higher engine speed to road speed ratio compared with an equivalent passenger car). In the past, these small and medium size vans have been fitted with petrol engines, but are today increasingly fitted with diesel engines. Large vans, however, have little in common with the passenger car. They are likely to have direct injection diesel engines and emissions will be more similar to those from a small heavy duty vehicle than a car.

Vans are typically used on short urban journeys, and are required to carry heavier or bulkier loads than passenger cars. However there are relatively few vans in use. For every nine cars on the British roads there is one van.

As there is such a large difference between the types of vehicles in this class there will be a larger spread in the emission rates compared with those from cars. This is shown in Figure 3.3. However, on-road emission measurements in the UK have been restricted to less than 20 vehicles - too small a sample to enable characterisation of the different vehicle types.

Figure 3.4b shows the average speed emission curve for four diesel vans for particulate matter and NO_X. These vehicles had naturally aspirated direct injection diesel engines in the range 2.0-2.5 litres. The shape of the speed emission curve is similar to those for diesel cars, but the emission rates are higher.

Figure 3.4 Speed Emissions Curves for Diesel Cars and Vans.



Note: Emissions from WSL on-road tests with 'hot' cars, as received.
Source: Farrow et al, 1993a.

3.5.4 *Heavy Goods Vehicles*

The heavy goods vehicle category is also wide with lorries ranging from 3.5 to 38 tonnes. These may be rigid or articulated vehicles, and their engines may be naturally aspirated, turbocharged, or turbocharged and intercooled. In recent years there has been a trend towards both turbocharging and turbocharging with intercooling.

On-road emissions have been measured on less than 40 lorries in the UK, although emissions from heavy duty engines have been more widely measured on bench dynamometers and these have been used to estimate emissions from road vehicles.

Typically, heavy goods vehicles are used for long distance trips. For much of these journeys the vehicle will be travelling at constant speeds. Figure 3.5 shows the average speed emission curve for particulate matter and NO_X for one unloaded 17 tonne turbocharged lorry. There is a less clear speed emission curve for this vehicle compared to those for the cars and vans shown in Figure 3.4, although emissions appear to be higher at the lower speeds typical of urban driving.

Initial results from in-service measurements carried out by the Transport Research Laboratory suggest that the method of aspiration can have significant effects on emissions (Hickman, 1993). Turbocharging tends to offer the best compromise in the trade-off between the different pollutants for vehicles in the current fleet. Intercooling appears to increase the average NO_X emissions while decreasing the particulate emissions (Figure 3.6). However, there is evidence to suggest that the latest intercooling technology can reduce NO_X emissions from direct injection diesel engines. The Transport Research Laboratory study also suggests that for NO_X, CO and CO_2 emissions increase with vehicle weight while for particulate matter there appears to be no variation with weight (Figure 3.7).

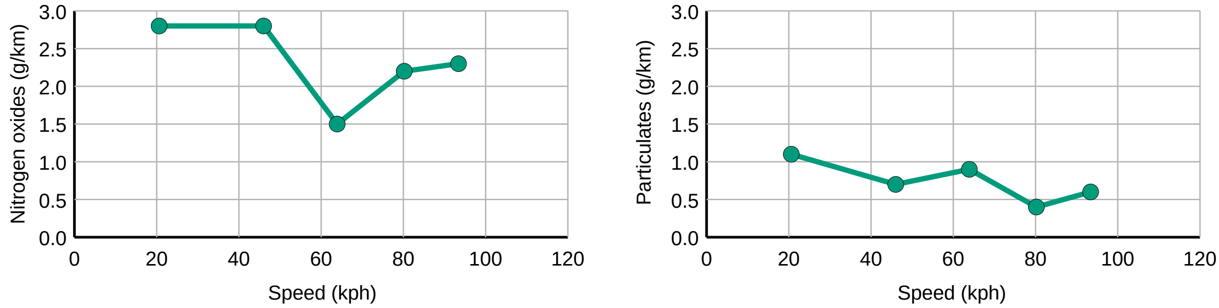
Lorries will usually be travelling fully laden, although on occasion only partially laden or empty. Emissions generally increase by a factor of between one and two when laden.

3.5.5 *Buses*

The little on-road emissions testing of heavy duty vehicles has tended to focus on goods vehicles rather than buses, largely because there are more of them on the road (450,000 compared to 110,000) and they are easier to obtain, from hire companies, for testing. Therefore bus emission factors used for estimating total emissions (for the National Emissions Inventory, for example) are derived from three sources of information. Firstly, the very limited measurements of emissions from buses (it appears that the results of on-road emission testing on only one bus has been published in the UK). Secondly, measurements of emissions from trucks, and finally calculations of emissions based on engine tests.

The operating conditions of buses, especially in urban areas where their use dominates, is characterised by acceleration followed by a short journey, which may or may not be ‘stop-start’ depending on the level of congestion, followed by a stop at the next bus stop.

Figure 3.5 Speed Emission Curve for One 17 Tonne Turbocharged Lorry (unloaded).



Source: Hickman, Personal Communication.

Figure 3.6 Variation in Average Emissions with Method of Aspiration.

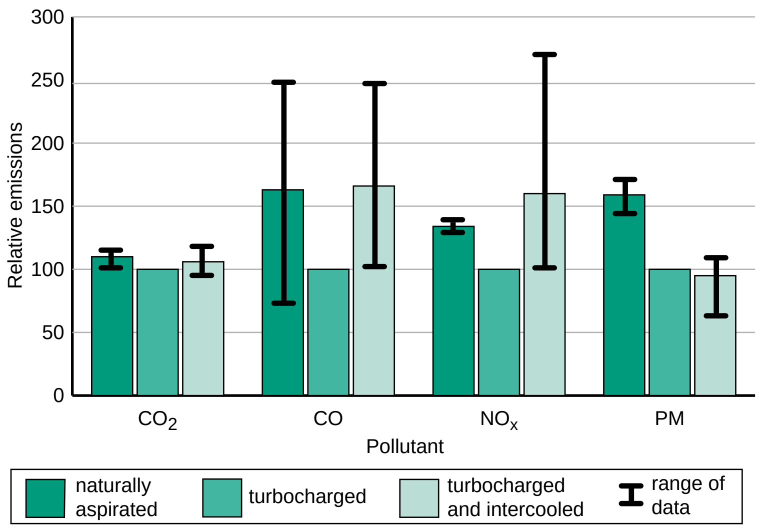
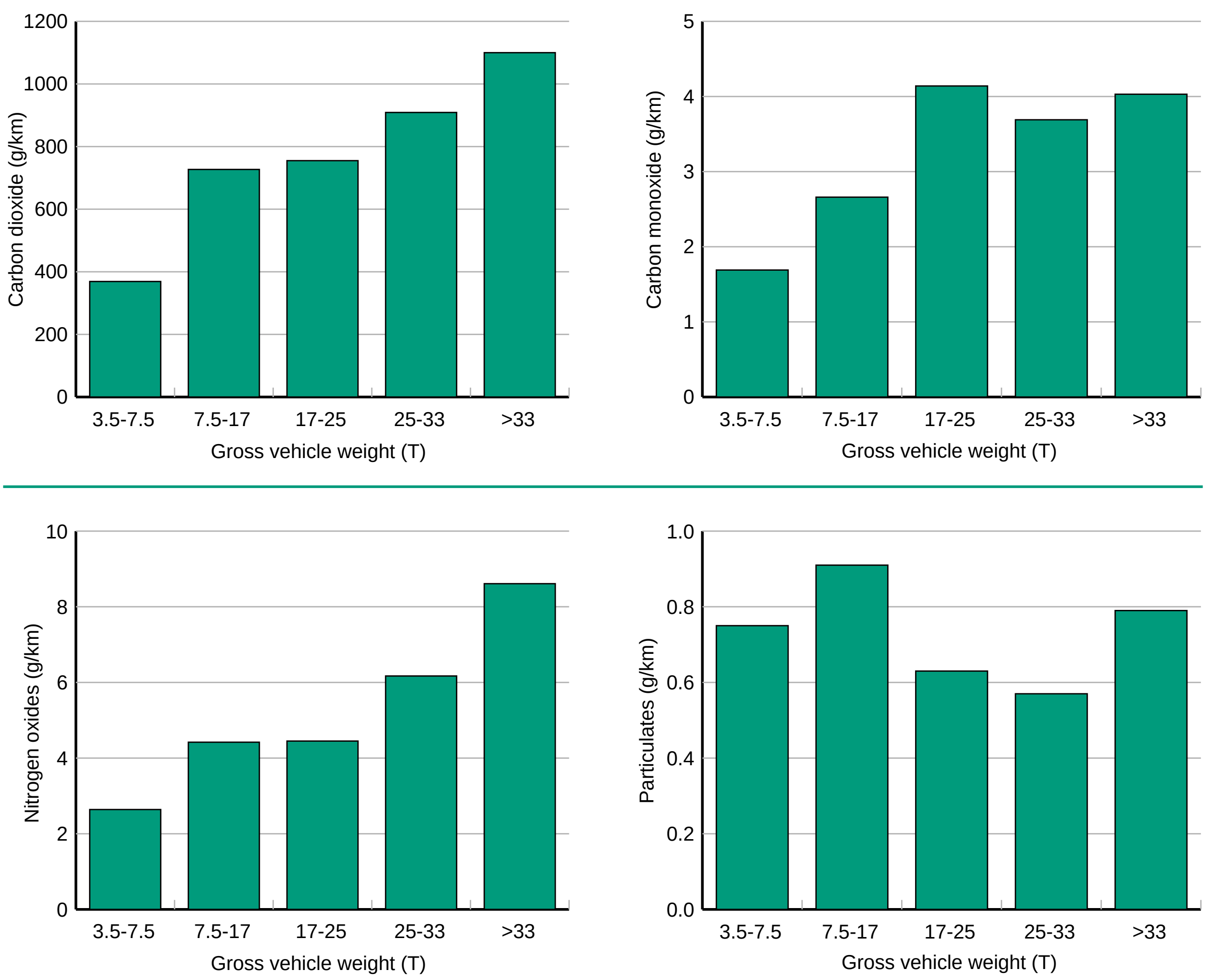


Figure 3.7 Variation in Average Emissions with Vehicle Weight.



This type of journey is characterised by low speed and high acceleration. Studies on a London bus suggest emissions of particulate matter, hydrocarbons and NO_X are highly dependent on driving patterns, particularly acceleration rates (Reynolds et al, 1992).

Typically turbocharged engines emit about half the particulates of a naturally aspirated engine when measured on the standard ‘steady state’ test cycle (R49) used in European legislation. However, the weighting factors applied to the R49 results reflect truck operation on motorways, which is different from bus operation in city centre traffic. Tests of in-service emissions of heavy duty vehicles, driven in 'stop-start' conditions, suggest that turbocharged engines may have higher on-road emissions than a naturally aspirated engine.

There appears to be no direct comparison between the in-service emissions measured from a bus and those measured from the same engine type over the R49 test cycle. In the London bus study (see above) the bench dynamometer test gave significantly lower emission rates.

Given the slow rate of replacement of buses and the problems outlined above, the use of different pollution abatement strategies may be appropriate, such as the retro-fitting of particulate traps or conversion to allow the use of compressed natural gas.

3.6 FUEL QUALITY

The relationship between the properties of the fuel, engine performance and exhaust emissions is complex, and there is often a trade-off between measures taken to benefit one pollutant and its effect on others.

It is often difficult to isolate the effect on emissions of one fuel characteristic from another. For example, high aromatic content gives rise to a denser fuel and a lower cetane number (cetane number is used to predict a fuel’s ignition quality; the higher the cetane number the shorter the delay between ignition and combustion). As a number of studies have pointed to a relationship between aromatic content and particulate emissions it has been suggested that aromatic content should be specified on automotive diesel fuel. A number of recent studies have, however, suggested that aromatic content is not the key factor.

There is general agreement that, for any particular engine, there is a linear relationship between fuel sulphur content and particulate emissions. However, the size of the effect may be small for indirect injection diesel cars. There is also a large intercept, that is much of the particulate formation is unrelated to the sulphur content, and even if all the sulphur were removed significant emissions of particulate matter from current engines would remain. However, as emissions of particulate matter resulting from the combustion process and from lubricants are reduced through improved engine design, the contribution from the fuel sulphur becomes more important. Thus, to meet the 1996 emission limits for heavy duty engines, it is generally agreed that the level of sulphur will have to be reduced. The average sulphur content of diesel is currently about 0.2% (by volume). This is to be reduced to a mandatory maximum of 0.05% by the 1st October 1996. A recent study from Shell has predicted that reducing the fuel sulphur content from 0.2% to 0.05% will result in a reduction of particulate emissions equivalent to 17% of the 1996 particulate emissions limit (Cowley et al, 1993).

The Shell study showed that particulate emissions from heavy duty diesel engines were also strongly dependent on the fuel density and, to a lesser extent, on cetane number. The importance of fuel density on particulate emissions has also been shown in a joint Esso/Statoil study on European diesel cars (Betts et al, 1992).

However, although the Shell study used specially formulated fuels in an attempt to break the aromatics-fuel density correlation, this was not always possible. Further work is needed, in particular to look at the influence of specific aromatic species.

The European automotive and oil industries have recently announced the setting up a joint research programme with the aim of looking at the influence of fuel quality and new engine design on emissions (European Programme on Engines, Fuels and

Emissions; EPEFE). This follows on from the US Auto/Oil Research programme that has looked into the impact of petrol fuel quality on emissions, and is likely to focus on diesel emissions (ACEA and Europia, 1993).

3.7 MAINTENANCE

One of the attractions of diesel engines, particularly to those operating commercial vehicle fleets, is that they are able to sustain their power output for long periods with very limited maintenance. However, emissions from diesel vehicles can increase as a result of, for example, deposits building up in the fuel injector or wear of cylinders or piston rings leading to increased consumption of lubricant. Emissions of particulates (including black smoke) and unburnt hydrocarbons are likely to increase, while those of NO_X are likely to remain more constant or even to decline as the efficiency of combustion falls.

As emission of visible smoke is a clear sign of a poorly maintained vehicle smoke tests have been introduced into the annual MoT test. From September 1992 a free acceleration smoke test was introduced for heavy duty vehicles and from January 1993 were introduced for diesel cars. However, a number of car engines in poor condition were damaged as a result of the test and it was withdrawn within three months. The Department of Transport is currently investigating alternative means of testing smoke emissions from cars and the aim is to introduce a new test as soon as possible.

3.8 KEY POINTS

- *Relatively little is known about on-road emissions of diesel vehicles. Those studies that have been undertaken by the Transport Research Laboratory and Warren Spring Laboratory should be analysed and published as soon as possible.*

- *Emissions of particulate matter (including black smoke) and nitrogen oxides are of particular concern from diesel vehicles.*

- *Pollution abatement technology for diesel vehicles is evolving such that refinements in engine design are likely to be sufficient to meet the 1995/6 emission limits for the largest heavy duty vehicles. However, manufacturers are currently arguing for a slightly less stringent particulate emission standard for smaller, high speed diesel engines used in commercial vehicles.*

- *The emission limits for 1995/6 are forcing the introduction of turbocharging and intercooling on heavy duty engines, but this may have only limited impact on urban air quality. This is because of turbolag, that is the time lag between the throttle being pressed and the turbine reaching full speed. As buses operate in 'stop-start' mode in urban areas, for a large proportion of the time the turbocharger may not be fully operational. This may not be appropriate technology for this application, and new solutions may be needed. These may include the use of alternative fuels such as compressed natural gas .*

- *The smoke test in the MoT for light duty vehicles should be re-introduced as soon as the current problems have been resolved.*

- *Further studies are needed to characterise emissions from diesel vehicles. These should include studies of on-road emissions for the full range of diesel vehicles and the effects of fuel properties on emissions.*

REFERENCES

ACEA (Association des Constructeurs Europeen d'Automobiles and Europia (European Petroleum Industries Association) (1993) **Press Release: European Auto/Oil Research Programme Launched**, 19th July 1993, Brussels.

Betts W E, Fløysand S A and Kvinge F (1992) **The Influence of Diesel Fuel Properties on Particulate Emissions in European Cars,** Society of Automotive Engineers Technical Paper No. 922190, Warrendale, PA.

Cowley L T, Le Jeune A and Lange W W (1993) **The Effect of Fuel Composition Including Aromatics**

Content on Emissions From a Range of Heavy-Duty Diesel Engines, Fourth International Symposium on the Performance Evaluation of Automotive Fuels and Lubricants, CEC, Birmingham, May 1993.

Department of Transport (1992) **Vehicle Speeds in GB 1991,** HMSO, London.

Eggleston S (1993) Warren Spring Laboratory, personal communication.

Heaton D M, Rijkeboer R C and van Sloten P (1992) **Analysis of Emission Results from 1000 In-use Passenger Cars Tested Over Regulation Cycles and Non-Regulation Cycles,** Paper presented at 'Traffic Induced Air Pollution' Symposium, Graz Technical University, 10th and 11th September 1992.

Hickman A J (1993) Transport Research Laboratory, personal communication.

Jost P, Hassel D, Weber F J, Hickman A J and Joumard R (1992) **Emission and Fuel Consumption Modelling Based on Continuous Measurements,** Report of the DRIVE Project V 1053 of the European Commission, TÜV Rheinland, Köln, Germany.

Martin D J and Shock R A W (1989) **Energy Use and Energy Efficiency in UK Transport up to the Year 2010,** Number 10, Energy Efficiency Series, Energy Technology Support Unit, Department of Energy, HMSO, London.

Royal Commission on Environmental Pollution (1991) Fifteenth Report: **Emissions from Heavy Duty Diesel Vehicles**. HMSO, London

Reynolds E G, Gore B M and Hickman A J (1992) **A Procedure to Measure On-road Emissions From A City Bus,** 'Bus '92: The Expanding Role of Buses Towards the Twenty-First Century,' Conference held 17th to 19th March 1992, Institute of Mechanical Engineers, London.

4 Nature and Effects of Emissions from Diesel Vehicles

4.1 INTRODUCTION

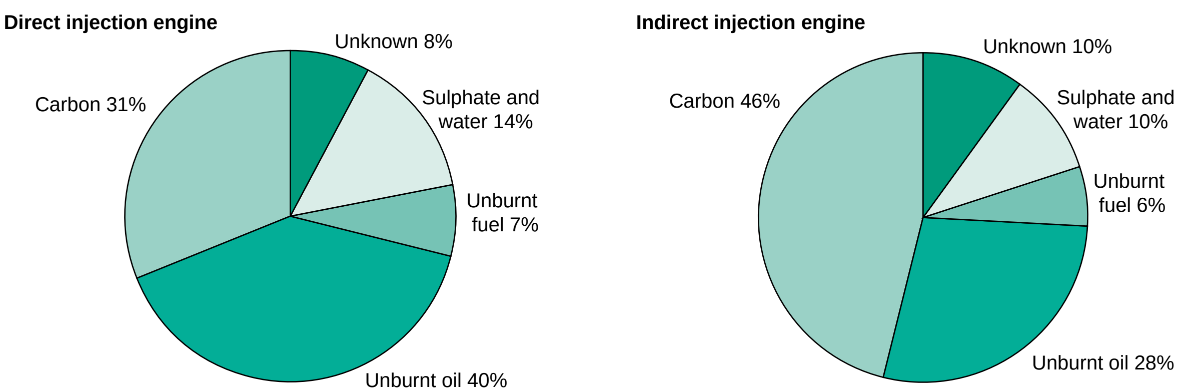
The pollutants in diesel vehicle exhaust that are legally controlled are carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_X) and particulates. Of these only CO, produced by the incomplete combustion of carbon in the fuel molecules, is a simple, individual compound. The other terms are used by convention to include a range of compounds. HC refers to the many different organic compounds emitted, some of which are not, in fact, hydrocarbons. As well as molecules containing only carbon and hydrogen, there are compounds containing oxygen, nitrogen, sulphur and other elements. They are derived from fuel passing through the engine unburnt, from fuel that is not burnt completely and also by evaporation from various parts of the fuel system (though, because diesel is relatively involatile, evaporative emissions are not usually thought to be significant). NO_X is the collective name for nitrogen oxide emissions. The most abundant is nitric oxide (NO), but there is also a smaller proportion of nitrogen dioxide (NO_2) in the exhaust. NO_X are formed by the combination of oxygen with nitrogen from the air, fuel or lubricating oil. The composition of particulate emissions is determined to an extent by the standard method by which they are measured. Exhaust is passed through a filter which has specific retention properties and is maintained below a certain temperature; all the material collected on the filter is termed particulate. Thus, particulates include carbon, a variety of organic and inorganic solids and some liquid droplets. Tonkin and Etheridge (1987) reported typical compositions of diesel particulate as shown in Figure 4.1. The particulates form around carbon nuclei, created by incomplete combustion in fuel-rich zones of the cylinder, onto which the other components are adsorbed.

Other compounds in addition to these legally regulated emissions are also of environmental concern. Carbon dioxide (CO_2) is one of the normal end-products of the combustion of any carbon containing fuel. It is the most abundant of the greenhouse gases in the atmosphere (other than water vapour) and is thus of great importance in the enhanced global warming that many consider to be a major environmental threat for the future. Diesel fuel contains rather more sulphur than petrol, and diesel vehicles are therefore the main road transport source of sulphur dioxide. Although the overall contribution of road transport emissions to atmospheric sulphur dioxide is small (of the order of 2% in the UK), road vehicles are often the main source near to heavily trafficked roads and can lead to locally elevated concentrations.

4.2 CARBON MONOXIDE

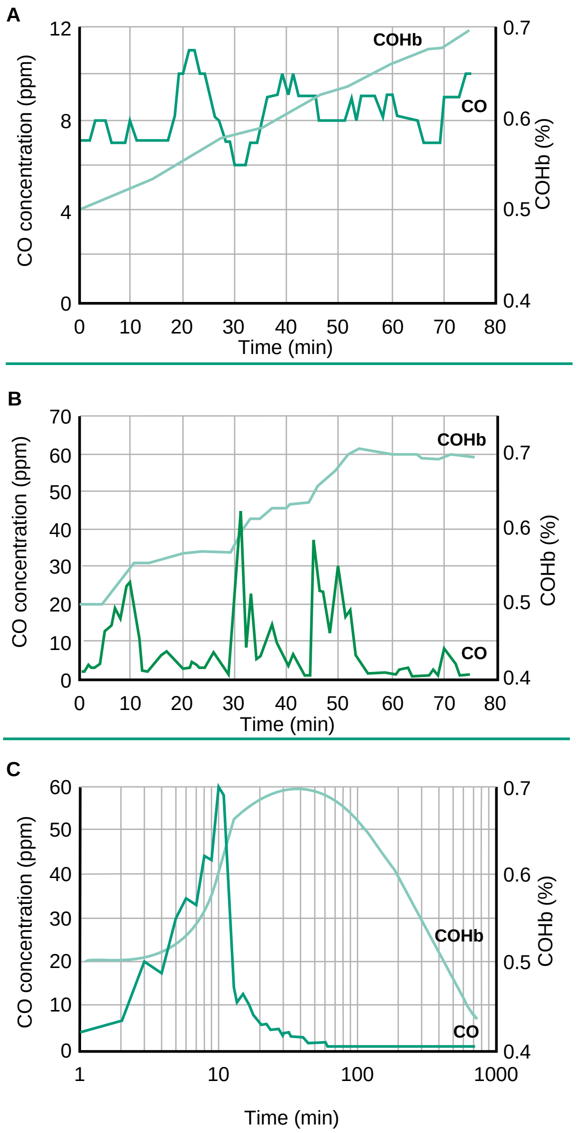
Carbon monoxide is a colourless, odourless gas that is formed during combustion by the incomplete oxidation of the fuel. Under normal circumstances, diesel engines produce only small amounts of CO

Figure 4.1 Typical Composition of Diesel Exhaust Particulate Matter.



compared with petrol engines. It is a toxic gas that combines with hæmoglobin in the blood more readily than oxygen and thus reduces the blood's capacity to transport oxygen. The reaction is reversible, so exposure to unpolluted air for a few hours removes most of the gas from the body. Examples of the body's uptake of carbon monoxide for different types of exposure are given in Figure 4.2 (Hickman, 1989). The amount of carboxy-hæmoglobin (COHb) in the blood is a good indication of recent exposure to CO and is usually used as the criterion on which exposure

Figure 4.2 Carboxyhaemoglobin Produced from Different Patterns of Exposure to Carbon Monoxide.



Note: In each case the overall exposure to CO was the same. The timescale in graph C is extended to show the elimination of CO when the exposure source is removed.
Source: Hickman (1989).

limits are based. The World Health Organization (1987), for example, recommended a COHb level of 2.5-3% for the protection of the general public, including those with impaired health. They suggested the following guidelines for limiting exposure to CO in order to maintain COHb below that level:

- *a maximum level of 100 mg/m^3 (85 ppm) for periods not exceeding 15 minutes*

- *time-weighted average exposures at the following levels for the exposure periods indicated:*

  60 mg/m^3 (50 ppm) for 30 minutes

  30 mg/m^3 (25 ppm) for 1 hour

  10 mg/m^3 (10 ppm) for 8 hours.

Carbon monoxide is a relatively stable compound and thus takes part only slowly in atmospheric chemical reactions. It may, however, make some contribution to secondary pollutant formation. The Photochemical Oxidants Review Group (1987) regarded the most important pollutants for the formation of ozone and other secondary pollutants to be HC (and other volatile organic species) and NO_X, but they considered that oxidation of CO might lead to net ozone production, and Buckley-Golder (1984) showed reaction mechanisms linking the oxidation of CO with the formation of acids in the atmosphere. Thus, while less reactive than some other pollutants, CO does contribute to an extent to these wider scale pollution problems.

The main reaction in which the CO is oxidized is with the hydroxyl radical:

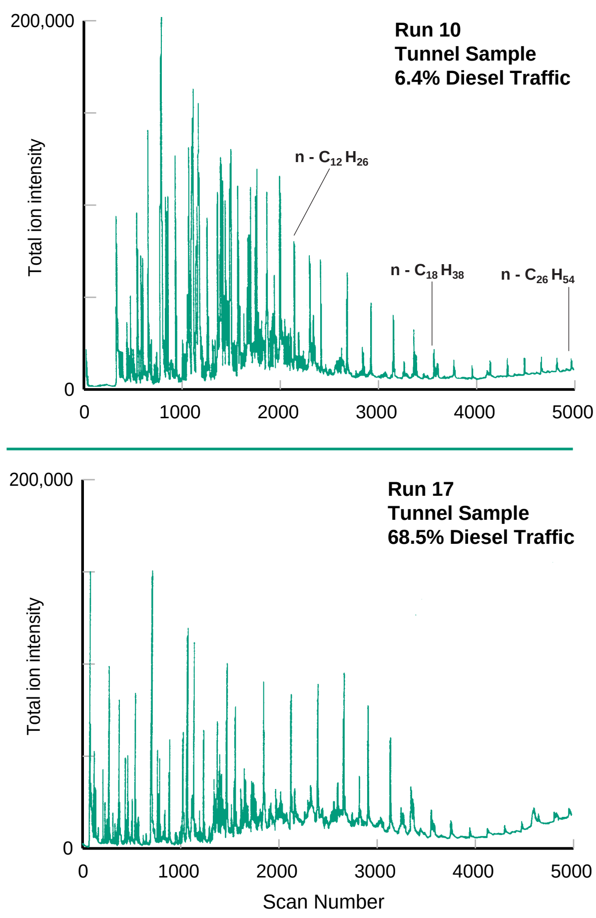
$$OH + CO \rightarrow CO_2 + H$$

Thus, CO also acts indirectly as a greenhouse gas in the atmosphere. In their supplementary report, the Intergovernmental Panel on Climate Change (IPCC) state that the complexity of the chemical reactions involved, and uncertainties about many aspects of the indirect effects of trace gases on the earth's radiation balance made it impossible to give numerical estimates of those effects (IPCC, 1992). They concluded, however, that CO produced a net reduction in hydroxyl radicals and a net increase in ground level ozone. Both of these in turn contribute to an enhancement of global warming: the reduction in hydroxyl radicals restricts the removal of other greenhouse gases, primarily methane, while ozone is itself a powerful greenhouse gas.

4.3 HYDROCARBONS (AND OTHER ORGANIC COMPOUNDS)

This group of organic pollutants is perhaps the most difficult to characterize briefly because it contains so many different compounds whose abundance and environmental significance vary widely. Ball et al (1991) (quoting Graedel et al, 1986) listed almost 400 organic compounds that had been identified in vehicle exhaust. They represent most of the major classes of organic compounds, including saturated and unsaturated aliphatic hydrocarbons, aromatic hydrocarbons including polycyclic compounds, oxygen-containing compounds including aldehydes, ketones, alcohols, ethers, acids and esters and a number of nitrogen, sulphur and organometallic compounds. Despite its extensiveness, this compilation is by no means exhaustive. The compounds emitted include many of those found in the fuel, which have passed through the engine unchanged. There are, therefore, differences in the hydrocarbon composition of exhaust from diesel and petrol engines as a consequence of fuel differences. Generally, diesel exhaust contains a larger proportion of higher molecular weight hydrocarbons. Figure 4.3 illustrates this variation by showing gas chromatograms of air samples from a road tunnel in the USA. In the case where the percentage of diesel vehicles in the traffic was low, it is clear that more low molecular weight hydrocarbons were detected than when diesels predominated. In both cases, though, compounds are also seen that are not present in the fuel, but are produced by its partial combustion. Siegl et al (1992) reported analyses of the hydrocarbon emissions derived from the combustion of a number of single compounds found in petrol. From the combustion of iso-octane, as an example, they detected methane, ethane, ethene, ethyne, propene, propadiene, propyne, 2-methylpropene, 1,3-butadiene, benzene and iso-octane in the exhaust.

Figure 4.3 Gas Chromatography/Mass Spectrometry Analysis of the Hydrocarbon Composition of Air from a Road Tunnel with Different Amounts of Diesel Traffic.



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The presence of 11 different hydrocarbons in the exhaust from an individual compound again demonstrates the complexity of the organic products of the combustion of full blend fuels such as diesel, which are themselves mixtures of hundreds of compounds.

Hydrocarbons as a group of compounds range, in toxicological terms, from essentially non-toxic compounds such as methane to highly toxic compounds such as 4-hydroxybiphenyl. Some are irritants and have few systemic effects whereas exposure to others may have far reaching toxicological consequences including damage to the central nervous system. As is generally the case as regards non-carcinogenic effects, the dose controls the response and exposure to low concentrations of many hydrocarbons in urban air is unlikely to be associated with a significant risk of damage to health.

Amongst the hydrocarbons, the aldehydes have been identified as a potentially toxic component of the urban air pollution mixture. Some 50% of total aldehydes may be present as formaldehyde and some 5% as acrolein (Klassen et al, 1986). Both are irritants and it may be that some of the eye irritation experienced by some people in busy streets is caused by these compounds. Formaldehyde has been identified as an important component of indoor air pollution and the WHO recommended a guideline of 100 ppb (30 minute average) for formaldehyde in non-industrial buildings (WHO, 1987). Close to roads in Switzerland levels of 10-15 ppb have been recorded.

A number of organic compounds encountered in urban air and found in both petrol and diesel engine exhaust are carcinogenic. Such compounds include benzene, 1,3-butadiene and a range of polycyclic aromatic hydrocarbons. The difficulties encountered in trying to predict the effects of exposure to low concentrations of carcinogens were considered in the first QUARG report (QUARG, 1993). These have led UK regulatory toxicologists to avoid the use of techniques of quantitative risk assessment as a sole means of defining standards for carcinogens in air. Concerns about the carcinogenicity of diesel generated particles will be dealt with in a later section.

The role of hydrocarbons in atmospheric photochemistry is very important. The rate of formation of photochemical oxidants is closely related to the rate at which hydrocarbons are scavenged by hydroxyl radicals, since it is this scavenging that produces organic peroxy radicals which subsequently produce ozone and other oxidants through the oxidation of NO to NO_2. The influence of hydrocarbons was emphasised by the Photochemical Oxidants Review Group (1987), who pointed out that "under most circumstances during the first day's photochemistry, control of hydrocarbon emissions would always decrease ozone, whereas control of NO emissions may in some cases increase or in other cases decrease ozone concentrations".

These same reactions, leading to the formation of ozone in the troposphere and their oxidation ultimately to carbon dioxide, implicate HC emissions also in the global warming mechanism. The IPCC (1990) defined the 'global warming potential' of a gas as "the time-integrated change in radiative forcing due to the instantaneous release of 1 kg of a trace gas expressed relative to that from the release of 1 kg of carbon dioxide". The global warming potential of any particular gas depends on both its ability to absorb radiation (or the ability of its reaction products to absorb radiation) and its lifetime in the atmosphere: thus, global warming potentials vary depending on the timescale of the evaluation. The 'global warming potentials' for a range of greenhouse gases, including methane and non-methane hydrocarbons were estimated. The figures were expressed relative to the effect of the same mass of carbon dioxide. Table 4.1 gives the IPCC estimates for methane and non-methane hydrocarbons. The approximate nature of these values and the extensive uncertainties involved in their calculation are stressed in the IPCC report. Nevertheless, they serve to show that HC do contribute to the enhanced greenhouse effect. It should be noted that the contribution is estimated to be small, since the amount of HC emitted is small relative to carbon dioxide, even though the global warming potential is higher.

Table 4.1 Global Warming Potentials of Hydrocarbons.

Trace gas	Greenhouse gas affected	Global warming potential Integration time horizon (years)		
		20	100	500
CO_2	direct effect	1	1	1
CH_4	total - direct + indirect	63	21	9
CH_4	tropospheric O_3	24	8	3
CH_4	CO_2	3	3	3
CH_4	stratospheric H_2O	10	4	1
NMHC*	tropospheric O_3	28	8	3
NMHC	CO_2	3	3	3

* non-methane hydrocarbons

4.4 OXIDES OF NITROGEN

Nitrogen and oxygen combine to produce a number of compounds. The most important, because of their relatively high stability and abundance, are nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). N_2O is, in fact, the most prevalent of the oxides in the atmosphere, but it is produced mainly by bacterial activity in soil. Anthropogenically produced NO_X are emitted predominantly as NO; the NO_2 is formed mainly by the oxidation of NO in the atmosphere.

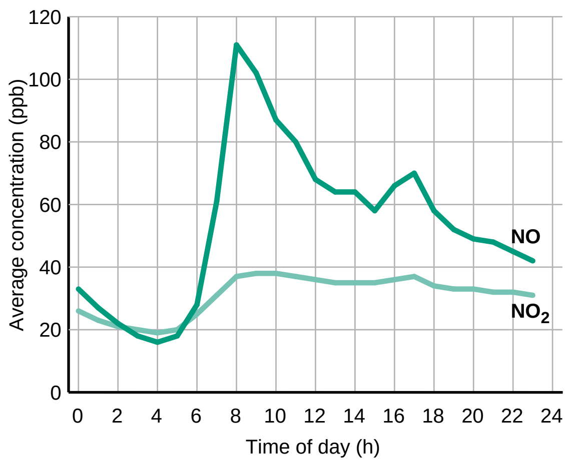
Of the oxides of nitrogen only NO_2 is of such toxicity to raise concern at ambient levels. Exposure to high concentrations of nitrogen dioxide leads to constriction of the airways and an increase in airway resistance. At extreme levels of exposure, encountered in industrial accidents, pulmonary oedema and severe inflammatory damage to small airways may occur. At peak ambient levels only asthmatics are likely to experience any change in airway resistance when levels of NO_2 exceed 300 ppb. This was recognised by WHO experts (WHO, 1977) who identified 300 ppb as the lowest level at which effects, of admittedly questionable significance, were likely to be demonstrable in asthmatics. The WHO Air Quality Guideline of 210 ppb (1 hour average) incorporates a further safety factor. In London, in December 1991, levels of nitrogen dioxide exceeded 300 ppb for 8 hours. The effects upon health of this episode are currently under investigation by the Department of Health.

Prolonged exposure of young children to elevated levels of nitrogen dioxide, as occur in kitchens equipped with unventilated gas cookers, has been suggested to be associated with an increased risk of respiratory infection (Hasselblad et al, 1992). This view is supported by work in animal models which has shown that nitrogen dioxide can damage the immune defences of the respiratory system. It is not known whether, or to what extent, exposure to urban ambient levels of nitrogen dioxide contributes to background levels of respiratory infection.

The EC Directive dealing with nitrogen dioxide (European Community, 1985) specifies that the 98th percentile of one hour average concentrations should not exceed 200 µg/m^3 (104.6 ppb) during a calendar year. A standard defined in this way does not specify or control, directly, peak levels of NO_2.

In the year Jan-Dec 1991, at the Bridge Place monitoring station in London, the 98th percentile of hourly means for NO_2 was 95 ppb, though the peak hourly concentration recorded in the December episode was 432 ppb. Concern regarding the possible effects of NO_2 upon health should include concern about peak concentrations and long-term average concentrations.

Figure 4.4 Average Concentrations of Nitrogen Dioxide and Nitric Oxide at a Kerbside Site in Glasgow.

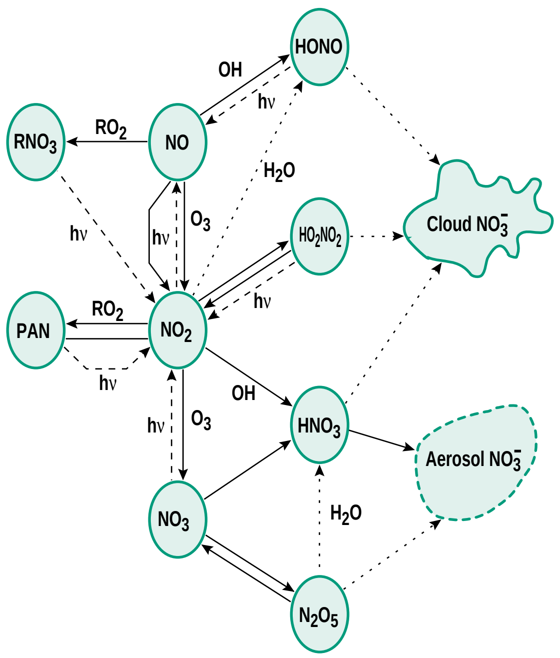


Because most of the NO_X from road traffic is emitted as NO, and because the atmospheric processes by which this is converted to NO_2 are very complex, concentrations of NO_2 near to traffic sources are much less directly associated with the level of traffic activity than are the concentrations of other primary pollutants. This is shown in Figure 4.4, which presents average hourly NO_X concentrations measured at a kerbside location in Glasgow (Bower et al, 1989).

The oxides of nitrogen and the products of their reactions in the atmosphere play a significant part in the important regional air pollution problems, contributing to the formation of photochemical oxidants, acid deposition and the greenhouse effect. Figure 4.5 summarises, in a simplified way, some of the more important interactions between nitrogen species.

Many of the species involved in these reactions are in some way associated with environmental problems. The oxides of nitrogen can damage vegetation directly

Figure 4.5 Some Reactions in the Atmospheric Chemistry of Nitrogen Species.



(exposure to high concentrations of NO_2 for a few hours has been shown to cause leaf damage; less is known of the effects of NO, but it is thought that it can also cause damage to plants), or indirectly by contributing to the acidification of rainfall and other precipitation that may be partly responsible for widespread damage to forests. Other ecological systems, in particular, freshwater lakes, have also been seen to suffer from increased acidity. Moreover, in many natural and semi-natural soil/plant systems, increased atmospheric inputs of nitrogen can lead to nutrient imbalances with resulting changes in species diversity. NO_2 is deposited directly onto vegetation and it is possible to model inputs to the land surface of the UK (INDITE, 1993). Over the country total dry deposition is of the order of 100 kT N/year. This value is similar to measured nitrate deposition in precipitation, but the spatial patterns of wet and dry deposition are quite different. Dry deposition is greatest in the Midlands and SE England, where it lies in the range 10-15 kg N/ha, while wet deposition is largest in upland areas of northern and western Britain, where it can exceed 10 kg N/ha (RGAR, 1990). Nitrogen compounds are important in the chemistry by which ozone, peroxyacetyl nitrate and other oxidants are created and destroyed in the troposphere. Ozone is a powerful oxidizing agent that is harmful to animals and plants and, as has been seen earlier, it is a powerful greenhouse gas. NO_X emissions are the second most important (after CO_2) of the traffic derived contributors to the greenhouse effect.

4.5 PARTICULATES

Examples of the composition of particulates emitted by diesel engines are shown in Figure 4.1, where it can be seen that they consist mainly of carbon and organic compounds derived from the fuel and lubricating oil. Particulate emissions from diesel combustion are much greater than from petrol combustion. Van den Hout and Rijkeboer (1986) reported emission factors of 4-7 g/litre of fuel for light duty diesel vehicles and 7-14 g/litre for heavy duty diesels, compared with 0.65 g/litre for petrol vehicles. In the UK, most diesel is used by heavy duty vehicles whose rate of fuel consumption is much higher than that of petrol cars. Thus, the difference in the emission rate of particulates per vehicle kilometre for typical diesel and petrol vehicles is even more than is suggested by these factors. Moreover, much of the particulate emitted by petrol vehicles consists of inorganic lead compounds created by the combustion of lead additives. The rapidly decreasing use of lead in petrol will continue to reduce the average emission of particulates from that source and emphasises again the importance of diesels as a source of particulate pollution.

There are a number of concerns over possible adverse health effects of diesel particles. Potentially the most serious arises from recently published research in which mortality and morbidity have been shown to correlate with the concentrations of fine particles (termed PM_{10}) in the atmosphere (eg Pope et al, 1992). The findings are broadly consistent between a number of high quality studies, including a re-analysis of data collected during historic London smog episodes. The research demonstrates an apparently linear positive relationship between the airborne concentration of PM_{10} and both daily mortality from all causes and respiratory morbidity. The data indicate no threshold for these effects, and hence it may be concluded that, as for genotoxic carcinogens, there is no totally safe concentration. There remains some caution in accepting the results of these studies as demonstrating a causal relationship since no convincing biological mechanism for the effects has yet been advanced. Nonetheless Bates (1992) has argued cogently that coherence of results supports the idea of a causal relationship. A number of independent studies have suggested that a 10 µg/m^3 rise in PM_{10} concentration is associated with an approximately 1% increase in mortality from all causes (eg Pope et al, 1992). As these findings are very recent, air quality standards have yet to be reviewed in their light. In the United Kingdom, this process has begun and a recommendation from the Expert Panel on Air Quality Standards is expected during 1994.

Until recently the major concern over health effects has focussed on the organic fraction of the particulates, and especially on the carcinogenic effects of polycyclic aromatic compounds. The International Agency for Research on Cancer (IARC) classifies chemicals as proven human carcinogens (IARC Group 1), probable human carcinogens (Group 2, subdivided into Group 2A, for which there is at least limited evidence of carcinogenicity in humans, and Group 2B, where there is evidence of carcinogenicity in animals) and unclassified chemicals (Group 3). Table 4.2 lists the IARC classifications for a range of polycyclic aromatic compounds that have been found in vehicle exhaust. A significant number of these compounds fall into IARC Group 2. IARC have also classified diesel engine exhaust as probably carcinogenic to humans (Group 2A), whilst gasoline (petrol) engine exhaust was classified as possibly carcinogenic to humans (Group 2B).

But there is still much uncertainty over the significance of these compounds as carcinogenic agents in people exposed to normal levels of vehicle pollution, or even higher levels that might be experienced by some occupational groups. In 1987 the DHSS reviewed the health aspects of diesel engine emissions including carcinogenic effects of diesel particulates. It was concluded that animal studies lent support for the possibility of a carcinogenic effect, but that human exposure would fall far short of the cumulative doses received by animals even in low dose groups in the experimental inhalation studies, in which there were no positive results.

Table 4.2 Classifications of Carcinogenicity of Some Particulate Associated Exhaust Pollutants.

Compound	IARC Group
anthracene	3
phenanthrene	3
fluoranthene	3
pyrene	3
benzo(a)anthracene	2A
chrysene	3
benzo(a)pyrene	2A
benzo(e)pyrene	3
benzo(ghi)perylene	3
benzo(j+k)fluoranthene	2B
coronene	3
2-nitrofluorene	2B
1-nitropyrene	2B
1,8-dinitropyrene	2B
6-nitrobenzo(a)pyrene	3
3-nitrofluoranthene	3
1,3-dinitropyrene	3
1,6-dinitropyrene	2B
2-nitrofluorene	2B
9-nitroanthracene	3

There has also been some interest in the elemental carbon fraction of diesel particulates. Carbon, per se, has generally been regarded as non-toxic but its physical properties might lead to it causing damage to cellular functioning in the lung. Particles of carbon emitted by diesel vehicles are very small and penetrate deeply into the lung, where they accumulate. The accumulation of large quantities of carbon may retard pulmonary clearance mechanisms. This has been demonstrated in rats exposed to high levels of ‘carbon black’. Particles may also act as vectors and produce raised local concentrations of adsorbed material in the lung.

The possibility that carbon particles, even without adsorbed organic compounds, might be carcinogenic has been raised by Nikula et al (1993). Studies by the authors showed that in rats prolonged exposure to high concentrations of diesel exhaust particles and organic mutagen-poor carbon black particles led to a similar increase in prevalence of lung tumours.

The carbon content of the particles is also significant in relation to other environmental problems. It is the

Table 4.3 European Community Air Quality Standards for Suspended Particulates and Sulphur Dioxide.

Reference period	Limit value for SO_2	Associated value for particulates	Absolute limit for particulates
Year*	80 µg/m^3	>34 µg/m^3	68 µg/m^3
	120 µg/m^3	≤34 µg/m^3	
Winter*	130 µg/m^3	>51 µg/m^3	111 µg/m^3
	180 µg/m^3	≤51 µg/m^3	
Year (24h measuring periods)	250 µg/m^3†‡	>128 µg/m^3†	213 µg/m^3‡
	350 µg/m^3†‡	≤128 µg/m^3†	

* Median of daily mean values for appropriate period
† 98th percentile of all daily mean values throughout the year
‡ Not to be exceeded for more than 3 consecutive days
Particulate concentrations expressed as British Standard Smoke

main factor determining the darkness of diesel smoke and its ability to cause visual nuisance and to soil materials. On a mass basis, diesel vehicles were estimated to produce 42% of black smoke in the UK in 1990. The situation in towns is more extreme since a greater proportion of the total smoke, and therefore of soiling, is from traffic. Ball and Caswell (1983) estimated that two thirds of smoke in London was from road traffic; national statistics suggest that the proportion may now be approximately 85%.

Air quality standards for smoke and particulate pollution have been established at a national and international level, often in association with standards for sulphur dioxide (this is mainly for historical reasons, relating to coal combustion that produces high levels of both smoke and sulphur dioxide, though there is some evidence that effects increase if the two pollutants are simultaneously present). European Community Directive 80/779/EEC (European Community, 1980) is of this type, and gives a number of limit values for various combinations of the two pollutants, for different averaging periods and different seasons of the year. They are listed in Table 4.3. The standard is based on measurement of particulates according to the darkness of stains on filter papers through which the polluted air is drawn, and is therefore relevant to the problem of soiling. By contrast, the US air quality standard is related specifically to possible health effects and uses a gravimetric measurement.

Little is known in detail of the effects of particulate pollution on atmospheric chemistry, though some influence may be assumed. Particles act as nuclei for larger aerosol droplets and may therefore promote liquid phase chemical reactions. They may also have some catalytic activity. Their effects on the earth's climate are also uncertain. They absorb and scatter radiation directly and are important in the formation of clouds, but the net effect is unclear. Model calculations indicate that light scattering by sulphate aerosols may have an effect upon global warming opposite to that of greenhouse gases; airborne particles might thus offset part of the effects of carbon dioxide and other radiatively active gases. Diesel exhaust particles, because of their high elemental carbon content may have a significant influence in reducing the magnitude of this process. Because, unlike sulphate, elemental carbon absorbs visible light, incorporation of 20% carbonaceous soot into atmospheric particles may lead to almost complete neutralisation of the negative effect of airborne particles on global warming (Preining, 1993). Whilst much remains to be done to complete our comprehension of climatic change phenomena, it may be that diesel emissions have a greater net positive effect upon global warming than emissions from an equivalent fleet of petrol vehicles.

4.6 SULPHUR COMPOUNDS

Crude oil naturally contains a proportion of sulphur compounds. Because they are concentrated in the heavier parts of the crude, there are more in the diesel than in the petrol fraction, and it is only the sulphur in diesel that is generally recognised as a problem. However, Eggleston (1992) estimated that the amounts of sulphur dioxide (SO_2) emitted by motor cars (mainly petrol) and HGVs (diesel) were similar, the larger amount of petrol used off-setting its lower sulphur content. The amount of sulphur in diesel varies somewhat and is determined by the type of crude oil from which the fuel is refined and the extent to which it is treated to remove sulphur. The maximum permissible amount of sulphur in diesel is currently set at 0.3% (by weight) (British Standards Institution, 1988). This will be reduced to 0.05% in 1996, following the implementation of a new European Community Directive (see Annex A).

When diesel fuel is burnt, most of the sulphur in the fuel is converted to SO_2. A smaller amount (typically 2%) (RCEP, 1991) is oxidised further to sulphur trioxide which combines with water and other compounds in the exhaust forming sulphuric acid and sulphates which contribute to total particulate emissions (see Figure 4.1).

Nationally, road transport is only a minor contributor to the emission of sulphur compounds and the pressure to reduce the amount of sulphur in diesel fuel stems more from the need to control particulate emissions than from concern over the emission of SO_2. As particulate emission limits are made increasingly demanding, engine manufacturers may need to use exhaust after-treatment systems in order to satisfy them. One effective technique to reduce both particulate and volatile hydrocarbon emissions is to use an oxidation catalyst. When these are used, however, they also promote the oxidation of sulphur dioxide to sulphur trioxide, thus increasing the proportion of sulphur that is emitted in particulate form. With fuel sulphur at the current level, total particulate emissions can actually increase as much as three fold when a catalyst is used, in spite of a large reduction in the hydrocarbon fraction.

It was pointed out in the First Report of the Quality of Urban Air Review Group (QUARG, 1993) that it can be misleading to apply national statistics to the evaluation of urban air pollution problems. This is particularly true for SO_2 since the main emission is from electricity generation and therefore takes place largely outside urban areas. In cities, much of the pollution is produced by smaller, local sources including road traffic.

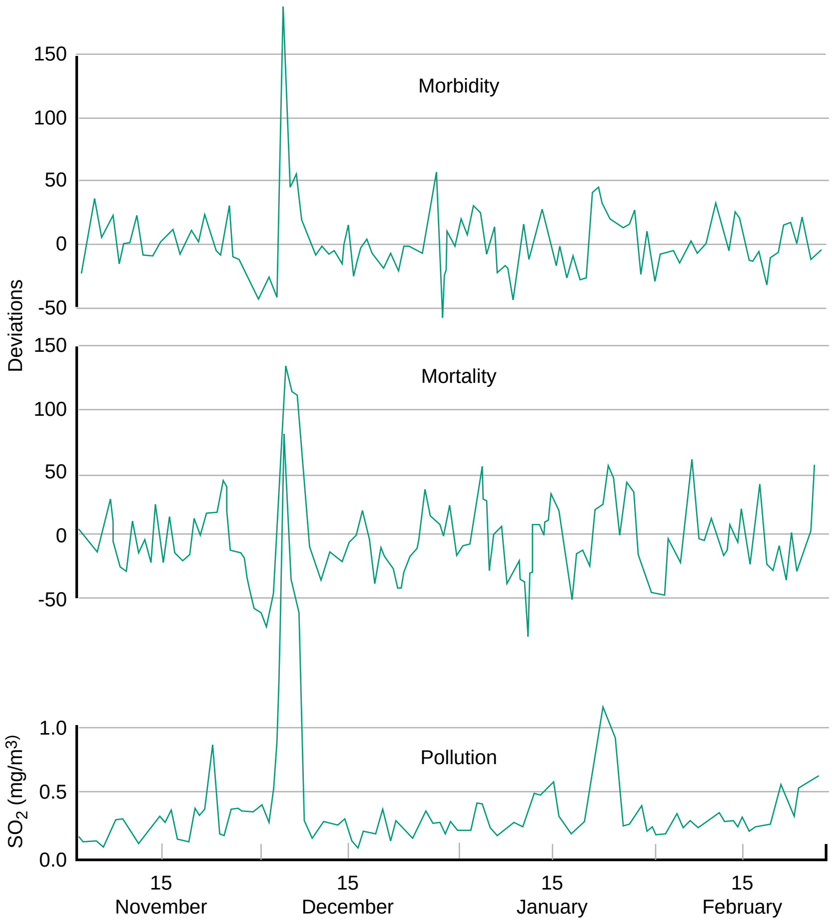
The effects of sulphur compounds on human health were recently reviewed by the Department of Health's Advisory Group on the Medical Aspects of Air Pollution Episodes (1992). They concluded that exposure to sulphur dioxide at concentrations in excess of 400 ppb could cause broncho-constriction in asthmatics. The response to exposure is rapid, peaking after about 5 minutes, and reversible, with recovery after 15-30 minutes.

The Advisory Group also examined epidemiological evidence to determine whether, and at what levels, exposure to SO_2 and related pollutants caused acute or chronic health effects in human populations. They concluded that acute effects were demonstrated with some certainty, but that chronic effects, if any, were small, and their significance in the longer term not known. Perhaps the most graphic example they give of the link between SO_2 and human health is reproduced in Figure 4.6, which shows a marked correlation between the SO_2 concentration in London and the variation in the numbers of deaths and emergency hospital admissions during the winter of 1962-63. The pollution recorded at that time was mainly from coal burning, not traffic, and levels have reduced substantially since then. The data are therefore shown as a clear example of the effects of SO_2 in the past, and do not relate to present day conditions.

The European Community (1980) has established air quality standards for SO_2 in conjunction with those for suspended particulates. They are given in Table 4.3.

SO_2 is one of the principal pollutants associated with the problem of acid deposition. The gas is deposited directly on vegetation and soil, where it is oxidised to sulphuric acid. In the atmosphere, SO_2 is oxidised to sulphuric acid, which is generally present as an acid aerosol, often associated with other pollutants in droplets or in solid particles. These aerosols are

Figure 4.6 Daily Average Suphur Dioxide Concentrations and Variations in the Numbers of Deaths and Emergency Hospital Admissions in London, Winter 1962-1963.



Source: Advisory Group on the Medical Aspects of Air Pollution Episodes (1992).

incorporated into clouds to form 'acid rain'. (RGAR, 1990).

The damage attributed to acidity in the environment includes effects on vegetation, aquatic life and structural materials. The Terrestrial Effects Review Group (TERG, 1988) reported that amenity grasslands in urban areas with mean SO_2 concentrations of 15-25 ppb and with higher concentrations for short periods, could suffer adverse effects without taking into account the presence of other pollutants. So far as damage to vegetation is concerned, attention has been given primarily to the effects on trees. It is not possible, however, to isolate specific causes of damage. Following an extensive survey in Britain, Innes and Boswell (1988) concluded that there were statistical associations between forest health indices and factors including climatic conditions and levels of pollution, but that inter-correlations between variables made their interpretation very difficult. They further stated that the correlations suggested that the deposition of some atmospheric pollutants was having a fertilising effect on trees and improving the density of their crowns. There is evidence from field observations and controlled experiments that growth of some tree species (Scots pine, poplar) may be decreased in or near urban areas. These effects may be attributed to SO_2, NO_2 and periodic episodes of ozone (TERG, 1993). The evidence for an adverse impact on aquatic systems seems clearer, with the loss or depletion of freshwater fish stocks reported in many parts of Europe, including Scotland and Wales, as a result of the increasing acidity of lakes and rivers.

Exposed construction materials degrade by natural weathering processes, but the rate of degradation can be increased by dry and wet deposition of acid pollutants. Materials such as stone, metals and paints are well known to be susceptible in this way. The quantitative interaction between pollution levels and new building materials has been investigated on site and in the laboratory. It is clear from studies on a comprehensive range of exposure sites (Butlin et al, 1992a, Butlin et al, 1992b) that the main source of damage to stone and metals is the dry deposition of sulphur dioxide, the dose-response functions being of a form;

$$\text{rate (of decay)} = a + b\,(SO_2) + c\,(\text{rainfall}) + d\,(H^+)$$

The relative contributions of dry SO_2, H^+ and rainfall (which will dissolve calcareous stone in the absence of pollution) depend on the area in which the material is exposed. The contribution of the acidity term to the total decay rate is rarely more than 5% whereas for dry deposition of sulphur dioxide the range is 5-60% and for dissolution in rainfall (of stone) 40-90%.

The rate of decay of old stone is less clear as exemplified by studies on St Paul's Cathedral (Trudgill et al, 1990) when a six-fold reduction in SO_2 (300 $\mu g/m^3$ to 50 $\mu g/m^3$) from the 1950s to the 1980s does not appear to have been reflected in a reduced rate of decay for Portland stone on a balustrade. Historical exposure to very high levels of pollution in the past may have had some effect.

4.7 SUBJECTIVE EFFECTS OF TRAFFIC

Much of the preceding discussion has focussed on the physical effects of traffic pollution on human health and on the natural and man-made environment. One further aspect that is of particular relevance in the consideration of pollution from diesel vehicles is the nuisance that it causes. Even if exposure levels are such that risks to health are insignificant, many people find the smell and smoke from traffic highly offensive and annoying.

Information about public attitudes and opinions to traffic nuisance is usually obtained through survey data via questionnaires and personal interviews, although at present, there is only a limited data base available. Two organisations who have performed major studies of traffic disturbance in the UK are the Transport Research Laboratory (TRL) and Social and Community Planning Research (SCPR). In Europe, since 1983, the Royal Norwegian Council for Scientific and Industrial Research (NTNF) has been running a programme of research on traffic and the environment which has studied a broad range of issues including traffic nuisance. Work of this kind has shown the major disturbances to the public from road vehicles to be (not in any order of priority):

- *pedestrian danger*
- *visual intrusion*
- *severance*
- *noise*
- *vibration*
- *dust and dirt*
- *fumes*
- *smoke & odour*
- *visibility reduction*
- *soiling*
- *physical irritation*

The following paragraphs will review attitude and opinion survey data on the last five of these features (ie those depending on air pollution levels). The role of pollution produced by road vehicles, and especially diesel vehicles will be emphasised, although clearly many sources in an urban environment will contribute to the overall nuisance.

4.8 NUISANCE FROM DUST AND DIRT

Airborne dust arises from a variety of sources and is always present to some degree. Vehicle derived dust and dirt includes exhaust particulates (mainly from diesel vehicles), dust resuspended by the movement of vehicles, particulates created by the wear of vehicle components (tyres, brakes, clutch linings etc) and the road pavement, and salt and sand used for winter road maintenance. In questionnaire surveys it is difficult to distinguish between different types and sources of dust and dirt, so results give respondents' views regarding the cause of a problem, which may not always correspond with physical and scientific facts.

A number of surveys have been conducted which provide some data on the degree of public annoyance arising from vehicle generated dust and dirt. SCPR conducted an extensive national survey in England in 1972 showing that "many people believe that traffic is responsible for much of the dust and dirt that settles on the window ledges, curtains or bookshelves in their homes" (Morton-Williams et al, 1978). The survey also suggested that there was a relationship between public disturbance from vehicle-derived dust and dirt and increases in vehicle flow. The amount of disturbance becomes slightly more marked for peak hour traffic flows in excess of 200 vehicles/hour (an extremely modest flow for UK roads). Research by TRL also supported the relationship between traffic density and disturbance from dust and dirt, and further suggested that there may be a link between the number of lorries and this type of nuisance (Mackie and Davies, 1981). Similarly, a study in Norway by NTNF showed a relationship between dust and dirt nuisance and traffic flow (Clench-Aas et al, 1991).

A recent TRL study at two locations in London indicated a high level of indoor and outdoor disturbance to the public from dust and dirt (McCrae and Williams, 1992). At Ealing, road traffic was blamed by 36% of householders for the dust and dirt on furniture and indoor walls, and by 50% for dust and dirt on curtains and window sills. About 25% of householders were concerned that outdoor dust and dirt would damage their health, and 30-50% of respondents thought that road traffic was the primary cause of outdoor dust and dirt. This study further suggested that dust may cause a tactile nuisance to people if it is felt on the skin, hair or mouth, and can contribute to irritation of the eyes and throat.

4.9 NUISANCE FROM SMOKE, FUMES AND ODOUR

Although in strict scientific terms, smoke, fumes and odour may be different and distinguishable, it is often found difficult to isolate their effects in questionnaire surveys. For example, though respondents may use the word 'fumes' when asked what bothers them about road traffic, the real cause of their displeasure could be malodour.

SCPR found in their national survey of England in 1971-72 that more than 90% of their sample were not bothered at all by traffic fumes in their homes. On the other hand, more than half the sample noticed traffic fumes when they were outdoors, and almost a quarter were bothered 'very much' or 'quite a lot' (Morton-Williams et al, 1978). They also noted an increase in the amount of disturbance as traffic flow increased.

More recent studies have indicated the public's disturbance by smoke, fumes and odour to be far greater. McCrae and Williams (1992) reported that more than half of their household respondents were bothered at least occasionally by indoor smoke, fumes and odour from traffic while most respondents were 'moderately' or 'very' bothered about outdoor levels. Half the respondents felt that the fumes would damage their health. Studies by the Department of the Environment (1986 & 1989) also indicated that the public perceive fumes from traffic to be a nuisance and that they consider them to be a health hazard. This apparent increase in concern may be attributable partly to the large increase in traffic flows since the early 1970s and partly to the general increase in peoples' awareness of the environmental impacts of road traffic.

NTNF attempted to link nuisance and pollutant concentrations by comparing reported 'annoyance' with estimated carbon monoxide indices for individual respondents' homes (Clench-Aas et al, 1991). The results indicated that annoyance increased as carbon monoxide levels increased, indirectly supporting the trends with traffic flows observed in earlier studies.

It has been stated that odours from diesel exhaust are a public nuisance. Diesel vehicles are generally regarded as more odorous than petrol-engined vehicles, though exhaust odours are difficult to quantify in an urban atmosphere as odourants are poorly characterised, rapidly dispersed in the air and are present in very low concentrations. However, responses to odours are likely to be to specific events that are very localised and short-lived, rather than to average concentrations of odourants in the air. These may result from individual vehicles performing manoeuvres that create high transient odour levels and not to the average composition or behaviour of the traffic. On this basis, Cernansky (1983) argued that instantaneous odour levels at receptor locations may be high, and it is these that cause most offence. There is, however, very little direct evidence that vehicle derived odours are a significant public nuisance.

The public opinion surveys quoted earlier, by SCPR, TRL and NTNF identified complaints about ‘fumes’ from vehicles, but it appears that the public associate fumes with health effects rather than odour. The NTNF study suggested a correlation between the frequency of being inconvenienced by smells and estimates of atmospheric NO_2 concentrations, with 13% of their sample showing a significant positive relationship between odour nuisance and NO_2 exposure. Although NO_2 levels can give a general indication of road traffic pollution levels, it should be noted that it is not a major primary vehicle pollutant, and concentrations are less well linked to traffic activity than those of other gases.

4.10 NUISANCE FROM VISIBILITY REDUCTION

Light extinction is caused by the scattering and absorption of light by atmospheric particulate matter and gases. Diesel emissions, being the most important UK source of urban black smoke and carbon particles, are a major contributor to urban visibility reduction. It has been estimated that particulate elemental carbon is responsible for 25-45% of the visibility reduction (Hamilton and Mansfield, 1991). Limit values for emissions of visible smoke from diesel road vehicles were introduced in the early 1970s because it was felt that the public were concerned about the visibility reduction it caused. However, the social research currently available provides no evidence to support that belief. Though this does not conclusively demonstrate that the public are not bothered by traffic induced visibility reductions, it does indicate that it is not a major public concern.

4.11 NUISANCE FROM SOILING

It was shown earlier that particulate emissions from diesel vehicles are responsible for much of the soiling of buildings in urban areas. TRL’s survey (McCrae and Williams, 1992) found that 30-40% of respondents were bothered by the blackening of building walls, with 20-30% pinpointing road traffic pollution as the primary cause. These figures are in good agreement with those reported by Ball and Caswell (1983), who suggested that one third of the UK population were concerned about vehicle induced soiling of property in the early 1980s.

Improvements in the level of SO_2 and smoke experienced in our cities over the past 30 years have provided an impetus for stone cleaning. Buildings were not cleaned in earlier times when smoke levels were greater than they are now, because property owners felt re-soiling would occur too quickly and that they would be wasting their money. For example, it was reported in 1955 that buildings in Pall Mall were painted cream in colour and that even before the paint was dry the surfaces had collected numerous black specks and that within two years such buildings had lost their 'exterior freshness' and were distinctly soiled. However, there is every reason to believe that as time progresses, the trend towards cleaner buildings will continue. Research undertaken from 1987 to 1991 indicates that stone cleaning may have benefits to property owners other than purely aesthetic ones and that the public will continue to remain intolerant of soiled buildings. However, if re-soiling occurs more quickly in the future, it may lead to a decline in the amount of stone cleaning undertaken. The stone cleaning industry currently recommends buildings in cities are cleaned once every 8 years.

There have been several estimates of the annual cost of cleaning buildings. In 1972, Jones et al estimated the size of the market in Britain to be about £1.5 million. In 1990/91 a survey estimated that the UK stone cleaning industry had a value of £79 million compared to a value of £110 million in 1987. The current recession was mentioned as a factor contributing to this decrease (Mansfield, 1992). The total cost is influenced by the price per square metre and by the cleaning frequency, with the latter reflecting public attitudes and company policy.

4.12 NUISANCE FROM PHYSICAL IRRITATION

Physical irritation includes effects such as coughing, sneezing, blinking and sore or runny eyes, nose and throat etc. Compounds that have been identified as potential irritants in urban situations include ozone, ethylene oxide, biphenyl and a number of aldehydes and ketones, although studies of irritation caused by air pollutants are rare. American studies in the 1950s and 1960s suggested a general increase of eye irritation with increasing levels of oxidant (though the oxidant measurement techniques available at the time were of low accuracy).

In TRL's recent opinion surveys (McCrae and Williams, 1992), respondents were asked to say whether they were bothered by particular health and nuisance effects. Less than 10% felt that road traffic was to blame for a range of effects indoors, including sore and runny eyes, sneezing, an irritated throat, an unpleasant taste in the mouth, headaches and difficulty in breathing. Outdoors, the level of concern was greater, with 20-30% of respondents blaming vehicle derived pollution for these effects.

4.13 KEY POINTS

- *Vehicular emissions of carbon monoxide are of concern primarily in relation to human health impacts.*

- *Vehicles emit a very wide range of hydrocarbons and other organic compounds. These compounds are of concern due to the direct toxicity of some species, their role in atmospheric photochemistry and impact upon global warming.*

- *Motor vehicles are the major source of urban emissions of oxides of nitrogen. As well as adverse health effects of nitrogen dioxide, the oxides of nitrogen are implicated in a number of environmental problems, including photochemical smog, acid deposition and damage to vegetation.*

- *Diesel engines emit larger quantities of particulate matter than arise from petrol. These are of concern due to their possible carcinogenicity and probable impact upon global warming. Concentrations of fine particulate matter (PM_{10}), to which vehicle-emitted particles contribute substantially, correlate with human mortality and respiratory morbidity, apparently without a no-effect threshold.*

- *Sulphur oxides are important air pollutants due to their impact upon human health, especially in asthmatics, as well as making a contribution to acid deposition and decay of building materials.*

- *Road traffic is widely perceived by the public as causing nuisance. This is connected with dust deposition and soiling, odours, noise and vibration as well as other problems.*

REFERENCES

Advisory Group on the Medical Aspects of Air Pollution Episodes (1992) Second Report: **Sulphur Dioxide, Acid Aerosols and Particulates.** HMSO, London.

Ball D, Brimblecombe J P and Nicholas F M (1991) **Review of Air Quality Criteria for the Assessment of Near-Field Impacts of Road Transport.** TRRL Report CR 240, Transport and Road Research Laboratory, Crowthorne.

Ball D J and Caswell R (1983) **Smoke from Diesel Engined Road Vehicles - an Investigation into the Basis of British and European Emission Standards.** Atmos. Environ., **17**, 169-181.

Bates D V (1992) **Health Indices of the Adverse Effects of Air Pollution: the Question of Coherence.** Environ. Res., **59**, 336 - 349.

Bower J S, Broughton G F J, Dando M T, Lees A J, Stevenson K J, Lampert J E, Sweeney B P, Parker V J, Driver G S, Waddon C J, Wood A J (1989) **Monitoring for the European Community Nitrogen Dioxide Directive in the UK: a Review of Data for 1987.** WSL Report LR 734, Warren Spring Laboratory, Stevenage.

British Standards Institution (1988) **British Standard 2869: Part 1. Fuel Oils for Non-Marine Use - Specification for Automotive Diesel Fuel (Class A1).** British Standards Institution, London.

Buckley-Golder DH (1984) **Acidity in the Environment**. Energy Technology Support Unit, Harwell.

Butlin R N, Coote A T, Devenish M, Hughes I S C, Hutchens C M, Irwin J G, Lioyd G O, Massey S W, Webb A H and Yates T J S (1992a) **Preliminary Results from the Analysis of Stone Tablets from the National Materials Exposure Programme**. Atmos. Environ., **26B**, 189-198.

Butlin R N, Coote A T, Devenish M, Hughes I S C, Hutchens C M, Irwin J G, Lioyd G O, Massey S W, Webb A H and Yates T J S (1992b) **Preliminary Results from the Analysis of Metal Samples from the National Exposure Programme**. Atmos. Environ., **26B**, 199-206.

Cernansky N P (1983) **Diesel Exhaust Odour and Irritants: a Review.** J. Air Poll. Control Assoc., **33**, 97-104.

Clench-Aas J, Larssen S, Bartonova A, Aarnes M J, Myhre K, Christensen C C, Neslein I L, ThomassenV J and Levy F (1991) **The Health Effects of Traffic Pollution as Measured in the Vålerenga area of Oslo**. Norwegian Institute for Air Research, Lillestrøm.

Department of the Environment (1986) **Digest of Environmental Protection and Water Statistics**, **9**, HMSO, London

Department of the Environment (1989) **Digest of Environmental Protection and Water Statistics**, **12**, HMSO, London

DHSS (1987) **Diesel Engine Emissions-Health Aspects**, in, Particulate Emissions from Diesel Engined Cars-with Evidence, the House of Lords Select Committee on the European Communities. House of Lords Paper No.32, Session 1987-1988, 7th Report, HMSO, London

European Community (1980) **EC Directive 80/779/EEC**, Official Journal of the European Communities, L229, 30.

European Community (1985) **EC Directive 85/203/EEC**, Official Journal of the European Communities, L87, 1.

Eggleston H S (1992) **Pollution in the Atmosphere: Future Emissions from the UK.** Report LR 888 (AP), Warren Spring Laboratory, Stevenage.

Graedel T E, Hawkins D T and Claxon L D (1986) **Atmospheric Chemical Compounds.** Academic Press, Orlando.

Hamilton R S and Mansfield T A (1991) **Airborne Particulate Carbon: its Sources, Transport and Contribution to Dark Smoke and Soiling.** Atmos. Environ., **23**, 1591-1599.

Hampton C V, Pierson W R, Harvey T M, Updegrove W S and Marano R S (1982) **Hydrocarbon Gases Emitted from Vehicles on the Road. 1. A Qualitative Gas Chromatography/Mass Spectrometry Survey.** Environ. Sci. Technol., **16**, 287 - 298.

Hasselblad V, Eddy D M and Kotchmar D J (1992) **Synthesis of Environmental Evidence: Nitrogen Dioxide Epidemiology Studies.** J Air Waste Manag. Assoc., **42**, 662-671.

Hickman A J (1989) **Personal Exposures to Carbon Monoxide and Oxides of Nitrogen.** TRRL Report RR206, Transport Research Laboratory, Crowthorne.

INDITE (1993) **Impact of Nitrogen Deposition in Terrestrial Ecosystems**, First Report, HMSO, London.

Innes J L and Boswell R C (1988) **Forest Health Surveys 1987. Part 2. Analysis and Interpretation.** Forestry Commission Bulletin 79, HMSO, London.

IPCC (1990) **Climate Change. The IPCC Scientific Assessment.** Cambridge University Press, Cambridge.

IPCC (1992) **Climate change 1992: the Supplementary Report to the IPCC Scientific Assessment.** Cambridge University Press, Cambridge.

Jones P M S, Taylor K, Store D J and Clifton M (1972) **A Technical and Economic Appraisal of Air Pollution in the UK**, Programme Analysis Unit Report, M20, HMSO, London.

Klassen C O, Amdour M O and Doull J (Eds.) (1986) **Casarett and Doull's Toxicology,** Macmillan, London.

Mackie A M and Davies C H (1981) **Environmental Effects of Traffic Change**. TRRL Report LR 1015, Transport Research Laboratory, Crowthorne.

Mansfield T (1992) **Sources of Building Soiling and a Review of the Stone Cleaning Industry 1991**, International Conference on Stone Cleaning, Edinburgh.

McCrae I S and Williams I D (1992**) Road Traffic Pollution and Public Nuisance**. Proceedings of the Fourth International Highway Pollution Symposium, Paper No. III.B.3, Madrid.

Morton-Williams J, Hedges B and Fernando E (1978) **Road Traffic and the Environment**, Social and Community Planning Research, London.

Nikula K J, Snipes M B, Griffith W C, Henderson R F and Mauderly J L (1993) **Influence of Soot-Associated Organic Compounds on Pulmonary Carcinogenicity of Diesel Exhaust in Rats. Toxic and Carcinogenic Effects of Solid Particles in the Respiratory Tract,** 4th International Inhalation Symposium, Hannover.

Photochemical Oxidants Review Group (1987) **Ozone in the United Kingdom**. AEA Technology, Harwell.

Photochemical Oxidants Review Group (1990) **Oxides of Nitrogen in the United Kingdom.** AEA Technology, Harwell..

Pope C A III, Schwartz J and Ransom M R (1992) **Daily Mortality and PM_{10} Pollution in Utah Valley**, Arch. Environ. Health, **47**, 211-217.

Preining O (1993) **Global Climate Change Due to Aerosols**, in 'Global Atmospheric Chemical Change', C N Hewitt and W T Sturges (Eds), Elsevier Applied Science, London, pp 93-122.

Quality of Urban Air Review Group (1993) **Urban Air Quality in the United Kingdom**. QUARG, London.

Review Group on Acid Rain (1990) **Acid Deposition in the United Kingdom 1986-1988**. HMSO, London.

Royal Commission on Environmental Pollution (1991) **Fifteenth Report: Emissions from Heavy Duty Diesel Vehicles.** HMSO, London.

Siegl W O, McCabe R W, Chun W, Kaiser E W, Perry J, Henig Y I, Trinker F H and Anderson R W (1992) **Speciated Hydrocarbon Emissions from the Combustion of Single Component Fuels. 1. Effects of Fuel Structure.** J. Air Waste Manage. Assoc., **42**, 912 - 920.

TERG (UK) (1988) **The Effects of Acid Deposition on the Terrestrial Environment in the United Kingdom**, HMSO, London.

TERG (UK) (1993) **Air Pollution and Tree Health in the UK.** HMSO, London.

Tonkin P R and Etheridge P (1987) **A New Study of the Feasibility and Possible Impact of Reducing Emission Levels from Diesel Engined Vehicles**. Report No DP 87/0927, Ricardo Consulting Engineers, Shoreham-by-Sea.

Trudgill S T, Viles H A, Cooke R U and Inkpen R J (1990) **Rates of Stone Loss at St Paul's Cathedral, London.** Atmos Environ, **24B**, 361 - 363.

Van den Hout K D and Rijkeboer R C (1986) TNO Road Transport Research Institute, Delft.

World Health Organization (1977) **Environmental Health Criteria 4: Oxides of Nitrogen.** WHO, Geneva.

World Health Organization (1987) **Air Quality Guidelines for Europe**. European Series No 23, WHO Regional Publications, Copenhagen.

5 Diesel Contribution to Emissions and Air Quality

5.1 ESTIMATING EMISSIONS FROM MOTOR VEHICLES

Earlier chapters have discussed the range of pollutants emitted from motor vehicles and how these emissions vary with vehicle type, engine load, speed and other factors. Hence, in order to estimate emissions on a national or regional scale, performance-related emission factors must be used. These have been studied in the United Kingdom (Eggleston, 1987) and in Europe as part of the EC CORINAIR programme (Eggleston et al, 1989 & 1992).

Emission estimates, however, contain a number of implicit assumptions as the methodology is currently limited by both the experimental results and the statistical data available. For example, the influence of load on emissions from heavy goods vehicles is not explicitly included as there are insufficient measurements to quantify this effect. The methodologies also assume that the vehicles are not grossly abused.

The methodology is most advanced for motor cars. Curves relating emissions to average trip speed have been constructed from emission measurement programmes. In the most recent of these, emissions from 200 current cars have been measured using a dynamometer and 50 of these have also undergone on-the-road test procedures (TRL, 1993). This latter study measured emissions of nitrogen oxides (NO_X), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs) and, in the case of diesel cars, particles as the vehicles were driven along real roads. There are a number of standard drives covering a range of driving conditions. These are, together with their average speeds:

Urban (20 kph)

Suburban (40 kph)

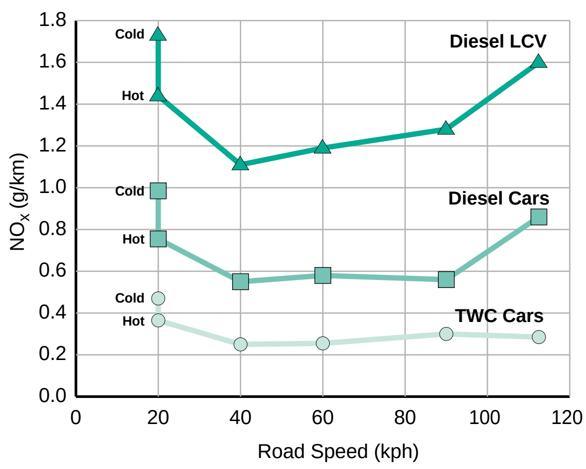
Rural (60 kph)

Motorway (90 kph)

Motorway (113 kph)

The results are then used to produce curves of emissions against speed which are used in compiling national emission estimates. An example, showing average emissions of NO_X from three diesel cars and four diesel vans, together with the corresponding data for three catalyst-equipped cars, is given in Figure 5.1. Such speed-emission curves vary according to the vehicle technology. This is classified according to the regulations with which the vehicle was designed to comply; hence emissions have to be calculated separately for vehicles built to each regulation. In the case of diesel cars there are insufficient measurements to characterise on-the-road emissions adequately over the range of engine technologies and, hence, emissions calculations are less accurate than for their petrol-engined counterparts. In order to allow the proportion of vehicles with differing technologies to change over time, a model which estimates fleet composition is used. This incorporates sales and scrapping data, fleet age distribution and the distances travelled by cars as a function of age.

Figure 5.1 Nitrogen Oxides Emissions - Effect of Capacity and Technology.



Diesel Cars: average of 3 vehicles, 1.4-2.0 litres.
Diesel Light Commercial Vehicles (LCV): average of 4 vehicles, >2.0 litres.
TWC Cars: average of 3 vehicles, 1.4-2.0 litres.
Cold and hot start results are shown at 20 kph.

The UK vehicle-speed distribution has been compiled from a number of sources. Originally (Eggleston, 1987) the distribution was based on four Gaussian distributions for urban, rural single-carriageway, rural dual-carriageway and motorway roads. Data from TRL provided the mean speed and standard deviation for each of these, while Department of Transport vehicle kilometre statistics allowed the overall distribution to be estimated. These estimates have now been improved in two ways. Speed distribution data have been measured for many roads in London and these have been incorporated into the urban distribution. Similarly, preliminary data from automatic speed measurements on some motorways and major roads have also been included in the appropriate part of the distribution.

Data for the vehicle-speed distribution for the UK as a whole are then combined with the appropriate point on the emission-speed curve, at 5 kph increments, to estimate emissions from all cars driven with that average speed. The emissions from vehicles at all speeds can then be summed to give total emissions.

There are two additional factors to be considered. These are 'cold start' emissions and evaporative losses (Eggleston, 1992). In the case of diesels these are believed to be small compared to the situation with petrol-engined vehicles, but as yet there are inadequate data to allow their incorporation into inventories.

While emissions are actually calculated from speed distributions it is possible to work backwards to average emission factors for each road type and vehicle type. These have been published (Gillham et al, 1992) and are based on a wider, but in some instances earlier, data base than the examples given in Chapter 3.

The emissions from other forms of road transport, most of which are predominantly diesel (eg heavy goods vehicles and buses), are not so well known and so single emission factors for each road type are used. These are applied to the number of vehicle kilometres driven in each year by a type of vehicle on a single road type. The CORINAIR study (Eggleston et al, 1992) lists the reliability of emission factors for all forms of road transport. The HGV factors are based on limited measurements at Warren Spring Laboratory and some German results. As there are insufficient measurement data to include the effect of load on HGV emissions explicitly, the factors are based on results for half-laden vehicles.

5.2 UNCERTAINTIES IN EMISSION ESTI MATES

Each year revised statistics for past years become available and these, together with improved measurements of emission factors, are applied retrospectively to earlier estimates. The effects of this procedure are illustrated in Figure 5.2 which shows how estimates of total and vehicular NO_X emissions for 1980 have varied over the succeeding 12 years. For the first five years the estimates were unchanged, but then further measurements of emission factors resulted in increased estimates. Similarly, in 1991

Figure 5.2 Historical Development of UK NO_x Emission Estimates for 1980.

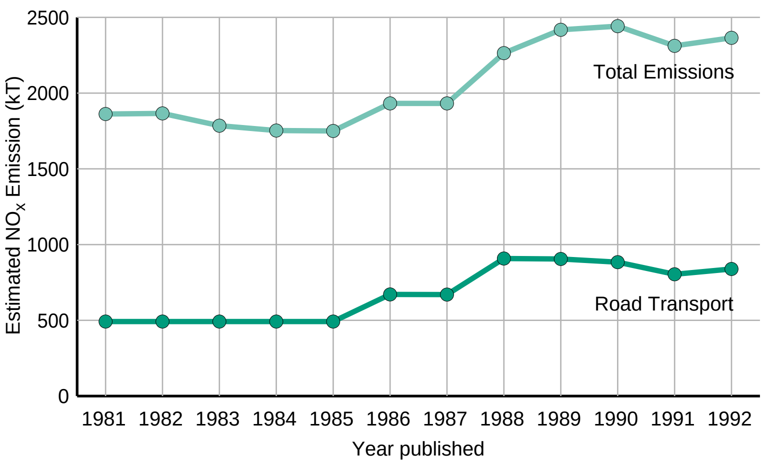
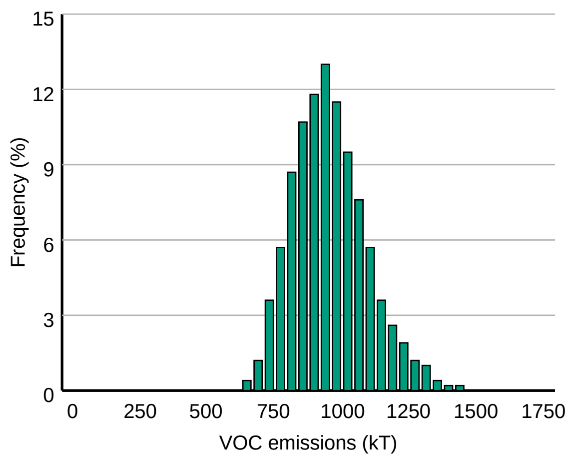


Figure 5.3 Results of Monte Carlo Simulation of Non-Methane VOC Emissions from Petrol-Engined Motor Cars.



Note: All sources of uncertainty in the input data are included in these models.

changes in emission factors led to a small decrease in the emission estimate, whereas incorporation of improved data on cold start emissions increased the estimate in 1992.

As described in Chapter 3, emission measurements can have a wide scatter and a statistical approach has been used to investigate the precision of emission estimates of non-methane VOCs from vehicles (Eggleston, 1993). All the inputs, including emission factors, speeds, traffic flows and fleet composition were allowed to vary according to predefined distributions. Figure 5.3 shows the resulting frequency distribution which indicates that VOC emissions from road traffic in the UK are likely to be uncertain by at least ±27% (2 standard deviations). This is a probability distribution of the true emission based on the input uncertainties, but may underestimate the range of the actual emission value as the errors introduced by the methodology itself have not been assessed. The probability curve contains both variation that changes from year to year and some that arises from a constant systematic error. For example, any bias in the speed distribution data due to atypical measuring sites is likely to be constant, or at least to change only slowly from year to year. Thus trends in emissions are likely to be more accurately represented than annual values.

5.3 TRACERS FOR DIESEL EMISSIONS

Although the accuracy of estimated emissions and emission factors are difficult to assess directly, they may be addressed by the use of tracers as indicators of the source of a particular pollutant. Tracers are chemical compounds which are uniquely identifiable with a specific source of pollution. A good example of this technique is provided by the use of lead as a tracer for emissions from petrol-engined vehicles.

A direct apportionment of diesel emissions can be made by adding a suitable tracer to diesel fuel. Such a tracer needs to be easily detectable, unique to diesel emissions and relatively uncommon in the urban atmosphere. In addition, the majority of the diesel vehicles in the vicinity of the sampling location must use fuel marked with the tracer. Such a study was carried out in Vienna in 1984 (Horvath et al, 1988) using an organo-metallic compound, tris-dipivalyl-methanato-dysprosium.

The tracer was added to refinery diesel in June and July 1984. The study was feasible because all the diesel fuel used in Vienna and its immediate surroundings was supplied by a single refinery. No significant interferences from vehicles using unmarked fuel occurred as vehicles from outside the area were rare. Diesels accounted for about 7-8% of vehicles registered in Vienna in 1982, which is similar to the diesel car and light van population of, for example Leeds (about 8%), but lower than London (about 11%).

Analysis of ambient particulate samples from Vienna showed that the mass concentrations of diesel particles in the atmosphere varied between 5 and 23 $\mu g/m^3$ and that diesel particles settling to the ground formed 1-7% of dust collected from the road surface.

The data also indicated a positive correlation between diesel vehicle density and the sampled mass concentrations of diesel particles. In Vienna, a background diesel particle concentration of 11 $\mu g/m^3$ was found, which was found to increase by 5.5 $\mu g/m^3$

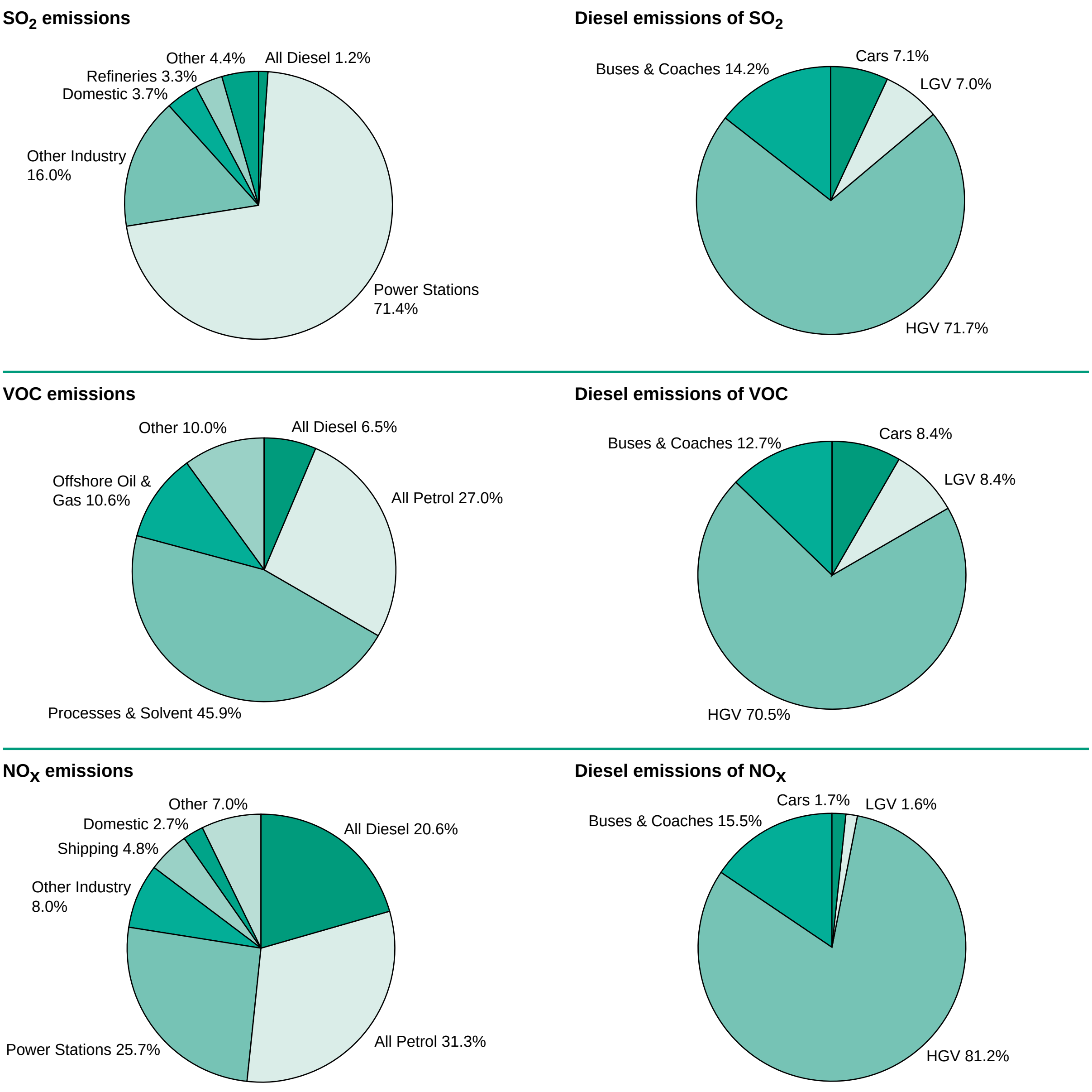
Figure 5.4 UK National Air Pollutant Emissions 1991.

per 500 diesel vehicles per hour passing near a sampling location.

The mass concentrations of diesel particles in busy streets was expected to be higher than in calm residential areas, but the difference was not as marked as anticipated. The mass fraction of diesel particles in the total aerosol mass varied between 12-33%, with the higher values being found in more remote areas, suggesting that diesel particles spread easily once emitted into the atmosphere.

Data collected in central London at an urban background site and a nearby roadside site indicate concentrations of suspended particulate matter 2-3 fold higher at the roadside site (London Scientific Services, 1990). Over the period 1986 and 1988-9, the average background site concentration was 24 µg/m^3 and that at the roadside site was 62 µg/m^3. This is indicative of the substantial contribution made by vehicles to airborne particulate matter concentrations, although resuspended surface dusts are expected to contribute as well as exhaust emissions.

Figure 5.4 UK National Air Pollutant Emissions 1991 (continued).



Diesel vehicle fuel in the UK typically contains 5 to 10 times more sulphur than petrol. Most of this sulphur is emitted (via the exhaust) into the atmosphere as sulphur dioxide (SO_2). Sulphur dioxide is therefore a potential tracer for diesel vehicles, although this is only true close to roads, as traffic is only a minor contributor to total emissions (2% nationally and 22% in London). Measurements made at County Hall in central London have shown that traffic accounts for an average of 44% of roadside SO_2 concentrations alongside a busy street (London Scientific Services, 1990). Recent research (Chen, 1992) has indicated that diesel fuel accounts for less than 20% of roadside SO_2 in Leeds.

5.4 CURRENT NATIONAL EMISSIONS

The contributions of different source sectors to total UK emissions of a number of pollutants are given in Table 5.1 and illustrated in Figure 5.4 where the contribution from diesel vehicles is further sub-divided by vehicle type. As discussed in Chapter 3 diesel vehicles are much more significant sources of some pollutants than others, notably NO_X and black

Table 5.1 Source Contributions to Total UK Emissions, 1991 (%).

		NO_X	CO	VOC	CO_2	SO_2	PM_{10}	Black Smoke
Road Vehicles								
Cars	**petrol**	29	80	22	12	<1	9	3
	diesel	<1	<1	1	<1	<1	1	3
	total	29	81	22	12	1	10	6
LGV	**petrol**	2	6	2	1	<1	1	<1
	diesel	<1	<1	1	<1	<1	1	3
	total	3	6	3	1	<1	2	3
HGV	**large**	7	1	1	2	<1	5	2
	small	10	1	3	2	<1	7	16
	total	17	2	4	4	1	12	28
Buses		3	<1	1	1	<1	2	6
Motorcycles		<1	1	2	<1	<1	<1	<1
Exhaust Emissions		52	90	32	19	2	27	42
Evaporation				5				
Total Road Vehicles		***52***	***90***	***37***	***19***	***2***	***27***	***42***
Other Sources								
Domestic		3	5	2	15	4	47	36
Commercial etc		2	<1	<1	6	2	1	1
Power Stations		26	1	<1	33	71	7	5
Refineries		1	<1		3	3	<1	1
Agriculture		<1	<1		1	<1	<1	<1
Other Industry		8	4	2	21	16	18	15
Offshore Oil & Gas		2	<1	10	1			
Railways		1	<1	<1	1	<1		
Civil Aircraft		1	<1	<1	1	<1	<1	<1
Shipping		5	<1	1		2	<1	1
Processes & Solvents				44				
Gas Leakage				1				
Forests				3				

smoke where the diesel contributions are about 20% and 40% respectively. The relationships between emissions of particulate matter, smoke and black smoke are discussed in Annex B.

It is notable that the split between diesel cars and other diesel vehicles is the same for SO_2 and CO_2. This arises because emissions of these pollutants are related solely to the quantity of fuel used. In the case of NO_X, cars and light goods vehicles are responsible for a smaller fraction of emissions than fuel consumption alone would suggest, while emissions from heavy goods vehicles are proportionately more. In most cases, however, insufficient measurements are available to characterise fully the effects of different engine technologies.

5.5 TRENDS IN NATIONAL EMISSIONS

Trends in total UK emissions of NO_X and black smoke, the pollutants where the diesel contribution is greatest, are shown in Figures 5.5 and 5.6, together with the corresponding data for total vehicle emissions and emissions from diesels alone. From 1970 total emissions of NO_X remained fairly constant until the mid-1980s, a gradual increase in emissions from motor vehicles being largely offset by decreases in other source categories. Subsequently vehicle emissions increased more rapidly resulting in an increase in total emissions which have now started to level off. Hence, over the period from 1970, the proportion of total NO_X emissions arising from road transport has increased from about one quarter to just

Figure 5.5 UK NO_x Emissions 1970-1991 (as kT NO_2).

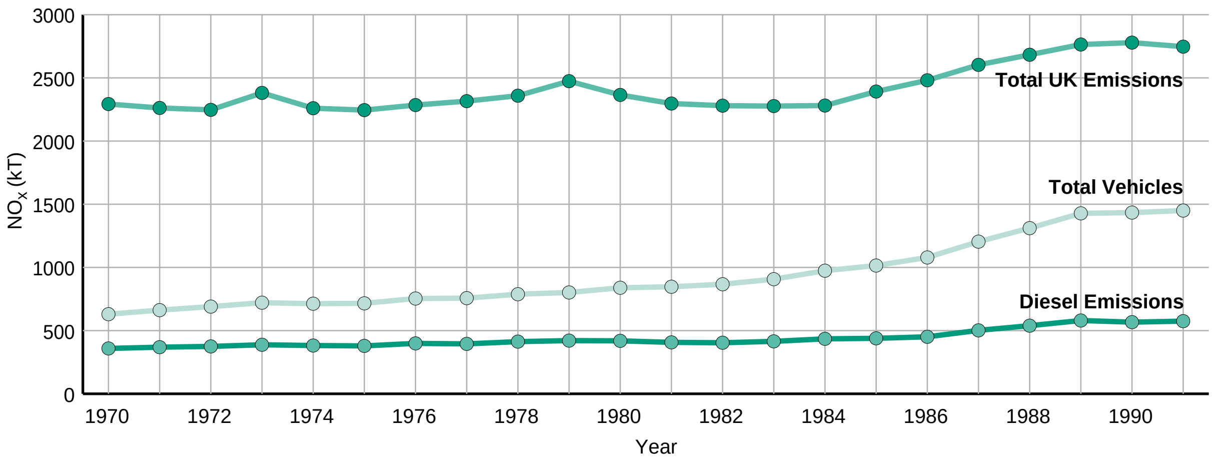
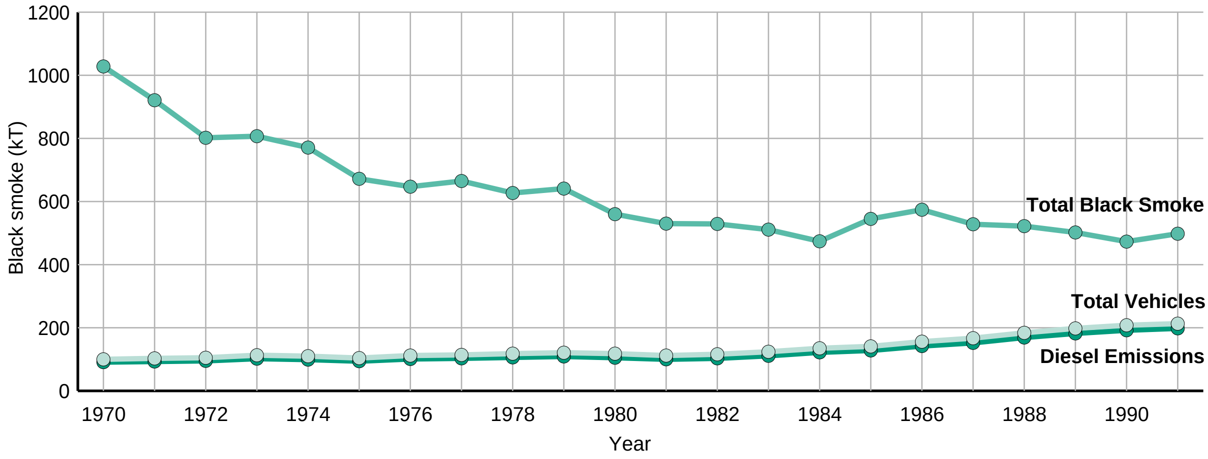


Figure 5.6 UK Black Smoke Emissions 1970-1991.



over a half. The increase in diesel emissions has been less marked, however, with the result that while the percentage of total emissions arising from diesel vehicles has increased from 16 to 21%, they now comprise only 42% of vehicle emissions compared with 60% in 1970.

In contrast, following the Clean Air Act and measures to control domestic sources, emissions of black smoke halved over the same period. Emissions from diesels account for most of the vehicular emission and have increased steadily with the result that, on a national scale, diesels now account for 39% of black smoke emissions compared with only 9% in 1970.

5.6 EMISSIONS IN LONDON

Relatively few emission inventories have been compiled for urban areas in the United Kingdom, and these have often focussed on just one or two pollutants. In London, however, a number of spatially disaggregated emission inventories have been undertaken. The most recent, carried out within the London Energy Study (London Research Centre, 1993), was for the year 1990 and included six different pollutants.

Details of the methodology and some results from this study are given below. It should be remembered, however, that results for London may not necessarily

Table 5.2 Source Contributions to Emissions from Energy Use in London (%).

		NO_X	CO	VOC	CO_2	SO_2	Black Smoke
Road Vehicles							
Taxi	**diesel**	0.4	0.1	0.7	0.5	0.7	4.3
Car	**petrol**	37.9	85.6	63.9	17.5	6.4	5.9
	diesel	0.4	0.1	0.7	0.4	0.7	4.2
	total	38.3	85.7	64.6	18.0	7.1	10.2
LGV	**petrol**	4.1	7.6	8.8	5.1	1.9	1.7
	diesel	0.5	0.2	1.0	0.6	0.9	5.7
	total	4.6	7.8	9.8	5.7	2.8	7.4
HGV	**large**	9.9	0.8	3.9	2.7	4.0	25.1
	small	14.6	1.5	8.9	3.7	5.5	34.4
	total	24.5	2.3	12.9	6.3	9.4	59.5
Bus		4.9	0.4	1.9	1.4	2.0	12.7
Motorcycle		0.1	2.0	5.7	0.2	0.1	0.1
Total diesel		31.6	3.2	17.4	9.4	14.2	86.6
Total petrol		42.1	95.2	78.4	22.8	8.4	7.7
Total road vehicles		***73.7***	***98.4***	***95.8***	***32.3***	***22.6***	***94.3***
Other Sources							
Domestic		6.2	0.2	1.2	29.5	0.7	0.1
Commercial etc		7.4	0.1	0.2	18.3	32.1	1.6
Industrial		5.0	0.1	0.6	12.6	42.4	1.0
Railways		1.9	0.1	0.3	1.9	0.7	0.1
Air		5.6	1.1	2.0	5.4	1.3	2.9
Water		0.1	0.0	0.0	0.0	0.3	0.0

Note : In the case of VOCs, non-energy sources comprise a large fraction of total emissions (compare with Table 5.1).

be representative of other urban areas in the United Kingdom. For example, the city benefits from extensive underground and suburban railway systems. As a result the commuting pattern in London is different from many other cities, with a much larger percentage of journeys being undertaken by public transport than elsewhere. In addition, dedicated diesel taxis are widely used especially in the inner city area. In other areas taxis may predominantly be petrol cars. The bus stock is also different from many other cities. There are fewer minibuses in use, although this is unlikely to be an important factor in the inventory as insufficient data are as yet available to differentiate between different types of buses.

The London inventory has a spatial resolution of 1km x 1km. Emissions from road traffic sources have been calculated using the speed-dependent emissions factors described in section 5.1. Mean speeds and total vehicle kilometres were calculated separately for the major roads (including motorways) and minor roads, for each kilometre grid square. Different methods were used to derive these numbers for the two categories of road.

For major roads, mean speeds and traffic flows on each link in the major road network were derived from a traffic activity model. For the minor roads, vehicle kilometres were calculated by allocating road lengths to each grid square. Average speeds were calculated for these road lengths using multipliers based on traffic surveys carried out in various London Boroughs.

Data on traffic composition and speed were based on surveys carried out in three concentric zones: central, inner and outer London. These numbers were multiplied by the relevant emission factor and summed to obtain total emissions for each grid square.

Table 5.3 Diesel Contribution to National and London Emissions (%).

	Black Smoke	NO_X	CO	VOC	SO_2	CO_2
National	39	21	2	6	1	6
London	87	32	3	17	14	9

The inventory also includes emissions from other forms of transport including railways, aircraft and shipping. All of these are minor sources compared to road transport but the inventory does reveal the differences between electrified and non-electrified railway lines.

The contributions of different source sectors to emissions of a number of pollutants in London are presented in Table 5.2. Differences from the national situation (summarised in Table 5.1) relating to diesels are summarised in Table 5.3.

While the diesel contribution to all pollutants is greater in the city, this particularly so for NO_X, VOCs and black smoke. Sulphur dioxide is unusual in that, nationally, power stations account for over 70% of emissions but none lie within the London inventory area. As a result the percentage contribution from diesel vehicles rises dramatically.

Within London there is considerable spatial variability in NO_X emissions from diesel vehicles as shown in Figure 5.7a. Emissions are largest in Central London and along major motorways, eg the M4 in west London can be identified. Figure 5.7b shows that, typically, diesel vehicles account for about 25-40% of total NO_X emissions. Other pollutants show broadly similar spatial patterns although there are differences arising from the differing relationships of emission factors with vehicle mix and mean speed. For example, the map of black smoke emissions, shown in Figure 5.8, has many features in common with NO_X but in this case the percentage contribution to total emissions lies in the range 85-95% over most of the city.

5.7 LONDON MODEL

Pollutant concentrations have been calculated from the London emissions inventory data using a long-period Gaussian plume dispersion model. This model has previously been used and validated in a number of urban air quality studies, eg London and Belfast (Munday et al, 1989; Adams et al, 1992).

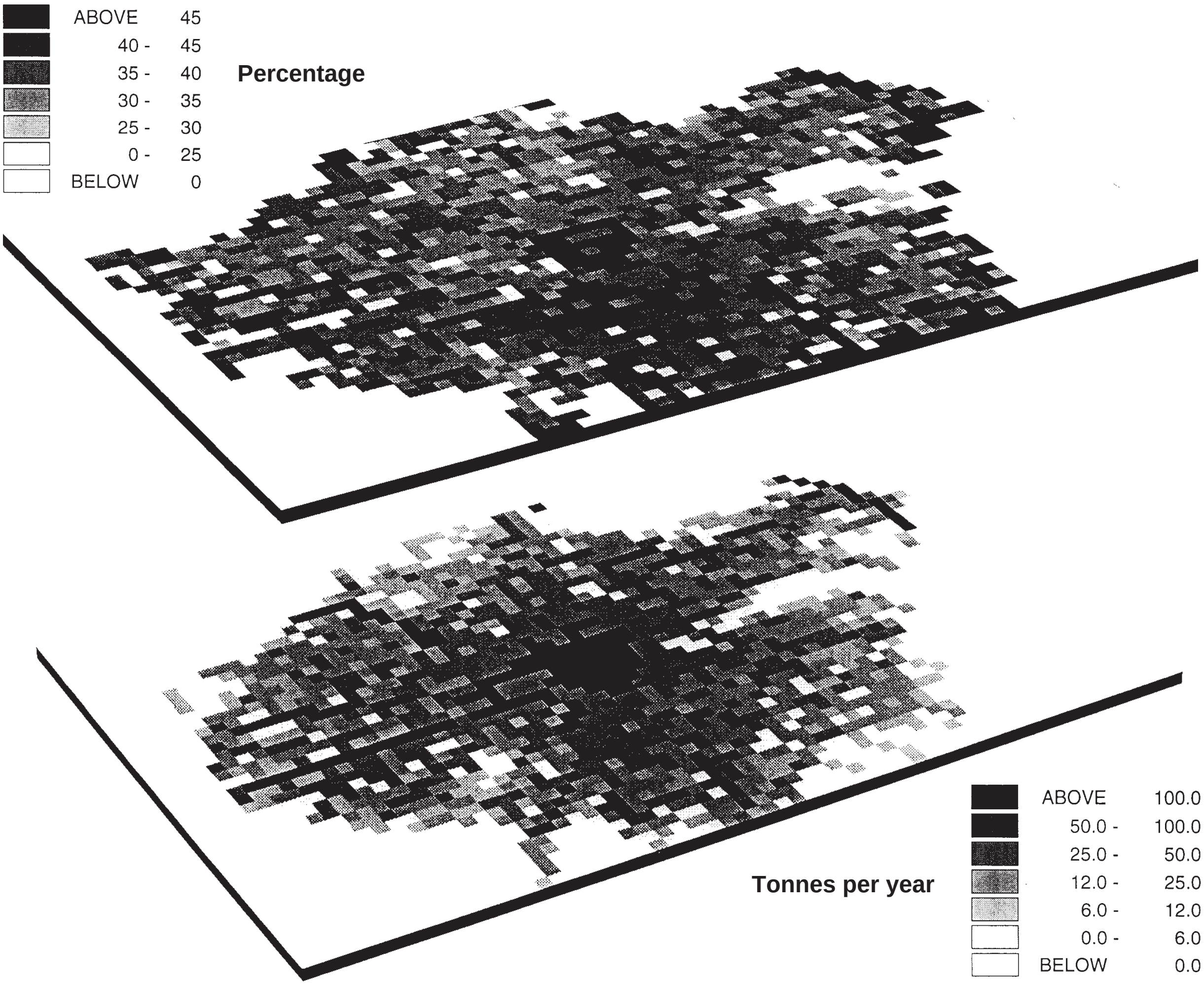
The model has been used to calculate total NO_X and black smoke concentrations and also the diesel contribution. In the case of NO_X a background of 20 $\mu g/m^3$ NO_X has been added based on interpolated data from surrounding rural sites. Figure 5.9 shows the NO_X case. While the diesel contribution is reasonably constant across the conurbation two features are noticeable, the elevated contributions along the M25 (in the north-east) and the very small values around Heathrow airport in the west, where the diesel contribution drops to about 5%.

Figure 5.10 shows the corresponding map for black smoke. The pattern is generally similar with an area of small contribution around Heathrow. Contributions along the major motorways are again elevated but this is less obvious as the average contribution is typically about 90% in any case. More detailed analysis reveals decreased contributions around some large industrial sources.

5.8 KEY POINTS

- *On-the-road emissions have been measured for a number of diesel vehicles but, as yet, fewer data are available than for petrol-engined vehicles.*
- *To date few emission measurements are available for heavy goods vehicles, buses and other large diesel-engined vehicles.*
- *Methodologies to calculate total national emissions from road transport have been developed and their accuracy assessed.*
- *Particulate tracers may be used as indicators of diesel emissions.*

Figure 5.7 NO_X Emissions from Diesel Vehicles in London (T/year) and as a Percentage of Total Emissions.



- *Nationally, diesel vehicles currently account for about one-fifth of NO_X and particulate emissions, and two-fifths of black smoke emissions. Their contribution to other major pollutants is less than 10%.*

- *Since 1970 NO_X emissions from road transport have more than doubled and now account for over half of the national total. Within this vehicular fraction the proportion arising from diesels as opposed to petrol-engined vehicles has decreased from about 60% to 40%.*

- *Within London diesel vehicles are responsible for a larger fraction of emissions than on a national scale. This is particularly true for black smoke where emissions from diesel vehicles account for almost 90% of the total, although diesel cars and taxis are responsible for only about 10%.*

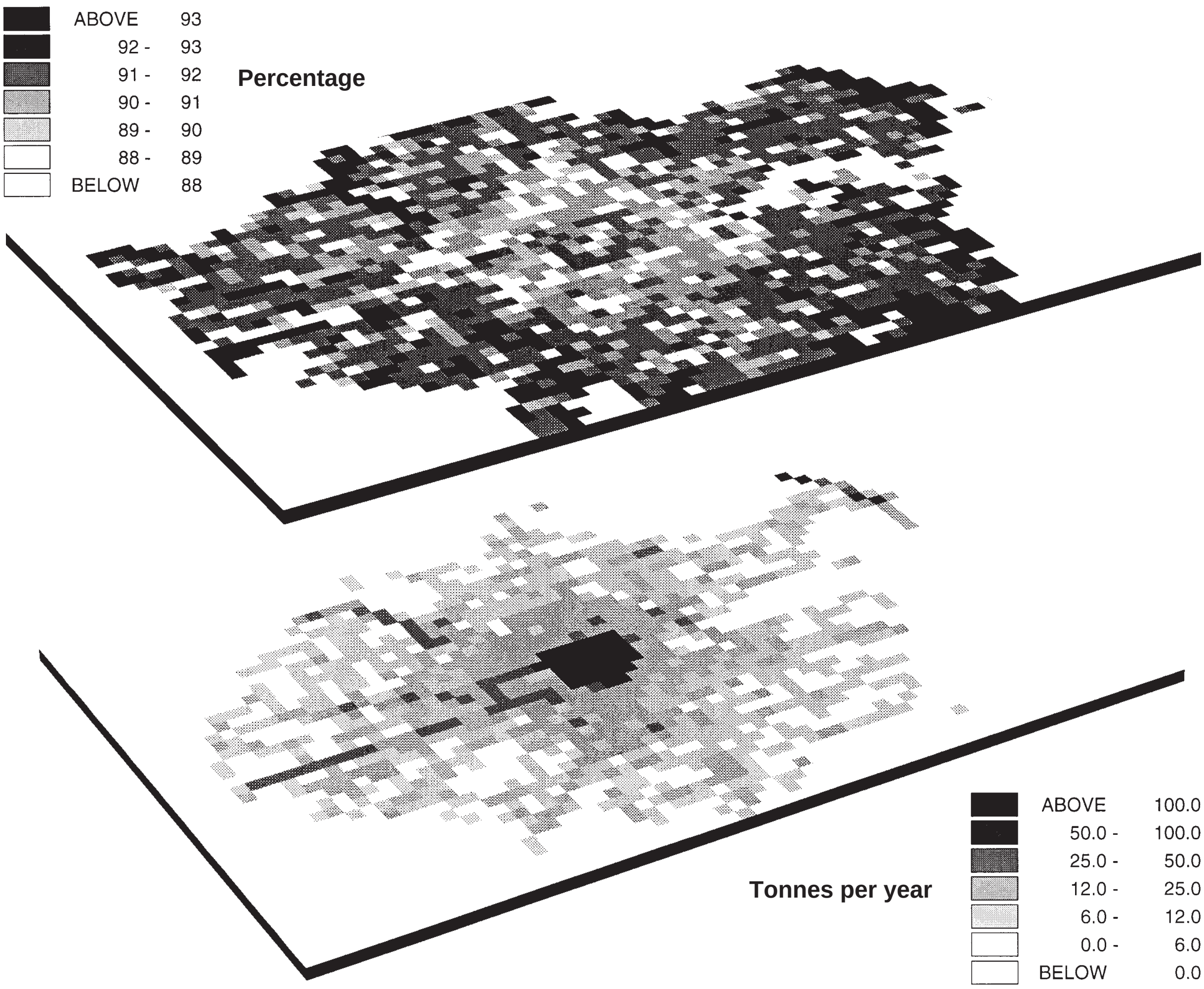
- *Models show that over most of London emissions from diesel vehicles account for 30-40% of ambient NO_X concentrations but that this figure can increase to over 50% in the vicinity of some motorways.*

REFERENCES

Adams W J, Hackman M P, Parkes S N, Roberts C S and Timmis R J (1992) **Assessment and Prediction of Smoke and Sulphur Dioxide Concentrations in Northern Ireland**. First Progress Report. Warren Spring Laboratory. Report LR 926. Stevenage.

Chen J C (1992) **Roadside Air Pollution - A Study of Particulate Emissions from Vehicles**. MSc Thesis, University of Leeds.

Figure 5.8 Black Smoke Emissions from Diesel Vehicles in London (T/year) and as a Percentage of Total Emissions.



Eggleston H S (1987) **The Calculation of Emissions from UK Petrol Engined Motor Vehicles**. Warren Spring Laboratory. Report LR 612. Stevenage.

Eggleston H S (1992) **Pollution in the Atmosphere: Future Emissions from the UK.** Warren Spring Laboratory. Report LR 888. Stevenage.

Eggleston H S (1993) **Uncertainties in the Estimates of Emissions of VOCs from Motor Cars**. Proc. TNO/EURASAP workshop on the reliability of VOC emission databases, Delft, June 1993. IMW/TNO publication, P 93/040.

Eggleston H S, Gorißen N, Joumard R, Rijkeboer R C, Samaras Z and Zierock K-H (1989) **CORINAIR Working Group on Emission Factors for Calculating 1985 Emissions from Road Traffic. Volume 1: Methodology and Emission Factors**. Final report, EUR 12260 EN, Luxembourg.

Eggleston H S, Gaudioso D, Gorißen N, Joumard R, Rijkeboer R C, Samaras Z and Zierock K-H (1992) **CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic - Volume 1.** Brussels: Commission of the European Communities, Final Report Contract No. B4-3045(91) 10PH.

Gillham C A, Leech P K and Eggleston H S (1992) **UK Emissions of Air Pollutants**. Warren Spring Laboratory. Report LR 887. Stevenage.

Horvath H, Kreiner I, Norek C, Preining O and Georgi B (1988) **Diesel Emissions in Vienna**. Atmos. Environ., **22**, 1255-1269.

London Research Centre (1993) **London Energy Study, Energy Use and the Environment** (M. Chell and D. Hutchinson, eds).

Figure 5.9 A Model of the Percentage Contribution By Diesels to NO_X in London.

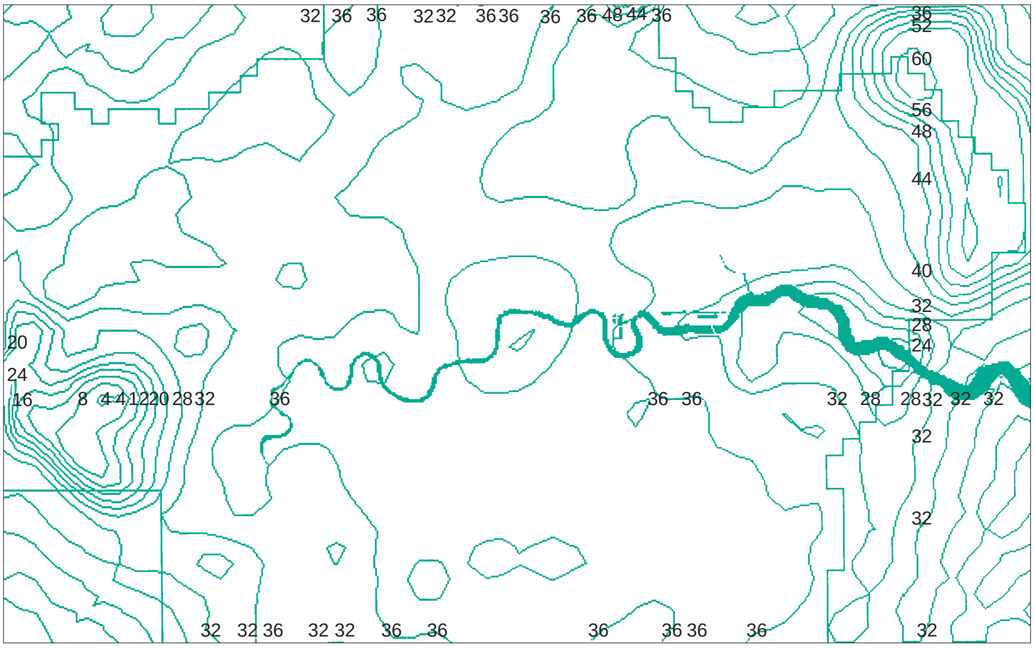
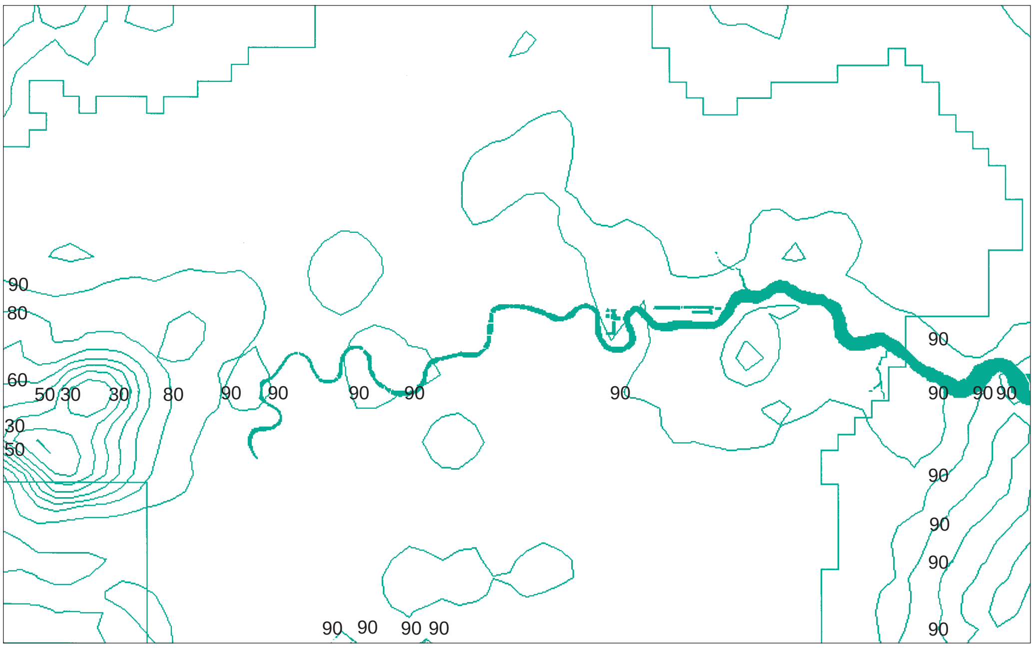


Figure 5.10 A Model of the Percentage Contribution by Diesels to Black Smoke in London.



London Scientific Services (1990) **London Air Pollution Monitoring Network, Fourth Report 1989**. Available from TBV Science, London.

Munday P K, Timmis R J and Walker C A (1989) **A Dispersion Modelling of Present Air Quality and Future Nitrogen Oxides Concentrations in Greater London.** Warren Spring Laboratory. Report LR 731. Stevenage.

TRL (1993) **Survey of Exhaust Emissions from Light Duty vehicles in the UK**, in press.

6 Future Trends in Diesel Emissions and Related Air Quality Issues

6.1 ESTIMATING FUTURE EMISSIONS FROM MOTOR VEHICLES

As outlined in Annex A, existing and planned regulations will affect future emissions. Taking account of these, and the performance of abatement technologies, it is possible to prepare projections of future emissions. These projections are based on economic forecasts and are intended to show general trends in emissions. They should not be regarded as detailed forecasts for any one individual year.

In the case of emissions from motor vehicles, basic forecasts of the likely growth in vehicle kilometres driven by motor cars, light goods vehicles, small heavy goods vehicles and large HGVs are supplied by the Department of Transport (DoT, 1992). For buses and coaches the forecasts assume no growth in kilometres driven.

As noted above, future emissions will also be greatly affected by new regulations. As far as overall traffic emissions are concerned, the most important of these is EC Directive 91/441/EEC (European Community, 1991a) which came into force in 1992. Table 6.1 gives the emission limits specified in this Directive. All petrol-engined motor cars will have to be fitted with closed loop three-way catalysts in order to meet these new, stricter emission limits. This will reduce emissions of nitrogen oxides (NO_X), carbon monoxide (CO) and volatile organic compounds (VOCs). For HGVs there is a proposed two-stage reduction in the maximum permitted emissions of NO_X, CO, VOC and particulate material that is due to come fully into force in October 1996 (Directive 91/542/EEC)(European Community, 1991b). As these regulations only apply to new vehicles, it is necessary to estimate future fleet composition as described in Section 5.1. Another regulation affecting emissions from diesel vehicles is limiting the sulphur content of diesel fuel to 0.05% from 1996 (Directive 93/12/EEC).

A methodology for estimating future emissions has been described by Eggleston (1992). The forecasts in that report have subsequently been revised to take account of lower new car sales in the early 1990s and increased diesel penetration of the new car market. The forecasts presented here assume that 16% of new car sales are diesel vehicles and that this fraction remains constant throughout the period of the forecast. The emission factors used are broadly consistent with those proposed in a study for the European Commission (Samaras & Zierock, 1990). Exceptions are NO_X and VOC emissions from diesel cars in the future. EC Directive 91/441/EEC specifies a single combined limit for NO_X + VOC of 1.13 g/km (conformity of production). While the EC study assumed a proportional reduction in both species, the UK analysis assumed that the NO_X emissions would not decline; all the reduction necessary to meet the Directive would be achieved by reducing VOC emissions.

Additional assumptions in the projections concern the rate at which catalyst performance degrades, future changes in driver behaviour, vehicle age profiles and road type split. Catalysts have been assumed to fail at a rate of 5% a year with failed catalysts being detected in the annual MoT test and repaired with a 95% success rate. They will also degrade with use and the projections are based on this degradation just meeting US federal requirements and being linear with mileage.

Table 6.1 Emission Limits for Motor Cars (EC Directive 91/441/EEC).

	Type approval (g/km)	Conformity of production (g/km)
Carbon monoxide	2.72	3.16
Hydrocarbons + oxides of nitrogen	0.97	1.13
Particulate (diesel only)	0.14	0.18

Note: "Type Approval" is the test that sample cars have to undergo to receive a type approval certificate. "Conformity of Production" is the lesser standard that production cars have to meet.

Driver behaviour has been taken to remain constant into the future with the fraction of short journeys remaining unchanged. This is a significant source of emissions particularly in the future when emissions from warm vehicles will be substantially reduced and cold start emissions will be proportionately more important.

Vehicle age profiles have been derived from the DoT Statistics for each vehicle type. These are also assumed to remain constant into the future. While this may be a reasonable estimate over the longer term, short term deviations may occur. For example if a recession causes owners to delay replacing old vehicles the introduction of new technologies will be delayed leading to under-estimates of future emissions.

The projections assume the split in usage between differing road types, urban, rural and motorway remains constant into the future. The effect of extrapolating current trends in this split has been investigated but did not lead to a significant change in the predicted emissions. Such an extrapolation does not take into account real factors such as congestion, road building schemes and public transport policy, all of which could have a significant influence.

Figures 6.1, 6.2 and 6.3 show examples of these projections for NO_X, sulphur dioxide (SO_2) and black smoke emissions from vehicles up to the year 2010. In each case the higher and lower emission scenarios are based on DoT forecasts of vehicles kilometres driven.

In the case of NO_X emissions, current regulations will reduce emissions back to the levels of the early 1970s before increasing vehicle kilometres result in emissions increasing again. The proportion of emissions arising from diesel vehicles will increase sharply over the next decade, however, as emissions from petrol-engined vehicles decrease as catalyst cars penetrate the vehicle fleet.

The SO_2 emission projections clearly illustrate the effect of the limitation of the sulphur content of diesel

Figure 6.1 UK Road Transport Emissions of NO_X, 1970-2010.

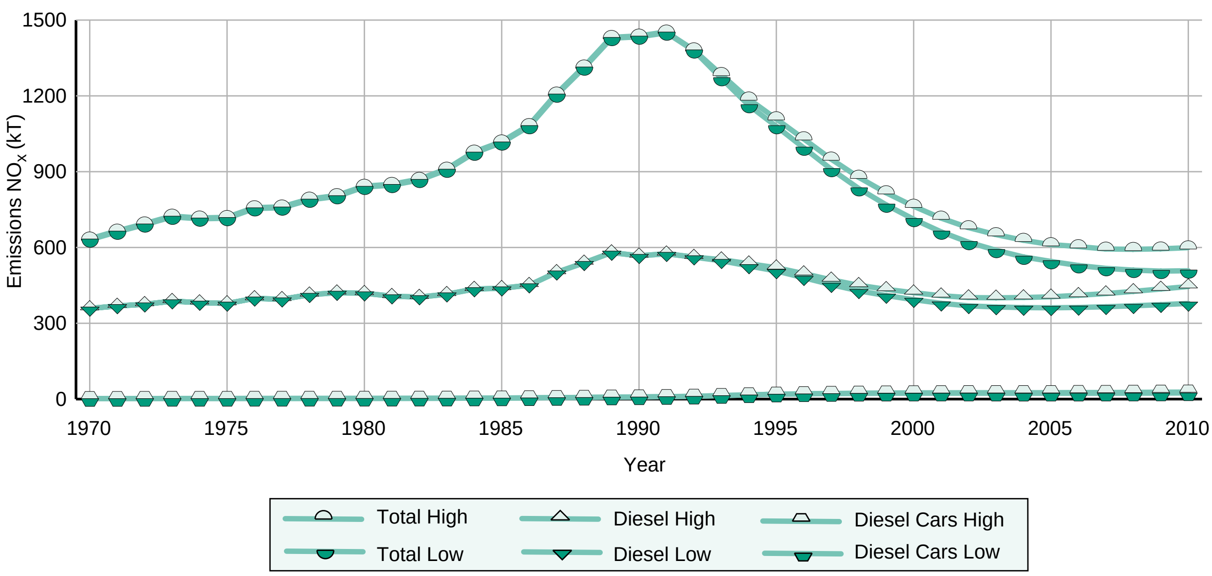


Figure 6.2 UK Road Transport Emissions of SO_2, 1970-2010.

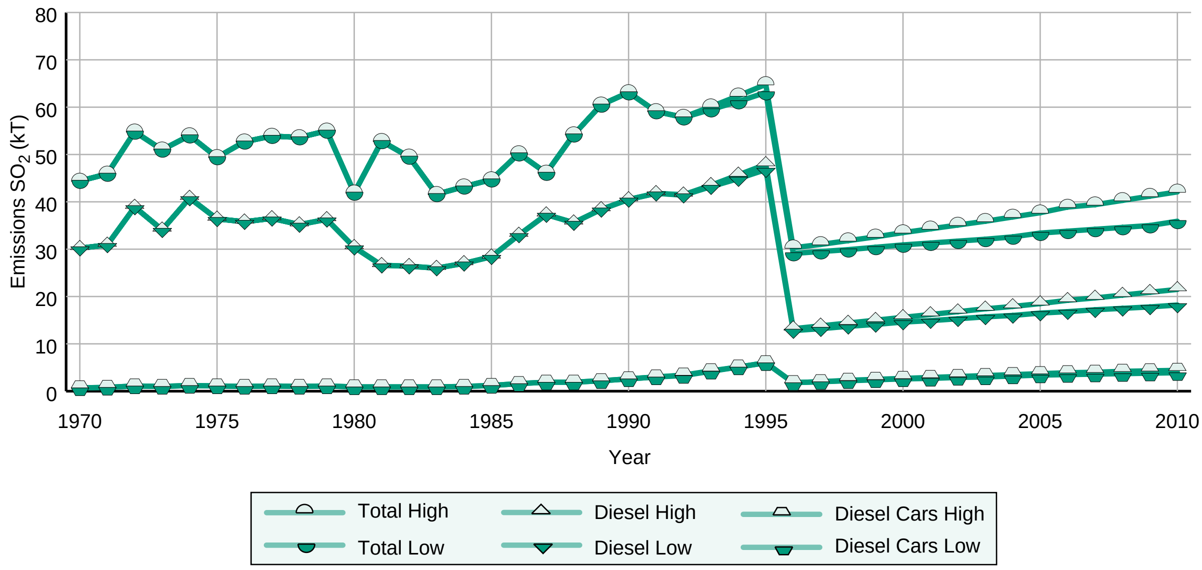
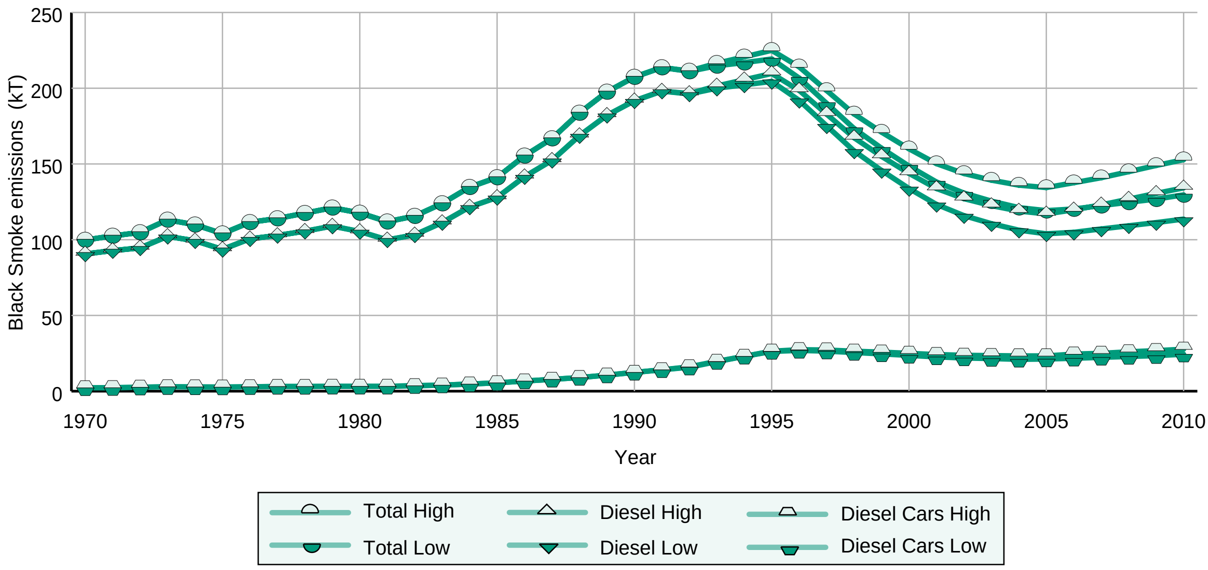


Figure 6.3 UK Road Transport Emissions of Black Smoke, 1970-2010.



fuel, emissions dropping to about one-third of present values before subsequently increasing as vehicle kilometres increase.

In the case of black smoke the larger fraction of diesel cars leads to increasing emissions until the implementation of emission controls in 1996, for example in the form of particle traps or other technologies, after which emissions from cars are likely to remain fairly constant.

Holman et al (1993) have noted that currently the majority of particulate matter emissions occur outside urban areas, where the impact on human health and buildings is less important. If in future, however, the number of diesel cars continues to grow, there is likely to be less difference between urban and non-urban emissions as much of the increased emissions from diesel cars will occur on urban roads. Thus, there is likely to be less improvement in urban emissions than the national forecasts would suggest.

Emissions of particulate matter from urban buses are often perceived by the public as being a special problem. Their contribution to total urban emissions is not large (Table 5.2), but as they generally operate in close proximity to the public a large number of people (and buildings) are potentially at risk from their adverse effects. A recent study (Holman et al, 1993) has looked at the effect of introducing cleaner new buses and fitting particulate traps to existing urban buses. It concluded that a modest programme of retrofitting, combined with incentives to encourage bus operators to buy the best available technology could lead to 25% lower emissions in the year 1995 than would otherwise be the case.

6.2 EFFECT OF INCREASED MARKET PENETRATION OF DIESEL CARS ON EMISSIONS AND AIR QUALITY

In the projections above the percentage of diesel car sales was taken to remain constant over the period at 16%. This was based on the considerable increase in diesel car sales over recent years. The effects of further increases have also been investigated. The scenarios chosen correspond to 17.5% (case 1), 31% (case 2) and 49% (case 3) penetration of the vehicle fleet. This can be seen in the context of current new car registrations comprising 20% diesels.

The results of these projections are summarised for the years 1995, 2000 and 2005 in Figure 6.4, together with the present situation for comparison. In each case the estimates take account of the regulations described above.

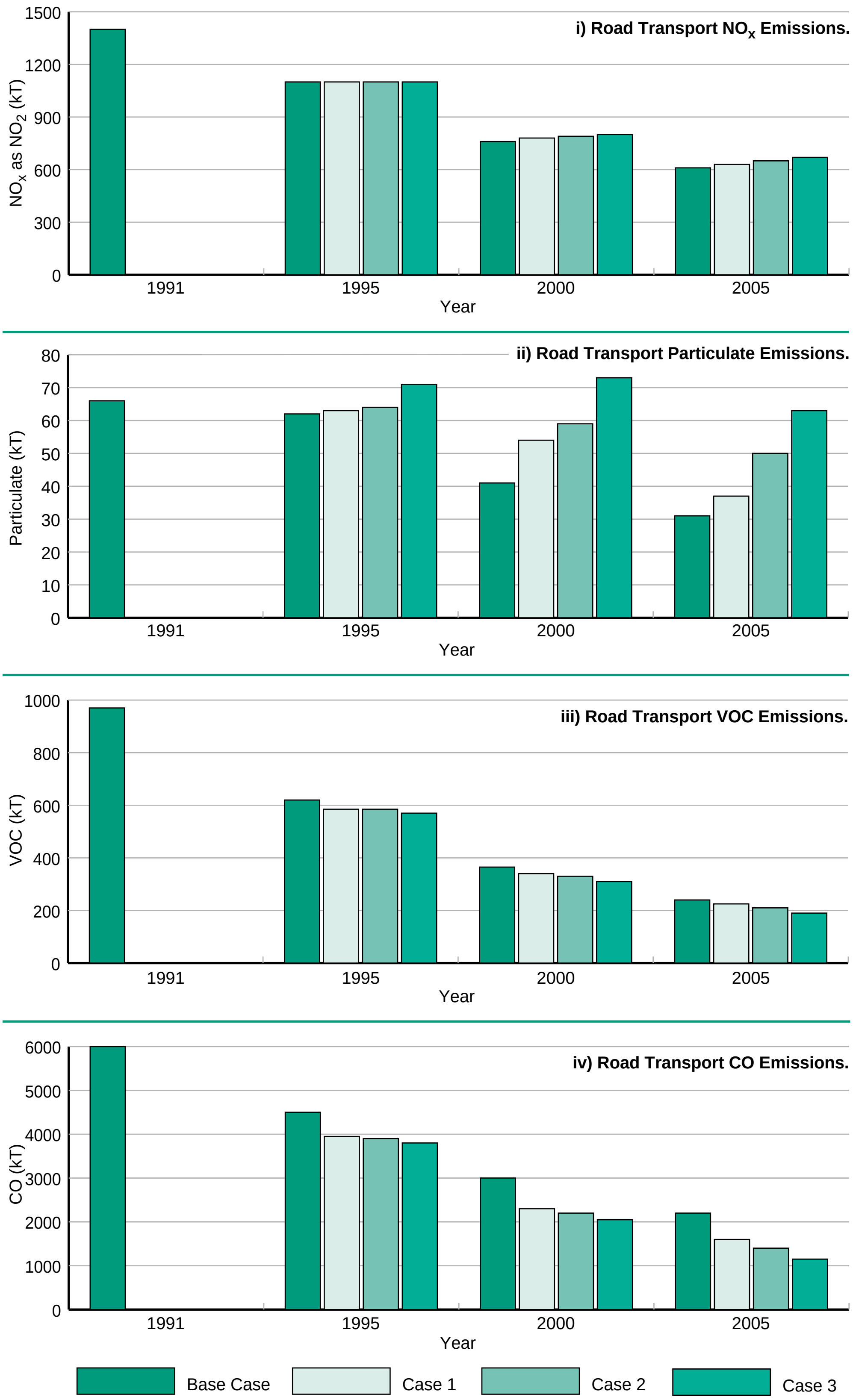
The results, as expected, show improvements in emissions of CO and VOCs (hydrocarbons) with increased diesel market share, and a deterioration with respect to NO_X and particulate emissions. In the case of NO_X the difference is not large, but may be significant in the context of a need to halve low-level emissions of NO_X (see Section 6.3).

The most marked impact of an increased proportion of diesels is upon emissions of particulate matter. In case 1, corresponding approximately to a continuation of current diesel penetration of the car market, road transport particulate emissions are forecast to halve by 2005 due to lower emissions from catalyst-equipped cars burning unleaded petrol, and a tightening of emission standards for diesels (Appendix A). However, in the case 3 scenario, of 49% diesel fleet share, particulate matter emissions from road transport are almost doubled in 2005 relative to case 1, and almost equal to the 1991 base case.

Because of the complex make-up of urban airborne particulate matter (QUARG, 1993), it is not possible to quantify precisely the impact of these emission scenarios upon air quality. However, the Vienna study (Section 5.3) indicates the major contribution which diesel particles make to airborne particle mass - in that instance a background of 11 $\mu g/m^3$ which increases markedly close to roads. This may be viewed against typical UK urban total fine particle (PM_{10}) concentrations of 25-35 $\mu g/m^3$. Thus scenario 1 offers a very substantial improvement in air quality with respect to PM_{10} by the year 2000, whilst scenario 3 shows a deterioration to the year 2000 and only a most marginal improvement in 2005.

This analysis obscures the fact that whilst a modestly increased diesel market penetration will not lead to an

Figure 6.4 Road Transport Emissions.



Note: Base Case = WSL forecast based upon constant 16% diesel proportion of new car sales.
Case 1 = 17.5%, Case 2 = 31%, Case 3 = 49%, of diesel cars in the fleet.

increase in road transport particulate emissions, it will cause an increase in the blackness of those emissions, hence delaying the onset of the improvement of black smoke emissions, currently predicted to commence in 1995 (see Figure 6.3). An increase in urban black smoke emissions may have implications for exceedence of the EC smoke/sulphur dioxide Directive Limits (Table 4.3) since the UK uses the smoke shade method for evaluating suspended particulate matter. In a few parts of the country a very modest increase in smoke concentration would lead to an exceedence of the "associated value for particulates" (Table 4.3) hence triggering a lower limit value for sulphur dioxide, and causing an exceedence of the EC Directive Limit.

6.3 FUTURE TRENDS IN URBAN AIR QUALITY FOR NO_2

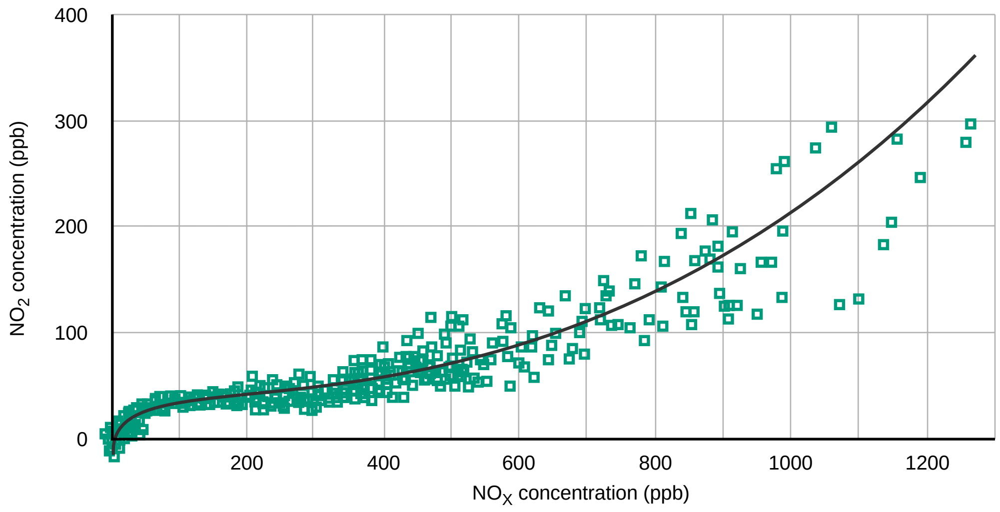
In the first report of QUARG, the view was expressed that it seemed unlikely that a decrease in NO_X emissions would lead to an equal decrease in atmospheric nitrogen dioxide (NO_2) concentrations, or arguably a decrease at all in some urban areas. Results were reported from a dispersion modelling study which had concluded that NO_2 concentrations were only likely to decrease by 5% in Central London, as compared with 1984/5 levels, despite the introduction of vehicle emission control measures. These statements were made against the background of an incomplete understanding of the chemistry of the nitric oxide (NO) to NO_2 conversion in the urban environment.

From an analysis of the December 1991 episode in London and the 1992 episode in Manchester, it has become clear that there is one class of urban NO_2 episode for which typical meteorological conditions can be defined. Seriously elevated hourly mean concentrations appear to be caused during wintertime stagnation by low windspeeds, low boundary layer depths, low temperatures (< 0°C), high humidity and the presence of fog. The observed time development of the NO_2 concentrations in the above mentioned episodes appears to be consistent with its formation from the third order reaction of NO with oxygen. The details of the mechanism are currently unknown, as is the extent of involvement of heterogeneous reactions on the surface of airborne particles, including fog droplets. However, the likely explanation of the origin of the NO_2 in the oxidation of NO by oxygen is beyond doubt and this has important policy implications.

In Figure 6.5, the mean hourly mean NO_2 concentrations observed for a given hourly mean NO_X concentration are presented for the 8000 hours or more during one year's continuous monitoring for the roadside site in Exhibition Road, London. The chosen year includes one of the serious wintertime NO_2 pollution episodes described above, and its influence is clearly apparent in the elevated hourly mean NO_2 and NO_X concentration data reported. The response of the hourly mean NO_2 concentrations to changes in NO_X concentrations is seen to change markedly across the range of NO_X concentrations. At low NO_X concentrations, NO_2 concentrations rise quickly above zero and then level out. In the level region, despite large changes in NO_X concentrations, NO_2 concentrations remain unaffected, showing the limited oxidising capacity of the urban atmosphere. When studying both daily and annual mean NO_2 and NO_X concentrations, as is often the case with the dispersion model studies referred to above, concentrations are necessarily in the low-NO_X regime of Figure 6.5, and the conclusions about future NO_2 concentrations in our first report appear justified.

If attention is shifted to the very high NO_X concentration regime, NO_2 concentrations appear to rise very quickly with increasing NO_X concentrations. This is most likely to be due to the third order reaction of NO with oxygen alluded to above. A consequence of the steepening observed curve for NO_2 with increasing NO_X concentrations, is that peak NO_2 concentrations should decline quite dramatically with reducing NO_X emissions. This is the exact opposite to the behaviour expected under low NO_X conditions. The Review Group is therefore able to reconcile the apparently conflicting views that NO_X emission reductions will have both little impact and a significant impact on urban NO_2 concentrations. The first statement applies on the annual timescale and the second on the hourly timescale during wintertime high pollution episodes. The Review Group takes the view

Figure 6.5 Relationship Between Hourly Mean NO_2 and NO_X Concentration.



Note: Measurements taken 20th May 1991- 30th June 1992 in Exhibition Road, London.

that the latter conditions are more important for urban air quality management and has focussed its attention upon them.

On the basis of Figure 6.5, to reduce peak NO_2 concentrations such that none exceed the 100 ppb threshold in the Department of the Environment "POOR" air quality bulletin category, it is estimated that NO_X concentrations will need to be reduced by about 50% of current levels. This will require a halving of nitrogen oxide emissions from low-level sources. Assuming that NO_X emissions from petrol cars are required to contribute at least a 50% reduction, then any appreciable penetration of diesel cars as an alternative to three-way catalyst cars will delay the time taken to achieving this target for NO_X concentrations.

By the same arguments, at least a 50% reduction in other traffic NO_X emissions will need to be sought in the major urban and industrial centres such as London. Whilst NO_X emission controls on HGVs offer some future scope, traffic management and other measures seem to offer the main opportunities. Such measures should also be used to reinforce the anticipated downwards trend in NO_X emissions from cars.

6.4 DIESELS AND SECONDARY POLLUTANT AIR QUALITY

Detailed computer modelling studies have been performed of the impacts on secondary pollutant air quality of both light duty and heavy goods vehicles with diesel engines. HGVs are a major source of NO_X and this pollutant acts as a precursor of the aggressive secondary air pollutants produced during summertime photochemical episodes.

The impact of diesel emissions during photochemical episode conditions is complex. Close to busy roads, the NO_X from HGVs reacts with ozone and depletes ground level concentrations. Further downwind, vertical dispersion re-supplies this ozone and levels rise to background levels. The NO emitted by the diesels is converted to NO_2 which disperses throughout the boundary layer and is transported with the wind. Nitrogen dioxide has a lifetime of about 10 hours or so before it is converted to gaseous nitric acid. During this lifetime, the NO_2 from diesels will stimulate photochemical ozone formation from any hydrocarbon precursors which may be present in the atmospheric boundary layer. Since HGVs account for about one half of UK low-level NO_X emissions, they have a very important role in ground level photochemical ozone formation.

There are also questions concerning the impact of future increased penetration of light duty diesels on secondary pollutant air quality. Here the issue focuses on the impact of diesel versus three-way catalyst cars as possible sources of ozone precursors: CO, NO_X and hydrocarbons. Detailed studies have been performed using computer models of ozone formation in South East England. There is little importance to be given to the CO and hydrocarbon emissions from either diesel or three-way catalyst-equipped vehicles in terms of their contribution to summertime ozone under warm start driving conditions.

There are however differences in potential ozone formation due to the increase in NO_X emissions from light duty diesels over three-way catalyst cars. A detailed modelling study was able to detect this impact based on a total penetration of 8% into the mix of cars on the road in 2000 (Derwent and Hough, 1988). More recent estimates of the penetration of diesel cars are significantly higher. This would increase their likely impact on secondary pollutant air quality and delay the time when air quality standards for ozone will be met in the UK.

This difference in NO_X emissions between diesel and three-way catalyst cars becomes of greater significance in the less polluted areas of the UK. Here, ozone formation is in its NO_X-limited regime. That is to say, ozone levels are determined by long range transport into the region and not by local production. In this regime, photochemical production merely needs to re-supply losses caused by ozone dry deposition to maintain long range transport. This production is NO_X limited, because of the short lifetime for NO_2 alluded to above. Motor vehicles are the major source of low-level NO_X emissions in remote regions and hence they are the main policy focus in the control of ozone long range transport.

6.5 KEY POINTS

- *Projections of future emissions show diesel vehicles contributing an increasing proportion of NO_X emissions.*

- *Increases in the percentage of diesel cars sold will result in larger NO_X and particulate emissions but smaller emissions of CO and VOCs .*

- *If diesel car sales remain close to their present level, national emissions of particulate matter will halve by the year 2005. However, should market penetration substantially increase this will lead to an almost unchanged national emission of particulate matter from road transport.*

- *An increased proportion of diesel cars will lead to an increase in black smoke emissions peaking in 1995 if present market share persists. It is possible that increased emissions of black smoke may lead to exceedences of the EC smoke/sulphur dioxide limit value in a few parts of the country.*

- *Recent analyses of urban NO_2 pollution episodes indicate that emissions from low-level NO_X sources will need to be cut by approximately 50% to eliminate the occurrence of episodes. The time period over which this can be achieved will be extended if there are greater NO_X emissions due to increased diesel market penetration.*

- *Since an increased proportion of diesels will lead to reduced hydrocarbon emissions and increased NO_X from road transport, the impact upon photochemical ozone will be complex and may differ between urban and rural sites. The greatest impact is likely to be in less polluted areas where increased NO_X emissions will lead to an increase in photochemical ozone.*

REFERENCES

DoT (1992) **Transport Statistics Great Britain 1992**. HMSO, London.

Derwent R G and Hough A M (1988) **The Impact of Possible Future Emission Control Regulations on Photochemical Ozone Formation in Europe.** AERE Report R12919, HMSO, London.

Eggleston H S (1992) **Pollution in the Atmosphere: Future Emissions from the UK.** Warren Spring Laboratory, Report LR 888, Stevenage.

European Community (1991a) **EC Directive 91/441/EEC**, Official Journal of the European Communities, L242, 1.

European Community (1991b) **EC Directive 91/542/EEC**, Official Journal of the European Communities, L295, 1.

Holman C, Wade J, Fergusson M, Reinhardt G and Höpfner U (1993) **Reducing Particulate Emissions from Buses: a Comparison of Future Trends in Germany and the United Kingdom.** TRL, in press.

QUARG (1993) **Urban Air Quality in the United Kingdom**. QUARG, London.

Samaras Z C and Zierock K-H (1990) **Study on the Forecast of Emissions from Motor Vehicles in the European Community.** Brussels: European Community Study Contract Nos B6611-50-89, B6611-56-89 and B6611-62-89.

7 Conclusions

The First Report of this Review Group highlighted *inter alia* the fact that for many pollutants national inventories do not well represent urban air pollutant emissions and that urban areas may have special air pollution problems. This is particularly true in the case of low level sources, which impact directly on local air quality, and hence motor vehicles are a very major contributor to urban air pollution. The limited urban inventory data for London make this point very clear in relation to pollutants such as oxides of nitrogen (NO_X) and black smoke for which vehicular emissions make a predominant contribution to urban pollution levels, but contribute much less to the overall national picture.

Our first report also highlighted the considerable benefits which will accrue from the introduction of three-way catalyst-equipped petrol cars from the beginning of 1993 in relation to emissions of carbon monoxide, nitrogen oxides and hydrocarbons. It pointed out that the most effective way to improve urban air is to cut urban vehicle use and warned that based upon current projections of traffic growth, even the very considerable benefit gained through catalytic converters might be squandered in time due to increased traffic volumes. Another factor which may influence future air quality in our cities, which was not explicitly considered in our First Report, was a change in the relative proportion of petrol and diesel vehicles operating on our roads. Whilst diesel cars have with good reason been perceived as largely better than conventional petrol cars in relation to emissions of most pollutants, in a comparison with three-way catalyst-equipped cars the benefits become far less marked and certain disadvantages become more clear. In this report we have examined in a quantitative sense the impact of diesel vehicle emissions on urban air quality and have sought to examine the possible future consequences if the present trend of increased market penetration of diesel cars at the expense of three-way catalyst equipped petrol cars continues.

A question which is often posed by the layman is whether the diesel car is less polluting than the petrol car. There is of course no simple answer to this question as the two have major differences. Firstly, it is difficult to know exactly which specific vehicles to compare in that the petrol and diesel vehicle could be matched in terms of engine capacity, engine power, top speed or some other parameter. Ignoring the difficulties of comparing like with like, the question then arises as to which pollutant(s) is/are most important. In general, the diesel car puts up a better performance than the near equivalent three-way catalyst petrol vehicle in relation to carbon monoxide and carbon dioxide, but is currently inferior in terms of NO_X and notably so in relation to particulate matter emissions. Which emissions are more important? There is not a simple answer to this question as the consequences of the different pollutants vary markedly.

So, upon which criterion or criteria should we make our judgement? If, for example, human health is taken as the most important factor, it is still not possible to come to a straightforward judgement as to whether the petrol car is superior or inferior to the diesel. However, on the basis of the pollutants emitted in greatest quantity, the advent of three-way catalysts has pushed the focus very much onto diesel cars because emissions of particulate matter from the diesel are far greater than those from the petrol car, and because of greater emissions of nitrogen oxides from diesel cars (urban nitrogen dioxide concentrations at many locations currently exceed the EC guide value for this pollutant). The former pollutant has attracted a great deal of attention in the last two or three years as a result of epidemiological studies in North America and Europe which have shown increases in morbidity and mortality with increased loadings of airborne particulate matter. Although the studies are highly consistent in their findings and coherence between different effects has been demonstrated, the lack of a plausible biological link between cause and effect is presently leading to some caution in accepting the assertion that the effects demonstrated are causal. Nonetheless, the current view of some workers in the United States and Canada is that the potential health problems posed by particulate matter far exceed those posed by current levels of some of the gaseous pollutants which have drawn our attention in past years. The question of the possible carcinogenicity of diesel emissions at ambient environmental levels is as yet unresolved, but there are legitimate concerns that they may be a greater problem in this regard than emissions from

oxidation catalysts in relation to particulate emissions are small. Particulate traps are a developing technology and may prove very valuable in the long term if the concerns over particulate emissions continue. There is also a hope of developing a NO_X reduction catalyst for diesels, but currently this appears to be some way off. On balance, however, unless some improvements in the emissions from diesel vehicles can be achieved, there must be considerable concern over any increase in the proportion of diesel vehicles on our urban streets as their impact on urban air quality is undoubtedly quite serious.

A Legislative Controls

A.1 EUROPEAN VEHICLE EMISSION STANDARDS

A.1.1 Introduction

As road traffic has increased, legislation has been progressively tightened in response to environmental and public concerns about associated pollution. Considerable action has already been taken to reduce toxic emissions from vehicles.

Originally emission limits for motor vehicles were set by the United Nations Economic Commission for Europe (UNECE), and then introduced into European Community legislation. As the UNECE has no powers of enforcement these regulations were voluntary. That is, member states could choose whether to introduce them or not. However over the last few years the European Community has set its own emission standards that have been more stringent than those of the UNECE. This has enabled the legal basis of the legislation to change and the current emissions legislation for passenger cars is mandatory.

For cars and vans emissions are measured using a chassis dynamometer over a test cycle that is designed to simulate a period of driving under urban conditions followed by a period of faster driving such as may be experienced outside urban areas. The full test cycle is approximately 11km long and emissions are expressed in grams per kilometre.

For heavy duty vehicles (lorries and buses) emissions are measured from the engine (not the vehicle) using a bench dynamometer over a 13-mode steady state test cycle. Emissions are measured in grams over the complete cycle and the limit values are expressed in terms of grams per kilowatt hour. That is, the more powerful the engine the greater the permitted emissions. Due to the wide variety of different types of vehicle in which any one engine may be installed, it is not possible to correlate the results of the emissions test to on-road emissions in g/km.

A.2 NEW VEHICLE EMISSION STANDARDS

A.2.1 Historical Background

The first legislation dealing with exhaust emission control was the Construction and Use (C&U) Regulations (Her Majesty's Government, 1986), Regulation 61 of which provides that no person shall use a motor vehicle 'from which any smoke, visible vapour, grit, sparks, ashes, cinders or oily substance is emitted'. With the development of the diesel engine for road use, a further amendment to the C&U Regulations was made to limit 'visible' emissions by requiring manufacturers to obtain approval to a new British Standard controlling smoke, BS Au 141a: 1971 (British Standards Institution, 1971). This British Standard was subsequently embodied into an EC Directive, 72/306/EEC (European Community, 1972), which is still the benchmark for diesel exhaust smoke.

A.2.2 Light Duty Vehicles

In parallel with the development of visible emission standards, 'invisible' emissions started to receive attention in Europe through the UNECE, culminating in ECE Regulation No.15 (UNECE, 1970). This regulation set, for the first time, European gaseous exhaust emission standards for motor vehicles. Applying to cars, light vans and commercial vehicles below 3.5 tonnes maximum mass, it limited the maximum quantities of carbon monoxide (CO) and hydrocarbons (HC) that could be emitted from the exhaust under a prescribed dynamometer test cycle designed to simulate the typical emissions that would occur in an urban driving situation.

ECE Regulation No.15 was embodied into EC Directive 70/220/EEC (European Community, 1970). This was incorporated into national law in 1976 with consequential amendment to C&U Regulation 61.

As environmental concerns continued to grow, so motor vehicle exhaust emission limits became progressively tighter. By 1983, four amending ECE regulations had been issued, mirrored by equivalent EC directives. The first amendment also introduced limits for oxides of nitrogen (NO_X). The complete series of light duty vehicle regulations and equivalent directives up to this stage were:

ECE Reg No.15 - Dir 70/220/EEC

ECE Reg No.15.01 - Dir 74/290/EEC

ECE Reg No.15.02 - Dir 77/102/EEC

ECE Reg No.15.03 - Dir 78/665/EEC

ECE Reg No.15.04 - Dir 83/351/EEC

The earlier ECE Regulations related only to petrol cars. The 15.04 amendment included light duty diesel vehicles for the first time.

A.2.3 The Luxembourg Agreement

The Council of Ministers in Luxembourg in 1985 agreed to press for standards equivalent to those in the USA for large cars (>2 litres) while allowing less stringent standards for medium (1.4-2.0 litres) and small cars (<1.4 litres). This required the use of catalytic converters on large cars for the first time in Europe. The standards were included in Directive 88/76/EEC. This was closely followed by Directive 88/436/EEC which added limits for diesel particulate matter (PM).

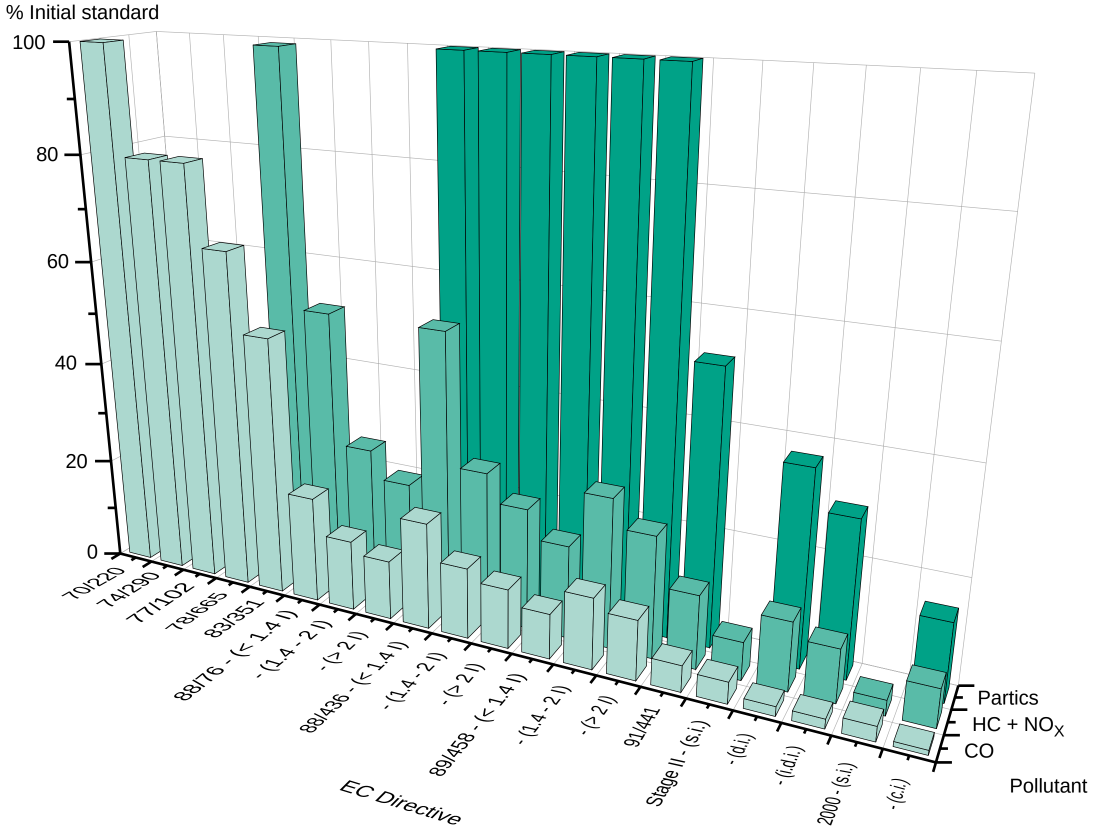
A.2.4 Light Duty Vehicle Standards

Following the Luxembourg Agreement the EC introduced a series of Directives aimed at tightening up the requirements for small and medium sized cars but these actually had little material effect as the emissions regulations were brought together under the consolidated Directive 91/441/EEC (European Community, 1991a). This Directive effectively mandates the fitting of closed loop three-way catalysts to all petrol cars, irrespective of size. The emissions limits are summarised in Table A.1. The gradual tightening of car emission standards is shown in Figure A.1.

Table A.1 Directive 91/441/EEC Limit Values.

	CO g/km	HC+ NO_x g/km	PM g/km
Type approval 1 July 1992	2.72	0.97	0.18
Entry into service 31 December 1992	3.16	1.13	0.14

Figure A.1 EC Passenger Car Exhaust Emission Standards 1970-.



A.2.5 Heavy Duty Vehicles

Legislation on heavy duty diesel vehicles has followed along a similar path to that on light duty vehicles. In 1982, ECE Regulation No.49 (UNECE, 1982) was introduced, aimed specifically at diesel-engined vehicles over 3.5 tonnes maximum mass. It established limits for CO, HC and NO_X. The limits are shown in Table A.2.

Table A.2 Regulation No.49 Limit Values.

	CO g/kWh	HC g/kWh	NO_X g/kWh
Type approval	11.2	2.4	14.4
Entry into service	12.3	2.6	15.8

The UK, along with several other Member States, did not introduce these limits into national law, but Directive 88/77/EEC, which closely mirrored the technical requirements of ECE Regulation No.49 and with limit values for CO and NO_X reduced by 20% and HC by 30%, was introduced in 1990.

A.2.6 Heavy Duty Vehicle Standards

Directive 91/542/EEC (European Community, 1991b) introduced limit values for particulates for the first time and, additionally, applied a two-stage reduction in limit values for mandatory introduction in 1992/93 (Stage I) and in 1995/96 (Stage II). (See Table A.3).

Table A.3 Directive 91/542/EEC Limit Values.

	Stage I		Stage II
	Type approval	Entry into service	Type approval & entry into service
g/kWh			
CO	4.5	4.9	4.0
HC	1.1	1.23	1.1
NO_X	8.0	9.0	7.0
PM ≤85kW	0.61	0.68	0.15
PM >85kW	0.36	0.4	
Type Approval date:	July '92		Oct '95
Entry Into Service date:	Oct '93	Oct '96	

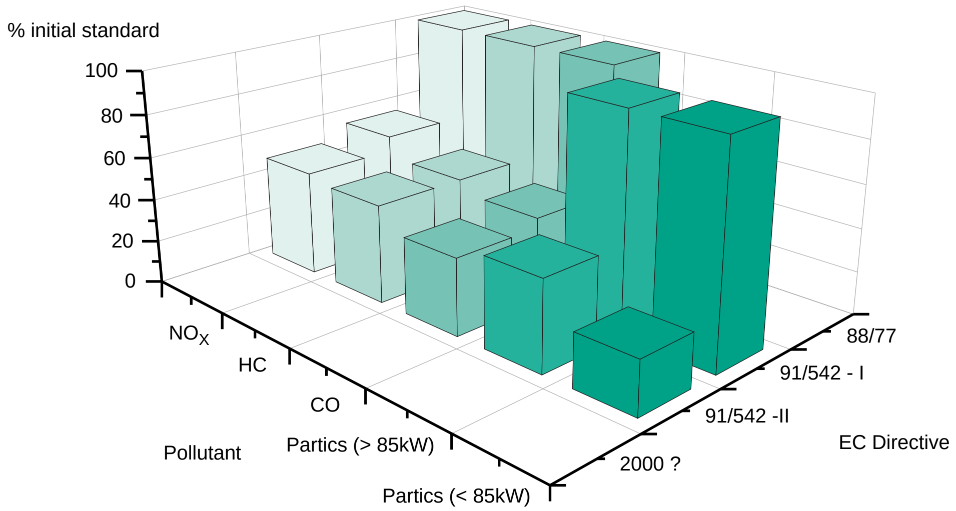
To remove one of the obstacles in the development of traps, catalytic traps in particular, Directive 91/542/EEC permits manufacturers the option to certify on low-sulphur (0.05% by weight) fuel. Directive 93/12/EEC on diesel fuel quality amends Directive 75/716/EEC (as amended by Directive 87/219/EEC) and requires the widespread introduction of low-sulphur fuel by 1 October 1996 so that engines in use would have access to supplies of this fuel to enable their emissions systems to operate to maximum effect.

The gradual tightening of heavy duty diesel engined vehicle standards is shown in Figure A.2.

A.3 RECENT MEASURES

New EC type approval emission directives are imminent that will come into effect before 1996 and further measures are being discussed in the Commission's Motor Vehicle Emissions Group for implementation by the year 2000.

Figure A.2 EC Heavy Duty Diesel Engine Standards 1988-.



A.3.1 The 'Vans' Directive

A new directive, 93/59/EEC, the so-called 'Vans' Directive (European Community, 1993) was adopted on 28 June 1993. Effective for new type approvals from 1 October 1993 and for all vehicles entering into service from 1 October 1994, it applies limits to light vans and commercial vehicles below 3.5 tonnes of similar technical severity to those for cars (Table A.4).

Table A.4 'Vans' Directive Emission Limits.

Mass kg	Dates	CO g/km	$HC+NO_X$ g/km	PM g/km
≤1250	Type approval	2.72	0.97	0.14
	Entry into service	3.16	1.13	0.18
1251-1700	Type approval	5.17	l.4	0.19
	Entry into service	6.0	1.6	0.22
>1700	Type approval	6.9	1.7	0.25
	Entry into service	8.0	2.0	0.29

Its primary aim is to remove an anomaly in Directive 91/441/EEC which allows a car-derived van to comply with less stringent limits than an equivalent catalyst-equipped passenger car. In tightening the limits for the heavier vehicles, although higher than for cars, a similar regime of emissions control technology is applied.

A.3.2 New Car Limits for 1995/96

In February this year the Commission issued a new draft directive aimed at tightening the car limits yet further (see Table A.5). This Directive (European Community, 1992a) is significant in that it also incorporates a totally new annex for conformity of production (COP) testing which may well form the basis for COP testing in many other directives not necessarily confined to emissions testing.

Table A.5 1995/96 Emission Limits.

Category	M (*)	
Mass	all	
Dates	Type approval - 1 January 1995 Entry into service - 1 January 1996	
CO (g/km)	Petrol	2.2
	Diesel	1.0
$HC+NO_X$ (g/km)	Petrol	0.5
	Diesel	0.7 (**)
PM (g/km)	Diesel	0.08 (**)

(*) Except - vehicles designed to carry more than 6 occupants including the driver
- vehicles whose maximum mass exceeds 2500kg

(**) For vehicles fitted with direct injection diesel engines, the $HC+NO_X$ limit is 0.9 g/km and the particulate limit is 0.10 g/km until 30 September 1999.

A.4 TOWARDS THE YEAR 2000

It is likely that yet more stringent emission standards will be introduced for passenger cars around the year 2000. In addition, it appears probable that there will be tighter fuel specifications in line with the greater impact of fuel quality on emissions from low emitting cars. The emission standards are likely to be roughly equivalent to those permitted for California's ultra low emitting vehicles.

A.4.1 Test Cycles - Heavy Duty Vehicles

The 13-mode steady-state test has served emission control from heavy duty vehicles well in the past, but as limits tighten and technology advances the doubts are emerging as to whether a steady-state test can continue to offer the degree of control needed, especially for particulates, in the years beyond 1996.

In September 1992 the Royal Commission on Environmental Pollution, in its report on emissions from heavy duty diesel vehicles (RCEP, 1991), concluded that ‘It will not provide a reliable indication of the likely emissions performance on the road of an engine which is fitted with electronic controls, turbocharging or exhaust aftertreatment, still less one which is fitted with all three ...’. In consequence, the Department of Transport is chairing a sub-group under the auspices of the ECE vehicle emissions group, with the remit to investigate typical driving patterns of vehicles in everyday use and recommend a test cycle that can adequately represent the emissions characteristics of such vehicles. Should this work prove that a transient cycle of whatever form is necessary, then the eventual objective will be to replace the 13-mode cycle within ECE Regulation No.49 (now Regulation No.49.02) and EC Directive 91/542/EEC and adopt new emission limits appropriate for the year 2000.

A.4.2 Fuel Quality

Directive 75/716/EEC (as amended by Directive 87/219/EEC) introduced a limit of 0.3% by weight of sulphur in gasoils from 1 January 1989. In order to achieve the stringent particulate emissions limits set for heavy diesel engined vehicles Directive 93/12/EEC further reduces the sulphur content limit to 0.2% by weight as from 1 October 1994 and to 0.05% by weight as from 1 October 1996.

Limits for cetane number and other properties of automotive diesel fuel are recommended in BS 2869: Part 1: 1988 (British Standards Institution, 1988) although at the time of writing this standard is not legally enforceable in the UK. As noted below, once the CEN (European Committee for Standardisation) standard for diesel is adopted by the UK, and as recommended by the Royal Commission on Environmental Pollution, its requirements will be written into UK law.

CEN have also been developing a European standard for diesel fuel for introduction in 1996. All properties of diesel fuel have been considered including the major characteristics of cetane number, density, sulphur content, volatility and viscosity. This work is complete and a final communication from CEN is awaited before this standard can be adopted by the British Standards Institution later this year.

A.4.3 Carbon Dioxide Emissions

A number of measures have existed for many years aimed at promoting fuel economy, but Directive 91/441/EEC (specifically Article 5) broke new ground with a request to the Commission to bring forward proposals designed to limit CO_2 emissions from motor vehicles. Proposals are under discussion.

A.5 IN-SERVICE INSPECTION AND MAINTENANCE

Apart from new vehicle standards, the EC Council are taking steps to ensure that complex engine systems are maintained in good working order throughout a vehicle's life. They adopted the roadworthiness Directive

92/55/EEC (European Community, 1992b) in June 1992. This sets in-service standards for both petrol- and diesel-powered vehicles to be implemented by Member States between 1 January 1994 and 1 January 1997, depending on vehicle class (see Table A.6).

Table A.6 Requirements of Roadworthiness, Directive 92/55/EEC.

Vehicle	Date	Type of test
Petrol non-catalyst	1 January 1994	visual check
		CO check at idle speed
		CO = 4.5% pre Oct '86 and 3.5% post Oct '86
Diesel all sizes	1 January 1996	free acceleration test
		limits as plated value or $2.5m^{-1}$ for naturally aspirated engines and $3.0m^{-1}$ for turbos
Petrol catalyst	1 January 1997	visual check
		CO checks at idle and high idle of at least 2000rpm
		CO = manufacturer's specification or 0.5% at idle and 0.3% at high idle
		additional check on λ ratio to 1 ± 0.03

A.6 AIR QUALITY STANDARDS

There are long standing European statutory air quality standards for suspended particulates (black smoke) in combination with sulphur dioxide, and for lead, nitrogen dioxide and ozone. Table A.7 sets out these standards.

A.7 CONCLUSIONS

Substantial advances in vehicle emission control technology have been made, and are still being made in response to ever increasing legislation. Whilst progress will continue to be made up to the year 2000, it is becoming increasingly recognised that the emphasis must start to move away from the preoccupation with type approval standards. It is the standards achieved by vehicles in use which will have the greatest impact on environmental pollution. In moving towards the turn of the century, it is expected that the EC will continue to address new type approval standards, but fuel quality, conformity of series production vehicles, in-use testing and on-board vehicle diagnostic systems will receive a much greater focus of attention.

REFERENCES

British Standards Institution (1971) **Specification for the Performance of Diesel Engines for Road Vehicles**, BS Au141a.

British Standards Institution (1988) British Standard, **Specification for Automotive Diesel Fuel (Class A1)**, BS 2869: Part 1.

European Community (1970) **EC Directive 70/220/EEC**, Official Journal of the European Communities, L76, 1.

Table A.7 European Air Quality Standards.

Pollutant	Regulation	Type	Period	Value ($\mu g/m^3$)
Nitrogen Dioxide	85/203/EEC	Limit Value Guide Value	98th percentile of yearly mean hourly concentrations	200 135
		Guide Value	50th percentile of yearly mean hourly concentration	50
Lead	82/884/EEC	Limit Value	Annual mean	2
Sulphur Dioxide	80/779/EEC	Limit Value	98th percentile of yearly mean daily concentrations	350
		Limit Value	50th percentile of yearly mean daily concentrations	120
		Guide Value	24 hour mean	100-150
		Guide Value	Annual mean	40-60
Smoke*	80/779/EEC	Limit Value	Annual mean Limit Value	80 40
Ozone	92/72/EEC	Health Protection Threshold	8 hour mean	110
		Vegetation Protection Threshold	1 hour mean 24 hour mean	200 65
		Population Information Threshold	1 hour mean	180
		Population Warning Threshold	1 hour mean	360

* Smoke expressed according to OECD calibration

European Community (1972) **EC Directive 72/306/EEC**, Official Journal of the European Communities, L190, 1.

European Community (1991a) **EC Directive 91/441/EEC**, Official Journal of the European Communities, L242, 1.

European Community (1991b) **EC Directive 91/542/EEC**, Official Journal of the European Communities, L295, 1.

European Community (1992a) **Proposal for Council Directive, COM (92) 572 Final SYN 448**, 23 December 1992.

European Community (1992b) **EC Directive 92/55/EEC**, Official Journal of the European Communities, L225, II.

European Community (1993) **Proposal for Council Directive, 4063/1/93**, 1 February 1993.

Her Majesty's Government (1986) **The Road Vehicles (Construction and Use) Regulations**, Statutory Instrument No.1078, HMSO, London.

RCEP (1991) **15th Report on Emissions from Heavy Duty Diesel Vehicles**, HMSO, London.

UNECE (1970) **ECE Regulation No.15, Addendum 14**, 30 January 1970.

UNECE (1982) **ECE Regulation No.49, Addendum 48**, 5 April 1982.

B Emissions of Particulate Matter

The terms used to describe particulate matter were summarised in the First QUARG Report (1993) as follows:

Suspended Particulate Matter (SPM), a general term embracing all airborne particles.

Aerosol, a suspension of particles in a gas.

Total Suspended Particulates (TSP), a term describing the gravimetrically determined mass loading of airborne particles, most commonly associated with use of the US high volume air sampler in which particles are collected on a filter for weighing.

PM_{10}, particulate matter less than 10µm aerodynamic diameter (or, more strictly, particles which pass through a size selective inlet with a 50% efficiency cut-off at 10µm aerodynamic diameter).

Smoke, particulate matter, <15µm, derived from the incomplete combustion of fuels.

Black Smoke, non-reflective (dark) particulate matter, associated with the smoke stain measurement method, described later.

Inhalable Particles (also termed respirable), particles which may be breathed in - inhalability is the orientation-averaged aspiration efficiency for the human head.

Respirable Particles, particles which can penetrate to the unciliated regions of the deep lung.

Thoracic Particle Mass, describes that fraction of the particles which penetrates beyond the nasopharynx and larynx.

In connection with the estimation of vehicle emissions, the difference between 'smoke' and 'black smoke' needs to be emphasised. The term 'smoke' refers to primary particles irrespective of their darkness. However, because measurements of airborne smoke by the smoke stain test depend upon the blackening of a filter paper, the term 'black smoke' (or dark smoke) was introduced to allow for the different soiling capacities of smoke particles from different sources. 'Black smoke' is calculated by multiplying the mass or concentration of smoke by a soiling factor.

Calculations of emissions can be made as follows. Table B.1 shows relevant emission factors. Emissions are then calculated as shown in Table B.2.

Extending this approach to data from 1981-1991 generates Figures B.1 and B.2, which clearly display the differing vehicular contributions to smoke and black smoke emissions, and emphasise the need to distinguish between these two types of particulate matter. It needs to be remembered that the monitoring technique will record only one of

Table B.1 Smoke Emission Factors and Relative Soiling Factors for Vehicle Fuel Used in the UK.

	Smoke emission factor (% by mass)	Soiling factor relative to coal	Black smoke emission factor (% by mass)
Motor spirit	0.15	0.43	0.065
Diesel fuel	0.6	3.0	1.8

the particulate matter types described above, eg the smoke stain technique BS1747 measures black smoke whereas the Tapered Element Oscillating Microbalance used in the enhanced urban network measures gravimetric PM_{10} levels which are likely to be close to smoke levels. Figure B.3 shows trends in black smoke emissions from petrol and diesel vehicles since 1981.

Table B.2 Smoke and Dark Smoke Emissions from Motor Vehicles in 1991.

	Fuel consumption (tonnes)	Smoke emission (tonnes)	Black smoke emission (tonnes)
Motor spirit	24×10^6	36×10^3	15×10^3
Diesel fuel	10.7×10^6	64×10^3	192×10^3

Figure B.1 Smoke Emissions UK.

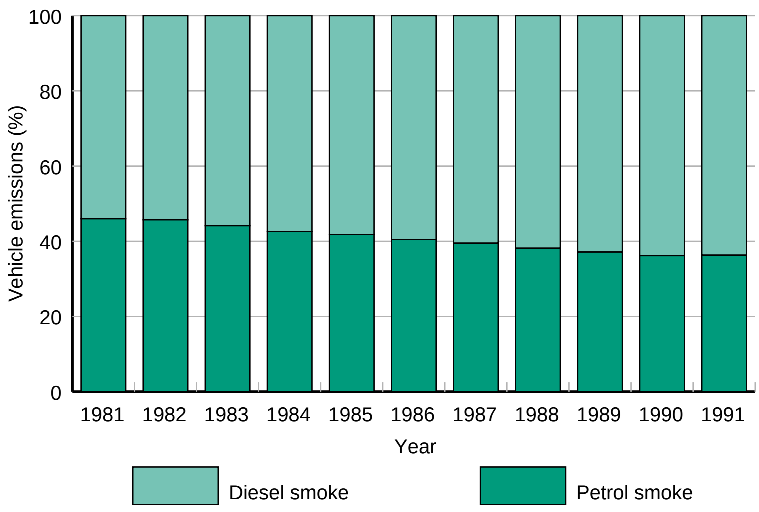


Figure B.2 Black Smoke Emissions UK.

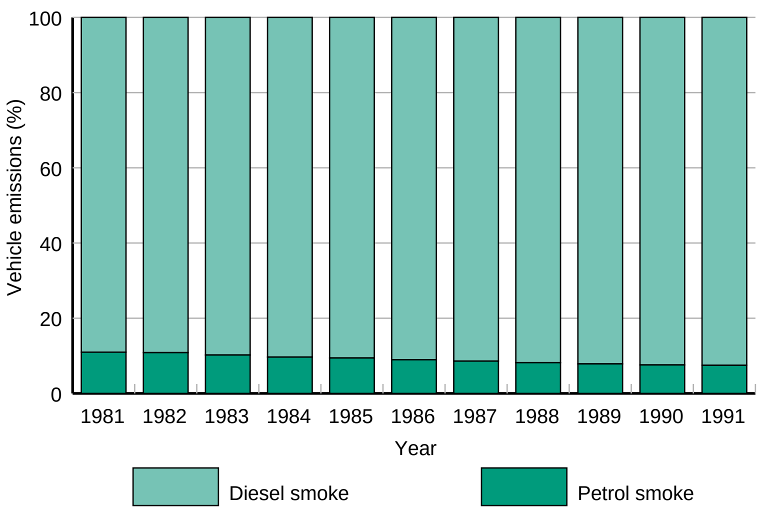
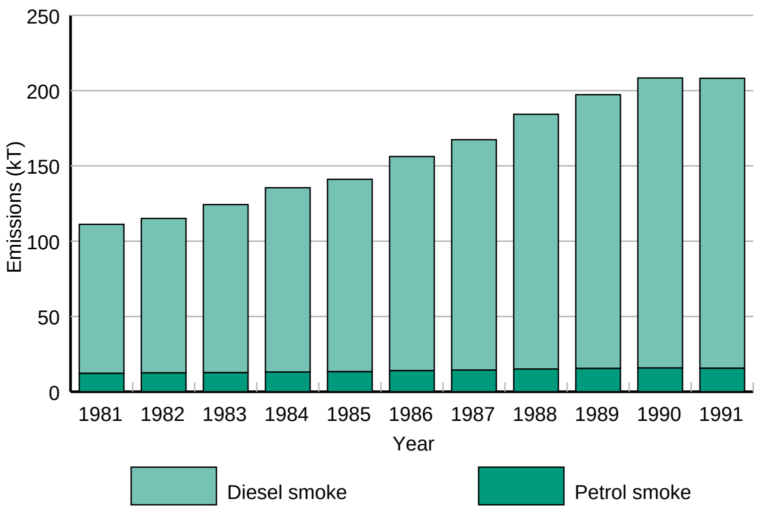


Figure B.3 Trends in UK Black Smoke Emissions.



C Terms of Reference and Membership

TERMS OF REFERENCE

1. The UK Review Group on Urban Air Quality is a working group of experts established by the Department of the Environment to review current knowledge on urban air quality and to make recommendations to the Secretary of State for the Environment.

2. The initial objective of the Group is to prepare a review of urban air quality and how it is assessed in the United Kingdom especially in relation to public exposure, and how this information is passed on to the public. To this end the Group will consider:

   i) the pollutants measured,

   ii) the extent of monitoring networks,

   iii) the consistency of data,

   iv) the types and location of monitoring equipment and

   v) any other relevant material.

3. The longer term objectives of the Group will be to:

   i) perform a rolling review of the subject in the light of scientific and technological developments,

   ii) consider, in the light of national and international guidelines and advice, the need to add or subtract sites from the networks and the need for additional networks for different pollutants and

   iii) to consider arrangements for the public availability of data.

4. The Group will identify areas of uncertainty and recommend where further research is needed.

5. The Group will make recommendations for changes to relevant monitoring networks and public information systems.

6. The Group will act as an informal forum for the discussion of research plans and results.

7. The Group will act as a point of liaison with relevant international bodies.

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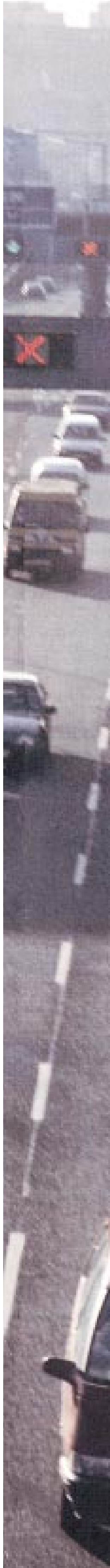

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