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ROAD VEHICLE NON-EXHAUST PARTICULATE MATTER: INITIAL AIR QUALITY MODEL DEVELOPMENT AND APPLICATION, MODEL UNCERTAINTY ANALYSIS AND FURTHER MODEL IMPROVEMENTS

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Executive summary

This report describes the work involved in Task 3 and Option 5c of the 'Road vehicle non-exhaust particulate matter' project (CPEA23/SPU82), commissioned by DEFRA and the Devolved Administrations.

The aim of this project was to investigate the accuracy of PM_{10} and $PM_{2.5}$ non-exhaust emission factors. The non-exhaust emission factors of interest were the resuspension factors derived using data from Marylebone Road during Task 2 [1], and tyre, brake and road wear emission factors from the EMEP methodology [2]. As the original derivation of the resuspension factors in Task 2 assumed that exhaust emissions do not include any coarse component, the current task began by deriving further resuspension emission factors that assumed a 6% coarse component for exhaust emissions. The resuspension values derived in this further analysis were included in the current work as an alternative resuspension emission scenario.

The emission factors were used to calculate emissions for the London area, and an area of Birmingham centred on Selly Oak. For London, the emissions calculations used traffic count, source geometry and emissions data from the London Atmospheric Emissions Inventory [3], and for Birmingham, data were obtained from a number of sources, as no detailed emissions inventory was available. Emissions totals from traffic for the London area showed that non-exhaust emissions make up nearly 50% of PM_{10} emissions, over 25% of $PM_{2.5}$ emissions and nearly 90% of PM_{coarse} emissions.

Dispersion modelling was performed at 16 sites within the London area, and one in Birmingham using the air dispersion model ADMS-Urban [4]; all the sites selected measured PM_{10} concentrations, and 10 additionally measured $PM_{2.5}$. The predicted PM_{10} modelled concentrations compare well with the measured values, with a model overestimate of approximately 6% (for both resuspension emission scenarios). $PM_{2.5}$ modelled values are more significantly overestimated (26%), but this is likely to be related to the uncertainty of the factor required to convert the TEOM measured concentrations to their gravimetric equivalent.

It is expected that the model would result in a small underestimate of concentrations, as no account was taken of other non-combustion sources of coarse particulates, such as construction sites. Thus the small model overestimate seen may indicate that the non-exhaust particulate emission factors are too high. One reason for the resuspension emission factors being too high is that in their derivation during Task 2, it was assumed that the ratio of the road traffic emissions of PM_{10} to NO_X is equal to the ratio of PM_{10} and NO_X concentrations. This may not be the case as the source characteristics of exhaust and non-exhaust emissions are different, resulting in different relative concentrations. Initial investigations into this have been undertaken during the current work.

1 Introduction

This report describes the work involved in Task 3 of the 'Road vehicle non-exhaust particulate matter' project (CPEA23/SPU82), commissioned by DEFRA and the Devolved Administrations. In addition, details of the investigations performed as 'Option 5c' of this project are given.

The current methodologies for estimating non-exhaust particulate matter emissions were assessed in Task 2 of this project. The final report [1] concluded that none of the other methods for estimating particulate emissions from tyre, brake and road wear investigated offered any improvement over the EMEP [2] methodology, which is currently used in the UK National Atmospheric Emissions Inventory (NAEI) [5]. It was therefore proposed that the EMEP emission factors for these abrasion sources should be used in the current dispersion modelling study.

In Task 2, particulate emissions data measurements at Marylebone Road were used to derive new particulate emissions estimates for resuspension, and resuspension plus road wear combined. These new emission factors have been used in the current study. However, the derivation of these resuspension emission factors included the assumption that vehicle exhaust emissions do not have any coarse component. As this assumption may lead to an overestimation of emissions due to resuspension, it was decided to begin Task 3 by repeating the calculations, including a coarse exhaust component. The dispersion modelling study and source apportionment analyses have been performed with both the resuspension emissions calculated in [1], as well as the new factors derived in Section 2.2.2 below.

In addition to the above, Task 3 of this project comprised the setting up of the ADMS-Urban model [4] to estimate PM_{10} and $PM_{2.5}$ concentrations and their component parts at representative locations across the UK. This involved two subtasks:

- Model development, and
- Model application.

The model development required the inclusion of the non-exhaust emission factors into the emissions software toolkit, EMIT [6]. This subtask also required the extension of EMIT to include emissions of $PM_{2.5}$, as the release version of the model only includes PM_{10} emission factors. A number of different combinations of resuspension/resuspension plus road wear factors have been included in EMIT. No specific ADMS-Urban model developments were required.

The model application involved the selection of a number of roadside and background locations in the UK where PM_{10} and $PM_{2.5}$ concentrations have been monitored over various time periods. At these sites, the ADMS-Urban model has been used to predict PM_{10} and $PM_{2.5}$ concentrations using the new emissions estimates. Source apportionment of modelled concentrations has been performed in terms of the various constituents (tyre, brake and road wear, resuspension, exhaust and non-traffic sources).

A significant number of the DEFRA automatic monitoring stations record hourly values of PM_{10} concentrations; a few of these additionally record $PM_{2.5}$. A selection of these sites within the London area were chosen, as it is this region where detail fleet composition and traffic count data are known (through use of the London Atmospheric Emissions Inventory, LAEI, [3]). In addition, during the TRAMAQ project UG250 [7], coarse and fine particulate (PM) measurements were made at four locations (three in London, one in Birmingham) for three-week periods, during the different seasons of the year. Although some chemical analyses of the PM measurements were made during these TRAMAQ experiments, it has not been possible to include these data in the source apportionment analyses presented in the current work. This is because there remain a number of questions regarding the methodology; these issues are discussed in Section 8.1.

Task 3 has been approached in relation to Option 5c: 'Model uncertainty analysis', and 'Further model improvements'. Various uncertainty investigations have been performed throughout the project, including:

- The emissions investigations have shown that it is not necessary to use the combined resuspension and road wear the emission estimates derived in [1] and the current document (Section 2.5).

- Investigations into the correct value of the conversion factor that has to be applied to the $PM_{2.5}$ TEOM measurements at rural and urban have been made (Section 5.2.2). The significant uncertainty regarding these factors affects both $PM_{2.5}$ and PM_{coarse} modelled and monitored concentrations.

- Ranges of concentration values are given in terms of mean, minimum and maximum values, which indicate the uncertainty in the calculated values of emissions and concentrations (see Tables 20 and 21).

- In Section 5.5, it has been shown that the split between the concentrations due to the various traffic components predicted at the monitor locations correlate remarkably well with the emissions totals for the whole area. This supports methodologies that use scaling of concentrations by emissions.

Further modelling work performed as part of Option 5c has involved looking at the relative contribution from all the traffic emission sources to emissions and concentrations from two idealised roads – one major road and one minor road. The significant effect of the proportion of HGVs on the relative concentrations has been investigated, both in terms of the light and heavy fractions, and the exhaust and non-exhaust components.

In the base case modelling scenarios, all the traffic emissions have been modelled with the same source properties and are therefore dispersed linearly according to their relative emissions. Physically, it is known that the buoyancy (and consequently dispersion) of the exhaust emissions is very different to the emissions from, say, tyre wear and road wear. As part of the 'Further Model Improvements' section of Option 5c, a non-standard version of the ADMS-Urban model has been used to investigate the effects of different source heights on the different traffic components.

The exhaust and non-exhaust emissions from road traffic are summarised in Section 2. This section includes the details of derivation of the resuspension and resuspension plus road wear emission factors by applying the methodology outlined in [1], with and without including a coarse exhaust component. The different emission scenario descriptions are summarised in Section 2.3, and details of the emissions calculations in EMIT, including required model developments, are given in Section 2.4.

The sites selected for dispersion modelling are described in Section 3, and Section 4 describes the dispersion model set up, including details of the emissions (Sections 4.2 4.3 and 4.4), background concentrations (Section 4.5).

Results from the dispersion modelling are presented in Section 5. This includes comparison of both long-term PM_{10}, $PM_{2.5}$ and PM_{coarse} modelled and measured concentrations at all the selected sites (Section 5.2), and some short-term analysis at the TRAMAQ sites (Section 5.3). Source apportionment analyses of the modelled concentrations have been presented in Section 5.4, and the relationship between the modelled concentrations and the emissions has been further investigated in Section 5.5.

Investigations using idealised roads are presented in Section 6, including consideration of how the emissions of, and concentrations from, the different traffic sources change between road types, and between light and heavy vehicles. Section 6.4 shows how improvement to the source properties of the various emission components can significantly change concentrations.

The results from this report are summarised in Section 7, and details of possible further work are given in Section 8; references are given in Section 9. Appendices A to D give additional information that is referred to in other sections of the report, specifically: calculation of new resuspension emission factors (Appendix A), an ADMS-Urban model description (Appendix B), some details of edits made to the London Atmospheric Emissions Inventory (Appendix C), and description of how ADMS-Urban models road sources (Appendix D).

2 Emission from road traffic

2.1 Introduction

This section outlines the traffic emission estimates that are to be used to in the dispersion modelling. Direct exhaust and four types of non-exhaust emissions are considered, specifically, emissions from:

- Exhaust
- Tyre wear
- Brake wear
- Road wear, and
- Resuspension

Section 2.2 gives further information regarding these emissions. Subsections 2.2.1 and 2.2.2 derive resuspension and resuspension plus road wear emission factors for use in the dispersion modelling, and these are summarised in Subsection 2.2.3. Four emission scenarios are proposed in Section 2.3. EMIT, an emissions database software tool, has been developed by CERC to calculate emissions from road traffic sources; Section 2.4 gives details of this model, and the model developments required during the project. Some preliminary emission scenario investigations are described in Section 2.5, which lead to the conclusion that it is not necessary to perform dispersion modelling with both the resuspension, and the resuspension plus road wear emission factors.

2.2 Summary of emission factors to be used in the dispersion modelling

Road traffic PM_{10} emission factors, E_{PM10} (g/km), have the following contributions:

$$E_{PM10} = E_{exhaust} + E_{tyre} + E_{brake} + E_{rw} + E_{resus}, \quad (1)$$

where $E_{exhaust}$, E_{tyre}, E_{brake}, E_{rw} and E_{resus} are the emissions from exhaust, tyre wear, brake wear, road wear and resuspension, with particle sizes less that 10 μm.

Table 1 summarises the PM_{10} emission factor components in terms of particle size contributions.

Factor	Description	Pollutant type				Source of data for use in modelling
		PM_{10}	$PM_{2.5}$	PM_1	$PM_{0.1}$	
$E_{exhaust}$	Exhaust emission factors	✓	✓	✓	✓	[8],[9]
E_{tyre}	Tyre wear	✓	✓	✓	✓	[2]
E_{brake}	Brake wear	✓	✓	✓	✓	[2]
E_{rw}	Road wear	✓	✓	?[1]	?[1]	[1],[2]
E_{resus}	Resuspension	✓	0[2]	0[2]	0[2]	[1]

Table 1 – Summary of traffic-induced PM_{10} emission factor components ([1] According to [1], 'Very little information on the size distribution of road wear particles is available', and no information on PM_1 and $PM_{0.1}$ from this source are given; [2] [1] assumes that all emissions from resuspension are in the $PM_{10-2.5}$ category).

2.2.1 Derivation of the resuspension emission factors in the Boulter et al report [1]

A fundamental assumption in calculating the resuspension emission factors is that the incremental concentrations of roadside NO_X and PM_{10}, ΔNO_x and ΔPM_{10} respectively, are assumed to be solely due to the emissions from traffic (see equation (2) in [1]):

$$E_{PM10} = E_{NOx}\left(\frac{\Delta PM_{10}}{\Delta NO_x}\right), \quad (2)$$

where E_{NOx} are the NO_X emissions from vehicles. In addition, it was assumed that the exhaust emission factors are solely in the $PM_{2.5}$ range.

In [1], the following relationship between the coarse fraction, E_{coarse} ($PM_{10-2.5}$) and total PM_{10} emissions is assumed:

$$E_{coarse} = \beta\, E_{PM10}, \quad (3)$$

where β is originally assumed to be 0.4 (Section 4.2.4, and taken from the literature), but this estimate is subsequently revised to become a year-dependent value in order to obtain more realistic results (Section 4.2.7, Table 26, [1] with values of β ranging from 0.32 to 0.35).

In summary, [1] assumes the following relationships for the PM_{10} and $PM_{2.5}$ components of the road traffic particulate emissions:

$$E_{coarse} = E_{tyre,\,coarse} + E_{brake,\,coarse} + E_{rw,\,coarse} + E_{resus}, \quad (4)$$

$$E_{PM2.5} = E_{exhaust} + E_{tyre,\,2.5} + E_{brake,\,2.5} + E_{rw,\,2.5} \quad (5)$$

where $E_{tyre,\,coarse}$, $E_{brake,\,coarse}$ and $E_{rw,\,coarse}$ are the coarse parts of the tyre, brake and road wear emissions; $E_{tyre,\,2.5}$, $E_{brake,\,2.5}$ and $E_{rw,\,2.5}$ are the $PM_{2.5}$ contributions to the tyre, brake and road wear emissions; and $E_{PM2.5}$ is the total $PM_{2.5}$ emission.

Including assumption (3) in equations (2) and (4) leads to an equation that allows the resuspension component of particulate emissions to be evaluated *i.e*:

$$E_{resus} = \beta\left(\frac{\Delta PM_{10}}{\Delta NO_x}\right) - E_{tyre,\ coarse} - E_{brake,\ coarse} - E_{rw,\ coarse}. \quad (6)$$

Due to the uncertainties associated with estimates of road wear emissions, in addition to evaluating a single emission factor due to resuspension given by (6) above, a combined factor was also derived:

$$E_{resus} + E_{rw,\ coarse} = \beta\left(\frac{\Delta PM_{10}}{\Delta NO_x}\right) - E_{tyre,\ coarse} - E_{brake,\ coarse} \quad (7)$$

2.2.2 Extension of the Boulter et al [1] method, including a coarse component of the exhaust emission factors

Table 4.10 in the PM AQEG report [9] gives emission estimates for PM by size fraction for the various sources within the UK. Included in this table are PM emissions from road transport, categorised into petrol and diesel vehicles. The relevant information is summarised in Table 2 below.

Source	PM_{10} emissions (kt)	Percentage by size fraction			
		$PM_{10-2.5}$	$PM_{2.5}$	PM_1	$PM_{0.1}$
Petrol vehicles	3.0	16.7	83.3	70.0	33.3
Diesel vehicles	27.4	10.2	89.8	85.0	50.0

Table 2 – Emission estimates for particulates by size fraction for the UK, 2001.

Table 2 allows the calculation of an estimate of the coarse component of exhaust emissions for all vehicles; this is evaluated as 10.8%. This percentage applies to the total UK fleet, and therefore its application to any particular road carries very significant uncertainty. In addition, the size estimates are derived from the US EPA Compilation of Emission Factors document (AP-42, [10]) and are likely to be out of date.

In the following private communication with Leonidas Ntziachristos[1], it seems that recent measurements show the proportion of coarse component to be much lower than 10.8%:

In principle, all engine exhaust generated PM should fall within the $PM_{2.5}$ category. There is no physical process occurring in an engine that could produce primary particles as large as 2.5 μm. However, when we measure PM using cascaded filters with different cut points, we do get some negligible PM (maybe 1-2%) above 2.5 μm. However, this is mainly gas adsorption on the filter or particles that have been resuspended from the sampling system walls and not primary engine exhaust. Therefore, I should consider it safe to consider that all engine exhaust PM is $PM_{2.5}$ for any practical application, this being particularly true for gasoline-powered vehicles.

[1] Laboratory of Applied Thermodynamics, University of Thessaloniki (lead developers of CORINAIR/COPERT)

After some discussion between DEFRA, TRL and NAEI, it was decided that the coarse component of PM_{10} vehicle exhaust is taken as 6%, as whilst it is likely that the 10.8% is too high, measurements do indicate that there is still some particulates present in the 2.5 – 10 μm diameter range. Taking this value to be the best approximation available, the exhaust emissions can be divided into a coarse emission, $E_{exhaust,\ coarse}$ and $E_{exhaust,\ 2.5}$, where, using the notation introduced in Section 2.2.1 above:

$$E_{exhaust} = E_{exhaust,\ coarse} + E_{exhaust,\ 2.5}, \quad \text{and} \tag{8}$$

$$E_{exhaust,\ coarse} = \chi\, E_{exhaust}, \tag{9}$$

where $\chi = 0.06$. This leads to the following two equations, which correspond to equations (4) and (5) given in Section 2.2.1 above:

$$E_{coarse} = E_{exhaust,\ coarse} + E_{tyre,\ coarse} + E_{brake,\ coarse} + E_{rw,\ coarse} + E_{resus}, \tag{10}$$

$$E_{PM2.5} = E_{exhaust,2.5} + E_{tyre,\ 2.5} + E_{brake,\ 2.5} + E_{rw,\ 2.5} \tag{11}$$

Finally, equation (10) can be rearranged, and combined with equations (2), (3) and (9) to give:

$$E_{resus} = \beta\left(\frac{\Delta PM_{10}}{\Delta NO_x}\right) - \chi\, E_{exhaust} - E_{tyre,\ coarse} - E_{brake,\ coarse} - E_{rw,\ coarse}. \tag{12}$$

The equation for combined resuspension and road wear emissions, corresponding to equation (7) in Section 2.2.1 is:

$$E_{resus} + E_{rw,\ coarse} = \beta\left(\frac{\Delta PM_{10}}{\Delta NO_x}\right) - \chi\, E_{exhaust} - E_{tyre,\ coarse} - E_{brake,\ coarse}. \tag{13}$$

Equations (12) and (13) for resuspension and resuspension plus road wear respectively will predict lower emission factors compared to equations (6) and (7).

Appendix A gives details of the derivation of resuspension and resuspension plus road wear emission factors by applying this extended methodology to the Marylebone Road dataset.

2.2.3 Resuspension/Resuspension plus road wear emission factors for use in the dispersion modelling

Table 3 summarises the resuspension and resuspension plus road wear emission factors derived in [1], and Section 2.2.2 above, for use in the dispersion modelling. For details of the modelling scenario references 1a, 1b, 2a and 2b, refer to Section 2.3.

Source of factor	Emission scenario	Resuspension emission factor (mg/km)		Emission scenario	Resuspension plus road wear emission factor (mg/km)	
		HDV	LDV		HDV	LDV
Boulter *et al* [1]	**1a**	141	0.8[2]	**1b**	158	4.2[2]
Current document	**2a**	116	0.02	**2b**	134	3.47

Table 3 – Summary of resuspension/resuspension plus road wear emission factors to be used in the dispersion modelling.

2.3 Emission scenario descriptions

Four emission scenarios will be investigated. Full details are given in Table 4 below.

Emission source	Particle size	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Resuspension	**PM_{10}**	Equation (6) in Section 2.2.1, [1]	Equation (7) in Section 2.2.1, [1]	Equation (12) in Section 2.2.2	Equation (13) in Section 2.2.2
	$PM_{2.5}$	Assumed to be zero			
Road wear	**PM_{10}**	EMEP [2]	Equation (7) in Section 2.2.2, [1]	EMEP [2]	Equation (13) in Section 2.2.2
	$PM_{2.5}$	EMEP [2]	EMEP [2]	EMEP [2]	EMEP [2]
Tyre wear	**PM_{10}**	EMEP [2]			
	$PM_{2.5}$	EMEP [2]			
Brake wear	**PM_{10}**	EMEP [2]			
	$PM_{2.5}$	EMEP [2]			
Exhaust	**PM_{10}**	NAEI [8]			
	$PM_{2.5}$	Derived from the NAEI factors, assuming 94% of the PM_{10} emissions are $PM_{2.5}$			

Table 4 – Summary of emission scenarios to be investigated.

In summary:

- All scenarios use the same tyre, brake and exhaust emission factors for PM_{10} and $PM_{2.5}$, the same $PM_{2.5}$ road wear factors, and assume a zero $PM_{2.5}$ emission factor for resuspension;
- Scenarios 1a and 2a use new, derived PM resuspension emission factors (equations (6) [1] and (12) respectively), with the EMEP PM_{10} road wear factors;

Scenarios 1b and 2b use a new, derived combined resuspension and road wear coarse component emission factors (from equations (7) [1] and (13) respectively);

[2] Note that the values in [1] were only given to 2 significant figures

2.4 Calculation of emissions in EMIT

2.4.1 Background

The commercially available emissions database software tool, EMIT, has been used to perform the emissions calculations required for this project. EMIT (version 2.2) includes up-to-date exhaust emission factors from light and heavy vehicles categorised into 101 different vehicle sub-categories, dependent on vehicle type, age, engine size and so on. These factors include year-dependent scaling factors that account for the effects of new fuels and vehicle technologies within the fleet.

In order to use the emissions factors within EMIT to perform calculations that result in total emissions for a particular road, fleet composition data are required. In most cases, detailed fleet data are unknown for each road within an area, but basic traffic counts, either measured or from a traffic model are known. These data can be used in combination with a predefined 'route type', to calculate total emissions[3]. For the exhaust emission dataset used in the current work, the 'route type' data are based on UK fleet composition data provide by the NAEI.

2.4.2 EMIT model developments

For this project, it was necessary to make a number of changes to the release version of the EMIT software. The changes required were:

1. Editing the 'EURO SCALED 03' to include $PM_{2.5}$ emission factors.

2. Adding new emission factor datasets to EMIT for:

    i. Tyre wear,

    ii. Brake wear,

    iii. Road wear, and

    iv. Resuspension (emission scenarios 1A, 1B, 2A and 2B)

3. Adding year-dependent scaling factors for the new emission factor datasets i. to iv. listed above.

4. Including appropriate 'route types' for each of the emission factor datasets.

The EMIT model developments were carried out in accordance with CERC's strict Quality Assurance procedures, including full documentation describing the model changes, testing performed and the peer review undertaken.

Table 5 summarises the traffic emission factor datasets included within the EMIT database model, after development. The tyre, brake and road wear emission factors were calculated according to the EMEP methodology, and the resuspension emission factors were as summarised in Table 3 above.

[3] For further details of the EMIT software tool, please refer to the EMIT User Guide, a copy of which can be obtained in .pdf format from CERC on request

It is interesting to note that the non-exhaust datasets have varying degrees of categorisation. For example, the tyre wear emission factor dataset is the most detailed, with speed-dependent emission factors for eight vehicle categories. The simplest emission factor dataset is the resuspension dataset, which includes only two, speed-independent values.

Traffic emissions dataset	Number of vehicle categories	Speed dependent?	Description of vehicle categories
Exhaust	101	Yes	Categories depending on vehicle type, age, and engine size
Tyre wear	8	Yes	3 LDV (motorcycles, cars, LGVs) and 5 HDV categories
Brake wear	4	Yes	3 LDV (motorcycles, cars, LGVs) and one HDV category
Road wear	4	No	
Resuspension[a]	2	No	LDV and HDV categories

Table 5 – Summary of the traffic emission factor datasets included within EMIT (dataset name in italics implies added for the current project; [a] four resuspension datasets were included within EMIT, for emission scenarios 1A, 1B, 2A and 2B).

The year-dependent scaling factors for all the non-exhaust emission factor datasets were assumed to be unity. It was decided to make all new datasets compatible with an 11 'fleet component' categorisation. This was a practical requirement because the London Atmosphere Emissions Inventory includes traffic count data in this format.

Each dataset required at least one 'route type' to be defined, which related the emissions factor data to the traffic count data. In most cases, the chosen relationship between the traffic count data categorisation and the emission factor categorisation was straightforward, but for the tyre wear 'route type', it was necessary to make the following assumptions:

- In the absence of any other available data, a 0.5 / 0.5 split was assumed between 3- and 4- axled vehicles within the LAEI fleet component 'Artic HGVs 3&4 axles'.
- All vehicles included in the LAEI fleet component 'Rigid HGVs 4+ axles' have 4 axles.
- All vehicles included in the LAEI fleet component 'Artic HGVs 6+ axles' have 6 axles.
- All vehicles included in the LAEI fleet component 'Buses and coaches' are assumed to have two axles, when in fact in the original EMEP classification, buses could either be V4 (HGVs (2-axle)/bus) or V5 (HGVs (3-axle)/bus).

2.4.3 EMIT calculations

Emissions databases were set up to cover the two regions of interest – greater London, and a region approximately 150 km^2 centred on the Selly Oak site in Birmingham (please refer to Section 3 below for further discussion of sites). Full details of the emissions held in these databases are given in Section 4.

In order to perform source apportionment calculations, the emissions for each of the traffic emission components (exhaust, tyre wear, brake wear, road wear and resuspension) were calculated separately, so that they could be modelled separately.

2.5 Preliminary emission scenario investigations using EMIT

Prior to any dispersion modelling calculations, it is interesting to consider the emission totals calculated using all the traffic emission factor datasets. This investigation was performed using the data for major roads from the London Atmospheric Emissions Inventory.

Table 6 summarises the emissions totals for major roads within the London area for 2002, for the various resuspension emission scenarios. This table shows that the difference in emission totals between scenarios 1A and 1B is negligible, similarly for scenarios 2A and 2B. The reason for this is outlined below.

As expected, the $PM_{2.5}$ emission totals remain constant for all scenarios, as the resuspension emissions do not include a fine fraction.

Scenario	Emissions (tonnes/year)	
	PM_{10}	$PM_{2.5}$
1A	3762	2532
1B	3762	2532
2A	3648	2532
2B	3650	2532

Table 6 – Summary of emission totals for major roads within the London area (2002), for the various resuspension emission scenarios.

The EMEP emissions for the coarse component of road wear are linear in the number of heavy vehicles (N_{HGV}), as well as being dependent on the number of motorcycles (N_{MC}), cars (N_{CAR}) and light goods vehicles (N_{LGV}). That is, using the notation introduced in Section 2.2:

$$E_{rw,\,coarse} = \alpha_{MC}\ N_{MC} + \alpha_{CAR}\ N_{CAR} + \alpha_{LGV}\ N_{LGV} + \alpha_{HGV}\ N_{HGV},$$

where α_{MC}, α_{CAR}, α_{LGV} and α_{HGV} are speed independent constants.

The linear analysis used to derive the resuspension emission factors is described in Section 2.2. The derived light vehicle emission factor is less than 1% of the heavy vehicle factor. This means that, despite the fact that there are proportionally a greater number of light vehicles on the road than heavy vehicles, the vehicle resuspension emission are effectively linear with the number of heavy vehicles. That is, to leading order:

$$E_{resus} = \beta_{HGV}\ N_{HGV}\ (+ \text{negligible contribution from light vehicles}).$$

Thus, when the emissions of resuspension and road wear are treated separately, the total emission is:

$$E_{resus} + E_{rw,\,coarse} = \alpha_{MC}\ N_{MC} + \alpha_{CAR}\ N_{CAR} + \alpha_{LGV}\ N_{LGV} + (\alpha_{HGV} + \beta_{HGV})\ N_{HGV}.$$

When a linear correlation is used to derive the emissions of resuspension plus road wear combined, the factors derived are the same as when the resuspension values are derived separately. This can clearly be seen by comparing the values derived in [1] and the current document, with the EMEP values – refer to Table 7 below.

Source of factor	**Calculation**	**$E_{rw,coarse}$ (mg/km)**	
		Light vehicles[a]	**Heavy vehicles**
Boulter *et al* [1]	Resuspension plus road wear factor subtracted from resuspension alone (Table 3).	3.4[b]	17.0
Current document		3.45	18.0
EMEP	$PM_{2.5}$ emission factor subtracted from the PM_{10} emission factor	3.45	17.5

Table 7 – Summary of coarse component of road wear emission factors ([a] Note that the emissions from motorcycles have been neglected in these calculations for EMEP; [b] Note that the values in [1] were only give to 2 significant figures).

The result of this investigation is that it is not of interest to investigate the resuspension plus road wear combined factors, as the emissions calculated, and hence concentrations predicted by the dispersion modelling will be the same, to within the margin of error of the calculations.

3 Site descriptions

3.1 Introduction

The concentrations of both PM_{10} and $PM_{2.5}$ at the following locations have been modelled:

- Four sites at which coarse and fine ($PM_{2.5}$) particle fractions were collected during the TRAMAQ project UG250 (as used in Section 4.1 [1]):

    1. Elephant and Castle (EC), London
    2. High Holborn (HH), London
    3. Park Lane (PL), London
    4. Selly Oak (SO), Birmingham

    At each of these sites, both roadside measurements and 'urban background' values were recorded using gravimetric monitors

- The DEFRA Automatic Monitoring Stations sites in London that measure both PM_{10} and $PM_{2.5}$ concentrations:

    5. Bloomsbury
    6. Marylebone Road

In addition, concentrations of PM_{10} at the following locations were calculated:

- The DEFRA Automatic Monitoring Stations sites in London that measure only PM_{10} concentrations:

    7. Camden
    8. Haringey
    9. A3
    10. Bexley
    11. Brent
    12. Hillingdon
    13. North Kensington

The majority of the monitors at the DEFRA sites are TEOM. Sites 1-4 have 24-hour average monitored particulate data, whereas the remaining sites all have hourly data for comparison purposes.

The data for sites 1-4 were collected between April 2000 and January 2002, and therefore concentrations have been modelled for this period. The remaining sites have been modelled for 2002.

Note that due to the fact that the monitor data at the TRAMAQ sites is more detailed than at the other sites, these sites have been modelled in more detail than the remaining sites.

Further site-specific information is given below.

3.2 Site-specific information

Site-specific information is summarised in Table 8 below. Further site information for the four TRAMAQ sites can be found in [7], and further information for the DEFRA sites can be found at http://www.stanger.co.uk/siteinfo/. All TRAMAQ monitor inlet heights are at 2m above ground level, and all DEFRA Automatic Monitoring Stations have inlet heights at 3m. It has been assumed that all PM_{10} and $PM_{2.5}$ devices are co-located. Although this is not absolutely correct (see, for example, the issues arising from the discussions regarding the monitors are Marylebone Road [11]), it is unlikely that the improving the accuracy of the location of the monitors would improve modelling results; other aspects of the model set up involve much larger margins of error.

Both roadside and 'urban background' sites have been included in the modelling study – for the TRAMAQ and the DEFRA sites.

In general, it was relatively straightforward to set up the dispersion modelling at the DEFRA sites, because these sites had been studied by CERC during previous projects; the modelling at the TRAMAQ sites was more challenging.

Site No.	Site name	Site description[a]	Street canyon?	Measured pollutants
1a	Elephant and Castle - Roadside	0.5m from the kerb, North-West of the busy Elephant and Castle roundabout, on the junction with St Georges Road.	No	PM_{10}, $PM_{2.5}$
1b	Elephant and Castle – 'urban background'	Approximately 200m from the road, within a fenced off garden in the grounds of the Imperial War museum.	No	
2a	High Holborn - Roadside	On St Giles Street, close to a busy junction in Camden.	No	
2b	High Holborn - 'urban background'	In a pedestrianised area in Macklin Street.	No	
3a	Park Lane - Roadside	Next to the busy A4202 Park Lane Road, opposite Hyde Park.	No	
3b	Park Lane - 'urban background'	In the centre of Hyde Park.	No	
4a	Selly Oak - Roadside	On the kerb of the busy A38 Bristol Road. A number of sets of traffic lights are close by, and there is significant queuing traffic.	No	
4b	Selly Oak - 'urban background'	On Katie Road, a quiet one-way street.	No	
5	Bloomsbury	In a central London square, 25m from the nearest road.	No	
6	Marylebone Road	1m from the kerb on this busy central-London road.	Yes	PM_{10}
7	Camden	North side of the very busy Swiss Cottage junction.	No	
8	Haringey	In a park, 50m from the nearest road.	No	
9	A3	On the 6-lane A3 Kingston bypass, approximately 2.5m from the kerb.	No	
10	Bexley	40m from the nearest road in a residential area.	No	
11	Brent	30m from the nearest road in a relatively open residential area.	No	
12	Hillingdon	2.5m from a residential road, 40m from the M4 motorway.	No	
13	North Kensington	Residential area.	No	

Table 8 – Summary of sites for used for dispersion modelling. Note that all sites are within London, with the exception of sites 4a and 4b, which are located in Birmingham ([a] for the TRAMAQ sites, further information cane be found in [7]; for the London sites, please refer to http://www.stanger.co.uk/siteinfo/).

4 Dispersion model set up

4.1 Introduction

The comprehensive atmospheric dispersion model ADMS-Urban [4] is used to perform the dispersion modelling for this project. ADMS-Urban is a PC-based model of dispersion in the atmosphere of pollutants released from industrial, domestic and road traffic sources in urban areas. ADMS-Urban models these using point, line, area, volume and grid source models.

A significant difference between ADMS-Urban and other models used for air dispersion modelling in urban areas is that ADMS-Urban applies up-to-date physics using parameterisations of the boundary layer structure based on the Monin-Obukhov length, and the boundary layer height. Other models characterise the boundary layer imprecisely in terms of the Pasquill stability parameter. In the up-to-date approach, the boundary layer structure is defined in terms of measurable physical parameters, which allow for a realistic representation of the changing characteristic of dispersion with height. The result is generally a more accurate and soundly based prediction of the concentrations of pollutants.

Further details of the ADMS-Urban model are given in Appendix B.

Sections 4.1.1 and 4.1.2 below summarise the emissions for the London and Birmingham sites respectively. Details of major road emissions, minor road emissions and background emissions are given in Sections 4.2, 4.3 and 4.4 respectively, and background concentrations are described in Section 4.5. Additional model set up information is given in Section 4.6.

4.1.1 Summary of emissions modelled for the London sites

When modelling concentrations at a particular receptor, emissions from sources close to the receptor are modelled explicitly, specifically:

- For the London sites, all major roads within 2km of the receptor, and all industrial sources within 5km of the receptor.

- For the Birmingham site, a relatively small selection of major roads up to 1km from the site, for which detailed traffic information could be obtained.

Emissions further away from the monitor in question are also included in the dispersion calculations, but as aggregated ‘gridded’ emissions. Finally, background concentrations that are advected into the region are taken into account by including measured concentration data from suitable upwind rural sites.

For London, emissions data were taken from the LAEI 2002, and adjusted where required, as outlined below. Table 9 summarises the emissions data included within this emissions inventory. Note that:

- Major roads are the only sources for which activity rather than explicit emissions data are given.

- The source data are given for 2002. Adjustments to account for changes in emissions for other modelled years (2000 and 2001) have only been made to the road sources (major and minor) *i.e.* emissions from all sources apart from roads are assumed to remain constant for the different years.

- The minor road emissions data include exhaust, tyre and brake wear emissions. These emissions have therefore been adjusted to include road wear and resuspension emissions. Further details are given in Section 4.3.1.

- The LAEI 2002 does not include $PM_{2.5}$ emissions. These emissions had to be estimated for all sources apart from the major road sources (where emissions are calculated using the datasets described in Section 2.3). Details of how this has been done are given in Sections 4.3.1 and 4.4.1.

Emissions from the geographical area (501000,152000) to (562000,204000) were considered.

<table>
<tr><th>Source description</th><th>Explicit emissions or activity data?</th><th>Source type</th></tr>
<tr><td>Major roads</td><td>Activity (traffic flows)</td><td>Road</td></tr>
<tr><td>Rail</td><td rowspan="23">Explicit emissions</td><td>Rail</td></tr>
<tr><td>Part A sources</td><td rowspan="3">Point</td></tr>
<tr><td>Part B sources</td></tr>
<tr><td>Boilers</td></tr>
<tr><td>Agriculture</td><td rowspan="19">Aggregated onto 1km^2</td></tr>
<tr><td>City airport</td></tr>
<tr><td>Cold starts</td></tr>
<tr><td>Commercial gas</td></tr>
<tr><td>Domestic coal</td></tr>
<tr><td>Domestic gas</td></tr>
<tr><td>Domestic oil</td></tr>
<tr><td>Evaporative emissions</td></tr>
<tr><td>Gas leaks</td></tr>
<tr><td>Heathrow airport</td></tr>
<tr><td>Industrial coal</td></tr>
<tr><td>Minor roads</td></tr>
<tr><td>Nature</td></tr>
<tr><td>Sewage</td></tr>
<tr><td>Shipping</td></tr>
<tr><td>Solvents</td></tr>
</table>

Table 9 – Summary of sources included within the LAEI 2002.

The LAEI traffic flows and speeds do not account for queuing traffic, although it is possible that the speeds in the inventory are reduced in some way to account for the diurnal variation. However, as it was known that at least two of the London TRAMAQ sites, queuing was likely, corresponding emissions were included; details are given in Section 4.2.3.

4.1.2 Summary of emissions modelled for the Birmingham site

For Birmingham, an accurate, up-to-date emissions inventory was not available. The traffic emissions for Site 4 (Selly Oak) roadside and background sites were therefore compiled using data from a combination of sources, including:

- Traffic flows for the A38 and A4040 near Selly Oak were downloaded from the NAEI website.
- Some traffic flow information for roads in the area was obtained from the TRAMAQ study archive.

It was then useful to view the Birmingham site using Google Earth, as shown in Figure 1. Using the information given in [7] and some additional site photographs, it was possible to pin down the location of the roadside site to that shown in Figure 1.

Using a 1:10 000 colour Ordnance Survey digital map of the area, all the roads close to the site for which traffic flow information was known were digitised. In addition, as the flows on the slip roads to the North and the South of the Selly Oak junction were likely to influence the concentrations at the receptor, these roads were digitised, and certain assumptions were made regarding their flows. Similarly, the bus lanes on both carriageways of the A38 just next to the monitor were included in the modelling explicitly.

Finally, as for a selection of the London TRAMAQ sites, it was known that there was significant queuing close to this monitor (due to the high traffic volumes and large numbers of traffic lights); emissions for the queuing traffic were calculated.

Figure 1 – The Site 4 Selly Oak (Roadside) as viewed in Google Earth.

The remaining emissions data for the Birmingham site were taken from the NAEI. The NAEI emissions data are aggregated onto a 1 km^2 grid. Data are given for the following categories:

- Energy Production and Transformation
- Commercial, Institutional and Residential Combustion
- Industrial Combustion
- Industrial Processes
- Production and Distribution of Fossil Fuels
- Solvent Use
- Road Transport
- Other Transport
- Waste Treatment and Disposal
- Agriculture
- Nature

4.2 Major road emissions

4.2.1 London sites

For the London sites, the LAEI provides traffic count and speed data for major roads. The new emission factors for PM_{10} and $PM_{2.5}$ derived in Section 2.2 and held in EMIT were used to calculate the emissions for all these roads within the London area.

Some corrections to the LAEI major roads data were made; details are given in Appendix C.

For each of the sites, only major roads within 2km of the site were modelled explicitly. The remaining roads were modelled in the ADMS-Urban 'grid source', as 1km x 1km square cells, with a source height of 10 m. Although some additional traffic count data were provided with the TRAMAQ sites, this seemed to be older and less detailed than that available in the LAEI, and therefore it was not used.

Year of calculation	Adjustment factor to be applied to the 2002 data (to traffic flows for major roads, and emissions for minor roads)
2000	0.982
2001	0.991

Table 10 – Summary of adjustment factors used to estimate road emissions for 2000 and 2001.

The major road traffic flows for 2002 were used to estimate the major road traffic flows for 2000 and 2001 by applying scaling factors that have been calculated using the software tool Tempro [12]; these are summarised in Table 10.

4.2.2 Birmingham site

For the Selly Oak site, the traffic count data for the roads close to the monitor was compiled by a combination of data from the NAEI and the TRAMAQ archive. In addition, flows for additional slip roads and bus lanes close to the monitor were derived using logical assumptions, for example:

- The flow on the southern slip road between Oak Tree Lane and Bristol Road South was assumed to be one third of the northbound flow on Oak Tree Lane (towards the Selly Oak junction).

- The flow on the northern slip road between Bristol Road North and Harborne Road was assumed to be one third of the southbound flow on Bristol Road North (towards the Selly Oak junction).

- All buses were assumed to travel on bus lanes, where these were considered.

EMIT was used to calculate PM_{10} and $PM_{2.5}$ emissions for these roads.

The remaining road traffic emissions data was obtained from the NAEI. It was known that the NAEI data for road transport included emissions for exhaust, tyre and brake wear, but not road wear or resuspension. Therefore, the road transport emissions were adjusted accordingly, using values derived from the PM_{10} and $PM_{2.5}$ emission totals for the London area, for major and minor roads. The adjustment factors are summarised in Table 11.

Note that for these non-explicitly modelled roads, different calculations for the various resuspension emission scenarios were not performed.

Exhaust component	**Percentage increase**	
	PM_{10}	**$PM_{2.5}$**
Road wear	14.8	9.8
Resuspension[a]	14.3	0.0

Table 11 – Summary of factors used to account for the increase in the NAEI gridded emissions data due to road wear and resuspension ([a] note that these values are averaged over all emission scenarios).

4.2.3 Queuing traffic

Queues were modelled at TRAMAQ sites Park Lane, High Holborn and Selly Oak. Explicit data for queuing traffic were not available, therefore certain assumptions were made in order to calculate approximate emissions. These included:

- The length of queues at junctions close to the sites were estimated, using the aerial view of each site obtained using Google Earth.

- A speed of 5km/hr was assumed for all queues.

- During the week, an Annual Average Daily Traffic flow (AADT) of 30 000 was assumed for all roads apart from bus lanes, where an AADT of 15 000 was taken (these values were derived using an algorithm that includes the average length of each vehicle, which was assumed to be 4m for all roads, apart from bus lanes where a value of 8m was used).

- Queues were assumed to be 50% and 20% of the weekday AADT on Saturdays and Sundays respectively.

- A time-varying emissions profile for the queues which included:

    - Weekday queuing between 7and 10am, and 4 and 7pm;

    - Saturday queuing between 8 and 11am, and 3 and 6pm; and

    - Sunday queuing between 9 and 12 am, and 3 and 6pm.

In general, queues extend up to a junction for half the road width. However, for the queues modelled at High Holborn and Park Lane, the road is one way and therefore the queue covers the full road width.

4.3 Minor road emissions

4.3.1 London sites

The minor road emissions are included in the LAEI are gridded emissions. Exhaust, tyre and brake wear have been included in these emission estimates, but road surface wear and resuspension have not. This means that the LAEI minor road emissions should be adjusted accordingly, in order to remain consistent with the major road emissions.

Minor roads typically have little HGV or bus traffic. The 2001 LAEI includes the vehicle breakdown that was assumed for minor roads within London. This is given as Table 12 below.

Vehicle type	%
Motorcycles	1.20
Cars	86.50
Bus and coaches	0.97
LGV	9.79
Rigid 2 axle	1.15
Rigid 3 axle	0.13
Rigid >=4 axle	0.10
Artic 3 & 4 axle	0.05
Artic 5 axle	0.07
Artic >=6 axle	0.03

Table 12 – Vehicle breakdown assumed for minor roads within London.

For PM_{10}, the minor road emissions had to be increased by 12% to account for resuspension and road wear emissions; for $PM_{2.5}$ the increase was 5% (smaller because

all resuspension emissions are assumed to be coarse, so this is effectively just the road wear contribution).

$PM_{2.5}$ emissions are not included in the LAEI. Using the above traffic breakdown, and the derived PM_{10} emissions (including non-exhaust emissions) it was possible to estimate that the proportion of PM_{10} that is $PM_{2.5}$ is 0.79.

In addition, the minor road emissions for 2000 and 2001 were calculated by scaling the 2002 minor road emissions. The factors used to do this are those derived using the Tempro software tool, as for major roads, and are summarised in Table 10.

4.3.2 Birmingham site

Minor road emissions are not treated explicitly in the NAEI gridded emissions data.

4.4 Background emissions

4.4.1 London sites

The LAEI emissions are summarised in Table 9. All emissions excluding those from major roads within 2km of the receptor, and industrial sources within 5km of the receptor were modelled as an aggregated $1km^2$ grid.

For the major roads, emissions were calculated using the traffic emission factors included in EMIT, which resulted in PM_{10} and $PM_{2.5}$ emission estimates. For the remaining sources, however, an assumption had to be made regarding the proportion of PM_{10} emissions that are $PM_{2.5}$. It was decided that this fraction could be based on the ratio of the measured background concentrations; that is, $PM_{2.5}$ emissions were 69% of PM_{10} emissions (refer to Table 13 below).

4.4.2 Birmingham site

For the Birmingham site, the NAEI gridded emissions data for a radial distance of approximately 7.5km centred on the Selly Oak site were modelled. As for the London background emissions data, no emission estimates for $PM_{2.5}$ were available.

For the traffic emission factors 69.3% of the PM_{10} emissions were assumed to be $PM_{2.5}$; this fraction has been calculated from the total emissions from major roads within the London area.

$PM_{2.5}$ emissions from all non-traffic sources were assumed to be 73% of the PM_{10} emission factors. This value is the average ratio of $PM_{2.5}$ to PM_{10} background concentrations for the three years under consideration, as summarised in Table 14 below.

4.5 Background concentrations

The background concentration of PM_{10} and $PM_{2.5}$ are included in the dispersion modelling. The sources of these background data are described below.

The majority of PM_{10} and $PM_{2.5}$ background concentrations are recorded using TEOM monitors. TEOM monitors are known to record systematically lower particulate concentrations compared to gravimetric monitors. For PM_{10}, the factor used to convert

the TEOM concentrations to equivalent gravimetric values is 1.3, and this factor has already been applied to all the PM_{10} concentration data downloaded from the UK National Air Quality Archive. However, there is uncertainty regarding the conversion factor that should be applied to TEOM-measured $PM_{2.5}$ concentrations in order to convert them to their gravimetric equivalent. For this reason, the $PM_{2.5}$ data available from the UK National Air Quality Archive are downloadable in 'TEOM units'.

For the purposes of this study, a factor of 1.3 has also been applied to the $PM_{2.5}$ TEOM values to convert them to gravimetric units. However, this factor is a significant source of uncertainty in the $PM_{2.5}$ results presented below, and this issue had been investigated further in Section 5.2.2.

4.5.1 London sites

The rural background concentrations for London are taken as a combination of the monitored rural background values at Harwell (to the West of London) and Rochester (to the East of London). Previous dispersion modelling of particulates in London by CERC for DEFRA found that:

- For 2002, there was a significant amount of missing data[4] for Rochester, and
- The particulate concentrations recorded at Rochester were very much greater than those at Harwell. Further investigation indicates that there is a background particulate concentration gradient across the UK, increasing from West to East.

These first of these issues was dealt with by calculating wind-dependent ratios of Harwell:Rochester background concentrations, for all day/hour combinations where values at both sites were recorded. Then, for hours where there were missing data for one (but not both) of the sites, the appropriate ratio was used to scale the concentration at the site where data was recorded to estimate the value at the site where data were missing.

For the case where there were no values recorded at either site for a particular hour, the value at the previous hour was used.

The second of the issues listed above led to the derivation of an algorithm that accounts both for the distance of each of the monitoring sites from the London area, and the incoming wind direction. Specifically:

$$\text{Total London background concentration} = \frac{C_R \times L_H\left(1+\sin(\Phi)\right) + C_H \times L_R\left(1-\sin(\Phi)\right)}{L_H\left(1+\sin(\Phi)\right) + L_R\left(1-\sin(\Phi)\right)},$$

where C_R and C_H are the Rochester and Harwell recorded (or estimated, as outlined above) concentrations, L_R and L_H are the corresponding distances of the sites from central London, and Φ is the wind direction.

[4] Note that here 'missing data' includes values recorded by the monitor as less than or equal to zero.

Year	PM_{10}	$PM_{2.5}$	$PM_{2.5}$ / PM_{10}
2000[a]	19.8	13.0	0.66
2001	19.5	14.0	0.72
2002	19.5	13.5	0.69
Average	19.6	13.5	0.69

Table 13 – Summary of rural background concentrations for London ([a] note that the 2000 average was calculated from the April – December values, as the TRAMAQ modelling only included data from these months).

Table 13 summarises the rural background concentrations for London, giving the annual averages of PM_{10} and $PM_{2.5}$ for 2000, 2001 and 2002. In addition, the fourth column of this table lists the ratio of $PM_{2.5}$ to PM_{10} values. For all years, this ratio averages to be 0.69, and this value is used in calculations to approximate the $PM_{2.5}$ emissions for the non-road sources.

4.5.2 Birmingham site

The Birmingham background concentrations were taken to be those from Harwell (no other suitable rural particulate monitoring sites were located close to Birmingham).

As for the London data, missing data values were replaced with the last 'good' value.

Year	PM_{10}	$PM_{2.5}$	$PM_{2.5}$ / PM_{10}
2000[a]	18.08	12.46	0.69
2001	18.86	14.24	0.76
2002	16.76	12.40	0.74
Average	17.90	13.03	0.73

Table 14 – Summary of rural background concentrations for Birmingham ([a] note that the 2000 average was calculated from the April – December values, as the TRAMAQ modelling only included data from these months).

Table 14 summarises the rural background concentrations for Birmingham, giving the annual averages of PM_{10} and $PM_{2.5}$ for 2000, 2001 and 2002. In addition, the fourth column of this table lists the ratio of $PM_{2.5}$ to PM_{10} values. The average of this ratio for all years 0.73; this value is used in calculations to approximate the $PM_{2.5}$ emissions for the non-traffic sources.

4.6 Additional model set up information

4.6.1 Meteorological data

For the London sites, the meteorological data have been taken from Heathrow. The Birmingham meteorological data have been taken from Birmingham Airport (Elmdon). The difference in surface roughness between the meteorological sites and the dispersion sites is accounted for in the ADMS-Urban model.

4.6.2 Diurnal profiles for emissions data

Different central, inner and outer London diurnal profiles were used for modelling the sites in London. For the Birmingham site, no such profile data were available, so the outer London profile was used.

4.6.3 Additional site data

A surface roughness of 1m was used for all sites within London, and a value of 0.75m for the Birmingham site. The minimum Monin-Obukhov length, which allows for the effect of heat production in cities (not represented by the meteorological data), is taken to be 75m in London, and 50m in Birmingham.

5 Results from dispersion modelling of London and Birmingham sites

5.1 Introduction

The section presents the concentrations modelled at the selected sites, and compares results to the monitored values. This has been done in a number of ways, including tabular format, scatter graphs, and bar charts. It is of interest not only to compare the total PM_{10}, $PM_{2.5}$ and PM_{coarse} values to the monitor data, but also to look at how each source of emission contributes to the total concentration modelled.

Section 5.1.1 below gives some information regarding the way in which the measured and modelled data have been manipulated prior to presentation in the report. A discussion of the long-term PM_{10} and $PM_{2.5}$ results is given in Section 5.2, including an investigation into the factor required to convert $PM_{2.5}$ TEOM concentrations to their gravimetric equivalent. Some short-term analyses of the results at the TRAMAQ sites is presented in Section 5.3. Source apportionment results are presented in Section 5.4, and emissions totals are discussed in Section 5.4.

5.1.1 Manipulation of monitoring and modelled concentration data

This section gives some information regarding how the monitored and modelled data have been manipulated in order to present the result. In most of the analysis presented in this report 'long-term average' concentrations have been presented. It is important to be aware of how these values have been calculated. The method depends on whether the monitor is a DEFRA or a TRAMAQ monitor.

- DEFRA monitoring data

  The monitoring data for the DEFRA sites have been downloaded from the UK National Air Quality Archive [14]. The PM_{10} and $PM_{2.5}$ monitor data for the sites of interest are hourly values. As mentioned in Section 4.5 with regard to the background concentrations used in the modelling, the PM_{10} concentrations are supplied in 'gravimetric units', whilst the $PM_{2.5}$ concentrations are given in 'TEOM units'. A factor of 1.3 has been used to convert the monitored values to gravimetric values. However, this is a significant source of uncertainty in the modelling of the $PM_{2.5}$ values, and this issue has been discussed further in Section 5.2.2 below.

  Each of the DEFRA sites has been modelled for the whole of 2002.

- TRAMAQ monitoring data

  The monitoring data for the TRAMAQ sites have been supplied as daily average values, with the approximate collection time 'around midday'. PM_{10} and $PM_{2.5}$ measurements have been taken at each of the sites for between 77 to 98 days between April 2000 and January 2002. As the same type of gravimetric monitor was used to record both the PM_{10} and $PM_{2.5}$ values (for further information please refer to [7]), no conversion factor was

applied to the $PM_{2.5}$ values prior to comparison with the modelled concentrations.

There is a significant amount of missing data at both the DEFRA and TRAMAQ sites. For the DEFRA sites, data capture is usually over 90%, although for Bloomsbury in 2002, it was less than 40%. For the TRAMAQ sites, it varies between just under 70% to 93%.

ADMS-Urban calculates concentrations for each hour. A concentration will be predicted for all hours, unless the meteorological data for a particular hour is invalid in some way. (for example, a wind speed value may not have been provided). For 2002, just less than 99.7% of hours were modelled; values for 2000 and 2001 are similar.

When comparing the modelled and monitored concentrations, it is important only to compare values when there is both a monitored and a modelled value. In addition, for the TRAMAQ sites, when 24-hour measurements have been taken, the ADMS-Urban concentrations must be averaged into 24-hourly values, covering the period up until midday.

Site	Monitor type	Monitored value	Modelled value		Ratio[a]	
			Resuspension 1A	Resuspension 2A	Resuspension 1A	Resuspension 2A
EC Roadside	TRAMAQ	39.3	39.1	38.7	1.00	0.99
EC Background	TRAMAQ	23.8	28.0	27.9	1.18	1.17
HH Roadside	TRAMAQ	38.4	42.0	41.7	1.09	1.09
HH Background	TRAMAQ	27.9	29.5	29.4	1.06	1.05
PL Roadside	TRAMAQ	35.0	47.2	46.6	1.35	1.33
PL Background	TRAMAQ	16.7	22.7	22.7	1.36	1.36
SO Roadside	TRAMAQ	25.9	24.1	24.0	0.93	0.93
SO Background	TRAMAQ	15.7	21.4	21.4	1.37	1.37
Bloomsbury	DEFRA	33.0	27.7	27.7	0.84	0.84
Marylebone Rd	DEFRA	44.6	46.3	46.3	1.04	1.03
Camden	DEFRA	30.7	29.4	29.4	0.96	0.95
Haringey	DEFRA	27.4	26.7	26.7	0.97	0.97
A3	DEFRA	23.9	27.5	27.5	1.15	1.14
Bexley	DEFRA	25.0	22.2	22.2	0.89	0.88
Brent	DEFRA	24.5	22.0	22.0	0.90	0.90
Hillingdon	DEFRA	24.7	25.1	25.1	1.01	1.01
N Kensington	DEFRA	25.3	24.5	24.5	0.97	0.97
Average[b]		**28.3**	**29.7**	**29.6**	**1.06**	**1.06**

Table 15 – Summary of long-term average PM_{10} concentrations for resuspension emission scenarios 1A and 2A (µg/m³, [a] Modelled value / Monitored value, [b] Note that the value given in the ratio column is the 'average of the ratios', not the 'ratio of the averages').

5.2 Long-term PM_{10} and $PM_{2.5}$ concentrations

The modelled and monitored concentrations of PM_{10} and $PM_{2.5}$ at sites 1-13 are presented in Tables 15 and 16 respectively. Table 15 gives the PM_{10} modelled value for resuspension emission scenarios 1A and 2A (columns 4 and 5), and the ratio of the modelled to observed concentrations for each case (columns 6 and 7); Table 16 gives the $PM_{2.5}$ modelled value in column 4, and the ratio of modelled to observed concentration in column 5. Figures 2 and 3 show these results as scatter plots.

Site	Monitor type	Monitored value	Modelled value	Ratio[a]
EC Roadside	TRAMAQ	28.8	29.5	1.02
EC Background	TRAMAQ	15.8	20.5	1.30
HH Roadside	TRAMAQ	26.1	30.6	1.17
HH Background	TRAMAQ	17.9	20.6	1.15
PL Roadside	TRAMAQ	21.6	33.6	1.55
PL Background	TRAMAQ	10.4	16.1	1.54
SO Roadside	TRAMAQ	16.7	16.5	0.99
SO Background	TRAMAQ	9.0	14.6	1.63
Bloomsbury	DEFRA	17.8	18.6	1.05
Marylebone Rd	DEFRA	28.0	32.4	1.16
Average		**19.2**	**23.3**	**1.26**

Table 16 – Summary of long-term $PM_{2.5}$ concentrations (µg/m³, Modelled value / Monitored value, [b] Note that the value given in the ratio column is the 'average of the ratios', not the 'ratio of the averages').

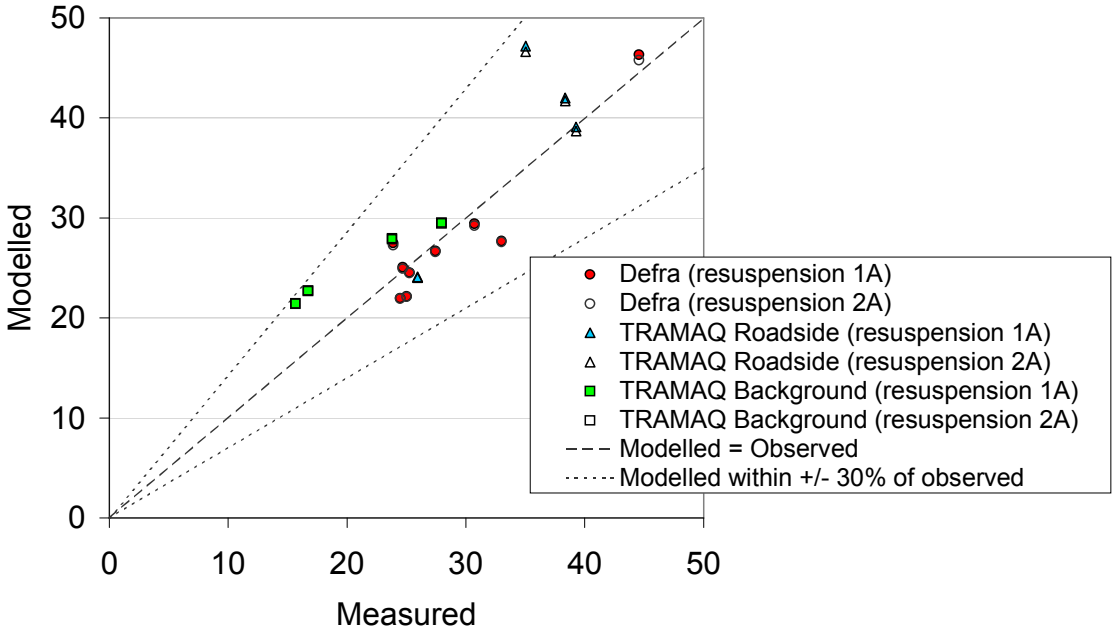

Figure 2 – Long-term average PM_{10} concentrations at all sites.

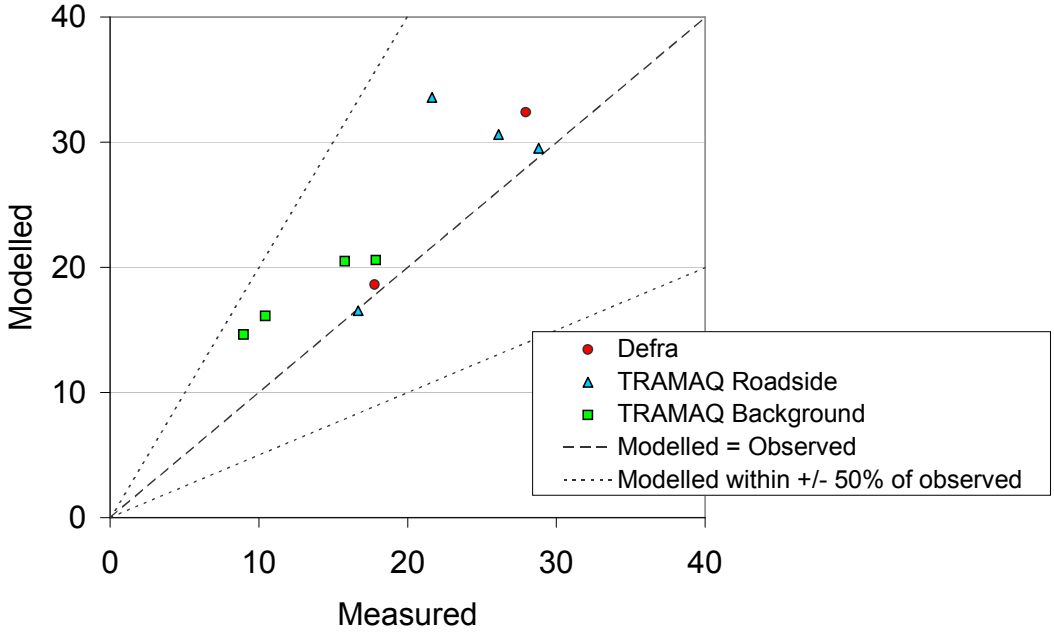

Figure 3 – Long-term average $PM_{2.5}$ concentrations at all sites.

5.2.1 Discussion of long-term PM_{10} and $PM_{2.5}$ concentrations

Including the non-exhaust particulate emission factors in the ADMS-Urban dispersion model leads to good predictions of monitored PM_{10} values in almost all cases. Using the resuspension emission scenario 1A values, on average, the ratio of the modelled to observed concentrations is just over 1.06 (and just under this value for emission scenario 2A) *i.e.* there is no significant difference between the two emission scenarios.

The model generally over predicts the $PM_{2.5}$ values, by an average of 26%. As the accuracy of the dispersion modelling of PM_{10} and $PM_{2.5}$ must be approximately the same, this is possibly be due to the fact that the emission factors for $PM_{2.5}$ are less accurate than the corresponding factors for PM_{10}. Alternatively, the model overestimation may be due to the factors used to convert the TEOM measured / background concentrations to gravimetric values. That is:

- A factor of 1.3 has been used to convert the monitored $PM_{2.5}$ rural background from TEOM to gravimetric units, to be used in the dispersion modelling (refer to Section 4.5) and

- A factor of 1.3 has been used to convert the monitored $PM_{2.5}$ concentration data from TEOM to gravimetric units for the DEFRA sites only (refer to Section 5.1.1).

Regression analysis regarding this conversion factor has been performed in Section 5.2.2 below. **However, the results from this analysis have not been applied in the subsequent modelling. That is, all concentration results presented in the remainder of the report use the 1.3 conversion factor.**

5.2.2 Investigation of the $PM_{2.5}$ TEOM to gravimetric conversion factor

If it is assumed that the accuracy of the $PM_{2.5}$ and PM_{10} emissions estimates using in the modelling are similar, and that the dispersion characteristics of the pollutants are the same, then the ratio of the modelled to measured concentrations of $PM_{2.5}$ and PM_{10} should be the same at each site.

An investigation was performed using the data from the two DEFRA sites that measure $PM_{2.5}$ as well as PM_{10} (Marylebone Road and Bloomsbury), and all of the TRAMAQ sites. A wide range of conversion factors were applied to the background concentrations, and additionally for the DEFRA sites, to the measured data.

Assumed conversion factor for $PM_{2.5}$ TEOM concentrations	Average ratio of (Total modelled $PM_{2.5}$/Measured $PM_{2.5}$) to (Total modelled PM_{10}/Measured PM_{10})		
	DEFRA sites	TRAMAQ sites	All sites
0.8	1.49	0.82	0.95
0.9	1.40	0.88	0.98
1	1.33	0.93	1.01
1.1	1.27	0.99	1.05
1.2	1.22	1.05	1.08
1.3	1.18	1.11	1.12
1.4	1.15	1.16	1.16
1.5	1.11	1.22	1.20
1.6	1.09	1.28	1.24
1.7	1.06	1.34	1.28
1.8	1.04	1.39	1.32
1.9	1.02	1.45	1.36
2	1.01	1.51	1.41
2.1	0.99	1.57	1.45

Table 17 – Investigation into conversion factors for $PM_{2.5}$ TEOM concentrations.

Table 17 summarises the initial results of this investigation. The first column gives the conversion factor used in the calculations. The second and third columns give the average ratio of (Total modelled $PM_{2.5}$/Measured $PM_{2.5}$) to (Total modelled PM_{10}/Measured PM_{10}) for the DEFRA and TRAMAQ sites respectively. The final columns give the average of this ratio for all sites. Note that a ratio of unity is expected if the dispersion of PM_{10} and $PM_{2.5}$ is the same.

These calculations predict very different conversion factors using the data from the DEFRA sites, compared to the TRAMAQ sites. That is, the DEFRA sites require a conversion factor of just over 2.0, whereas the TRAMAQ sites require a value of 1.12. The average for all sites is just under 1.0.

The reason for the increase in ratio with TEOM factor for the DEFRA sites, and the decrease in ratio with TEOM factor for the TRAMAQ sites is merely a consequence of the fact that the $PM_{2.5}$ TEOM conversion factor has only been used to convert the background value at the TRAMAQ monitors, but both the background and the measured values at the DEFRA monitors. However, this investigation leads us to propose that it

may be appropriate to use a different conversion factor for the background $PM_{2.5}$ and the local $PM_{2.5}$.

The calculations at the DEFRA sites were repeated by calculating the following ratio:

$$\frac{\text{Modelled concentrations} + 1.12 \times \text{Rural background}}{\beta(\text{Measured concentrations - Rural background}) + 1.12 \times \text{Rural background}}$$

where different values of β were assessed to find which gave the closest match to the PM_{10} Total modelled/Measured concentrations. For Marylebone road, this value is 1.59, whereas for Bloomsbury it is over 2. Analysis in a subsequent section of this report (Section 5.4.2) indicates that is it likely that at Bloomsbury there is an intermittent source of coarse particulates, which have not been included in the modelling. If this is the case, then the above analysis for Bloomsbury will be incorrect, and it would be more valid to consider the factor derived from the Marylebone Road data.

Therefore, applying $PM_{2.5}$ TEOM conversion factors of 1.12 and 1.59 to the rural and local TEOM concentrations leads to a $PM_{2.5}$ model overestimate of 4% at Marylebone Road (*i.e.* the same as for PM_{10}), but to an almost exact model prediction at Bloomsbury.

The above analysis has made some significant assumptions, in particular regarding the relative accuracy of the PM_{10} and $PM_{2.5}$ emissions and very few data points have been used in the calculations. Therefore, reliable conclusions cannot be drawn. For the remainder of the results presented in this report, the usual $PM_{2.5}$ TEOM conversion factor of 1.3 has been applied and, as mentioned in Section 5.2.1 above, this leads to model overestimation of the $PM_{2.5}$ measurements.

5.3 Short-term analysis of the TRAMAQ results

Whilst this report generally focuses on the long-term results, it is also of interest to compare results over shorter time scales. As mentioned previously, the TRAMAQ data were recorded as daily average PM_{10} and $PM_{2.5}$ values, and the corresponding modelled concentrations have been calculated. Tables 18 and 19 below show a number of statistical parameters for the PM_{10} and $PM_{2.5}$ results, specifically the:

- Mean (a dimensional measure of the average)
- Variance (a dimensional measure of the spread of the data)
- Normalised Mean Square Error (NMSE – a non-dimensional measure of the overall error, with the most accurate results giving a value of 0)
- Correlation (a non-dimensional measure of the 'pattern' of results, with the most accurate results giving a value of 1.0)
- Within a factor of 2 (a non-dimensional measure of the magnitude of results, with the most accurate results giving a value of 1.0)

It would be possible to spend a long time analysing these results in relation to the accuracy of each of the modelling set ups. For example, although the mean modelled value at High Holborn is an overestimate for both the roadside and background sites, for PM_{10} and $PM_{2.5}$, the remaining statistics (variance, NMSE, correlation and within a factor of 2) are very good. This implies that there are a few experiments where the modelled value overestimates the measured concentration, but in general, results are good. The likely reason for a few high modelled concentrations may be due to an inaccurate rural background value for certain hours.

Conversely, the model overestimate at Park Lane gives generally bad statistics compared to all other sites. This implies that there is something wrong with the model set up or emissions.

Although it would be possible to perform similar analyses using the DEFRA monitoring data, those results have not been presented in the current study.

Location		Concentration type	Mean	Variance	NMSE	Correlation	Within a factor of 2
Elephant and Castle	Roadside	Measured	39.3	20.4	0.00	1.00	1.00
		Modelled (1A)	39.1	11.6	0.29	0.23	0.83
		Modelled (2A)	38.7	11.5	0.29	0.23	0.87
	Background	Measured	23.8	12.8	0.00	1.00	1.00
		Modelled (1A)	28.0	9.4	0.25	0.44	0.86
		Modelled (2A)	27.9	9.3	0.24	0.44	0.87
High Holborn	Roadside	Measured	38.4	16.8	0.00	1.00	1.00
		Modelled (1A)	42.0	16.7	0.12	0.69	0.94
		Modelled (2A)	41.7	16.6	0.12	0.69	0.94
	Background	Measured	28.0	15.5	0.00	1.00	1.00
		Modelled (1A)	29.5	12.8	0.02	0.67	0.89
		Modelled (2A)	29.4	12.7	0.17	0.67	0.90
Park Lane	Roadside	Measured	35.0	22.4	0.00	1.00	1.00
		Modelled (1A)	47.2	12.0	0.45	0.10	0.59
		Modelled (2A)	46.5	11.8	0.44	0.10	0.62
	Background	Measured	16.7	9.4	0.00	1.00	1.00
		Modelled (1A)	22.8	8.2	0.29	0.53	0.75
		Modelled (2A)	22.7	8.2	0.29	0.53	0.77
Selly Oak	Roadside	Measured	25.9	10.7	0.00	1.00	1.00
		Modelled (1A)	24.1	7.4	0.19	0.33	0.92
		Modelled (2A)	24.0	7.4	0.19	0.34	0.93
	Background	Measured	15.7	8.6	0.00	1.00	1.00
		Modelled (1A)	21.4	7.2	0.36	0.31	0.77
		Modelled (2A)	21.4	7.2	0.36	0.31	0.77

Table 18 – Summary of PM_{10} short-term statistics for the TRAMAQ sites.

Location		Concentration type	Mean	Variance	NMSE	Correlation	Within a factor of 2
Elephant and Castle	Roadside	Measured	28.8	17.7	0.00	1.00	1.00
		Modelled	29.5	9.9	0.32	0.41	0.81
	Background	Measured	15.8	11.1	0.00	1.00	1.00
		Modelled	20.5	7.5	0.40	0.42	0.61
High Holborn	Roadside	Measured	26.1	14.3	0.00	1.00	1.00
		Modelled	30.6	13.7	0.15	0.74	0.92
	Background	Measured	17.6	13.3	0.00	1.00	1.00
		Modelled	21.0	10.7	0.26	0.72	0.80
Park Lane	Roadside	Measured	21.6	13.8	0.00	1.00	1.00
		Modelled	33.6	9.6	0.48	0.29	0.55
	Background	Measured	10.4	7.7	0.00	1.00	1.00
		Modelled	16.1	7.2	0.44	0.62	0.58
Selly Oak	Roadside	Measured	16.7	8.5	0.00	1.00	1.00
		Modelled	16.5	5.6	0.24	0.39	0.86
	Background	Measured	9.0	6.2	0.00	1.00	1.00
		Modelled	14.6	5.5	0.56	0.41	0.66

Table 19 – Summary of $PM_{2.5}$ short-term statistics for the TRAMAQ sites.

5.4 Source apportionment of PM_{10}, $PM_{2.5}$ and PM_{coarse} results

5.4.1 Introduction

The total concentration at a particular location consists of contributions from a number of different sources. In this study, the modelled concentration have been calculated by summing the contributions from the following sources:

- Exhaust emissions
- Tyre wear emissions
- Brake wear emissions
- Road wear emissions
- Resuspension emissions
- Other source emissions
- Background concentrations

5.4.2 Source apportionment results for PM_{10} and $PM_{2.5}$

The PM_{10} results for all sites considered for resuspension emission scenarios 1A and 2A are presented in Figures 4 and 5 respectively.

As would be expected when considering particulate concentrations, a significant proportion of the concentration consists of the background concentration advected in from outside the urban area. (Note that the reason that the background contribution is not constant at each site is because the long-term average concentrations have been calculated based on hours where there was both a valid measured and modelled value – as discussed in Section 5.1.1.) At roadside sites, there is also a significant contribution to the concentration from the traffic emissions (see for example, Marylebone Road and the TRAMAQ roadside sites). Looking at the results in this way, the non-exhaust contribution to the total traffic concentration is between 30 and 50% at all sites. The results shown in Tables 20 and 21 support this – these tables summarise the percentage contribution to the modelled concentrations from traffic sources, for resuspension emission scenarios 1A and 2A respectively.

It is likely that the lack of a detailed emissions inventory for the Birmingham area has resulted in an inaccurate prediction of the concentrations at the Selly Oak TRAMAQ site. This has been deduced from the fact that the modelled concentrations at the roadside and background sites are quite similar, whereas there is a much greater variation in the measured values. Indeed, the fact that the rural background concentrations exceed the measured concentrations at the Selly Oak background site implies the model set up could be improved, if appropriate information were available.

Figure 5 shows the source apportionment results for $PM_{2.5}$. As for the PM_{10} concentrations, a significant proportion of the modelled value is made up of the background value, in particular for the background sites. The remaining concentration consists mainly of the exhaust contribution, as the emissions from non-exhaust $PM_{2.5}$

traffic sources is much lower than for PM_{10} *i.e.* most of the non-exhaust particulate emissions are coarse. This leads to Figures 7 and 8, which show the source apportionment results for the coarse fraction, for resuspension emission scenarios 1A and 2A respectively.

Inspection of Figures 6 and 7 (or 8) together indicate that at a site such as Bloomsbury, where the $PM_{2.5}$ concentration is very well predicted, but the coarse fraction is significantly underestimated, there is likely to be an intermittent local source of coarse particulates, such as a construction site. This may also be the case for the roadside Selly Oak site, as it is known that there is an incinerator relatively close to this monitor (the location and emissions for this source of PM emissions were *not* made available by the Environmental Protection Unit of Birmingham City Council).

In general, Figures 6, 7 and 8 show that the modelled $PM_{2.5}$ values are overestimates, whereas the coarse fractions are underestimates. As was discussed in Section 5.2.2, this may be related to the uncertainty in the conversion factor of $PM_{2.5}$ TEOM measured values to gravimetric values.

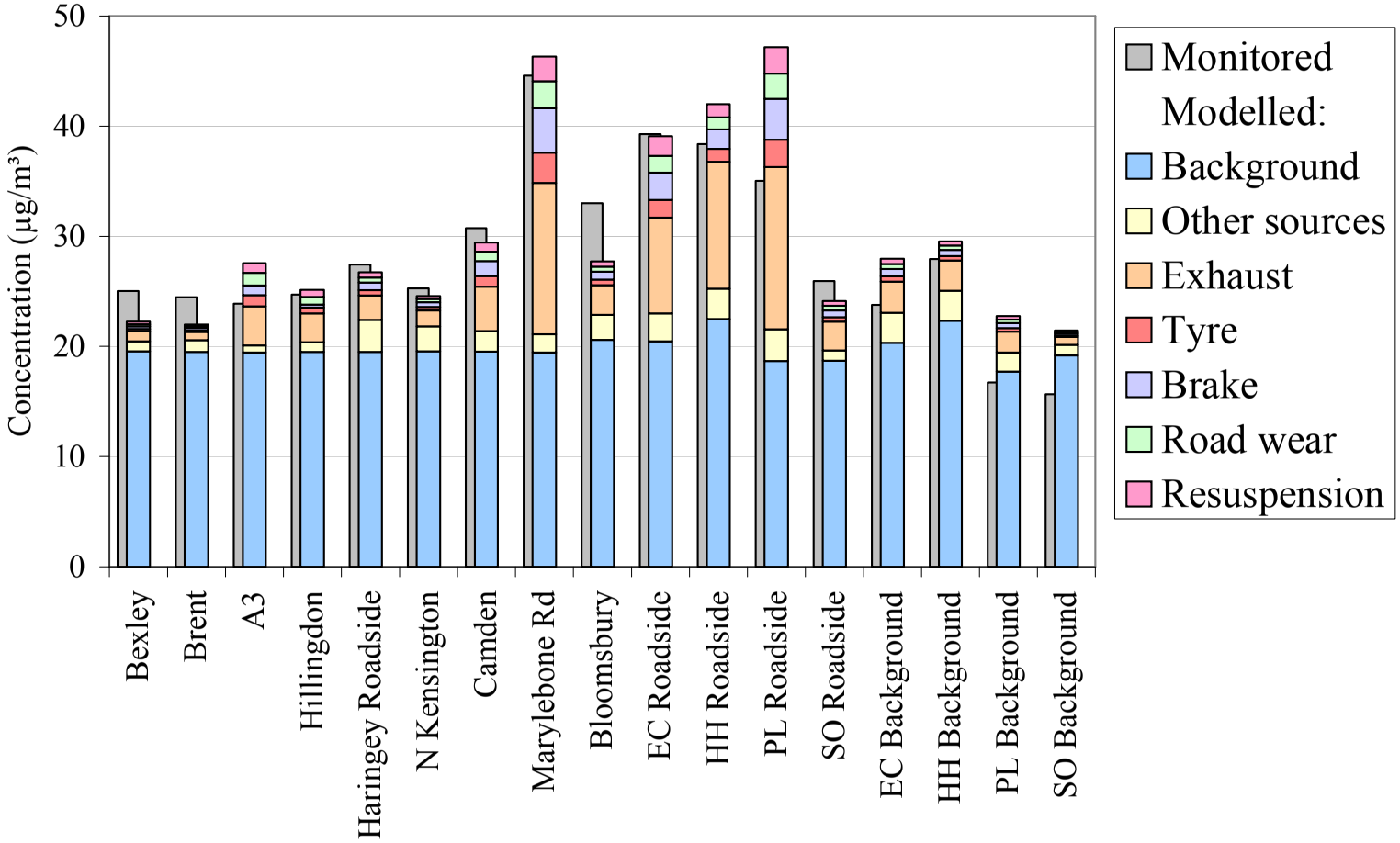

Figure 4 – Source apportionment of PM_{10} results (resuspension scenario 1A values).

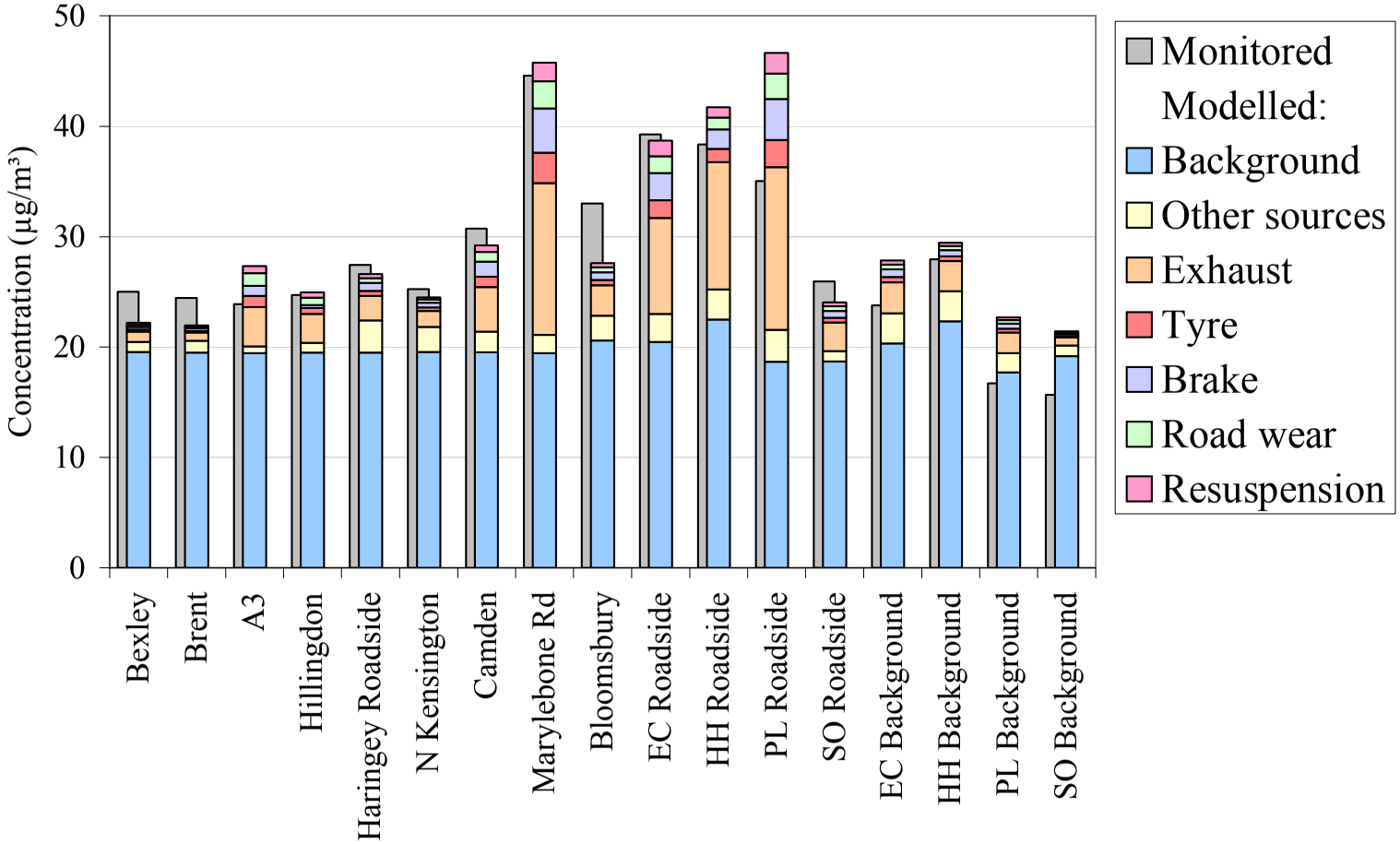

Figure 5 – Source apportionment of PM_{10} results (resuspension scenario 2A values).

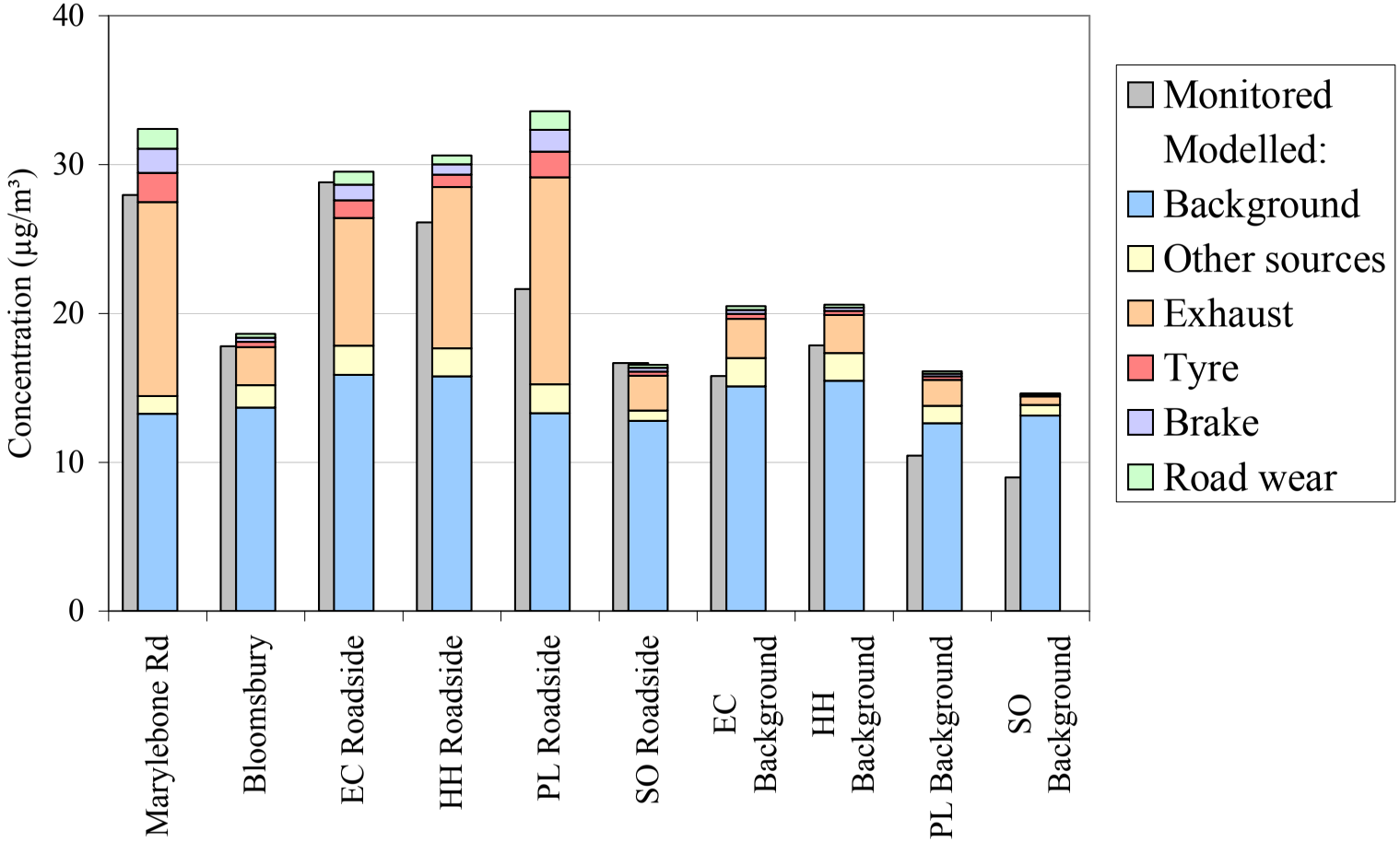

Figure 6 – Source apportionment of $PM_{2.5}$ results.

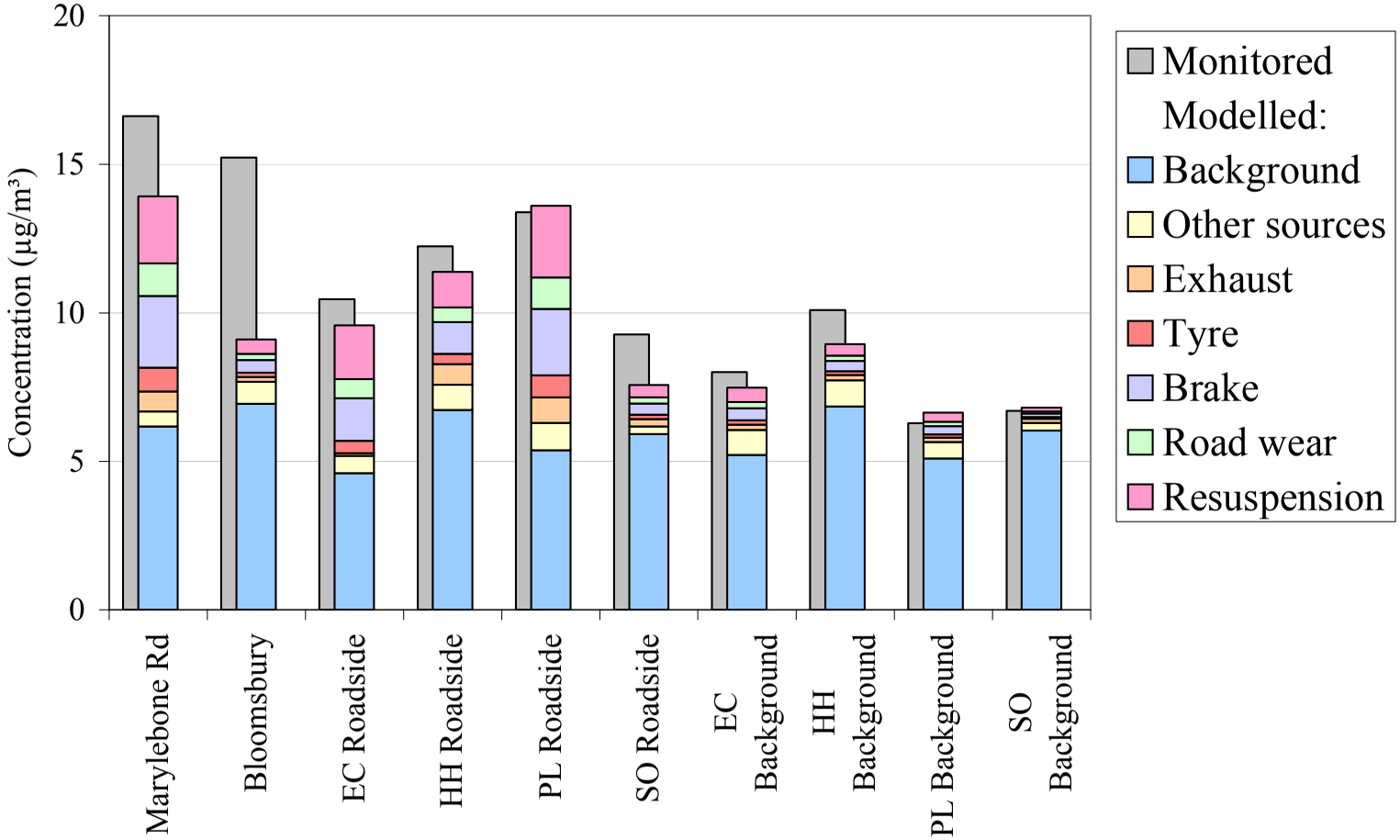

Figure 7 – Source apportionment of PM_{coarse} results (resuspension scenario 1A values).

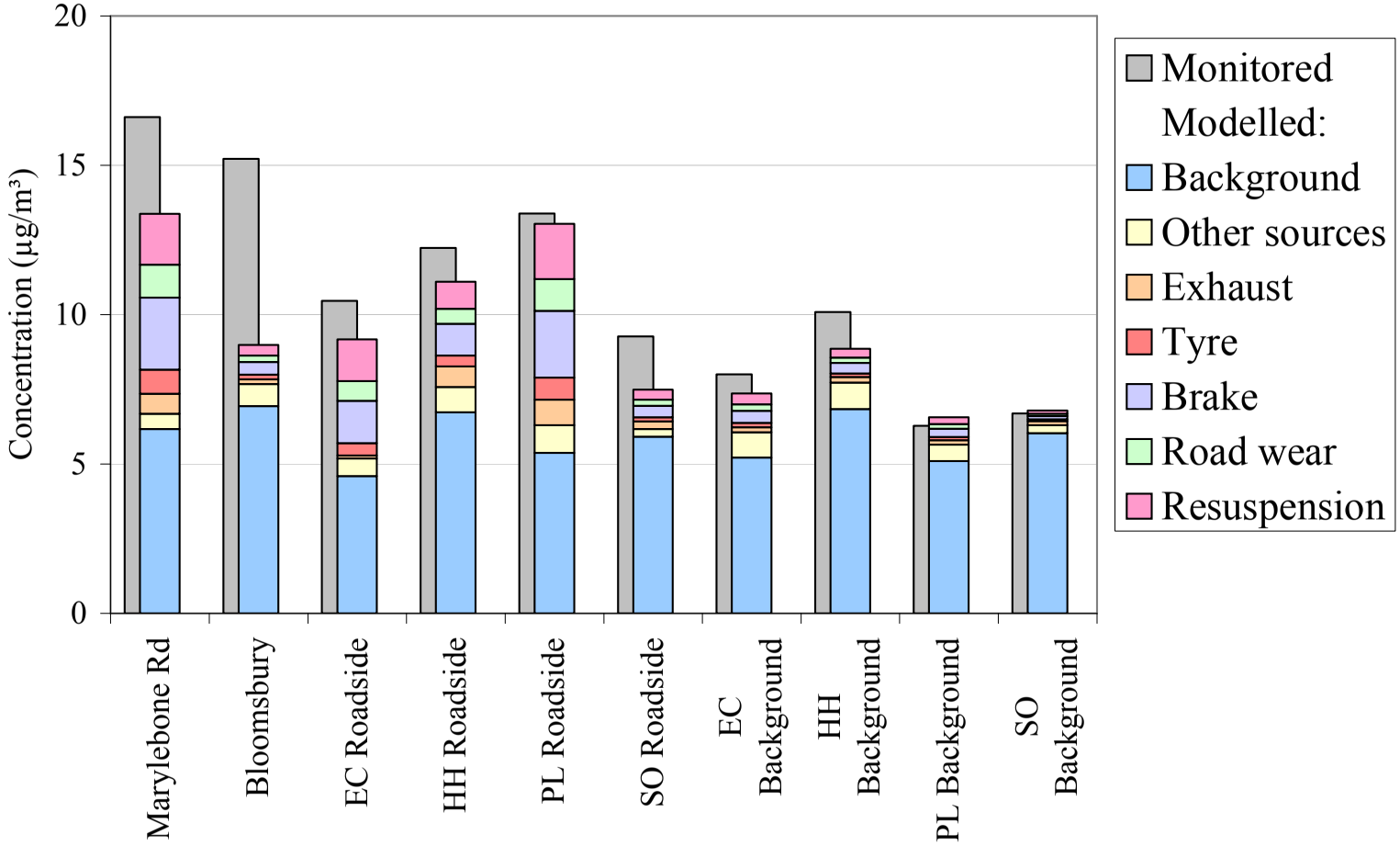

Figure 8 – Source apportionment of PM_{coarse} results (resuspension scenario 2A values).

Traffic source	PM_{10}			$PM_{2.5}$			PM_{coarse}		
	Mean (%)	Minimum (%)	Maximum (%)	Mean (%)	Minimum (%)	Maximum (%)	Mean (%)	Minimum (%)	Maximum (%)
Exhaust	55	47	69	76	73	84	14	2	27
Tyre	11	7	14	9	6	11	10	9	11
Brake	14	6	17	8	5	9	29	23	33
Road wear	10	6	15	7	5	8	15	13	15
Resuspension	10	7	14	n/a	n/a	n/a	32	25	41

Table 20 – Percentage contribution to modelled concentrations from traffic sources (resuspension scenario 1A values).

Traffic source	PM_{10}			$PM_{2.5}$			PM_{coarse}		
	Mean (%)	Minimum (%)	Maximum (%)	Mean (%)	Minimum (%)	Maximum (%)	Mean (%)	Minimum (%)	Maximum (%)
Exhaust	57	49	70	76	73	84	15	2	28
Tyre	11	7	14	9	6	11	11	10	12
Brake	14	6	18	8	5	9	31	23	36
Road wear	10	7	16	7	5	8	16	14	17
Resuspension	8	6	11	n/a	n/a	n/a	27	23	35

Table 21 – Percentage contribution to modelled concentrations from traffic sources (resuspension scenario 2A values).

5.4.3 Analyses of concentrations from traffic sources

Tables 20 and 21 summarise the PM_{10}, $PM_{2.5}$ and PM_{coarse} concentrations for all sites considered, for resuspension emission scenarios 1A and 2A respectively. The mean contribution is shown, along with the minimum and maximum values.

These tables show that on average, for the sites considered, the non-exhaust contribution to the PM_{10} concentration is approximately 45%. Further breakdown of this concentration shows that the $PM_{2.5}$ concentration is just under a quarter non-exhaust values, whilst the PM_{coarse} concentration is over 85% non-exhaust. These average values have been displayed as pie charts for resuspension emission scenario 1A in Figures 9, 10 and 11 for PM_{10}, $PM_{2.5}$ and PM_{coarse} respectively.

The range of values shown in Tables 20 and 21 are of interest. As indicated by the source apportionment graphs shown in the previous section, the non-exhaust contribution to the total concentration due to traffic varies considerably from site to site. This proportion depends on the traffic composition in terms of the different vehicle types on the road; this is investigated further in Section 6, using some simplified roads, with different traffic compositions to represent a major and a minor road within an urban area.

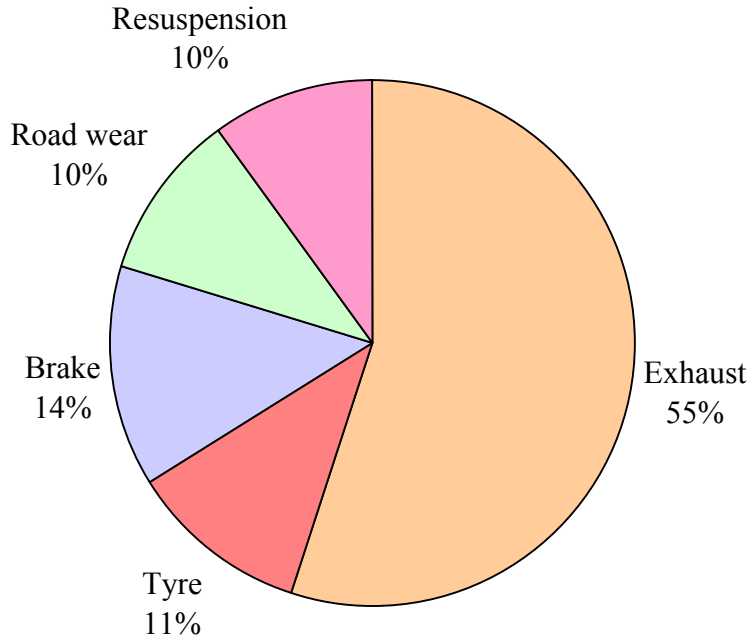

Figure 9 – Pie chart showing PM_{10} mean percentage contribution to modelled concentrations from traffic sources (resuspension emission scenario 1A value).

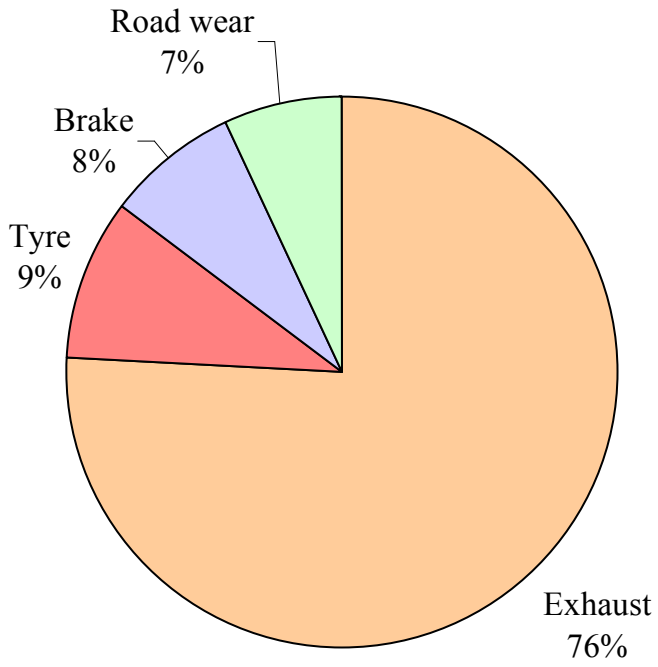

Figure 10 – Pie chart showing $PM_{2.5}$ mean percentage contribution to modelled concentrations from traffic sources.

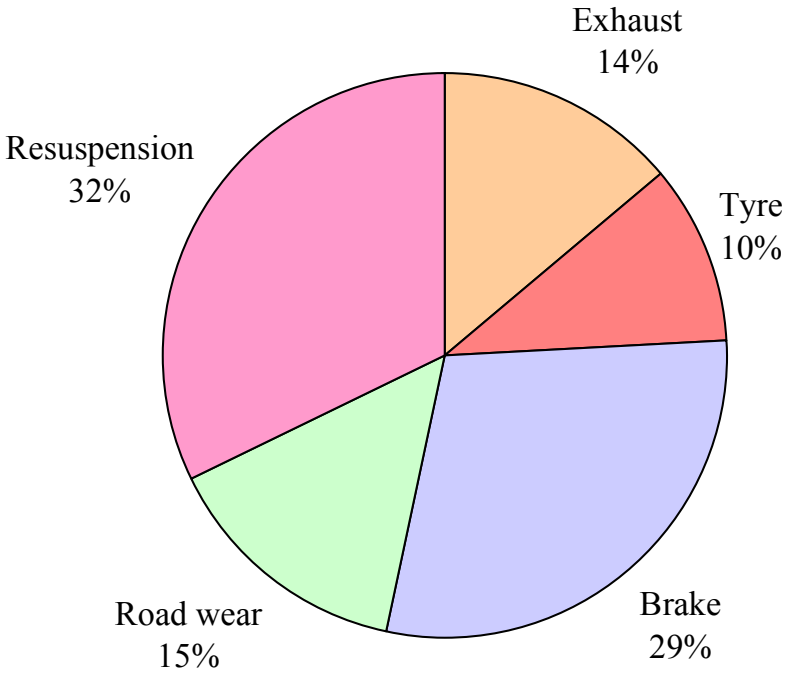

Figure 11 – Pie chart showing PM_{coarse} mean percentage contribution to modelled concentrations from traffic sources (resuspension emission scenario 1A value).

5.5 Revisiting the emissions

Finally, it is of interest to consider the relationship between the emissions and the modelled concentrations. For this analysis, only the London area has been considered, as the emissions inventory for the Birmingham region is incomplete.

Figure 12 shows the emissions totals for 2002 for resuspension emission scenario 1A; PM_{10}, $PM_{2.5}$ and PM_{coarse} emissions are shown, apportioned into the 5 traffic source emissions, and 'other source' emissions. The relationship between the emissions shown in this chart is similar to that we have seen in the concentration results. Obviously, this is expected to some extent within the traffic sources, as the emissions are modelled in the same way for each source type.

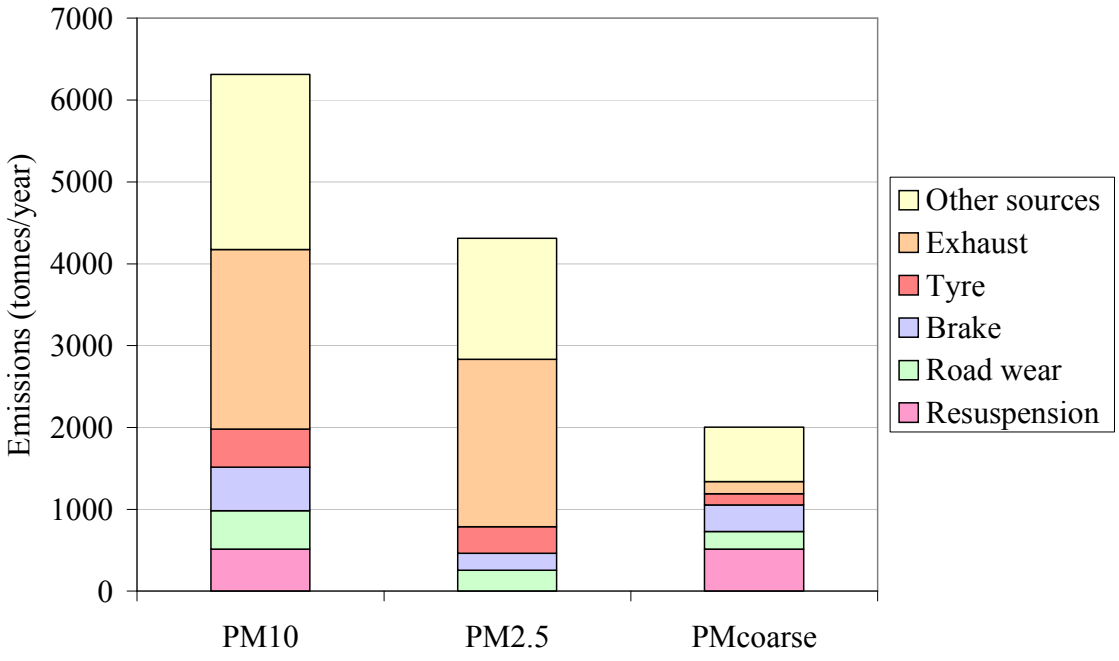

Figure 12 – Emissions totals for London for 2002 for resuspension scenario 1A (note that emissions total vary between years, and for the different scenarios considered).

The traffic emission totals have been presented as pie charts in Figures 13, 14 and 15 for PM_{10}, $PM_{2.5}$ and PM_{coarse} respectively. These figures can be compared to the corresponding source apportionment figures (9, 10, 11). The similarity is surprising, recalling that the concentration charts are an average over a relatively few sites in London, whilst the emission totals cover the whole London area. The relationship between emissions and concentrations is further investigated in Section 6 below.

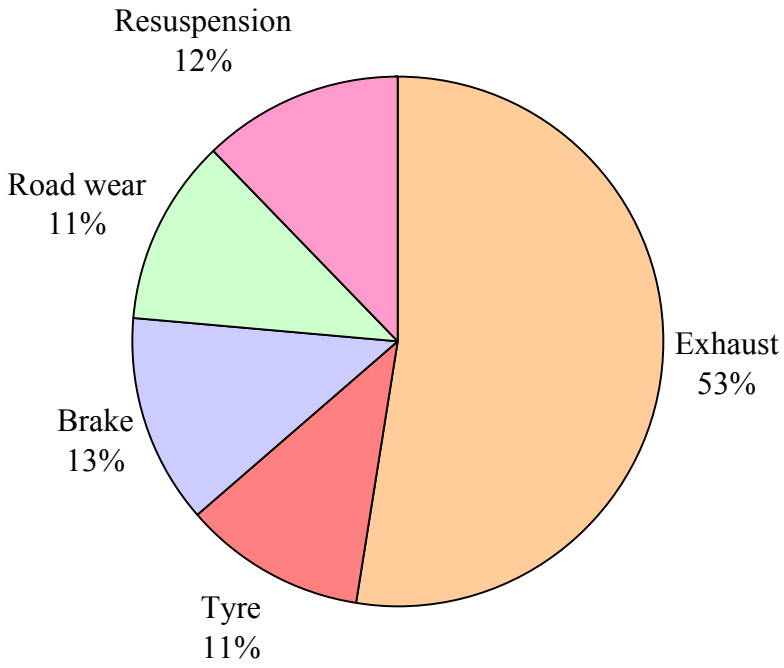

Figure 13 – Pie chart showing PM_{10} traffic sources emission totals for London 2002 (resuspension scenario 1A value).

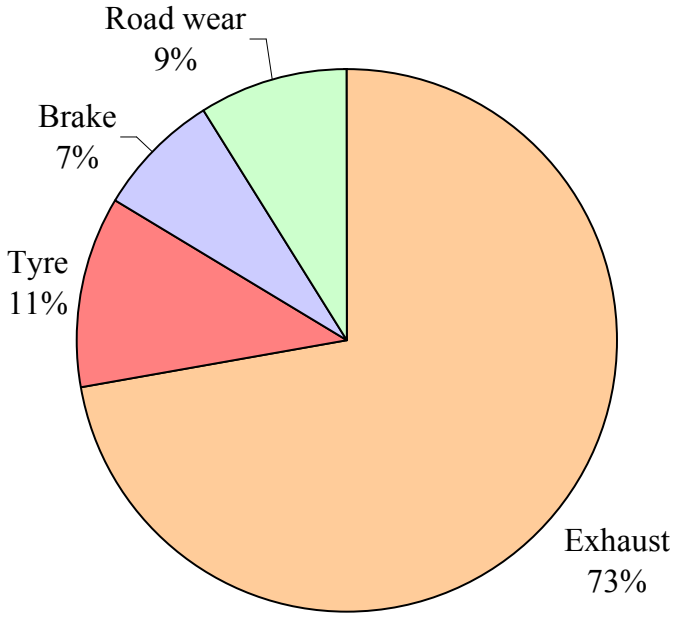

Figure 14 – Pie chart showing $PM_{2.5}$ traffic sources emission totals for London 2002.

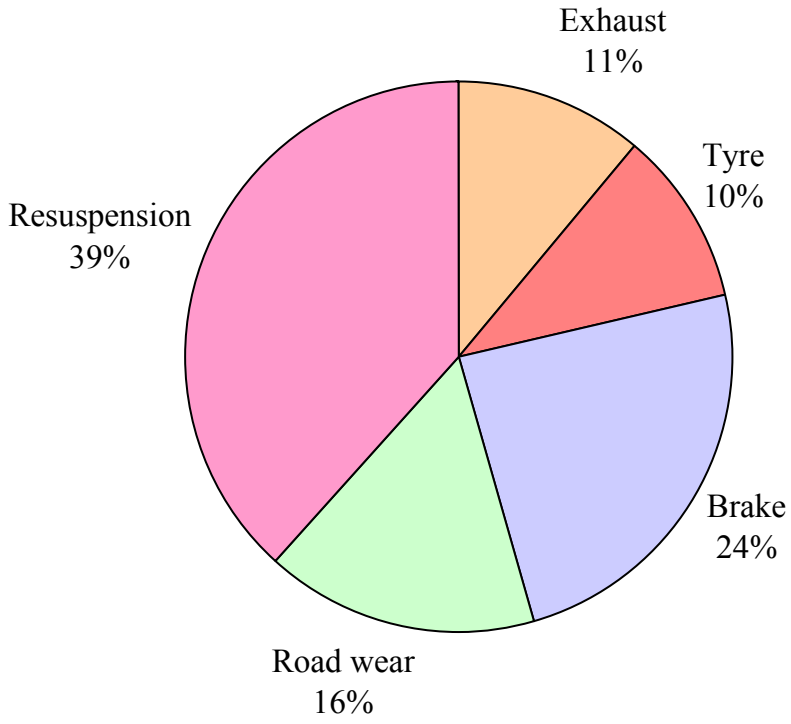

Figure 15 – Pie chart showing PM_{coarse} traffic sources emission totals for London 2002 (resuspension scenario 1A value).

6 Further investigations using idealised roads

6.1 Introduction

The results presented in Section 5 indicate that, in general, when the emissions estimates described in Section 2 are modelled using ADMS-Urban, the predicted PM_{10} concentrations compare well with monitored values. $PM_{2.5}$ concentrations seem to be overestimated, and PM_{coarse} underestimated, but this may well be due to the problems with converting the $PM_{2.5}$ monitored measurements from TEOM to gravimetric units, as discussed in Section 5.2.1.

However, a number of questions have arisen during this work, and some of these will be addressed in this section. These include:

- How do emissions and concentrations vary between road types, for example between major and minor roads? (Section 6.3)
- What proportion of the concentrations is from light vehicles as opposed to heavy vehicles? (Section 6.3)
- Is it correct to model the near-source characteristics of exhaust and non-exhaust traffic emissions in the same way? If not, what effect does it have on results? (Section 6.4)

Further questions that have not been investigated fully in this section are discussed in Section 8, 'Further Work'.

For the purposes of these investigations, it has been assumed that ADMS-Urban can be used to predict relatively accurate concentrations. Therefore, rather than consider one of the sites selected for dispersion modelling in the previous sections, idealised roads are used in this part of the study. One of the advantages of this approach is that the variation of concentrations across the road can be investigated.

6.2 Idealised road model set up

For these investigations, both a minor and a major road were modelled. The minor road, was taken to have traffic flows given in Table 12; the major road was an example London main road. For this investigation, St Giles at High Holborn was taken to be an example main road, with 19% heavy vehicles. Although this is a high proportion of heavy vehicles, with the average in London being closer to 9%, it is useful as a 'worst case' example.

Both roads are taken to have a traffic flow of 10 000 vehicles per day, and have the same dimensions (2km in length, road width 10m, no canyon). The speed on the minor roads was taken to be 30km/hr and 40km/hr on the major road. The exhaust and non-exhaust traffic emissions from these roads are modelled component by component, as for the source apportionment calculations described in Section 5.4 above. In addition, the emissions from light vehicles are modelled separately from those for heavy vehicles.

One year of meteorological data was considered; this was taken to be Heathrow 2002. The other model parameters were taken to be the same as described in the dispersion model set up, Section 4.

6.3 Variation of emissions and concentrations for different road types

Section 6.3.1 discusses the emissions from the example major and minor roads, and Section 6.3.2 discusses the corresponding resultant long-term concentrations.

6.3.1 Emissions from the example major and minor road

Both roads studied were assumed to have traffic flows of 10 000 per day. As the traffic composition for each road is different, the resultant total emissions are different, with the major road having higher concentrations due to the higher proportion of heavy vehicles. However, for the purposes of these investigations, it is the relative contribution of emissions to the different traffic source categories that are of interest, so results are presented relative to the total emissions for each road.

Figures 16, 17 and 18 show the relative emissions for the example major and minor roads for PM_{10}, $PM_{2.5}$ and PM_{coarse} respectively. Results for all vehicles, and for the heavy and light fraction are shown separately.

Figure 16 shows that for the major road, with the higher proportion of heavy vehicles, emissions consist of over 60% from heavy vehicle emissions; the heavy vehicles on the minor road contribute around 20% of the emissions. The spread between the different traffic emissions within the heavy vehicle emissions is approximately the same for both major and minor roads; this is also true for the light fraction. As expected, there is a much smaller contribution from resuspension emissions for light vehicles. However, it is interesting to note that the proportion of non-exhaust emissions from light vehicles actually exceeds that from heavy vehicles. This may be contrary to expectation, but can be explained by the relative light and heavy emissions, which are summarised in Table 22. This table shows that for exhaust emissions, light vehicle emissions are about a tenth of heavy vehicle emissions. This fraction is significantly lower than for tyre, brake and road wear, where light emissions vary between 20% and 31% of the heavy emissions. Therefore, on a road such as the minor road where the traffic is made up mostly of light vehicles, the proportion of non-exhaust emissions is more significant than on a road with more heavy vehicles.

Figure 17 shows the $PM_{2.5}$ emissions from the example major and minor roads. This figure also shows the considerable contribution to emissions from heavy vehicles on the major roads, although the percentage contribution is slightly reduced relative to the PM_{10} emissions, due to the fact that resuspension emissions do not have a fine fraction. As seen in previous $PM_{2.5}$ emissions investigations, the exhaust emissions contribute significantly to the total emission. Also, as seen in the corresponding PM_{10} figure, the non-exhaust contribution on the minor roads exceeds that on the major roads, due to the relatively low light vehicle exhaust emissions.

Finally, Figure 18 shows the PM_{coarse} emissions from the example major and minor roads. The relatively small contribution to coarse emissions from exhaust is clearly seen, and for this fraction, the non-exhaust contribution on each of the roads is similar.

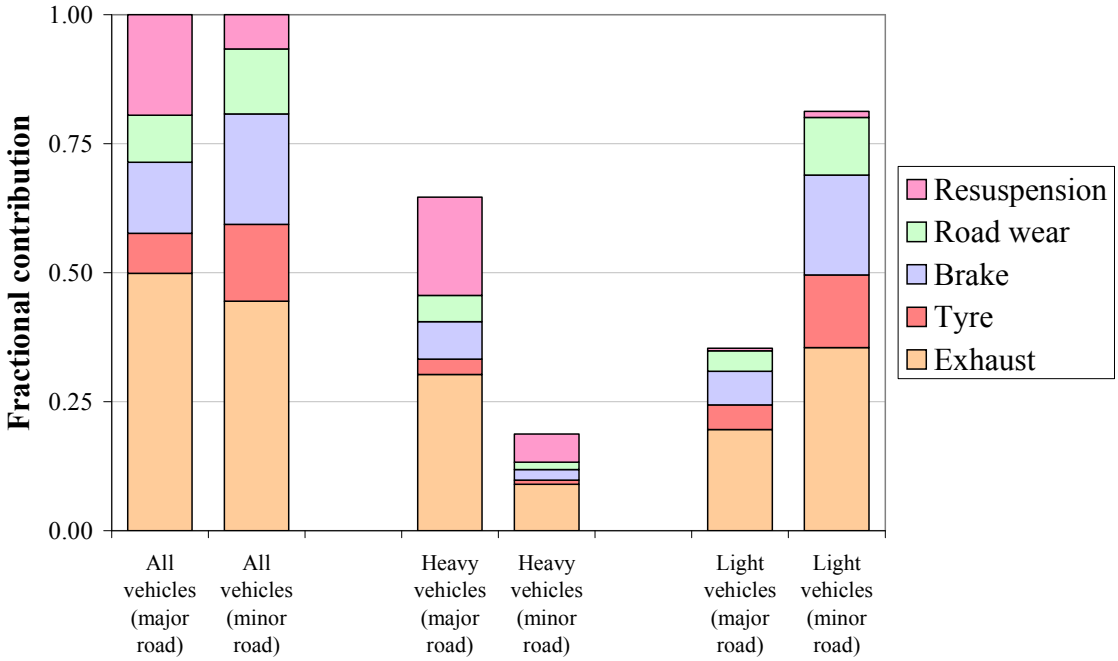

Figure 16 – Relative PM_{10} emissions for the example major and minor roads, for all vehicles, and the heavy and light fraction separately.

Traffic source	Representative emission factors at 35km/hr (mg/km) [a]		Ratio Light / Heavy
	Heavy	Light	
Exhaust	214.3	21.2	0.10
Tyre	37.5	11.5	0.31
Brake	53.6	15.7	0.29
Road wear	38.0	7.5	0.20
Resuspension 1A	141.0	0.8	0.01
Resuspension 2A	116.0	0.0	0.00

Table 22 – Summary of representative emission factors from the various traffic emission sources ([a] the exhaust emissions are for a typical urban road, the tyre, brake and road wear emissions have been calculated from the EMEP factors neglecting emissions from motorcycles, and the resuspension emission factors are from Table 3).

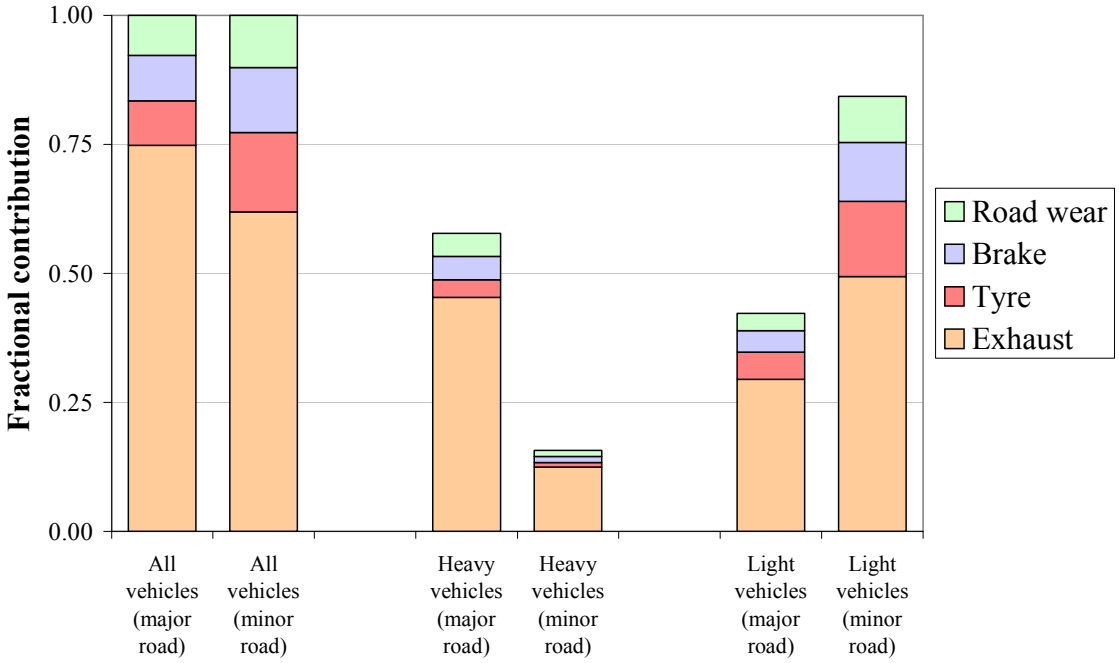

Figure 17 – Relative $PM_{2.5}$ emissions for the example major and minor roads, for all vehicles, and the heavy and light fraction separately.

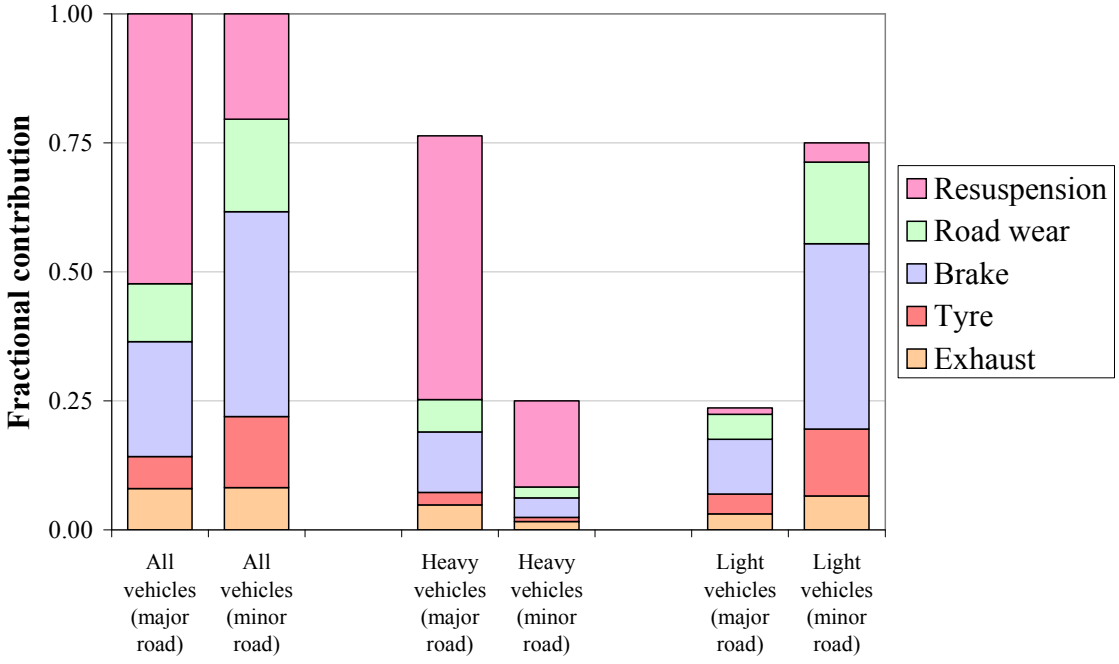

Figure 18 – Relative PM_{coarse} emissions for the example major and minor roads, for all vehicles, and the heavy and light fraction separately.

6.3.2 Concentrations from the example major and minor road

For the example major road, the variation of concentrations across the road for PM_{10} and $PM_{2.5}$ are shown in Figures 19 and 20 respectively. In fact, as each component emission (exhaust, tyre *etc*) is modelled in exactly the same way, the proportion of each component does not vary across the road (for further details of the way in which ADMS-Urban models emissions from roads, please refer to Appendix D) and the proportion of each component is the same as the proportion of the emissions. Therefore, the spread of concentrations for PM_{10}, $PM_{2.5}$ and PM_{coarse} are exactly as shown in the emission Figures 16, 17 and 18.

A discussion on the validity of modelling all the traffic emission sources in the same way is given in the next section.

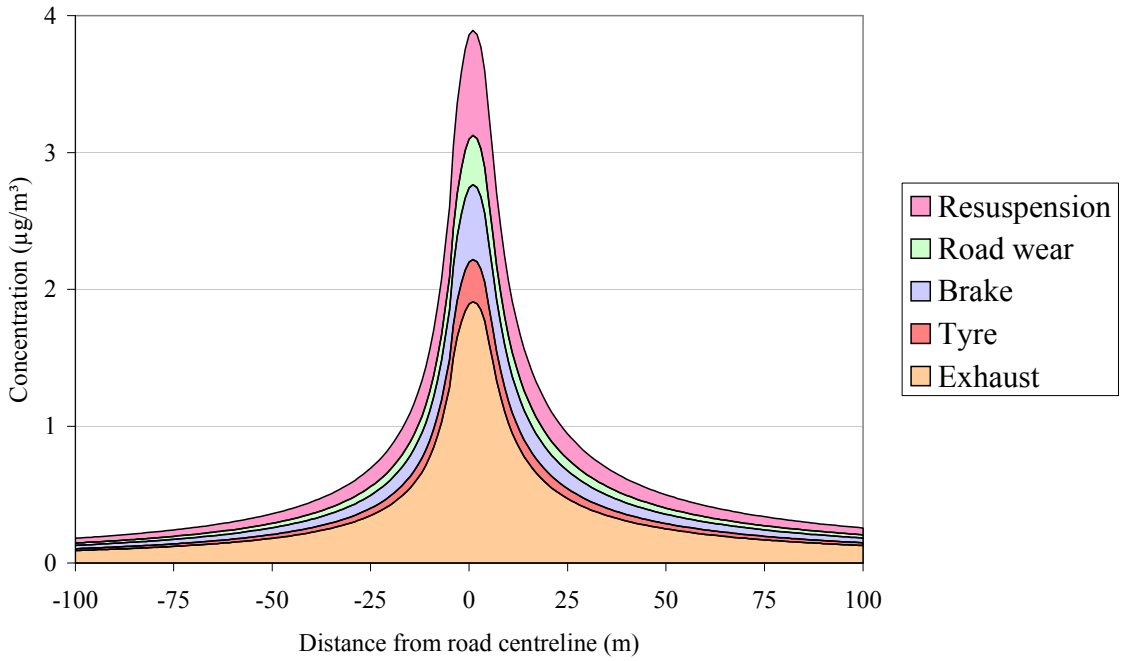

Figure 19 – PM_{10} concentrations from an idealised major road (road width 10m, no canyon, AADT 10 000, speed 40km/hr).

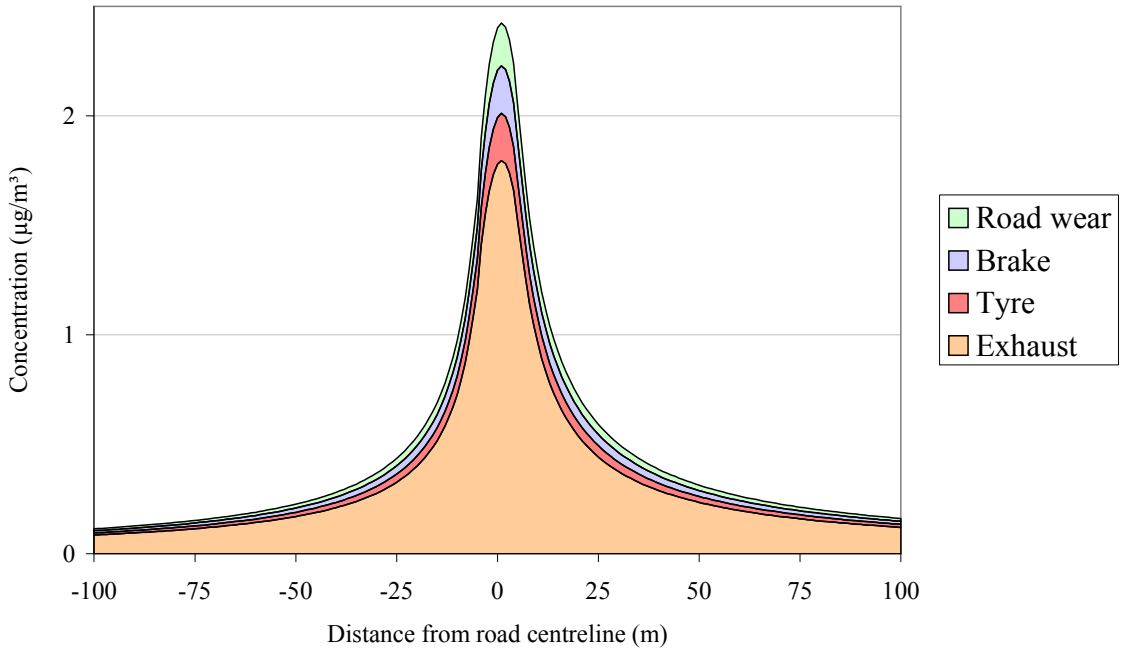

Figure 20 – $PM_{2.5}$ concentrations from an idealised major road (road width 10m, no canyon, AADT 10 000, speed 30km/hr).

6.4 Investigations into different emission properties for the various traffic components

6.4.1 Introduction

In all the dispersion modelling work presented in this document so far, the emission properties of all traffic emission components are treated in the same way. In fact, the different traffic components have different properties. For example:

- Exhaust emissions are buoyant due to their temperature because they have just been released from combustion processes. The non-exhaust emissions are closer to ambient temperature, although tyre and brake wear may be also be warm.

- Exhaust emissions have an exit velocity of between 2 and 40m/s (depending on vehicle size and type, for further information, please refer to [13]); the non-exhaust traffic emissions are likely to have a much lower initial velocity, related to the process by which they are emitted.

- The various traffic components have different emission heights. For example, exhaust emissions emitted from the exhaust pipe, with the location varying with vehicle type. Brake wear emissions are released at the wheel axle height. Tyre wear, road wear and resuspension emissions are all close to the ground.

In addition, both exhaust and non-exhaust emissions from light and heavy vehicles have different properties, for example:

- Source heights of emissions from light and heavy vehicles are different, with some heavy vehicles (particularly construction vehicles, and large articulate trucks) having vertical exhausts.

- Brake wear emissions will be emitted at different heights for light and heavy vehicles, due to the fact that light and heavy vehicle wheels are different sizes.

In ADMS-Urban, roads are modelled as line sources, with modifications to account for traffic-produced turbulence and street canyons (the latter being included as a model option). Full details of the way in which road sources are modelled are given in Appendix D.

In the current ADMS-Urban model, the source height for all ground-level roads is taken to be 1m, with the initial vertical mixing over 2m. This formulation has been developed in order to represent exhaust emissions of all pollutants (*i.e.* NO_X, CO, VOC in addition to particulate emissions). That is, although exhaust heights for most vehicles are less than 0.5m, due to the temperature and speed of the exhaust, and the turbulence generated in the wake of a moving vehicle, the initial spread of exhaust emissions can be taken to be over a relatively large volume. Comparing concentrations predicted by ADMS-Urban using this formulation with monitored values gives generally good agreement.

However, as indicated above, the situation for non-exhaust particulate emissions is somewhat different. The emission temperature, velocity and heights for all the non-exhaust emissions are not the same as exhaust emissions, although all emissions will be influenced to some extent by the turbulence generated in the vehicle wake. As a first step to investigate the variation in properties of the non-exhaust emissions, a non-standard version of the ADMS-Urban model code was used, which allowed the variation of the model initial mixing height parameter h_0 (for further details, please refer to Appendix D). This parameter defines not only the source height, but also the initial vertical plume spread. Table 23 summarises the proposed values of initial mixing height to be used in this investigation.

Note that due to an additional model feature that ensures that source heights are greater than 1.5 times the roughness length, it was necessary to perform these investigations with a roughness length of 0.33m, although this value is rather low for urban areas. As these analyses are intended to give an indication of how results may change, rather than predict accurate values.

Traffic	Exhaust	Tyre	Brake	Road wear	Re-suspension
Light vehicles	1.00	0.50	0.75	0.50	0.50
Heavy vehicles	1.50	0.50	1.00	0.50	0.50

Table 23 – Summary of possible initial mixing heights, h_0 (m), for the various traffic components, and vehicle types.

6.4.2 Results

The investigations were performed with the light and heavy fractions from the example major and minor roads used in Section 6.1. Results are similar for major and minor roads, and are the same for PM_{10} as for $PM_{2.5}$ (as expected).

Figure 21 shows the way in which the concentrations from the various traffic components change across the road for light vehicles, compared to the base ADMS-Urban model run (which had the initial mixing height for all components set at 1m); Figure 22 shows the corresponding results for heavy vehicles. As for the investigations presented in Section 6.1, these are annual average concentrations.

Figures 21 and 22 show that changing the initial mixing height has a significant effect on concentrations, particularly close to and above the road. The drop off in difference in concentrations with distance from the road is expected as local source properties such as dimensions only influence concentrations close to a source – further away, meteorology has a stronger influence.

For both light and heavy vehicles, the concentrations due to the tyre, road wear and resuspension emissions are increased significantly due to the fact that these emissions have been released closer to the ground (source height 0.5m instead of 1m) and have been spread over a smaller vertical height (1m instead of 2m). For light vehicles, the brake wear concentrations have also been increased due to the reduction of the initial mixing height to 0.75m. For heavy vehicles, the increase in initial mixing height to 1.5m for exhaust emissions decreases the resultant concentrations.

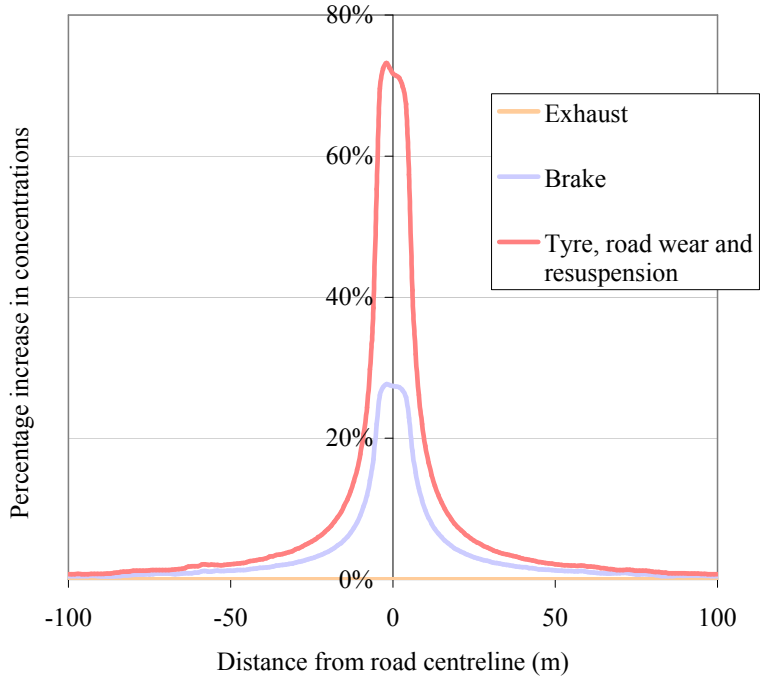

Figure 21 – Example variations in concentrations due to different values of initial mixing height (light vehicles).

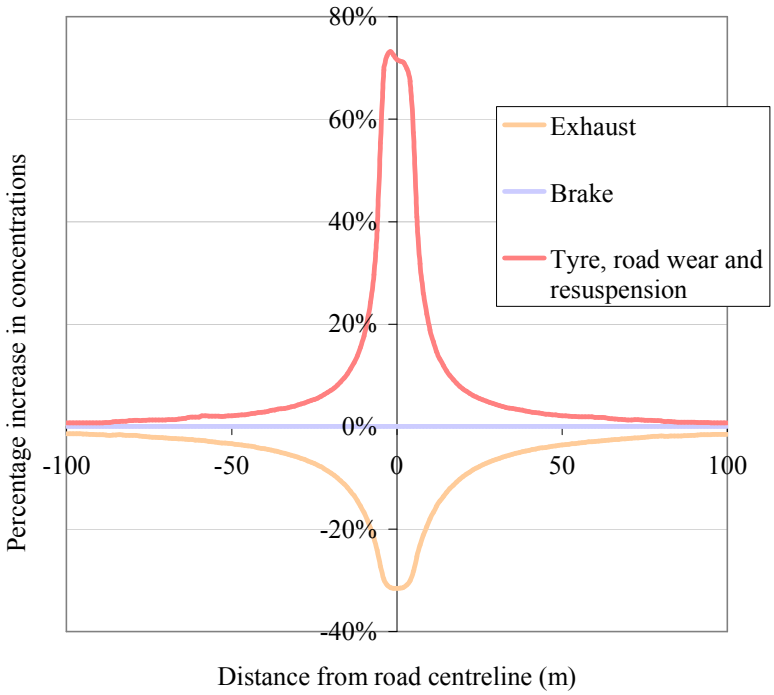

Figure 22 – Example variations in concentrations due to different values of initial mixing height (heavy vehicles).

6.4.3 Further analyses

The results of the investigations presented in Section 6.4.2 show that changing the emission characteristics of a particular source may have a significant effect on concentrations, particularly close to the road. It would be interesting to see the effect that these results would have on the dispersion modelling results and source apportionment analyses presented in Section 5. As the values shown in Figures 21 and 22 are for a particular road width, and include example rather than exact values for the initial mixing heights (and number of other assumptions), it was decided that a good representation of the change in concentrations may be found by taking the average of the increase/decrease across the road. Table 24 summarises the minimum, maximum and average percentage increase in concentrations due to the changes in initial mixing height for the example light and heavy vehicles. Here, the minimum, maximum and average values have been calculated over points a distance of up to 50m from the road centreline, as 50m is the approximate average distance of the monitors from the road centreline.

In order to apply these average values to the modelled concentrations at the sites investigated in Section 5, it was necessary to calculate the proportion of heavy vehicles at each location. For roadside / kerbside sites, this was a straightforward calculation using the traffic counts on the road adjacent to the site, but a number of the sites were in 'urban background' locations, whose concentrations are influenced by a number of roads in the vicinity. For these sites, a rough estimate of the average proportion of heavy vehicles was estimated from the information available.

Traffic	Statistic[a]	Exhaust	Tyre	Brake	Road wear	Re-suspension
Heavy vehicles	Min	-32	2	0	2	2
	Max	-3	73	0	73	73
	Average	-11	14	0	15	15
Light vehicles	Min	0	2	1	2	2
	Max	0	73	28	73	73
	Average	0	14	7	14	14

Table 24 – Minimum, maximum and average percentage increase in concentrations due to the change in initial mixing heights given in Table 23 ([a] take over –50 to 50m).

Figure 23 shows the new source apportionment results after applying the average initial mixing height adjustment values presented in Table 24, for resuspension emission scenario 1A; Figure 24 shows the corresponding $PM_{2.5}$ results. These figures correspond to Figures 4 and 6 in Section 5. It is not particularly easy to see any difference in results between the two sets of figures, and in fact, consideration of the overall statistics shows that:

- For PM_{10}, the ratio of modelled to observed concentrations is 1.06 for the base case, and 1.08 for the adjusted initial mixing height calculations; and

- For $PM_{2.5}$, the ratio of modelled to observed concentrations is 1.26 for the base case, and 1.27 for the adjusted initial mixing height calculations.

Thus, these relatively significant adjustments to the modelled concentrations do not change the predicted concentration significantly. In the above, it has been shown that taking account of the height of the different road traffic sources has some impact on the relative contributions of non-exhaust and exhaust emissions, and also on the total concentrations. This could affect the derived resuspension emission factors since the method applied (as shown in Section 2.2.1) assumed that the ratio of road traffic emission of PM_{10} to NO_X is equal to the ratio of PM_{10} and NO_X concentrations. In fact, the PM_{10} sources are closer to the ground than the NO_X sources, and the assumption that the source heights are the same may lead to an overestimation of the resuspension emission factors.

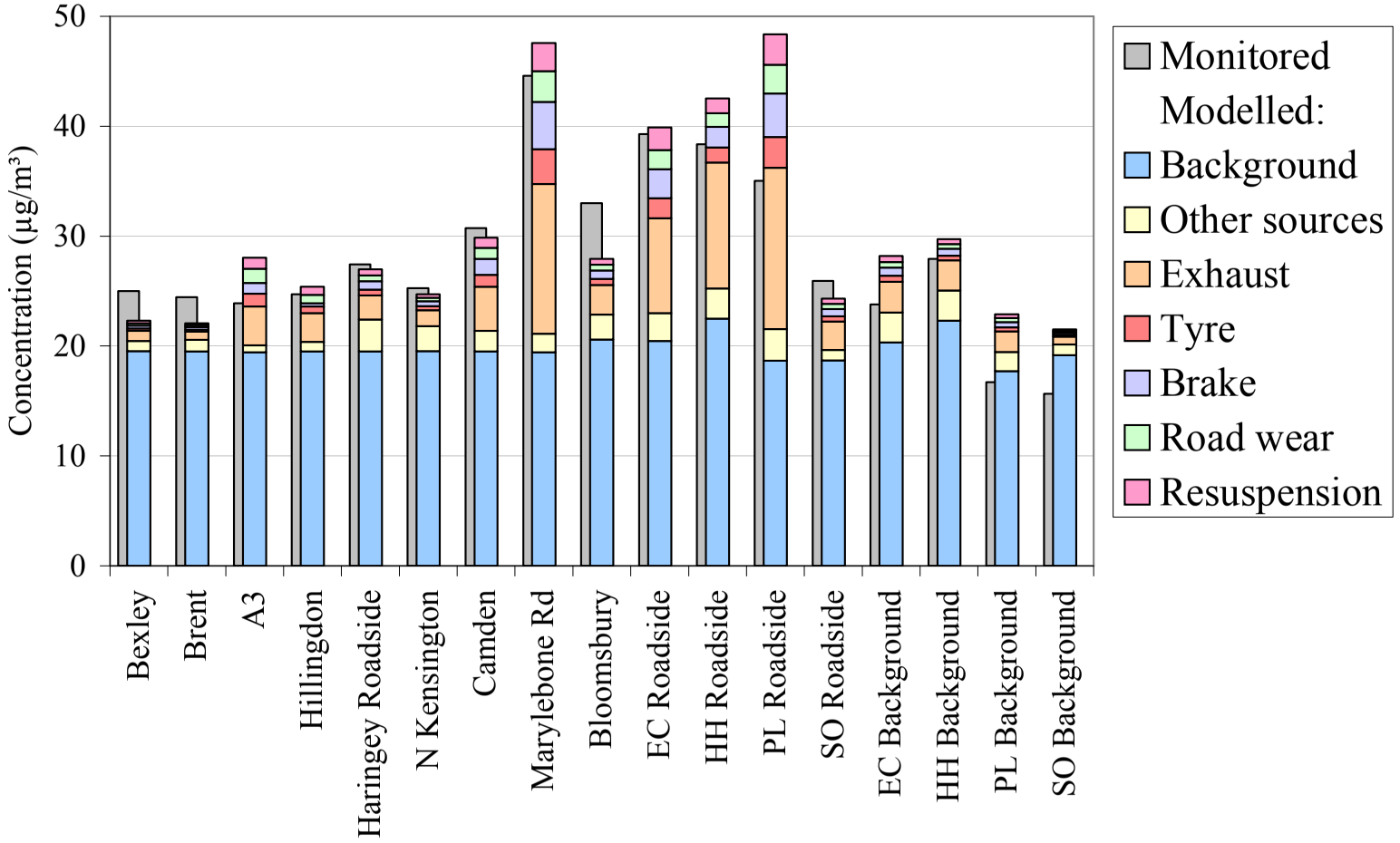

Figure 23 – Source apportionment of PM_{10} results after applying the initial mixing height adjustment (resuspension scenario 1A values).

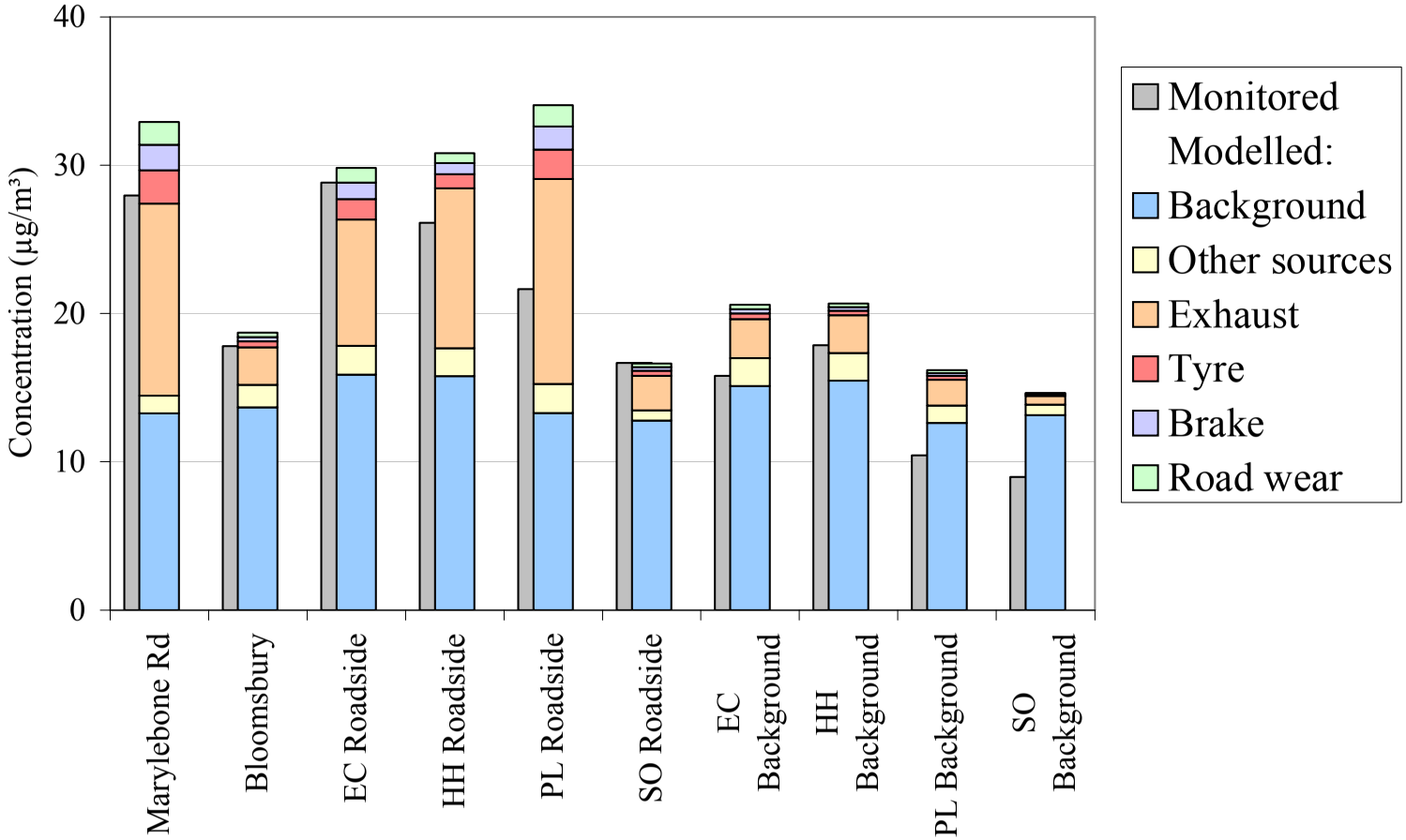

Figure 24 – Source apportionment of $PM_{2.5}$ results after applying the initial mixing height adjustment.

7 Discussion

This report describes the work involved in Task 3 and Option 5c of the project 'Road vehicle non-exhaust particulate matter' (CPEA23/SPU82), commissioned by DEFRA and the Devolved Administrations.

The work follows on from that presented in the Task 2 report [1], which concluded that the methodologies for estimating tyre, brake and road wear emissions outlined in the EMEP documentation [2] were the most suitable for application generally, and in the current work. Task 2 also derived new emissions factors for resuspension and resuspension plus road wear, by analysing data measured at Marylebone Road and Bloomsbury in London.

As the derivation of the resuspension and resuspension plus road wear factors assumed that exhaust emissions do not include any coarse component, the current work began by recalculating the emission factors including a coarse component (refer to Table 3 for a summary of the resuspension and resuspension plus road wear factors). The values for resuspension and resuspension plus road wear combined, derived including a coarse component of exhaust emissions, are lower by between 15 and 20% compared to the original values calculated in [1].

Section 2.4 describes the way in which the traffic emission factors have been included within the emissions database model, EMIT. EMIT has then been used to calculate for the dispersion modelling exercise.

It was originally proposed that dispersion modelling of four emission scenarios was performed, but analysis of emissions totals and the emission factors themselves showed that it was unnecessary to model both the resuspension and the resuspension plus road wear factors as separate scenarios (refer to Section 2.5).

The dispersion modelling exercise was performed at 12 locations within Greater London, and one in Birmingham. Four of the locations were where data had been collected during the TRAMAQ project and included both a background and a roadside site; the remaining sites were DEFRA automatic monitoring stations. Both PM_{10} and $PM_{2.5}$ were recorded at the TRAMAQ sites and two of the monitoring stations; the remaining sites recorded PM_{10} measurements only.

Brief site descriptions are given in Section 3, with additional information being available in the TRAMAQ project report [7], and on the website http://www.stanger.co.uk/siteinfo/. The sites vary in type, with some being located on the kerb, and others up to 200m away from the nearest major road.

The ADMS-Urban dispersion model was used to predict concentrations at the chosen sites for comparison with the measured values (for more details, see [4] and the model description given in Appendix B). In order to obtain accurate modelled concentrations using this complex model, it is important to include emissions from all local sources explicitly, and account for other emissions as an aggregated 'grid source', in addition to concentrations advected into the area from rural locations. For London, comprehensive emissions data were available for all sites from the London Atmospheric Emissions

Inventory [3]; for Birmingham, a detailed emissions inventory was not available so emissions estimates were made using data from a number of sources (for further information, please refer to Section 4.1.2).

The emission data, background concentrations and any assumptions made have been discussed in detail in Section 4.2 to 4.5; further model set up information is given in Section 4.6.

It was found that the PM_{10} concentrations predicted by ADMS-Urban compare well with the measured values (see Table 15 and Figure 2), with an over prediction by the model of approximately 6%. It is interesting to note that the difference between the model predictions of total concentrations using resuspension emissions scenario 1A and 2A are small – a maximum of 1%. The average modelled to measured ratio is very slightly better for resuspension emission scenario 2A, but the difference between results from the two scenarios is not significant. The reason for the difference in results between the two emissions scenarios being small is that:

- At roadside sites, traffic emissions contribute to approximately half of modelled PM_{10} concentrations, with the remainder being background concentrations. At 'urban background' sites, this fraction reduces to a minimum of 20% of the modelled concentrations (see, for example, Figure 4).

- Resuspension is about 12% of total traffic emissions (see for example, Figure 13), and as is assumed in the original calculations, the traffic emissions are all dispersed in the same way, this corresponds to resuspension contributing 12% of the total traffic concentrations.

Therefore, recalling that the difference between the resuspension emission factors for scenarios 1A and 2A is between 15 and 20%:

15 – 20%	of	12%	of	20 – 50%
(Difference in resuspension emission scenario values)		(Fraction of traffic concentration that is resuspension		(Traffic contribution to total concentration)

then the difference between in concentrations between the scenarios expected is 0.36 – 1.20%; this justifies the difference seen of less than 1%.

Another point to note from looking at Figure 2 that compares the long-term average PM_{10} concentrations at all sites is that the model over-predict concentrations slightly at the majority of the TRAMAQ sites, whereas at the DEFRA sites, a better comparison with measured data is seen. This is discussed further below, in regard to the monitors used to measure the concentrations at the different sites.

The $PM_{2.5}$ modelled concentrations are generally over predicted, by an average of about 26% (see, for example, Table 16 and Figure 3). This may well be due to the factor used to convert the $PM_{2.5}$ TEOM measured concentrations to gravimetric equivalent being too high. This has been discussed in Section 5.2.2. The conclusions of this discussion are that it may be appropriate to use a different factor to convert rural background

TEOM $PM_{2.5}$ concentrations and the $PM_{2.5}$ concentrations measured close to the road, due to the higher proportion of volatile particulates at urban sites. However, the $PM_{2.5}$ results presented in the current report use a conversion factor of 1.3. With regard to the PM_{10} monitors, it is interesting to note that where the results from ADMS-Urban model has been compared to the TRAMAQ measured concentrations, the model tends to slightly over estimate the values; the monitors used in the TRAMAQ study were gravimetric. This is in contrast to the DEFRA monitors, which are TEOM; at these monitors, ADMS-Urban predicts better results. It may not be possible to draw specific conclusions from this, but the results add to the continuing uncertainty surrounding measurements taken from TEOM monitors, and how they relate to their gravimetric equivalent.

As it is generally only long-term concentration data that are analysed, it was interesting to look at some short-term statistics of the TRAMAQ data. These statistics have been discussed in Section 5.3.

The source apportionment of modelled concentrations is a useful way of assessing the composition of the measured value. Section 5.4 presents and discusses source apportionment of the PM_{10}, $PM_{2.5}$ and PM_{coarse} results, for both resuspension emission scenarios. The figures presented in this section clearly show the significant contribution of non-exhaust traffic emissions to total concentrations, particularly at roadside sites. It is also interesting to see the major contribution from the rural background concentrations to estimates of total concentrations, and also the relative insignificance of emissions from non-traffic sources in urban areas.

The minimum and maximum percentage contribution to the modelled concentrations from traffic sources predicted in Tables 20 and 21 show how the exhaust and non-exhaust emissions contribute different amounts at different sites. This is due to the various road types, and the corresponding mix of vehicles on the road. This variation is discussed further in Section 6, where emissions and concentrations from an idealised major and minor road are investigated using EMIT and ADMS-Urban. Observations from these further investigations include that the non-exhaust emissions may be a higher proportion of concentrations on a minor road compared to a major road, due to the relatively low light vehicle exhaust emissions; and that coarse emissions are mainly non-exhaust.

Comparing the average total emissions for the London area with the average modelled concentrations at the sites considered shows the clear relationship between traffic emissions and modelled concentrations (Section 5.5). This is actually quite surprising as the modelled concentrations are from a relatively few sites, but this close relationship shows that the sites are representative.

Obviously, as all the traffic emissions are modelled in the same way, for a specific road, the relationship between emissions and modelled concentrations is linear, as mentioned in Section 6.3.2. This is not totally correct however, as the sources, and consequently the dispersion properties of the various traffic emissions are different. For example, the exhaust emissions are much more buoyant than the emissions from, say, road wear, due to the former being emitted as buoyant gases at a higher velocity; the dispersion of all traffic emissions are, however, affected by turbulence generated by the wake of moving vehicles. Section 6.4 attempts to investigate the effect that improvement to the

modelling of the different traffic emission sources may have on modelled concentrations, by looking at different source heights and vertical spreads. This investigation demonstrates the significant effect changing the source properties has on concentrations, particularly close to the road. Further, in the Task 2 report [1], the derivation of the resuspension emission factors assumed that the ratio of road traffic emissions of PM_{10} to NO_X is equal to the ratio of PM_{10} and NO_X concentrations, and this may lead to an over estimation of the resuspension emission factor derived.

One particular aspect of this work that it has not been possible to complete is the analysis of the modelled concentrations in terms of their chemical constituents. If this was done it would be possible to relate the chemical breakdown at the TRAMAQ sites to the modelled concentrations, allowing further insight into the particulate concentration make up. There remain a number of unanswered questions regarding this work; these have been summarised in the 'Further work' Section 8.

8 Further work

This section discusses some further work that has not been undertaken within the current project, but which would allow further insight into the validity of the non-exhaust emission factors.

Section 8.1 discusses the issues that need to be resolved regarding the chemical constituents of the various modelled emissions and background concentrations before full source apportionment of the TRAMAQ data can be performed. Consideration of seasonal variation in non-exhaust emission factors is discussed in Section 8.2, and Section 8.3 briefly mentions some further improvements to the way in which non-exhaust emissions are modelled in ADMS-Urban.

8.1 Source apportionment of the TRAMAQ data

The particulate measurements taken during the TRAMAQ experiments were analyses in terms of their chemical components. Specifically, in addition to the amount of PM_{10} and $PM_{2.5}$, each sample was analysed to give the coarse and fine fraction of:

- Iron
- Calcium
- Chloride
- Nitrate
- Sulphate
- Organic carbon
- Elemental carbon

Following the mass closure methodology proposed by Harrison et al [15], it is possible to use these chemicals to represent the major components of airborne particulate matter. Further, if all modelled emissions were to be defined in terms of these chemicals, then it would be possible to apportion both the emissions and the measured data into these components, and this would give significant insight into the validity of the non-exhaust emissions estimates that are currently of interest.

Table 25 summarises the emissions that contribute to the measured concentrations. The second column in this table lists the proposed chemical constituent(s) of the emission. Note that in some cases, the emission is made up of more than one of the chemicals listed above. This means that a methodology is required to split the emission up into the relative chemical components; comments regarding how this could be done are given in the third column of this table.

Note:

- The chemical constituents of the emissions from 'other sources' within the London area must be based on the information summarised in Table 26.

- Currently, in Table 25, brake wear is the only source contributing to iron concentrations, whereas in the AQEG report, paragraph 549 [9], it says that iron is 'representative of soil and road dust'. It is likely therefore that iron should be included in other emissions.

Modelled component	Chemical components	Comments
Exhaust	Organic and elemental Carbon	***Proposed methodology:*** *It has been suggested that the data given in Table 6.7, page 172 of the AQEG PM report [9] can be used to estimate the relative proportions. The difference between the kerbside Marylebone measurement and the urban background North Kensington value can be taken as a 'traffic increment', which gives 55% / 45% elemental / organic carbon split.* ***But****, this isn't completely correct, because the 'traffic increment' includes all the non-exhaust sources, but tyre wear is also elemental carbon. This could be accounted for by making an approximation using the modelled values.*
Tyre	Elemental Carbon	***Requires confirmation***
Brake	Iron	***Requires confirmation***
Road wear	Calcium Sulphate	***Requires confirmation***
Resuspension	Calcium Sulphate	***Requires confirmation***
Non-traffic urban sources	?	***Proposed methodology:*** *In terms of concentrations, the non-traffic urban sources make up 5-10% of modelled concentrations. Table 26 summarises the* ***emissions*** *of these sources within the London area, in terms of tonnes per year, and percentage of the non-traffic urban sources. Certain assumptions must be made regarding the chemical composition of these sources.*
Rural background	Organic and elemental Carbon, Sulphate, Nitrate and Chloride	***Proposed methodology:*** *The rural background must be apportioned between the various components. For some previous work CERC have done for DEFRA, the 2001 rural background was apportioned as shown in Table 27. Here the 'other' component represents 'additional sources of* PM_{10} *such as salt and wind-blown dust'. This significant portion needs to be included in terms of the correct chemical components with the salt being 'Chloride', and the 'wind-blown dust' being a combination of the other compounds.*

Table 25 – Summary of modelled sources, with their associated chemical compositions.

Group	Emission (Tonnes/year)	Percentage of total
Agriculture	119	5.6 %
Boilers	15	0.7 %
Cold starts	90	4.2 %
Commercial gas	312	14.6 %
Domestic coal	0	0.0 %
Domestic gas	590	27.6 %
Domestic oil	7	0.3 %
Heathrow	77	3.6 %
Industrial coal	0	0.0 %
Part A sources	346	16.2 %
Part B sources	393	18.4 %
Rail	149	7.0 %
Shipping	2	0.1 %
Solvents	38	1.8 %
TOTAL	2140	100.0 %

Table 26 - Summary of the 'other sources' modelled in the London urban area (2002).

Chemical component	Percentage of total
Organic Carbon	14.2 %
Elemental Carbon	3.4 %
Ammonium Sulphate	20.1 %
Ammonium Nitrate	23.6 %
Sodium Nitrate	6.2 %
'Other'	32.5 %

Table 27 – Possible chemical composition of rural background.

8.2 Seasonal analysis of results

The data for the TRAMAQ sites were collected between April 2000 and January 2002. The sampling plan for this project was to incorporate measurements at each of the four sites during each of the four seasons of a year. This was to ensure that sampling covered any variations in pollutant concentrations as a result of different weather conditions characteristic of each season.

Figure 25 shows the seasonal variation of the sampling in the TRAMAQ experiments. It would be interesting to analyse the results of the dispersion modelling and measurements in terms of the seasonal variations in order to assess whether or not the seasonal variation has a significant effect on results; it may be that the non-exhaust emission factors require a seasonal component.

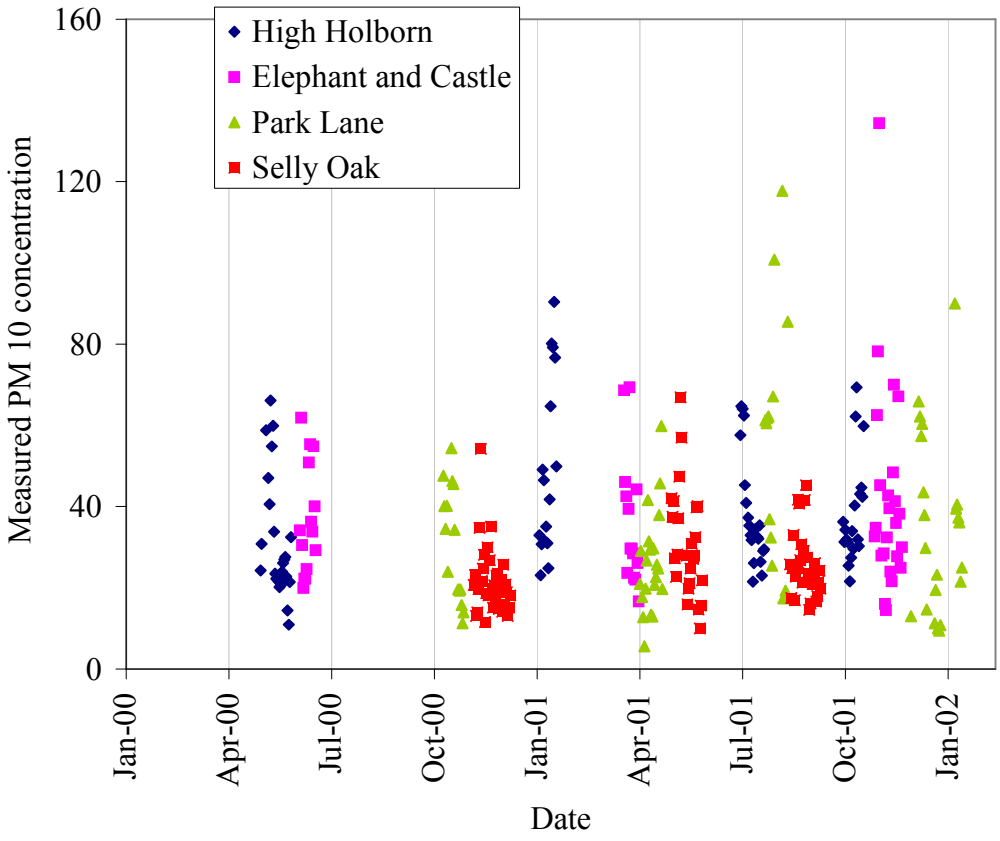

Figure 25 – Spread of TRAMAQ measurements between April 2000 and January 2002.

8.3 Improvement to dispersion modelling of non-exhaust emissions

Section 6.4 discusses the possible effect the different emission properties of the various source components may have on the measured concentrations. The results presented in this section show that changing the initial mixing height of the source can have a significant effect on the concentrations, particularly close to the road.

Further work includes improving the modelling of the non-exhaust components, by correctly defining not on the source height, but also the relative buoyancy of the release. It would also be of interest to implement a speed-dependent source height, and to account for heavy vehicles with high level exhausts within the fleet.

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Appendix A – Calculation of new resuspension emission factors

A.1 Introduction

Full details of the method used to calculate new light and heavy resuspension/resuspension plus road wear emission factors are not given, as the methodology is described in Section 4.2.6 of [1]. The coarse component of the exhaust emission factors has been calculated in the following way:

- The daily traffic count data supplied in terms of 6 categories (TWMVs, car/van < 5.2m, car plus trailer, rigid lorries, articulated lorries and buses/coaches), were binned into 3 categories (TWMVs, light and heavy vehicles).

- Total PM_{10} emissions were calculated for each day using the Urban DMRB emission factor datasets for the appropriate years [16]. Note that this emission factor dataset accounts for the same fleet composition (given in [17]) that was used to calculate the total tyre, brake and road wear emission factors.

- 6.0% of the total PM_{10} exhaust emissions are assumed to be PM_{coarse}.

The coarse component of the emission factor was included in the calculation of the resuspension/resuspension plus road wear emission factors by applying equations (12)/(13). The apportionment of the resuspended component between light duty and heavy duty vehicles was recalculated using the new factors. Estimated emission factors are presented in Tables 28 and 29 below, for resuspension, and resuspension plus road wear respectively; these tables correspond to Tables 24 and 25 in [1].

Year	Emission factors for resuspension only (mg/km)			
	HDV	±	LDV	±
2000	125 (120)	5 (5)	1.30 (1.57)	0.5 (0.4)
2001	122 (111)	5 (9)	-0.91 (-0.18)	0.7 (0.8)
2002	123 (118)	4 (2)	-1.64 (-1.32)	0.3 (0.1)

Table 28 – HDV and LDV emission factors and associated uncertainties for resuspension (PM_{coarse}) calculated from simultaneous equations, with the bracketed values being those derived after further data filtering.

Year	Emission factors for resuspension and road wear (mg/km)			
	HDV	±	LDV	±
2000	143 (138)	5 (5)	4.75 (5.02)	0.6 (0.4)
2001	139 (128)	4 (7)	2.54 (3.27)	0.9 (0.7)
2002	141 (135)	5 (2)	1.81 (2.13)	0.6 (0.1)

Table 29 – HDV and LDV emission factors and associated uncertainties for combined resuspension + road wear (PM_{coarse}) calculated from simultaneous equations, with the bracketed values being those derived after further data filtering.

As for the values presented in [1], the HDV emission factors for resuspension/resuspension plus road wear are quite consistent over the three years considered, with the values being between 15-20 mg/km lower than the aforementioned values due to the inclusion of the coarse exhaust component. However, the LDV emission factors for resuspension derived here (Table 28) are negative for both 2001 and 2002, resulting in a negative average value; [1] only predicts a negative value for 2002, and gives a positive average value.

The reason for the prediction of the negative values was investigated. Firstly, the data were filtered further to remove anomalous values (the data had already been filtered in order to removed days with unphysical values of NO_X or PM_{10} roadside increment, see Section 4.2.2 [1]). Specifically:

- Weekdays where the HDV/LDV ratio was less than usual were removed, for example on during national holiday periods such as Bank Holidays;
- Weekdays where the number of LDVs was significantly less than usual were removed (this relates to a period during 2001 where it is likely some route diversions were in operation);

In addition, due to the different LDV/HDV relationship observed on Saturdays as opposed to Sundays, three different factors were derived for the combinations: Weekdays and Saturdays, Weekdays and Sundays, and Saturdays and Sundays. The results from these calculations were averaged, and presented in Tables 8 and 9 in brackets. It can be seen that the further filtering of the data slightly improved the LDV predicted emission values, and resulted in a small positive average value.

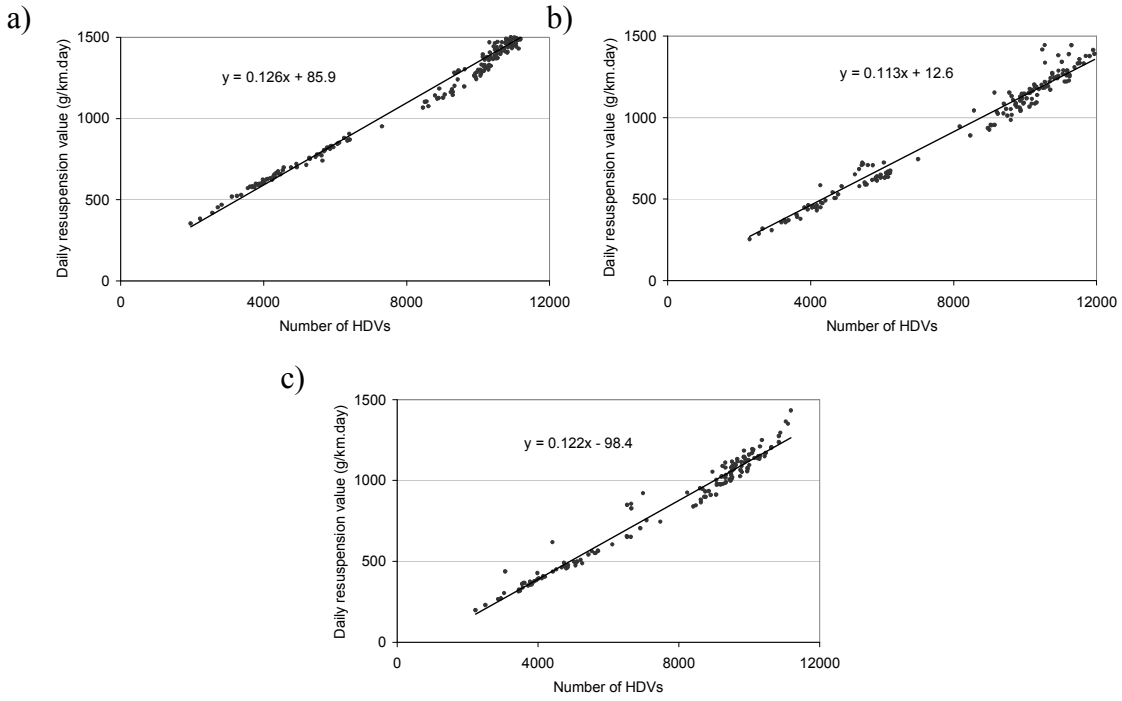

Figure 26 – Relationship between the daily resuspension values and the number of heavy vehicles for a) 2000, b) 2001 and c) 2002.

Figures 26 a), b) and c) show the relationship between the resuspension emission values used in the above analysis, against number of heavy vehicles, for 2000, 2001 and 2002 respectively. Each figure has cluster of points around the 'Number of HDVs = 4000' and 'Number of HDVs = 10000' values – these clusters correspond to the grouping of data into weekend and weekday measurements respectively. The number of light vehicles throughout the week does not vary significantly.

These figures show that there is a strong relationship between the number of HDVs and the resuspension value, which is linear – a trend line has been added to each figure. It can be seen that the intercept of the linear trend line with the vertical axis is a relatively large negative value for 2002; this goes some way to explaining why the method of using linear simultaneous equations to calculate both the light and heavy vehicle emission factors results in a 'significant' negative value for the 2002 light emission factor (note that the negative light vehicle emission factor for 2001 is within the uncertainty of the calculation). These figures indicate that there may be a problem with the urban background site (London Bloomsbury), which appears to have a local source of coarse particles leading to apparently low resuspension values at Marylebone Road.

For completeness, although these arithmetic mean values are not used in the final calculations, Table 30 summarises the mean emission rates (g/km.day) for each of the emission sources of PM_{coarse} considered in the calculation. The sources of these data are given in the second column. Note that these mean values have been calculated using the full traffic dataset – the final calculations of the light and heavy resuspension/resuspension plus road wear values described above were calculated using a reduced (filtered) dataset.

Emission type	Data source	PM_{coarse} emission (g/km.day)		
		2000	2001	2002
Total emissions	Table 10 [1]	2999.3	2571.3	2393.8
Tyre wear	(Table 11 [1])[3]	269.8	247.5	237.3
Brake wear	(Table 12 [1])[3]	856.2	788.3	755.1
Road wear	(Table 13 [1])[3]	411.5	378.7	361.8
Exhaust	Calculated in EMIT using DMRB emission factors	266.7	222.5	189.3
Resuspension	Calculated using equation (12)	1195.1	934.4	850.3
Resuspension + road wear	Calculated using equation (13)	1606.6	1313.0	1212.1

Table 30 – Summary of arithmetic mean total PM_{coarse} emissions at Marylebone Road, 2000-2002 ([3] the values presented in [1] were not the finalised values – these data have been supplied by Alistair Thorpe, University of Birmingham, private communication).

A.2 Discussion of new results

Values of resuspension/resuspension plus road wear emission factors for using the dispersion modelling can be calculated by averaging the values presented in Tables 8 and 9 respectively. This gives values of 116/134 mg/km for heavy vehicles, and 0.02/3.47 mg/km for light vehicles, with the values being derived from the 'further filtered' dataset.

Further analyses, ideally using a similar dataset from another site, would help to explain the inconsistencies with the light vehicle resuspension emission factors derived above. There are a number of factors that may be relevant. For example:

- Speed dependence

Most emission factors vary with speed. The average speed data from the Marylebone Road site showed very little variation, but it may be on days where the traffic is freer flowing and peak speeds are higher, resuspension values may be different.

- Driver behaviour/congested conditions

At the site considered, during the week, there are almost twice as many heavy vehicles on the road compared to at the weekend. Although this increases total vehicle numbers only slightly, it may affect driving behaviour. Also, during the week, peak 'rush hours' are better defined, compared to the weekend, where there is a more steady level of traffic. A combination of these effects may mean that the weekday 'congested' resuspension value would be different from an 'uncongested' value. Analyses using data from a site on a free-flowing road would go some way to investigating this hypothesis.

- TWMVs

The derivation of the resuspension emission factors does not include emission factors for two wheeled motor vehicles (TWMVs), despite the fact that 'the tyres of motorcycles are known to wear at a relatively high rate' [1].

- Urban background

Considerable care must be taken when calculating the 'measured' roadside increments of particulate concentrations. Sites that measure urban background values should be treated with caution.

Appendix B – ADMS-Urban model description

B.1 Introduction

ADMS-Urban is a practical air pollution modelling tool, which has been developed to provide detailed predictions of pollution concentrations for a range of sizes of study area. The model can be used to look at concentrations near a single road junction or over a region extending across the whole of a major city. ADMS-Urban has therefore been extensively used for the Review and Assessment of Air Quality carried out by Local Authorities in the UK. The following is a summary of the capabilities and validation of ADMS-Urban. More details can be found on the CERC web site at www.cerc.co.uk.

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which was developed to investigate the impacts of emissions from industrial facilities. ADMS-Urban allows full characterisation of the wide variety of emissions in urban areas, including industrial, road and domestic emissions. ADMS-Urban also includes an extensively validated model for the calculation of road traffic emissions from traffic count data, and boasts a number of other features, which include consideration of:

- the effects of vehicle movement on the dispersion of traffic emissions;
- the behaviour of material released into street canyons;
- the chemical reactions occurring between nitrogen oxides, ozone and Volatile Organic Compounds (VOCs);
- the chemical reactions between sulphur dioxide and other pollutants to produce particulates;
- the pollution entering a study area from beyond its boundaries;
- the effects of complex terrain on the dispersion of pollutants.

More details of these features are given below.

Studies of extensive urban areas are necessarily complex, requiring the manipulation of large amounts of data. To allow users to cope effectively with this requirement, ADMS-Urban has been designed to operate in the widely familiar PC environment, under Microsoft Windows (2000 or XP). The manipulation of data is further facilitated by the possible integration of ADMS-Urban with a Geographical Information System (GIS) such as MapInfo or ArcView, and with the CERC Emissions Inventory Toolkit, EMIT.

B.2 Dispersion modelling

The dispersion modelling features of ADMS-Urban include the following.

- ADMS-Urban is an advanced dispersion model in which the boundary layer structure is characterised by the height of the boundary layer and the Monin-Obukhov length, a length scale dependent on the friction velocity and the heat flux at the surface. This method supercedes earlier simpler methods based on Pasquill Stability Categories, as used in, for example, CALINE and ISC.

- A meteorological pre-processor calculates boundary layer parameters from a variety of input data, typically including date and time, wind speed and direction, surface temperature and cloud cover. Meteorological data may be raw hourly averaged or statistically analysed data.
- In stable and neutral conditions meteorological conditions, a Gaussian vertical profile of concentration is used. In convective conditions, a non-Gaussian vertical profile of concentration is used, to allow for the skewed nature of turbulence within the atmospheric boundary layer, which can lead to high concentrations near to the source.

B.3 Sources and emissions

Emissions into the atmosphere across an urban area typically come from a wide variety of sources. There are likely to be industrial emissions from chimneys as well as emissions from road traffic and domestic heating systems. To represent the full range of emissions configurations, the explicit source types available within ADMS-Urban are:

- **Point sources**, typically used to represent industrial emissions from chimneys. The effect of the buoyancy and momentum of the release on the height of the plume ('plume rise') can be modelled.
- **Roads**, for which emissions can be specified explicitly or calculated from vehicle flows. The additional initial dispersion caused by moving vehicles is also taken into account.
- **Line, area or volume sources**, where a source or sources is best represented as uniformly spread along a line (for example rail emissions), over an area (for example evaporation from an open tank) or throughout a volume (for example dust emissions from a quarry).

In addition, emissions from multiple sources can be combined and modelled as a regular grid of emissions. This allows the contributions of large numbers of minor sources to be efficiently included in a study while the majority of the modelling effort is used for the relatively few significant sources.

ADMS-Urban can be used in conjunction with CERC's Emissions Inventory Toolkit, EMIT, which facilitates the management and manipulation of large and complex data sets into usable emissions inventories.

B.4 Presentation of results

The results from the model can be based on a wide range of averaging times, and include rolling averages. Statistics such as annual average concentrations, maximum concentrations, percentile concentrations and the number of exceedences of limit concentrations can be calculated where appropriate meteorological input data have been input to the model. This allows ADMS-Urban to be used to calculate concentrations for direct comparison with existing air quality limits, guidelines and objectives, in whatever form they are specified.

ADMS-Urban can be integrated with the ArcView or MapInfo GIS to facilitate both the compilation and manipulation of the emissions information required as input to the model and the interpretation and presentation of the air quality results provided.

B.5 Complex effects

B.5.1 Street canyons

The *Operational Street Pollution Model (OSPM)* [18], developed by the Danish National Environmental Research Institute (NERI), has been incorporated within ADMS-Urban. The OSPM uses a simplified flow and dispersion model to simulate the effects of the vortex that occurs within street canyons when the wind-flow above the buildings has a component perpendicular to the direction of the street. The model takes account of vehicle-induced turbulence. The model has been validated against Danish and Norwegian data.

B.5.2 Chemistry

In most urban areas, the dominant pollution source is road traffic, and the pollutants usually of major interest are nitrogen oxides (NOx) and particulates.

The chemical reactions involving **nitrogen oxides** take place over a relatively short time period, so in order to get accurate predictions of NO_2 concentrations NOx chemistry should be taken into account. ADMS-Urban includes a modified version of the *Generic Reaction Set (GRS)* [19] atmospheric chemistry scheme, which includes reactions including those occurring between nitrogen oxides and ozone, parameterisations of the large number of reactions involving a wide range of Volatile Organic Compounds (VOCs), and a reaction for the situation when high concentrations of nitric oxide (NO) can convert to nitrogen dioxide (NO_2) using molecular oxygen.

ADMS-Urban also models the chemical reactions between sulphur dioxide and other pollutants which result in the production of **particulates** [20].

ADMS-Urban includes a Lagrangian **trajectory model** [21] for use when modelling large areas. This is used to calculate background concentrations for the air approaching the main modelling area, and includes the effects of emissions, chemistry, deposition and entrainment.

B.5.3 Terrain

As well as the effect that complex terrain has on wind direction and, consequently, pollution transport, it can also enhance turbulence and therefore increase dispersion. These effects are taken into account in ADMS-Urban using the FLOWSTAR [22] model developed by CERC.

B.6 Data comparisons – model validation

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which is used throughout the UK by industry and the Environment Agency to model emissions from industrial sources. ADMS has been subject to extensive validation, both of individual components (*e.g.* point source, terrain effects and meteorological pre-processor) and of its overall performance.

ADMS-Urban has been extensively tested and validated against monitoring data for large urban areas in the UK, including Central London and Birmingham, for which a large scale project was carried out on behalf of the DETR (now DEFRA).

Further details of ADMS-Urban and model validation, including a full list of references, are available from the CERC web site at www.cerc.co.uk.

Appendix C – Edits to the major road source data in the LAEI

The LAEI is an extensive and very useful database for emissions in London. However, as to be expected from such a large collection of data, some information within the inventory is approximate, or inaccurate. Specifically, with regard to the major road traffic information:

- Road locations are not accurate *i.e.* they do not agree with the road locations as viewed on an Ordnance Survey map viewed in a GIS;
- Some road features, for example canyon heights, are not accurate; and
- Traffic flows are not always consistent.

For this reason, some of the data for roads close to sites of interest have been edited to be more consistent with the other available data, for example, road widths and locations as viewed in Google Earth or on Ordnance Survey maps.

Appendix D – Modelling road sources in ADMS-Urban

D.1 Introduction

The information presented in this section is taken from the ADMS-Urban Technical Specification document, P31/01 [23].

In ADMS-Urban, roads are modelled as line sources, with modifications to account for:

- traffic-produced turbulence, and
- street canyons (optional).

The specification for the street canyon module within ADMS-Urban is given in the Technical Specification document P28/01A [24]. Details of the way road sources are represented are given in Section D.2. A description of traffic-produced turbulence is given in Section D.3.

D.2 Road source representation

Road sources are represented as line sources with no plume rise. The concentration C from a finite crosswind line source of length L_s is given by

$$C(x,y,z) = \frac{Q_s}{2\sqrt{2\pi}\sigma_z(x)U}\exp\left(-\frac{(z-z_p)^2}{2\sigma_z^2}\right)\times \left[\operatorname{erf}\left(\frac{y+L_s/2}{\sqrt{2}\sigma_y}\right)-\operatorname{erf}\left(\frac{y-L_s/2}{\sqrt{2}\sigma_y}\right)\right] + \text{reflection terms}$$

where Q_s is the source strength (g/m/s), z is the height above the ground (m), y is the lateral distance from the plume centreline (m), z_p is the height of the plume above the ground (m), U is the wind speed at the plume height (m/s), σ_y is the horizontal plume spread (m) and σ_z is the vertical plume spread (m).

For a road, the height of the plume above the ground is set to be $z_p = z_{s\_road}$ where

$$z_{s\_road} = z_s + h_0 .$$

Here, h_0 is usually referred to as the initial mixing height, and is set to 1m, and z_s is the road height as entered by the user.

In order to represent traffic-produced turbulence in the source, the vertical plume spread parameter, σ_{z_road}, is increased:

$$\sigma_{z\_road}^2 = \sigma_z^2 + h_0^2 .$$

D.3 Traffic-produced turbulence

For busy roads, where the wind direction is near to parallel to the road, extra lateral turbulence will be induced by the traffic. To model this, an extra component of σ_y is included when modelling road sources. (Note that this extra component is not included when modelling street canyons. The street canyon module includes a separate treatment of traffic-produced turbulence.) The formulation of this extra component, $\sigma_{y_{vehicle}}$, is as follows (formulation by D. J. Carruthers):

$$\sigma_{y_{vehicle}} = \sigma_{v_{vehicle}} t \left\{ 1 + \left(\frac{t}{t_d} \right)^2 \right\}^{-1/2}$$

where

$$\sigma_{v_{vehicle}} = b \cdot \left(\frac{N_H U_H A_H + N_L U_L A_L}{W} \right)^{1/2}$$

and the turbulence decay time, t_d, is given by

$$t_d = \left(\frac{w}{\tau} \right) / \sigma_{v_{vehicle}}$$

In the above definitions,

t = time to travel from source to this point(s)
b = constant (0.3) [from OSPM street canyon model]
τ = constant (0.1) [chosen by CERC after testing]
N_H, N_L = number of (heavy, light) vehicles per second
U_H, U_L = speed of (heavy, light) vehicles (m/s)
A_H, A_L = area covered by (heavy, light) vehicle (m^2)
W = road width (m)

The formulation implies that $\sigma_{y_{vehicle}} / \sigma_{v_{vehicle}} \to 0$ as $t \to 0$ and $\sigma_{y_{vehicle}} / \sigma_{v_{vehicle}} \to t_d$ as $t \to \infty$.

If traffic counts are unknown, they are back-calculated by the model from the user-defined emission rate of NO_X, VOC, PM_{10} or CO. For this calculation, it is assumed that the traffic is 95% light goods vehicles, and 5% heavy goods vehicles, and that the speed of the traffic is 50km/hr. If no emissions are defined for any of these pollutants, no traffic-produced turbulence is modelled.