APPENDIX AVAILABLE ON REQUEST

Research Report 155

The Impact of the Congestion Charging Scheme on Air Quality in London

Part 1. Emissions Modeling and Analysis of Air Pollution Measurements

Frank Kelly et al.

Appendix D. London Atmospheric Emissions Inventory — Road Traffic Emissions Summary

Note: Appendices Available on the Web may appear in a different order than in the original Investigators' Report, and some remnants of their original names may appear in Table and Figure numbers. HEI has not changed the content of these documents, only the letter identifier.

Appendix D was originally Appendix A.

Correspondence may be addressed to Dr. Frank Kelly, Professor of Environmental Health, Environmental Research Group, MRC-HPA Centre for Environment & Health, School of Biomedical Sciences, King's College London, 150 Stamford Street, London SE1 9NH, U.K.
Tel ++44 20 7848 4004 Fax ++44 20 7848 3891 frank.kelly@kcl.ac.uk.

Although this document was produced with partial funding by the United States Environmental Protection Agency under Assistance Award CR–83234701 to the Health Effects Institute, it has not been subjected to the Agency's peer and administrative review and therefore may not necessarily reflect the views of the Agency, and no official endorsement by it should be inferred. The contents of this document also have not been reviewed by private party institutions, including those that support the Health Effects Institute; therefore, it may not reflect the views or policies of these parties, and no endorsement by them should be inferred.

This document was reviewed by the HEI Health Review Committee but did not undergo the HEI scientific editing and production process.

APPENDIX D

London Atmospheric Emissions Inventory (LAEI) — Road Traffic Emissions Summary

The basis of the HEI model runs was the London Atmospheric Emissions Inventory (LAEI) 2003. Whilst the Greater London Authority (GLA) compiles all emission sources other than road transport, the Environmental Research Group (ERG) at King's College London has been instrumental in the development of road traffic emissions, which presently covers 14 pollutants. For a more detailed description of the development of the LAEI the reader should consult Mattai and Hutchinson (2006).

Pollutants included in the LAEI

- Benzene
- 1-3 Butadiene
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Hydrocarbons (HC) [1]
- Oxides of nitrogen (NO_X)
- Particles with an aerodynamic diameter of 10 µm or smaller (PM_{10}) (exhaust and tyre and brake wear)
- Particles with an aerodynamic diameter of 2.5 µm or smaller ($PM_{2.5}$) (exhaust and tyre and brake wear)
- Sulphur dioxide (SO_2)
- Methane (CH_4)
- Polyaromatic hydrocarbons (PAH)
- Nitrous oxide
- Petrol and diesel fuel use

For the pollutants used in the HEI analysis emissions were calculated in a number of formats. First, for each road link explicitly considered, estimates of g km^{-1} s^{-1} were provided. These were in a suitable format for use with dispersion models. Second, for each road link a total emission rate (tonnes $annum^{-1}$) was calculated and third, these totals are combined to give emissions (tonnes $annum^{-1}$) for each of the 2466 km^2 that cover the emissions model domain. For minor roads total emissions in tonnes $annum^{-1}$ were calculated over the 2466 km^2 plus for the ERG Air Pollution Toolkit an average g km^{-1} s^{-1} emission rate for minor roads in each km^2 separately. Finally, cold start and evaporative emissions were added for some vehicle types and for some pollutants.

The LAEI road network

The 2003 road network forms the basis of the road traffic emissions calculations and is shown in Figure D1. All roads were based upon Ordnance Survey Landline road centreline data and are geographically accurate and compatible with other geographic features, including building and postcode data. A Geographical Information Software (GIS) map layer

[1] Note – any reference to hydrocarbons excludes methane

and Microsoft Access database have been created which combines the geographic features of the road traffic network with other road details, such as the road length, road type (dual carriageway, slip road, minor road etc) as well as with traffic count and speed on the road. Furthermore, this network forms the basis of the 10m road traffic source dataset used in the air pollution model.

Road traffic datasets

All of the updates to the LAEI were based upon 3 data sources and these provided the basis for all emissions calculations. These were:

- **Major road network** – road link based flow (11 vehicle types) and speed by hour using manual classified count (MCC) data converted to annual average daily totals (AADT). Approximate number = 1724;
- **London Transport Survey (LTS) road network** - road link based flow (11 vehicle types) and speed by hour using LTS traffic model predictions and a small number of MCC traffic data converted to AADT. Approximate number = 4620;
- **Minor roads** - vehicle km totals (7 vehicle types) in each of the 2466 km^2 of the LAEI.

Minor road vehicle km were re-calculated in the LAEI based on the Department for Transport (DfT) estimates (DfT, 2001-04) for each year separately. The aim of these calculations was to ensure that the total vehicle km from the explicit road network (Major + LTS) plus the minor road network vehicle km (in km^2) equals the DfT published total.

Speed data for all roads was gathered using the ‘Floating car’ that records second by second speed along each major road link in Figure D1 and provides survey data that is updated annually. The car is driven in such a way as to represent the average speed of all the traffic along each link and crosses the same link a number of times in both directions during each survey period. These data were then summarised to give an average speed for each road link and each hour of the day.

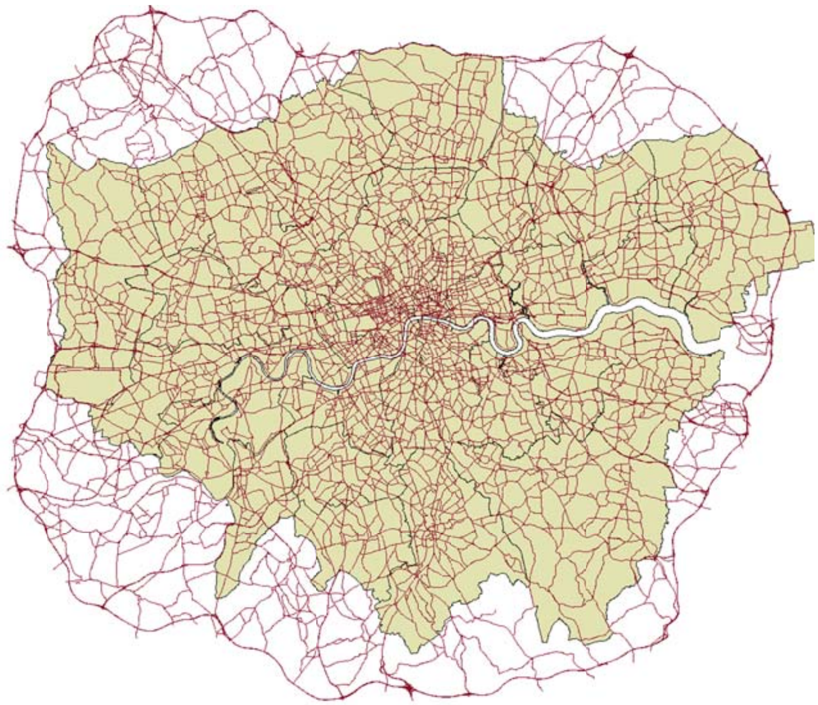

Figure D1 LAEI 2003 Road Network

Updating the ERG emissions toolkit - Changes to the national stock model

Calculating emissions from the road traffic flows and speed requires knowledge of the vehicle age profile and subsequent emissions technology to which each vehicle complies. This was summarised as a proportion for each vehicle type in specific Euro classes. These vehicle stock proportions were routinely updated each year, through the use of the ‘UK Fleet composition from 1999 to 2025’ data. These data are based upon the DfT vehicle market model and are provided to ERG (Tim Murrells, personal communication).

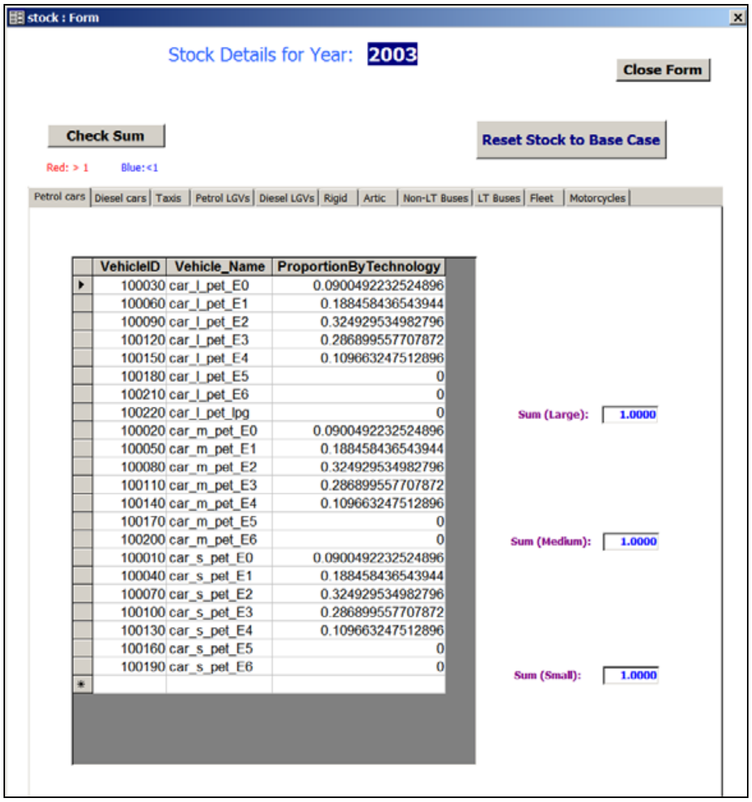

Figure D2. ERG emissions toolkit stock information

Taxi stock and flow information

Some vehicle types (taxis and buses) were dealt with individually in London and do not use the stock model described above. Taxi stock was updated based on information from the GLA (Sarah Legge, personal communication) for the following vehicle categories: Pre Euro 1, Euro 1, Euro 2, Euro 3 and Euro 4 plus any alternatively fuelled or hybrid vehicles. The composition assumed for the four years were:

Table D1. Taxi composition by year

Technology	2001	2002	2003	2004
Pre Euro 1	0.285	0.263	0.155	0.1201
Euro 1	0.473	0.448	0477	0.438
Euro 2	0.242	0.255	0.258	0.258
Euro 3	0	0.034	0.11	0.184
Euro 4	0	0	0	0

Not all traffic counts include the taxi category and so for these vehicles taxis were calculated as a proportion of cars. In the congestion charging zone (CCZ) and inner ring road (IRR) during 2003 large reductions in cars (-26.2 %) and increases in taxis (15.1 %) has meant that taxis in the CCZ/IRR have become a larger component of the vehicle fleet. The above changes have resulted in adjustments to the proportion of taxis and these are summarised in in Table D2.

.

Table D2. Proportion of taxis (as a % of total cars) by area of London

Area of London	2001	2002	2003	2004
CCZ	0.22	0.22	0.33	0.33
IRR	0.22	0.22	0.26	0.26
Inner	0.04	0.04	0.06	0.06
Outer	0.01	0.01	0.01	0.01

London Transport (LT) Buses stock information

LT Bus stock was also based upon actual on road fleet statistics, provided by London Transport Buses (Anna Rickard, personal communication) and summarised by technology (Euro) class. The number of vehicles fitted with a particle trap, using alternative fuels and alternative technology was also provided. A summary for these vehicles across all years is given in Table D4 below.

Particle traps, Selective Catalytic Reduction (SCR) and other emissions control assumptions

Between 2001 and 2004 many buses were fitted with particle traps. The assumptions used to factor euro class vehicle emissions to simulate the introduction of such traps are given in Table D3. With the addition of NO_X abatement (+ NO_X) for buses, using a combination of Exhaust Gas Recirculation (EGR) and SCR, a 50% reduction in NO_X was also assumed. Finally, the assumption for Hybrid buses[2] was that they have 30% less NO_X, PM_{10} and CO_2 emissions than a standard Euro 4 bus.

Table D3 Particle trap assumptions for pollutant emissions

NO_X	PM_{10}[3]	CO	HC[4]	SO_2	CO_2
0.95	0.05	0.1	0.1	1.008	1.008

2 uses a 1.9-ltr diesel engine/battery pack

3 Also applied to PaH and $PM_{2.5}$

4 Also applied to CH_4, Benzene and 1-3 Butadiene

Table D4. Bus fleet projected stock by year including the Mayor's bus fleet strategy

YEAR	VEHICLE TYPE											TOTAL
	H2FC[5]	Hybrids[6]	E5	E4	E3 + DPF + No_x[7]	E3 + DPF	E2 + DPF + No_x	E2 + DPF	E2	E1	pre-Euro	
Mar-02	0	0	0	0	0	572	0	2060	2565	269	1237	6703
Dec-02	0	0	0	0	0	1780	0	2050	2264	204	1074	7373
Mar-03	0	0	0	0	0	2183	0	2047	2164	182	1020	7596
Dec-03	0	0	0	0	0	3177	0	2055	1733	205	705	7874
Mar-04	0	0	0	0	0	3508	0	2057	1589	212	600	7966
Mar-05	3	0	0	0	14	4209	10	3279	186	72	255	8028

5 Fuel cell bus

6 uses a 1.9ltr diesel engine/battery pack

7 DPF – diesel particle filter, NO_x – indicates additional control through use of SCR.

Vehicle km estimates for 2001 to 2004

Total vehicle km estimates for London have changed very little between 2001 and 2004 (Dft, 2001 – 2004) and hence the vehicle km estimate for one year would provide a reasonable estimate for an adjoining year. Therefore between the years for all areas, except, CCZ/IRR only small changes in vehicle km were made. These changes were supplemented by traffic flows for roads where new counts existed. In contrast to this the CCZ and IRR showed marked changes in the vehicle km travelled for a number of vehicle types immediately after implementation of the CCS and hence specific changes were applied between 2002 and 2003.

These changes were based upon figures published by TfL, 2004 and after being converted to AADT equivalent values, were incorporated separately for the CCZ and IRR. AADT vehicle km changes brought about by the CCS were applied to all hours of the year rather than over the specific weekday charging hours. The changes were calculated using the same method as for all 12 hour road traffic data within the LAEI, that is the 12 hour counts were expanded to 24 hours using count information on overnight periods. The 24 hour weekday totals were then converted to AADT using both the changes in traffic flow on Saturday, Sunday and during holiday periods. To estimate the CCS weekday hourly impacts as an AADT figure the same traffic data was converted to AADT after adjusting the vehicle flows during charging hour periods according to published TfL changes (TfL 2004). This resulted in an estimate of road traffic before and after the CCS. Comparison of these AADT changes are summarised in Table D5.

Table D5 The percentage changes applied to roads in the CCZ and on the IRR by vehicle type (AADT)

Location	Motorcycles	Taxis	Cars	Buses	LGVs[1]	HGVs[2]
CZ	7.1	15.1	-26.2	15.9	-1.2	-7.4
IRR	43.3	15.1	-8.7	21.9	16.3	5.6

[1]Light goods vehicles
[2]Heavy goods vehicle

Emission Factors used in the emissions inventory compilation

Use has been made of the most recent set of UK national emission factors, available from Atomic Energy Authority Technology, based upon information from Transport Research Laboratory (Barlow et al, 2001). Polynomial expressions (see equation below) were used to express emissions in g/km vs speed for different pollutants and vehicle types an example of which is given in Figure D3 below. An additional spreadsheet of year dependent factors was also used to account for fuel and exhaust treatment influences. Further information related to the emissions factors can be found at http://www.naei.org.uk/emissions/index.php.

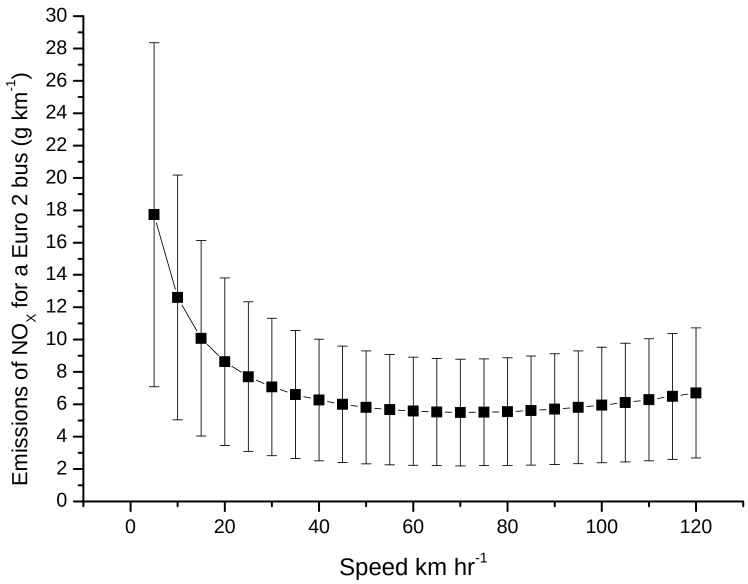

Figure D3 A typical speed emission curve used in the LAEI (Bus Euro 2) – error bars represent uncertainty at ± 60% (2σ□. (Tim Murrells – personal communication)

The above speed emissions relationship takes the form of the polynomial expression below.

$$\text{Emission Factor (g km}^{-1}) = (a + b.v + c.v^2 + d.v^e + f.\ln(v) + g.v^3 + h/v + i/v^2 + j/v^3 + k.v^4 + l.v^5 + m.v^6) * x$$

where a - m are constants, v – velocity (km/hr) and x – emissions scaling factor associated with a switch between euro 2 and euro 3 and 4 vehicles.

Tyre and Brake Wear

Emissions from tyre and brake wear were included in the LAEI. The method used was consistent with the methods described in COPERT III, details of which can be found in Ntziachristos and Boulter, 2003. Tyre and brake wear have been calculated for both PM_{10} and $PM_{2.5}$, based upon the number of vehicles (6 vehicle categories), vehicle speed and assumptions made regarding the number of axles and estimated load.

Primary NO_2 emissions

Primary NO_2 emissions were based upon proportions of NO_X emissions from different vehicle categories and with different technologies. The vehicle class assumptions have been taken from various sources and are summarised in Table D6. Note that the assumptions used for bus and HGV particle traps, oxidation catalysts and SCR were sourced from TfL vehicle tests. Those relating to diesel car Euro 3 +, diesel cars with oxidation catalysts and diesel LGV Euro 3 + were sourced from DfT vehicle tests.

Table D6 NO_2 : NO_X ratios for different vehicle classes

Vehicle category	Motorcycles	Petrol Cars	Diesel Cars	HGV	Bus	Petrol LGVs	Diesel LGVs
Pre Euro1	0.04	0.04[1]	0.105[2]	0.14[1]	0.175[1]	0.04	0.22[1]
Euro 1	0.04	0.04	0.105	0.14	0.175	0.04	0.22
Euro 2	0.04	0.04	0.105	0.14	0.175	0.04	0.22
Euro 3	0.04	0.04	speed related (0.2 to 0.4)[3]	0.14	0.175	0.04	speed related (0.2 to 0.4)[3]
Euro 4+	0.04	0.04	speed related (0.2 to 0.4)	0.14	0.175	0.04	speed related (0.2 to 0.4)[3]
Oxidation Catalyst	-	-	speed related (0.2 to 0.4)	-	0.35[3]	-	-
Particle trap	-	-	0.23	0.48[3]	0.4[3]	-	0.23
Selective catalytic reduction	-	-	-	-	0.4[3]	-	-

1 (Latham et.al, 2001), 2 (Richards et. al, 2002), 3 (D Carslaw, personal comm.)

Cold start emissions

The emission factors described above do not include the effect of cold starts on emissions, which were included as an additional emission source dependent on the number of trips a vehicle makes and the mean length of each trip among other factors. The methodology that has been used in the LAEI is the same as that used in the COPERT III methodology, details of which can be found in (http://vergina.eng.auth.gr/mech/lat/copert/copert.htm).

Data from the London Research Centre LAEI inventory (Buckingham et al. 1997) gave trip starts in each km^2 (derived from the LTS traffic model). These have been used in the calculation of cold start emissions for cars and LGVs for CO, Non-methane Volatile Organic Compounds, NO_X and PM_{10} on a km^2 basis, expressed as tonnes $annum^{-1}$.

Uncertainty in the LAEI Emissions Estimates

A comprehensive assessment of uncertainty in both the air pollution modelling and emissions inventory estimates is very difficult to provide. The figures given below (Table D7) were obtained using Monte-Carlo simulation based upon expert judgement rather than on measured quantities of parameter uncertainty. These were taken from Mattai and Hutchinson 2008 and are considered to be representative of LAEI 2003 results for total emissions for the base year but do not reflect the increased uncertainty associated with future forecasts.

Table D7 Uncertainty estimates of LAEI road traffic emission sources.

Pollutant	NO_X	CO_2	HC	PM
Vehicles	±24%	-	±25%[8]	±22%

Figures show 2*SD of the uncertainty distribution obtained by MCS, expressed as a % of the estimate.

References

Barlow TJ, Hickman AJ, Boulter P. 2001. Exhaust emission factors: database and emission factors, TRL, Project report PR/SE/230/00.

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

Latham S, Kollamthodi S, Boulter PG, Nelson PM, Hickman AJ. 2001. Assessment of Primary NO_2 Emissions, Hydrocarbon Speciation and Particulate 27 Sizing on a Range of Road Vehicles, Transport Research Laboratory (TRL): PR/SE/353/2001.

Mattai J, Hutchinson D. 2006. The London Atmospheric Emissions Inventory 2003. CD available from the Greater London Authority, London.

Mattai J, Hutchinson D. 2008. The London Atmospheric Emissions Inventory 2004. CD available from the Greater London Authority, London.

Ntziachristos L, Boulter PJ. 2003. Road Vehicle Tyre Wear and Brake Wear and Road Surface Wear. Chapter taken from EMEP/CORINAIR Emission Inventory Guidebook, 2006. European Environment Agency.

Richards P, Terry B, Pye D. 2002. Experience of fitting London black cabs with fuel borne catalyst assisted diesel particulate filters - Part 2 Non-regulated emissions measurements. Society of Automotive Engineers 2002-01-2785.

---

8 Does not include evaporative emissions

Abbreviations

AADT	Annual average daily totals
ATC	Automatic traffic counts
CCZ	congestion charge zone
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DfT	Department for Transport
EGR	Exhaust gas re-circulation
ERG	Environmental Research Group
GLA	Greater London Authority
GIS	Geographic Information System
HC	hydrocarbons
HGVs	heavy goods vehicles
IRR	Inner Ring Road
LAEI	London Atmospheric Emissions Inventory
LGVs	light goods vehicles
LT	London Transport
LTS	London Transport Survey
MCC	Manual Classified Counts
NO_x	oxides of nitrogen
PAH	polyaromatic hydrocarbon
$PM_{2.5}$	particles with an aerodynamic diameter of 2.5 μm or smaller
PM_{10}	particles with an aerodynamic diameter of 10 μm or smaller
SCR	selective catalytic reduction
SO_2	sulphur dioxide