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PUBLISHED PROJECT REPORT PPR230

A REVIEW OF ABATEMENT MEASURES FOR NON-EXHAUST PARTICULATE MATTER FROM ROAD VEHICLES

Version: Final

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Prepared for: Project Record:	**CPEA23** **NON-EXHAUST PARTICULATE MATTER EMISSIONS FROM ROAD TRAFFIC**
Client:	**Department for the Environment, Food and Rural Affairs, Scottish Executive, Welsh Assembly Government, and the Department of Environment in Northern Ireland** **(Tim Williamson)**

This report has been prepared for DEFRA and the Devolved Administrations under Project CPEA23/SPU82. The views expressed are those of the authors and not necessarily those of DEFRA and the Devolved Administrations.

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Executive summary

TRL Limited, the Division of Environmental Health & Risk Management at Birmingham University and Cambridge Environmental Research Consultants Limited were commissioned by DEFRA 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, 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 Report presents the findings of Task 5. Potential abatement options include a mixture of technical and policy approaches, and relate to both vehicles and infrastructure. Some types of abatement measure address a single source, whereas others address more than one source. However, there are relatively few technologies and policies which have been developed specifically to address non-exhaust PM emissions from road vehicles. Consequently, the literature on the effectiveness of such measures is limited.

The most effective measures are likely to be those which target with high efficiency those sources making the largest contribution to non-exhaust particles. The analysis of data from Marylebone Road in London showed that two sources are dominant: resuspension and brake wear. The means of controlling these two sources (or, more generally, resuspension and abrasion) are, in most cases, rather different. The abatement measures discussed in the Report include the following:

- Improved materials, such as hard-wearing tyre, brake and road surface compounds.
- Particle collection and destruction methods, such as enclosed brakes and wheels, filtration and electrostatic precipitation.
- Improved vehicle design.
- Infrastructure, such as the planting of vegetative particle traps.
- Road and vehicle cleaning measures, such as street sweeping and vehicle washing.
- Improved inspection and maintenance regimes.
- Other measures, including the use of dust suppressants and de-icing liquids, and the regulation of agricultural practices.

The various measures were tentatively rated according several factors, including the likely impact in terms PM emissions and technical feasibility. With the exception of road sweeping/washing and the use of de-icing compounds, hardly any of the published literature refers specifically to the effectiveness of abatement options for non-exhaust PM emissions.

According to the resuspension function in the USEPA's AP-42 model, reductions in average vehicle weight and road silt loading ought to have significant benefits in terms of reducing resuspension. One control option might therefore be to introduce vehicle weight restrictions (particularly for HGVs) in areas where PM levels are close to air quality standards and objectives.

The available data do not support the idea that de-icing salt is a significant source of airborne PM in UK cities, and a reduction of road salt grit application is likely to have minimal influence. There is evidence that some de-icing compounds, such as calcium magnesium acetate (CMA), can lead to reductions in PM_{10} concentrations. The application of CMA may therefore be one option for ensuring compliance with air quality standards, in particular in relation to the number of exceedences of the PM_{10} daily mean limit of 50 μgm^{-3}. However, other liquids, such as brine, appear to have a detrimental effect on resuspension. This area requires further research in the UK.

The evidence currently indicates that road sweeping is not a particularly effecting means of reducing PM_{10} concentrations, but sweeping may have a beneficial effect on air quality over the long term if it can remove particles that may evolve into PM_{10}. Further work is required to determine the evolution of the size distribution of the material on the road surface, and to establish the mechanism of fragmentation, as this could have important implications for the effectiveness of street sweeping programmes. It is thus proposed that consideration should be given to establishing a testing scheme that would identify the most effective road sweeping systems. This could be used as the basis for a certification scheme.

The planting of vegetative traps may have a minor effect on resuspension via the retention of particles which would otherwise be available for resuspension. However, the effects are not well known, and large-scale planting is not a realistic proposition for urban areas where exceedences of PM limit values are the most common.

The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could also have an impact on the amount of material deposited on the road, and hence resuspension. It is also fairly undemanding technically, although changes to the infrastructure would be required to allow for the routine washing of heavy-duty vehicles.

The vehicle-based collection and destruction of some types of particle is feasible and could be effective. However, as there are currently no legislative requirements for vehicle manufacturers to control non-exhaust PM, it is doubtful that the relevant technologies will be introduced into vehicles in the near future. Little is known about the effectiveness of vehicle-based abatement options.

Regenerative braking could lead to significant reductions in brake wear particles, but this applies principally to electric and hybrid vehicles, and these are currently only produced in small numbers.

Further work is required to evaluate the potential for using dust suppressants at locations where PM concentrations are high. Such work would need to consider the effectiveness of different suppressants, as well as potential effects on health and the local ecosystem.

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1 Introduction

1.1 Overview

TRL Limited, the Division of Environmental Health & Risk Management (DEHRM) at Birmingham University and Cambridge Environmental Research Consultants Limited (CERC) have been commissioned by DEFRA to investigate non-exhaust emissions of particulate matter (PM) from road traffic. The main aim of the project is 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 is 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.

The work on these five Tasks will be summarised in a Final Report, in which future data collection requirements will also be prioritised.

The Task 1 review summarised the available information on particle emissions from 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). 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.*, 2006). Tasks 3 and 4 addressed the issues relating to the development of an improved dispersion modelling capability for non-exhaust PM. This work involved the adaptation and development of the ADMS-Urban air pollution model to estimate PM_{10} and $PM_{2.5}$ concentrations and their component parts, based upon the non-exhaust emission factors from Task 2 (Stocker, 2006).

This Report presents the findings of Task 5 - a review of abatement measures for non-exhaust PM. It is assumed that the reader is familiar with the general terminology employed to describe airborne PM. Readers seeking a comprehensive discussion are directed to the reports of APEG (1999) and AQEG (2005). A glossary, explaining some of the terminology used in this Report, is provided in Appendix A.

1.2 Airborne particulate matter

Airborne PM is a complex mixture of organic and inorganic substances, in solid or liquid form, which undergoes modification or transformation in the atmosphere. It is derived from a wide variety of sources, both natural and anthropogenic, and displays a range of physical and chemical properties. Particles are termed either ‘primary’, where they are emitted directly into the atmosphere, or ‘secondary’ where they are formed by reactions between gas-phase components such as sulphur and nitrogen oxides, ammonia, and organic compounds.

Particles in the atmosphere range in size from less than 10 nm to around 100 µm. It is common to see them described in terms of three recognised modes relating to the typical shape of the size distribution and corresponding sources: the nucleation mode, the accumulation mode, and the coarse particle mode. The contributions of different sources to mass concentrations in these different modes vary with many factors, including location, season, time of day, and both local and regional weather conditions.

The nucleation mode consists of particles emitted directly from combustion sources, such as road vehicle exhaust, waste incineration, and industrial and domestic burning. Nucleation mode particles typically have a diameter of less than around 0.05 µm. Even though such particles may be present in large numbers, each particle is so small that this mode usually forms only a small proportion of the total aerosol mass. Nucleation mode particles reside in the atmosphere for a few hours, and are transformed by coalescence and condensation into larger accumulation mode particles.

Accumulation mode particles range between around 0.05 µm and 1 µm in diameter, have atmospheric residence times of tens of days, and usually form a significant fraction of the total aerosol mass. They are also efficient light scatterers, and often dominate optical effects such as visibility. As well as being formed via the coagulation of nucleation mode particles, accumulation mode particles originate from primary emission sources and gas-to-particle transformations in the atmosphere.

Particles larger than around 1 µm form the coarse particle mode, and typically include wind-blown crustal matter and material released during abrasion processes. It is clear that the alternative definition of coarse particles based on measurement metrics (*i.e.* PM_{10} minus $PM_{2.5}$) is not altogether consistent with this definition. Coarse particles have shorter residence times than accumulation mode particles, although they can contribute substantially to total aerosol mass.

1.3 Non-exhaust particulate matter

The PM generated by road transport activity can also be categorised according to its mechanism of formation. It is often assumed that diesel exhaust is the main source of PM from road vehicles, and exhaust emissions have been extensively characterised in the laboratory under well-defined test conditions. However, there are a number of non-exhaust processes, involving mechanical abrasion and corrosion, which can also result in PM being released directly to the atmosphere. The main abrasion processes leading to the direct emission of PM are tyre wear, brake wear and road surface wear. Other potential sources of direct emissions are clutch wear, engine wear, the abrasion of wheel bearings, and the corrosion of other vehicle components, street furniture and crash barriers. In addition to direct non-exhaust emissions, material previously deposited on the road surface can be suspended or resuspended in the atmosphere as a result of tyre shear, vehicle-generated turbulence, and the action of the wind. In the case of road transport, it is commonly assumed that most primary fine particles ($PM_{2.5}$) are emitted from the exhaust, whereas many of the coarse particles ($PM_{2.5-10}$) are considered to originate from non-exhaust sources. This over-simplifies the situation somewhat; whilst there is a general agreement that exhaust emissions can be classified as $PM_{2.5}$, there is evidence to suggest that non-exhaust particles contribute to both the fine and coarse modes.

Some of the concerns relating to non-exhaust particular matter were highlighted by Boulter (2005). These include the lack of regulation, the increasing contribution to total PM emissions, uncertainties, and health effects. As a result of increasingly stringent exhaust emission legislation, and the associated development and application of new technologies, the mass concentration of particles in the exhaust of diesel engines has reduced steadily over the last 20 years. As exhaust emission control technology improves and traffic levels increase, the proportion of total PM mass emissions originating from the uncontrolled non-exhaust sources will increase. Resuspension is a particular concern. Studies show that dust and silt from paved roads and other traffic-related emissions are major sources of suspended PM in the urban areas (*e.g.* Chow *et al*., 1990; Kuhns *et al*., 2003). Specific health concerns include the allergenicity of paved road dust emissions (Miguel *et al*., 1999), tyre constituents such as polycyclic aromatic hydrocarbons (PAHs) and latex, and the heavy metals used in brake linings. Furthermore, many of these compounds, in addition to having potentially 'toxic' properties are classified as respiratory sensitizers, which can trigger irreversible allergic reactions in the respiratory system. Once this sensitising reaction has taken place, even trace repeat exposure to these substances can produce symptoms. However, the data relating to the emission rates, physical properties, chemical characteristics, and health impacts of non-exhaust particles arising from such sources are far from comprehensive.

1.4 Abatement measures for non-exhaust particulate matter

Knowledge of the effectiveness of emission abatement strategies is needed to develop practical strategies for reducing ambient pollutant concentrations. Compliance with air quality standards for PM_{10} requires control of both fine and coarse particles. As the two modes tend to have different sources and formation mechanisms, different tyres of control are required. Primary fine particles from combustion sources are subject to regulation. For example, all new light-duty vehicle (LDV[1]) models and heavy-duty engine models sold in the UK must be type approved with respect to exhaust emissions in accordance with European Union Directives. The measurement of total exhaust particulate mass has been defined in regulation for diesel engines and vehicles since 1988. The control of coarse particles is less straightforward (Harrison *et al*., 2001), as such particles arise from natural and anthropogenic disruption and attrition processes which are difficult to characterise (*e.g.* non-exhaust emissions, resuspension, dust from industrial processes, quarrying). There are currently no legal requirements for the control of road vehicle non-exhaust PM in the EU, although certain regulations which are designed for other purposes could influence non-exhaust PM emissions indirectly. Such regulations include restrictions on the use of studded tyres in certain countries to reduce damage to the road surface, and road/tyre noise standards.

Potential abatement options for non-exhaust PM include a mixture of technical and policy approaches, and can relate to both vehicles and the infrastructure. Some types of abatement measure address a single source, whereas others address more than one source. In terms of controlling resuspension from paved roads, measures can either be designed to prevent material from being deposited onto the surface in the first place (preventive controls) or to remove any material that has already been deposited (mitigative controls) (Fitz and Bufalino, 2002). Improvements in vehicle technology are essentially preventative in nature, in that they reduce the primary generation or release of abrasion products, whereas policies (*e.g.* road sweeping programmes) tend to be mitigative in nature. Another potential type of measure involves 'adaptation' to reduce exposure to existing levels of pollution. Measures of this type might include improved sealing of vehicle passenger compartments and buildings, or re-routing main roads away from areas of population. However, such measures are beyond the scope of this Report.

Given the range of possible measures, it is difficult to provide a definitive classification, and some measures are likely to have dual benefits. For example, a system designed to reduce brake wear particle emissions could affect both the quantity of particles released directly into the air and the amount of material deposited on the road surface for subsequent resuspension. Road surface wear is mentioned only very briefly in the Report. According to Kennedy *et al.* (2002), there are no industry publications, standards or rules of thumb relating to actual material loss rates from road surfaces. Where there is reference to road surface wear, this usually concerns rutting, deformation, roughness and cracking rather than material loss by attrition. The loss of material is not actually recognised as a phenomenon. In most work looking at tyre/road surface interactions, any material loss is dominated by the wear material from the tyre treads. Only in the Scandinavian countries has any work been done on material loss from the road, usually in the special case of using studded tyres.

Clearly, the most effective measures are likely to be those which target with high efficiency those sources making the largest contribution to non-exhaust particles. Using the data for Marylebone Road, London, from the earlier part of this study, it was possible to disaggregate the non-exhaust particles in the $PM_{2.5-10}$ size range according to their individual source type. The results of this exercise are given in Table 1.

Table 1: Emissions of $PM_{2.5-10}$ from abrasion and resuspension sources at Marylebone Road, London (adapted from Boulter *et al*., 2006).

Year	Brake wear ($g\ km^{-1}\ d^{-1}$)	Tyre wear ($g\ km^{-1}\ d^{-1}$)	Road wear ($g\ km^{-1}\ d^{-1}$)	Resuspension* ($g\ km^{-1}\ d^{-1}$)
2000	854	270	411	1696
2001	794	250	382	1366
2002	764	250	365	1300
2003	783	242	376	1541
Average (%)	799 (27.5)	251 (8.6)	384 (13.2)	1476 (50.7)

* Taking an average of the values calculated using London Bloomsbury and Bexley as background.

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[1] In this report, the term 'light-duty vehicle' refers to all vehicles with a gross weight of less than 3.5 tonnes, and includes both cars and light goods vehicles. All vehicles having a gross weight of more than 3.5 tonnes are termed heavy-duty vehicles (HDVs).

Since our earlier work showed different results when using London Bloomsbury and Bexley as representative of the urban background concentrations, an average of the two has been taken in estimating the resuspension component. The abrasion components (brake wear, tyre wear and road surface wear) have been estimated from standard emission factors, as outlined in the Task 2 Report (Boulter *et al*., 2006). Table 1 shows clearly that two sources are dominant, and together represent more than three quarters of the source strength of non-exhaust particles. These are resuspension (50.7%) and brake wear (27.5%). The means of controlling these two sources (or, more generally, resuspension and abrasion) are, in most cases, rather different and they will be examined separately.

1.5 Report structure

Measures which are currently available for the abatement of non-exhaust PM, and those which have the potential to make an impact in the future, have been be considered in this review, and the findings are presented in the subsequent Chapters. It should be noted that measures which will normally (in very general terms) lead to reductions in all pollutant emissions (*e.g.* reducing the amount of traffic on the road, reducing journey lengths, promoting fuel-efficient driving styles or limiting the speed and weight of vehicles) are not included here.

In the opinion of the authors, the most important non-exhaust source is, at many locations, likely to be resuspension. Consequently, the most attention has been given to this source, and it is addressed in Chapter 2. Chapter 3 deals with tyre wear and brake wear emissions, with the abatement options relating primarily to preventative vehicle technologies. For the reasons stated earlier, road surface wear is mentioned only very briefly.

In Chapter 4, consideration is given to the likely effectiveness of the various abatement options. This is highly speculative at this stage, given the scarcity of relevant information in the literature. Chapter 5 summarises the main findings of the Report, and Chapter 6 provides the conclusions and recommendations.

2 Control of resuspension

The control of resuspension is likely to be the most effective means of reducing the contribution of non-exhaust sources to ambient concentrations of PM. Furthermore, the control of other non-exhaust PM sources, such as tyre wear and brake wear, could also influence resuspension by reducing the amount of material deposited on the road surface and/or the ability of vehicles to render that material airborne. Consequently, the control of resuspension is discussed in some detail in this Chapter.

2.1 Resuspension Sources

The US Environmental Protection Agency (USEPA) has recently produced a revised version of relevant sections from its AP42 compilation of emission factors. Specifically, an update to Section 13.2.1 on paved roads has been proposed (USEPA, 2006). The AP42 model for resuspension has been heavily criticised in the past (*e.g.* Venkatram, 2000), but has the advantage of being an empirically-based model which gives some feeling for the dependence of the rate of resuspension emissions upon the controlling variables. The proposed modifications to this section of AP42 are concerned with the subtraction of other vehicle emissions (both exhaust and non-exhaust) which were previously included within the overall emission estimate. A factor has now been included in the algorithm which subtracts the vehicle fleet exhaust, brake wear and tyre wear PM using emission factors for the 1980s when the model was devised.

It is instructive to review the material within AP42 Section 13.2.1, which starts by considering the controls upon resuspendable material on the surface (*i.e.* the surface loading). Figure 1, taken from the USEPA document, reviews the sources and removal mechanisms for material on the road surface.

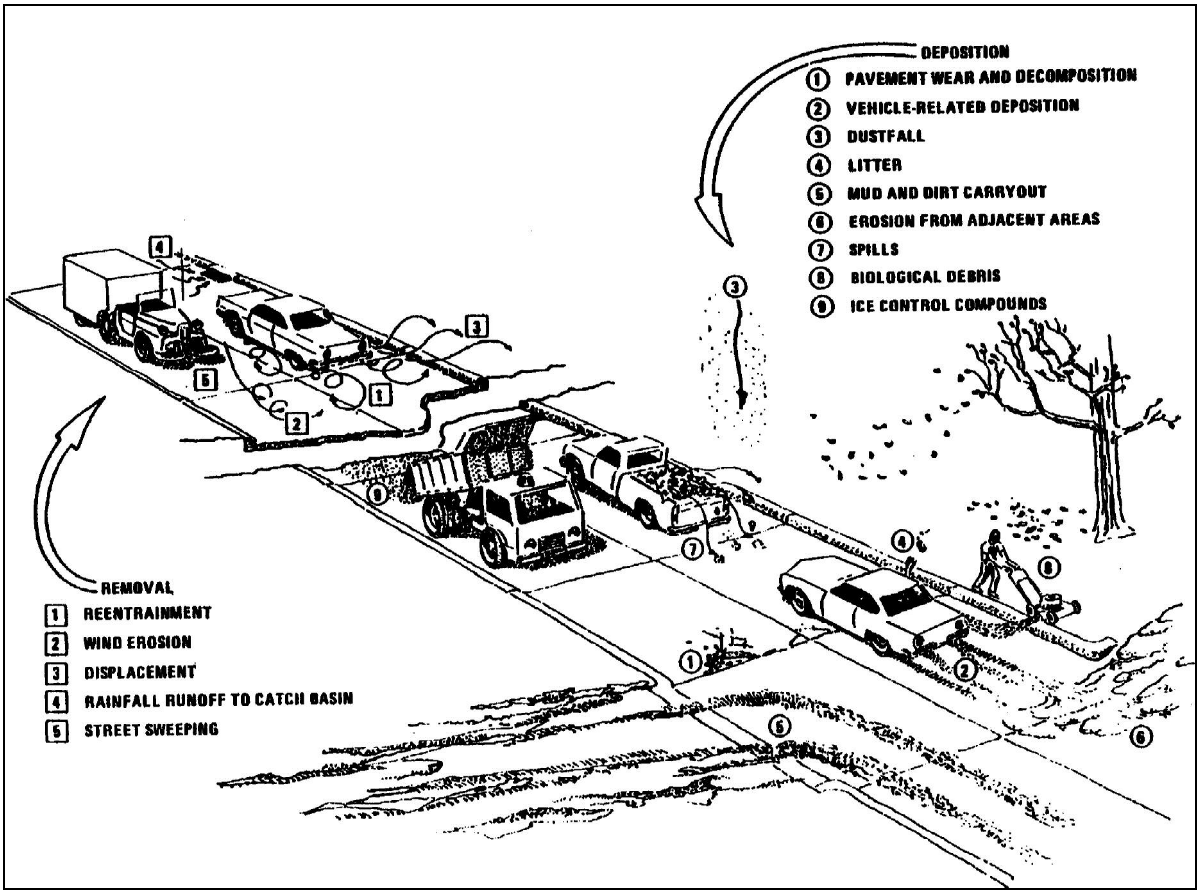

Figure 1: Silt deposition and removal processes (USEPA, 2006).

The sources include the following:

- Road surface wear and decomposition
- Vehicle-related deposition
- Dustfall
- Litter
- Mud and direct 'carry-out'
- Erosion from adjacent areas
- Spills
- Biological debris
- Ice-control compounds

The removal mechanisms include:

- Re-entrainment
- Wind erosion
- Displacement
- Rainfall run-off
- Street sweeping

In the absence of exceptional additions of fresh material, the outputs will reach equilibrium with the inputs and an equilibrium surface loading will be established. Deviations from this equilibrium appear to be short-lived (of the order of several hours) on typical urban roads. Kuhns *et al.* (2003) found that the application of sand (the size range of this material was not stated in the study report) for traction control on dry roads was found to increase PM_{10} emissions by up to 75% 2.5 hours after application. However, emissions returned to the pre-sanding levels within 8 hours. The rapid removal rate of the sanding material from the road surface suggests that the levels of loading on street surfaces are dynamic. If fine material loading on the road (*i.e.* PM_{10} sized particles) exhibit a similar behaviour, the loading of suspendable material must be recharged quickly or else there would be a negligible reservoir of material on the road.

According to AP42, it is believed that the most important factors are the mean speed of vehicles travelling on the road, the average daily traffic (ADT), the number of lanes and ADT per lane, the fraction of heavy vehicles (buses and trucks), and the presence/absence of kerbs, storm sewers and parking lanes[2].

The dust emissions from paved roads have been found to vary with the silt loading of the road surface, which describes the mass of silt-size material ($\leq 75\ \mu m$ diameter) per unit area of the travel surface. This is not a variable which is normally measured in the UK, and the range of values proposed by the USEPA is given later.

The function recommend by the USEPA to express the emission rate of particulate matter from resuspension of loose material on the road surface appears below as Equation 1.

$$\boldsymbol{E = k\left(\frac{SL}{2}\right)^{0.65}\left(\frac{W}{3}\right)^{1.5} - C} \qquad (1)$$

where: E = particulate emission factor (having units matching the units of k)
k = particle size multiplier for particle size range and units of interest (see below)
sL = road surface silt loading ($g\ m^{-2}$)
W = average weight (tons)[3] of the vehicles travelling the road
C = emission factor for 1980s vehicle fleet exhaust, brake wear and tyre wear

The USEPA point out that the equation applies only to the mean emissions for a fleet of traffic of average weight W, and cannot be used to calculate a separate emission factor for each vehicle weight class. Since the values of k and C are fixed for a particular particle size range, the only variables used to predict the particulate emission factor are the road surface silt loading and the average weight of the vehicles travelling on the road. The values of k, the particle size multiplier, appear in Table 2. The values include unit conversions to produce emission factors in the units shown for the indicated size range from the mixed units required in Equation 1. The ratio of $PM_{2.5}$ to PM_{10} is taken from earlier research. PM_{30} is sometimes termed 'suspendable particulate' (SP) and is often used as a surrogate for TSP. Values of C, describing the emission factor for the 1980s vehicle fleet exhaust, brake wear and tyre wear, appear in Table 3.

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[2] It is not clear from the AP42 documentation why not all of these variables are included in the USEPA formulae for resuspension.

[3] It does not appear to be specified whether these are imperial tons or short tons. It is assumed for this Report that the latter is intended, where 1 short ton = 907 kg.

Table 2: Particle size multipliers for paved road equation (USEPA, 2006).

Size range	Particle size multiplier k (g vehicle^{-1} km^{-1})
$PM_{2.5}$	0.66
PM_{10}	4.6
PM_{15}	5.5
PM_{30}	24

Table 3: Emission factors for 1980s vehicle fleet exhaust, brake wear and tyre wear (USEPA, 2006).

Particle size range	C, emission factor for exhaust, brake wear and tyre wear (g vehicle^{-1} km^{-1})
$PM_{2.5}$	0.1005
PM_{10}	0.1317
PM_{15}	0.1317
PM_{30}	0.1317

Equation 1 was derived from a regression analysis of emission tests on a range of paved roads. All sources, however, were freely-flowing vehicles travelling at constant speed on relatively level roads. These factors are therefore only questionably applicable to traffic which is not free-flowing or vehicles travelling up or down an incline. The range of variables encountered in deriving the equations are as follows:

Silt loading	0.03-400	g m^{-2}
Mean vehicle weight	1.8-38	Mg (2.0-42 tons)
Mean vehicle speed	16-88	km h^{-1}

It is interesting to examine the implications of Equation 1, which include the following:

(a) The implication of the values for k in Table 2 is that resuspension emissions of $PM_{2.5\text{-}10}$ outweigh those of $PM_{2.5}$ by a factor of six.

(b) There is a weak but significant dependence on silt loading. The dependence on an exponential of 0.65 implies that for every 10-fold increase in silt loading there is a 4.5-fold increase in resuspension if all other variables are constant. Hence, on moving through the USEPA range of silt loadings, a 10,000-fold increase from 0.03-300 g m^{-2} causes a 410-fold increase in resuspension. Consequently, activities which substantially decrease the silt loading of the road surface (as opposed to redistributing material across the road surface, as with gutter sweeping) are likely to have a significant and beneficial impact.

The other key term is the average weight[4], W, of the vehicles travelling along the road. In this case the exponent is 1.5 and moving through the range of values used by the USEPA is again instructive. In this case a 10-fold increase in vehicle weight from 2 tons to 20 tons gives a 32-fold increase in resuspension. Changing the vehicle fleet from light-duty vehicles only (2 tons - heavy in UK terms) to HGVs only (40 tons) (*i.e.* a 20-fold increase in mean vehicle weight) leads to a 90-fold increase in resuspension, provided the number of vehicles remains the same. There is a very clear implication therefore that a reduction in mean vehicle weight could be highly beneficial.

The extension of Equation 1 to include periods of rain leads to Equation 2:

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[4] The reasons for the use of vehicle weight as a parameter are not clear. Heavier vehicles may contribute to resuspension by causing more rapid deterioration of the road surface, or weight may be a surrogate for vehicle dimensions, which affect wake turbulence. Vehicle weight is also a parameter which cannot easily be determined accurately by model users.

$$E = \left[k \left(\frac{sL}{2} \right)^{0.65} \left(\frac{W}{3} \right)^{1.5} - C \right] \left(1 - \frac{P}{4N} \right) \qquad (2)$$

where: k, sL, W, and C are as defined in Equation 1

E_{ext} = annual or other long-term average emission factors in the same units as k

P = number of ‘wet’ days with $\geq$0.254 mm (0.01 in)[5] of precipitation during the averaging period

N = number of days in the averaging period (*e.g.* 365 per year, 91 per season, 30 per month)

The only modification to this equation is the addition of the final term, and the implications of this term can be crudely assessed. AP42 presents, for the United States, the mean number of days with 0.01 inches or more of precipitation. Taking values for the East Coast - which are likely to be broadly comparable with the UK - gives values of around 120-180 days per year. Taking this range of values, and calculating the entire final term of Equation 2 (*i.e.* 1 - $P/4N$), gives values of 0.88-0.92, implying that the effect of rainfall is only to cause a reduction of about 10% in resuspension processes. This is consistent with the very modest effects of precipitation seen in the analysis of the Marylebone Road data (Boulter *et al.*, 2006). It is worthy of note that Equation 1 gives emissions per vehicle kilometre, and there is an implicit assumption that the emissions increase linearly with the volume of traffic, an assumption inherent in the calculation of emission factors for resuspension at Marylebone Road.

As expressed in the introduction to this section, there are distinct weaknesses in the AP42 method for calculating resuspension. Nevertheless, it is empirical and therefore valuable for gaining at least an approximate understanding of the influential factors, *i.e.*:

- The loading of resuspendable material on the road surface for which resuspension increases less than linearly with increased loading.
- The mean vehicle weight on the road for which resuspension increases more than linearly with mean vehicle mass.
- Rainfall, which is predicted to have a relatively minor influence.

As stated earlier, activities which substantially decrease the silt loading of the road surface are likely to have a significant and beneficial impact. Such activities involve either decreasing the rate of input to the silt loading, or increasing the rate of removal, and these two aspects are discussed in the following Sections.

2.2 Decreasing the inputs to the silt loading

As detailed above in the discussion of the AP42 document, there are numerous potential sources of silt on the road surface. Each of these sources is addressed in turn in the following Sections.

2.2.1 Road surface wear and decomposition

Particles of road surface material have the potential to be either resuspended directly through the action of the tyre on the road surface - causing both the break-off of particles and atmospheric suspension - or through the two processes being separated in time, with the surface wear process preceding a resuspension process. In the latter case, the wear of the road surface contributes to the silt loading.

Irrespective of whether the suspension of particles occurs in a one-stage or two-stage process, the reduction of road surface wear is key to reducing the road surface as a source of atmospheric particles, and this could be achieved through appropriate choice of road surface materials which wear only very slowly whilst retaining a high level of skid resistance. The properties of concrete-based and asphalt-based road surfaces ought to be examined in this context. Harder-wearing road markings (*e.g.* more durable paints) could also contribute a little to the reduction of abrasion products on road surfaces. In addition, the adoption of minimum standards for road surface durability, reinstatement, maintenance and surface dressings, could be potential means of source reduction.

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[5] This value is very low compared with the average daily rainfall in London (around 2 mm). However, the threshold is merely used to determine whether rain has occurred or not, and for this the Met Office uses a value of 0.2 mm.

2.2.2 Vehicle-related deposition

This appears to relate to dirt and corrosion products falling from the vehicle whilst in motion. There is a tendency for vehicles to accumulate mud when in service, especially under the wheel arches. The mud can subsequently fall onto the road surface during dry conditions, or when affected by spray from the wheel. Such sources are likely to prove difficult to control, although wheel washing, which is dealt with later in the context of mud and direct carry-out, would help to reduce vehicle-related deposition. However, other than by enforcing regular vehicle under-body cleaning, this source is extremely difficult to control.

An important question is the origin of the material which collects under vehicles and inside wheel arches. As most drivers keep their cars on the road rather than in, say, muddy fields, the material inside the wheel arch must come predominantly from the road surface itself, and probably during wet weather. In this sense, the wheel arch could potentially be viewed as a short-term sink as long as cleaning takes place. The timing of the cleaning may well be important – if most of the material accumulates during wet weather, then it would be preferable for cleaning to take place once the wet-weather period has ended.

2.2.3 Dustfall

This term describes the atmospheric deposition of particles, which in the UK is generally a very minor source of input to the road surface. It is only in very dusty areas and during dry weather conditions that significant inputs from dustfall are likely to occur. As dustfall can originate from the resuspension of soils or industrial emissions at some distance from the road, its abatement is a matter of general pollution control policy rather than the control of automotive pollution.

However, on a global scale wind blown dusts are the second largest natural source of particles, after sea spray. These are largely derived from desert regions, and whilst the larger particles are rapidly removed by gravitational settling, the sub-micron particles can have atmospheric lifetimes of many weeks (AQEG, 2005). The UK is subject to approximately two Saharan dust episodes a year, where 24-hour PM_{10} concentrations are elevated above 50 $\mu g\ m^{-3}$. These are associated with the deposition of red deposits following rainfall associated with air masses originating over the Sahara. Therefore, the potential role of pollution-responsive sweeping regimes should be considered.

2.2.4 Litter

Most litter items discarded from vehicles or by pedestrians are relatively large in size, and unless they are of a nature which rapidly breaks down into relatively small particles, litter is unlikely to be a major source of resuspended PM_{10}.

2.2.5 Mud and direct carry-out

This term refers to the dust and mud which becomes attached to the wheels of vehicles entering the highway from industrial, agricultural and other sites adjacent to the road. For dusty industrial activities the installation of wheel washes is standard good practice. These typically involve water sprays but there are also dry systems for which a very high efficiency is claimed[6]. A situation might be envisaged where dry wheel washes were installed in cities at locations with slow-moving traffic. However, these might require some re-design, as currently they are scaled to take heavy-duty vehicles and would need modification to take both heavy- and light-duty vehicles. Pilot studies of their effectiveness in reducing silt loads and resuspension would be essential before widespread installation could be countenanced.

2.2.6 Erosion from adjacent areas

The USEPA appear to envisage this source as some kind of erosion of roadside soil banks to bring soils onto the road surface. Such erosion processes are most uncommon within UK urban areas where the issue of non-exhaust particles is likely to be most acute. There could, however, be scope for better management of roadside verges in rural areas.

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[6] For example, see http://www.wheelwashing.co.uk/.

2.2.7 Spills

This term refers to material which spills from moving vehicles on the road. This is likely to be a very minor source of road surface silt within UK urban areas, but might be a cause of problems in some specific localities such as those with major soil-moving activity, such as construction and demolition sites and waste transfer stations. Potential preventative measures would include better management of the loading of wagons, the covering of loads, and the paving of access areas to unpaved lots or construction sites.

2.2.8 Biological debris

This includes leaf fall and grass cuttings. Leaf fall can be a very significant source of road surface debris within the UK but it will only become a significant source of road surface silt if it is not promptly swept up and removed. The removal of such material could also have additional benefits, such as reducing the frequency of gully pot blockages. The remedy, therefore, is straightforward.

2.2.9 Ice-control compounds

In the UK the role of road surface de-icing with gritting salt as a source of airborne PM is currently unclear. Within the DAPPLE study, Imperial College (London) arranged for road salting to take place at the maximum normal level of application on a road within London. Subsequent measurements of salt in the roadside atmosphere showed very significant resuspension losses (Patra *et al*., 2005). On the other hand, analysis of roadside and urban background data collected from sites within London and Birmingham as part of the TRAMAQ programme failed to show any significant enhancement of chloride at roadside sites, suggesting that road de-icing in London and Birmingham is either extremely infrequent or, when averaged over 24 hours (the duration of individual sample collection in the TRAMAQ project), contributes only minimally to airborne concentrations (Harrison *et al*., 2004).

Road salt and grit applied to dry road surfaces is visibly subject to significant resuspension by vehicles moving at high speed, as may be seen on motorways. However, it is unlikely that a substantial proportion of the resuspended mass is within the PM_{10} size range, the majority being very much coarser, although fragmentation processes could result in the generation of PM_{10}. On the other hand, most de-icing salt application occurs either to wet roads or during periods of low temperature and high humidity, when road salt rapidly enters solution through dissolving in water already on the road surface or by hygroscopic uptake of water. Once in solution, the road salt is readily amenable to resuspension by the action of the tyre shear, as is evidenced by driving on motorways after the application of road salt, when it is common for the vehicle windscreen to become rapidly soiled with salt-laden spray. However, the salt droplets are relatively coarse, and there is little salt in the PM_{10} size range. On balance, the available field data do not support the idea that de-icing salt is a significant source of airborne PM in UK cities, and therefore any approach to abatement through a reduction of road salt grit application is likely to have minimal influence.

In many areas of the United States, liquid de-icers are used to reduce the impact of abrasive traction control material on PM re-entrainment. Calcium magnesium acetate (CMA) has been used as an anti-freezing agent on roads in a number of countries. Norman and Johansson (2006) applied CMA in liquid solution to a highway in Stockholm during dry conditions. The daily average PM_{10} concentration along the CMA-treated stretch showed a reduction of between 15% and 60% compared with an untreated stretch. During the treated days the observed effect was lower in the afternoon, probably due to the removal of the CMA solution as it stuck to the tyres on passing vehicles, but also as a result of evaporation. The reduction in the PM_{10} levels was slightly greater when CMA was applied several days in a row. The hygroscopic properties of the CMA solution might change with the relative humidity in the air, which in turn might influence the potential reduction in the PM_{10} levels. However, no consistent relation between the relative humidity and the reduction in PM_{10} levels could be deduced from the observed data. In Trondheim (Norway) Berthelsen (2003, cited in Norman and Johansson) reported that following the application of a 15% solution of magnesium chloride on a highway an average reduction in PM_{10} levels of 17% was observed during dry days. The effect was increased if the application was repeated several days in a row. However, Gertler *et al.* (1996) found that following the application of brine (NaCl) solution and the drying out of the road surface there was 30% increase in the paved road emission factors for PM_{10} and $PM_{2.5}$. During a prolonged snowstorm an abrasive was applied to the road surface to improve traction. The abrasive consisted of a mix of hard sand and cinders, along with a small amount of salt, designed to minimize material breakdown to form PM_{10} and $PM_{2.5}$ sized particles that could be re-entrained. The PM_{10} emission factors measured directly after the storm and after the road had dried showed a doubling, from 310 to 612 mg km^{-1}. PM_{10} emissions remained elevated (660 mg km^{-1}) on the next day.

2.2.10 Other measures

Dust suppressants

Dust suppressants appear to be an obvious choice for the mitigation of resuspension due to road vehicles. Dust suppressants are chemicals applied to surfaces to maintain the moisture levels in, for example, exposed soils, or actually chemically bind the surface material to reduce fugitive dust emissions. Many different forms of chemical dust suppressants are available, including:

- Chloride salts, such as calcium chloride and magnesium chloride
- Petroleum asphalt and resin emulsions
- Organic emulsions (*e.g.* soybean oil by-products)
- Polymers (*e.g.* polyvinyl acetate-acrylic polymer, starch-based polymers)
- Surfactants
- Bitumen
- Foams
- Gels
- Adhesives (*e.g.* lignin sulphonate - tree sap)
- Microbiological binders
- Fibres and textiles
- Wind screens
- Water spray systems
- Dry fog system

However, few tests on roads appear to have been reported in the literature. Much of the literature which does exist appears to relate to unpaved roads (*e.g.* Sanders *et al.*, 1997). One concern is that some of these products pose environmental hazards which are worse than the dust itself, and the effects of others are unknown. Other concerns are cost, and the possibility that suppressants create an impervious surface, resulting in increased run-off and hydrological impacts during periods of rainfall. Before dust suppressants can be used on UK roads there is a need for further research into both their effectiveness on paved roads and their health impacts.

Particle capture by vegetation

Particle capture by vegetation is usually associated with the reduction of human exposure to airborne particulate matter, but in the context of this Report it is also useful to view this process in terms of reducing the amount of material which is available for resuspension.

There has long been interest in the use of trees and shrubs to create shelter belts from wind, and also as a means of cleansing the atmosphere of airborne pollutants, especially particulate matter. As long ago as 1977, Smith was able to identify a wide range of studies in which some aspect of the collection of airborne particles by urban vegetation had been the subject of research. Much of that research had involved extremely coarse particles and was probably of very limited relevance to inhalable particles (PM_{10}). At that time there remained much uncertainty around the issue of efficiency of trees as air filters, as Smith (1977) finished his review by posing research questions which needed to be answered before it would be possible to support or reject the hypothesis that trees are effective air filters. There has been rather little interest since that time except, for example, in relation to very coarse particles such as might be created in agricultural spraying (Raupach *et al.*, 2001).

Recently, however, Tiwary *et al.* (2006) returned to this issue and developed a size-segregated model of particle collection efficiency for three hedgerow species of different aerodynamic porosities. The model was subsequently tested for particles within the range 0.5-20 μm. Collection efficiency was described in terms of the coupled effects of the deviation of the approach flow and the filtration through the foliage elements. Computational fluid dynamic methods were used to simulate velocity and turbulence fields which were subsequently used to predict particle deposition. Probably the most useful results of the paper are the experimental measurements of particle collection efficiency, which were made using Grimm optical particle counters. The results of such experiments appear in Table 4, which includes a comparison of the theoretically estimated collection efficiencies and those measured experimentally in the case of a hawthorn hedge. The hawthorn was far more efficient than either the holly or yew hedge, but in the relevant range of sizes (2.75-6.25 µm diameter) had an experimentally measured collection efficiency for particles of only 0.75-5.8%. The holly and yew were significantly less efficient. Although the yew hedge is denser it tends to lift the approaching airflow more strongly and increase turbulence in its wake, thereby encouraging recirculation of fine particles on the downwind side. Consequently, the overall efficiency of hedges appears to be very modest in the context of the collection of particles in the appropriate size range.

Table 4: Collection efficiencies (%) of the three hedges after accounting for the flow and filtration effects (from Tiwary *et al*., 2006).

Particle diameter (µm)	Hawthorn		Holly	Yew
	CE (%)	CE_{exp} (%)	CE (%)	CE (%)
0.875	1.8	1.2	1.3	0.8
1.5	1.1	0.8	1.1	0.7
2.75	0.9	0.75	0.6	0.5
4.25	2.6	3.5	0.5	0.4
6.25	7.0	5.8	1.7	0.5
8.75	15.0	12.7	4.6	0.8
12.5	19.8	17.6	11.7	1.9
15	29.4	27.3	17.7	3.0

CE = calculated value CE_{exp} = measured value

Additionally, there are many associated problems. These include the following:

(a) In the context of urban streets, there are relatively few situations where it would be practicable to build a vegetative barrier between the traffic and pedestrians.

(b) The most efficient of the vegetative barriers was hawthorn which is deciduous and therefore loses its leaves in the winter which would significantly reduce the efficiency of particle collection.

Vegetation grown very close to the roadside would collect a great deal of very coarse particulate matter by mechanisms including water splashes and spray and thereby become extremely soiled.

2.3 Increasing the effectiveness of removal mechanisms

Other than reducing the rate of input of material, the other approach to reducing the silt loading is to increase the effectiveness of removal mechanisms. Those removal mechanisms described by the USEPA are listed in the following Sections. Again, other measures are also considered.

2.3.1 Re-entrainment

This appears to relate to resuspension by moving vehicles, and is therefore not an option for cleansing the road surface.

2.3.2 Wind erosion

There is considerable evidence of resuspension of $PM_{2.5-10}$ particles from the road surface as wind speeds increase (*e.g.* Harrison *et al*., 2001). This is not, however, a process which could be influenced artificially, and therefore does not provide an option for cleansing the road. On the other hand, it might be possible to introduce this phenomenon as a consideration in urban planning.

2.3.3 Displacement

The meaning of this mechanism is most unclear, but the USEPA diagram (Figure 1) appears to suggest mechanisms by which the moving vehicles displace silt onto the roadside, rather than into the air. Otherwise, it is hard to see how this process is significantly different from that referred to as re-entrainment, and it does not appear to provide a mechanism for independently cleaning the road surface.

2.3.4 Rainfall run-off

The available data, as explained above, deriving both from the USEPA algorithm and from the analysis of data from Marylebone Road, suggest that rainfall and consequent cleansing of the road surface have little influence upon the rates of particle resuspension.

2.3.5 Road sweeping and vacuuming

Sweeping and vacuuming have regularly been tested, especially in the United States, as means of decreasing the silt loading of paved roads (thus reducing PM re-entrainment), and there is a significant body of literature relating to these control options. Chang *et al*, (2005) also noted that street sweeping is also one of main control methods for ambient PM available to local governments in Taiwan.

Several types of street sweeper are available, including mechanical brooms, vacuum cleaners, or a combination of the two. The mechanical broom sweeper typically uses a broom to lift material from the street surface onto a conveyer belt. The material is then delivered to a collection hopper. The vacuum sweeper uses a gutter broom to loosen dirt and debris from the road surface and direct it to a vacuum nozzle that sucks it into a hopper (*e.g.* Kuhns *et al.*, 2003). In the past, the primary objective of a street sweeper was to remove debris from the roadways for reasons of aesthetics and safety, and most street sweepers were not designed for fine particle removal. However, some new street sweepers are specifically designed to reduce PM_{10} concentrations. In California, Rule 1186 of the South Coast Air Quality Management District requires local governments to procure street sweepers which are certified as being PM_{10} efficient. Regenerative air sweepers – in which the cleaning air is filtered and re-used - and vacuum-assisted dry sweepers are used to meet the requirements. However, the literature indicates that the general effectiveness of road sweeping as means of controlling airborne PM_{10} is questionable.

A number of studies have been undertaken in an attempt to quantify road dust emission reductions as a result of sweeping, and these are summarised below. The results are rather mixed, probably because ambient particle concentrations are influenced by several factors which add large uncertainties to what appears to be a small effect (Kuhns *et al.*, 2003). Wind speed, mechanical disturbance by sweeping vehicles, the amount of sprayed water, and silt loading of the tested road are considered to be some of the main factors affecting sweeping performance (USEPA, 1995). Experiments by Kuhns *et al.* (2001) also demonstrated that distribution of suspendable material on roadways is highly variable. Vaze and Chiew (2002) found that particle size distribution of street dust after street sweeping is finer compared to that before sweeping. Street sweeping may have an adverse impact on pollutant wash-off because the street sweeper releases the finer material but only removes some of it.

Early studies in the 1980s showed promising results. Ellis and Revitt (1982) found street sweeping to be particularly efficient at removing solid particles larger than 250 µm, and Duncan *et al.* (1985) designed an 'improved' sweeper to remove finer solids. It was found that a broom sweeper removed 20% of the solid particles on the road surface, a vacuum sweeper removed 70%, and the improved sweeper removed 80%. It was estimated that a thorough sweeping programme could reduce the emissions from paved roads by approximately one-third. Similarly, Cowherd (1988) found that the emission reduction for PM_{10} on paved roads was in the range of 33–37% following a street sweeping programme. More recently, Fitz and Bumiller (2000) noted that most sweepers achieved greater than 97% collection efficiency on their first pass, and concluded that emissions during the operation of street sweepers to remove fine particles from a paved road are not significant compared with the benefit in reduced emissions provided by a cleaned road.

However, when Chow *et al.* (1990) determined the source contributions to PM_{10} concentrations during street sweeping periods and non-street sweeping periods in Reno, Nevada, no significant differences in the resuspended contributions to PM_{10} were detected. Fitz and Bufalino (2002) suggested that explanations for this may include the silt loading being rapidly replaced after sweeping to an equilibrium level which is dependent on factors such as vehicle speed and traffic density, and the Reno study not being sufficiently sensitive to detect a change. Other recent studies have also shown a tendency towards only limited effects. Work in California by Fitz (1998) concluded that street sweeping had no significant effect on the PM_{10} levels, and Kantamaneni *et al.* (1996) only observed a significant decrease in PM_{10} emission by sweeping when the relative humidity was lower than 30%. In Taiwan, Chang *et al.* (2005) undertook extensive measurements to evaluate the effectiveness of modern street-sweeping equipment (modified regenerative vacuum sweeper and efficient washer) for controlling ambient TSP. Various wind speeds, traffic volumes and silt loading levels were investigated. The results indicated that street sweeping followed by washing offers a measurable reduction in TSP emission potentials. However, the direct impact of sweeping on ambient PM emissions is short-lived, lasting no more than 3-4 hours.

The effectiveness of measures to control the resuspension of paved road dust has also recently been investigated in the United States using the TRAKER[7] vehicle. Using TRAKER, Kuhns *et al.* (2003) and Etyemezian *et al.* (2003) compared the PM_{10} emissions from paved roads that had been swept or vacuum cleaned with roads with no treatment. Neither the sweeping nor the vacuum cleaning had any significant effect on the emitted PM_{10} levels. Indeed, the results indicated that PM_{10} emissions immediately after sweeping increased by up to 40% (Kuhns *et al.*, 2003). Norman and Johansson (2006) evaluated the PM_{10} levels associated with intense sweeping of the road surface in Stockholm. A street in the city was cleaned nightly using mechanical sweepers, and the PM_{10} levels were compared with those on another street having the same orientation and similar meteorological factors, such as wind direction, wind speed and road surface dryness. No statistically significant reduction in PM_{10} could be observed alongside the swept street during the periods with intense sweeping. Indeed, in most cases the results showed an increase in the PM_{10} during days with sweeping. PM_{10} levels were also found to be higher than during the same period of the previous year, when the street was swept at a normal frequency. Another recent study during winter conditions in Nevada by Gertler *et al.* (2006) also found a significant increase in the PM_{10} emissions (from 660 to 735 $\mathrm{mg\,km^{-1}}$) after the sweeping and washing of the roads. For $PM_{2.5}$ there was a more dramatic increase after sweeping (from 133 to 211 $\mathrm{mg\,km^{-1}}$).

If street sweeping can remove particles that could evolve into TSP or PM_{10}, then sweeping may have a beneficial effect on air quality over a long term. Norman and Johansson (2006) considered that although the sweeping did not cause any significant decrease in the PM_{10} levels during the following days, it might still have an effect in the long term, as the removal of large gravel might prevent some of the formation of smaller PM_{10} particles later due to a reduction of the ‘sandpaper effect’ (the abrasion of the road surface by traction sand or grit - see Kupiainen *et al.*, 2003).

2.3.6 Washing the road surface

Bris *et al.* (1999) tested the efficiency of particle removal of the water jet street cleaning procedure used by Paris city workers. Surface loads were compared before and after the cleaning procedure. The cleaning efficiency for solids was highly variable (20–65%), and somewhat higher for larger solid particles. The removal efficiency for the total street deposit was around 25%. The authors also concluded that the removal and collection efficiency for particles smaller than 50 μm was probably small. Gromaire *et al*. (2000) found that the pollutant load removed from the street surface by cleaning water on a daily basis was similar to that removed during one rainfall event, and that street cleaning can preferentially wash away the suspendable solids and organic matter on road.

The Regional Environmental Agency for Lombardy undertook a field test in Milan during the winter of 2002 aimed at determining whether any reduction in PM_{10} concentrations could be obtained by the washing and mechanical brushing of roads (cited in CAFÉ, 2004). An area of 1 $\mathrm{km^2}$ in the city centre was washed several times every night for ten days. The variation in PM_{10}, both in concentration and composition, at two different heights (2 m and 25 m) was investigated and compared with a reference site outside the test area. No substantial reductions in PM_{10} concentrations were observed. Between the 2 m and 25 m sites there was a vertical concentration gradient of about -10%, and this was not influenced by the road washing.

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[7] TRAKER = testing re-entrained aerosols kinetic emissions from roads.

The study in Taiwan by Chang *et al.* (2005) showed reductions in TSP concentrations of up to 34% when both street sweeping and high pressure washing were used, but no reductions in PM_{10} were observed. Tests of the effects of washing with a high-pressure water system were also performed in Stockholm by Norman and Johansson (2006). The verge next to the carriageway was washed during the night when the weather forecast predicted dry road conditions for the next day. On most days slightly lower PM_{10} concentrations were observed due to the washing. The reduction was often greater than 10%, but on two days there were increases in PM_{10} levels of more than 10% higher. The average reduction for the study period (21 days) was 6%. For 10 out of the 21 days the daily average PM_{10} level exceeded 50 μgm^{-3}, compared with 12 days for the untreated stretch. The reduced PM_{10} levels on the washed stretch could, however, have been due to the wetting of the road surface, which reduced suspension of dust, rather than actually removing PM_{10} particles.

2.3.7 Other measures

The aerodynamic shape of a vehicle is modified by the manufacturer to minimise turbulent air flows in vehicle wakes, with the primary goal of reducing fuel consumption. Providing a smooth surface to the underside of a vehicle, with a slightly upturned rear, is beneficial in this respect (Barnard, 1997). Wake turbulence can also lead to the resuspension of road dust. Whether the different design possibilities available to manufacturers can be used to reduce the disturbance of road dust is an area for further investigation.

‘Active Asphalt’ is a material developed jointly by Shell and the Norwegian company Applied Plasma Physics. A Shell product information sheet describes Active Asphalt in the following terms. When two surfaces are in frictional contact, an electrical charge can be induced via a process known as triboelectrification. The intensity and polarity of the charge depends upon the types of material, the characteristics of the surfaces and the conditions (*e.g.* temperature, pressure, relative speed). Asphalt road surfaces normally carry a positive electrostatic charge due to friction between the road surface and the rubber of vehicle tyres. Any positively charged particles will therefore remain suspended in the air above the road surface, rather than settling on the road surface under gravity. Active Asphalt is described as a ‘conductive’ wearing course which works by preventing the build up of static charges, thus attracting the PM to the road surface. Accumulated dust is then removed from the Active Asphalt surface by rain or mechanical road cleaning. According to Shell, PM in the air, including rubber dust and soot in vehicle exhaust, will be reduced by up to 10%. The asphalt was trialled in Trondheim, Norway on a 300 m stretch of highway (Hansford, 2001). At this stage it is unclear whether such a road surface would decrease or increase resuspension. If particles are more tightly bound to the surface then it is possible that resuspension could become less effective. On the other hand the silt loading of the road could increase. Again, further research is required to determine the overall effects of such surfaces on resuspension.

3 Control of tyre and brake wear particles

3.1 Overview

As noted in the introduction, there are currently no legal requirements for the control of road vehicle non-exhaust particle emissions in the EU, and there are very few technologies which have been developed specifically for this purpose. There would appear to be two principal ways of reducing the rate of release of tyre and brake wear particles. These are (i) reducing the production of tyre and brake wear particles at source through the development of new materials and systems, and (ii) collecting/destroying brake particles as they are produced. Improvements in vehicle design, such as suspension, traction control and regenerative braking, and improvements in inspection and maintenance procedures, may also have some influence on direct particle emissions. These different types of abatement measure are reviewed in the following Sections.

3.2 Improved materials

The manufacture of tyres, brake pads, brake discs and brake shoes from alternative, and possibly more hard-wearing materials, could contribute to the reduction of PM emissions from these sources. Tyres are traditionally made from a composite of natural or synthetic rubbers with a filling material. Fillers are added to the rubber to improve its strength characteristics (in terms of hardness and wear resistance). Carbon black is by far the most commonly used filler, though in recent years other materials have been used in its place in attempt to decrease rolling resistance without compromising strength and longevity. The vital constituent of tyres which has allowed this innovation is silica, used with a silane coupling agent, which replaces some of the carbon black filler in the tyre. The Michelin ‘Energy Tyre’ was one of the first silica-containing tyres to be developed in the early 1990s.

Silica has the effect of reducing hysteresis in a tyre, and therefore its resultant energy losses as heat. Hysteresis occurs when the sidewalls of a tyre deflect and the tread flattens into the contact patch. Silica has the effect of making the rubber more resilient and reducing these energy losses, without compromising wet grip and wear resistance (Ten Brinke, 2002). Since the first silica containing tyre became commercially available, alternatives to compete with silica have been developed. These alternatives include carbon-silica dual-phase filler (CSDP) and ‘nanostructure’ carbon blacks. One particular research organisation (TARRC) - has added commercially available sulphur to the first stage mix of a tyre polymer blend - has achieved a 20 % reduction in tyre wear over longer mileage tests (Cook, 2004). To produce the desired blend, ‘reactive mixing’ technology is used to chemically modify a SBR/BR (styrene butadiene rubber/butadiene rubber) blend during the mixing process. Using these novel compounds as fillers in tyres may potentially reduce levels of PM emissions due to tyre wear.

Reducing the production of brake wear particles depends upon the use of brake pads and discs of high durability which do not readily abrade. There are, however, technical limitations to what can be achieved. The properties which are desirable in brake linings include a high coefficient of friction, stability at high temperatures, durability and low noise. Brake pad linings are composed of a relatively soft but tough material, whereas the harder brake discs are usually made from cast iron. Automotive engineers use a variety of materials in brake linings to maximise performance in the aforementioned areas, depending on the intended use of the vehicle, but there must always be trade-offs between the different requirements. For example, soft linings tend to create less noise and function well at the relatively low temperatures experienced during normal urban driving, but they generally wear faster and create more dust. Hard linings are more durable and better suited to high-performance applications, but are noisier and tend to cause excessive wear of the discs. The options for reducing PM emissions via the use of alternative brake materials therefore appear to be rather limited at present. The manufacturers of ceramic linings claim that their use leads to reduced amounts of dust, but the implications in terms of respirable particles need to be further investigated.

It has been suggested that the use of high-quality anti-skid aggregates in road material (high resistance to fragmentation) can reduce the amount of PM generated compared with hard minerals (such as quartz) with low resistance to fragmentation, although there is little supporting evidence (Tervahattu *et al,* 2006).

3.3 Particle collection and destruction

The collection of particles in the vehicle itself could be broadly classified as being ‘passive’ or ‘active’. For example, the passive collection of brake wear particles could be achieved through partial enclosure of disc brake mechanisms. Drum brakes are already enclosed, but these tend to be fitted to rear wheels and therefore do not carry much of the braking load. An enclosed disc brake mechanism would need to be designed so that there is no significant reduction in the ventilation of the brake, which is necessary to avoid over-heating, and no increase in the weight or complexity of the vehicle.

One company which produces an enclosed braking system is Safe Effect Technologies[8]. The ‘sealed integrated braking system’ (SIBS) is a fully enclosed braking system which was originally designed to protect brakes in harsh environments. An outer casing protects the brakes against contaminants, and an oil medium acts to avoid overheating. Any particles which do result from brake wear will remain in the liquid medium to be disposed of at service intervals. The manufacturers claim that brake pads suffer little abrasion due to the lubrication of the surrounding oil.

Another passive measure which may have some effect in controlling how both tyre and brake wear emissions propagate from vehicle wheels is the enclosed wheel arch. Increased coverage of the wheel may be beneficial, by allowing more wheel-derived emissions to be collected. Enclosed wheel arches may be used in conjunction with some of the other particle collection and destruction techniques (which are explored later in this Section), to make collection more effective. Enclosing the wheel arches would involve extending the side bodywork of the vehicle downwards, visually covering any proportion of the wheel, but perhaps covering half or more of the wheel would have the greatest effect in reducing emissions. Modifications to the vehicle of this type would have safety and maintenance implications, and this would need to be considered fully in any development work. Any additional weight caused by the extended bodywork could also affect fuel economy, but on the other hand drag may be reduced, and enclosed wheel arches have been used on some hybrid cars[9].

The ‘active’ collection of brake wear particles could be achieved using any of the following techniques:

- Filtration
- Electrostatic precipitation
- Cyclone dust collection

Filtration is simply the process of removing suspended particles from the air by passing it through a porous medium such as a fabric filter. An electrostatic precipitator (ESP) is device which removes particles from a flowing gas using the force of an induced electrostatic charge. ESPs are in common domestic use (as ‘air purifiers’) and industrial use. ESPs operate by the electrostatic attraction of airborne particles to a collecting section. Typically, the particles are ionised by high-voltage wires. The negatively charged particles then adhere to positively charged collecting surfaces. ESPs have a very low pressure drop and a high efficiency for very small particles. However, they become less efficient as the collecting surface becomes dirty. The ESP must therefore be cleaned regularly to maintain maximum efficiency. In a cyclone dust collector, as the dirty air enters the cyclone it is forced into a swirling movement. The suspended particles, being denser than the air, are forced to move outwards, towards the cyclone wall. They then fall downwards towards the collection section. The clean air is eventually directed towards the centre of the cyclone dust collector and leaves through the gas exit.

Typical efficiency curves for the three options appear in Figure 2. All can be of high efficiency in the typical size range of brake dust particles (1-10 μm) with ranking typically in the order:

filtration > electrostatic precipitation > cyclone dust collector

The cyclone is likely to be the lowest consumer of energy due to a low pressure drop and no requirement for high voltages (as in the electrostatic precipitator). Cyclone systems are now mass produced for vacuum cleaners. At a high air flow rate (as in a vacuum cleaner) the air flow across the brake disc would serve to provide the necessary ventilation. The collection bowl would require emptying periodically, but this could be carried out as a routine service task. However, as seen in Figure 2, the efficiency of the cyclone falls severely

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[8] www.safeeffect.com

[9] See, for example, http://automobiles.honda.com/models/model_overview.asp?ModelName=Insight

for small particles, and is less than 50% for particles of below about 2.8 µm. Hence, for reasons of high efficiency across the full particle size range, a filter or electrostatic precipitator may be required. Of these, the filter is likely to have the lower capital cost, but greater operational costs in terms of energy consumption for the essential air pump.

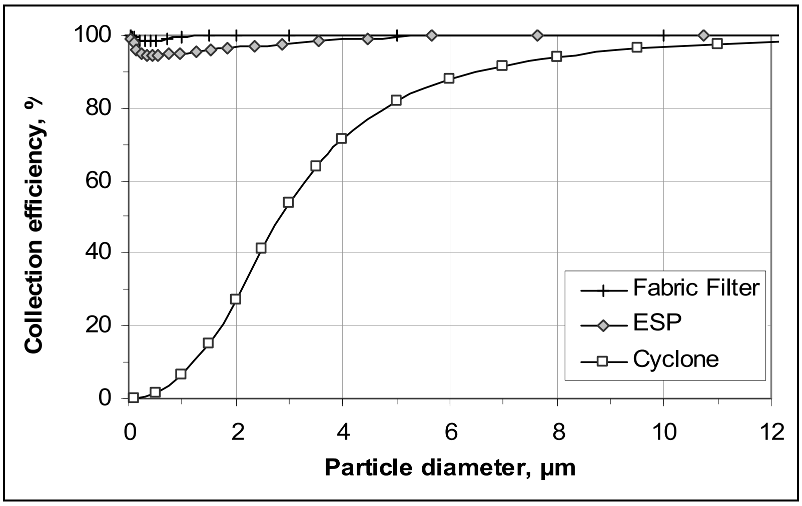

Figure 2: Fractional efficiency curves for a typical fabric filter, electrostatic precipitator and cyclone dust collector.

Particle collection systems, such as those mentioned above, could be more effective overall when used in combination with enclosed brakes and wheel arches.

There are various systems now available, some of which are in use within the vehicle parc, designed to trap and destroy diesel exhaust particles prior to emission from the vehicle. The systems have a number of common features, the primary ones being a filter trap which collects the diesel particles, and a catalyst which facilitates the destruction of the particles. In the Continuously Regenerating Trap (CRT)[10] the catalyst is contained within the filter trap, whilst in some other systems the catalyst is added to the fuel and thereby becomes incorporated within the particles themselves. The main function of the catalyst is to reduce the oxidation temperature of the carbonaceous diesel particles so that they can be oxidised using the heat of the exhaust itself rather than additional heating. In the CRT, a proportion of the nitric oxide in the exhaust gas is oxidised to nitrogen dioxide, which then acts as the oxidant for the particles.

Diesel particle traps with *in situ* destruction of particles are designed to remove carbonaceous particles from engine exhaust. Brake wear particles comprise abrasion products from the brake disc or drum, normally constructed of cast iron and from the brake pad which, although of mixed composition, contains a high proportion of inorganic materials. Particles resuspended from the road surface contain a large proportion of crustal elements such as aluminium, silicon, iron and calcium. As such, they are not susceptible to oxidative decomposition in the same manner as diesel exhaust particles. Consequently, whilst *in situ* trapping is feasible and is discussed above, *in situ* destruction of brake wear and resuspended particles is not a viable option.

3.4 Improved vehicle performance

Modifying a vehicle's performance can indirectly affect the PM emissions it produces. Improvements in vehicle operation in the following areas may affect PM emissions in the ways indicated:

- Vehicle suspension. The suspension of vehicles could be optimised in such a way as to reduce tyre abrasion, and could potentially cause a lower level of PM emissions.

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[10] CRT is a trademark of Johnson Matthey.

- Traction control. Excessive wheel spin causes unnecessary tyre wear, and therefore potentially unnecessary particulate emissions. Traction control on vehicles is a feature which aims to prevent wheel spin as the vehicle accelerates. Sensors are used to measure the difference in the rotational speed of the four wheels, and excessive differences in rotational speed indicate that the wheels have lost traction. Should the wheels be determined to be spinning by the sensors then either the power distribution to the wheels can be reduced or the brakes can be 'pulsed' until traction is regained.
- Development of the anti-lock braking system (ABS). ABS utilises the same technology as traction control to prevent wheels locking and skidding as the vehicle decelerates, and therefore avoiding excessive tyre wear. Whereas traction control works by detecting excessive rotational wheel speed, ABS detects unusually low rotational speeds. The ABS feedback mechanism works to ensure that the rotational speed of the wheels is reduced at the same rate at which the car decreases speed. By ensuring that these two speeds are matched, the wheels are kept spinning during deceleration, and maximum grip is imparted by the road on the tyres, essentially avoiding wheel lock and the associated skidding.
- Speed/acceleration limiters. Fast acceleration or cornering produces more tyre wear and possibly therefore more airborne PM, although such conditions may also produce large shreds rather than fine particles. In addition, vehicles create more disturbance and re-suspension of road dust at higher speeds. The use of speed or acceleration limiters, based on cruise-control technology, or technologies such as in-car 'eco-driving' indicators may therefore act to reduce PM. In the same way, public awareness programmes may produce a similar effect.
- Innovative and regenerative braking systems. Regenerative braking systems aim to capture some of kinetic energy which is lost as a vehicle slows down, and is usually dissipated as heat energy from the brake pads. Recently, regenerative braking systems have been developed for hybrid vehicles which have electric motors[11]. Instead of using friction to slow the vehicle, hybrid cars can make use of their electric motors at slower speeds by reversing the direction of the electric motor, thereby creating a resistance to the forward momentum of the car and generating electrical energy which can be stored in a battery for later use at the same time. From the point of view of reducing non-exhaust emissions, the use of regenerative braking is advantageous since the wear on brake pads and associated PM emissions are reduced.

3.5 Improved inspection and maintenance

The main other type of approach for reducing tyre wear and brake wear particles is the improvement or extension of inspection and maintenance practices. This might include, for example, more frequent in-service checks on the condition of tyres, brakes, and suspension. It might involve the roadside testing of vehicle roadworthiness, with a greater level of enforcement of correct settings for wheel alignment and suspension. No evidence was found in the literature relating to the effectiveness of such policies.

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[11] www.hybridcars.com

4 Assessment of abatement options

In this Chapter, the likely effectiveness of several different abatement options for non-exhaust PM is considered. With the exception of road sweeping/washing and the use of de-icing compounds, little of the published literature refers specifically to the effectiveness of the options. Consequently, based on current information and understanding, this assessment is largely subjective.

The various measures discussed in the Report are tentatively rated according to a series of factors in Table 5. These factors are (i) potential impact in terms of PM emissions according to the source(s) affected, (ii) technical feasibility, (iii) the time scale necessary for introduction, (iv) the spatial scale involved and (iv) the likely cost. Where a measure requires the introduction of a policy rather than a specific vehicle technology, it is assumed that the policy will tend to be introduced on an ad hoc basis. For example, it would be usual for road gritting to be undertaken only during cold weather periods. This makes the cost implications extremely difficult to estimate, as they are largely dependent upon the scale of application and location-specific factors. Another issue is that the costs of the various options will be borne by different organisations and bodies. For example, the costs of developing vehicle-based particle collection devices would largely be borne by vehicle manufacturers, with these costs being passed on to the public, whereas the costs of sweeping and washing roads would generally be borne by local authorities. Given the uncertainties involved, no attempt has been made at assessing the effects for different PM size ranges.

Hard-wearing tyre, brake and road surface materials are technically feasible and, in some cases, are already in use. The wider adoption of such materials would undoubtedly involve the consideration of various other aspects, such as skid resistance and cost, and the market for such materials will develop at its own speed in due course. Significant reductions in PM emissions from tyres and brakes may be possible, but the impact on resuspension is likely to be negligible.

The vehicle-based collection and destruction of particles would be the responsibility of vehicle manufacturers and their suppliers. Historically, vehicle emission-control technology has developed in response to legislative requirements. As there are currently no requirements for vehicle manufacturers to control of tyre and brake wear particles, and such legislation does not appear to be imminent, it is doubtful that the relevant technologies will be introduced into vehicles in the near future. Hence, although such measures are technically feasible, they are only likely to be implemented in the long term, if at all.

Other improvements to vehicle design which do not involve the direct control of PM, such as developments in vehicle suspension and aerodynamic design, are probably unlikely to have a significant impact on emissions. One possible exception is the wider adoption of regenerative braking, although this applies principally to electric and hybrid vehicles, and these are currently only produced in small numbers. Another possible exception is a reduction in vehicle weight, which was discussed earlier in the Report in relation to the USEPA AP42 calculation method for resuspension from paved roads. According to the AP42 function, reductions in vehicle weight ought to have significant benefits in terms of reducing resuspension. However, many current vehicle models have increased in weight due to the installation of additional safety features. The introduction of longer and heavier HGVs on the EU road network is also being considered.

The planting of vegetative traps may have a minor effect on resuspension via the retention of particles which would otherwise be available for resuspension. However, the effects are not well known, and large-scale planting is not a realistic proposition for urban areas where exceedences of PM limit values are the most common.

As this review has shown, the studies relating to the effectiveness of road sweeping and washing have yielded rather variable results. Nevertheless, these are measures which are already available and can be implemented immediately, although it appears that further development and certification of sweepers is required to improve the collection efficiency for PM_{10}. The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could also have an impact on the amount of material deposited on the road, and hence resuspension. It is also fairly undemanding technically, although changes to the infrastructure would be required to allow for the routine washing of heavy-duty vehicles.

Table 5: Assessment of potential abatement options.

Type of measure	Actual measure	Estimate of impact			Technical feasibility	Time scale	Spatial scale	Cost
		Tyre	Brake	Resusp.				
Improved materials	Hard-wearing tyre compounds	--	n/s	n/s	✓✓	*T*	*I*	Medium
	Hard-wearing brake compounds	n/s	--	n/s	✓✓	*T*	*I*	Medium
	Hard-wearing road surfaces and road markings	+	n/s	-	✓✓	*T*	*I*	Medium
Particle collection and destruction	Passive - enclosed brake mechanisms	n/s	--	n/s	✓✓	*TTT*	*I*	Low
	Passive - enclosed wheel arches	-	-	n/s	✓✓	*TTT*	*I*	Low
	Active collection of particles (not inc. passive methods)	--	-	n/s	✓✓	*TTT*	*I*	High
	In-situ destruction of particles	n/s	n/s	n/s	×/✓[a]	*TTT*	*I*	High
Improved vehicle design	Developments in vehicle suspension	n/s	n/s	n/s	✓✓	*T*	*I*	Medium
	Traction control	-	n/s	-	✓✓	*T*	*I*	Medium
	Speed/acceleration limiters	-	-	-	✓✓	*T*	*I*	Medium
	Innovative and regenerative braking mechanisms	n/s	--	n/s	✓✓	*TTT*	*I*	Medium
	Development of ABS	n/s	-	n/s	✓✓✓	*T*	*I*	Medium
	Vehicle aerodynamic design	n/s	n/s	n/s	✓✓	*TT*	*I*	Medium
	Reduction in vehicle weight	-	-	--	✓✓	*TT*	*I*	Medium
Infrastructure	Planting of vegetative particle traps	n/s	n/s	-	✓✓✓	*T*	*L*, *R*	Low
Road and vehicle cleaning	Vacuuming or sweeping the road surface	n/s	n/s	-/+	✓✓✓	*T*	*L*, *R*	Medium
	Washing the road surface/verges	n/s	n/s	-/+	✓✓✓	*T*	*L*, *R*	Medium
	Washing vehicles (*e.g.* wheels, chassis, bodywork)	n/s	n/s	-	✓✓✓	*T*	*L*, *R*	Medium
Improved I/M	More frequent in-service checks on tyres/brakes/suspension	-	-	n/s	✓✓✓	*T*	*R*, *N*	Medium
	Roadside testing of vehicle roadworthiness	-	-	n/s	✓✓	*T*	*R*, *N*	Medium
	Enforcement (*e.g.* wheel alignment, suspension)	-	-	n/s	✓✓	*T*	*R*, *N*	Medium
Other measures	Reduced winter gritting	n/s	n/s	-	✓✓✓	*T*	*L*, *R*, *N*	Low
	Use of dust suppressants	n/s	n/s	--	✓✓✓	*T*	*L*, *R*	Medium
	Use of de-icing liquids	n/s	n/s	--	✓✓✓	*TT*	*L*, *R*	Medium
	Covering loads to/from construction sites	n/s	n/s	-	✓✓✓	*T*	*L*	Low
	Paving access roads to construction sites	n/s	n/s	-	✓✓	*TT*	*L*	High
	Regulation of agricultural practices	n/s	n/s	-	✓✓	*TT*	*R*, *N*	Low

a Depends on the source. Not feasible for brake particles, but feasible for tyre particles.

Key

Impact

+	slight increase in emissions possible
++	substantial increase in emissions possible
-	slight reduction in emissions possible
--	substantial reduction in emissions possible
n/s	effect probably not significant

Technical feasibility

×	Unlikely to be feasible
✓	Feasible but difficult
✓✓	Intermediate
✓✓✓	Straightforward

Timescale

T	Short-term
TT	Medium-term
TTT	Long-term

Spatial scale

I	International
N	National
R	Regional
L	Local

Improved vehicle inspection and maintenance procedures and greater levels of enforcement may reduce tyre and brake wear emissions slightly, but are unlikely to affect resuspension significantly. However, these are measures which are relatively straightforward and do not pose many technical difficulties, although the cost of adoption on the national scale would be high.

The other measures considered, such as the use of dust suppressants and the regulation of agricultural practices, could be beneficial in terms of reducing the road silt loading. Each of the measures considered has its own implications, and must be discussed on a case-by-case basis, but the arguments are beyond the scope of this Report. Further experimental work is required to assess the effectiveness of such measures.

5 Summary

This Report has presented a review of abatement measures for non-exhaust PM. Potential abatement options include a mixture of technical and policy approaches, and relate to both vehicles and infrastructure. Some types of abatement measure address a single source, whereas others address more than one source. Given the range of possible measures, it is difficult to provide a definitive classification, and some measures are likely to have dual benefits. The most effective measures are likely to be those which target with high efficiency those sources making the largest contribution to non-exhaust particles. The analysis of the data from Marylebone Road showed that two sources are dominant: resuspension (50.7%) and brake wear (27.5%). The means of controlling these two sources (or, more generally, resuspension and abrasion) are, in most cases, rather different. Abatement measures for resuspension and abrasion (tyre wear and brake wear) were therefore examined separately. The most important non-exhaust source is, at many locations, likely to be resuspension.

5.1 Control of resuspension

The US EPA's AP42 compilation of emission factors includes a function which expresses the emission rate of particulate matter from resuspension of loose material on the road surface. The only variables used to predict the emission factors (per vehicle-km) are the road surface silt loading and the average weight of the vehicles travelling on the road. A 20-fold increase in mean vehicle weight leads to a 90-fold increase in resuspension, provided the number of vehicles remains the same. There is therefore a very clear implication that a reduction in mean vehicle weight could be highly beneficial.

There is a weak but significant dependence on silt loading, a 10,000-fold increase in which leads to a 410-fold increase in resuspension. Consequently, activities which substantially decrease the silt loading of the road surface ought to have a significant and beneficial impact. This involves either decreasing the rate of input to the silt loading, or increasing the rate of removal. AP42 also considers several sources and removal mechanisms for material on the road surface, and potential abatement measures for resuspension were discussed in terms of these mechanisms.

A significant amount of literature was only found in relation to ice-control compounds and street sweeping/washing. The available data do not support the idea that de-icing salt is a significant source of airborne PM in UK cities, and therefore any approach to abatement through a reduction of road salt grit application is likely to have minimal influence. However, there is evidence that some de-icing compounds, such as CMA, can lead to reductions in PM_{10} concentrations, and that other solutions, such as brine, can lead to increased PM concentrations, but more work is needed. The results of street-sweeping experiments have been rather mixed, with some studies showing increased airborne PM concentrations and other studies showing decreases. This may be because ambient particle concentrations are influenced by various factors, and these lead to uncertainty in the findings. Any effects also appear to be short-lived, although if street sweeping removes particles that have the potential to evolve into PM_{10}, then sweeping may have a beneficial effect on air quality over a long term. Existing street washing techniques do not appear to be a particularly effective means of controlling PM_{10}.

An examination of the AP42 function for rainfall conditions which were likely to be fairly typical of those in the UK indicated that rainfall would only cause a reduction of about 10% in resuspension processes. This was consistent with the Marylebone Road data.

5.2 Control of tyre and brake wear particles

The following categories of measure were considered for the control direct emissions of tyre and brake wear particles: improved materials, particle collection and destruction, improved vehicle design and improved inspection and maintenance

The manufacture of tyres, brake pads, brake discs and brake shoes from alternative, and possibly more hard-wearing materials, could contribute to the reduction of PM emissions from these sources. In recent years silica has been used to replace some of the carbon black filler in tyres to this effect. Reducing the production of brake wear particles depends upon the use of brake pads and discs of high durability which do not readily abrade to form particles. It has been suggested that the use of high-quality anti-skid aggregates in road material (high resistance to fragmentation) can reduce the amount of PM generated compared with hard minerals (such as quartz) with low resistance to fragmentation. In all cases there is little evidence relating to effectiveness.

The collection of particles in the vehicle itself could be broadly classified as being ‘passive’ or ‘active’. For example, the passive collection of brake wear particles could be achieved through partial enclosure of the brake mechanism, and at least one company already produces an enclosed braking system. Another passive measure which may have some effect in controlling how both tyre and brake wear emissions propagate from vehicle wheels is the enclosed wheel arch. Any measure of this type would have safety and maintenance implications, and this would need to be considered fully in any development work. The ‘active’ collection of brake wear particles could be achieved using filtration, electrostatic precipitation and/or cyclone dust collection. It should be noted that the collection of particulate matter in an ESP or other collection device could potentially present a health and safety risk during its cleaning and the disposal of the collected material. The cyclone is likely to be the lowest consumer of energy due to a low pressure drop and no requirement for high voltages. However, for reasons of high efficiency across the full particle size range, a filter or electrostatic precipitator may be required. Of these, the filter is likely to have the lower capital cost, but greater operational costs in terms of energy consumption for the essential air pump. Brake wear particles are composed of iron and other inorganic materials. Particles resuspended from the road surface contain a large proportion of crustal elements such as aluminium, silicon, iron and calcium. As such, they are not susceptible to oxidative decomposition. Consequently, the *in situ* destruction of brake wear and resuspended particles is not a viable option.

Modifying a vehicle’s performance can indirectly affect the PM emissions it produces. PM emissions may be reduced by improvements in, for example, vehicle suspension, traction control, the development of ABS, speed/acceleration limiters and regenerative braking systems. No evidence was found of the effectiveness of such measures in terms of PM control.

The other main type of approach for reducing tyre wear and brake wear particles is the improvement or extension of inspection and maintenance practices. This might include, for example, more frequent in-service checks on tyres, brakes and suspension. It might involve the roadside testing of vehicle roadworthiness, with a greater level of enforcement of correct settings for wheel alignment and suspension. Again, no evidence was found in the literature relating to the effectiveness of such policies.

5.3 Assessment of abatement options

The various measures discussed in the Report were tentatively rated according several factors, including the likely impact in terms PM emissions and technical feasibility. With the exception of road sweeping/washing and the use of de-icing compounds, hardly any of the published literature refers specifically to the effectiveness of abatement options for non-exhaust PM emissions. Consequently, the assessment was largely subjective. Few of the measures reviewed could be considered to be likely to have a definitive and substantial overall impact on non-exhaust PM emissions, usually because there are no supporting experimental data. The following are possibly the more effective and feasible measures:

Vehicle weight reduction. According to the AP42 resuspension function, reductions in average vehicle weight ought to have significant benefits in terms of reducing resuspension. However, it should be noted that passenger car weights have increased over the last two to three decades, and that there is pressure to increase the total weight of HGVs from the current 40-44 tonnes to over 60 tonnes. Whilst this would not necessarily change the maximum axle weight of these larger HGVs, the dimensions of the truck trailer units would increase.

Application of de-icing compounds. There is evidence that some de-icing compounds, such as CMA, can lead to reductions in PM_{10} concentrations.

Road sweeping and washing. Although the evidence currently indicates that road sweeping and washing are not particularly effecting means of reducing PM_{10} concentrations, according to the AP42 resuspension function reductions in silt loading ought to have significant benefits. These are measures which are already available and can be implemented immediately, although it appears that further development and certification of sweepers is required to improve the collection efficiency for PM_{10}.

The vehicle-based collection and destruction of some types of particle is feasible and could be effective, but as there are currently no legislative drivers it is doubtful that the relevant technologies will be introduced into vehicles in the near future. Regenerative braking could lead to significant reductions in brake wear particles, but this applies principally to electric and hybrid vehicles, and these are currently only produced in small numbers. The planting of vegetative traps may have a minor effect on resuspension via the retention of particles which would otherwise be available for resuspension. However, the effects are not well known, and large-scale planting is not a realistic proposition for urban areas where exceedences of PM limit values are the most common. The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could also have an impact on the amount of material deposited on the road, and hence resuspension. It is also fairly undemanding technically, although changes to the infrastructure would be required to allow for the routine washing of heavy-duty vehicles. The application of dust suppressants may be effective, but there are various concerns, not least the potential health impacts of the compounds used.

6 Conclusions and recommendations

6.1 Conclusions

The main conclusions of this Report are summarised below.

(i) As yet, there are relatively few technologies and policies which have been developed specifically to address non-exhaust PM emissions from road vehicles. Consequently, the literature on the effectiveness of such measures is limited.

(ii) Data from Marylebone Road suggest that the most effective measures for controlling total non-exhaust PM are likely to be those which have a significant impact on resuspension and brake wear.

(iii) According to the AP42 resuspension function, reductions in average vehicle weight and road silt loading ought to have significant benefits in terms of reducing resuspension.

(iv) The available data do not support the idea that de-icing salt is a significant source of airborne PM in UK cities, and a reduction of road salt grit application is likely to have minimal influence. The use of certain de-icing liquids appear to be associated with a reduction in ambient PM_{10} levels, whereas other liquids, such as brine, appear to have a detrimental effect.

(v) The evidence currently indicates that road sweeping is not a particularly effecting means of reducing PM_{10} concentrations. Further development of sweepers is required to improve the collection efficiency for PM_{10}.

(vi) The planting of vegetative traps may have a minor effect on resuspension via the retention of particles which would otherwise be available for resuspension. However, the effects are not well known, and large-scale planting is not a realistic proposition for urban areas where exceedences of PM limit values are the most common.

(vii) The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could also have an impact on the amount of material deposited on the road, and hence resuspension. It is also fairly undemanding technically, although changes to the infrastructure would be required to allow for the routine washing of heavy-duty vehicles.

(viii) The vehicle-based collection and destruction of some types of particle is feasible and could be effective. However, as there are currently no legislative requirements for vehicle manufacturers to control non-exhaust PM, it is doubtful that the relevant technologies will be introduced into vehicles in the near future. Little is known about the effectiveness of vehicle-based abatement options.

(ix) Regenerative braking could lead to significant reductions in brake wear particles, but this applies principally to electric and hybrid vehicles, and these are currently only produced in small numbers.

(x) The application of dust suppressants may be effective, but there are various concerns, not least the potential health impacts of the compounds used.

6.2 Recommendations

The following recommendations have resulted from this work:

(i) As stated earlier in this project, more comprehensive information on non-exhaust emissions would help to clarify the mechanisms by which particles affect human health, and would foster the development of pollution abatement strategies. The work clearly shows that little is known about the effectiveness of vehicle-based abatement options. In all cases, further research work is required. More information on the influence of different materials and different techniques is needed. This information should also cover reduction potentials, costs, side effects (*e.g.* on road safety) *etc.*

(ii) Previously developed technologies could potentially be used to counter each of the main sources of non-exhaust emissions including resuspension, brake and tyre sources, though their effectiveness for these purposes would have to be tested extensively, as their appropriateness for this application is only speculated upon in this Report.

(iii) According to the AP42 resuspension function, reductions in average vehicle weight ought to have significant benefits in terms of reducing resuspension. One control option might therefore be to introduce vehicle weight restrictions (particularly for HGVs) in areas where PM levels are close to air quality standards and objectives.

(iv) There is evidence that some de-icing compounds, such as CMA, can lead to reductions in PM_{10} concentrations. The application of CMA may therefore be one option for ensuring compliance with air quality standards, in particular in relation to the number of exceedences of the PM_{10} daily mean limit of 50 μgm^{-3}. However, other liquids, such as brine, appear to have a detrimental effect on resuspension. This area requires further research in the UK. The role of CMA in the reduction in $PM_{2.5}$ concentrations (significant with respect to discussions under the EU air quality thematic strategy) remains unknown.

(v) The evidence currently indicates that road sweeping is not a particularly effecting means of reducing PM_{10} concentrations, but sweeping may have a beneficial effect on air quality over the long term if it can remove particles that may evolve into PM_{10}. Further work is required to determine the evolution of the size distribution of the material on the road surface, and to establish the mechanism of fragmentation, as this could have important implications for the effectiveness of street sweeping programmes.

(vi) It is thus further proposed that consideration should be given to establishing a testing scheme that would identify the most effective road sweeping systems. This could be used as the basis for a certification scheme. Finally, whilst these systems could be measured under laboratory conditions, it is recommended that real-world environments are used within this testing regime. Experience has indicated that road tunnel environments could be successfully used for this purpose.

(vii) Further work is required to evaluate the potential for using dust suppressants at locations where PM concentrations are high. Such work would need to consider the effectiveness of different suppressants, as well as potential effects on health and the local ecosystem.

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Appendix A: Glossary

Accumulation mode	Particles formed via the coagulation of nucleation mode particles, primary emission sources, and gas-to-particle transformations. Particles range between around 0.05μm and 1 μm in diameter, and have an atmospheric residence time of tens of days.
Coarse particle mode	Particles larger than around 1 μm, including wind-blown crustal matter and material released during abrasion processes. Coarse particles have shorter residence times than accumulation mode particles. This is not consistent with the definition for PM_{coarse} given below.
Dustfall	Particles larger than 100μm, which tend to fall out of the atmosphere within minutes.
ESP	Electrostatic precipitator
GVW	Gross vehicle weight.
HDVs	Heavy-duty vehicles (heavy goods vehicles and buses) >3.5 tonnes GVW
HGVs	Heavy goods vehicles, >7.5 tonnes GVW
LDVs	Light-duty vehicles (cars and light goods vehicles), <3.5 tonnes GVW
LGVs	Light goods vehicles <7.5 tonnes GVW
NAEI	National Atmospheric Emissions Inventory
Nucleation mode	Particles emitted directly from combustion sources, having a diameter of less than around 50 nm and an atmospheric residence time of a few hours. They are transformed by coalescence and condensation into larger accumulation mode particles.
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.
Primary particles	Particles emitted directly to the atmosphere.
Secondary particles	Particles formed within the atmosphere from gas phase precursors. This includes particles originating from atmospheric oxidation of sulphur and nitrogen oxides, and their reaction products with ammonia, and from the oxidation of organic compounds.
TSP	Total suspended particulate.