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NON-EXHAUST PARTICULATE MATTER EMISSIONS FROM ROAD TRAFFIC: SUMMARY REPORT

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1 Introduction

TRL Limited, the Division of Environmental Health & Risk Management (DEHRM) at Birmingham University and Cambridge Environmental Research Consultants Limited (CERC) were commissioned by Department for the Environment, Food and Rural Affairs (DEFRA) and the Devolved Administrations to investigate non-exhaust emissions of particulate matter (PM) from road traffic. The main aim of the project was to develop improved prediction methods for emissions and air pollution, primarily for use in the UK National Atmospheric Emissions Inventory (NAEI), based on the existing literature and data. The project was divided into five main Tasks:

- Task 1: A literature review.
- Task 2: Emission model evaluation, development and application.
- Task 3: Initial air pollution model development and application.
- Task 4: Further air pollution model development.
- Task 5: Discussion of abatement options.

This brief Summary Report describes the key findings and recommendations of these Tasks. For more detailed information, the reader is directed to the specific Task Reports. Recommendations for future data collection requirements are also provided. A glossary, explaining some of the terminology used in this Report, is provided in Appendix A.

2 Task 1: Literature review

The Task 1 review summarised the existing information on particle emissions from road vehicle non-exhaust sources, including the methodologies currently employed to measure and model emissions, and provided recommendations for model development during the remainder of the project (Boulter, 2005).

The most important sources of vehicle non-exhaust emission were found to be tyre wear, brake wear and road surface wear (other potential sources include clutch wear, engine wear, abrasion of wheel bearings, corrosion of other vehicle components, street furniture and crash barriers). In addition to these direct sources of particulates, material deposited on the road surface can be resuspended by tyre sheer, vehicle-generated turbulence and the wind. The contribution of each source varies considerably, both temporally and spatially. At present there are no EU regulations designed to control non-exhaust particle emissions, but their relative importance will increase as traffic volume and control of exhaust particle emissions increases.

There was found to be a lack of information in the literature on emission rates, physical properties, chemical characteristics and health impacts of non-exhaust particles. There was also found to be a general lack of consistency in the definitions, terminology and metrics used in the study, and in the reporting of non-exhaust particulate matter, particularly in the case of resuspension. It is not always clear whether primary emissions due to abrasion are included in emission factors for resuspension, and a number of emission models do not include resuspension at all. The findings and recommendations of Task 1 are described in more detail below.

2.1 Emission sources

2.1.1 Tyre wear

Tyre wear is caused by the frictional energy between the tread and road surface. It depends upon the tyre, the vehicle, the road characteristics (surface type, condition, camber *etc*), and how the vehicle is operated. Most tyre rubber is lost during acceleration, braking and cornering. In one study city driving was reported to account for 65% of wear, although only 5% of the distance travelled. It was concluded that for European passenger cars a wear factor of around 100 mg/vkm is typical for average driving conditions, whereas for HDVs the wear factor appears to be an order of magnitude higher. Less than 10% of tyre wear is emitted as PM_{10} under normal conditions. It was concluded that more information is required to link tyre wear PM emissions to real-world driving conditions.

2.1.2 Brake wear

There are two main braking systems, disc brakes and drum brakes. During rapid deceleration, brakes are subject to large frictional heat generation, which leads to the wear of linings and discs. Brake wear emissions tend to occur at junctions, traffic lights, corners and other sites where rapid deceleration occurs. For LDVs and HDVs, total brake wear factors are around 10-20 mg/vkm and 50-80 mg/vkm respectively. Around 50% of the particles generated normally enters the atmosphere, and 80% of the emissions appear to be PM_{10}. The proportion originating from the wear of the brake linings compared with wear of the disc or drum is uncertain. More information is required on the types of brake lining used in the UK, their wear characteristics, and the associated PM emission rates.

2.1.3 Road surface wear

Most of the information on road surface wear comes from Nordic studies on studded tyres, and around 20-30% of airborne dust in major cities in Norway is thought to be due to studded tyres. A wide range of road surface wear factors have been reported, ranging from less than 4 mg/vkm to more than 400 mg/km. This can increase to 4 to 24 g/vkm when road sanding and studded tyres are used in winter. The wear rate increases when the road surface is wet. Vehicle speed, tyre pressure and air temperature are also factors. Surface wear increases at lower temperatures, as the tyre rubber is less elastic. There is little information on the particle size of road wear emissions, although one study found a mean diameter of 1µm.

2.1.4 Corrosion

The corrosion of vehicle components, crash barriers and street furniture can contribute to the particles deposited on the road surface, and consequently to the material resuspended. There is little information on its significance as a direct source of airborne particles.

2.1.5 Resuspension

The dust that collects on the road surface comes from a wide range of sources, not just from vehicles but also from vegetation and nearby sources such as industrial and domestic activities. This dust can be resuspended by vehicle-generated turbulence, tyre shear and the wind. Resuspension is probably one of the larger non-exhaust contributor to roadside PM_{10}. A study in France showed that resuspension may be 3 to 7 times higher than exhaust emissions. Winter maintenance plays a significant part in this, but there is a lack of information on the effects of road salting on resuspension in the UK.

2.2 Emission factors

There are two main approaches for determining emission factors for non-exhaust sources, and the contributions they make to atmospheric particle concentrations. These are direct measurement (either *in situ* or under controlled laboratory conditions) and receptor modelling. However, tyre, brake and road surface wear are difficult to simulate in controlled tests. Resuspension is also particularly difficult to measure, as there is not a closed systems around a vehicle with clear inlets and outlets.

Receptor models are used to allocate PM to a range of sources. There are two main methods of allocating particulates to a source: chemical mass balance, where it is assumed each source emits a characteristic ratio of chemical species, and multivariate statistical techniques which uses techniques such as multi-linear regression and principal component analysis to identify common trends. Identification of the sources of PM at the roadside is very complex.

Models for non-exhaust PM emissions tend to be crude, and often do not take into account vehicle operation, such as the variation in braking under different traffic conditions. More detailed methodologies are required to estimate brake wear more accurately. Most of the information on resuspension is from Nordic countries where studded tyres are used. However, studded tyres are not used in the UK. The contribution from resuspension is a significant weak area in current models. The emission factors used in the United States are much higher than those measured in Europe, and this may be because of particularly dry and dusty conditions in the former.

2.3 Recommendations

It was concluded that more detailed information needs to be obtained on the non-exhaust emission sources mentioned in the review, as well as specific data for UK conditions, to enable models to be applied in this country. It was recommended that the performance of various models should be evaluated for a range of UK conditions using real data, and alternative development methods for modelling emissions sources and resuspension should be explored. These points were addressed in Task 2.

3 Task 2: Emission model evaluation, development and application

In Task 2, a number of existing emission modelling approaches for non-exhaust PM were assessed, and recommendations were made for the NAEI. Some initial steps were taken towards further model development, although this development was restricted by the lack of suitable experimental data. Emission factors for resuspension were estimated using traffic data and ambient air pollution data from a number of sites in London (Boulter *et al.*, 2006a). The Task 2 report describes the findings of the evaluation of existing non-exhaust particulate models, the development of improved modelling approaches, and the application of these to the UK.

Task 2 was broken down as follows:

Task 2a Model evaluation and development
2a(i) Emissions due to abrasion sources
2a(ii) Emissions due to re-suspension
Task 2b Model application

3.1 Model evaluation and development

3.1.1 Emissions due to abrasion

In Task 2a(i) existing models for the abrasion sources (tyre wear, brake wear and road surface wear) were identified and evaluated. The evaluation focussed on the EMEP, RAINS, CEPMEIP and MOBILE methods. Prediction methods for total emissions of non-exhaust particles were also examined. No independent test data were available to assess the absolute accuracy of the models, and therefore the evaluation was based on comparisons between the emission factors for the different PM fractions and vehicle categories. The size fractions considered in most detail were PM_{10} and $PM_{2.5}$, for which all models provided information. PM_1 and $PM_{0.1}$ were examined in less detail. The models varied considerably in the emission factors they produced. The EMEP method, which is currently used in the NAEI, is the most detailed approach, incorporating corrections for both speed and, in the case of HDVs, load. No new data sets or methodologies have been created since it was developed, so no improvements could be made to the EMEP methodology. The HDM-4 tyre consumption model offers possibilities in terms of modelling PM emissions, but further work is required. There is only a limited amount of PM emissions data from brake wear, so no prediction model could be developed.

3.1.2 Emissions due to resuspension

In Task 2a(ii), different emission modelling methods were used to develop an improved method for estimating emissions due to resuspension at specific locations. In order to estimate PM_{10} emissions due to resuspension, simultaneous measurement of PM_{10} and $PM_{2.5}$ in ambient air at roadside and background monitoring sites was carried out. The main location monitored was Marylebone Road in London. The total emissions attributable to non-exhaust sources were expressed as the sum of the direct contribution of abrasion sources (brake, tyre, and road wear) and the resuspended component.

It was found that resuspension accounted for 43-49% of total non-exhaust emissions. Resuspension emissions were around 30% of the magnitude of exhaust emissions, and HDVs were responsible for the vast majority of resuspension. Emission factors for resuspension due to HDVs ranged from 139 mg/vkm to 145 mg/vkm. These values appeared to be lower than those reported in the literature. Much smaller emission factors were obtained for LDVs. It was proposed that vehicle-related turbulence initially suspends particles, and then the natural wind keeps the particulates suspended. This results in the amount of resuspension increasing with wind speed.

One issue which could have potentially affected the results was the different placement of the PM_{10} and $PM_{2.5}$ instruments on Marylebone Road. The instruments were located at slightly different distances from the road, and the presence of a concentration gradient perpendicular to the road could have affected the resuspension emission estimates. In a study of the concentration gradients on Marylebone Road, Green and Fuller (2004) carried out two kinds of investigation. The first was an instrument co-location study, and the second a gradient study. The co-location study used identical instruments placed at the same distance from the kerb but at a separation of a few metres from each other, and showed differences between the two instruments of 3.6 $\mu g\ m^{-3}$ for PM_{10} and 2.9 $\mu g\ m^{-3}$ for $PM_{2.5}$. In the gradient study, the mean differences (kerbside minus roadside) were 3.5 $\mu g\ m^{-3}$ for PM_{10} and 1.7 $\mu g\ m^{-3}$ for $PM_{2.5}$. The gradient study therefore showed smaller mean differences between instruments than the co-location study. The reasons for the differences in the co-location study were unclear, but could have been related to instrument factors such as the inlet cut-point or the accuracy of the gravimetric sensors, or could have reflect real spatial gradients which, in a location such as Marylebone Road, are as likely to occur in the plane parallel to the kerbside as in the orthogonal plane. It was concluded that the data from the study by Green and Fuller (2004) did not give a clear insight into the magnitude of a concentration gradient on Marylebone Road, and could not therefore be used to assess the sensitivity of the resuspension estimates to instrument location in this project.

3.2 Model application

Task 2b involved the calculation of non-exhaust PM emissions in the UK, based on a revised set of emission factors. However, due to the lack of new data, the production of revised emission factors for tyre, brake and road surface wear was not possible. Therefore, for these sources the EMEP modelling method was used for this work. For resuspension only broadly indicative values were available from the analysis of the Marylebone Road and Bloomsbury data. The emission factors were weighted by the traffic activity statistics used in the NAEI in order to calculate emissions of PM_{10}, $PM_{2.5}$, PM_1 and PM_{coarse} in the UK. Regional emissions for 2002 and 2003 were also calculated.

3.3 Recommendations for future work

It was concluded that more extensive empirical data were needed to improve emission models. This includes information on the following:

- Tyre, brake and road surface materials in use.
- Component wear factors for real-life vehicle operation in UK.
- Compositions of tyre and brakes available in UK.
- Sampling of tyre, brake and road surface wear particles in controlled laboratory conditions (*e.g.* to determine particle size distributions).
- *In-situ* measurements of non-exhaust particulates using instrumented vehicles with PM sensors being used to capture tyre, brake, road surface and resuspended particles as they are produced.
- Receptor modelling studies based on new source profiles at a range of locations (ideally 5 or 6 roadside and urban background pairs), including chemical composition measurements to identify source of particulates. Comparisons between receptor modelling studies inside and outside of road tunnels could assist in the understanding of resuspension processes.
- Investigation to the wind speed dependence of the calculated resuspended particle emission factor.

- Investigation into precipitation-related effects as total rainfall appears to be inadequate. Duration of rainfall events, the rainfall intensity and hence run-off should be included in the study.
- Investigation into the role of winter maintenance regimes in the UK.

4 Tasks 3 and 4: Initial and further air pollution model development and application

Tasks 3 and 4 involved the development of an improved dispersion modelling capability for non-exhaust PM. This work was based upon the adaptation and development of the ADMS-Urban air pollution model to estimate PM_{10} and $PM_{2.5}$ concentrations and their component parts, using the non-exhaust emission factors from Task 2 (Stocker and Carruthers, 2007). The emissions software tool EMIT was used to perform the emission calculations. Model outputs were compared with concentration data obtained from London and Birmingham, and the accuracy of non-exhaust emission factors was discussed.

4.1 Findings

Non-exhaust processes are an important source of particulate matter, constituting approximately 50% of PM_{10}, 25% of $PM_{2.5}$ and 90% of the coarse fraction (PM_{coarse}) of road traffic emissions. Vehicle exhaust is primarily in the $PM_{2.5}$ range, although there is some debate regarding the exact proportion of coarse component. Derivation of the resuspension emission factors using the method developed in Task 2 assumed that vehicle exhaust is wholly $PM_{2.5}$. It was then assumed that the coarse component represented 6% of the total exhaust PM, and this led to a reduction in the resuspension emission factor for heavy-duty vehicles of almost 18%. This uncertainty led to two emissions scenarios being developed, the first using the resuspension emission factor derived in Task 2, and the second using the factor derived assuming that the coarse component of vehicle exhaust is 6%.

Due to the lack of information on road surface wear and resuspension emissions, the emission factors from these sources are sometimes combined in order to reduce the errors generated when deriving values from small datasets. One objective had been to investigate how the predicted PM concentrations differed when these emission factors were treated first separately, and then as a combined value. However, during preliminary emissions investigations it was shown that the way in which the resuspension emission factors had been derived from the Marylebone dataset during Task 2 (*i.e.* assigning the 'remainder' of concentrations to resuspension, and using the EMEP emission factors for road wear in both sets of calculations) resulted in a negligible quantitative difference between treating the road surface wear and resuspension emission factors separately, or as a combined value. Therefore, two emissions scenarios were carried forward through to the dispersion modelling stage of the project. Both scenarios used the same tyre, brake and exhaust emission factors for PM_{10} and $PM_{2.5}$, the same $PM_{2.5}$ road wear factors, and a zero $PM_{2.5}$ emission factor for resuspension. The year-dependant scaling for non-exhaust emissions was assumed to be unity (*i.e.* no year-on-year changes were included in the non-exhaust emission factors).

ADMS-Urban was used to predict concentrations of PM_{10} and $PM_{2.5}$ at seventeen monitoring sites. Emissions from road and industrial sources near to the monitors were modelled explicitly, and emissions from a larger area were included in a grid. Hourly mean background PM concentrations, which were dependent upon wind direction, were used in the model.

The inclusion of the non-exhaust PM emission factors in the ADMS-Urban dispersion model led to good predictions of the monitored PM_{10} values at the majority of sites. For both the emission scenarios considered, on average, the model over predicted the measured concentration values by 6%. The lack of a significant difference in the results between the two scenarios is of interest, as it demonstrates that whilst including all the non-exhaust emission factors is important, it is useful to remember that even at heavily trafficked sites the proportion of PM_{10} concentrations due to the traffic itself is less than 50%, with the remainder of the concentration being from background sources (these conclusions were confirmed by the source apportionment analyses performed as part of the project).

The concentrations of $PM_{2.5}$ at the monitoring sites were, on average, over-predicted by 26% when using the model. PM_{coarse} concentrations were under-predicted by just over 10%. However, a significant source of uncertainty in the comparison of modelled and measured data for $PM_{2.5}$ is the factor used in the conversion from TEOM PM units to gravimetric PM units. In general, for $PM_{2.5}$ a conversion factor of 1.3 has been used. Different ratios have been tested, and these indicated that ratios other than 1.3 might be appropriate at different sites. Further work is required to clarify this issue.

Emissions from major and minor roads were modelled using example roads. For the major road having a higher proportion of heavy vehicles, total vehicle emissions consist of over 60% from the heavy vehicles. For the minor road this fell to 20%. However, the proportion of non-exhaust emissions from light vehicles actually exceeded that from heavy vehicles. This was explained by the relative proportions of emissions from light and heavy vehicles. Exhaust emissions for light vehicles are about 10% of those from heavy vehicles, emissions from tyre, brake and road wear are between 20% and 31% of heavy vehicle emissions and resuspension emissions from light vehicles are negligible compared with heavy vehicles. As a result, it was found that on a road where the traffic predominately consists of light vehicles, the proportion of non-exhaust emissions is more significant than for a road with more heavy vehicles.

In the standard version of the ADMS-Urban model, all emissions from traffic are modelled as if they are derived from the exhaust. That is, in an attempt to represent the average height of the exhaust pipe, the buoyancy of the release and, to some extent, the turbulence generated in the wake of a moving vehicle, the line source that represents the road is taken to be at a height of 1 m and the emissions are assumed to be well mixed over a height of 2 m. For the special case of particulates, however, a significant proportion of the emission does not come from the exhaust pipe. Both the source height and the buoyancy of non-exhaust emissions differ from exhaust emissions, although the dispersion of all emissions is affected by the vehicle wake. The impact of altering emissions properties of the various traffic components was therefore investigated. In particular, the initial mixing height parameter for various elements - exhaust, tyre, brake, road wear and re-suspension - was varied. This had a significant effect on concentrations, particularly close to the road. However, as would be expected, this effect decreased with distance from the road. Further work on this, including the relative buoyancy of the releases, would help to clarify the significance of these effects.

4.2 Recommendations

The small model overestimate of the PM_{10} values may indicate that the non-exhaust emission factors are slightly too high. Although a 6% difference between modelled and measured values is acceptable, one would expect that for the particular case of modelling PM emissions - where, during some of the modelling period and at some of the sites there was likely to have been a local source of coarse PM (such as a construction site that was not accounted for in the study) - the model should slightly underestimate measured values. Furthermore, it is possible that the method used to derive the resuspension emission factors during Task 2 may have led to an overestimation of the resuspension emission factors. That is, the method assumed that the ratios of the measured roadside concentration increment to traffic emissions of NO_x and PM_{10} are the same, whilst in reality the results from Task 3 demonstrated that the ‘concentration per emission’ value for some of the non-exhaust emissions that are released close to the ground (tyre, brake and road wear) is greater than the higher, more buoyant, exhaust emissions. Further work could involve revisiting the derivation of the resuspension emission factor, taking into account the different emission properties of the various traffic components.

As mentioned earlier in this Report (Section 3.1.2), the $PM_{2.5}$ and PM_{10} monitors at Marylebone Road were not exactly co-located. In the ADMS-Urban modelling, the location of the $PM_{2.5}$ monitor was taken to be at the same location as the PM_{10} monitor, whereas in fact the $PM_{2.5}$ monitor was located around 2.5 m further away from the kerb. It is likely that the model over-prediction of $PM_{2.5}$ concentrations at Marylebone Road of 16% can be explained by this error in model set up. It is recommended (at the very least) that the model be re-run using the correct location of the $PM_{2.5}$ monitor. Then, ideally, it would be useful to repeat the investigations into the $PM_{2.5}$ TEOM to gravimetric conversion factors presented in Section 5.2.2 of Stocker and Carruthers (2007).

In addition, further work to investigate whether the use of a single conversion factor from TEOM units to gravimetric units at all sites is appropriate. This would particularly help in the comparison of modelled and measured $PM_{2.5}$ results. However, since the completion of this phase of the study, Defra have published the results of the particulate monitoring equivalence study, which has recommended the use of Filter Dynamics Measurement System (FDMS) in conjunction with TEOMs. Therefore the use of the TEOM conversion factor will eventually become a less significant issue, as units are updated with FDMS or replaced.

In order to gain further insight into the validity of non-exhaust emission factors, the modelling of emissions in terms of their chemical components would allow comparisons to be made with measured data. Similarly, the analysis of results of dispersion modelling and measurement in terms of seasonal variation would determine whether non-exhaust emission factors require a seasonal component.

Finally, further work on the effect of varying the initial mixing height parameter, and the inclusion of the relative buoyancy and velocity of exhaust and non-exhaust particulate emissions, is required to quantify the effect on concentrations levels close to the road.

5 Task 5: Discussion of abatement measures

The work on Task 5 involved a review of abatement measures for non-exhaust PM (Boulter *et al*., 2006b). The findings and recommendations of the review are summarised below. As a result of limited data in a number of key areas, the assessment was largely subjective.

5.1 Findings

The Report indicated that the two principle non-exhaust PM sources are likely to be resuspension and brake wear, and potential abatement measures for these two sources (and abrasion sources other than brake wear) were addressed separately.

The AP-42 emission calculation method of the United Stated Environmental Protection Agency (USEPA) strongly implies a link between mean vehicle weight and resuspension. One control option might therefore be to introduce vehicle weight restrictions in areas where PM levels are close to air quality standards and objectives. The AP-42 also implies a weaker, but still significant, dependence on silt loading. Therefore, measures to reduce silt loading would be beneficial in areas where PM levels are close to air quality standards and objectives. However, the evidence indicates that current street-sweeping practices are not particularly beneficial in reducing airborne particulate matter, although street sweeping may have a beneficial effect in removing larger particles before they can evolve into small airborne particles. There are many factors which appear to affect this, and further research may clarify the picture.

The effects of de-icing compounds on ambient concentrations of particulate matter are mixed. Some have led to a reduction in PM¬10 concentrations, whereas others appear to show a detrimental effect on resuspension. Further work is required in this area.

Research in the US into the effect of rainfall shows little impact on resuspension. This finding is consistent with the modest effects seen in the analysis of UK data during the project.

Few tests have been reported on the use of dust suppressants, and most relates to unpaved roads. The effectiveness of these on paved roads, and their environmental and health impacts, require further work.

The planting of vegetative traps may have a minor effect on resuspension, but large-scale planting is not a realistic proposition in urban areas.

Vehicle design measures have the potential to have some effect on non-exhaust PM emissions, but in most cases these are generally not likely to be significant. Regenerative braking systems and enclosed braking systems appear to offer some effectiveness as abatement measures.

5.2 Recommendations

Further research is required into the evolution of the size distribution of the material on the road surface. This could have important implications for the effectiveness of street-sweeping programmes. It is further recommended that consideration be given to establishing a testing and certification scheme for street-sweeping systems, with the explicit objective of not only reducing the mass of particulate matter on the road surface, but through their performance in influencing the removal of the finer particles.

The effects of de-icing compounds on resuspension are mixed. This area requires further research in the UK. Similarly, the potential use of dust suppressants in locations where PM concentrations are high (*e.g.* construction sites and waste transfer stations) requires further research. As well as evaluating their effectiveness the potential environmental and health impacts must be considered.

Some basic measures, such as regular washing of vehicle wheels, wheel arches, *etc*. could impact the quantity of material deposited on the road, and hence resuspension.

6 Overall recommendations from the project

One of the clearest messages from this project was that without new experimental data the emission factors for non-exhaust PM sources will remain highly uncertain. In order to improve the understanding of non-exhaust PM in the UK, a number of general recommendations are provided below.

1. *Tyre, brake and road surface materials in use*. Many different brake and tyre types are in use in the UK, but little information on the structure of the UK market, the performance of different materials, and the use of different types by location, has been reported in the scientific literature. Similarly, there is a need to understand the different road surfaces used in the UK by road type and geographic location. A survey of materials in use would assist in the design of future experimental work and modelling approaches.
2. *Component and road surface wear factors*. Although some wear factors for tyres and brake linings are available in the literature, there is little information specifically for the UK, and the relationships between wear and real-world vehicle operation are not well understood. Furthermore, the relative wear factors for brake linings and brake discs are not well documented. Even within the UK, there are many types of road surfacing materials, sources of aggregates and fillers. Little information exists on the abrasion of road surfaces and their contribution to roadside PM concentrations. Further information of this type is required for modelling purposes.
3. *Source characterisation*. The compositions of the various tyre and brake lining formulations used in the UK have not been reported in detail. An extensive examination of the composition of the tyres and brakes available on the UK market is required. It would also be useful to examine the extent to which tyre tread and brake lining material are altered during use, and to analyse the tyres, the brake lining, and the brake dust from same in-service vehicles at regular intervals. Further work is also required on the quantification and evolution of the amount and size distribution of the material on the road surface, and with the composition of non-exhaust emissions determined more precisely, particulates sampled in ambient conditions should be analysed to determine the occurrence of the species. Where possible, elemental and/or organic molecular tracers for the different source materials need to be identified.
4. *Laboratory-based experiments*. Further sampling and measurement of tyre, brake and road surface wear particles is required under controlled laboratory conditions (*e.g.* to determine particle size distributions), and using analytical equipment which cannot easily be deployed in the field.
5. *Real-world measurements using instrumented vehicles*. The measurement of non-exhaust particles could be conducted *in situ* using instrumented vehicles under a range of real-world operating conditions. Some experiments of this type have already been conducted in the United States.
6. *Further source apportionment studies*. Source apportionment studies for airborne PM at a varied range of locations, and based on new source profiles, would contribute significantly to the understanding of non-exhaust PM in the UK. A combination of measurement and modelling would provide the greatest

insights. Comparisons between apportionment studies inside and outside of road tunnels could also assist in the understanding of resuspension processes, including the effects of wind-speed and rainfall. The sensitivity of emission estimates to factors such as instrument location need to be further investigated.

7. *Recalculation of emission factors.* The study has been valuable in developing plausible emission factors for particles resuspended from the road surface. However it is recommended that a new derivation of emissions factors be undertaken using more precise descriptions of the different source characteristics of the different particulate components thus avoiding the implicit assumption in the current derivation that PM_{10} and NO_X are all emitted from identical sources. In addition, an analysis of similar datasets from other sites with different traffic characteristics would considerably enhance knowledge of the emission factors for abrasion products and resuspended particles, and their dependence upon traffic speed, driving mode and road surface condition.

8. *Assessment of abatement measures*. The effects of abatement measures - such as road-sweeping, de-icing compounds and dust suppressants - on resuspension are mixed. This area requires further research in the UK. Some basic measures, such as regular washing of vehicle wheels, wheel arches, *etc*. could impact the quantity of material deposited on the road, and hence resuspension. It is further recommended that consideration be given to establishing a testing and certification scheme for street-sweeping systems.

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Appendix A: Glossary

ADMS-Urban	Air pollution model developed by Cambridge Environmental Research Consultants.
CEPMEIP	Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance.
EMEP	Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air pollutants in Europe.
HDM-4	The Highway Development and Management Model developed by the World Bank.
HDVs	Heavy-duty vehicles (heavy goods vehicles and buses) >3.5 tonnes gross vehicle weight.
HGVs	Heavy goods vehicles, >7.5 tonnes gross vehicle weight.
LDVs	Light-duty vehicles (cars and light goods vehicles), <3.5 tonnes gross vehicle weight.
MOBILE	A road transport emission model developed by the USEPA.
NAEI	National Atmospheric Emissions Inventory.
PM_{10}	Mass concentration of particles passing through a size-selective inlet designed to exclude particles greater than 10 µm aerodynamic diameter.
$PM_{2.5}$	Mass concentration of particles passing through a size-selective inlet designed to exclude particles greater than 2.5 µm aerodynamic diameter. These are sometimes referred to as 'fine' particles.
$PM_{2.5-10}$ or PM_{coarse}	Mass concentration of 'coarse' particles, determined as the difference between PM_{10} and $PM_{2.5}$.
PM_1	Mass concentration of particles passing through a size-selective inlet designed to exclude particles greater than 1 µm aerodynamic diameter.
$PM_{0.1}$	Mass concentration of particles of diameter smaller than 0.1 µm. These are sometimes referred to as 'ultrafine' particles.
RAINS	Regional Air Pollution Information and Simulation model, developed by the International Institute for Applied Systems Analysis.
TEOM	Tapered Element Oscillating Microbalance – an instrument for measuring airborne PM.
USEPA	United States Environmental Protection Agency.
vkm	vehicle-kilometre.