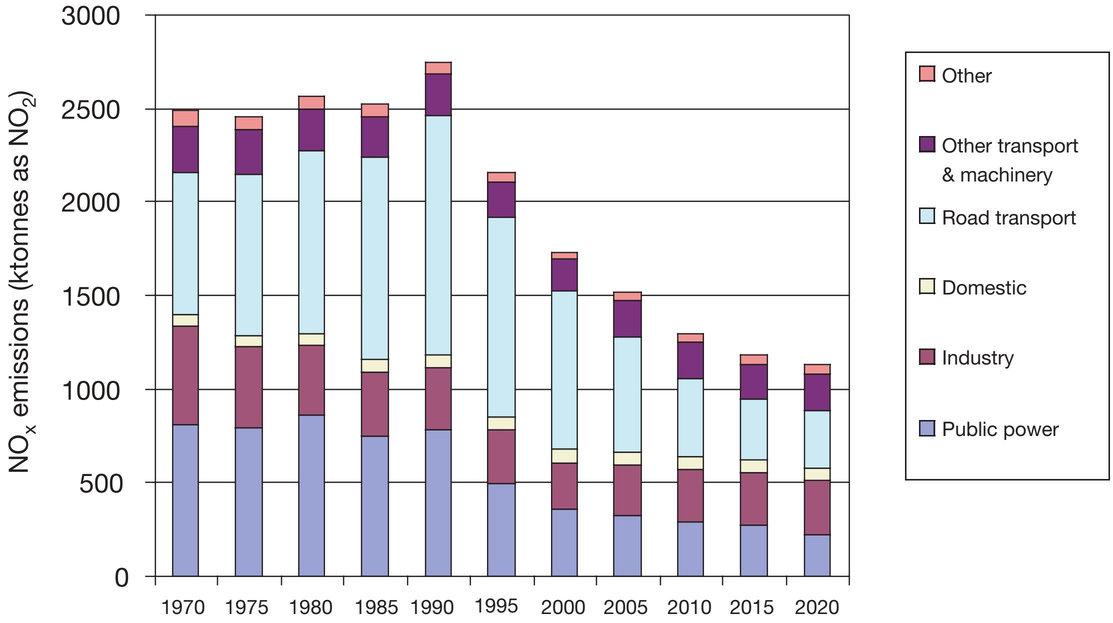
Chapter 2

NO_x emissions and emission inventories

Key points

Figure 2.1 shows the time series of NO_x emissions in the UK from 1970 projected to 2020.

Figure 2.1 NO_x emissions in the UK by source from 1970–2020.



- Emissions of NO_x have fallen by 37% from 1990 to 2000. This has been mainly due to reductions in emissions from road transport and public power generation.
- Road transport is the largest source of NO_x emissions in the UK, contributing 49% of total emissions in 2000. However, emissions from road transport have fallen by 34% between 1990 and 2000 due to improvements in engine design and fitting of three-way catalysts to petrol cars driven by increasingly tighter European vehicle emission standards.
- The contribution of road transport to NO_x emissions in urban areas is generally higher than the national average. In London, 68% of NO_x emissions come from road transport.
- Total UK NO_x emissions are projected to fall by a further 25% from 2000 levels by 2010. This is largely driven by a continuing decline in emissions from road transport as vehicles meeting tighter emission standards penetrate the UK fleet.
- Emissions of NO_x from road transport in London are predicted to decline by 53% from 1999 levels by 2010. This compares with a predicted decline of 49% in emissions from total urban UK road transport emissions over the same period. Little, if any, decline is expected in emissions from other sources in London.

- The total UK NO_x emission projections depend critically on assumptions based on traffic growth, energy demand and fuel mix for electricity generation, as well as emission performance of new vehicles, especially heavy duty diesel vehicles, and implementation of the EC's Large Combustion Plant Directive. The assumptions underlying the emission projections will need to be continuously monitored in order to ensure the UK complies with the emission targets for 2010 set in the Gothenburg Protocol and National Emissions Ceilings Directive.
- Heavy duty diesel vehicles currently emit 43% of NO_x emissions from UK road transport, but these figures are based on relatively few real world emission tests on these vehicles. Evidence suggesting that real-world NO_x emissions from HGVs and buses have changed little during the 1990s from pre-Euro I to Euro II standards needs verification with further tests.
- Local and spatially resolved inventories help identify pollution 'hot spots' and provide vital input data to atmospheric dispersion models. Considerable advances have been made in spatially resolving emission estimates. Local inventories need to be regularly updated and developed using a consistent approach.
- Uncertainties in national emission estimates need to be continuously re-evaluated. Current assessments suggest a ±7% uncertainty in total UK NO_x emission estimates for 2000 at the 95% confidence level. However, uncertainties of emissions from specific sources and their spatial distribution are much higher than this and need to be carefully considered in any inventories developed for local air quality modelling.
- There is evidence for significant amounts of NO_2 emitted directly from the tailpipe of diesel vehicles, with levels possibly as high as 25% of total NO_x emissions in mass terms. This will have a significant impact on roadside NO_2 concentrations in areas where there is considerable diesel vehicle activity and this needs to be taken into account in modelling of ambient concentrations. The effect of new exhaust after-treatment technologies on primary NO_2 emissions from diesel exhaust needs to be monitored, especially catalytically regenerating traps used to reduce particulate emissions.
- Current evidence suggests that increasing the diesel car penetration rate in the UK fleet would lead to a small increase in NO_x emissions from road traffic in urban areas, but a more significant increase in primary NO_2 emissions. An increase in diesel car sales in 2010 from 22% of new car sales (close to the current rate) to 30% would increase urban UK road transport emissions of NO_x in 2010 by 0.7% and NO_2 emissions by 3%.

2.1 Introduction

22. Almost all of the NO_x emitted to air in the form of NO and NO_2 are from combustion sources. Collectively, these two species are referred to as NO_x ($NO_x = NO + NO_2$). Combustion sources may also emit small quantities of nitrous acid (HONO) which is also photochemically active in the atmosphere. This chapter discusses the main sources of NO_x emissions and the fundamentals of NO_x formation in combustion systems. It also discusses some of the main abatement options that are used in the UK to control NO_x emissions from different sources. Different technologies for reducing NO_x emissions are available for both stationary and mobile sources. These are discussed in the context of the regulatory framework setting limits on emissions from specific sources in the UK and Europe as well as the national emission targets which countries in Europe must achieve by the year 2010.

23. Emission inventories are an important means of quantifying emissions of NO_x from different sources in different locations. These provide the necessary input data for atmospheric models predicting NO_2 concentrations and photochemical activity in general at different geographical scales. Emission inventories are produced at European, national and regional and local levels using common methodologies, but using information at different levels of geographical detail. The principles and methodologies behind the inventories compiled in the UK are discussed, with particular attention given to the sources of information used to compile the inventories from mobile and stationary combustion sources. The time series of NO_x emissions in the UK from 1970 to 2000 is shown, broken down by emission source sector. This information is vital for explaining the trends in emissions over the past 30 years and for directing future policy making in areas that will affect emissions and air quality in future years.

24. Some of the principles behind the development of spatially resolved local inventories and differences that occur with the national emission maps are discussed. The national inventory for the UK is currently mapped on a 1x1 km spatial scale. Both this and more detailed local inventories play a key role in local policy making and understanding of ambient concentrations of NO_x and NO_2. Local inventories produced for different areas of the UK are discussed, with particular attention given to the London Atmospheric Emissions Inventory. These play a key role in local scale modelling of air quality in the UK.

25. It is important to understand the nature and extent of uncertainties in the NO_x emission estimates, both in individual sources and in the overall UK inventory, if the results are to be compared each year and the potential impact of measures to reduce emissions are to be understood in terms of their impact on ambient concentrations. A rigorous, quantitative analysis of the uncertainties in the overall national emission estimates has been undertaken using statistical methods. The results will help to prioritise future work by pointing to those areas where further information is required to improve the reliability of the inventory. Uncertainties in emission estimates in local areas are of more consequence to local air quality modelling of pollutant concentrations and are usually of greater magnitude than the uncertainties in the national emission totals. Consideration is given to the factors influencing uncertainties in modelling the spatial distribution of emissions.

26. Emission projections are used to inform Government policy and to forecast the likelihood of attaining the UK's emissions targets for 2010. They are one of the principal drivers in forecasting the UK's air pollution climate and achievement of air quality objectives. The UK's base emission projections for NO_x take account of current Government policies, European Directives and Regulations on emissions, technology improvements and current understanding of future growth in energy demand, transport and industrial activity. The base projections for UK emissions in 2005, 2010, 2015 and 2020 are shown, as well as emissions forecasts for specific urban areas like London. The UK projections for 2010 are put into context with the country's emission targets set in terms of the National Emissions Ceilings Directive. Road transport is a major contributor of NO_x emissions in urban areas and illustrative transport scenarios have been assessed to highlight the sensitivity of projected urban NO_x emissions to key transport factors.

27. Combustion sources emit NO_x mostly in the form of NO. However, for some sources, especially road vehicles, direct emissions of NO_2 appear to be significant. This chapter points to evidence for direct NO_2 emissions from road vehicles based on tailpipe emission measurements. There may also be evidence for direct emissions of HONO from vehicles. The conditions and technologies that favour NO_2 emissions from vehicle exhausts are discussed. The extent of primary NO_2 emissions from other sources such as stationary combustion has not been considered as no new evidence of these as significant sources of primary NO_2 has emerged.

28. Combustion sources can also emit NO_x in the form of nitrous oxide (N_2O). This is an inert and relatively harmless compound which takes no part in ground-level photochemical activity. However, there are concerns over its emissions because it is a potent greenhouse gas implicated in potential global climatic changes. Some abatement technologies designed to reduce NO_x emissions can lead to higher emissions of N_2O as a by-product of the NO_x control process. This report is not primarily concerned with N_2O, but the secondary effects of NO_x control measures on emission projections of N_2O in the UK are briefly discussed. Similarly, the possible secondary effects that certain NO_x abatement technologies may have on ammonia (NH_3) and primary NO_2 emissions are also briefly discussed.

2.2 NO_x formation in combustion sources

29. Combustion of fossil fuels is by far the dominant source of NO_x emissions. There are three main mechanisms by which NO_x is formed in combustion systems (Miller and Bowman, 1989). Thermal-NO and prompt-NO mechanisms produce NO_x by the high temperature oxidation of elemental nitrogen present in the combustion air. Fuel-NO is formed from nitrogen chemically bound in certain fuels. High temperatures and oxidation-rich conditions generally favour NO_x formation in combustion.

2.2.1 Thermal-NO mechanism

30. Formation of NO by the thermal-NO mechanism is initiated by the reaction of O atoms with N_2:

$$O + N_2 \rightarrow N + NO$$

$$N + O_2 \rightarrow O + NO$$

$$N + OH \rightarrow H + NO$$

31. This process is also known as the Zel'dovich mechanism (Zel'dovich, 1946). The initial step is the rate determining step in the mechanism, influencing the amount of NO which gets formed. O atoms are abundant in combustion systems under oxygen rich and near-stoichiometric conditions, but the rate of the reaction with N_2 is highly dependent on temperature, reflecting the high activation energy of the $O + N_2$ reaction. The reaction is extremely slow at low combustion temperatures, but increasing the temperature rapidly increases the rate of the reaction. For example, increasing temperature from 1200°C to 2000°C increases the rate of this reaction by a factor of ten thousand (Baulch *et al*., 1994). Hence, controlling combustion temperature in the flame is one means of controlling the amount of NO_x which is produced. NO forms by this process in both the flame front itself and in the postflame gases (Heywood, 1988). However, NO formation in the hot postflame gases usually dominates any flamefront-produced NO.

2.2.2 Prompt-NO mechanism

32. The prompt-NO mechanism forms NO from nitrogen much earlier in the flame than the thermal-NO mechanism, as its name suggests. The mechanism is initiated by the reaction of CH radicals with N_2:

$$CH + N_2 \rightarrow HCN + N$$

33. Both N and HCN react rapidly with oxidant to form NO in the flame. CH radicals are formed as intermediates in the combustion of hydrocarbons, but compared with O atoms, only small concentrations of CH radicals are formed. However, the reaction of CH with N_2 is much faster at low temperatures and the rate shows a much lower dependence on temperature due to its lower activation energy. Hence, they lead to NO being formed earlier in the flame (Miller and Bowman, 1989; Fenimore, 1971; Hayhurst and Vince, 1980).

34. Overall, the amount of NO formed by the prompt-NO mechanism is small compared with the amount formed by the thermal-NO route because of the lower abundance of CH radicals in the flame. However, it makes a significant contribution under fuel-rich conditions when higher concentrations of hydrocarbon radical species like CH are present.

2.2.3 Fuel-NO mechanism

35. Certain fuels contain appreciable amounts of nitrogen chemically bound in the fuel. For example, coal contains 0.5 to 2% nitrogen by weight chemically bound in large heterocyclic compounds with pyridine and pyrrole-type structures and aromatic amines (Solomon and Colket, 1978). A fraction of the nitrogen compounds is released into the gas-phase through the process of devolatilisation when the coal particles are heated. As they are released, the fuel-nitrogen undergoes rapid pyrolysis to form small nitrogen compounds such as hydrogen cyanide (HCN), CN radicals and ammonia (NH_3). These species are then rapidly converted to NO_x by a complex sequence of reactions involving the small gas-phase radicals (O, OH, H) produced in the main combustion process (Miller and Bowman, 1989). Additional NO_x is produced by heterogeneous oxidation of the nitrogen remaining in the coal char particles (Pershing and Wendt, 1977; Wendt, 1980). Unless combustion conditions are controlled, the fuel-NO mechanism leads to very significant amounts of NO_x being formed in the flame. The nitrogen content of petroleum-based fuels is usually lower then in coal, but varies significantly from less than 0.05% in light distillates (for example, diesel) to 1.5% in some heavy fuel oils. Fuel nitrogen is virtually absent in gaseous fuels. Consequently, the amount of fuel-NO produced in gas combustion is negligible compared with the amounts produced in coal combustion.

2.2.4 Formation of NO_2 in combustion

36. Nitrogen oxides formed in combustion systems by these mechanisms are mainly released in the form of NO. As a general rule of thumb, it is assumed that about 5% of NO_x released from combustion is in the form of NO_2, although this assumption for many sources still remains poorly quantified. While this is usually the case in many systems, there are certain combustion conditions that can lead to higher proportions of NO_x emitted as NO_2. There is also evidence that small amounts of nitrous oxide (N_2O) and nitrous acid (HONO) are emitted from combustion systems (Miller and Bowman, 1989, and references therein; see also Section 2.6.2.7).

37. NO_2 is readily formed in combustion systems if the conditions are favourable. A combustion system that has pockets of gas at low temperatures under oxygen rich conditions are those conditions which favour formation of NO_2.

38. NO formed in the high temperature flame zone can be rapidly converted to NO_2 via the reaction:

$$NO + HO_2 \rightarrow NO_2 + OH$$

39. However, HO_2 is only abundant in low temperature combustion regions and any NO_2 which is formed is readily removed by reaction with other combustion radicals, for example, O and H, and converted back to NO:

$$NO_2 + O \rightarrow NO + O_2$$

40. Hence, in combustion systems that are well-mixed, most of the NO_x remains as NO. This is generally the case for burners and spark-ignition engines. However, in compression-ignition diesel engines, combustion does not generally occur in such a well-mixed environment and cooler regions exist which quench the combustion chemistry (Heywood, 1988). Then, NO formed in the flame may react to form NO_2, but the conversion of NO_2 back to NO is quenched in the cooler regions. It has been previously found that the highest NO_2/NO ratio occurs in a diesel engine at light load, where cooler regions are more widespread. Early engine research showed that as much as 30% of NO_x is emitted as NO_2 from a diesel engine at low engine speed and light load (Hilliard and Wheeler, 1979). The oxygen rich environment of combustion in a diesel engine also aids formation of NO_2.

41. If NO concentrations are high in the presence of excess oxygen downstream of the engine or burner in the tailpipe or flue gas, NO_2 can be formed by the reaction:

$$NO + NO + O_2 \rightarrow 2\ NO_2$$

42. The rate of this reaction is quite slow at the NO concentration levels found in the exhaust pipe and has a weak negative temperature dependence (Atkinson and Lloyd, 1984). To illustrate this point, for typical NO concentrations of 500 ppm found in the presence of excess oxygen in the tailpipe of a heavy duty diesel vehicle, it would take at least 5 seconds for 1% of the NO to be converted to NO_2 by this reaction. This is a conservative lower limit on the NO conversion time. It should also be noted that the thermodynamics favours NO over NO_2 at higher temperatures.

2.3 Emission sources and regulatory framework

43. The major emission sources of NO_x in the UK are combustion for public power generation, combustion in industry and road transport. These were responsible for 82% of all UK NO_x emissions in 2000 and it is in these areas where most effort has been undertaken in reducing emissions (Goodwin *et al*., 2002).

44. Reductions in emissions of NO_x from stationary combustion and mobile sources have been driven by various national regulations and European Directives covering different emission sources combined with international protocols aimed at achieving emission targets in each country for future years.

45. Emissions from stationary combustion plant in the UK have been regulated under the Environmental Protection Act 1990. Integrated Pollution Control (IPC) is a system established under Part I of the Act to control pollution from industry. It applies to Part A processes which are potentially the most polluting or technologically complex processes in England and Wales and is enforced by the Environment Agency. A parallel, but separate, system of IPC is used in Scotland and enforced by the Scottish Environment Protection Agency, SEPA. IPC is concerned with the release of polluting substances to air, land and water. Part B processes, also covered under the Environmental Protection Act, refer to less polluting, less complex processes and these are regulated by local government. In Scotland, Part B processes are being regulated by SEPA under the Pollution Prevention and Control (Scotland) Regulations 2000 (PPC). Although less important in a national context, these processes can be influential in a local context.

46. Directives regulating emissions from new petrol passenger cars have been around since the 1970's, but these focused on CO and hydrocarbon emissions. It is only since the early 1990's that tough standards on NO_x emissions from new cars sold in Europe were introduced. This first came about with EU Directive 91/441/EC which effectively mandated the fitting of three-way catalysts to all new petrol cars to significantly reduce emissions of CO, hydrocarbons and

NO_x (Official Journal, 1991). This Directive set limits on the sum of hydrocarbon and NO_x emissions, rather than NO_x itself, but it did lead to very substantial decreases in NO_x emissions. Standards for this Directive, frequently referred to as Euro I, were followed by Euro II standards implemented by Directive 94/12/EC during the mid-90s. Yet more stringent EU Directives have been put in place to reduce NO_x emissions further, the most recent of these (98/69/EC) setting emission limits on NO_x itself for petrol cars sold after 2000 and then after 2005 (Euro III and Euro IV standards, respectively (Official Journal, 1998)).

47. NO_x emissions from diesel vehicles have also been regulated since the early 1990's (since 1988 for heavy duty diesel vehicles). These have been tightened up with the introduction of a succession of more stringent EU Directives, currently extending to tougher limits on emissions from heavy duty vehicles sold after 2008 (Official Journal, 1999). However, none of the emission reductions required to meet the tighter standards on diesel vehicles have been as dramatic as the 91/441/EC Directive was on petrol cars in the early 1990s.

48. Table 2.1 shows the limit values on NO_x, hydrocarbons (HC) and particulate matter (PM) set by the various Directives for the different vehicle types since 1990. The limit values for each Euro standard refer to tests over specified vehicle or engine test cycles, some of which have changed in recent years in order to make the test more representative of the performance of the vehicle on real road conditions.

49. As well as regulations on emissions from specific sources, the UK is subject to certain national emission targets to be achieved by 2010. In the mid-1990s, the UNECE started negotiating a multieffect, multipollutant protocol on NO_x and related substances. This was aimed at addressing photochemical pollution, acidification and eutrophication. The Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone was adopted in Gothenburg in December 1999, where it was signed by the UK. The Gothenburg Protocol set emissions ceilings for nitrogen and sulphur oxides, ammonia and NMVOCs to be achieved by each country by 2010. The Gothenburg Protocol forms a part of the Convention on Long-Range Transboundary Air Pollution (UNECE, 1999).

50. Within the EU, the National Emissions Ceilings Directive (NECD) set emissions ceilings for 2010 for each Member State for the same four pollutants as in the Gothenburg Protocol (Official Journal, 2001). A number of Member States reduced their ceilings somewhat below the levels included in the Protocol. The UK reduced its ceiling for NO_x emissions from 1181 ktonnes (as NO_2) set in the Gothenburg Protocol to 1167 ktonnes for the NECD.

51. Within the UK, the implementation of the EC's Large Combustion Plant Directive and other associated policy measures have led to a substantial reduction in NO_x from power plant and industrial sources. This, combined with further stringent vehicle emission and fuel quality Directives being implemented over the next 10 years, will help the UK towards meeting its emission target. Integrated Pollution Prevention and Control (IPPC) is a system following the European Community Directive (96/91) which will introduce a more integrated approach to controlling pollution from industrial sources across the UK.

52. Section 2.7 provides a more detailed account of the inventory of NO_x emissions in the UK by sector and trends over time. Since 1990, emissions from public power generation, combustion in industry and road transport have been reduced by 49%. In the power generation and industrial combustion sectors, the reductions have been partially achieved through the switch from coal to gas. However, emission abatement technologies in remaining coal plant, gas turbines and road vehicles have made a significant contribution to these emission reductions.

Table 2.1 Emission limit values for different vehicle types in Europe since 1990. Dates of implementation refer to new registrations.

	Directive		Date of implementation		Test cycle	Units	NO_x*	HC*	NO_x + HC*	PM*
Petrol cars	91/441/EEC	Euro I	1/7/1992		ECE15 + EUDC	gkm^{-1}			0.97	
	94/12/EC	Euro II	1/1/1997		ECE15 + EUDC	gkm^{-1}			0.50	
	98/69/EC	Euro III	1/1/2001		ECE15 + EUDC	gkm^{-1}	0.15	0.20		
	98/69/EC	Euro IV	1/1/2006		ECE15 + EUDC	gkm^{-1}	0.08	0.10		
Diesel cars	91/441/EEC	Euro I	1/7/1992		ECE15 + EUDC	gkm^{-1}				0.14
	94/12/EC	Euro II	1/1/1997	IDI	ECE15 + EUDC	gkm^{-1}			0.70	0.08
				DI	ECE15 + EUDC				0.90	0.10
	98/69/EC	Euro III	1/1/2001		ECE15 + EUDC	gkm^{-1}	0.50		0.56	0.05
	98/69/EC	Euro IV	1/1/2006		ECE15 + EUDC	gkm^{-1}	0.25		0.30	0.025
Petrol vans	96/69/EEC	Euro II	1/1/1998	<1305kg	ECE15 + EUDC	gkm^{-1}			0.50	
			1/1/1998	1305 – 1760kg					0.65	
			1/1/1998	>1760kg					0.80	
	98/69/EC	Euro III	1/1/2001	<1305kg	ECE15 + EUDC	gkm^{-1}	0.15	0.20		
			1/1/2002	1305 – 1760kg			0.18	0.25		
			1/1/2002	>1760kg			0.21	0.29		
	98/69/EC	Euro IV	1/1/2006	<1305kg	ECE15 + EUDC	gkm^{-1}	0.08	0.10		
			1/1/2006	1305 – 1760kg			0.10	0.13		
			1/1/2006	>1760kg			0.11	0.16		
Diesel vans	93/59/EEC	Euro I	1/10/1994	<1305kg	ECE15 + EUDC	gkm^{-1}			0.97	0.14
			1/10/1994	1305 – 1760kg					1.40	0.19
			1/10/1994	>1760kg					1.70	0.25
	96/69/EEC	Euro II	1/1/1998	<1305kg	ECE15 + EUDC	gkm^{-1}			0.60	0.10
			1/1/1998	1305 – 1760kg					1.10	0.15
			1/1/1998	>1760kg					1.30	0.20
	98/69/EC	Euro III	1/1/2001	<1305kg	ECE15 + EUDC	gkm^{-1}	0.50		0.56	0.05
			1/1/2002	1305 – 1760kg			0.65		0.72	0.07
			1/1/2002	>1760kg			0.78		0.86	0.10
	98/69/EC	Euro IV	1/1/2006	<1305kg	ECE15 + EUDC	gkm^{-1}	0.25		0.30	0.025
			1/1/2006	1305 – 1760kg			0.33		0.39	0.04
			1/1/2006	>1760kg			0.39		0.46	0.06
Heavy-duty vehicles	91/542/EEC	Euro I	1/10/1993		ECE R49	gkW^{-1}h^{-1}	8.0	1.10		0.36
	91/542/EEC	Euro II	1/10/1996		ECE R49	gkW^{-1}h^{-1}	7.0	1.10		0.15
	99/96/EC	Euro III	1/10/2001		ESC + ELR	gkW^{-1}h^{-1}	5.0	0.66		0.10
					ETC	gkW^{-1}h^{-1}	5.0	0.78		0.16
	99/96/EC	Euro IV	1/10/2006		ESC + ELR	gkW^{-1}h^{-1}	3.5	0.46		0.02
					ETC	gkW^{-1}h^{-1}	3.5	0.55		0.03
	99/96/EC	Euro IV (Pt 2)	1/10/2008		ESC + ELR	gkW^{-1}h-^{1}	2.0	0.46		0.02
					ETC	gkW^{-1}h^{-1}	2.0	0.55		0.03

*Where no data is shown no limit values apply to these pollutants.

2.4 Emission controls and abatement technologies

53. Emissions of NO_x from both stationary and mobile combustion sources can be reduced by careful control of the combustion conditions in the burner or engine and by after-treatment of the exhaust gases. Control over the combustion environment usually entails manipulating the mixing of fuel and air to affect the temperature and fuel/air ratio in the burner or engine. The aim is to minimise the formation of NO_x in the first place. This is the concept behind the operation of low-NO_x burners for stationary combustion and the effectiveness of exhaust gas recirculation (EGR) in internal combustion engines. After-treatment of exhaust gases generally relies on catalyst technologies to reduce NO_x concentrations in the exhaust, although other methods have been developed which do not involve catalysts.

54. This section provides a brief description of three of the main techniques used to control NO_x emissions from combustion sources in the UK. These are low-NO_x burners for stationary combustors and exhaust gas recirculation and three-way catalysts for mobile combustion sources. A description of other technologies showing promise for NO_x abatement currently available and still under development is provided in the Technical Annexe to this chapter (Appendix 1). These include Selective Catalytic Reduction (SCR) methods for NO_x reduction in stationary and mobile combustion sources, non-catalytic reduction technologies and NO_x traps for mobile sources.

2.4.1 Emission abatement for stationary combustion sources

55. Low-NO_x burners work on the principle of staged combustion in which the fuel and air are mixed in the burner in stages to create regions of different temperature and fuel/air ratio in the flame. Some regions of the flame are fuel-rich and it is here that chemical reactions take place converting NO and its precursors to N_2.

56. Low-NO_x burners have been fitted to all coal-fired power stations in the UK with generating sets of 500 MW or more. They are currently considered the most cost-effective method of achieving NO_x reduction from existing coal-fired plant, with around 30-60% reduction in emissions being achieved (IEA, 2001). Although after-treatment methods such as SCR and other, non-catalytic processes offer potentially greater NO_x reduction efficiencies, the capital and operating costs of these technologies are considerably higher and there are still some operational concerns over the lifetime and costs of the catalyst. SCR and other after-treatment methods are not operational on a large scale in the UK, but are in commercial use on large combustion plant overseas, especially in Japan and Germany. Demonstration and full scale systems are also being installed in US coal-fired plant. These abatement technologies are believed to become more economically competitive over longer operating periods (IEA, 2002).

2.4.2 Emission abatement for mobile combustion sources

57. Road vehicles are a major source of NO_x emissions in the UK. Emissions of NO_x are different for different types and sizes of vehicle and they depend on the type of fuel the vehicle runs on (petrol or diesel) and the load on the engine.

58. In order to achieve increasingly stringent emission standards placed on road vehicles, reductions in NO_x emissions have been and continue to be achieved through a combination of engine design improvements, engine management systems, exhaust after-treatment systems and on-board diagnostics.

59. For petrol vehicles, the main achievements have been through the introduction and refinement of three-way catalyst technology, supplemented by Exhaust Gas Recirculation (EGR). EGR works by recycling a fraction of the exhaust gases through a control valve from the exhaust to the engine intake system where it is mixed with fresh fuel-air mixture. EGR gases act as a diluent, thereby reducing the peak flame temperature and hence the rate of NO formation in the burned gases through the thermal-NO mechanism (Heywood, 1988). Substantial reductions in NO_x emissions (60-80%) can be achieved by EGR.

60. Three-way catalysts have been fitted on all new petrol cars and vans sold in Europe since 1992 in order to meet the stringent emission standards set in Directive 91/441/EEC. It is effectively the only way of meeting the challenge of reducing emissions of CO, hydrocarbons (HC) and NO_x from vehicle exhausts simultaneously. A single catalyst bed can reduce NO and oxidise CO and HC if the fuel/air ratio is maintained close to stoichiometric (i.e. neither fuel or oxygen are in excess). The catalyst effectively brings the exhaust gas composition to a near-equilibrium state: enough reducing gases are present to reduce NO to N_2 and enough O_2 to oxidise CO and HC to CO_2 and H_2O. Around 80-90% reduction in NO_x emissions have been achieved with the three-way catalyst. These figures are based on tests on in-service cars under real-world drive cycles when the vehicle is at normal operating temperature (Euro II relative to pre-Euro I cars, see Section 2.6.2.1). For the most modern cars, the reductions in emissions may be higher than this, including the time when the vehicle is started cold, thanks to improvements in the time it takes for the catalyst to warm up to its normal efficiency (see Section 2.6 and Technical Annexe in Appendix 1). Further details on three-way catalyst technology are given in the Technical Annexe (Appendix 1).

61. Reductions in NO_x emissions are harder to achieve for diesel vehicles, due in part to the oxygen rich regime of the engine. Improved engine design and management systems and EGR have led to the reductions in emissions seen so far, but exhaust after-treatment methods may be necessary to achieve further, more stringent standards on diesel exhaust emissions in the future. A number of these are being developed (see the Appendix 1).

62. Since the introduction of three-way catalysts, emissions of NO_x from petrol cars have decreased below levels from diesel cars of a similar size. Before this, petrol car emissions of NO_x were rather higher than for diesel cars.

63. In parallel with vehicle technology developments, improvements in the quality of petrol and diesel fuels have been made. Fuel quality has little effect on emissions itself, but improvements, especially through reductions in the sulphur content, have opened the gate to emerging exhaust emission after-treatment technologies and better catalyst performance. The EU Directive on fuel quality 98/70/EC has driven the improvements being made to the quality of petrol and diesel fuels sold in the UK.

2.4.3 Formation of NO_2 in diesel exhaust after-treatment systems

64. After-treatment catalyst systems on diesel exhausts can enhance the proportion of NO_x emitted as NO_2. This may be particularly true in an oxidising environment above the catalyst surface where the catalyst may promote the oxidation of NO to NO_2.

65. There is also some concern that certain particulate emission abatement devices may increase the proportion of NO_x emitted as NO_2. Diesel particulate filters (DPF) are increasingly being fitted to buses and other heavy duty diesel vehicles and are very much seen as the solution to the challenge of reducing particulate emissions from these vehicles. There are a number of designs of particulate reduction technologies on the market. The most common of these in the UK are the type that work on the principle of deliberately converting NO in the exhaust stream to NO_2 over an oxidation catalyst unit and using the NO_2 to oxidise the particulates held on the filter, thus regenerating the trap. Continuously Regenerating Particulate Traps (CRTs) which use these techniques do also lead to a small decrease (5-10%) in NO_x emissions, but if no additional measures are put in place, a greater proportion of the NO_x can be expected to be emitted as NO_2. Some studies in the U.S. have suggested as much as 50% of NO_x emissions from a diesel vehicle with this type of DPF may be emitted as NO_2 (CARB, 2002; DaMassa, 2002; IDRAC, 2002), although systems there may not be as well optimised.

66. However, this may only be a temporary problem perhaps restricted to retrofit applications because to comply with tighter Euro IV standards on NO_x emissions, manufacturers of new heavy duty diesel engines will need to find ways of reducing total mass of NO_x emissions substantially. Then, even though the proportion of NO_x emitted as NO_2 is higher, the total mass emissions of primary NO_2 will be reduced compared with levels from existing vehicles. Furthermore, the proportion emitted as NO_2 may depend on duty cycle and could be low at low speeds (for example, in urban areas) when the exhaust temperature is low and the catalyst is not at its working temperature. It is also the case that a number of catalyst optimisation and thermal management strategies exist to minimise the emissions of NO_2 from these types of catalyst-based diesel particulate filter systems (McKinnon, 2002; IDRAC, 2002). These have reduced levels of NO_2 in the exhaust to less than 20% of total NO_x emissions. Certain fuel additives may assist in this. With the increasing need to simultaneously reduce both particulate and total NO_x emissions from diesel exhausts to comply with tighter emission legislation, some manufacturers of particulate traps are developing combined CRT/SCR systems. These work on the principle of using a Selective Catalytic Reduction system with urea injection downstream of the CRT unit to reduce NO and NO_2 (CARB, 2002; IDRAC, 2002).

67. The 50% figure for the proportion of NO_x emitted as NO_2 from these types of DPFs based on studies in the U.S. is almost certainly a ‘worst case’ estimate and figures for CRTs used in the UK may be lower than this where systems are better optimised. However, the lack of data on primary NO_2 emissions from these types of particulate traps does need to be addressed through further independent research on in-service vehicles over real-world cycles and operating conditions. It is understood that the CleanUp programme, run by the Energy Saving Trust to promote and fund grants towards the cost of fitting emission abatement equipment to commercial and public service vehicles in the UK, is addressing this issue by supporting emission testing programmes that will lead to results in the near future. Other types of particulate reduction technologies are not widespread in the UK at the moment, but may show a greater market share in the future. The effectiveness of these and their penetration (and that of combined NO_x reduction technologies) into the UK market will need to be closely monitored. A number of combined particulate and NO_x reduction systems for diesel vehicles are becoming available or are under development for both original equipment and retrofit applications.

2.4.4 By-product emissions of N_2O and NH_3

68. It is known that some of the NO_x abatement technologies discussed above can lead to increased emissions of N_2O and NH_3 formed as by-products of the NO_x emission reduction process. This is particularly the case for after-treatment systems using catalyst technology. Emissions of N_2O and NH_3 are not regulated, but there are wider environmental concerns about the impact that increased emissions of these pollutants will have. N_2O is a greenhouse gas implicated in global climate change (DETR, 2000a); ammonia plays an important role in the long range transport of acidifying pollutants and is also involved in formation of secondary particulate matter aerosols in the atmosphere (NEGTAP, 2001; APEG, 1999).

69. N_2O is formed in combustion systems, but is removed rapidly in flames by reaction with small combustion radicals (H, O atoms), so under normal conditions, only small amounts of N_2O are actually emitted (Miller and Bowman, 1989). However, N_2O can be formed on catalyst surfaces as a by-product of the catalyst chemistry that reduces the NO_x to N_2. N_2O can be formed in stationary and mobile SCR systems.

70. Cars fitted with three-way catalysts may emit as much as ten times more N_2O than cars without catalysts, leading to a growth in overall emissions from road transport as catalyst cars penetrate the UK fleet (EEA, 2000; Pringent and de Soete, 1989). It is possible that advanced catalyst systems may address the problem of N_2O emissions otherwise increased emissions from the road transport sector in particular will counteract the downward trend in N_2O emissions being achieved with other sectors, for example, industry. There is some evidence to suggest that the enhanced emissions of N_2O from catalyst vehicles occur in just the first few minutes after engine start up when the catalyst has not yet reached its optimum operating temperature. This may be addressed in modern cars (Euro II-IV) equipped with close-coupled catalyst technologies reducing the time it takes for the catalyst to warm up, thereby reducing emissions of a number of different pollutants at engine start-up.

71. Increased NH_3 emissions have also been observed from cars with three-way catalysts. Early catalyst cars (Euro I models) may emit as much as 50 times more NH_3 than non-catalyst cars (pre-Euro I) (EEA, 2000; Baum *et al.*, 2000; Baum *et al.*, 2001; Färnlund and Kågeson, 1998). Measurements on more recent models (Euro II and III) have suggested a fall in NH_3 emissions probably due to better engine management systems and catalyst technology, although emissions still remain higher than levels for non-catalyst cars (Barlow *et al.*, 2001). Formation of NH_3 on the catalyst is a by-product of the NO_x reduction mechanism and depends on the amount of time the engine strays off running at stoichiometric into the fuel rich condition. These are the conditions which favour NH_3 formation. Improvements in engine control systems are significantly reducing the time combustion occurs under fuel rich conditions by narrowing the width of the fuel/air ratio fluctuations (see Technical Annexe, Appendix 1). This is likely to lead to further reductions in NH_3 emissions from advanced three-way catalyst cars (for example, Euro IV).

72. SCR deNO_x systems use NH_3 or a derivative such as urea to reduce NO_x emissions in stationary combustors and diesel engines (see Technical Annexe, Appendix 1). Without effective controls, NH_3 slip can occur in the exhaust leading to higher emissions (CONCAWE, 1999; Koebel *et al*., 2000). This has been a concern for urea-based SCR deNO_x systems being developed for heavy duty diesel vehicles. However, a combination of NO_x sensors with feedback to carefully meter the amounts of urea being injected and downstream oxidation catalyst units to oxidise any NH_3 slip which does occur are expected to address this problem and prevent any excess NH_3 emissions.

2.5 Emission inventories – general principles

2.5.1 General requirements

73. Emission inventories provide an estimate of the mass release rate of emissions of NO_x (expressed as tonnes of NO_2 equivalent) from different sectors at national, regional and local scales. Inventories are compiled on a regular basis so that trends in emissions can be seen. They also have other applications in that emission estimates provide an essential input into air quality modelling activities.

74. The UK's National Atmospheric Emissions Inventory (NAEI) is compiled each year by netcen and provides the time-series in annual emissions of a large number of pollutants by source sector from 1970 to the most recent inventory year, currently 2000 (Goodwin *et al*., 2002). The information is provided in various formats to ensure the UK meets its international reporting commitments to bodies such as IPCC and UNECE. The trends in UK emissions over time and the contribution made by different sectors are used by the national and regional Governments to see the effect of national policies, European directives and economic and energy trends.

75. The Environment Agency compiles a Pollution Inventory of air emissions from around 2,000 major point sources in England and Wales. The Pollution Inventory (PI) database is compiled from a large number of different source sectors. The PI can be accessed through the Environment Agency website at www.environment-agency.gov.uk/pi. Information from the PI is fed into the NAEI either directly as emissions data from specific point sources or used in the NAEI as surrogate data to derive emission factors for particular source sectors. Data from the PI also feeds into the European Pollutant Emission Register (EPER) which provides useful information establishing compliance with international treaties and conventions. Under the IPPC Directive the UK Government must report emissions from PPC permitted sites to EPER. The UK PI has been adapted to meet this reporting requirement and the Environment Agency is responsible for gathering the data. SEPA is required under the Directive to report emissions from PPC permitted sites in Scotland. The requirement to report to EPER is statutory on the UK Government and the Environment Agency can use a legal notice to gather the necessary data. Processes are contacted when the Environment Agency has reason to believe that they will be permitted under the PPC Regulations in future. All Integrated Pollution Control (IPC) authorisations and certain waste management licenses will be subject to PPC. Inventory data are also being collected for EPER purposes for those installations falling under the IPPC Directive which are being regulated by local government.

76. A number of local inventories have been compiled for different areas of the country, usually for the major conurbations. These take advantage of local knowledge and usually more detailed activity data, but they generally use the same emission factors and overall methodology that is used for the national inventory. Local inventories may be able to use emissions or activity data held by Local Authorities for small combustion plant and industrial processes under their jurisdiction (Part B processes regulated by Local Authorities under the 1990 Environment Act, Part I) and also local domestic and transport data. In Scotland, SEPA regulate both Part A and Part B processes. Local inventories can provide data at a fine spatial and temporal resolution and incorporate additional information such as release heights which are required for dispersion modelling exercises, such as those associated with local air quality management activities.

2.5.2 Basic inventory methodological approaches

77. The general approach in compiling an emission inventory is to use where possible measured and reported emission rates for a particular point source, for example, a power station, refinery, or major chemical or industrial plant. These may be held in the PI or registers held by SEPA and local authorities. However, the bulk of emissions are estimated using source-specific emission factors and activity statistics. For combustion sources which are the source of NO_x emissions, emission factors are usually fuel-related and expressed in grammes NO_x emitted per kg fuel consumed. They are then combined with fuel consumption statistics for the relevant source. For road transport, emission factors are traffic-related and expressed in grammes NO_x emitted per kilometre travelled and combined with vehicle kilometre figures from transport statistics publications. Other statistics like population and employment might be used for area-type emission sources such as domestic and commercial combustion at a local level.

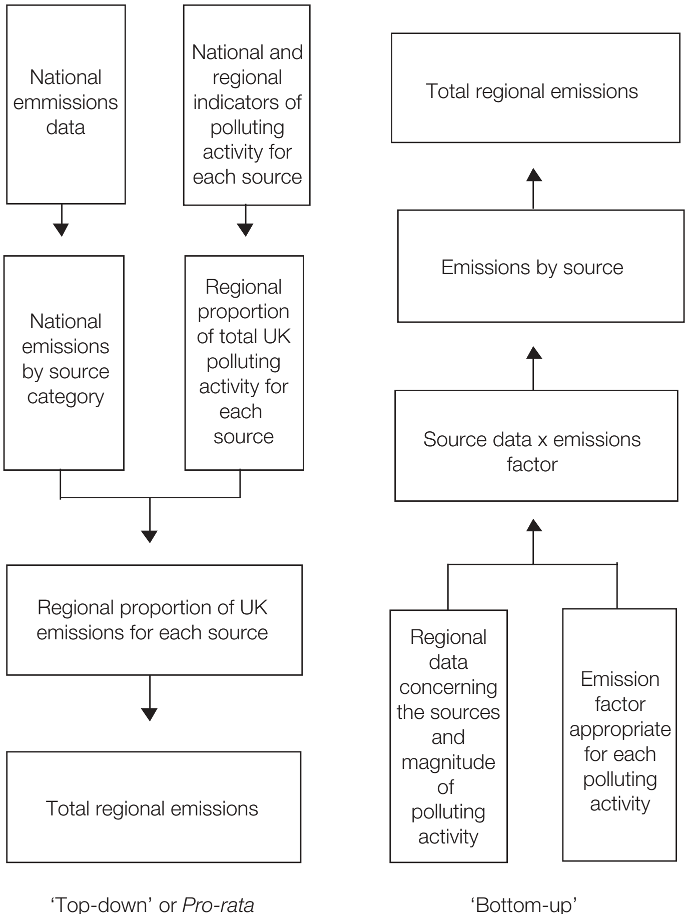
78. Section 2.6 describes the methodologies for estimating emissions from specific source sectors in the national inventory, in most local inventories and in inventories focused on specific local sources (for example, airports).

2.5.3 Spatially resolving emission inventories

79. The national emissions inventory for NO_x refers to emissions in the whole of the UK over an entire year. For many sources, the UK inventory is compiled using national fuel consumption and transport statistics. There will be areas in the country, as well as times of the day and year, where the contribution from certain sources (traffic for example) will be higher than indicated proportionally by the national inventory figures. Emissions from different sources also vary in height of release.

80. Spatially resolved emission estimates are required for ambient NO_x and NO_2 concentration modelling. The development of spatially resolved emission inventories requires information about the geographical location of sources as well as an estimate of mass emissions. There are two approaches (Figure 2.2) to the generation of spatially resolved emission inventories which have been termed ‘top-down’ and ‘bottom-up’. The ‘bottom-up’ approach provides an estimate of emissions for a particular area by utilising geographical source data with local datasets and appropriate emission factors. This provides the most reliable indication of the magnitude and spatial distribution of emissions. The ‘top-down’ or pro-rata approach involves disaggregating national emission estimations to a local level through the use of geographical data and indicators of the proportion of a particular polluting activity occurring in the specified region. It is particularly useful when there is no direct measure of polluting activity available. In practice, individual inventories may make use of both ‘bottom-up’ and ‘top down’ methodologies for different source sectors.

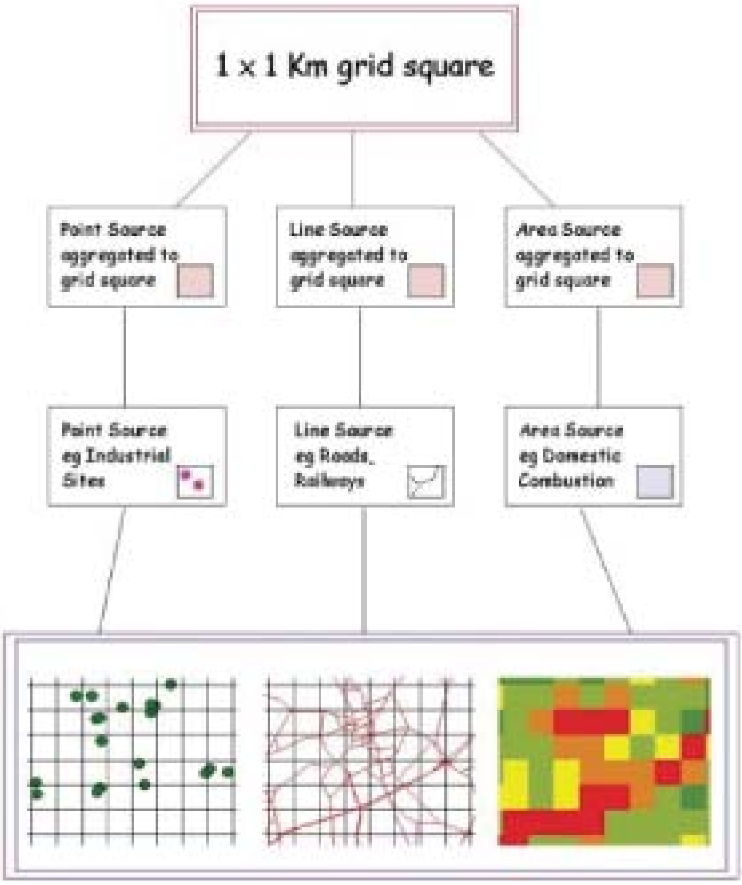
Figure 2.2 The ‘top-down’ and ‘bottom-up’ approaches to emission estimation (Lindley *et al.*, 1996).



81. Geographical Information Systems (GIS) have become increasing important tools for the development of spatially resolved emissions inventories and the mapping of national estimates. The use of GIS allows the application of complex emission estimation models to large spatially referenced datasets which can be relatively easily updated and manipulated. GIS technology is also useful in relation to the presentation or further application of resultant emissions data. This can provide a suitable platform for the generation of spatially resolved emissions data for particular time periods and the incorporation of contextual data which may be required for dispersion modelling such as stack heights, topography and surface roughness.

82. Vector-based GIS packages lend themselves to emissions inventory development since the representation of spatial entities as point, line and polygon (area) features can be readily applied to a characterisation of pollution sources as stationary (point), mobile (line) and diffuse (area) sources. Area-based representations are also used to make emission estimates for sources where individual treatment is either not desirable due to the quantities of sources and their relatively small contribution to overall emissions, such as with domestic combustion sources or not possible due to a paucity of appropriate spatial or attribute data. Within a GIS, data layers or themes are generated corresponding to individual sources which can then be aggregated to a uniform spatial unit for display or further use (Figure 2.3). The point, line and area representations may be used as a direct input to certain dispersion models such as ADMS Urban, which has its own emissions estimation module operating on a vector based environment.

Figure 2.3 Organisation of point, line and area emission sources in a GIS to produce a spatially resolved emission inventory (aric, 2000).



83. Local emission inventories generated from a ‘bottom-up’ approach and national emission maps generated from a ‘top-down’ approach should give broadly the same trends in terms of emissions per square kilometre and the contribution of different sources to total emissions in an area over the same time period. However, there will inevitably be differences in detail in the results between the two inventory approaches. These differences can result from variations in the source of spatial data used to represent the location of sources. For some sectors, for example, emissions from major roads and power stations, the emission maps and local inventories should provide the same emissions in each grid square because both approaches will use the same source of data, for example, major road traffic flows provided by the DfT traffic census. However, in deriving the national maps, emissions from some sources in a particular grid square will be estimated using surrogate data to spatially disaggregate national emission totals that might be derived from national fuel consumption data. Examples of this are emissions from domestic combustion, small industrial boilers and traffic on minor roads. In local inventories, detailed data may be available for these sources from local authorities, local traffic surveys and other local sources. Such detailed knowledge would be impossible to obtain and use in a consistent manner across the whole of the country when generating the national emission maps. Even on major roads which use the same traffic flow data, local inventories may take account of local differences in the age of the fleet from traffic camera information, local speed data or efforts made by local fleet operators (for example, buses) to reduce emissions from their fleet by, for example, retrofitting or engine upgrading.

84. Details of methods used to provide the 1x1 km map of UK NO_x emissions and local area inventories are described in Section 2.8 with particular attention given to the inventory for London.

2.6 Estimating emissions from different sources

85. The following sections describe the methodologies used for quantifying emissions of NO_x in the UK from each of the main sectors. Further details of the methods used for the national inventory can be found in the NAEI annual report (Goodwin *et al*., 2001) and website at www.naei.org.uk/index.php. Emission factors for specific sectors can be found in the Emission Factor Database also available on this website.

86. The measurement of NO_x and primary NO_2 emissions from road vehicles, the influencing factors and the derivation of emission factors are discussed in detail in this section.

87. Estimating emissions from a specific source at a finer temporal or spatial resolution may require more detailed approaches and emissions data to be used than is required for the national inventory. Some particular considerations related to this are discussed and examples shown where these have been applied to calculating emissions from different transport sectors.

2.6.1 Emissions from stationary combustion sources

88. Emissions of NO_x from public power generation are based on reported emissions data for individual power stations provided by the Pollution Inventory and station operators. These include all power stations running on coal, oil and gas, as well as Municipal Solid Waste. For the small amount of electricity generated from other fuels, such as landfill gas, emissions were estimated from fuel-based emission factors taken from the USEPA's Compilation of Air Pollution Emission Factors AP-42 (USEPA, 1997) and DTI figures on fuel consumption for this source.

89. Estimates are made of emissions of NO_x occurring from combustion in a number of industrial sectors. These include combustion at petroleum refineries, in the manufacture of solid fuels (for example, coke production), in iron and steel production and for processes in a variety of other industries. They are based on reported emissions data for individual plant operations provided by the Pollution Inventory and plant operators and also on fuel consumption data for different industries from DTI (DTI, 2002) combined with emission factors for each fuel type. Emission factors are taken from several sources, including CORINAIR (1999), USEPA (1997) and IPCC

(1997) manuals. Emissions data reported for large combustion plant in Scotland collected by SEPA are also used.

90. NO_x emissions from domestic consumption of coal, oil and gas and small boilers in the commercial and public sector are estimated from DTI fuel consumption data for these sectors by fuel type (DTI, 2002) and emission factors from USEPA and CORINAIR.

2.6.2 Emissions from road transport

91. The importance of road transport as a ground-level source of emissions in urban areas and the availability of appropriate emissions and transport data has meant that road transport emissions of NO_x are relatively well quantified. Exhaust measurement programmes within the UK and elsewhere have been on-going since the late 1960s. With the availability of fairly detailed traffic and fleet composition data, fairly sophisticated methods can be used to estimate emissions from this sector in contrast to other transport modes.

92. All vehicles and engines entering the UK market are subject to type approval and as part of this approval process, engines are required to comply with emission limits (Table 2.1). Compliance with these limits is established through the measurement of the vehicle (for light-duty vehicles) on a chassis dynamometer where it is driven over a regulated test cycle. The exhaust emissions over this test cycle are sampled using a constant volume sampler (CVS) and analysed either on a continuous basis, or through the use of bag samples, using conventional gas analysers. The total emissions recorded over this test cycle are then compared to the legislative limit value, routinely expressed in $gtest^{-1}$ or gkm^{-1}. In the case of heavy-duty vehicles, the existing legislative test is conducted on the engine alone, using an engine dynamometer, with the measurement of exhaust emissions at the sum of 13 engine load and speed conditions.

93. A comparison of driving characteristics demonstrates that the legislative test conditions poorly represent existing in-service conditions. In general, these test conditions are characterised by a passive driving style with constant and relatively slow changes in vehicle speed. A comparison of steady-state and transient driving conditions (rapidly varying speed, load and acceleration), demonstrate that emissions are considerably higher under conditions of transient operation (Joumard *et al*., 1995). Therefore, emission factors generated through the Type Approval procedure are not used within the derivation of standard emission databases used for emission modelling.

94. Emission factors for quantifying real world emissions are generated through the measurement of emissions from a selection of vehicles, driven over a range of real world driving cycles. Each of these driving cycles or associated sub-cycles are characterised by a specific average speed. It is this average speed that is used as a surrogate for vehicle operation, with emission factors allocated to a range of average speeds. The results from tests over a range of average speeds may then be used to derive an average speed-emission relationship. It is this approach that remains most widely used with average speed-emission curves generated for various vehicle types, engine sizes, fuel types, legislation classes and pollutants.

95. Emissions of NO_x from road transport are derived using these speed-related emission factors. Within the UK, emission factors for vehicles at their normal operating temperature come from a large database of emission measurements held by TRL. These are combined with fleet composition and traffic activity data for different years on the national road network provided by DfT. From this, the hot exhaust emissions are derived for each vehicle and road type.

96. Emission factors are intended to be representative of the vehicle fleet. Thus the selection of test vehicles routinely attempts to reflect the real fleet composition. This is obviously easier with larger sample sizes, and indeed large samples can not only reflect the vehicle type, fuel and engine size, but may also reflect various states of maintenance. This level of maintenance is difficult to assess in smaller samples, and whereas before this level of maintenance was built into the basic emission factors (Euro I and earlier), this factor is increasing handled separately.

97. Furthermore, because the emission database is dominated by results from conventional vehicles, these data will undoubtedly have the lowest uncertainty. For these conventional vehicles and fuels the repeat measurements of the same vehicle over the legislative test cycle can vary by approximately ±7% of the mean. For real-world cycles this repeatability can be considerably higher (±30% for the new ARTEMIS high speed driving cycle).

98. Vehicles generally emit more when the vehicle is started with the engine cold. This is partly due to the poor combustion efficiency when the engine is cold and the need to run the engine slightly fuel rich to achieve combustion stability. It is also due to the low efficiency of the three-way catalyst during the time it takes to reach the light-off temperature (see Technical Annexe, Appendix 1). The excess cold start emissions are calculated in the inventory using standard emission equations and vehicle trip start data. Cold start emissions of NO_x are relatively minor compared with hot exhaust emissions. This is not the case for CO and HC where cold start emissions are considerably more important.

2.6.2.1 Exhaust emission factors for NO_x

99. Surveys of road vehicle exhaust emission factors are on-going within the UK and elsewhere. The last revision to the UK database was undertaken by TRL on behalf of the DfT (Barlow *et al*., 2001). Historically these emission test programmes have involved relatively large vehicle samples (in excess of 200 vehicles), but more recently this sample size has been reduced, in favour of an increase in the number of pollutants and conditions analysed. Statistically this can result in an increase in the uncertainty associated with the basic emission factors. The NAEI incorporates the TRL emission factor database, but it should be recognised that this database is dominated by test data associated with conventional fuels and that the latest revision supplements the existing emission factors with data for Euro I and Euro II vehicles. Previously, with the exception of petrol cars, emission factors for these classes of vehicles were estimated based on changes in the emission directive's type-approval limit values. A substantial part of the new measurements of Euro I and Euro II emission factors come from several test programmes funded by DfT and Defra and carried out at UK test laboratories between 1999 and 2001 (Barlow *et al*., 2001). The measurements were made on dynamometer test facilities under various simulated real-road drive cycles.

100. Table 2.2 shows NO_x emission factors for each class of vehicles calculated from the emission factor equations at typical speeds on urban, rural and motorway roads. These emission factors are currently used in the NAEI. The vehicle types match the traffic activity data that are used in the national emission calculations.

101. Emissions from future emission classes yet to be introduced, must again be estimated through an examination of the proposed future legislation and the technical ability to meet these new limits. This estimation process can result in significant errors for future emissions factors. This was demonstrated with the previous over-estimation of the reduction in NO_x emission factors for Euro I and II diesel vehicles, when in fact the latest series of tests showed little difference between the emission factors for the pre-Euro I, Euro I and Euro II classes of vehicles. In some cases, the Euro I factors were higher than the pre-Euro I factors, or Euro II higher than Euro I, indicating that improved technologies during the 1990's had delivered little or no benefits to NO_x emissions from diesel vehicles. There are two possible explanations for this. One is the possibility of ‘cycle beating’, at least in the case of heavy duty vehicles (UBA, 2003; Kågeson, 1998). Modern engine management systems are tightly tuned and there is the possibility that legitimate NO_x emission reductions over the specified cycle for type-approval testing can be achieved, but when the vehicle is driven under real road conditions (as in the emission factor tests), the engine is frequently operating outside its ‘tuned’ condition and the emission reductions are not realised. The risk of cycle beating has been recognised by the EU by revising the test cycle for Euro III and Euro IV engines for heavy duty vehicles.

102. Another possibility that applies to the light duty diesel vehicles is the degree of tolerance that the regulations provide in the permitted levels of NO_x emissions, allowing the vehicle manufacturers to trade-off a certain amount of NO_x in order to achieve the more stringent limits set on particulate emissions. Examination of the NO_x emission factors for pre-Euro I diesel cars and vans at average speeds of the test cycle shows that they were close to or already below the limits set in the Euro II standards. Thus, manufacturers could concentrate their attention on methods to reduce particulate emissions, a more challenging problem at the time. It should be emphasised, however, that the new emission factors for Euro II diesel vehicles (and even Euro I factors for heavy duty diesel vehicles) are still based on a very small number of vehicles tested. An increase in this sample size will assist in assessing these conclusions, although it should be noted that these are already supported through other national test programmes, including those sponsored by the German and Austrian Environmental Protection Agencies (UBA, 2003).

103. Table 2.2 also provides emission factors for Euro III and Euro IV vehicles, the latter referring to standards which will come into effect in 2006 (and 2008 for heavy duty vehicles). These are based on scaling factors assumed to apply across all speeds relative to emission factors for Euro II vehicles. For light duty vehicles (petrol and diesel), the scaling factors were estimated by the NAEI on the basis of current emission levels for Euro II vehicles and the amount emissions will need to be reduced to achieve the type-approval limit values, taking into account differences in the drive cycles used and the contribution that cold start emissions will make to emission over the new 98/69/EC test cycle. A similar approach was used to estimate emissions from new motorcycles, using factors for pre-2000 models from TRL and scaling factors based on recently agreed emission limits (Official Journal, 2002). For heavy duty vehicles, it was assumed that Euro II vehicles are currently at their emission limits and will be reduced no more than required to achieve the new emission limits, using scaling factors from the COPERT III database (EEA, 2000). COPERT III is the methodology and database of road transport emission factors developed by a group of experts for the European Environment Agency and recommended for national emission inventory reporting under CORINAIR.

Table 2.2 Exhaust emission factors for NO_x (as NO_2) for different road types used in the National Atmospheric Emissions Inventory, based on data from TRL (Barlow *et al.*, 2001).

$gNO_x(as\ NO_2)km^{-1}$		Urban	Rural	Motorway
Petrol cars	ECE 15.04	1.644	2.211	3.164
	Euro I	0.257	0.368	0.663
	Euro II	0.229	0.245	0.370
	Euro III	0.137	0.147	0.222
	Euro IV	0.073	0.078	0.118
Diesel cars	Pre-Euro I	0.623	0.570	0.718
	Euro I	0.537	0.465	0.693
	Euro II	0.547	0.505	0.815
	Euro III	0.547	0.505	0.815
	Euro IV	0.273	0.253	0.407

gNO_x(as NO_2)km^{-1}		Urban	Rural	Motorway
Petrol LGVs	Pre-Euro I	1.543	1.783	2.351
	Euro I	0.361	0.356	0.531
	Euro II	0.319	0.385	0.567
	Euro III	0.192	0.231	0.340
	Euro IV	0.105	0.127	0.187
Diesel LGV	Pre-Euro I	1.332	1.254	1.549
	Euro I	1.035	0.892	1.384
	Euro II	0.983	0.848	1.315
	Euro III	0.735	0.634	0.982
	Euro IV	0.383	0.330	0.512
Rigid HGVs	Pre-1988	13.53	13.53	13.53
	88/77/EEC	6.02	4.96	5.91
	Euro I	7.63	6.87	7.23
	Euro II	6.51	5.78	6.02
	Euro III	4.49	3.99	4.15
	Euro IV (2006)	3.19	2.83	2.95
	Euro IV (2008)	1.82	1.62	1.69
Artic HGVs	Pre-1988	20.70	20.70	20.70
	88/77/EEC	16.93	12.93	11.52
	Euro I	20.25	18.25	19.22
	Euro II	13.96	12.40	12.91
	Euro III	9.63	8.56	8.90
	Euro IV (2006)	6.84	6.08	6.32
	Euro IV (2008)	3.91	3.47	3.61
Buses	Pre-1988	16.74	13.83	13.36
	88/77/EEC	13.62	5.45	6.13
	Euro I	10.93	6.18	6.51
	Euro II	9.78	5.52	5.75
	Euro III	6.75	3.81	3.97
	Euro IV (2006)	4.79	2.71	2.82
	Euro IV (2008)	2.74	1.55	1.61
Mopeds, <50cc, 2st	Pre-2000	0.030	0.030	0.030
	Euro I	0.010	0.010	0.010
Motorcycles, >50cc, 2st	Pre-2000	0.032	0.066	0.126
	Euro I	0.025	0.029	0.052
	Euro II	0.025	0.029	0.052
	Euro III	0.006	0.007	0.012
Motorcycles, >50cc, 4st	Pre-2000	0.156	0.229	0.385
	Euro I	0.210	0.279	0.448
	Euro II	0.210	0.279	0.448
	Euro III	0.048	0.064	0.103

2.6.2.2 Road transport activity data

104. To calculate UK emissions from road transport in the NAEI, the hot exhaust emission factors are combined with annual UK vehicle kilometre data for different vehicle types on different roads. For Great Britain, vehicle kilometre data are taken from the DfT annual traffic census for the national road network (DfT, 2002a). Vehicle kilometre data for Northern Ireland are derived from the survey by the Transportation Unit, Road Services Headquarters (NI Road Services, 2001).

105. Data are also required on the composition of the fleet for each type of vehicle and the petrol vs. diesel mix for cars and LGVs (light goods vehicles less than 3.5 tonnes). The fleet composition data required are the vehicle size mix (engine cc and gross vehicle weight) and the proportion of vehicle kilometres travelled in a year by each Euro standard. The latter is related to the age profile of the fleet, using year-of-first registration data from DfT's vehicle licensing statistics published each year (DfT, 2002b). Account is also taken of the fact that newer vehicles travel more miles in a year than older ones, using survey data from DfT.

106. It is assumed in the NAEI that 5% of cars fitted with three-way catalysts fail each year, but 95% of failed catalysts are repaired after the vehicle is 3 years old and reaches the age of MOT testing. This failure rate assumption was first adopted for early generation catalyst systems (Euro I) to reflect accidental damage and poisoning of the catalyst system by drivers. However, the application of the 5% failure assumption to more modern and future car models (Euro II-IV) is currently under review, in light of better system durability required as a condition of Type-Approval and advanced on-board diagnostic systems on cars which should be able to detect problems when they arise. It is indeed the case that although there are no definitive sets of data on failure rates, emissions information from MoT test returns and road-side testing, and data from car leasing companies, equipment suppliers and manufacturers' warranty returns are all pointing towards lower failure rates (and in some cases much lower) than 5% in recent years. For catalyst cars, a slow deterioration in emissions with vehicle mileage is taken into account in the NAEI.

107. Further details on the emission calculation methodology are provided in the NAEI report (Goodwin *et al.*, 2001).

2.6.2.3 Cold start emissions

108. The excess emissions that arise when the vehicle is started with its engine cold or below its optimum operating temperature are calculated using a method taken from COPERT III. The procedure uses equations that take account of the effects of ambient temperature on the excess emissions and its effect on the distances travelled with the engine cold. The distances travelled with cold engines also depend on average trip lengths: the shorter the average trip lengths are, the greater the contribution of cold start emissions. The method calculates the ratio of cold to hot exhaust emissions for light duty vehicles which are used to calculate the overall cold start emissions from these vehicles. Further details on the methodology used for cold starts are provided in the NAEI report (Goodwin *et al.*, 2001).

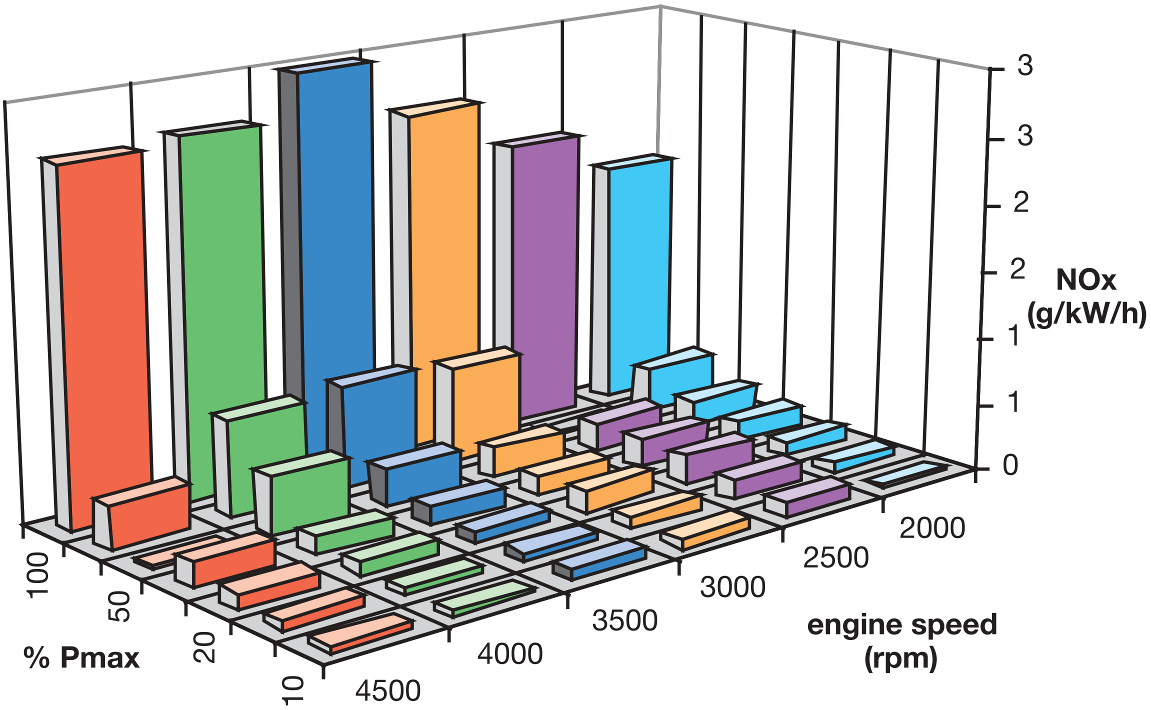
2.6.2.4 Emissions from instantaneous operations of road vehicles

109. Modelling and mapping emissions from road transport on a local scale involves simplifying the road network as a series of line sources subdivided into links (with uniform flows and speeds) and allocating fleet corrected average-speed emission rates in gkm^{-1}. These average speed emission rates are used for simplicity, as it has been considered that the average speed of a road link may be readily determined. However, this average speed emission factor has actually been a surrogate for vehicle operation, and in reality the emissions would be better described through the use of a number of other variables such as relative positive acceleration and engine load, rather than road speed itself. However, in practice these variables would be extremely difficult to determine for each vehicle.

110. For pre-Euro I vehicles, the average speed approach appears to be sufficient to simulate variations in emissions and thus roadside air pollution on a geographic and temporal scale. With the introduction of the three-way catalyst and its associated large reduction in exhaust emissions, the average speed approach appears to be becoming less appropriate.

111. For example, evidence suggests that catalysts tend to exhibit on/off control, and emission levels from catalyst-equipped vehicles are much more sensitive to operating conditions than those from non-catalyst vehicles. Under particular operating conditions the catalyst may be working at its maximum efficiency, but for slightly different conditions the conversion efficiency may be low. For example, measurements by Joumard *et al*. (1998) have shown that for engine loads (the actual power divided by the maximum power at a given engine speed) greater than 75%, instantaneous CO emissions can be 20,000 times higher, and NO_x emissions 10 times higher, than for lower loads (Figure 2.4). Over an entire motorway driving cycle around 90% of the total CO emissions occurred during only 15% of the time.

Figure 2.4 NO_x instantaneous emission versus engine speed and load over the motorway IM modem cycle for a catalyst-equipped light-duty vehicle (Joumard *et al*., 1998).



112. An examination of instantaneous exhaust emissions against vehicle speed (for a Euro III petrol vehicle) indicates that during the majority of a typical test cycle emissions remain very low, but are subject to substantial elevation when the engine is subjected to changes in engine load, such as gear change events. This type of observation would suggest that the use of an average speed based modelling approach in a typical urban street could over-estimate the emissions along the majority of the link, but underestimate them at situations where vehicles interact, such as junctions and during conditions characterised by stop-start driving. This has obvious implications for emissions and subsequent air quality modelling of NO_2 concentrations at specific points near a road junction or areas of congestion.

113. Research into the development and use of instantaneous emission models has been on-going for many years and includes studies by INRETS, TUEV Rheinland, LAT and TRL within the MODEM project (EU 4th framework project), and more recent studies by the Technical University of Graz and EMPA within the ARTEMIS project (EU 5th framework project) and separate studies by MIT. However, these studies do not fully address the most fundamental problem relating to instantaneous emission modelling: it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and the emissions and fuel-consumption values recorded in the one-second steps might not be successfully allocated to the associated operating conditions. For example, because of the time required to transport the exhaust gas to the analysers, and the actual response time of the analysers themselves, the emission signals are delayed relative to the driving cycle. Furthermore, the exhaust gas is mixed in the exhaust system. This results in a general flattening of instantaneous emission peaks over a period of more than one second. The dynamics of mixing also depend on the gas flow rate, and the situation is even worse when dilute exhaust gas is being sampled using a CVS (Boulter, 2002).

114. These results have obvious implications for the development of modal emission models based on instantaneous vehicle operation. Therefore, even if modal emission models were constructed using raw exhaust measurements, such results indicate that there would clearly be problems matching an emission signal in any given second to the appropriate speed or acceleration measurement.

115. Clearly, advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available. Efforts are now underway to reduce the dynamic distortion of the emission data (Weilenmann *et al.*, 2001).

116. In summary, it may be concluded that the transfer of instantaneous modelling to real-world conditions is considerably more complex than that of the average speed approach.

2.6.2.5 Impact of traffic management schemes

117. Much of the progress to date in the control and reduction of the environmental impact of traffic has been through the use of improved vehicle technology and fuels, often prompted by increasingly stringent legal limits and design standards. In addition, the way in which a vehicle is operated has a significant influence on its environmental performance. Traffic congestion and the associated driving pattern of stops and starts, accelerations and decelerations can produce excessive emissions. Thus, traffic management schemes that modify the behaviour of the traffic, as well as the volume of traffic, can supplement the effects of improving technology. In general traffic management that encourages drivers to drive in a more passive style are beneficial (Abbot *et al*., 1995).

118. In the mid-1990s the DfT commissioned a programme of research investigating the links between traffic management and air quality. This programme (TRAMAQ) is on-going, and comprises a number of inter-related studies largely focusing on urban traffic control (Abbot *et al*., 1995; Boulter *et al*., 2001; McCrae *et al*., 2000).

119. A review of the various traffic management case studies suggests that lower speed limits and traffic calming schemes usually reduce NO_x emissions on the affected roads.

120. The potential of Low Emission Zones (LEZ), restricting access of vehicles in a zone to those meeting a certain emission standard, has been assessed for London. An initial study carried out by TRL on behalf of Westminster Council (Cloke *et al*., 2000) concluded that restricting

HDVs to only those complying with Euro III limits could reduce NO_x emissions by up to 20%. A further feasibility study funded by the GLA, Transport for London, Defra and the Association of London Government has so far considered many of the issues of importance to an LEZ in London. These have included: emission change, impact on atmospheric concentrations of NO_2 and PM_{10}, implementation issues and the cost-effectiveness of any scheme considered. Initial results from the study (www.london-lez.org) suggest that the benefits of an LEZ in London would be less than those identified in the previous study carried out by TRL. The principal reason for a reduced impact is the use of the latest emissions factors for NO_x in the latter study, which for diesel vehicles show less benefits for new technologies than previously thought (Barlow *et al*., 2001). Most of the scenarios considered by the LEZ team have focussed on HGVs, taxis and LGVs, which are almost all diesel-engined.

121. Other traffic management schemes assessed include dedicated bus lanes in Copenhagan which were estimated to have reduced NO_x emissions by between 5-15%. A pilot study on the introduction of red-routes within London estimated that NO_x emissions would be reduced by between 1-3%. Finally, the introduction of variable speed limits on the M25 motorway, while demonstrating improvements in CO and CO_2 emissions, were judged to have a neutral effect on NO_x emissions (Barlow, 1997).

122. Traffic management may only be used to improve air quality if the area of influence of the management scheme is large. In the case of NO_2, roadside concentrations of NO_x are large and thus the limit on NO_2 is not necessarily NO_x emissions, but frequently the availability of oxidant to convert NO to NO_2 in the urban atmosphere, as will be discussed later in this report. Therefore, even if traffic management regimes are shown to reduce the emissions of NO_x, the resulting impact on NO_2 concentrations is always lower (McCrae et. al. 2000).

2.6.2.6 *Primary NO_2 emissions from road vehicles*

123. On behalf of the Highways Agency and DfT, TRL carried out a small investigation to determine the proportion of NO_x emitted as NO_2 from a range of road vehicles (Latham *et al*., 2001; McCrae *et al*., 2002). In order to determine the proportion of NO_x emitted in the form of NO_2, a vehicle test matrix was developed to provide a representative sample of vehicles in the UK vehicle fleet. A resulting small sample of eighteen vehicles was subsequently subjected to testing, covering 9 petrol cars, 3 diesel vans, 3 diesel heavy goods vehicles and 3 buses, meeting the pre-Euro I, Euro I or Euro II legislative standards. All testing was undertaken on vehicles taken from the in-service fleet and tested in the 'as-received' condition. The study did not include any diesel vehicles equipped with particulate traps or any other specific exhaust after-treatment devices.

124. The vehicles were subjected to tests on a chassis dynamometer over a series of legislative and real world driving cycles, while emissions were recorded on a continuous basis. These included the Warren Spring Laboratory (WSL) congested urban, urban, suburban and rural cycles and legislative 96/69/EC test and for heavy goods vehicles and buses over the simulated 13-mode FIGE cycle followed by the Millbrook bus cycle.

125. For the light duty vehicles (the petrol cars and diesel vans), the study examined for any statistically significant dependence of the measured NO_2/NO_x emission ratio on the sampling method used; the fuel type (petrol or diesel); average speed of the test cycle; and the emission standard of the vehicle. A smaller range of tests was carried out on the heavy duty vehicles.

2.6.2.6.1 The measurement techniques and sampling strategy for NO_2 emissions

126. The standard legislative method for measuring NO_x emissions from vehicles depends on the type of vehicle being measured. In the case of light-duty vehicles, NO_x measurements are made on diluted exhaust gas, whereas those for heavy-duty engines are made on raw exhaust. In addition, for the NO_x measurements from HGVs, the sample may be pre-conditioned by passing the gas stream to a chiller unit via a heated line, prior to analysis in an unheated NO_x analyser, in order to remove water from the exhaust sample. Alternatively, the legislation also allows for the measurement of NO_x in a heated NO_x analyser, delivered directly through a heated sample line. These various techniques, while not having a significant impact on total NO_x emission, could affect the fraction of NO_x that is measured as NO_2.

127. Conventionally, NO_x emissions are measured using chemiluminescence techniques (see Chapter 4). To achieve continuous measurements of both NO and NO_x, using a reducing agent to convert all NO_x to NO, requires either a switchable unit or the use of two separate analysers. Either way, the resultant NO_2 emissions are subject to a relatively large potential error, since the indirect NO_2 measurements are derived through the difference between two concentrations (NO_x and NO) of a similar magnitude.

128. Infra-red absorption spectroscopy relies on the principle that different chemical groups absorb radiation at different frequencies. The absorption spectra for NO and NO_2 are at different frequencies allowing for their direct, independent and continuous measurement, without introducing potential errors derived from the difference of two measurements. Fourier Transform Infrared Spectroscopy (FTIR) and standard chemiluminscence techniques were used to measure NO_2 in this study.

129. The sampling strategy may have a significant impact on the proportion of NO_2 measured in the NO_x sample, due to variations in the sample residence times, temperatures, and its subsequent dilution and reaction in the diluent air. Emissions of NO, NO_2 and NO_x were recorded using five different sampling and analysis approaches:

- raw exhaust with unheated chemiluminescent analyser,
- raw exhaust gas with heated chemiluminescent analyser,
- diluted exhaust gas with heated chemiluminescent analyser,
- diluted exhaust gas with a heated FTIR analyser, and
- raw exhaust gas with a heated FTIR analyser.

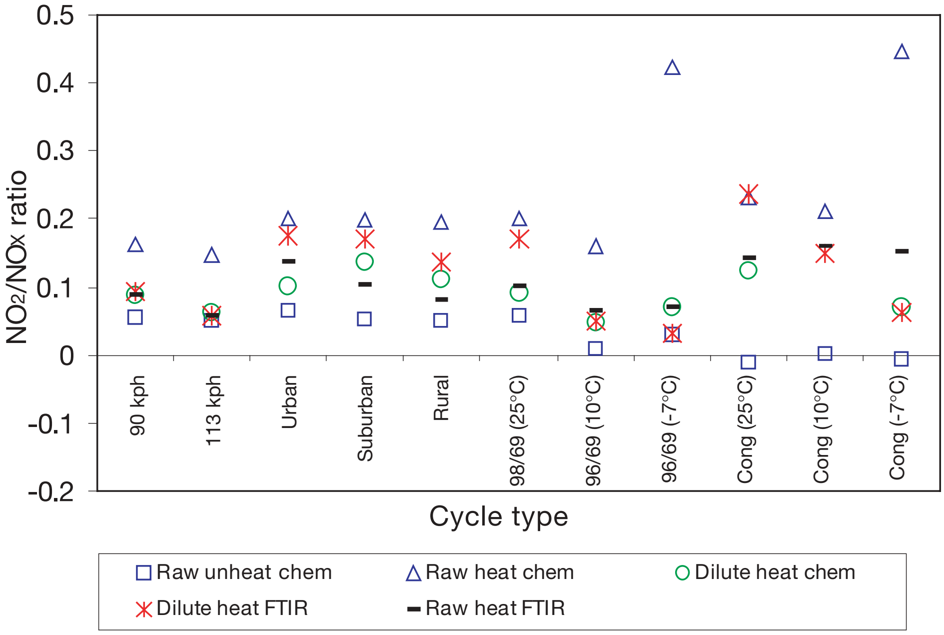
130. Different levels of NO_2 detected could be influenced by reaction of NO with O_3 in the diluent air and through the slow NO + NO + O_2 reaction which would occur to varying degrees in each sampling regime.

2.6.2.6.2 Emissions from light duty vehicles

131. The NO_2/NO_x ratios measured for light duty vehicles covered a broad range over the test matrix covered, with values as low as 0.03 to as high as 0.46. In general, the highest ratios were found for tests carried out using the raw exhaust with heated chemiluminescent analyser over the congested urban cycle. Figure 2.5 shows the average NO_2/NO_x ratios measured using the different sampling and analysis methods over the various vehicle test cycles.

132. With so may potentially influencing variables in the vehicle test matrix used, a detailed statistical analysis of the results was carried out to identify those factors that showed a statistically significant effect on the NO_2/NO_x ratio. The analysis was carried out on the results obtained using the FTIR detection method.

Figure 2.5 NO_2/NO_x ratios for light duty vehicles determined using different driving cycles and measurement techniques (Latham *et al*., 2001).



133. The results of the analysis showed there was a statistically significant relationship between the NO_2/NO_x ratio and the fuel type, the average cycle speed and the method of sampling used, but not with the vehicle's emission standard. The results indicated:

- The NO_2/NO_x ratio was significantly higher for diesel vehicles than for petrol vehicles. The difference in the ratio for the different fuels was statistically highly significant and estimated to be 0.25.
- The ratio increased with decreasing average speed of the drive cycle. The effect was small compared with fuel type, but the analysis suggested the effect was statistically significant and that the difference in the NO_2/NO_x ratio at speeds of 7 and 120 kph was 0.11.
- The ratio was higher when a dilute sample was used than for the raw exhaust.
- There was no statistically significant dependence of the ratio on the Euro standard of the vehicle. This implies that the effect of the legislation in reducing total NO_x emissions has been equally effective in reducing primary NO_2 emissions.

2.6.3 Emissions from heavy duty vehicles

134. A less detailed study was made on factors influencing the ratio of NO_2 to NO_x emissions from heavy duty diesel vehicles and the study did not quantify the magnitude of the NO_2/NO_x ratio for this class of vehicles. The study concluded that NO_2 emissions were not significantly affected by Euro standard and since NO_x emissions from pre-Euro I, Euro I and Euro II classes of HDVs are not significantly different, it has to be concluded that the NO_2/NO_x ratio is also similar for all the Euro standards.

2.6.4 Conclusions concerning primary NO_2 emissions from road vehicles

135. The results from this study have to be viewed in the context of the relatively small sample size investigated. The study has confirmed the higher fraction of NO_x emissions as NO_2 in the exhausts of diesel vehicles compared with petrol vehicles, but has also indicated the importance of sampling and measurement method used as well as average speed or drive cycle of the vehicle. Further measurements are needed to define and quantify the average speed dependence of the NO_2/NO_x ratio on all types of vehicles, but especially for heavy duty vehicles. The speed-dependence noted on emissions from light duty vehicles is significant as it implies a greater proportion of NO_x emitted as NO_2 in urban areas, where average speeds are lower, compared with rural areas and motorways. The possible implications this could have on primary NO_2 emissions from slow-moving buses and large HGVs, as well as possibly diesel vans and taxis, in the centre of towns and cities are significant.

136. It is hard to provide a firm and unambiguous value on the NO_2/NO_x ratio for emissions from road vehicles. On the basis of the results from this investigation carried out by TRL, an average value of 0.05 ± 0.03 is suggested for petrol vehicles and an average value of 0.25 ± 0.10 is suggested for diesel vehicles. For diesel vehicles, the value could be higher than this average value in urban areas and lower than this in rural areas and motorways. Further research is required to confirm these estimates at different speeds or cycles.

137. The possibility of higher primary NO_2 emissions from heavy duty diesel vehicles equipped with CRTs, relying on the deliberate formation of NO_2 in the exhaust for regeneration of the particulate trap, also needs to be investigated, especially for operation of the vehicles over urban drive cycles.

2.6.2.7 Primary emissions of nitrous acid (HONO) from road vehicles

138. A number of studies have demonstrated that nitrous acid (HONO) is emitted in vehicle exhaust in conjunction with NO and NO_2 (for example, Pitts *et al*., 1984; Kirchstetter *et al*., 1996; Martinez-Villa, 2001; Kurtenbach *et al*., 2001). Emissions of HONO have also been quantified from a diesel-fuelled electric power generator (Gutzwiller *et al*., 2002). The results of recent studies are summarised in Table 2.3. The vehicle exhaust studies have been made at roadside locations and in road tunnels, and have generally distinguished primary emissions of HONO from its secondary formation from subsequent reactions of NO and NO_2. The European studies generally indicate that HONO accounts for approximately 0.5–1.0% of emitted NO_x. Although this is a small fraction, it is potentially significant from a chemistry point of view, because HONO photolyses efficiently to generate free radicals, possibly leading to additional NO-to-NO_2 conversion (see Section 3.3). The measurements of Gutzwiller *et al*. (2002) indicate a similar proportion of emitted HONO from a diesel-fuelled electric power generator.

Table 2.3 Summary of reported information on primary emissions of HONO.

Study	HONO/NO_x (% v/v)	emission index (mg HONO)/kg fuel	location	note
Kirchstetter *et al.* (1996)	0.29 ± 0.05	–	Caldecott tunnel, San Francisco Bay, USA	f
Martinez-Villa (2001)	1.10 ± 0.09[a]	-	Marylebone Rd, London, UK	g
Kurtenbach *et al.* (2001)	0.80 ± 0.10	88 ± 18[b]	Kiesbergtunnel, Wuppertal, Germany	h
	0.53 ± 0.08	115 ± 10[c]		i
	0.66 ± 0.20	94 ± 27[d]		j
	0.65 ± 0.24	101 ± 37[e]		k
Gutzwiller *et al.* (2002)	0.65	71	Laboratory facility	l

Notes

[a] may include a secondary contribution;

[b] corresponding emissions of 7700 ± 1100 mg NO/kg fuel and 590 ± 80 mg NO_2/kg fuel reported (➢ 4.7 ± 0.6% v/v primary NO_2);

[c] corresponding emissions of 11900 ± 700 mg NO/kg fuel and 2000 ± 200 mg NO_2/kg fuel reported (➢ 9.8 ± 1.0% v/v primary NO_2);

[d] corresponding emissions of 8600 ± 1700 mg NO/kg fuel and <30 mg NO_2/kg fuel reported (➢ < 0.2% v/v primary NO_2);

[e] corresponding emissions of 9500 ± 1700 mg NO/kg fuel and 860 ± 230 mg NO_2/kg fuel reported (➢ 5.5 ± 1.5% v/v primary NO_2);

[f] >99% petrol vehicles; <0.2% heavy duty trucks;

[g] Measurements took place in October 1999; ca. 10% HGV;

[h] 74.7% petrol cars; 12.3% diesel cars; 6% commercial vans; 6% heavy duty trucks; 1% motorcycles;

[i] MAN truck (diesel) 0-40 km hr^{-1} over 3500 m;

[j] VW Golf (diesel) 0-40 km hr^{-1} over 3500 m;

[k] VW Golf (petrol) 0-40 km hr^{-1} over 3500 m;

[l] Kubota GL-4500s diesel electric generator, maximum load 4.5 kW.

2.6.3 Emissions from aviation and airports

139. Emissions from aviation are estimated within a 1000 metre ceiling of takeoff and landing. In the NAEI, emissions are calculated from the number of aircraft movements at all the British airports (DfT, 2002a) and emission factors expressed as emissions per landing and takeoff cycle. The emission factors are taken from the local inventory studies carried out for different conurbations by London Research Centre in the 1990s (discussed in section 2.8.3), with additional aircraft emission factors taken from the 1998 inventory for Heathrow Airport compiled by AEA Technology (Underwood and Walker, 1999).

140. The Heathrow Inventory is an example of a spatially resolved inventory centred on a specific source. This section focuses on the methods used in the 1998 Heathrow Inventory to calculate emissions from the airport and surrounding area rather than on the results from the inventory itself. Annual emission rates and their spatial distribution were prepared in a form suitable for input to an atmospheric dispersion model with a view to estimating the airport contribution to ambient concentrations in the area. It is these rather than the emission figures in their own right which provide a better measure of the impact of the airport on local air quality. All the modelling and assessments discussed in this report have been based on the 1998 version of the Heathrow Inventory, but it should be pointed out that an updated version of the inventory has just been completed for 2000 which incorporates a number of significant improvements to the methodology. However, the 2000 Heathrow Inventory was not made available in time for this report.

141. The Heathrow Inventory covered emissions from the aircraft during the landing and take-off (LTO) cycle up to 1000 m in height, emissions from road traffic on the surrounding road network, emissions from airside support vehicles and emissions from heating plant used for the airport.

142. To enable pollutant concentrations at the airport to be calculated by dispersion models, the emissions from ***all*** road traffic on the surrounding road network were estimated as these make a contribution to the background concentrations at the airport. However, only a portion of the traffic is airport-related.

143. Aircraft emissions were estimated from data on the number of aircraft movements during 1998, supplied by Heathrow Airport Ltd and broken down by aircraft type and airline, together with emission factors mainly given in the International Civil Aviation Organisation Engine Emissions Data Bank (ICAO, 1999). Emissions were estimated for eight phases of the LTO cycle:

1) taxi-out;
2) hold;
3) take-off roll;
4) initial climb (i.e. wheels-off to throttleback, assumed to occur at 450 m);
5) climb out (450 m to 1000 m);
6) approach (1000 m to touchdown);
7) landing roll;
8) taxi-in.

144. Emission factors for a given engine type vary with thrust setting. The ICAO database gives emission test results for different engines in service at four thrust settings: 7%, 30%, 85% and 100%. In general, each of the LTO cycle phases was assigned one of these thrust settings. A limited amount of information was used on operational procedures where aircraft do not use full thrust during take-off. It should be noted that emissions data in the ICAO database were not primarily intended for use in emissions modelling, as they may not be representative of real-world aircraft operations. However, these were the best data available for the Heathrow Inventory. There is a paucity of emissions data from aircraft engines operating over real-world cycles and clearly this is an area that needs attention. Further research is needed into actual aircraft operations, their impact on emissions and into the way aircraft emissions are modelled.

145. Emissions from road traffic on and around the airport were calculated from traffic volumes and speeds derived from the Heathrow Road Traffic Model (HRTM). This covered both airport- and non-airport-related traffic. Emissions from road traffic inside and outside the airport perimeter roads were calculated. The traffic model covered an extensive road network on and around the airport including sections of the M4 and M25 (Underwood *et al*., 1994). The traffic data were used in conjunction with NAEI road vehicle emission factors.

146. Emissions were spatially distributed in three dimensions by representing different sources as point, line and area sources. For aircraft emissions, taxi and hold routes to and from runway were used. Emissions for initial climb, climb-out and approach from and to runway were spatially distributed according to representative angles of climb and descent for each aircraft weight category. Road vehicle emissions from free-flowing traffic were distributed on a road link-by-link basis as line sources. Car park emissions were treated as area sources.

147. A portion of the aircraft and road traffic emissions included in the inventory occur at some distance horizontally away from the airport. Estimates of annual emission totals for the airport therefore reflect the fairly arbitrary choice of spatial boundaries used in the inventory, for example, the extent of the road network covered. The Heathrow Inventory study did produce emission totals by source category for sources designated as 'airport-related' even though much of these occur outside the physical domain of the airport. The 1998 Heathrow Inventory showed that over half of the NO_x emissions designated as airport-related occur from the aircraft during take-off and landing, but much of this will be at some distance from airport ground-level. Around a third of all NO_x emissions from the aircraft (including ground-level emissions from auxiliary power units, engine testing etc, as well as take-off and landing) occur below 100 m in height. The remaining two-thirds occur between 100 and 1000 m and contribute little to ground-level concentrations. Receptor modelling studies based on dispersion models and the 3-dimensionally resolved emission inventory show the impact of airport activities on ground-level NO_2 concentrations. Studies have shown that although emissions associated with road traffic are smaller than those associated with aircraft, their impact on population exposure at locations around the airport are larger (Farias and ApSimon, 2003).

148. An updated version of the Heathrow emissions inventory has just been compiled by AEA Technology for the 2000 calendar year, using more detailed aircraft activity information. The new inventory is based on a number of improvements to the data and methods used which have led to a reduction in the estimates of the amount of NO_x emitted from aircraft at Heathrow compared with the estimates made in the 1998 inventory. The new inventory has accounted for the usage of reduced thrust during take-off more fully than had been possible for the 1998 inventory and assumptions about reverse-thrust usage have been updated. Other improvements have included information on Auxiliary Power Unit running times. The improvements have led to an overall 38% reduction in the estimate of NO_x emissions from aircraft at Heathrow relative to the estimates made in the 1998 inventory. This reduction was made up of a 19% reduction in aircraft emissions at ground-level and 46% reduction in elevated emissions. It should be emphasised that these reductions mark improvements in the inventory estimate due to methodological improvements, not to actual reductions in emissions over this time period.

2.6.4 Emissions from shipping

149. A recent exercise to quantify and map emissions of NO_x from shipping across the EU (including emissions in the North Sea, English Channel, Irish Sea and in-port sources) has been undertaken by ENTEC for DG Environment for the year 2000 (ENTEC, 2002). This used activity data from the Lloyds Maritime Intelligence Unit on ship movements and considered seasonal variations in activity through selecting data for January, April, July and October indicative of winter, spring summer and autumn operations. Other sources of information used were: vessel characteristics (vessel type, engine size and type), a detailed shipping emission factor database developed by the Swedish Environmental Research Institute (IVL) (ENTEC, 2002), data reflecting the time spent in port from a questionnaire survey and data on fuel consumption from fishing vessels, fishing grounds and the size of catches. The study covered all ships greater than 500 gross tonnes. Typical NO_x emission factors for these vessels currently range from 13 to 19 $gkWh^{-1}$, approximately 3 to 4 times higher than those associated with a Euro III heavy-duty road vehicle.

150. Estimates were made using a GIS methodology and the results presented on the 50 x 50 km EMEP grid. The study showed that two British ports were ranked in the top 10 highest emitters of NO_x in the EU, Milford Haven and Immingham, with estimated emissions of 2 ktonnes and 1.3 ktonnes, respectivelty, in 2000. Within the ENTEC study area covered (North Sea, Irish Sea, English Channel, Baltic Sea, Black Sea and the Mediterranean), it was estimated that NO_x

emissions are likely to equal two thirds of land emissions by 2010. The European Union is thus working with member states to encourage tighter emission standards through the International Maritime Organisation. The model for these proposed emission reductions may already be seen in the Baltic area with fiscal benefits awarded to ships meeting low SOx and NO_x standards. With respect to shipping the dominant technology for NO_x reduction is currently SCR with urea injection, as being developed for heavy duty road diesel engines (see the Technical Annexe, Appendix 1).

151. In the NAEI, total UK emissions from shipping cover fishing and coastal shipping in UK waters. NO_x emissions are estimated from DTI fuel consumption data for this sector and emission factors from CORINAIR (1999).

2.6.5 Emissions from rail transport

152. Limited information exists for the emissions associated with rail locomotives. In the UK, less than 50% of the rail network is electrified and thus the use of diesel locomotives is common. With respect to NO_x, diesel locomotives have an emission rate of between 6 and 16 $gkWh^{-1}$. The most recent studies (ARTEMIS) on these emissions have been undertaken by the Danish Technical University and involve the development of a methodology that attempts to incorporate fundamental physical factors for determining driving resistance of the train as a function of speed, load and weight. This is subsequently used to calculate the energy required to move the train, and propulsion efficiencies are applied for diesel engines and transmissions. Operation is divided into elements in an acceleration-velocity matrix, and the driving resistance calculated for each condition in the matrix. Based on a distribution function for the frequency of occurrence of each condition, the total energy consumption of the train for a given driving pattern is evaluated. Since the frequency of driving conditions is used, the method can be applied to a wide range of conditions, from a single train on a single route to an entire fleet of trains of a given type averaged over a large geographical scale. In order to facilitate the use of available operation data, the model can use either temporal or spatial distribution of the operating conditions. The results of this method have been favourably compared to measurements from a small number of Danish trains (Hickman, 1999).

153. In the NAEI, emissions from railways cover emissions from the stationary combustion of oil and gas by the railway sector and emissions from diesel trains. Emissions from generation of power consumed by the railway sector for electric traction is reported under the ‘Public Power’ sector, following emission reporting guidelines. Emissions from stationary combustion are based on emission factors and fuel consumption data for the sector. Emissions from diesel trains are estimated for Intercity, regional and freight trains using railway kilometre data, gas oil consumption data for the sector and emission factors for different types of diesel locomotives used for each type of journey (Goodwin *et al*., 2001). All the fuel consumption data are from DTI (2002).

154. The NAEI maps UK emissions from the rail sector according to rail track data. No specific or detailed inventories of emissions from local rail operations have been generated. Emissions from diesel locomotives represent 0.6% of the total UK inventory of NO_x emissions and are not likely to pose significant urban air quality problems except possibly in the immediate vicinity of major rail terminii. Without improvements in the emission performance of diesel locomotives, it is conceivable that emissions from the rail sector will become a more important issue in transport inter-modal comparisons as emissions from road vehicles continue to decline. However, greater electrification of the rail network will lead to reduced emissions of NO_x from trains at the point of use.

2.6.6 Emissions from other mobile machinery

155. Emissions from off-road sources and mobile machinery cover a range of portable or mobile equipment powered by diesel or petrol engines. They include agricultural and forestry equipment such as tractors and combine harvesters; construction equipment such as bulldozers and excavators; industrial machines such as portable generators, compressors and forklift trucks; aircraft support vehicles; and domestic house and garden equipment such as lawn mowers. In the NAEI, emissions and fuel consumption are estimated from population and machinery lifetime data from a DETR sponsored survey covering around 70 classes of machinery, power rating, load and annual usage data for each class of machinery and emission factors (Goodwin *et al*., 2001; Murrells and Salway, 2000). The emission factors for each machinery class mostly come from CORINAIR (1999) and Samaras (1996) and are expressed in g NO_x (as NO_2).kWh^{-1}. Where possible, the emission estimates are normalised according to fuel consumption data available from DTI for certain groups of machinery or estimated from other surrogate activity factors.

2.6.7 Primary emissions of NO_2 from non-road transport combustion sources

156. Whilst there is no evidence for significant emissions of primary NO_2 from other combustion sources, the presence of primary NO_2 emissions in diesel vehicle exhausts suggests this should be verified in certain other key combustion sources where ground-level exposure could be significant. For example, it is conceivable that diesel locomotives could emit significant amounts of NO_x as primary NO_2 while their engines are idling at low load in major rail termini which are often in enclosed spaces. Levels of primary NO_2 emitted in domestic burners and combustion appliances should be monitored to determine whether these sources, which can be significant sources of total NO_x emissions in urban areas, produce significant amounts of primary NO_2.

2.7 Time series of NO_x emissions in the UK

2.7.1 UK emissions of NO_x from 1970 to 2000

157. The NAEI time series of UK emissions of NO_x are shown in Table 2.4 and were depicted in Figure 2.1. The sector ‘other’ includes combustion in agriculture, waste incineration, but is mainly emissions from small boilers in the commercial and public sector.

158. Based on the 2000 NAEI figures (Goodwin *et al*., 2002) using the latest vehicle emission factors (Table 2.2), road transport is the largest source of NO_x emissions in the UK, contributing 49% of total emissions. Public power generation is the next largest source, contributing 21% of UK emissions, followed by industry (14%) and other transport and machinery (10%).

Table 2.4 UK emissions of NO_x (ktonnes as NO_2).

ktonnes NO_x	1970	1980	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Public power	812	861	781	683	671	567	527	495	449	372	364	338	358
Industry	524	372	337	328	323	319	339	291	283	285	283	266	250
Domestic	62	64	64	71	69	72	69	66	75	69	71	71	72
Road transport	762	978	1286	1257	1208	1141	1111	1063	1062	1020	953	910	844
Other transport & machinery	241	220	220	224	218	212	199	194	204	197	187	176	169
Other	90	73	56	57	53	44	47	46	46	40	38	37	35
TOTAL	**2490**	**2568**	**2744**	**2620**	**2543**	**2355**	**2290**	**2154**	**2120**	**1983**	**1897**	**1799**	**1728**
Road transport – using old vehicle emission factors			*1305*	*1274*	*1224*	*1147*	*1084*	*997*	*956*	*881*	*788*	*716*	*629*
Totals submitted to UNECE			*2763*	*2637*	*2558*	*2361*	*2263*	*2088*	*2014*	*1844*	*1732*	*1604*	*1512*

Source: 2000 National Atmospheric Emissions Inventory. The road transport figures and emission totals shown in bold are based on the latest set of vehicle emission factors which were not available at the time of formal submission of the UK 2000 emission estimates to UNECE. The figures shown in italics are based on the old emission factors used for the UK submission of the 2000 NAEI data.

159. Emissions have fallen steadily since their peak levels in 1989, with a reduction of around 38% since then. The decline has mainly been due to reductions in emissions from road transport and public power generation; these fell by 34% and 54%, respectively, from 1990 to 2000. The reductions in road transport emissions have been mainly due to the penetration of cars fitted with three-way catalysts in the fleet. Emissions from power stations were fairly constant in the 1970s, but have been declining since 1979. In the 1980s this was due to the increased use of nuclear power and an increase in average efficiency of thermal power stations. However, since 1988, the electricity generators have adopted a programme of progressively fitting low-NO_x burners to their large coal-fired stations. The introduction of modern CCGT plant burning natural gas in the early 1990s and the decreased share of coal for power generation in favour of gas, further reduced NO_x emissions from this sector up until 1999. Emissions of low-NO_x gas turbines are lower than those of pulverised coal fired plant even when these are fitted with low-NO_x burners. However, this trend was broken in 2000 when output from coal-fired stations grew again at the expense of nuclear power production. Further growth in electricity output from coal-fired stations occurred in 2001, this time at the expense of gas possibly due to increased price of natural gas supplies.

160. Emissions from industry have declined by 26% since 1990, again mainly due to the decline in coal use in favour of gas.

161. It should be noted that the figures in Table 2.4 are based on the latest vehicle emission factors which were not available at the time the 2000 reported version of the National Atmospheric Emissions Inventory (2000 NAEI) was compiled in 2002. Using the new vehicle emission factors increased the emission estimates for this sector due to the higher factors for Euro I and Euro II diesel vehicles than had been used previously (Section 2.6.2.1). Table 2.4 also shows the road transport emission estimates and total UK NO_x emissions from 1990 to 2000 that were reported in the 2000 NAEI derived from the old vehicle emission factors (emissions from all other sectors are unchanged).

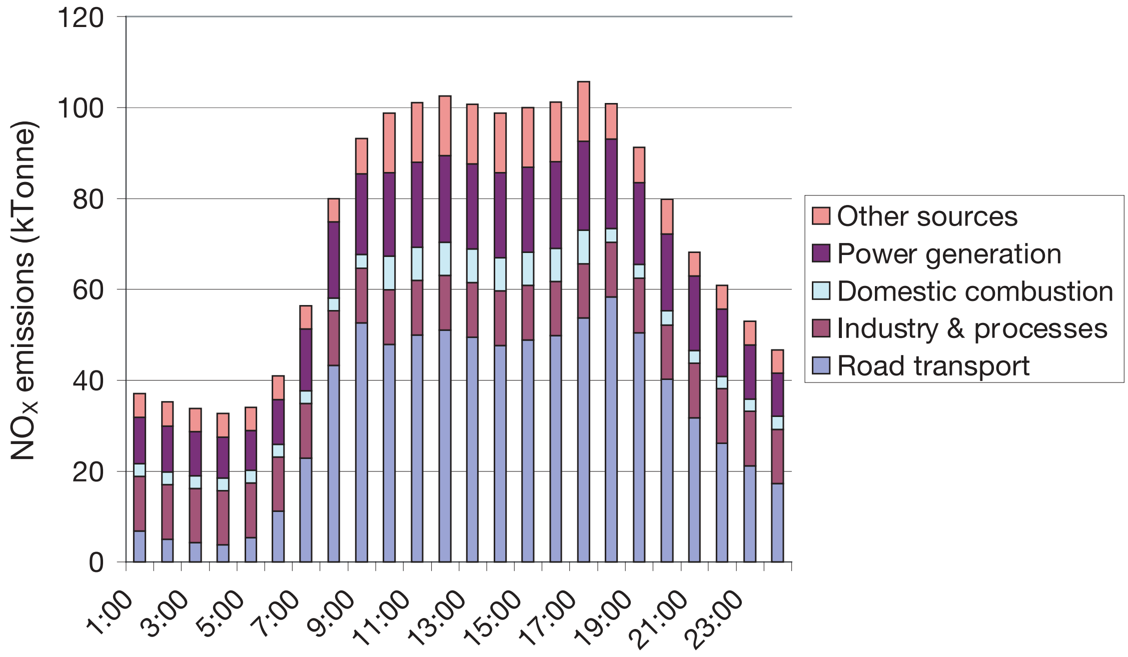
2.7.2 Temporal dependence of NO_x emissions

162. The emission figures shown in Table 2.4 refer to annual emission rates (ktonnes per year). Emissions vary with time of day and, for some sectors, with time of year and day of the week. The temporal dependence of emissions of NO_x and other O_3 precursors has been estimated by Jenkin *et al*. (2000) using the temporal activity profiles for key sectors like road transport and power generation. For road transport, hourly and daily average traffic flow data were used, taken from the DfT's Road Traffic Statistics publications. For power generation, hour of day and day of week profiles were based on activity data from the National Grid.

163. The diurnal variation in NO_x emissions is particularly significant, reflecting the varying nature of combustion activity associated with industrial, domestic and transport activity during the course of the day. Figure 2.6 shows the annual rates of NO_x emissions for each hour of the day broken down by sector. Emissions rise rapidly between 6 and 9am, remain fairly stable during the course of the day and fall off rapidly after 6pm. This diurnal behaviour is mainly because of the increase in road traffic activity between 6am and 6pm, but increased domestic combustion and power generation during the day time also contribute to the diurnal emission trends.

164. Emissions tend to be slightly lower in the summer months, owing to a decrease in the contribution made by space heating. The emissions are substantially lower (20-30%) at weekends compared with weekdays, owing to reduced contributions from a number of sources, but especially road transport. The results from this study were used by Jenkin *et al*. (2000; 2002) to model the formation of O_3 along trajectories arriving at rural sites in the UK at different days of the week during the conditions of an O_3 episode.

Figure 2.6 Diurnal variation in UK NO_x emissions (from Jenkin *et al*. (2000)).



2.8 Spatially resolved inventories of NO_x emissions

165. The NAEI produces national maps of NO_x emissions for the UK. While these will not replace detailed local inventories, they can provide a valuable basis from which a local inventory can be built and validated. They can also be used in assessments required for national policy making.

166. This section outlines the methods used to map national emissions data from the NAEI. There are many examples of local inventories that have been developed for specific areas of the UK, but one of the most recent and comprehensive local inventory is the London Atmospheric Emission Inventory (LAEI). A comparison between mapped estimates of the LAEI and the NAEI is provided in this section as a means of illustrating the effects of the different spatial inventory modelling approaches. Some indicative examples of the range of other local inventory activity in the UK are provided in this section.

2.8.1 The NAEI 1x1 km UK emission maps for NO_x

167. The NAEI national emissions inventory for NO_x is mapped over the UK on a 1x1 km grid. Figure 2.7 shows the map for UK NO_x emissions in 2000. Emissions are represented in tonnes of NO_x (as NO_2) per 1 km grid square. Details of the methods used for mapping emissions in the NAEI are given in Goodwin *et al*. (2001).

168. Sectors such as power stations, refineries and large industrial plant can be represented as point sources because their locations are known and reported emissions data or data to estimate emissions are available for the plant. Fuel consumption data for individual plants may be used as a surrogate to distribute national emissions from industrial combustion if emissions data are not directly available.

169. Emissions from road transport, rail and shipping are represented by lines where data are available, while source sectors such as domestic and commercial combustion are treated as areas. Emissions from road transport are mapped by treating major and minor roads separately. Major roads are treated as line sources using traffic flow data on road links in the national road network recorded each year. The traffic flow data come from the DfT 3 year rolling survey and the Annual Traffic Census Report for Northern Ireland. Emissions are calculated on each link using emission factors, traffic flows for the different vehicle types and average speeds appropriate for the road or area type. Emissions are mapped according to the Ordnance Survey grid reference for the road link. Minor roads are treated as area sources because centralised traffic flow data are not available for these roads. Emissions on minor roads are estimated at a national level and then distributed using surrogates derived from OS minor road maps, land cover data and regional average traffic flows on these types of roads.

170. Emissions from rail are mapped using track and train kilometre data available for each rail link. UK shipping emission totals are distributed according to port areas and routes defined by shipping arrival data from DfT. Aircraft emissions are treated as area sources for the 1x1 km grids covering the airports where take-off and landing occurs. The methods incorporate airport emission estimates from the London Research Centre (LRC) urban inventory studies and aircraft emission estimates from the Heathrow Inventory study. The number of aircraft movements at individual UK airports is used.

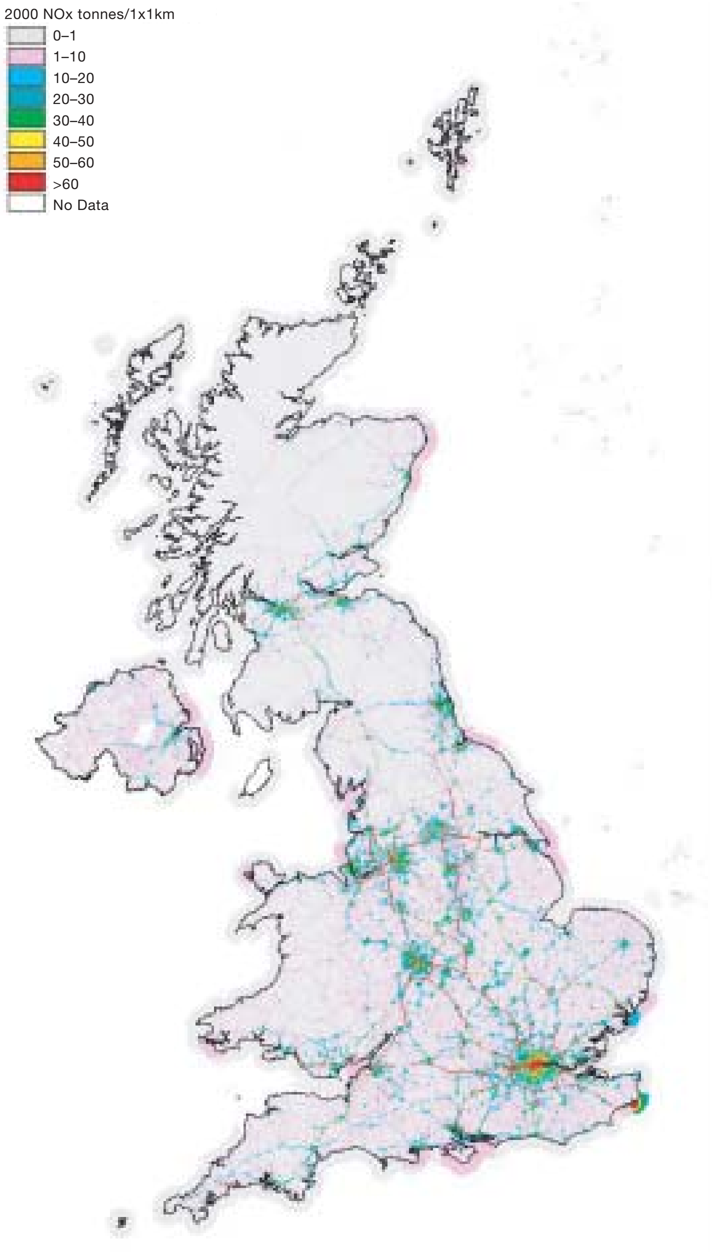
171. Emissions from domestic, small industrial and commercial combustion sources and off-road vehicles and machinery are treated as area sources. National totals for these sectors are distributed over the UK based on surrogate statistics represented in area grids. Area grids are compiled from geographical statistical data available on land use, population and employment.

172. The emission map shown in Figure 2.7 is available on the NAEI website (www.naei.org.uk/index.php) where the user can extract emissions for a particular area.

173. The frequency distribution of NO_x emission values is strongly positively skewed and it is important to note that a large fraction (around 30%) of the total emissions of NO_x are concentrated in a few grid squares which contain major combustion-related point sources. Road transport dominates total NO_x emissions with around one-third of total NO_x emissions occurring on major sections of road. Vehicles travelling at high speed contribute most and as a result the major motorways and primary routes are clearly defined on the map. Conurbations and city centres show high emissions resulting from large volumes of traffic, residential and commercial combustion. A combination of relatively high national shipping emission estimates and relatively few large ports result in significant localised emissions from shipping in port areas.

174. For a particular grid square, the difference in emissions derived from the national map and a detailed local inventory where available give a measure of uncertainty in the UK emission maps.

Figure 2.7 UK NO_x emission map from the NAEI.



2.8.2 NO_x emissions in London

175. The London Atmospheric Emissions Inventory (LAEI) was developed for 1999 by the Greater London Authority with Transport for London (TfL) and King's College, London (GLA, 2002). Recognising the importance of traffic as a source of emissions in London, this inventory used a great deal of detailed traffic activity data, but also other London-specific data for the inventory covering an area within and including the M25.

2.8.2.1 Overview of the London Atmospheric Emissions Inventory

176. The methodology for estimating road transport emissions in the LAEI recognises the importance of road traffic as a source of air pollution in London. Since, it is known that exceedences of air pollution objectives in London will increasingly be restricted to the near-road environment, the LAEI places considerable importance on the calculation of individual link emissions. It has therefore been produced primarily with dispersion modellers in mind and as a source of data for air pollution modelling runs in London. London is also unique in the UK in many respects:

- It is the largest urban area in the UK;
- Road traffic emissions are relatively more important than in many other urban areas in the UK;
- London has a unique vehicle stock, for example, TfL buses and taxis;
- There is a considerable amount of information available from which calculations of emissions can be made.

2.8.2.2 Calculating emissions from traffic in the LAEI

177. Most emphasis has been placed on observed manual counts of traffic in London, since these are more reliable on a link-by-link basis than traffic models or ad-hoc measurements. However, it is strongly linked with the LTS traffic model to assist with future traffic scenarios for London, for example, redistribution of traffic as a result of road user charging.[1] The LAEI uses count data for 11 different vehicle categories including taxis.

178. The analysis of on-road vehicle age data highlights significant variations in vehicle age by road type in London compared to the UK fleet represented in the NAEI model. It was found that in London, there is a slightly newer vehicle stock on motorways on average and older vehicle stock on minor roads compared with the national fleet. This was therefore accounted for in the inventory, although the overall effect was very small. Further investigations will take place into the age profiles of vehicles in London and will be included in future inventories.

179. The LAEI uses the same speed-dependent emission factors as the NAEI, but combines them with realistic speeds in London. The current inventory uses detailed speed data from actual measurements of speed derived from the 'floating-car' technique (Roland, 1998).

180. London buses and taxis make an important contribution to traffic flows in London, particularly central London, and are therefore important contributors to local NO_x emissions. Bus flow data for links were provided by DfT, but TfL Buses gave additional vehicle kilometre information (by location in London) as well as vehicle technology profiles of the TfL bus fleet. The bus vehicle stock was broken into two parts, central London (defined by LTS) and other London stock representing all other locations in London. LT bus services were assumed to represent 90% of the bus vehicle

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[1] This feature is retained because traffic models can be very useful in suggesting the likely future distribution of traffic, for example, greater growth in outer London compared with central London.

kilometres in London (TfL London Buses). Bus vehicle stock was then broken down by Euro class and included those vehicles fitted with an oxidation catalyst or particulate trap.

181. Taxi movements are important in London and particularly central London. Data relating to taxi activity in London has been analysed from several different sources including count data from London boroughs and specific studies in London concerned with taxi activity. Information provided by the Public Carriage Office enabled a specific breakdown of the taxi fleet by Euro class, the number of alternatively fuelled vehicles in the fleet, and an estimate of vehicle stock turnover year-on-year. An analysis of these data suggested that in central London taxis made up approximately 20% of the total car plus taxi total. In inner London the proportion was assumed to be 4% and 1% in outer London.

2.8.2.3 Calculating emissions from non-traffic sources in the LAEI

182. These calculations have mostly been made by the GLA, based on the original LRC inventory for London. Some modifications have been made to update these emissions.

183. For Heathrow, the inventory compiled by AEA Technology has been used (Underwood and Walker, 1999). Any overlap in emissions with the rest of the LAEI, i.e. some road emissions, were removed from the Heathrow Inventory. Various simplistic reductions were applied to some emission sources for future years.

184. Updates were also made to emissions of NO_x from natural gas combustion (domestic, commercial and small industrial). These emissions were increased in line with projected increases in natural gas use in London. These projections suggest that natural gas use continues to increase significantly year-on-year in London.

2.8.2.4 Results from the LAEI in comparison with data for London from the NAEI

185. Table 2.5 shows the amount of NO_x emitted in London calculated in the LAEI and the contribution from road traffic. Also shown are the results from the NAEI UK emission maps derived by putting a boundary around the M25, so including the same geographical area. The NAEI data refers to emissions in 2000, while the LAEI data is for 1999. It can be seen that the LAEI estimates 14% less NO_x than the NAEI, but the contribution from road traffic is not so different in each inventory. The LAEI estimates 64.7 kt of NO_x are emitted from traffic in London (in 1999); the figure from the NAEI is 73.0 kt (in 2000).

Table 2.5 Emissions of NO_x in London. Comparison of data from the LAEI and the NAEI. The LAEI data are for 1999; the NAEI data are for 2000. Both inventories are based on the new vehicle emission factors.

	Total emissions in London (ktonnes)		**% road transport emissions in London**		**% road transport emissions in UK**
	LAEI 1999	NAEI 2000	LAEI 1999	NAEI 2000	NAEI 2000
NO_x	94.7	110.3	68.3	66.2	49

186. However, comparing results from the two inventories is complicated by the fact they refer to different years. According to the NAEI, urban UK road transport emissions in 1999 were 7.5% higher than in 2000 due to the lower proportion of vehicles meeting the latest Euro standards in the fleet. If it is assumed this also applied to London, then the NAEI estimate for NO_x emissions from road transport in London in 1999 would be 78.5 kt, an increase of 5.5 kt above

2000 levels. If it is also assumed that emissions from other sources are unchanged from 1999 to 2000, then an NAEI estimate for total NO_x emissions in London in 1999 would be 115.8 kt. The LAEI estimate for 1999 would then be 18% lower than the NAEI estimate. However, the percentage contribution from road traffic based on the NAEI estimate for 1999 would be 67.8%, very close to the LAEI estimate.

187. Given the differences in the inventory approaches, with the LAEI using much more detailed and localised activity data than the NAEI map, the differences in emission estimates are not disturbing. In both cases, the contribution from road transport is higher in London than it is for the UK, as would be expected. It is worth noting that the road traffic contribution estimated for London of around 68% in 1999, is slightly down on the contribution previously estimated for 1996 of around 75% in the inventory developed by London Research Centre (Buckingham *et al*., 1998a). Comparing the LAEI and the earlier LRC inventory for London is complicated by the fact that different vehicle emission factors were used in each inventory. However, a significant drop in road transport emissions from 1996 to 1999 would have been expected due to the fleet penetration of newer and cleaner vehicles, accompanied by smaller reductions in emissions from other sources. This would lead to a decline in the traffic contribution to overall NO_x emissions in London. The LRC estimate for non-road transport emissions in London in 1996 was 36.7 kt compared with the LAEI figure for 1999 of 30.0 kt.

188. The contributions of different sources to emissions in London in 1999 are compared with the corresponding figures for the UK derived in the NAEI for the same year in Table 2.6. All the estimates are based on the new vehicle emission factors.

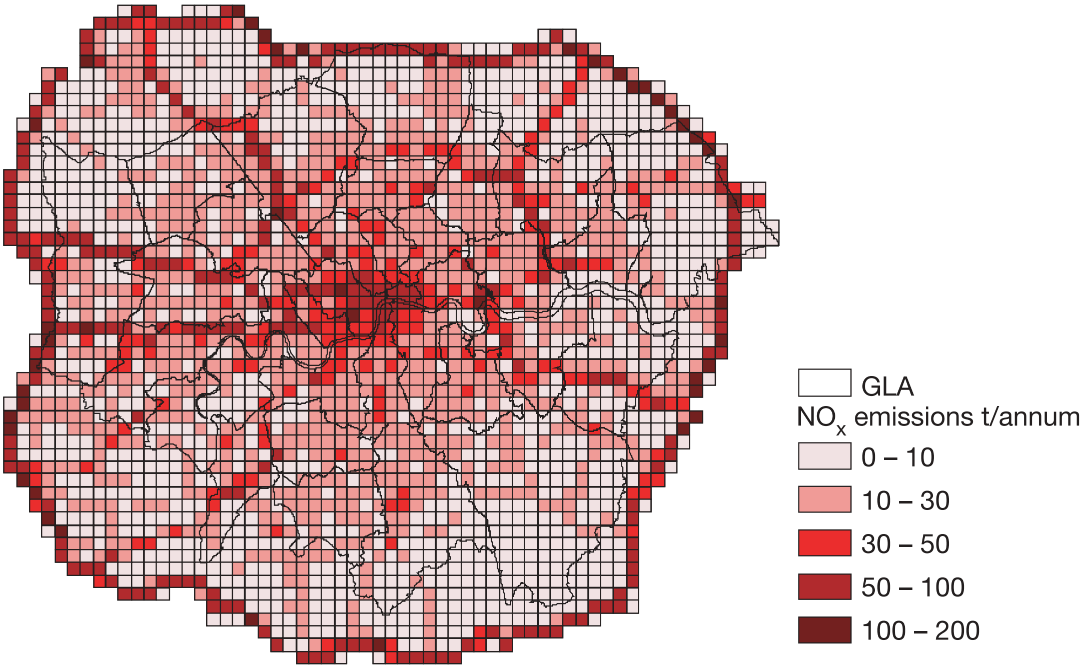
Table 2.6 Contribution of sources to NO_x emissions in London and the UK in 1999.

	% emissions in London LAEI	% emissions in UK NAEI
Road transport	68	50
Domestic and commercial combustion	17	6
Industry and public power	8	34
Other transport	6	10
Other	1	0

189. It can be seen that road transport and domestic and commercial combustion make a much bigger contribution to NO_x emissions in London than they do in the UK as a whole, as would be expected in a large conurbation. Industry and public power generation make a much smaller contribution to NO_x emissions in London than in the UK due to the lack of major industrial combustion plant in London. It should be noted though that the LAEI and the NAEI make slightly different definitions in terms of what is classified as 'commercial' and 'industrial' combustion processes, but this does not change the overall pattern of sector contributions to emissions shown in Table 2.6.

190. Figure 2.8 shows the contribution of road transport to total NO_x emissions in each grid square in London in 1999, according to the LAEI. It can be seen how much higher the contribution from traffic is to emissions in central London compared with outer parts of London, although the relatively high emissions from important radial roads and the M25 orbital can also be clearly seen.

Figure 2.8 NO_x emissions from road transport in London (1999).



191. The LAEI also addressed the contribution of traffic to emissions in central and Greater London separately and also the contribution made by different vehicle types. Overall, traffic made a similar (~60%) contribution to NO_x emissions in both central (defined by the inner ring road) and Greater London, but the contribution from different vehicle types was different in each area. In central London, buses and taxis made a larger contribution to NO_x emissions (~21% and 11%, respectively) than they did in London as a whole (7% and 1%), with a smaller proportion of emissions coming from cars. The contribution from buses is significant in spite of the fact that the bus fleet in London is among the cleanest in the UK. Cars are responsible for nearly a half of all NO_x emissions from road transport in London, with around 40% coming from vans and HGVs. Figures 2.9 and 2.10 summarise the percentage contribution to total emissions by vehicle type in central London and all of London (up to and including the M25).

192. The geographic variation in emissions might have important consequences for how emissions are expected to reduce. Section 2.6.2.1 showed that NO_x emissions from diesel vehicles have been declining more slowly with the introduction of the tighter emission standards than has been occurring with petrol vehicles. In central London, where there is a high proportion of diesel buses and taxis, the decline in emissions of NO_x in this area will not be as significant compared with other locations in London.

193. Any further emission inventories compiled for London would need to consider the effect of the recently introduced congestion charging scheme on traffic emissions. A report ‘Road Charging Options for London: A Technical Assessment’ was published in 2000 and concluded that the overall air quality benefits from fewer private cars would be offset by the impact of larger numbers of heavy duty vehicles. This assessment would need to be verified using real traffic flow data in the areas effected once the scheme has been operating long enough. Similarly, current work has investigated the ***potential*** emission benefits of a London Low Emission Zone of the type discussed earlier, restricting access to low emitting vehicles (see the London LEZ website, www.london-lez.org). However, emission inventories developed for London in the future would be able to show the actual benefits a scheme has had on emissions using actual traffic flow data available once the scheme has been implemented.

Figure 2.9 Percentage of total NO_x emissions from road transport in central London by vehicle type in 1999 (LAEI).

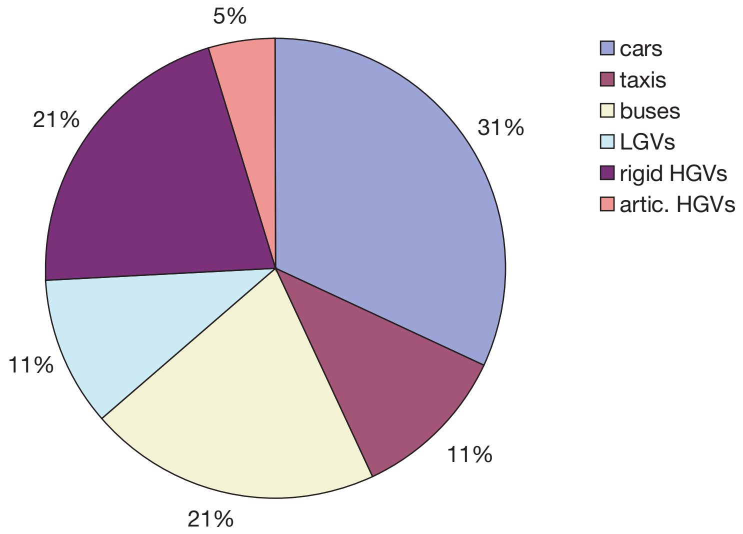
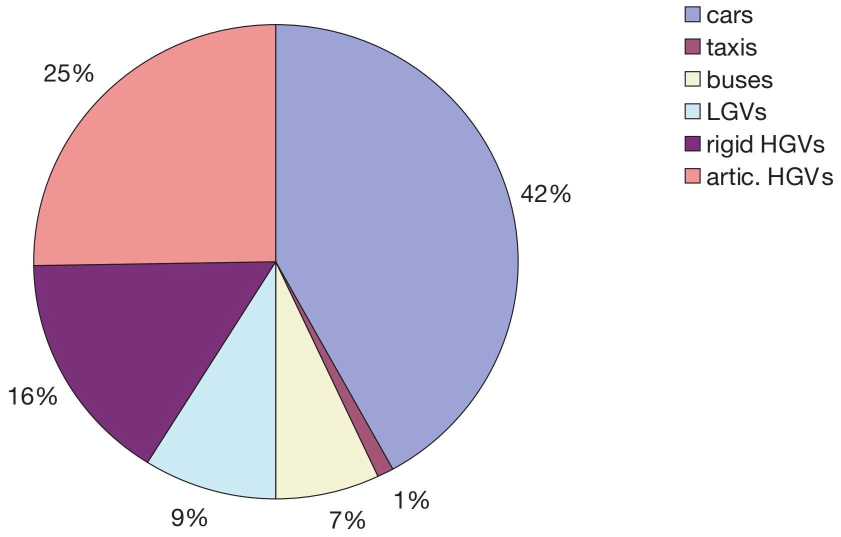


Figure 2.10 Percentage of total NO_x emissions from road transport in the whole of London by vehicle type in 1999 (LAEI).



2.8.3 Other local emissions inventories

194. A number of urban inventories have been compiled over the years, notably the ones produced by London Research Centre for several conurbations in the UK during 1995 and 1996: the West Midlands 1994; Merseyside 1995; Greater Manchester and Warrington 1995, Portsmouth and Southampton 1995; Bristol and Avonmouth 1995; Port Talbot and Swansea 1996; Middlesbrough 1996; City of Glasgow 1996; and Urban West Yorkshire 1996 (Hutchinson and Clewley, 1996; Buckingham *et al.,* 1997a; b; 1998b). As part of the same 'Ten Cities' initiative a further inventory was subsequently developed for the Greater Belfast area (1999). All of these inventories used 'bottom-up' methodologies for key sources, such as road transport and industry.

195. Greater Manchester, like a number of the urban areas for which emission inventories were produced in the 1990s, has continued to update and further develop inventory methodologies. The latest emission estimates available are for 1999 (aric, 2000) and these have been used for several local air quality management tasks including: Stage 3 and 4 Review and Assessment (Peace *et al.,* 2002a; b); air quality management planning; land use planning and the development of transportation policies.

196. Other detailed emission inventories have been produced independently of the Ten Cities initiative. Although not an exhaustive list, some examples include Sussex, Kent, Nottinghamshire (for 2001), Slough (for 2000), Cheshire (for 1998) and Stoke-on-Trent & Newcastle-under-Lyme. In addition to providing a foundation for dispersion modelling, the main benefit of compiling local inventories is the detailed examination of particular sources, such as specific industrial processes, that are known to be influential in a local context but which may not be well treated in the national inventory due to a lack of consistent national data.

197. In view of the importance of specific local sources, detailed emission inventories are also produced for discrete source sectors. Examples of spatially resolved airport inventories, include both major international airports such as Heathrow and Manchester (for 2000) and also regional airports such as Birmingham, Newcastle, East Midlands and Bristol (all for 2000). Emissions from shipping have been mapped across the EU, including the coasts and ports around the UK. These were discussed earlier.

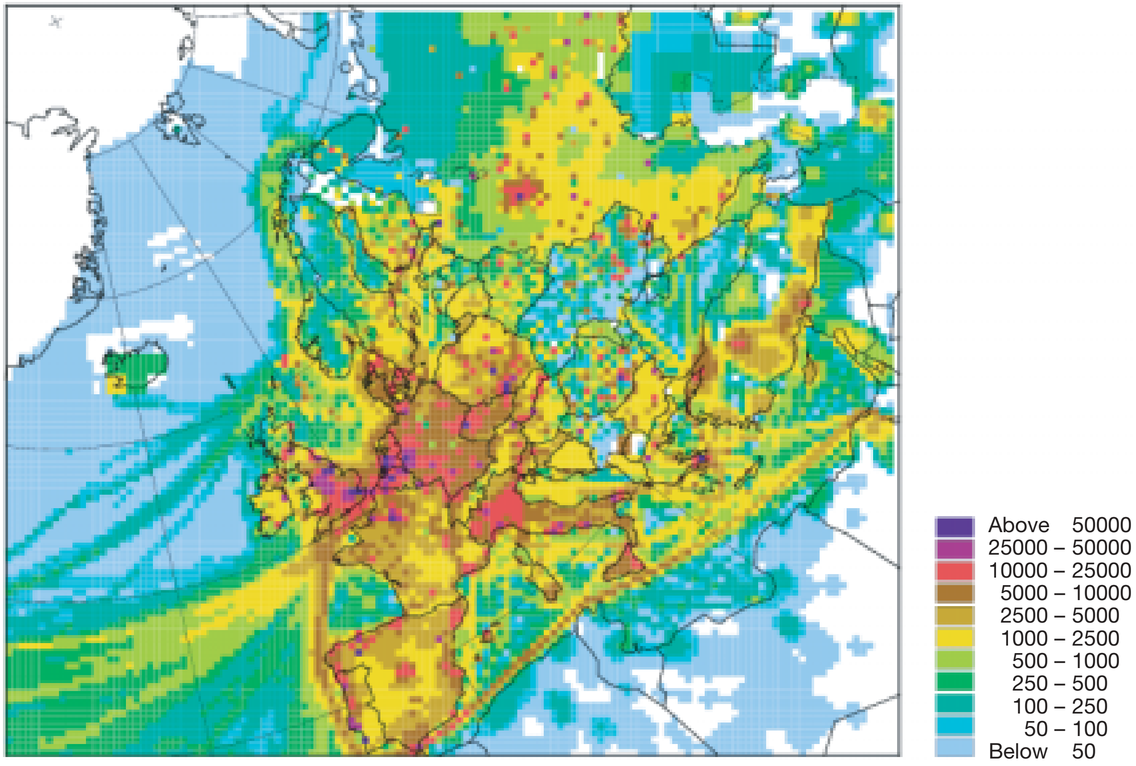
198. Local Authorities should refer to the Local Air Quality Management Technical Guidance Notes (LAQM, 2003) available on the Defra and Devolved Administration's websites when considering the requirements of an emissions inventory for their area. In the UK, the master source of information on emissions is the National Atmospheric Emissions Inventory (NAEI) providing emission maps on a 1x1 km grid. Local Authorities should use the emissions data within the NAEI first, and only compile their own inventory if these data are likely to be inadequate.

199. In many cases, compiling a complete local inventory from start is inappropriate and can be extremely time consuming and difficult without previous experience. This can lead to the generation of local inventories of varying degrees of quality. Using a common approach and methodology is crucial if inventories for different areas are to be comparable. However, where air quality exceedences are likely to occur as a cumulative result of a large number of different sources then the compilation of a more complete, local inventory may be useful.

2.9 NO_x emissions in Europe

200. Emission inventories for NO_x are compiled for other countries in Europe as required under UNECE/EMEP and IPCC reporting protocols. Table 2.7 shows the latest reported emission totals for NO_x in each of the EU15 countries, plus Norway and Switzerland and four central and Eastern European countries for which recent data are available (EMEP, 2002). Also shown are the emissions ceilings that apply to each country in 2010 (Official Journal, 2001). Table 2.7 also shows the data expressed as emissions per capita and per GDP in each country. Figure 2.11 shows the EMEP 50x50 km map of NO_x emissions in Europe for 2000.

Figure 2.11 Map of NO_x emissions in Europe in 2000 on a 50x50 km grid (EMEP 2002). Units are in tonnes NO_x as NO_2.



emep/msc–w

201. The emission figures in Table 2.7 refer to emissions in 1999, the most recent year data are available for most countries. For Greece and Portugal, the data are for 1998. The UK reports emissions data from the NAEI, but the figures shown are corrected for the latest vehicle emission factors. The table shows that all countries (except Bulgaria) need to reduce their emissions to achieve their emission ceilings, typically by around a third from 1999 values across all the EU15 countries. Emissions vary quite significantly on a per capita and per GDP basis. Emissions per capita vary from 13.9 kg NO_x per capita in Switzerland to 51.9 kg NO_x per capita in Norway. Emissions per GDP in western European countries vary from 0.41 tonnes NO_x per million ECU in Switzerland to 3.5 tonnes NO_x per million ECU in Portugal. The variation in these figures by country reflects the amount of economic, industrial and transport activity, fuel mix for energy production and amounts of emission abatement in each country. The low levels in Switzerland may be due to the amount of power generated by hydroelectric sources. The UK figure of 30.3 kg NO_x per capita is fairly close to the EU15 average value of 27.5 kg NO_x per capita. The emissions per GDP figure for the UK is also close to the EU15 average.

Table 2.7 Emissions of NO_x in Europe

	NO_x emissions (ktonnes as NO_2) in 1999	Emissions ceilings for 2010 (ktonnes as NO_2)	Emissions per capita (kg/capita)	Emissions/ GDP (tonnes/ million ecu)	% emissions from road transport sector	% emissions from energy production sector
Austria	172	103	21.3	0.87	50	5
Belgium	291	176	28.5	1.24	51	12
Denmark	210	127	39.6	1.27	33	27
Finland	247	170	47.8	2.05	46	13
France	1533	810	26.0	1.14	47	9
Germany	1637	1051	20.0	0.83	51	15
Greece	382	344	36.3	3.26	27	20
Ireland	119	65	31.7	1.33	42	33
Italy	1486	990	25.8	1.34	50	13
Luxembourg	16	11	37.5	0.87	42	1
Netherlands	409	260	25.9	1.09	42	12
Portugal	381	250	38.2	3.52	43	43
Spain	1379	847	35.0	2.44	-	-
Sweden	261	148	29.5	1.15	42	5
United Kingdom	1799	1167	30.3	1.31	51	19
EU 15	10321	6519	27.5	1.29	41	13
Norway	231	156	51.9	1.60	24	12
Switzerland	99	79	13.9	0.41	54	1
Bulgaria	203	266	25.3	-	26	31
Czech republic	391	286	38.0	-	43	21
Hungary	221	198	22.1	-	52	22
Poland	953	879	24.7	-	30	28

Emissions data are from EMEP (2002) and are for 1999, except for Greece and Portugal which are for 1998. The figures for the UK are taken from the NAEI, but corrected for the latest vehicle emission factors.

Emissions ceilings for all the EU15 countries are the NECD ceiling levels (Official Journal, 2001). For all other countries, the ceilings refer to limits agreed under the Gothenburg Protocol (UNECE, 1999)

202. It is also interesting to look at the breakdown in NO_x emissions by sector in each country. These are shown in Table 2.7 for the main sectors of emissions from road transport and energy production. Again, there is fairly significant variation in the sectorial split. For most countries in western Europe, the contribution made by road transport is in the region 40-50%, although there are some outliers like Denmark, Greece and Norway where the contributions are lower (33%, 27% and 24%, respectively). The contribution from the energy production sector is far more variable, probably reflecting the fuel mix and levels of emission abatement used for power generation, as well as variable contributions from other sectors, for example, industrial combustion. Particularly low contributions to emissions from power generation in Austria and Switzerland are probably due to the amount of power generated by hydroelectric sources, while low levels in France may reflect the use of nuclear energy for power generation.

2.10 Uncertainties in emission estimates

203. An appreciation of the uncertainties in emission estimates is important for different reasons, depending on the geographical scale of the inventory, detail in the emission sector split and intended application of the inventory results. For a particular area, an inventory is usually reported as tonnes emitted over a certain period of time, normally a calendar year. An inventory calculated for more than one year is useful because it demonstrates how emissions have been changing over a period of time. Such emission trends demonstrate the effectiveness of national or local policies in curbing emissions. However, emissions calculated over more than one year can only be interpreted if the uncertainties in the estimates for each year can be understood. For example, emissions calculated for two different years may be different because emissions really have changed; or because new sources were found in the inventory for the second year which were missing from the inventory for the first; or because different methodologies were used in calculating them. An uncertainty analysis would help to demonstrate whether any changes in emissions between years were significant.

204. In the NAEI, a complete time series of UK emissions from 1970 to the most recent year that data are available are calculated each year. In other words, emissions from earlier years are recalculated each year. This may lead to changes in historic emission estimates due to new emission factors becoming available, new emission calculation methodologies being used or changes to national activity statistics (for example, fuel consumption) in earlier years being made by government or industry sources. However, this does mean that emissions calculated for a stream of different calendar years in a particular inventory compilation are comparable and the emission trends probably robust. In the NAEI, it is possible that relative changes in emissions each year shown in a particular year's inventory are more accurate than the absolute emission rates in tonnes.

205. Local inventories are generally more difficult to calculate than the national figures because they have to rely on different sources of information which are generally more uncertain, incomplete or difficult to obtain. They are not generally calculated every year and emissions in an area in a previous year are not usually recalculated when an inventory for a new year is compiled. Because of this, inventories compiled at different times for a particular area covering different calendar years may not be comparable. New sources may be discovered and methodologies improved for the more recent inventory. An uncertainty analysis for each inventory would help to put this into context.

206. The uncertainties in emission estimates need to be quantified at different geographical levels and different levels of sector detail. The results are required for different purposes. Uncertainty estimates for the national totals are required for interpreting the effect of national policies on emission trends and for appreciating the emission levels in the context of national emission targets and emissions ceilings (for example, the NECD targets).

207. Uncertainties in emissions from individual sectors may be quite different to the overall uncertainties in the national totals, but may still be required when considering the direction of government policies towards specific sectors, for example, power station emissions, road transport emissions and emissions from specific vehicle types.

208. Uncertainties in emissions in local areas are of more consequence to air quality modelling of local pollutant concentrations than uncertainties in the national totals and they will usually be of greater magnitude. Uncertainties in local inventories are affected by different factors to those affecting uncertainties in the national inventory estimates. For example, the national emission estimates are often based on national statistics like fuel consumption which are generally quite reliable. Local inventories require more local knowledge on activity drivers, which, while more detailed, may be considerably more uncertain than national figures. The inventories are also affected by knowledge of emission location and GIS mapping techniques.

209. This section considers levels of uncertainties in the national totals, in individual sectors and in local inventories and issues relating to methods for estimating them.

2.10.1 Uncertainties in national emission estimates

210. Quantifying the uncertainties in the national NO_x emission estimates helps to prioritise future work by pointing to those areas where further information is required to improve the reliability of the inventory. The National Atmospheric Emissions Inventory has made a detailed and quantified assessment of the uncertainties in the national emission estimates for NO_x and other pollutants in 2000 using a direct simulation approach (Passant, 2003).

211. The procedure used corresponds to the IPCC Tier 2 approach discussed in the Good Practice Guidance (IPCC, 2000), as well as the Tier 2 method proposed in the draft 'Good Practice Guidance for CLRTAP Emission Inventories', produced for inclusion in the EMEP/CORINAIR Guidebook on Emission Inventories. The same approach has also been applied to the UK greenhouse gas inventory (Salway *et al*., 2001) and has been described in detail by Charles *et al*. (1998).

212. In the approach used, an uncertainty distribution was allocated to each emission factor and each activity rate. The distribution types used were drawn from a limited set of either uniform, normal, triangular, beta, or log-normal. The parameters such as mean value, standard deviation etc. of the distributions for each emission factor or activity rate were set either by analysing the available data on emission factors and activity data or by expert judgement. A calculation was set up to estimate the emission of each pollutant by sampling individual data values from each of the emission factor and activity rate distributions on the basis of probability density and evaluating the resulting emission. Using a Monte Carlo type software tool, this process could be repeated many times in order to build up an output distribution of emission estimates both for individual sources but also for total UK emissions of each pollutant. The mean value for each emission estimate and the national total was recorded, as well as the standard deviation and the 95% confidence limits.

213. Uncertainties in the emission estimates arise from uncertainty in both the emission factor and activity rate used in the calculations. In some cases, emission estimates are supplied directly by process operators or regulators (for example, the Pollution Inventory) and are converted into an overall emission factor using national activity data. In this case, the uncertainty in the activity data is ignored and an uncertainty distribution is selected for the emission factor reflecting the uncertainty in the supplied emission estimate. Where this is not known, there is a need to improve the understanding of uncertainties in emissions data provided directly by industry or regulators.

214. An important assumption made in this statistical approach for estimating uncertainties in national emissions is that uncertainties in each source are not correlated. If there are cross-correlations in emission estimates for different sources, the analysis becomes much more complex.

215. Fuel consumption is one of the main activity datasets used. The uncertainties and distribution parameters in these were taken from Salway *et al*. (2001) and were based on data from DTI. However, the main sources of uncertainty in emission estimates are in the emission factors used rather than the fuel consumption data. Uncertainty estimates for these are largely based on expert judgement, guided by the range in emission factors given by literature sources and elsewhere. Industrial trade associations and industrial process operators provided a final source of expert opinion. The report by Barlow *et al*. (2001) provided an indication of the range of measured emission factors for road vehicles.

216. Uncertainties in UK road transport emissions were based on estimated levels of uncertainty in the emission factor for each category of vehicle and in the vehicle kilometre activity data used. For NO_x, the emission factor uncertainties used ranged from 25% for non-catalyst petrol cars to 60% for heavy duty diesel vehicles, all at the 95% confidence level. These largely reflect the scatter in the emission factor results at different vehicle speeds which were statistically interpreted in the report by Barlow *et al*. (2001). It is assumed that the vehicles tested are representative of those in the UK fleet. However, the changes in the latest set of vehicle emission factors, discussed in Section 2.6.2.1, from earlier figures that were used in the NAEI, are consistent with the emission factor uncertainty estimates used in this analysis. Uncertainties in the national vehicle kilometre figures were estimated to be 5–10% for each vehicle category. Road tunnel exhaust measurements can be used to validate vehicle exhaust emission models and provide further insight into levels of uncertainties in road transport emission estimates (Sjodin and Cooper, 2001).

217. As a consequence of the way uncertainties in emissions from different sources overlap and cancel out in this type of statistical procedure, the uncertainty in total UK emissions are smaller than might be expected from the levels of uncertainties in emission factors and activity data for individual sources. The analysis gave an overall uncertainty in UK emissions from road transport of 12% (95% confidence limit). For power stations, the overall uncertainty estimate in UK emissions was 10% and for domestic combustion 17%.

218. The overall uncertainty in the annual total for UK NO_x emissions (all sources) in 2000 was estimated to be 7% at the 95% confidence level for the mean value emission figure of 1512 ktonnes (using the old vehicle emission factors). The relatively low uncertainty is a result of statistical interpretation of the contributions from the main emission sources each with moderately high uncertainties and a degree of cancelling out.

219. The uncertainty estimate quoted here only refers to uncertainty in the national annual emission totals, not to emissions from particular sources. It also does not reflect uncertainties in emissions at a particular time or location. However, it is worth noting that IIASA concluded a very similar level of uncertainty (±10%) in their independently-derived estimate of UK emissions of NO_x using a similar statistical approach (Suutari *et al.*, 2001).

220. Uncertainties in UK emissions for all other air quality pollutants were estimated and found to be higher than the 7% figure for NO_x. The exception was for SO_2 which had an estimated level of uncertainty in UK emissions of ±3%.

221. A ‘key source’ analysis was also undertaken following IPCC Tier 2 methodology to identify the major contributors to inventory uncertainty (Passant, 2003). Key sources will often, but not always, be those sources which contribute most to national emissions. For NO_x, a number of key sources were identified. These were:

- Road vehicle emissions
- Domestic and industrial gas consumption
- Cement production
- Use of coal and landfill gas for electricity generation
- Off-road vehicles and machinery
- Gas oil consumption for coastal shipping
- Offshore oil and gas installations

222. The results of the uncertainty analysis apply to the estimates for the year 2000 only. An issue to consider is that since emissions are believed to be declining from many sectors as a results of legislation, it is vital that the emission factors and other data used in the NAEI are updated regularly to reflect any reductions in emissions that are occurring. This will require continuous and detailed research be carried out to provide evidence for any reductions, thereby allowing the emission factors used for the annual NAEI emission estimates to continue being up-to-date. A case in point is the road transport emission factors.

223. The statistical method used in the uncertainty analysis is useful for investigating the likely impact of uncertainties in emission estimates. However, it is not helpful for identifying missing sources in the inventory and the impact this has on uncertainties. A few sources of NO_x emissions not currently included in the NAEI have been identified in Passant (2003), but none of these are considered significant. These included emissions from natural and accidental fires; chemical waste incineration; and flares at refineries, chemical sites and landfills. Estimates for these sources will nevertheless be added to the NAEI over the next few years.

224. The uncertainties in inventories are a reflection of the quality and quantity of data which are obtained when compiling the inventory. The current approach for analysing uncertainty in the inventory allows the most critical parameters to be identified, thus priority areas for research can be set and the national inventory improved in the most cost-effective way.

2.10.1.1 Uncertainty in local emission estimates and emission mapping

225. Although there has been some progress in making a quantitative assessment of uncertainty in national emission estimate totals and for individual source categories, the production of statistical error estimates on spatially resolved inventories is still problematic. The most robust uncertainty estimates would account for uncertainty in activity data, emission factors, the assumptions required to apply emission factors and the spatial data used to represent sources. There are several aspects of spatial data quality to be taken into account such as positional accuracy, logical consistency, completeness and temporal accuracy. As with any other source of data, the spatial data that are used in an inventory project will influence the results obtained, for example, through varying road lengths or influencing the accuracy with which sources are located. This is particularly important where data are to form an input into dispersion modelling activities.

226. In addition to classical statistical uncertainty tests, there are various verification techniques that can be undertaken to help assess the reliability of inventory data. These include clear and transparent documentation of data and procedures; basic quality checks through cross reference with other sources; comparison with alternative inventories and ground truth verification. A comparison of two spatially resolved inventories for the Greater Manchester and Warrington areas, one produced by the London Research Centre (Buckingham *et al*., 1997a) and the other as a research project, indicated broad agreement in overall totals. Despite some methodological and source data differences, estimates were within ~12% for road transport sources (47.5 ktonnes (LRC) compared to 42.2 ktonnes (Lindley *et al*., 1996)) and ~21% for all sources (75.4 ktonnes (LRC) compared to 62.3 ktonnes (Lindley *et al*., 1996)). The nominal base years were 1995 (LRC) and 1994 (Lindley *et al*., 1996) which will have accounted for some of the differences in emission totals and their spatial distribution and it should be noted that the LRC inventory covered a wider range of sources in total. Figure 2.12 illustrates the differences in the spatial distributions of emissions which were found to be due to differences in spatial data sources, completeness and consistency (Lindley *et al.*, 2000).

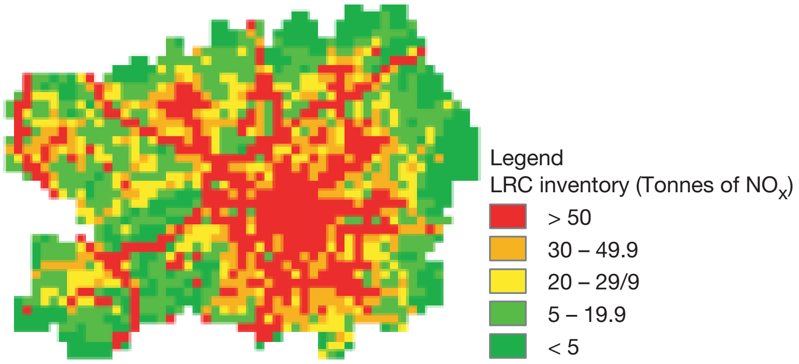
227. The comparison between the emission estimates for London from the LAEI and the NAEI maps also give a measure of uncertainties in an inventory for a local area based on the inventory technique used: ‘top-down’ or ‘bottom-up’. Overall NO_x emission estimates for London in the LAEI are 18% lower than the ‘top-down’ estimates of the NAEI for the same inventory year (Section 2.8.2.4).

228. One can also consider uncertainty in NO_x emissions on individual road links, again using a Monte Carlo analysis, where the range of speeds is taken into account. Consider the uncertainty in emissions for a typical traffic flow of 1000 vehicles per hour along a 1 km length of road, with a heavy duty vehicle mix of 10%. To illustrate this and assuming uncertainties in vehicle flow, speed and emission factors of ±10%, ±6 kph and ±15-25% (light and heavy-duty vehicles), respectively, the road link emissions have a calculated uncertainty of ±16% for an average speed of 30 kph. For an average speed of 15 kph, the road link emissions have a calculated uncertainty of ±28%. The relative uncertainty in emissions is considerably greater for lower vehicle speeds, as expected from the shape of the speed-emission curves which show emissions rising steeply at low speeds. This highlights the importance of good vehicle speed estimates.

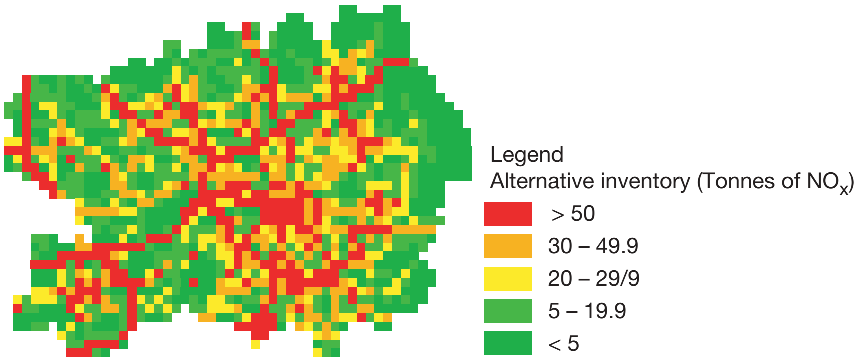
229. This simple uncertainty analysis illustrates that the uncertainty in individual road link emissions is significant when the potential range of vehicle speeds and driving patterns are considered.

Figure 2.12 Comparison of the results from two spatially resolved emissions inventories for Greater Manchester and Warrington (a) London Research Centre (Buckingham *et al.*, 1997a) (b) North West emissions inventory (Lindley *et al.*, 2000).

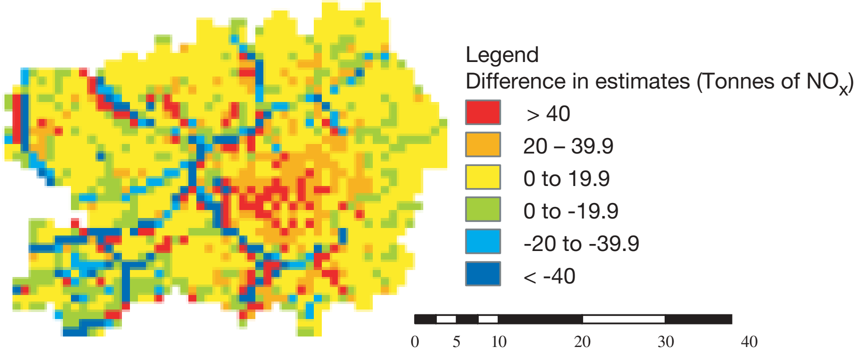
(a) Local emissions inventory produced by the London Research Centre



(b) Extract from an alternative local inventory



(c) Difference in estimates at the 1 x 1 km grid square resolution



2.11 NO_x emission projections

2.11.1 UK emission projections

230. The NAEI provides projections in UK emissions of all the major air quality pollutants by source sector. The projections are based on a number of different activity drivers, the most common one being fuel consumption forecasts for many of the sectors. Account is also taken of emissions legislation, fuel quality directives, abatement technology penetration and other factors which are likely to affect unit emissions. For road transport, a fairly detailed emission forecasting approach is used, adopting the latest traffic forecasts reflecting current Government policies on transport, fleet turnover and the penetration of vehicles meeting the tougher European vehicle emission Directives and the impact these will have on emissions from in-service vehicles.

231. The national projections are used by the Government to check against progress in achieving agreed emission reductions targets (for example, the National Emissions Ceiling Directive) and also in development of national strategies and policies. The emission projections are used for local air quality Review and Assessments.

2.11.1.1 Assumptions for non-traffic sources

232. For most of the sectors other than road transport, the main activity driver is forecasts in fuel consumption according to the central growth/high fuel price scenario in Energy Paper 68 (EP68), provided by the DTI. These estimates incorporate an assumed growth in economic activity of about 2.5% per year and the continuation of current trends towards greater use of natural gas and cleaner technologies (DTI, 2000). Industrial production activity projections from EP68 are also taken into account.

233. The projections take account of the impact, on emissions, of abatement in the electricity supply industry from EP68, the impact of the Large Combustion Plant Directive and improvements in efficiency in the cement industry and refineries.

2.11.1.2 Assumptions for road transport

234. The base emission projections for road transport are currently from a 2000 base year and are calculated from a combination of road traffic activity projections and knowledge of the expected emission characteristics of the vehicle fleet in the future.

235. The changes in emission factors for vehicles in the projections are largely driven by the legislative emission standards set in the European Directives for Euro III and Euro IV vehicles applying to conventional petrol and diesel powered vehicles. This means that no further improvements in new vehicle emissions occur beyond the limits set for introduction in 2006 for light duty vehicles and 2008 for heavy duty vehicles. In other words, the penetration of advanced vehicle types and technologies currently under development, such as fuel cell, hybrids and other electric powered vehicles are not considered in the base projections, neither are alternative fuels such as CNG.

236. Table 2.2 provided the vehicle emission factors for Euro III and Euro IV vehicles, based on scaling factors assumed to apply across all speeds relative to emission factors for Euro II vehicles. The basis for these factors was discussed in Section 2.6.2.1. In addition to this, the impact of current vehicles in the fleet (pre-2000 standards up to Euro II) running on ultra-low sulphur fuels meeting the 2005 Fuel Quality standards was accounted for. This grade of fuel is already widely available in the UK, but the effect on NO_x emissions (from 500 ppm to 50 ppm sulphur (ULS) grade) is quite small: reductions are typically less than 15%. The effects of fuel quality on emissions were based on empirical relationships taken from the European EPEFE Programme (EPEFE, 1995). It is assumed that 100% market penetration of 2005 standard fuels (ULSP and ULSD) is achieved by 2001.

237. The turnover rate for vehicles in the national fleet combined with new vehicle sales projections define the penetration rate for new vehicles meeting the tighter emission standards and the phasing out of older, higher emitting vehicles in the fleet (Goodwin *et al*., 2001). The fleet projections are calculated from survival rate functions implied by historic vehicle licensing statistics (number of new registrations and numbers still registered by age in each year). Growth in new car sales was taken from DfT's Vehicle Market Model. For other vehicle types, new sales and growth in the vehicle stock were related to the growth in number of vehicle kilometres. A number of assumptions relating to the composition of the national vehicle fleet were specified by the DfT in 2001 and are shown in Table 2.8. Note that the number of heavy duty vehicles fitted with particulate traps shown in the table is being reviewed in light of data from the Energy Saving Trust, on the number of grants provided under the Government's CleanUp programme, which suggest the actual figures may be higher than shown.

Table 2.8 Assumptions affecting the composition of the UK fleet provided for the NAEI base projections by DfT in 2001.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008+
Diesel penetration of new car market (%)	14	16	17	18	19	20	21	22	22
Proportion of Euro IV cars in the new petrol car market (%)	0	20	40	60	80	100	100	100	100
Proportion of new diesel cars with particulate traps (%)	0	5	10	15	20	25	25	25	25
Cumulative number of heavy duty vehicles retrofitted with particulate traps	4000	6000	8000	10000	12000	14000	14000	14000	14000

238. The current NAEI projections are from a 2000 base year which means that 2001 is treated as a 'projection year'. One of the key assumptions in the base projections is the rate of penetration of diesel cars in the fleet. This is driven by the percentage sales of new diesel cars. The 2000 NAEI base projections assumed only a modest growth in diesel car sales, as defined by DfT in 2001 and shown in Table 2.8. However, an accelerated growth in diesel car sales appeared to take place in 2001 so, whereas the predicted rate used in the projections was 16%, the actual rate was 18% for the year as a whole, but rising upwards during the course of 2001. This led DfT to re-forecast the rate of diesel car sales and the effect this has on NO_x emission projections for road transport will be discussed in Section 2.11.3.

239. DfT assumptions on the early introduction of Euro IV petrol cars in the UK market are shown in Table 2.8 expressed as the percentage of new petrol cars sold which meet these standards. Table 2.8 also shows the proportion of new diesel cars sold which are fitted with particulate traps. However, the fitting of a particulate trap on a diesel car does not have a significant effect on total NO_x emissions. A small number of heavy duty vehicles are also assumed to be retrofitted with particulate traps from 2000, the numbers growing to 2005. There is some evidence that CRT traps may lead to a small decrease in NO_x emissions from heavy duty vehicles.

240. In addition to these, the following assumptions are made concerning the introduction of new vehicle emission standards:

Petrol cars:
Euro III (98/69/EC) – 10% in 2000 (balance are Euro II's)
Euro IV (98/69/EC) – as in Table 2.8; balance from 2001 are Euro III

Diesel cars:
Euro III (98/69/EC) – 10% in 2000 (balance are Euro II's). 100% from 1 January 2001 to 2005
Euro IV (98/69/EC) – 100% from 1 January 2006

LGVs (petrol and diesel):
Euro III (98/69/EC) – 100% from 1 January 2002 (2001 for small LGVs)
Euro IV (98/69/EC) – 100% from 1 January 2006

HGVs and buses:
EURO III (1999/96/EC) – 100% FROM 1 OCTOBER 2001
Euro IV (1999/96/EC) – 100% from 1 October 2006 (standards for NO_x introduced in 2 stages, second stage from 1 October 2008)

Motorcycles:
97/24/EC – 100% from 1 January 2000

All these assumptions are factored into the fleet composition data.

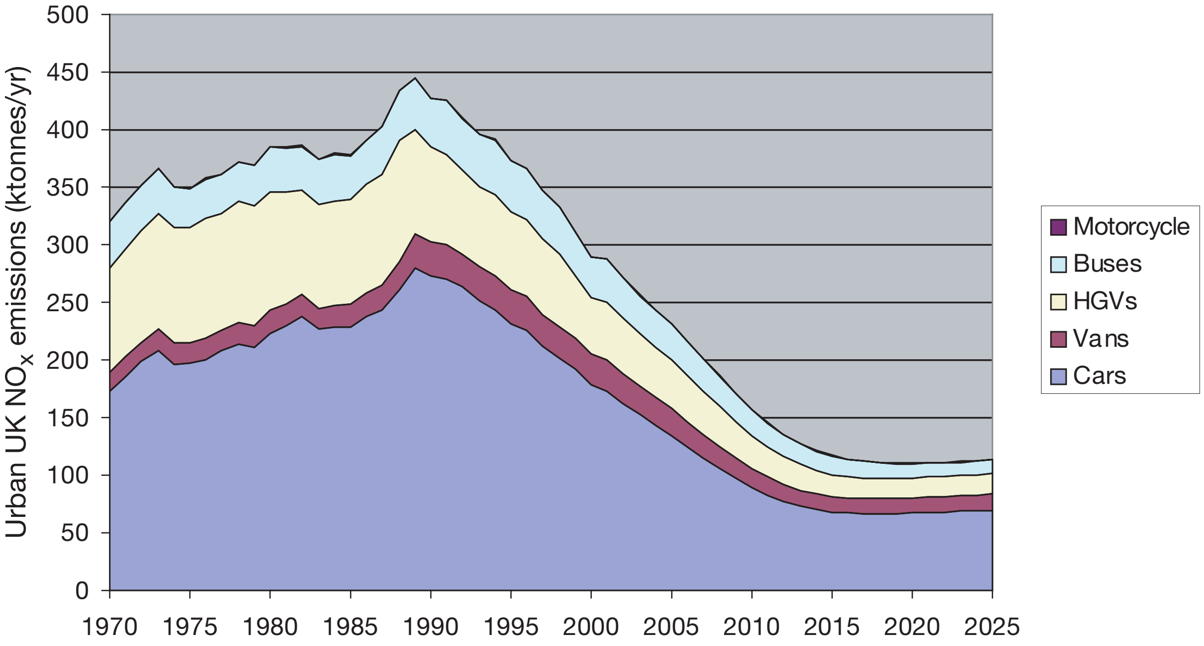
241. The other key driver in the road transport emission projections is the growth in traffic activity. The growth in UK vehicle kilometres is forecast from 2000 for each vehicle, road and urban area type, using separate forecasts for traffic in England, Scotland, Wales and N Ireland. A combination of data sources are used, including the Ten Year Plan for Transport 'Plan' scenario (DETR, 2000b), the 1997 version of the National Road Traffic Forecasts from DfT and the Central Scotland Transport Model (CSTM3) from the Scottish Executive.

2.11.1.3 Baseline NO_x emission projections for road transport

242. Tables showing UK and urban UK road transport emissions from 1990 to 2025 by vehicle type are provided in the Technical Annexe to this report (Appendix 1). All the figures are based on the new vehicle emission factors (not originally used for the 2000 NAEI base inventory, see section 2.7.1) and are projections from the year 2000.

243. Figure 2.13 demonstrates the trends in urban UK road transport emissions by vehicle type from 1970 to 2025. NO_x emissions from road transport are expected to continue to decline from 2000 until around 2015, due to the penetration of cleaner vehicles of all types in the fleet. After 2015, without any further improvements in vehicle emissions beyond those required by the Euro IV standards, emissions start to rise again as the continued growth in traffic starts to offset the gains achieved by penetration of cleaner vehicles in the fleet. Passenger cars are the dominant source of road transport emissions in 2000 contributing to 49% of road transport emissions nationally and 62% in urban areas. This dominance continues although it is slightly reduced to 44% of road transport emissions nationally and 57% in urban areas by 2010.

Figure 2.13 Urban UK road transport emissions of NO_x.



2.11.1.4 NO_x emission projections for all sources

244. The projections of UK NO_x emissions from all sources were displayed in Figure 2.1 which showed the complete time-series in emissions by sector from 1970 to 2020. These are based on the latest vehicle emission factors.

245. Emissions are predicted to fall by 25% from 2000 to 2010 and by 34% from 2000 to 2020. The fall is mainly due to the decline in road transport emissions and emissions from public power generation. From 2000 to 2010, road transport emissions fall by 50%, while emissions from public power generation fall by 18%. The contribution from road transport to total UK NO_x emissions also falls from 49% in 2000 to 32% in 2010.

246. In spite of this encouraging decline in emissions, without any further measures put in place the fall does not appear to be enough to reach the NECD emission ceiling of 1167 ktonnes which the UK must achieve by 2010. Based on the NAEI's current projections from 2000, emissions will be 1293 ktonnes in 2010, still 126 ktonnes short of the target. A further 10% reduction in emissions in 2010 will be required to meet this target. This requires the UK to find a cost-effective means of further reducing emissions to achieve the NECD ceiling. However, it also highlights the need to fully understand the uncertainty in the national emission projections and their sensitivity to key parameters such as the emission factors for current and future vehicles, forecasts in transport and industrial activity, effectiveness of abatement technologies and demand for energy and likely fuel mix for future electricity generation. The Government has recently proposed a National Emission Reduction Plan for implementation of the Large Combustion Plant Directive which is expected to deliver a greater degree of certainty in the outcome of the Directive by offering operators greater flexibility in achieving reductions cost effectively.

2.11.2 NO_x emission projections in specific urban conurbations

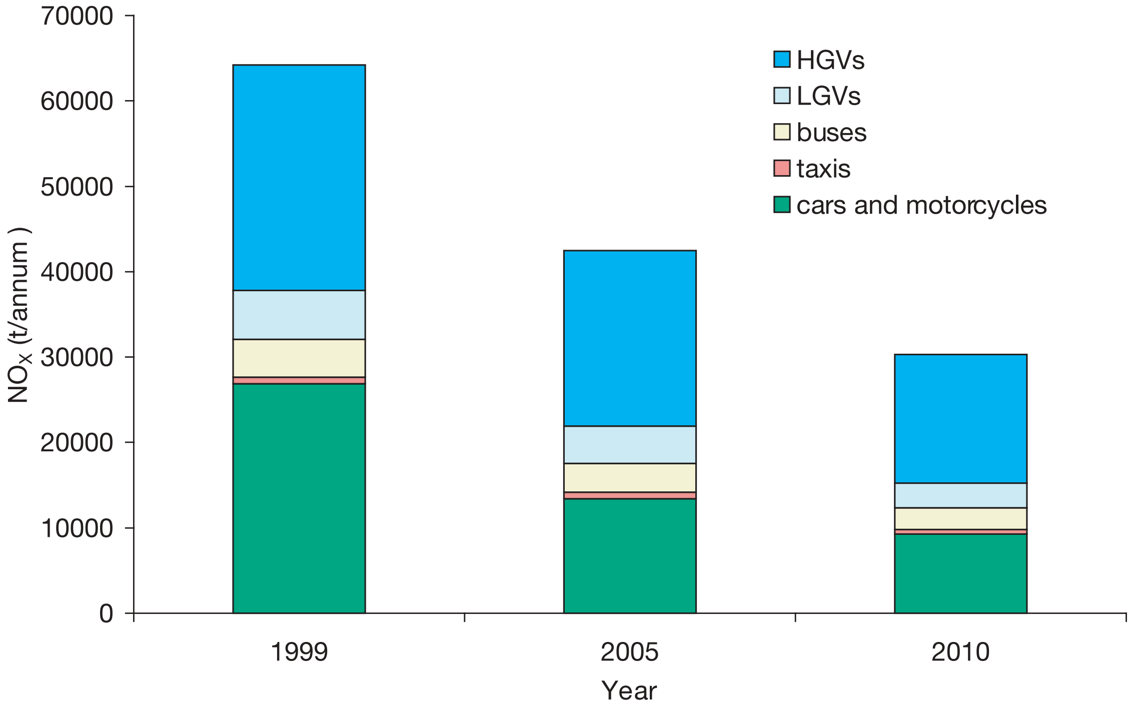
2.11.2.1 London

246. The LAEI has been developed to provide projected estimates of NO_x emissions in London.

247. A simple approach has been taken to the change in vehicle flows between 1999 and 2004/5, based on information from the GLA. The following traffic growth figures have been assumed: central London 0% per annum, inner London 0.2% per annum and outer London 1% per annum. These growth factors are assumed to apply equally to all vehicle types. Recent information from the GLA suggests that all TfL buses will be fitted with particulate traps by 2005. The NAEI emission factors are used for forecasting vehicle emissions in the LAEI projections.

248. Projections of road transport emissions of NO_x in London are shown in Figure 2.14. Between 1999 and 2010 total NO_x emissions from road transport are projected to decrease by 53%. This compares with a decrease of 49% in total urban UK road transport emissions over the same period according to the NAEI. The most significant decline is for passenger cars (65% reduction). HGV emissions only decline by 43%.

Figure 2.14 Projected emissions of NO_x from road transport in London (LAEI).

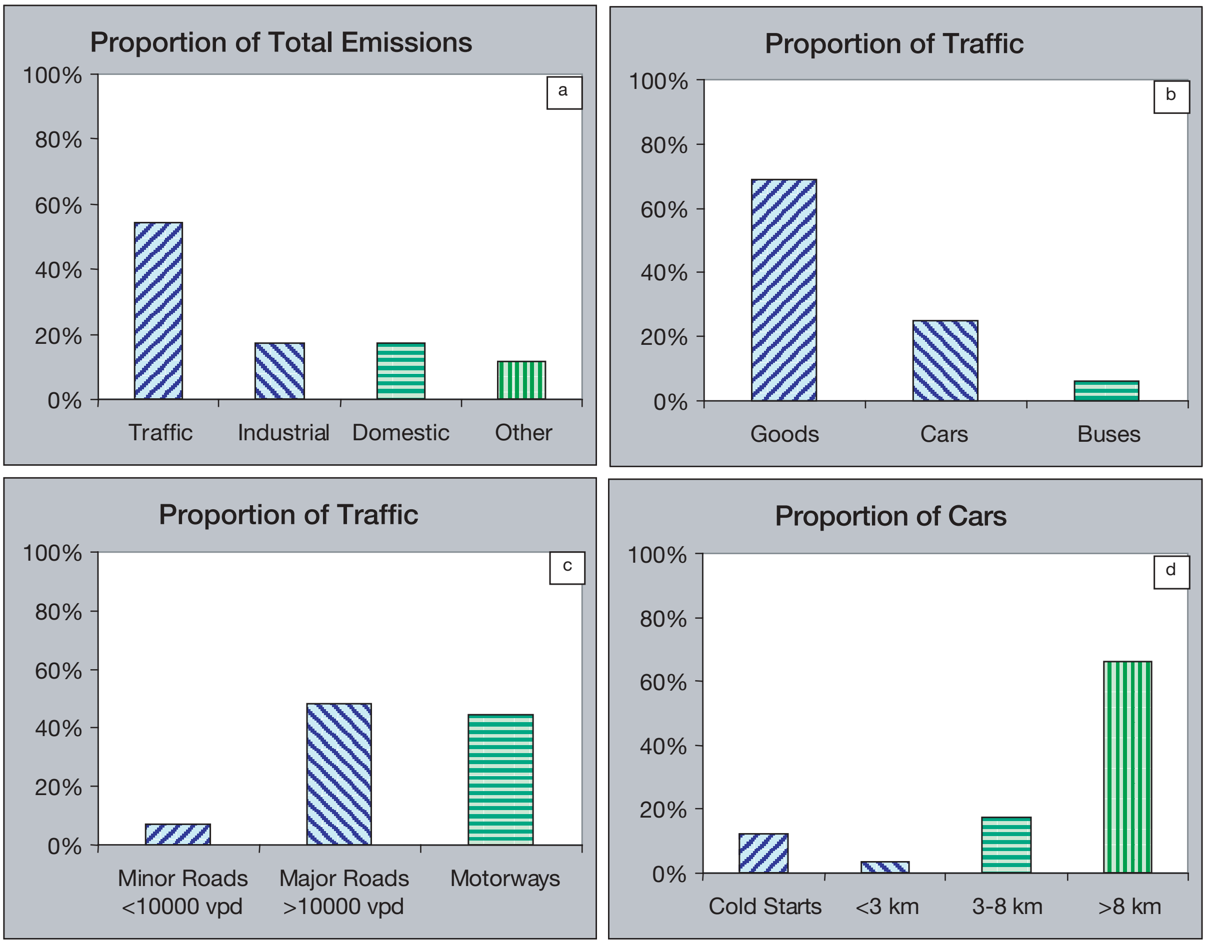


249. The change in non-road transport sources of NO_x is less certain. NO_x emissions from these sources are projected to increase slightly in London between 1999 and 2010, mostly as a result of a significant increase in natural gas use for domestic premises and commercial buildings. However, no account has been taken of the potential decrease in NO_x emissions through improvements in boiler technology. At present, emission factors for these sources are based on a single fuel-based factor and it is recognised that refinements are needed for these emission estimates. In the LAEI projections, emissions at Heathrow are expected to decline significantly for non-aircraft emissions, whereas aircraft emissions are assumed to remain at 1999 levels. The updated Heathrow emissions inventory currently being compiled by AEA Technology should lead to improved estimates of NO_x emissions from Heathrow.

2.11.2.2 Greater Manchester

250. An inventory recently completed by Aric for the Greater Manchester Area shows that traffic emissions will continue to dominate in 2005 (Figure 2.15a), with most of these emissions being due to goods vehicles rather than cars (Figure 2.15b). Traffic on motorways will account for over 40% of the emissions, with minor roads playing a small role (Figure 2.15c). Interestingly, the car emissions are dominated by vehicles on longer journeys >8 km, with short journeys playing an insignificant role (Figure 2.15d). These car journey emissions do not include cold start emissions, which would apply to all categories to some extent. However, the pattern would not be changed significantly, as cold start emissions only represent around 10% of car emissions (Figure 2.15d).

Figure 2.15 Estimated emissions of NO_x from the Greater Manchester area in 2005; a) Total emissions by source, b) traffic emissions by vehicle type, c) traffic emissions on different road types, d) car emissions by journey length and cold start emissions.



2.11.3 Road transport emissions: evaluation of current policies and directives and illustrative projection scenarios

251. The reduction in emissions from road transport that has occurred over the past decade and is expected to continue over the next decade is as a net result of technology improvements required to meet the European vehicle emissions Directives. Domestic transport policies will also have had a bearing on recent and future emission trends. The effect of individual policies and Directives has been evaluated by modelling UK road transport emissions in past and future years with the policy or measure excluded. The effect of the measure can be found by difference with the base projection figures. This procedure can be used, for example, to demonstrate the effect that the introduction of the three-way catalyst to new petrol cars and vans has made to the emission reductions achieved over the past 10 years. Emissions can also be further broken down by Euro standard to illustrate the contribution that vehicles meeting recent and future standards make to the inventory and how much remains from older vehicles in the fleet.

252. Studies of this nature have been carried out previously by netcen on behalf of Defra, as a policy evaluation exercise on measures to reduce air pollution from road traffic (Bush *et al.*, 2001a). Results are shown in this section from a revised study on a selected number of measures based on the new emission factors.

253. Projected emissions from road transport can be sensitive to the assumptions made about the penetration of diesel cars in the national fleet. Since the 2000 NAEI projections were compiled, DfT have revised their opinion on the likely growth in diesel car sales in response to a surge in sales which took place in 2001. The effect this has on the UK projections of NO_x emissions from road transport is shown. In effect, this also amounts to a form of sensitivity analysis, in this case showing the sensitivity of NO_x emissions to diesel car penetration rates.

254. The Air Quality Strategy consultation document published by Defra and the devolved administrations in 2001 showed the impact of a number of additional national policy measures on UK PM_{10} emission projections for road transport (AQS, 2001). These included the fitting of particulate traps to all new diesel vehicles, the early introduction of sulphur-free diesel fuel and a short-term retrofitting programme for older diesel vehicles, targeted at particular conurbations. These are not discussed further in this report, but illustrate the types of national transport measures that can be assessed.

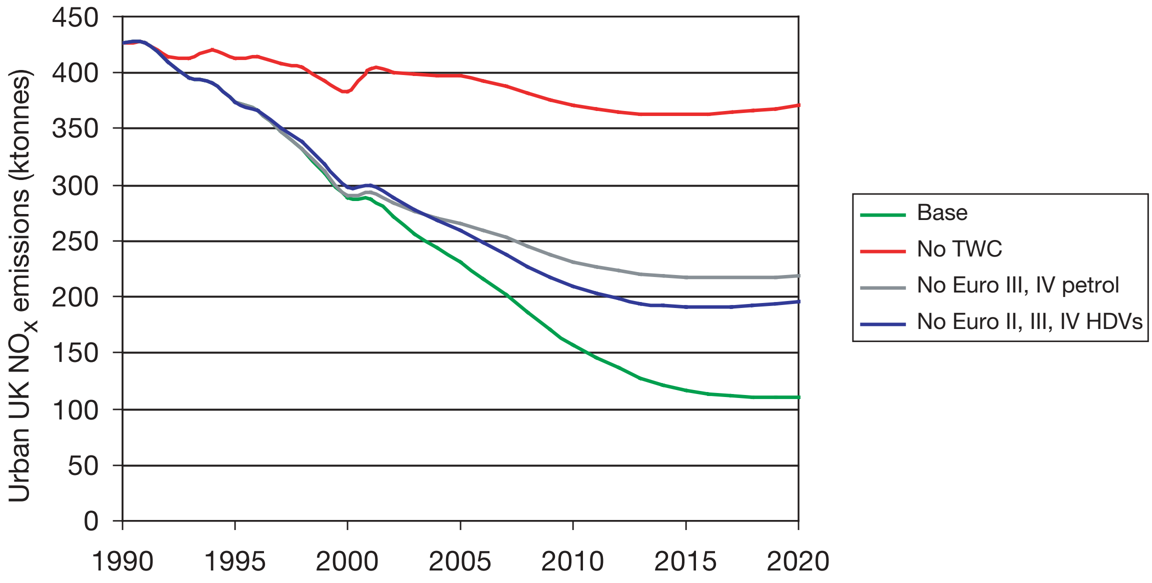
2.11.3.1 The impact of the introduction of the three-way catalyst on NO_x emissions from road transport

255. Emissions from road transport were calculated assuming Euro I standards (91/441/EEC) and beyond had not been introduced requiring petrol cars and light vans to be fitted with three-way catalysts. This meant that emission factors for these vehicles were retained at pre-Euro I levels. The effect this would have had on urban UK NO_x emissions from road transport is shown in Figure 2.16. All other assumptions remained as for the base case, including the implementation of standards for diesel vehicles (light and heavy duty vehicles). The difference in the results for this scenario and the base case (i.e. the effect of introducing three-way catalysts) are reflected by the difference in emissions.

256. Urban UK road transport emissions were reduced by 94 ktonnes (25%) from what they would have been in 2000 had three-way catalysts not been introduced. Without their introduction, NO_x emissions would have decreased at a much slower rate. The base inventory suggest urban UK NO_x emissions decreased by 32% from 1990 to 2000, but without the introduction of catalysts on petrol cars and vans, this would only have led to a 10% reduction.

257. Figure 2.16 shows the projected effects of having introduced the three-way catalyst and tighter Euro standards on petrol cars and vans. Emissions would continue to decrease at a much slower rate without catalyst introduction. By 2010, urban UK road transport emissions would have been only 13% less than 1990 levels, whereas a 63% reduction is anticipated with catalyst introduction and the progressive tightening up of emission standards down to Euro IV levels.

Figure 2.16 Urban UK road transport emissions of NO_x for different Euro standard and technology uptake scenarios.



2.11.3.2 The impact of the introduction of Euro III and IV standards for petrol cars on NO_x emissions from road transport

258. Emissions from petrol cars and light vans have been further tightened up with the introduction of Euro III and IV standards. The Directive 98/69/EC requires all new cars and light vans to meet Euro III standards by January 2001 (2002 for heavier vans) and Euro IV standards by January 2006. Some models already met Euro III standards before 2000 and some car models now on the market already meet Euro IV standards.

259. Emissions were calculated assuming Euro III and IV standards had not been introduced. This meant that emission factors for these vehicles were retained at Euro II levels from 1997 onwards. The effect this would have had on urban UK NO_x emissions from road transport is shown in Figure 2.16. All other assumptions remained as for the base case, including the implementation of all the standards for diesel vehicles (light and heavy duty vehicles). The difference in the results for this scenario and the base case (i.e. the effect of introducing Euro III and IV standards for petrol cars and vans) are reflected by the difference in emissions.

260. Emissions would continue to decrease, but at a slower rate without the introduction of the Euro III and IV standards for these petrol vehicles. By 2010, urban UK road transport emissions would be only 20% less than 2000 levels, even with all the standards for diesel vehicles up to Euro IV included. It is anticipated that a 46% reduction in urban NO_x emissions from road transport will actually occur with the introduction of standards for all vehicle types.

2.11.3.3 The impact of the introduction of Euro II – IV standards for heavy duty vehicles on NO_x emissions from road transport

261. Euro II standards for heavy duty diesel vehicles were introduced in 1996. Emissions were calculated assuming neither Euro II standards nor the successive Euro III and IV standards for Directive 99/96/EC (2001 and 2006) were introduced. This meant that emission factors for these vehicles were retained at Euro I levels from 1993 onwards. The effect this would have had on urban UK NO_x emissions from road transport is shown in Figure 2.16. All other assumptions remained as for the base case, including the implementation of all the standards for petrol vehicles. The difference in the results for this scenario and the base case (i.e. the effect of introducing Euro II-IV standards on HDVs) are reflected by the difference in emissions.

262. It can be seen that urban UK road transport emissions were reduced by 9 ktonnes (3%) from what they would have been in 2000 had the Euro II standards not been introduced. The effect of the Euro II standards on HDVs in reducing urban road transport NO_x emissions has been small during years up to 2000. However, the effect of these and tougher Euro III and IV standards becomes much more significant in future years. Without these standards, NO_x emissions would continue to decrease, but at a slower rate. By 2010, urban UK road transport emissions would be 30% less than 2000 levels, with all the standards for petrol vehicles up to Euro IV included. This compares with the 46% reduction that is actually expected.

2.11.3.4 The impact of higher penetration rates for diesel cars in the new car fleet on NO_x and NO_2 emissions from road transport

263. DfT have recently revised their opinion on the likely growth in diesel car sales in the UK in response to a surge in sales which took place in 2001. Sales were originally forecast to be 16% of all new car sales in 2001, but the actual figure was 18% for the year as a whole, growing to a level of around 23% in the early part of 2002.

264. The original growth estimates were designed to reflect the way car manufacturers would meet the voluntary agreement on CO_2 new car emissions by increasing diesel car sales. The recent rapid increase in diesel car sales is thought to be due to new company car taxation rules, but the view of DfT is that this trend may continue. The view now is that diesel car sales will increase to 25% in 2003 and increase linearly to 30% by 2010. As diesel cars emit more NO_x than petrol cars, this will lead to an increase in the overall emission projection estimates for road transport.

265. The effect of the higher diesel car penetration rate on NO_x emissions from traffic was modelled leaving all other assumptions the same. Emission projections were calculated based on the high diesel car growth assumption, reaching 30% of sales by 2010, and compared with the original baseline projections assuming a growth to 22% in sales by 2007, remaining constant thereafter (Table 2.8).

266. The amount of increase in urban UK road transport emissions of NO_x was found to be small. Urban UK road transport emissions of NO_x are increased by 0.7% in 2005 and 0.7% in 2010 relative to the baseline projections. The increase in total UK emissions of NO_x in 2010 is 3.5 ktonnes, or 0.3% relative to the baseline emission projections for all sources.

267. The effect on primary NO_2 emissions in urban areas would be more significant, however, if diesel cars emit a higher proportion of NO_x as NO_2, as suggested in Section 2.6.2.6. On the basis that diesel cars emit 25% NO_x as NO_2 (by mass) and with petrol cars emitting only 5% NO_x as NO_2, as concluded in Section 2.6.2.6, then increasing the diesel car penetration rate from 22% to 30% by 2010 would increase urban road transport emissions of primary NO_2 in 2010 by 3%.

268. Sales of diesel cars are currently on average around 35% of all new car sales in other European countries. The European car industry group ACEA predicts this will rise to 40% of new car sales to meet the voluntary agreement on CO_2 emissions. DfT consider that with current fuel duty policy, diesel car sales are unlikely to reach this level in the UK. However, in an extreme case where sales of new diesel cars rise to 50% of new car sales by 2010, then urban UK road transport emissions of NO_x in 2010 would increase by 1.2% and primary NO_2 emissions by 6% compared with the low (22%) penetration rate assumption.