ELSEVIER SCIENCE Ltd. [DTD 4.1.0]
JOURNAL TRD ARTICLE No. 159
PAGES 1-16 DISPATCH 7 March 2001

TRD 159
PROD. TYPE: FROM DISK
A

PERGAMON

Transportation Research Part D 000 (2001) 000–000

TRANSPORTATION RESEARCH PART D

www.elsevier.com/locate/trd

The efficacy of low emission zones in central London as a means of reducing nitrogen dioxide concentrations

David C. Carslaw *, Sean D. Beevers

Environmental Research Group, King's College London, Block 9, St Thomas' Campus, Lambeth Palace Road, London SE1 7EH, UK

Abstract

This paper considers the effects of different strategies that might be considered to reduce the impact made by road traffic on air pollution in London. The management of road traffic in large urban areas is one of many options being considered to reduce pollutant emissions to meet statutory air pollution objectives. Increasingly, the concept of a low emission zone (LEZ) is being proposed as a means of achieving this reduction. An assessment has been made of different LEZ scenarios in central London, which involve reducing traffic flow or modifying the vehicle technology mix. Methods of predicting annual mean nitrogen dioxide concentrations utilising comprehensive traffic data and air pollution measurements have been used to develop empirical prediction models. Comparisons with statutory air pollution objectives show that significant action will be required to appreciably decrease concentrations of nitrogen dioxide close to roads. The non-linear atmospheric chemistry leading to the formation of nitrogen dioxide, results in a complex relationship between vehicle emissions and ambient concentrations of the pollutant. We show that even ambitious LEZ scenarios in central London produce concentrations of nitrogen oxides that are achieved through a "do nothing" scenario only five years later. © 2001 Published by Elsevier Science Ltd.

Keywords: Exhaust emissions; Nitrogen oxides; Dispersion modelling

1. Introduction

During the past decade, there has been an increased interest in the relationship between air pollution and its affect on human health, as evidence has emerged that low concentrations of pollutants have significant health impacts (Schwartz, 1994; Committee on the Medical Effects of Air Pollution, 1998). Increasingly, governments are setting air pollution standards to protect both human health and the wider environment. The UK Air Quality Strategy sets out the UK Gov-

* Corresponding author. Tel.: +44-20-79605510; fax: +44-20-79605501.
E-mail address: david.carslaw@erg.kcl.ac.uk (D.C. Carslaw).

PII: S1361-9209(01)00008-6

ernment's approach to tackling air pollution for eight key pollutants (Department of the Environment Transport and the Regions, DETR, 1999a,b) including carbon monoxide, nitrogen dioxide (NO_2), fine particulate matter (PM10) and benzene. The strategy sets limits and objectives for these pollutants and the times scales by which they are to be met. Two objectives for NO_2 are being considered: an annual mean objective of 21 ppb (40 $\mu g\ m^{-3}$) not to be exceeded in any calendar year and a 1-h limit value of 105 ppb (200 $\mu g\ m^{-3}$) not to be exceeded more than 18 times in each calendar year. The 21 ppb limit is consistent with the European Union (EU) Directive 96/62/EC Framework Directive for NO_2 to be achieved by 1 January 2010. The UK aims however to meet this objective by 31 December 2005. The annual mean objective is considered more stringent than the 1-h objective, and this is borne out by pollution measurements in London (South East Institute of Public Health, SEIPH, 2000).

Recent studies of air pollution in the UK and London show that concentrations of key pollutants are likely to exceed statutory air pollution objectives (Carslaw et al., 2001; DETR, 1999a,b). Meeting air pollution objectives in London poses a unique challenge by virtue of its size. The 1991 census showed that the population of London of 7.5 million was at least twice as large as any other urban conurbation in the UK. Increasing attention has therefore been directed towards considering how air quality objectives can be met through the reduction in pollutant emissions, and in particular those from road traffic.

Emissions from road transport tend to account for a higher proportion of the total emission in urban areas compared with national totals. For example, in 1995 emissions of NO_x in London from road transport were estimated to be responsible for 75% of total emissions compared with 48% nationally for the UK (Buckingham et al., 1997; DETR, 1999b). Road transport is generally identified as the principal source of air pollution in urban areas and the most important source of NO_x to tackle.

Many studies have investigated the relationship between road vehicle emissions and urban air quality (Seika et al., 1998; Oduyemi and Davidson, 1998; Cloke et al., 2000). Seika et al. (1998) used a tiered modelling approach to assess the changes in concentrations of NO_x and other pollutants in London and Berlin, and in particular quantified the effect of different traffic management options. This study was, however, limited to primary pollutants and quantified the concentration changes in relatively few locations. Cloke et al. (2000) used a simple empirical technique to quantify the effects of different traffic management options on the concentration of NO_2 and particles. This study considered "typical" concentrations in three locations in London, for a large number of emission reduction scenarios. To date, few studies have attempted to assess the localised impact of emissions reduction on a secondary pollutant such as NO_2 and relate those changes to air pollution standards.

A low emission zone (LEZ) can be thought as specific action taken to reduce vehicle emissions, in a given geographical area, in order to improve local air quality. LEZs vary in terms of their concepts, but can be broadly categorised into air quality, vehicle technology and transport criteria types. A LEZ operating on an air quality basis would perhaps trigger action when exceedences of air pollutant criteria occur, or are predicted to occur. A LEZ based on technology would aim to restrict certain vehicle types entering part or all of an urban area. A transport based LEZ would aim to restrict, prioritise and optimise traffic flow in order to reduce emissions. A distinction can also be made based on the time scales considered for a LEZ. For example, some cities produce pollution forecasts for several days ahead and consider action based on the predicted concentrations of pollutants.

Most assessments of LEZs focus on the emissions reduction expected through different measures, few however consider the resultant effect on pollution concentrations. This paper considers the specific application of LEZs to addressing exceedences of the annual mean NO_2 objective of 21 ppb through different LEZ scenarios that are assumed to be in force year-round.

2. Traffic data and road vehicle emissions

The London Atmospheric Emissions Inventory (LAEI) has been used to provide information on NO_x emissions in London (Buckingham et al., 1997; SEIPH, 1997). The inventory provides estimates from many different source categories including major and minor roads, domestic fuel use, industrial and commercial, shipping, biogenic and airport emissions. The LAEI estimate of NO_x emissions from road sources differs from the UK National Inventory (Salway et al., 1999), as the former uses a transport model for London as the basis of estimating traffic activity. The transport model provides estimates of traffic activity, including vehicle speed estimates, for over 30,000 road links. A large strategic traffic model cannot be expected to accurately reproduce traffic data on a link-by-link basis, but is better suited at providing traffic information over wider areas, as used in compiling a km^2 emissions inventory.

Manual count data from the DETR have been used to provide vehicle flow and type information for all major roads in London. These data form the basis for national traffic estimates and forecasts. Data are collected regularly for sections of roads between major road junctions. The traffic data are collected by randomly choosing a sampling point on a major road link, typically every two years. In addition to traffic count data, information is collected about the characteristics of each link, such as its length, road class and the road width. Eleven vehicle types are recorded: pedal cycles, two-wheeled motor vehicles, cars and taxis, buses and coaches, light vans and six separate heavy goods vehicle categories for 12 h between 7 a.m. and 7 p.m. These counts are undertaken during weekday periods and in ‘‘neutral months’’, where the seasonal effects of public holidays, for example, can be minimised. Additionally, 56 continuous traffic-monitoring sites in London record total traffic flow. These data do not differentiate between different vehicle types and therefore require that manual counts of vehicle type be collected every three months by each hour of the day. The data from the manual counts surveys are combined with the automatic counts to provide estimates of the annual average daily flow (AADF) for each road link. In total, detailed traffic information is available for the estimation of emissions for over 1500 road sections covering the Greater London area.

Vehicle speed estimates are derived from the ‘‘floating-car’’ technique (Roland, 1998). The technique involves the use of an instrumented car driven at the prevailing traffic speed in such a way as to make equal the number of vehicles overtaken and the number of vehicles overtaken by the car itself. Journey times between successive junctions are recorded, and the speed calculated by weighting the speed against vehicle flow. Surveys are conducted throughout the year but are timed to avoid holiday periods or periods of particularly adverse weather. Each road link is surveyed in both directions on four separate occasions: once in the morning peak period between 7.45 a.m. and 9.15 a.m., one in the morning off-peak period between 10 a.m. and 12 noon, once in the afternoon off-peak period between 2 p.m. and 4 p.m., and one in the evening peak period between 4.45 p.m. and 6.15 p.m. The estimated speed on an individual link is subject to wide sampling variation. On average the 7.45 a.m. to 6.15 p.m. speed on a single link has a 95% confidence interval of about ± 10 km h^{-1}. Compared with fixed measurements of speed in one location, the floating-car technique should produce representative *mean* vehicle speeds.

Light and heavy-duty vehicles sold in the UK are required to meet emissions standards in accordance with European Community Directives. These emission standards have been progressively tightened since their introduction in 1970. Detailed speed-dependent emission factors have been derived for over 70 vehicle types and emissions technology classes (Design Manual for Roads and Bridges, DMRB, 1999). Emission factors have been derived for four principal legislation categories, termed pre-Euro I to Euro III, which relate to different EC Directives (see Table 1). The DMRB uses three main sources of emission factors: the UK Transport Research Laboratory database, the COPERT II computer program and the Swiss/German Workbook on emission factors for road vehicles (DMRB, 1999).

These factors reflect typical urban driving patterns and should be reasonably representative of emissions from vehicles in London. For example, at lower average speeds the functions implicitly include increased periods of idling. The proportion of vehicles in each emissions class were calculated for each year up to 2010. Table 2 shows the calculated emission factors for vehicles with an average speed of 25 km h^{-1} for NO_x.

3. Prediction of annual mean NO_x and NO_2 concentrations

The methodology for calculating concentrations of pollutants close to roads in central London is shown as a schematic in Fig. 1. Emission rates in g km^{-1} were calculated for each of the 11 vehicle types, by time of day, for each carriageway separately and for each vehicle emissions technology class. The emissions were then apportioned according to the predicted ratios of the different emissions technology classes for 2005. The predicted vehicle stock is the same as that used nationally in the UK National Atmospheric Emissions Inventory (Salway et al., 1999) and gives, for example, the predicted proportion of each technology class for each vehicle type for future years. These data are used to estimate the emissions of NO_x along each road link in g km^{-1} s^{-1}.

Table 1
Vehicle emission standards

Vehicle type	Emissions technology class			
	Pre-Euro I	Euro I	Euro II	Euro III
Petrol and diesel cars	83/351	91/441	94/12	98/69
LGVs	Pre	93/59	96/69	98/69
HGVs	88/77	91/542	91/542 II	98/69
Buses	Pre	91/542	91/542 II	98/69

Table 2
Emissions of NO_x from road vehicles for a 25 km h^{-1} vehicle speed

Vehicle type	Vehicle size	Pre-Euro I	Euro I	Euro II	Euro III
Petrol car	<1.4 l	1.23	0.30	0.13	0.08
	⩾ 1.4 l and <2.0 l	1.54	0.33	0.15	0.09
	>2.0 l	1.97	0.32	0.14	0.08
Diesel car	<2.0 l	0.71	0.44	0.19	0.17
	⩾ 2.0 l	0.87	0.34	0.15	0.13
Petrol LGV	Small	1.36	0.34	0.15	0.09
	Medium	1.54	0.34	0.15	0.09
	Large	1.81	0.34	0.15	0.09
Diesel LGV	Small	0.72	0.25	0.15	0.13
	Medium	1.06	0.37	0.22	0.19
	Large	1.70	0.59	0.35	0.31
HGV	Rigid	8.42	6.71	5.05	3.53
HGV	Articulated	22.75	13.67	10.22	7.12
Bus		10.85	7.63	5.42	3.80
Motorcycle	2 stroke 250 cc	0.02	0.02	0.02	0.02
	4 stroke 250 cc	0.12	0.12	0.12	0.12

To calculate the dilution of vehicle emissions near to each road, the CAR International model is used to estimate the near-road annual mean concentrations of NO_x (Eerens et al., 1993). The CAR model is attractive in this respect as it is based on extensive wind tunnel modelling trials of emissions from vehicles in built up areas and has been extensively validated in the Netherlands and the UK (Eerens et al., 1993). Comparison with air pollution measurements showed that the CAR model was ±19% accurate for annual mean NO_x and ±9% accurate for the calculation of the 98th percentile NO_2 concentration (Eerens et al., 1993). It is therefore suitable for the prediction of annual mean concentrations in street canyons in central London, where conventional modelling techniques can be difficult to apply. Although the model is simple, the complexity of central urban areas makes it difficult to improve the predictions without an appreciably more detailed approach.

The calculation of annual mean NO_2 in urban areas is complex. Road vehicles typically emit 90% by mass nitric oxide (NO) and 10% NO_2 (Shi and Harrison, 1997). Once released from the exhaust of vehicles, the NO is rapidly converted to NO_2 through the reaction with ozone (O_3). The final concentration of NO_2 observed close to roads therefore has three primary origins: directly emitted NO_2 from road vehicles, NO_2 formed through rapid atmospheric chemistry involving ozone, and a "background" component. In this context, the background component can be thought of as that which would be present in the absence of the road. The dilution of NO (and NO_2) away from a road in an urban area depends on complex micrometeorology and the turbulence generated by vehicles themselves. Any model attempting to describe these effects would need to reflect mixing and atmospheric chemistry on a timescale down to seconds to minutes and a spatial scale down to metres.

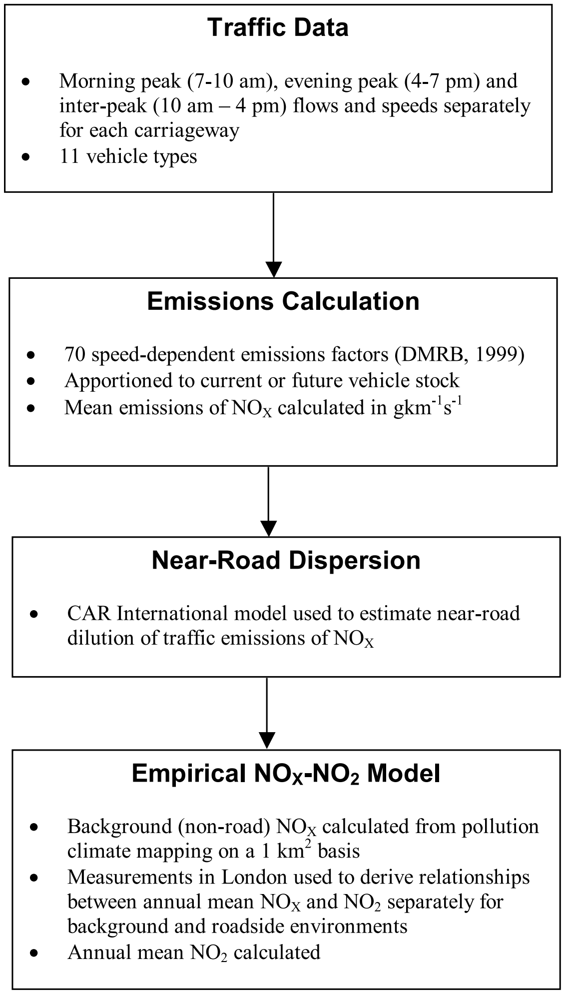

Fig. 1. Schematic of the modelling methodology for calculating annual mean NO_2 concentrations close to roads.

We have adopted an approach that is based on urban measurements of NO_x and NO_2 concentrations (Carslaw et al., 2001). Briefly, from hourly measurements of NO_x and NO_2 at measurement sites, a relationship between NO_x and NO_2 is derived by averaging the NO_x in 5 ppb intervals (0–5 ppb, 5–10 ppb...) and calculating the mean NO_2 for each interval, as shown in Fig. 2(a). The frequency distribution of NO_x concentrations is also calculated over the same intervals (Fig. 2(b)), "multiplied" by the NO_x–NO_2 relationship, and divided by the number of measurements, yielding an annual mean NO_2 concentration

$$NO_2 = \frac{\sum_{i=1}^{i=n} \overline{NO_2(i)} F(i)}{N_{obs}}, \tag{1}$$

where i is a NO_x interval e.g., 10–15 ppb, $\overline{NO_2(i)}$ is the mean NO_2 in the NO_x interval i, $F(i)$ is the number of measurements in interval i and N_{obs} is the total number of measurements.

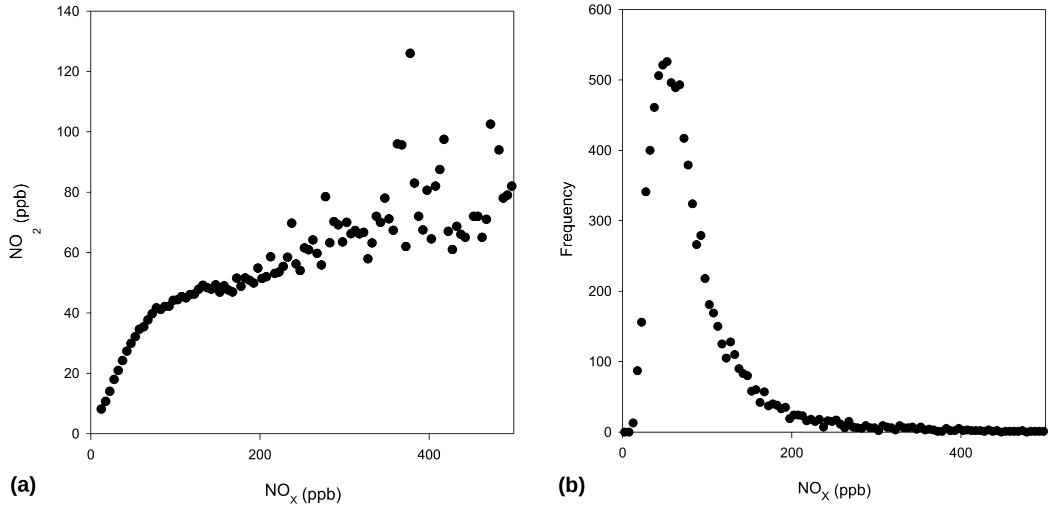

Fig. 2. (a) The hourly NO_x–NO_2 relationship for the central London Bloomsbury monitoring site (1997). (b) Frequency distribution of NO_x measurements at the Bloomsbury monitoring site (1997).

The process is repeated by considering different NO_x frequency distributions, $F'(i)$, by re-calculating the distribution for successive NO_x reductions, from 0% to 80% in 5% intervals. For each new annual mean NO_x concentration, the annual mean NO_2 concentration is also calculated using Eq. (1). The result is a new annual mean NO_x–NO_2 relationship that is specific to a particular location and which can be used to estimate future NO_2 concentrations as the NO_x concentration decreases. It is therefore possible to estimate future annual mean NO_2 concentrations, provided that an annual mean NO_x concentration is first calculated.

Two key assumptions are made when processing the data in this way. First, it is assumed that the NO_x–NO_2 relationship holds as NO_x concentrations decrease, as shown by Derwent (1999) using detailed Lagrangian trajectory modelling. Second, it is assumed that all NO_x concentrations decrease by the same proportion. The latter assumption is reasonable as urban roadside concentrations are mostly determined by road vehicle emissions, which can be expected to reduce in a consistent way across London in the future. The annual mean NO_x–NO_2 relationships inherently reflect the complex atmospheric mixing and chemistry of pollutants and they can be derived for different meteorological years. To estimate the concentration of NO_2 close to roads, the NO_x contribution from the road must first be added to the underlying background concentration.

Fig. 2(a) reveals the underlying important features of the atmospheric chemistry involved. From 0 to 100 ppb, the NO_2 concentration rises sharply with NO_x. In this regime there is generally enough ozone available to convert NO to NO_2 i.e., NO_2 is limited by the availability of NO_x. For concentrations of NO_x above 100 ppb, there is little or no ozone available to convert NO to NO_2 and the increase in NO_2 is mostly a result of direct emissions of NO_2 from road vehicles. In fact, the gradient of the relationship between 100 and 300 ppb NO_x does indeed correspond to the estimated proportion of NO_2 emitted directly from vehicles (Shi and Harrison, 1997).

A relationship between the annual mean NO_x and NO_2 has been derived separately for central London roadside and background locations, shown in Fig. 3. We show as an example data for

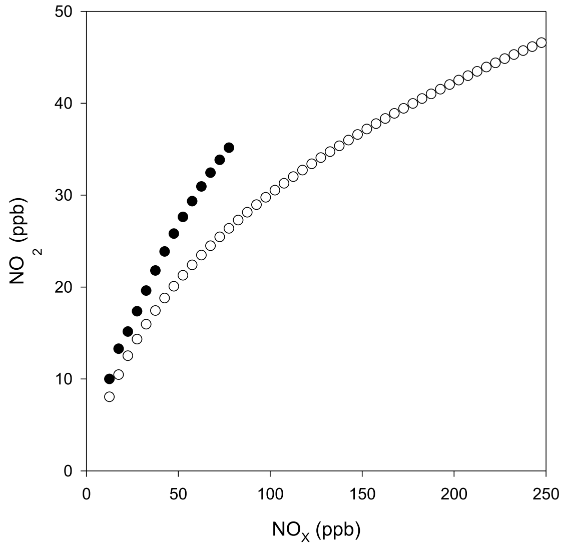

Fig. 3. Derived annual mean relationship between NO_x and NO_2 for 1997. The filled circles show the relationship at background locations in central London, the unfilled circles show the relationship at near-roadside locations.

1997, where two functions have been derived by fitting a curve though the relationships shown in Fig. 3. A third-order logarithmic function was used, which produced r^2 values of 1.0, to develop a relationship between the annual mean NO_2 concentration at urban background locations and close to roads from the predicted annual mean NO_x concentration

$$NO_2(b) = 119.88 - 95.695\ln[NO_x] + 26.0036(\ln[NO_x])^2 - 1.9499(\ln[NO_x])^3, \quad (2)$$

$$NO_2(r) = -2.655 + 3.1177\ln[NO_x] - 0.0721(\ln[NO_x])^2 + 0.2046(\ln[NO_x])^3, \quad (3)$$

where $NO_2\,(b)$ is the annual mean NO_2 concentration at background locations and $NO_2\,(r)$ is the NO_2 concentration at roadside locations.

An important finding from this approach is the very low concentration of annual mean NO_x required to reach 21 ppb NO_2 in central London (Carslaw et al., 2001). At background locations, concentrations of NO_x as low as 30–33 ppb are typically predicted to be required. Such low concentrations of NO_x imply that emissions must be significantly reduced in order that the 21 ppb NO_2 objective is met.

Eqs. (2) and (3) reflect the pattern of observed concentrations of NO_x and NO_2 in urban areas. They produce near-road concentrations of NO_2 that are always less than background concentrations of NO_2 for the *same concentration* of NO_x. Such relationships are intuitively correct because at increasing distances from roads there is more time available for the conversion of NO to NO_2 to take place, together with increased O_3 availability. The near-road Eq. (3) is used to calculate NO_2 close to roads unless Eq. (2) yields a higher concentration of NO_2 with the appropriate background concentration of NO_x, in which case Eq. (2) is used. This approach is adopted to prevent NO_2 concentrations falling below background values. In practice, for a typical road in central London, Eq. (3) would be used between the kerbside of a road to about 30 m from it. Beyond 30 m, Eq. (2) is used with the background concentration of NO_x. Note that the urban background curve is only valid up to 80 ppb NO_x, since measurements in central London do not exceed this value.

The underlying background concentration of NO_x has been estimated using a pollution climate mapping technique (Carslaw et al., 2001; Stedman et al., 1997). The mapping technique relies on the development of a relationship between emissions in a 5×5 km^2 area and the measured concentration at a background site. The technique yields the annual mean concentration on a 1 km^2 basis, which reflects the prevailing meteorology for different years. The pollution climate mapping technique is analogous to a simple box model, where emissions are released into a volume that is determined by the prevailing meteorology. The mapping technique therefore provides a method of relating emissions of primary pollutants e.g. NO_x, to the dilution caused by meteorology.

Estimates of concentrations have been made at the typical location expected of a building façade. The simple assumption has been made that the distance between the road centreline and a building façade depends on only the number of road lanes and an additional distance to account for the pavement. It has been assumed that each road lane is 3.5 m wide and the width of the pavement is 3 m.

4. Scenarios and results

Two principal types of LEZ will be considered in this analysis: the reduction of vehicle flows and the restriction of certain (higher emitting) vehicle types. The first type is a demand management strategy enabled through road user charging, parking controls and improving public transport, for example. The traffic reduction scenarios are considered only to illustrate the response of ambient concentrations of NO_x and NO_2 to changes in total traffic flow. The latter LEZ type is an emissions control strategy because vehicles are prevented from entering a defined area depending on the emissions control technology used. As well as a 2005 base case, the following scenarios have been selected, to cover a range of likely practical and achievable alternatives (Cloke et al., 2000):

1. Reducing all road traffic in central London by 10%.
2. Reducing all road traffic in central London by 20%.
3. Removing all pre-Euro I vehicles. It is assumed that the numbers of Euro II and III vehicles are increased in proportion to conserve total vehicle numbers.
4. Removing pre-Euro I cars and LGVs and pre-Euro III HGVs and buses. It is assumed that the numbers of Euro II and III cars and LGVs are increased to conserve total vehicle numbers, and all HGVs and buses are Euro III emissions technology, again conserving total numbers of these vehicles.

For the 2005 base case, vehicle emissions were calculated based on the predicted vehicle stock for 2005. No adjustment was made for traffic growth as little or no growth in vehicle km is expected in central London (DETR, 1997). All other sources of NO_x in London were assumed to remain unchanged between 1997 and 2005. Although some change in the emissions would be expected for non-road traffic sources over this period, the changes are expected to be very small compared with the change in vehicle emissions expected over the same period. The assumption is made that the specific action taken in the scenarios does not affect road traffic in any other location. In reality, some redistribution of traffic would be expected.

A total of 322 road links in central London have been analysed and are shown in Fig. 4. The selected roads account for 8.1% of the 48 billion-vehicle km of major roads within the Greater London area. A selection of roads from the total has been made to explore in detail the effect of different scenarios, as shown in Table 3 and Fig. 5. These cover a range vehicle flows from <20,000 to >80,000 vehicles per days. Also considered is a road with a high proportion of buses (Oxford Street).

Table 4 shows the predicted building façade concentrations of NO_x and NO_2 for the 5 roads and for each scenario. The predicted concentrations do not reflect vehicle flow: Oxford Street has the lowest daily flow but the highest predicted concentrations. Several factors contribute to high concentrations along Oxford Street. First, it carries a very high proportion of buses, with HGVs and buses accounting for 29% of the total traffic. Total HGV and bus proportions along other roads vary between 5.0% and 8.6%. Second, the mean speed of vehicles along Oxford Street is lower than the other roads on average and is especially low during the off-peak period. Finally, the width of Oxford Street is less than most of the other roads considered. Overall, there is a large range in the NO_x concentrations predicted for the base case, from 64.3 to 134.4 ppb. The range in predicted NO_2 concentrations from 28.0 to 35.0 ppb is considerably less, reflecting the non-linear nature of NO_2 formation. None of the roads is predicted to meet the 21 ppb annual mean NO_2 objective. Exceedences of an air pollution objective will require local authorities to declare air

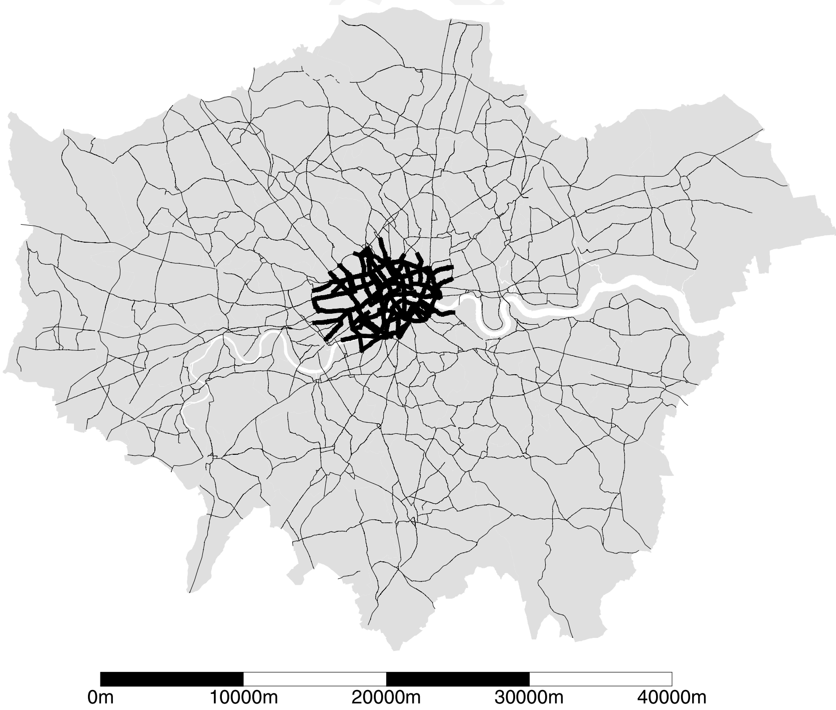

Fig. 4. Map showing the major road network in London. The roads in bold are those in central London.

Table 3
Road and traffic flow details

	Road				
Road Name	Shaftesbury Avenue	Chelsea Embankment	Marylebone Road	Oxford Street	Victoria Embankment
Road Number	A401	A3212	A501	A40	A3211
Number of lanes	3	2	4	2	4
Motorcycles (per day)	3155	1920	3452	708	2774
Cars (per day)	12,784	29,230	69,748	10,301	41,402
Buses and coaches (per day)	160	207	822	4525	1438
LGV (per day)	3009	4391	10,261	2065	5149
HGV (per day)	837	2500	4645	785	3175
Total (per day)	19,945	38,248	88,928	18,384	53,938
AM speed (km h^{-1})[a]	11.3	29.5	10.3	20.8	25.9
AM speed (km h^{-1})	19.9	22.3	27.7	15.6	8.0
Off-peak speed (km h^{-1})	5.6	18.1	19.0	4.2	27.4
Off-peak speed (km h^{-1})	10.9	14.7	21.5	5.8	41.7
PM speed (km h^{-1})	15.8	5.1	16.9	8.2	34.7
PM speed (km h^{-1})	29.7	19.4	22.5	17.2	38.1

[a] Speeds are for each carriageway.

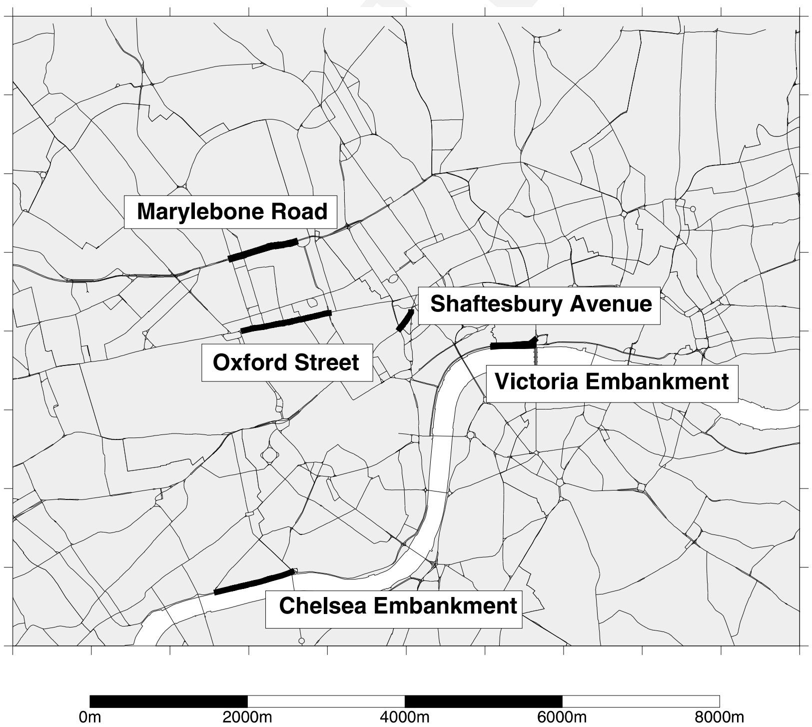

Fig. 5. Detailed map of the central London major road network. The five roads that are studied in detail are shown in bold.

Table 4
Predicted annual mean pollutant concentrations at the building façade of different roads (ppb)

Road	Base case		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	NO_x	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x	NO_2
Chelsea Embankment	95.9	29.5	90.4	28.6	84.8	27.7	89.4	28.5	81.7	27.1
Marylebone Road	113.5	32.2	106.2	31.1	98.9	30.0	102.4	30.5	93.2	29.0
Oxford Street	134.4	35.0	125.0	33.8	115.6	32.5	122.7	33.4	106.4	31.1
Shaftesbury Avenue	74.4	28.0	71.3	27.6	68.1	27.2	70.2	27.5	66.1	27.0
Victoria Embankment	64.3	28.0	62.2	27.6	60.1	27.2	60.6	27.5	58.0	27.0

quality management areas and develop action plans to tackle the problem. The scenarios presented in this paper are of the kind that local authorities might consider in their action plans.

Reducing the flow of vehicles by 10% in central London (Scenario 1) has a small effect on concentrations. NO_x decreases by 3.3–7.0% and at most by 9.4 ppb. Reductions of 10% are not observed because road traffic does not account for all of the NO_x measured in central London, and the scenario does not affect vehicle flows outside central London. For NO_2, much smaller reductions are predicted, from 1.4% to 3.4% and at most by only 1.2 ppb. Flow reductions of 20% (Scenario 2) result in a reduction of between 6.5% and 14.0% and 2.9% and 7.1% for NO_x and NO_2, respectively. The NO_2 concentration is reduced by only 2.5 ppb at most.

Preventing all pre-Stage I vehicles entering central London (Scenario 3) produces slightly lower concentrations than reducing traffic by 10%. However, restricting all but Stage III HGVs and buses in addition to Scenario 3 (Scenario 4) is significantly more effective than any other scenario considered. Compared with the base case, NO_x reductions of between 11.1% and 20.8% are predicted. Reductions for NO_2 are between 3.6% and 11.1%, or 3.9 ppb at most. Neither the traffic reduction scenarios nor the emissions technology scenarios are sufficient to ensure that the annual mean concentration of NO_2 meets the 21 ppb limit.

The results show that the annual mean concentration of NO_2 does not respond to reductions in NO_x on a pro rata basis. In fact, a reduction in NO_x will typically only produce half the change in NO_2. The response of NO_2 also depends on the magnitude of the NO_x concentration. For example, the maximum reduction in NO_x for Scenario 4 is predicted to be 28.0 ppb, but the corresponding change in NO_2 is only 3.9 ppb. This effect can be seen more clearly in Fig. 2(a), where at high NO_x concentrations the gradient of the relationship is low i.e., conditions limited by the availability of O_3. At lower NO_x concentrations the gradient of the relationship increases, and this means that a change in NO_x corresponds to a proportionately greater change in NO_2. Locations with the highest NO_x concentrations therefore have the *smallest* reduction in NO_2 concentrations as NO_x emissions reduce.

The reduction of annual mean NO_2 concentrations for a large urban area also depends on how the reduction is achieved. To illustrate this point, two monitoring sites in London can be considered: Marylebone Road, a busy roadside site, and Bloomsbury, a nearby urban background site. Bloomsbury represents a good background site for Marylebone Road i.e., if Marylebone Road had zero emissions; concentrations similar to Bloomsbury would be expected (Airborne Particles Expert Group, 1999). During 1998, the concentrations of NO_x and NO_2 at Marylebone Road and Bloomsbury were 202 and 42 ppb, and 67 and 34 ppb, respectively. Marylebone Road

Table 5
The effect of reducing road traffic emissions London-wide

Scenario	Roads exceeding 21 ppb NO_2	Mean NO_2 (ppb)	Road transport NO_x emissions (kt y^{-1})	Total London NO_x emissions (kt y^{-1})
Base case	1074	23.4	33.8	67.1
10% traffic reduction	952	22.6	30.4	64.1
20% traffic reduction	834	21.8	27.0	61.1
30% traffic reduction	703	20.9	23.7	58.1
40% traffic reduction	557	20.0	20.3	55.0
50% traffic reduction	424	19.0	16.9	52.0
Removal of pre-Euro III vehicles	716	20.9	24.1	57.6
Base case 2010	602	20.1	21.1	56.4

is therefore responsible for an estimated 202−67 ppb NO_x i.e., 135 ppb or 67% of the total NO_x. For NO_2 the estimated contribution is 42−34 ppb i.e., 8 ppb. The road vehicles on Marylebone Road are responsible for 67% of the NO_x measured, but only 19% of the NO_2. Removing *all* the vehicles on the road would therefore only be expected to reduce NO_2 by 19%. This example demonstrates that the scale of a LEZ is very important and will be limited in its effectiveness unless the background concentrations are reduced. In the case of NO_2 therefore, action would be required at a much wider level to deliver NO_2 concentrations that meet Government objectives.

Based on these findings, consideration has also been given to the effect of London-wide reductions in road traffic emissions by considering all 1553 major roads. London-wide road traffic reductions of 10–50% have been considered together with Scenario 4, applied London-wide. Table 5 summarises the results for the different scenarios. In 2005 (base case), 1074 roads are predicted to exceed 21 ppb of NO_2 at the building façade. The mean NO_2 concentration is predicted to be 23.4 ppb. With a 50% reduction in road traffic emissions in London, 424 roads are still predicted to exceed the objective. Fig. 6 shows the distribution of building façade concentrations of NO_2 for all 1553 roads analysed.

The London-wide scenarios considered highlight the effect of the sensitivity of roads to the pass/fail statistics of 21 ppb. The number of roads with concentrations above 21 ppb NO_2 is reduced by 55% to 424 roads with a 50% reduction in road traffic emissions. However, the mean concentration of NO_2 is predicted to decrease by 19%. When a large number of roads are at or near the objective, only small reductions are necessary to significantly affect the number of roads exceeding the objective. Table 5 shows that by 2010 road transport emissions of NO_x in London account for only 37% of the total compared with 75% in 1995 (Buckingham et al., 1997). Other emissions therefore become relatively more important, for example, natural gas use (29%) and airports (7.9%). It will become increasingly important therefore to investigate the effectiveness of reducing non-road transport sources of NO_x in London.

Emissions from road vehicles will decline beyond 2005, albeit at a lower rate than the years leading up to 2005, as the proportion of cleaner technology vehicles in the fleet increases. The LEZ scenarios considered effectively bring forward the date by which central London roads reach a certain pollution climate. An assessment has been made of the pollution climate in central London beyond 2005 assuming that no attempt is made to bring about the early introduction of new

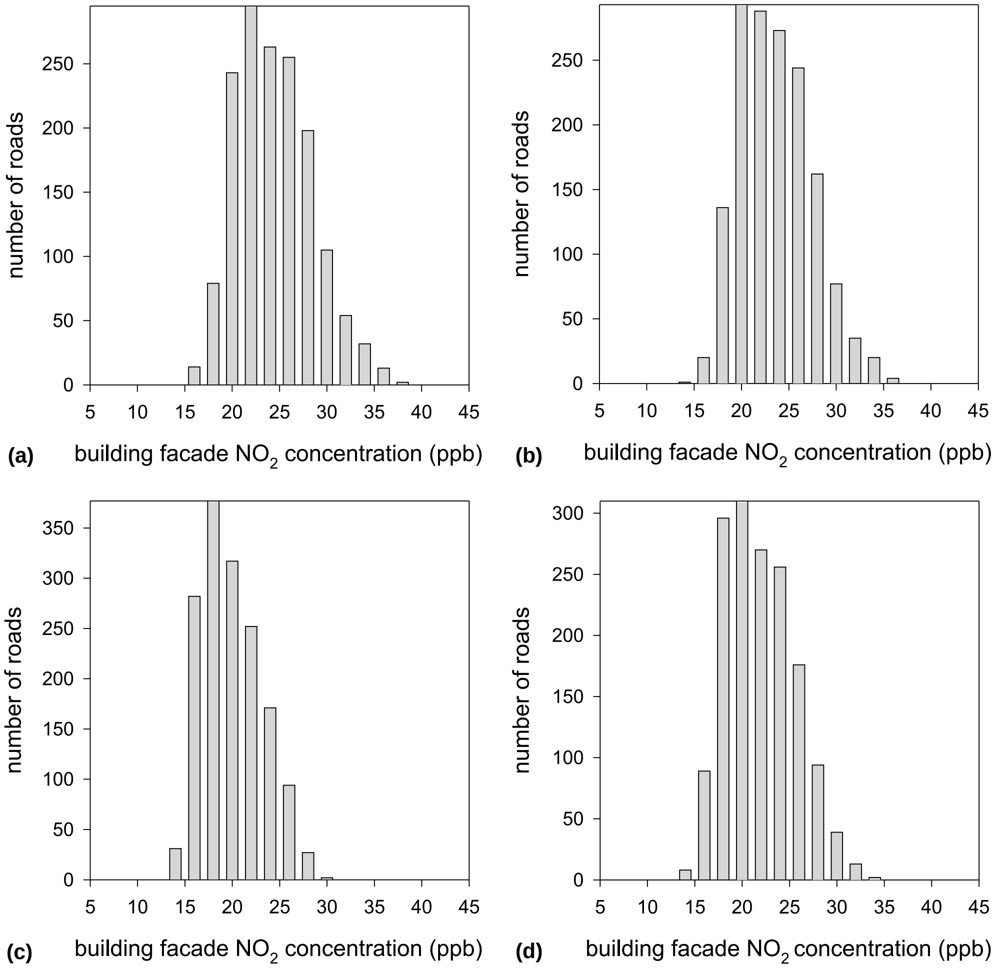

Fig. 6. Histogram of predicted annual mean NO_2 concentrations at building facades in London for all major roads: (a) base case 2005; (b) 10% reduction in road traffic on all major roads in London; (c) 50% reduction in road traffic on all major roads in London; and (d) removal of all pre-Euro I cars and LGVs and all pre-Euro III HGVs and buses.

technologies or to reduce total vehicle km. The predicted concentrations in 2010 are similar to those brought about by the most effective central London LEZ considered (Scenario 4). For example, Oxford Street is predicted to have a NO_x concentration at the building façade of 106.4 ppb with Scenario 5 by 2005 cf. 102.7 ppb in 2010 for the do nothing scenario. For less ambitious LEZs (Scenarios 1 and 2) the equivalent NO_x concentration will be achieved by 2007 in the ‘‘do nothing’’ scenario. The analysis shows that Scenario 4 would be achieved by waiting five years and relying on the ongoing turn over of vehicle technology. The results from Scenarios 1 and 2 would be achieved between 1 and 3 years on the same basis. These results raise the important issue of LEZ implementation time scales and whether the reductions predicted are regarded as significant enough to warrant the potentially high costs of implementing them.

5. Conclusions

Predictions of annual mean NO_2 concentration in central London for 2005 using simple empirical modelling techniques show that concentrations will be in excess of UK Government objectives. The targeted reduction of emissions from road traffic in central London through LEZs has the potential to reduce NO_2 concentrations close to roads. Analysis shows, however, that even significant reductions in road traffic emissions will not appreciably affect NO_2 concentrations. The limited response of NO_2 concentrations to changes in the concentration of NO_x, because of the non-linear chemistry of NO_2 formation, is an important characteristic of NO_2 pollution in urban areas. It is important therefore for policy makers to consider these effects when considering options to reduce NO_2 concentrations in central London. Furthermore, it would be advisable to consider the potential effects of road traffic displacement, which have not been considered in this paper. Displaced traffic avoiding a LEZ could frustrate attempts to reduce NO_2 concentrations. An assessment of ambitious LEZ scenarios in central London shows that attempts to reduce concentrations of nitrogen oxides in this way would be achieved through a do nothing scenario only five years later. Moreover, as the contribution made by road traffic to emissions of NO_x reduces in future, it will become increasingly important to consider options to reduce emissions from non-road traffic sources. Policy makers will therefore need to determine whether the costs of implementing LEZs justifies the benefits brought about by reducing NO_2 concentrations in central London.

References

Buckingham, C., Clewley, L., Hutchinson, D., Sadler, L., Shah, S., 1997. London Atmospheric Emissions Inventory. London Research Centre, London.

Carslaw, D.C., Beevers, S.D., Fuller, G., 2001. An empirical approach for the prediction of annual mean nitrogen dioxide concentrations in London. Atmospheric Environment, in press.

Cloke, J., Cox, J.A., Hickman, A.J., Ellis, S.D., Ingrey, M.J., Buchan, K., 2000. A low emission zone for London. Transport Research Laboratory, Crowthorne, Berkshire. ISSN 0968–4107.

Committee on the Medical Effects of Air Pollution, 1998. Quantification of the effects of air pollution on health in the United Kingdom. Department of Health, ISBN 0 11 322101 9.

Derwent, D.G., 1999. Oxides of nitrogen and ozone in the London routine column trajectory model. Report for the Department of Environment, Transport and the Regions, contract No. EPG 1/3/128. The Meteorological Office, Bracknell, UK.

Department of the Environment, Transport and the Regions, 1997. National Road Traffic Forecasts, Great Britain, DETR.

Department of the Environment, Transport and the Regions, 1999a. Review of the National Air Quality Strategy. The Stationary Office, January 1999.

Department of the Environment, Transport and the Regions, 1999b. The Air Quality Strategy for England, Scotland, Wales and Northern Ireland, August 1999.

Design Manual for Roads and Bridges, 1999. Vol. 11, Section 3, Part 1: Air Quality. The Highways Agency.

Eerens, H.C., Sliggers, C.J., Van den Hout, K.D., 1993. The car model: the Dutch method to determine city street air quality. Atmospheric environment 27B, 389–399.

Roland, M., 1998. Traffic Speeds in Inner London: 1998. Department of the Environment, Transport and the Regions. Statistics Bulletin 22(98), ISBN 1 85112 838 7.

Oduyemi, K.O.K., Davidson, B., 1998. The impacts of road traffic management on urban air quality. The Science of the Total Environment 218, 59–99.

Salway, A.G., Eggleston, H.S. Goodwin, J.W.L, Berry, J.E., Murrells, T.P., 1999. UK emissions of air pollutants 1970–1996. National Atmospheric Emissions Inventory, AEA Technology, National Environmental Technology Centre. Report AEAT-3092.

Schwartz, J., 1994. Air pollution and daily mortality: a review and meta-analysis. Environmental Research 64, 36–52.

Seika, M., Harrison, R.M., Metz, N., 1998. Effects of traffic-related control strategies on urban air quality. International Journal of Vehicle Design 20, 313–325.

Shi, J.P., Harrison, R.M., 1997. Rapid NO_2 formation in diluted petrol-fuelled engine exhaust a source of NO_2 in winter smog episodes. Atmospheric Environment 31, 3857–3866.

South East Institute of Public Health, 1997. The AIM Project and Air Quality in London 1996. SEIPH, ISBN 1 87 42 5742 6.

South East Institute of Public Health, 2000. Air Pollution in London 1998. SEIPH, King's College, London.

Stedman, J.R., Vincent, K.J., Campbell, G.W., Goodwin, J.W.L., Downing, C.E.H., 1997. New high resolution maps of estimated background ambient NO_x and NO_2 concentrations in the UK. Atmospheric Environment 31, 3591–3602.