JUSTIFICATION OF AN EXCEL SPREADSHEET APPROACH FOR PREDICTING ROAD RUNOFF POLLUTANT CONCENTRATIONS

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CONTENTS

Summary

A methodology, based on spreadsheet calculations, is described for the prediction of monthly average pollutant concentrations in road runoff. The accumulation of pollutants on road surfaces is estimated based on the emissions produced by vehicles (exhaust, brake and tyre wear, oil leakage) and by road surface wear and converted to a runoff concentration using the calculated runoff volume. For a 134 m stretch of a two lane highway in N London, the derived concentrations for zinc, copper, cadmium, pyrene, benzo(a)pyrene and total suspended solids are 601.5 µg/L, 58.6 µg/L, 0.098 µg/L, 1.98 µg/L, 0.25 µg/L and 193.1 mg/L, respectively. By comparing the results obtained for different roads in London it will be possible to identify ‘hot-spots’ where there is the greatest possibility of detrimental impacts occurring in receiving waters as a consequence of the discharge of contaminated runoff. Because the assessment approach considers the pollutant contributions from different types of vehicles (petrol, diesel and electric passenger cars, petrol, diesel and electric light duty vehicles, diesel rigid axle and articulated heavy goods vehicles, motorcycles, taxis, buses and coaches) it is feasible to identify those which pose the greatest contamination problem for road runoff. In addition, the described approach allows the vehicular and road surface associated processes leading to the highest production of specific pollutants to be ascertained. Hence, the most appropriate control procedures for effectively mitigating an identified pollutant problem can be established. For the road section described in this report, over 90% of the zinc is created by tyre wear with rigid axle HGVs providing the greatest input. Over 90% of the copper is derived from brake wear to which passenger cars make the greatest contribution (54%). Exhaust emissions and tyre wear are major contributors to the two monitored PAHs with fuel combustion being the predominant source (54% for pyrene; 64% for benzo(a)pyrene),

1. Introduction

Particles emitted as a result of road transport activity can be placed into two main categories according to their sources. These are exhaust traffic related particles, resulting from fuel combustion and non-exhaust traffic related particles. The latter category has been reviewed by Boulter (2006) and Grigoratos and Martini (2014) but in both these reports the emphasis is on the discussion of the resulting atmospheric concentrations. Because traffic exhaust related particles make significant contributions to ambient atmospheric particulate matter (PM) they have been widely studied and fully characterized in the laboratory under well-defined test conditions. In contrast, the different non-exhaust processes, involving, for example, mechanical abrasion and oil leakage have not been as extensively studied. The main abrasion processes leading to the direct emission of particulate matter to the road environment are tyre, brake and road surface wear. Other potential sources of direct particle emissions are clutch and engine wear, abrasion of wheel bearings, corrosion of other vehicle components as well as street furniture and crash barriers. However, given the current level of understanding, these sources of PM emissions are not easily quantified. All traffic related emissions can potentially be deposited to the road surface but can additionally be subjected to re-suspension processes as a result of tyre shear, vehicle-generated turbulence, and wind action leading to a reduction in the amount of PM available for wash-off and incorporation in road runoff.

Several difficulties arise when studying wear particles from non-exhaust traffic related sources. First of all, due to the lack of standard measurement procedures, researchers have employed many different sampling methodologies which often result in non-comparable results and conclusions. Additionally, there are many different parameters which affect wear particles in terms of their physicochemical characteristics and emission rates. For example, the content and emission rates of brake wear particles depend on driving behaviour (e.g. frequency and severity of braking), as well as on the conditions under which the braking event occurs (e.g. vehicle speed and ambient temperature). The generation and emission of tyre wear particles depends on the tyre characteristics (e.g. size, tread depth, chemical composition, accumulated mileage, set-up), road surface characteristics (e.g. material, porosity, condition) and state of maintenance, vehicle characteristics (e.g. weight, location of driving wheels, engine power), as well as on vehicle operating conditions (e.g. speed, linear acceleration, frequency and extent of braking and cornering). Depending on their size, wear particles may deposit on the road or very close to it, be partially attached to the vehicle, or in the case of smaller particles become airborne. The factors influencing the emissions from exhausts, brake wear, tyre wear and road surface wear as well as depositions due to oil leakage are discussed in the relevant sub-sections of Section 2 of this report.

The sizes of the particles produced from the different vehicle sources will be important in influencing whether they remain suspended in the atmosphere or will preferentially be initially deposited on the road surface. It is commonly assumed that most primary fine particles are emitted from the exhaust, whereas many of the coarse particles are considered to originate from non-exhaust sources. There is general agreement that exhaust emissions can be classified as $PM_{2.5}$ (particulate matter less than 2.5 μm) and will therefore be predominantly airborne. However, there is also evidence to suggest that while non-exhaust particles will demonstrate a greater tendency to be deposited, they are also able to contribute to the fine and coarse modes of PM_{10} (particulate matter less than 10 µm) (Boulter, 2006; Dahl et al., 2006; Gustafsson et al., 2008; Harrison et al., 2012) enabling them to potentially make a significant contribution to the atmospheric phase. It has been estimated that approximately 40-50% by mass of generated brake wear particles but only 0.1-10% of tyre wear particles are emitted as PM_{10} (Garg et al., 2000; Sanders et al., 2003; Mosleh et al., 2004; Wik and Dave, 2009; Kukutschová et al., 2011; Harrison et al., 2012; Kumar et al., 2013).

The pollutants which are considered in this report in assessing the quality of highway runoff are three metals (cadmium, copper and zinc) and two polycyclic aromatic hydrocarbons (pyrene and benzo(a)pyrene). All three metals can be found in both vehicle and road components although to different extents. The same is true, although usually to a lesser extent, for polycyclic aromatic hydrocarbons but in addition these organic compounds can be generated by road transport related processes, particularly during the burning of motor fuels within either petrol or diesel engine vehicles.

Polycyclic aromatic hydrocarbons (PAHs) are a group of more than 100 organic compounds found in coal and tar deposits and produced during the incomplete combustion of fossil fuels. They consist of fused aromatic rings with the simplest being naphthalene (2 rings). Higher molecular weight compounds consist of 3 fused rings (e.g. anthracene and phenanthrene), 4 fused rings (e.g. pyrene and fluoranthene), 5 fused rings (e.g. benzo(a)pyrene and benzo(e)pyrene) and 6 fused rings (e.g. benzo(g,h,i)perylene). The higher the molecular weight the greater the tendency of the PAH to be attached to particulates following release into the environment. A major concern regarding PAHs is their toxicity, in particular their carcinogenity, although this varies according to the specific PAH. The International Agency for Research on Cancer (IARC, 2010) classifies PAHs as having known, possible, or probable carcinogenic impacts on humans. Benzo(a)pyrene has been identified as a known carcinogen whereas pyrene is classified as a possible carcinogen. Both these PAHs are found in the UK road environment (Smith et al., 1995) with benzo(a)pyrene clearly representing a serious threat to human and environmental health. Pyrene is one of the most significant PAHs in traffic emissions and has been found to represent 14.7% of the total PAH content in Chinese road dusts followed by fluoranthene (12.9%) and chrysene (11.0%) (Cao et al., 2017).

In considering which PAHs to include in the spreadsheet prediction of highway runoff concentrations, the initial choice was to use one individual PAH as well as total PAHs. However, in compiling the relevant data it became clear that there was a lack of consistency regarding which PAHs were included in the total PAH category. This ruled out the use of total PAHs in the spreadsheet assessment and instead two individual PAHs have been selected. Pyrene is an automatic choice because of its predominance in the highway environment. However, as it is not one of the most carcinogenic PAHs, benzo(a)pyrene has also been included in the spreadsheet. Both these PAHs have been found to play a prominent part in a substance flow analysis of PAHs in road runoff with 4 fused ring compounds (including pyrene) exceeding 5 fused ring compounds (including benzo(a)pyrene) by a factor of over 5 (Siopi, 2015). This research identified that the major sources of both PAHs were vehicle tyre wear (31.2%-46.4%) and exhaust gases (48.4%-48.9%) followed by oil leakages (5.5%-16.4%) with road surface material and brake lining wear representing only minor sources (0.6%-1.8%).

The derivation of the identified pollutants (cadmium, copper, zinc, pyrene and benzo(a)pyrene) from five different traffic related sources (exhaust emissions, tyre wear, brake wear, road surface wear and oil leakage) are discussed in more detail in the following sections. From the reported literature data, a great deal of consideration has been put into choosing the relevant values to be used in the spreadsheet calculations. This includes taking into account the following factors where a number of alternatives exist:

- where ranges of metals are reported, the distribution of values within these ranges are considered in order to derive an overall average
- emphasis is given to those values which have been determined in studies which are most appropriate to the application of the spreadsheet in terms of the techniques used and the experimental conditions employed
- important consideration is given to the influence of operating conditions on the each parameter e.g. the involvement of heat and friction in amending metal concentrations in tyre wear compared with those in the tyre itself (see Section 2.3.2)

2. Traffic related pollutant sources

In order to estimate the overall pollutant loadings to the road surface deriving from exhaust emissions, brake wear, tyre wear, road surface wear and oil leakage, the parameter values available for each of these sources have to be converted to pollutant masses per vehicle-kilometre travelled. The procedures available for achieving this are described in the following sub-sections. In addition, it will be necessary to estimate the proportion of the emitted pollutant which remains deposited on the road surface and which is subsequently available for wash-off during a storm event. A critical factor in determining whether emitted particles are deposited or become dispersed in the atmosphere is their size distribution. Where the emitted particles are finer than 10 µm (PM_{10}) the probability is that they will be preferentially found in the atmospheric environment. How this influences the behaviour of particles from the individual sources will be discussed in Section 3.

2.1 Exhaust emissions

2.1.1 Emission factors for combustion of transport fuels

The majority of vehicles currently in the vehicle fleet rely on an internal combustion engine that burns fuel including petrol, diesel, compressed natural gas (CNG) and liquid petroleum gas (LPG). Exhaust emissions have been extensively investigated with emission controls and emission standards applied in many countries. In most cases, these standards relate to air quality and the emissions of gases (carbon monoxide, nitrogen oxides, hydrocarbons, sulphur oxides) and particulate matter. There is less information available that is relevant to stormwater quality issues, such as emissions of trace elements and the more complex organic compounds (Kennedy et al. (2002).

a) Metals

Pulles et al (2012) have published recommended metal emission factors associated with the combustion of transport fuels within Europe based on both their own tailpipe measurements as well as a comprehensive review of previously reported values. The results, expressed as µg per kg of fuel burnt, together with associated high and low values are given in Table 1 for nine metals. These values can be converted into emissions per vehicle-kilometre (vkm) using the density of the fuel (petrol, 0.74 kg/L; diesel, 0.83 kg/L) and the fuel consumption for each category of vehicle according to the mode of driving. Fuel consumption data for different types of vehicles under urban driving conditions are presented in Table 2. Where the ranges of values are reported they are converted into average values for use in this study. At this stage, no attempt has been made to determine how the variability influences the final calculated value.

Table 1. Metal emission factors (µg/kg) for combustion of road transport fuels (after Pulles et al., 2012)

Metal	Fuel	Emission factor	Emission factor range
As	Petrol Diesel	0.3 <0.1	0.26-0.34
Cd	Petrol Diesel	0.29 <0.05	0.24-0.34
Cr	Petrol Diesel	6.4 12	5.6-7.4 10-13
Cu	Petrol Diesel	4 7.3	3.4-4.7 6.1-8.7
Hg	Petrol Diesel	8.4 2.3	7.7-9.3 2.1-2.4
Ni	Petrol Diesel	0.94 <0.1	0.79-1.1
Pb	Petrol Diesel	1.5 <0.3	1.3-1.8
Sr	Petrol Diesel	0.19 <0.1	0.18-0.2
Zn	Petrol Diesel	36 19	29-44 16-21

Table 2. Average fuel consumption data for different vehicle types under urban driving conditions

	Average fuel consumption	
	Miles per gallon	L/km
Petrol passenger cars	38.6	0.074
Diesel passenger cars	49.7	0.057
Light commercial vehicles (LDVs) (petrol)	22.0	0.128
Light commercial vehicles (LDVs) (diesel)	28.0	0.102
Heavy goods vehicles (HGVs) (rigid axle)	9.2	0.309
Heavy goods vehicles (HGVs) (articulated)	9.0	0.317
Motorcycles	80.0	0.0355
Taxis	45.0	0.0633
Buses	6.0	0.475
Coaches	11.0	0.260

2.1.2 Calculation of pollutant emissions per vehicle-kilometre travelled due to exhaust emissions

The calculation of pollutant emissions per vehicle-kilometre is carried out using the following equation:

Pollutant emissions per vehicle-kilometre (mg/vkm) = pollutant emission factor (mg/kg fuel used) x fuel density (kg/L) x fuel consumption (L/vkm)

a) Metals

Two examples of typical calculations, for metal emission factors using the data provided in Tables 1 and 2, are shown below. These are representative of the procedures used in the spreadsheets (see Appendices 1, 2 and 3).

For petrol passenger cars:

Emissions of Zn per kilometre = 0.036 x 0.74 x 0.074
= 0.00197 mg/vkm
= 1.97 µg/vkm

For heavy goods vehicles (rigid axle; diesel):

Emissions of Cu per kilometre = 0.0073 x 0.83 x 0.309
= 0.00187 mg/vkm
= 1.87 µg/vkm

Multiplication of the emissions per kilometre by the vehicle kilometres travelled provides an estimation of the pollutant emissions produced by particular categories of vehicles for an identified stretch of road (see Section 3).

b) Polycyclic aromatic hydrocarbons

Because both pyrene and benzo(a)pyrene are large organic molecules (4 and 5 fused rings, respectively) they will be preferentially associated with particulates. Duran et al. (2001) examined the emission of PAHs in European diesel passenger cars and modelled the changing emissions under different conditions relating to fuel consumption parameters and vehicle operation. USEPA (2002) have identified over 32 PAHs in vehicle exhaust emissions and a large range of emission factors for PAHs have been reported. As in the case of metals, exhaust emission contaminant PAH loads can be derived using fuel consumption, the vehicle kilometres travelled and on the basis of particulate emissions. Using this approach for petrol engine vehicles, the emission factors (µg/vkm) reported by Gertler et al. (2002) and Norbeck et al. (1998) for cars and light duty vehicles for benzo(a)pyrene, pyrene and total PAHs are shown in Table 3. The discrepancy in the total PAH emission factors highlights the problem associated with different analyses involving different combinations of individual PAHs.

Because of continuous improvements in engine design leading to more efficient combustion of fuels it is important to use the latest available data relating to exhaust emissions from road transport. Currently, this is provided by the European Environment Agency (EEA) 2013 emission inventory guidebook (Ntziachristos and Samaras, 2013) where PAH emission factors are identified for both petrol and diesel engine vehicles. For petrol engines distinctions are made between the use of conventional or closed - loop catalysts and hence the ranges for the emission factor values shown in Table 3 (the averages are indicated within square brackets). Table 3 also identifies the emission factor values selected for use in the spreadsheet calculations for pyrene and benzo(a)pyrene (see Appendices 4 and 5). Emphasis is

Table 3. PAH emission factors for petrol vehicles (passenger cars and LDVs).

Vehicle type	Exhaust emission factors (µg/vkm)			
	Norbeck et al. (1998)	Gertler (2002)	Ntziachristos and Samaras (2013)	Values used in this study
Cars and LDVs	5.0 (BzPy)	6.5 (BzPy)	0.32-0.48 [0.40] (BzPy)	0.40 (BzPy)
	10.0 (Py)		1.8-5.78 [3.79] (Py)	6.90 (Py)
	10,128 (PAH)	1,883 (PAH)		

BzPy = benzo(a)pyrene; Py = pyrene; PAH = total PAH

given to the considerably lower 2013 values provided by Ntziachristos and Samaras (compared to those previously reported for both compounds) as these are representative of more recent engine emission performances. The vehicle flow data is not able to differentiate between the catalyst types fitted to petrol vehicles and therefore the average of the 2013 values is applied. For benzo(a)pyrene the pre-2013 values have not been included. For pyrene the discrepancy between the 2013 and pre-2013 values is not so large and therefore an overall average has been calculated (using the 10.0 and 3.79 µg/vkm values). The selected values are used in the spreadsheet for petrol passenger cars, petrol LDVs and motorcycles (although no specific data is available for the latter).

PAH emission factor data for diesel vehicles is available for both light duty and heavy duty vehicles as shown in Table 4. As for the petrol vehicle emissions, the variability in the total PAH values illustrates the different individual PAHs which have been included in different studies. The variations for pyrene and benzo(a)pyrene are less extreme but those values which do deviate substantially are highlighted in Table 4 and have not been included in the determination of emission factors to be used in the spreadsheet (see Appendices 4 and 5). As in the case of petrol vehicles, the 2013 values provided by Ntziachristos and Samaras for diesel vehicles are taken as the benchmark given their higher relevance to the current diesel vehicle fleet. The range of values quoted by Ntziachristos and Samaras (2013) distinguish between direct (DI) and indirect injection (IDI) diesel engine vehicles. Mid-point values in the reported ranges (shown in square brackets in Table 4) are used because the available vehicle flow statistics do not discriminate between DI and IDI diesel engine vehicles. In the spreadsheet, the emission factors shown in Table 4 for ‘Cars and LDVs’ are allocated to cars, taxis and LDVs with HGV values being used for rigid axle HGVs, articulated HGVs, buses and coaches.

Table 4. PAH emission factors for different types of diesel vehicles.

Vehicle type		Exhaust emission factors (µg/vkm)				
	Rogge et al. (1993)	Sjogren (1996)	USEPA (2002)	Gertler (2002)	Ntziachristos and Samaras (2013)	Values used in this study
Cars and LDVs			8.1 (BzPy) 152 (Py)		0.63-2.85 [1.74] (BzPy) 12.3-38.96 [25.63] (Py)	1.74 (BzPy) 25.63 (Py)
HGVs	1.3 (BzPy) 22.6 (Py) 209.9 (PAH)	0.19 (BzPy) 15.35 (Py) 46.4 (PAH)	8.1 (BzPy) 44 (Py)	6.2(BzPy) 40.7 (Py)	0.90 (BzPy) 31.59 (Py)	0.80 (BzPy) 30.85 (Py)

BzPy = benzo(a)pyrene; Py = pyrene; PAH = total PAH; highlighted values have been disregarded in the calculation of the values to be used in this study

2.2 Brake wear emissions

Cars are usually equipped with front disc brakes and either rear disc or drum brakes, and many modern vehicles are also equipped with anti-lock braking systems (ABS). Commercial vehicles tend to be fitted with drum brakes, although disc brakes are being increasingly used. Garg et al. (2000) have estimated that the front brakes have to provide around 70% of the overall braking power and therefore need replacing more frequently.

The different types of brake lining materials include non-asbestos organic (NAO), low-metallic, semi-metallic and metallic with the first three types having the most common applications. Although less noisy, NAO linings are relatively soft and generally wear faster and create more dust than the other types. Low-metallic linings are made from an organic formula mixed with small amounts (10 to 30%) of metal to help with heat transfer and provide better braking but the added metal creates more brake dust. Semi-metallic linings (typical metal content of between 30 and 65%) are more durable but have intrusive noise characteristics. Metallic linings tend to be used for high performance requirements or where extreme braking conditions are required. An extensive discussion of the nature and characteristics of the composition of brake lining material (binders, fibres, fillers, frictional additives, lubricants, and abrasives) is provided by Kennedy et al. (2002) and is also reported in the review of Boulter (2006).

The most important determinant of brake wear is driving behaviour, in particular the frequency and severity of braking events. The highest concentrations of brake wear particles are typically observed near busy junctions, traffic lights, pedestrian crossings, and corners as a consequence of the forced deceleration which occurs in these areas.

The particle size distribution of worn brake material indicates that a substantial proportion will be emitted as airborne particulate matter. Garg et al. (2000) have reported that the mass mean diameter of brake wear debris varies between 0.7 and 2.5 μm. For three different types of brake lining, Sanders et al. (2003) observed that although the mass-weighted size mean diameter over an urban driving cycle was approximately 5-6 μm, a significant proportion of the wear debris could be greater than 20 μm in diameter. In addition to being released to the atmosphere and being deposited on the road surface, small amounts of brake dust can be retained on the vehicle. It is estimated that approximately 50% of the generated brake wear particles become airborne (Garg et al., 2000; Sanders et al., 2003; Barlow et al., 2007; Kukutschová et al., 2011) with the rest being deposited on the road surface or being attracted to the vehicle. Braking is considered to be a major source of non-exhaust traffic-related emissions particularly in intra-urban locations.

2.2.1 Brake wear emission factors

It has been estimated that front disc brakes last for around 56,000 km under normal usage, whilst rear brakes can be expected to last around 112,000 km (Garg et al., 2000). The majority of published research work has considered the impact of brake wear on atmospheric pollution and therefore has concentrated on PM_{10} emissions and associated emission factors. Reported PM_{10} emission factors (mg/vkm) for passenger cars and LDVs are 7.9 (USEPA, 1995), 2.9-7.5 (Garg et al., 2000), 1.8-4.9 (Lükewille et al., 2001), 8.1 (Sanders et al., 2003), 8.8 (Luhana et al., 2004), 4.0-8.0 (Barlow et al., 2007), 5.8 (Iijima et al., 2008), 8.0 (Bukowiecki et al., 2009) and 7.0 (NAEI, 2012); giving an overall average of 6.7 mg/vkm. For HGVs, the reported PM_{10} emission factors (mg/vkm) are more variable and include 0-610 (Abu-Allaban et al., 2003), 24.5 (Rauterberg –Wulff, 1999), 20-32 (Barlow et al., 2007), 11.0 (NAEI, 2012).

When assessing the amount of brake wear material which can potentially be deposited on the road surface it is necessary to consider the full particle size range and not just the PM_{10} fraction. During the lifetime usage of a braking system, normally around 80% of the friction material can be expected to have worn away, and on this basis total wear amounts to 11-18 mg/vkm for cars and 29 mg/vkm for LDVs (Garg et al., 2000). Based on component size, density, and lifetime, Legret and Pagotto (1999) calculated brake lining wear factors of 20 mg/vkm for cars, 29 mg/vkm for LDVs and 47 mg/vkm for HGVs. In Stockholm, Westerlund (2001) estimated higher losses of material from cars (17 mg/vkm), HGVs (84 mg/vkm) and buses (110 mg/vkm). For cars, Luhana et al. (2004) determined an average brake lining wear factor of 8.8 mg/vkm. For HGVs in New Zealand, Kennedy et al. (2002) calculated the loss of brake lining material to be around 54 mg/vkm.

These values have been summarised by EMEP/EEA (2016) and are shown in Table 5 together with total wear factors used for urban roads in the Netherlands (Klein et al., 2017). Where more than value exists, the values selected to be used in this study are typically at the mid-point of those reported.

Table 5. Brake wear emission factors (total particulates) for different vehicle types.

Vehicle type	Brake wear emission factors (mg/vkm)		
	EMEP/EEA (2016)	Klein et al. (2017)	Value used in this study
Passenger cars	8.8-20	21	14
LDVs	29	23	26
HGVs	29-84	69	55
Motorcycles		8	8
Taxis			14
Buses	110	52	75
Coaches			52

2.2.2 Pollutant concentrations in brake wear material

a) Metals

The compositions of brake linings can vary remarkably (depending on manufacturer and lining type) and ranges of metal concentrations determined by a number of studies (often covering several orders of magnitude) have been reported (Thorpe and Harrison, 2008; Boulter, 2006). The metals which tend to be present in the highest concentrations are iron, copper, lead and zinc. The reported mass concentration ranges in the brake linings of cars are (1.17- 63.7%) for iron, (11-205,000 mg/kg) for copper, (1.28 -119,00 mg/kg) for lead, (14.5 -188,000 mg/kg) for zinc and (0.1 - 41.4 mg/kg) for Cd. Westerlund (2001) found that the concentration ranges for HGVs and buses were generally within those observed for car brake linings. From the ranges of published concentrations (Thorpe and Harrison, 2008; Boulter, 2006), average values can be deduced for Cd, Cu and Zn and are shown in Table 6. These are compared with the reported metal compositions of brake dust samples, which are of more relevance to this study. The concentration values recommended for use in this study are also reported in Table 6.

Table 6. Selected metal concentrations (mg/kg) in brake linings and brake lining dusts

	Metal concentration (mg/kg)				
	Brake lining dusts			Brake linings	
	Hildemann et al., 1991	Kennedy and Gadd, 2000	Garg et al., 2000	Average concentration deduced from values reported by Thorpe and Harrison, 2008	Concentration values used in this study
Cd		<0.6-2.6			2.6
Cu	370	71-1980	380-39300	Cars: 40,000 HGVs: 20,000	10,000
Zn	270	360-9630	120-27300	Cars: 25,000 HGVs: 15,000	7,500

b) PAHs

According to Kennedy et al. (2002) there is little information available from industry on the composition of brake linings with respect to particular organic compounds. It is also believed that the chemical composition of brake wear debris significantly differs from the chemical composition of the original lining material (Kukutschová et al., 2011; Österle et al., 2001). Grigoratos and Martini (2015) have emphasised the need to consider both lining and wear debris composition in order to gain a comprehensive view of how the braking process affects the chemical composition of brake wear particles. The chemical composition of organometallic brake wear particles was determined by Hildemann et al. (1991) and the same samples were subjected to a solvent-soluble organic analysis by Rogge et al. (1993). It was found that only a small fraction of the organic fraction of brake dust could be extracted which is not surprising given that brake linings are required to withstand excessive mechanical and heat stress and must be resistant to possible leaking brake fluid.

The identifiable portion of the brake particle organics determined by Rogge et al. (1993) consisted mainly of n-alkanoic acids (34.3%) and polyalkylene glycol ethers (56.9%), the latter being a typical component of brake fluid. These compounds are lost from the hydraulic brake systems to the drum assembly, and then find their way onto the brake lining and into brake dust. In addition, Rogge et al. (1993) detected n-alkanes and a number of PAHs and substituted PAHs, with a total concentration of 16.16 mg/kg. The build-up of heat during brake application is considered to be responsible for the generation of trace amounts of PAHs. However, there is a very limited database relating to PAHs in brake lining dusts with the results from the two available literature sources being shown in Table 7 for concentrations of benzo(a)pyrene, pyrene and total PAHs. There are no differentiating data for the brake wear produced by different vehicle types.

Table 7. PAH concentrations in brake lining dusts for all vehicles.

PAH	Brake lining dust concentrations (mg/kg)		
	Rogge et al. (1993)	Choplek et al. (2016)	Values used in this study
Benzo(a)pyrene	0.74	3.7	0.74
Pyrene	1.1	3.5	1.1
Total PAH	16.16		

2.2.3 Calculation of pollutant emissions per vehicle-kilometre travelled due to brake wear

The calculation of pollutant emissions from brake wear per vehicle-kilometre is carried out using the following equation:

Pollutant emissions per kilometre (µg/vkm) = pollutant emission factor (mg/vkm) x pollutant concentration in brake wear material (µg/mg)

a) Metals

Using the emission factors and metal concentrations reported in Tables 5 and 6, representative calculations are shown below for Zn emissions from passenger cars and for Cu emissions from HGVs. The values used in the spreadsheets (see Appendices 1, 2 and 3) were determined using similar appropriate calculations.

For passenger cars:

Emissions of Zn per kilometre = 14 x 7.5
= 105 µg/vkm
= 0.105 mg/vkm

For heavy goods vehicles (rigid axle and articulated):

Emissions of Cu per kilometre = 55 x 10
= 550 µg/vkm
= 0.550 mg/vkm

b) PAHs

Using identical calculations to those shown for metals, PAH concentrations can be converted into PAH emission factors for brake wear solids, using the brake wear emission factors shown in Table 5, for different classes of vehicles. The results, using the concentrations reported separately by Rogge et al. (1993) and Choplek et al. (2016) are compared in Table 8 to the ranges of emission factors for benzo(a)pyrene and pyrene reported by Siopi (2015). It is clear that the emission factor ranges derived using the Rogge et al. (1993) data are much more consistent with the values reported by Siopi (2015) than those derived using the Choplek et al. (2016) concentrations.

Therefore, the brake wear concentrations used in the spreadsheet calculations (see Appendices 4 and 5) are 0.74 mg/kg for benzo(a)pyrene and 1.1 mg/vkm for pyrene (as shown in Table 7).

Table 8. Ranges of benzo(a)pyrene and pyrene emission factors for brake lining wear dusts for all vehicles.

PAH	Emission factors for brake lining wear dusts (ng/vkm)		
	EF ranges using Rogge et al. (1993) data	EF ranges using Choplek et al. (2016) data	EF ranges reported by Siopi et al. (2015)
Benzo(a)pyrene	10.36-55.5	51.8-277.5	6.51-62.16
Pyrene	15.4-82.5	49.0-262.5	9.68-92.40

2.3 Tyre wear emissions

A new tyre fitted to an average European car weighs around 8 kg, and loses roughly 1-1.5 kg in weight during its service lifetime, which is typically around 3 years or 50,000 to 60,000 km. Thus, between around 10% and 20% of the tyre material will be released into the roadside environment during its lifetime (Environment Agency, 1998). Therefore, a typical ‘average’ tyre wear factor would be of the order of 100 mg/vkm for a passenger car (assuming four wheels per vehicle) (Boulter, 2006).

Tyre wear depends on several parameters such as:

a) tyre characteristics with the most important being size (radius/width/depth), tread depth, construction, pressure and temperature, contact patch area, chemical composition, accumulated mileage and set-up

b) vehicle characteristics such as weight, distribution of load, location of driving wheels, engine power, electronic braking systems, suspension type and state of maintenance

c) road surface characteristics with the most important being material (bitumen/concrete), texture pattern, porosity, condition, wetness and surface dressing

d) vehicle operation such as speed, linear acceleration, radial acceleration, frequency and extent of braking and cornering.

As a consequence of these influencing parameters it is not surprising that heavy goods vehicles have been reported to emit up to ten times higher amounts of tyre wear particles compared to light duty vehicles and passenger cars and that concrete pavements produce lower wear emissions compared to other types of pavements (Amato et al., 2011; Denier van der Gon et al., 2012). Modern radial-ply tyres have greater rigidity for cornering, better grip in the wet, and are much less susceptible to wear than the older cross-ply type. However, driving behaviour and driving conditions are well-recognised determinants of tyre wear. Most tyre rubber is lost during acceleration, braking, and cornering, such that the amount of rubber lost will be greatest near busy junctions and on bends. Luhana et al. (2004) found that tyre wear was around 50% higher at an average speed of 40 km/h (dominated by urban driving) than at average speed of 90 km/h (dominated by motorway driving).

As previously reported for brake wear emissions, finer tyre wear material may adhere to vehicle surfaces whilst the coarser material will be deposited on the road. Camatini et al. (2001) have shown that tyre debris collected from the road surface contains particles ranging up to a few hundred µm in size. Similar observations were made by Smolders and Degryse (2002), who found that roadside tyre debris had a mean diameter of 65 µm for cars and 80 µm for HGVs indicating the preference for this material to be deposited on the road surface rather than remaining airborne.

2.3.1 Tyre wear emission factors

Cadle and Williams (1978) found that airborne particles were emitted from car tyres at a typical rate of 4 mg/vkm compared to PM_{10} emission factors for LDVs of 5 mg/vkm (USEPA, 1995) and 13 mg/vkm (Lükewille et al. (2001). Rauterberg-Wulff (1999) determined PM_{10} emission factors for tyre wear for LDVs and HGVs of 6.1 mg/vkm and 31 mg/vkm respectively. Comparisons with material loss values suggest that less than 10% of car tyre wear material is emitted as PM_{10} under 'typical' driving conditions (Boulter 2006). Rauterberg-Wulff (1999) estimates a higher value of approximately 15% but CSTEE (2003) suggest a proportion of 5-6% and Pierson and Brachaczek (1974) found that only 2% to 7% of tread wear material could be classified as airborne PM.

To derive an emission factor for tyre wear which is expected to be deposited on a road surface it is necessary to consider the total particulate fraction and not the PM_{10} fraction alone, the majority of which will become airborne. A typical 'average' tyre wear emission factor of 100 mg/vkm has been estimated for a passenger car (Boulter, 2006) with Luhana et al. (2004) determining an average tyre wear for all particle sizes of 74 mg/vkm. Higher values would be expected for LDVs and HGVs. Legret and Pagotto (1999) proposed a wear factor for heavy goods vehicle tyres of 136 mg/vkm) but this is lower than earlier reported wear factors for 'heavy-duty vehicles', 'articulated lorries' and buses of 189 mg/vkm, 234 mg/vkm, and 192 mg/vkm respectively (Baumann and Ismeier, 1997). Other workers have reported considerably higher tyre wear factors for heavy-duty vehicles. Gebbe et al. (1997) identified a value of 539 mg/vkm with other values closer to 800 mg/km (Garben et al., 1997; EMPA, 2000) or even higher at 1403 mg/vkm (SENCO, 1999). The wide range of values illustrates the dependence of tyre wear factor on the vehicle configuration, such as the number of axles and the load.

The reported values are summarised in Table 9 together with results reported by EMEP/EEA (2016) and by Klein et al. (2017) for total tyre wear factors for urban roads in the Netherlands. The values selected to be used in this study are identified in Table 9 and are based on an assessed compromise of the values given in this Table.

2.3.2 Pollutant concentrations in tyre wear material

Tyre wear particles are generated either by shear forces between the tread and the road surface, in which case the emitted particles are mechanically generated and mainly distributed in the coarse size fraction (Kreider et al., 2010), or by volatilization which results in the generation of much smaller fine particles. The composition of tyres is dominated by organic compounds, with a wide variety of compounds being

Table 9. Tyre wear emission factors (total particulates) for different vehicle types.

Vehicle type	Tyre wear emission factors (mg/vkm)			
	Review of literature values	EMEP/EEA (2016)	Klein et al. (2017)	Value used in this study
Passenger cars	74-100	4-500; average 10	132	100
LDVs			159	159
HGVs	539-800	136-1403	850	850
Motorcycles			60	60
Taxis				100
Buses			415	415
Coaches				250

used in the manufacture of tyres (Hildemann, 1991; Rogge et al., 1993; Reddy and Quinn, 1997; Environment Agency, 1998; Gadd and Kennedy, 2000). Although tyre formulations vary according to required performance standards, they essentially consist of blends of different rubbers (40-60%) compounded with fillers (30%), reinforcing materials (15%), plasticizers (6%), chemicals for vulcanization (6%), and anti-aging agents (2%). Rogge et al. (1993) noted that tyre wear particles contain appreciable amounts of styrene and butadiene polymers and using GC/MS analysis determined the concentrations of more than 100 specific solvent-extractable organic compounds.

a) Metals

Zinc is found in significant quantities in tyre tread and tyre wear debris due to its use as an accelerator in the vulcanisation process. The zinc oxide content of tyres has been reported to range between 0.04 and 2% (400 – 20,000 mg/kg) (Ahlbom and Duus, 1994; Smolders and Degryse, 2002; Councell et al., 2004). Gadd and Kennedy (2000) reported a narrower range of Zn concentrations in passenger car tyres in New Zealand of between 0.6-1.0% (6,000-10,000 mg/kg). However, Panko et al. (2003) have noted that the heat and friction generated during the interaction of tyres with the road surface alters both the chemical composition and characteristics of the generated particles compared to the original tyre tread. Therefore, when considering road surface deposits, it is important to consider the zinc levels in tyre debris for which Smolders and Degryse (2002) have reported concentrations in particles finer than 100 µm of 11,400 mg/kg for car tyres and 24,100 mg/kg for truck tyres. However, Zn is also present in high concentrations in larger particles and Kreider et al. (2010) found Zn concentrations of 0.3 to 0.4% (3,000-4,000 mg/kg) for both road collected and laboratory generated wear particles. Thus it would appear that there is a reduction in Zn concentrations in tyre wear debris compared to in tyres themselves. This has been taken into account in assessing the Zn concentration (5,500 mg/kg) used in this study for car tyre wear debris. Unfortunately there is no data available for the Zn concentrations in tyre wear debris from heavy goods vehicles. However, given that it is also likely to be lower than the Zn concentration in HGV tyres themselves and assuming the same level of reduction as in car tyres, a value of 11,000 mg/kg has been selected for use in this study for the concentration of Zn in HGV tyre debris.

The concentrations of other metals deriving from tyre wear are generally several orders of magnitude lower than those for zinc, although significant amounts of aluminium, silicon, barium, calcium, copper, sulphur, iron, potassium, lead, sodium, cadmium, magnesium, tellurium, selenium and titanium have been found. For most metals the concentration ranges are rather wide, reflecting the different manufacturing techniques. The ranges of concentrations which have been reported for Cd, Cu and Zn in tyres and tyre wear debris are given in Table 10 together with the values which have been selected for use in this study. Emphasis has been placed on concentrations reported in tyre wear debris, where this is available.

Table 10. Selected metal concentrations (mg/kg) in tyres and tyre wear debris

	Metal concentration (mg/kg)			
	Tyre wear debris		Tyres	
	Kreider et al. (2010)	Smolders and Degryse (2002)	Range of concentrations extracted from Thorpe and Harrison, 2008; Boulter, 2006	Concentration values used in this study
Cd			Cars:<0.05-2.6 LDVs:<0.05-0.1 HGVs:0.28-0.56	Cars: 1.3 LDVs: 0.6 HGVs: 0.42
Cu			Cars:0.4-5.5 HDVs:1-3 HGVs:1-2.5	Cars: 2.8 HDVs: 2.0 HGVs: 1.8
Zn	3,000-4,000	Cars: 11,400 HGVs: 24,100	Cars:430-15,500 (average:7,400) LDVs:1,190-3,640 (average: 2,400) HGVs:13,800-18,300 (average: 16,050)	Cars: 5,500 LDVs: 2,400 HGVs: 11,000

b) PAHs

PAHs in tyres are found in the highly aromatic oils (HA oils) that are used during the manufacturing phase in order to make the rubber easier to work and also to make the tread softer. The addition of HA oils also improves the grip of the tyres making it easier to brake on a wet road. Therefore, although the reduction of PAHs in extender oils and tyres is desirable, CSTEE (2003) note that this will not have a large effect on the total amount of PAHs in the environment because tyre-related PAHs only represent 1% of the total PAH concentrations found in sediments. However since 1 January, 2010 mandatory legislation has been in place forbidding the use of HA extender oils in tyre production (Directive 2005/69/EC becoming European Regulation 1907/2006/EC (REACH), Annex XVII, entry 50). This regulation states that all tyres produced in the EU, as well as all imported tyres, shall not contain more than 1 mg/kg (0,0001 % by weight) of benzo(a)pyrene or more than 10 mg/kg (0.001 % by weight) of the sum of 8 PAHs (including benzo[a]pyrene but not pyrene) (ETRMA, 2010). Although this

Directive refers only to new tyres it is likely that by 2019 this will apply to the vast majority of vehicle tyres in use in the UK. However, it does mean that emphasis should be placed on using the most recent data available for concentrations of PAHs in tyres.

The concentrations of PAHs in tyre wear particles have been identified in several reviews (e.g. ten Broeke et al. (2008); Boulter et al. (2006); Kennedy et al. (2002)). Table 11 has been constructed by extracting the data provided in these reviews for benzo(a)pyrene, pyrene and total PAHs. In some cases this data is available for passenger cars and HGVs whereas other published works only report average values for all vehicles. Although total PAH values are given in Table 11 they are not used further in this study because of the lack of consistency regarding which individual PAHs are included. The concentrations for benzo(a)pyrene and pyrene in tyre wear have been fully assessed to derive values for use in the spreadsheets (see Appendices 4 and 5) and these are shown in Table 11. Unfortunately, none of the available data post-dates 2010 and therefore where elevated values exist these have not been included in determining average values for use in this study. The ignored values are highlighted in Table 11. The selected values for the concentrations of benzo(a)pyrene and pyrene are shown for cars (incorporating petrol passenger cars and LDVs, diesel passenger cars and LDVs, electric passenger cars and LDVs, taxis and motorcycles) and HGVs (incorporating rigid axle HGVs, articulated HGVs, buses and coaches) in Table 11.

2.3.3 Calculation of pollutant emissions per vehicle-kilometre travelled due to tyre wear

The calculation of pollutant emissions from tyre wear per vehicle-kilometre is carried out using the following equation:

Pollutant emissions per vehicle-kilometre (µg/vkm) = pollutant emission factor (mg/vkm) x pollutant concentration in tyre wear material (µg/mg)

a) Metals

Using the emission factors and metal concentrations reported in Tables 9 and 10, representative calculations are shown below for Zn emissions from passenger cars and for Cu emissions from HGVs. The values used in the spreadsheets (see Appendices 1, 2 and 3) were determined using similar appropriate calculations.

For passenger cars:

Emissions of Zn per kilometre = 100 x 5.5
= 550 µg/vkm
= 0.550 mg/vkm

For heavy goods vehicles (rigid axle and articulated):

Emissions of Cu per kilometre = 850 x 0.0018
= 1.53 µg/vkm
= 0.00153 mg/vkm

Table 11. Reported concentrations of benzo(a)pyrene, pyrene and total PAHs in vehicle tyre wear.

Pollutant		Concentration in vehicle tyre wear (mg/kg)*		
		Cars	HGVs	All vehicles
Total PAHs	CSTEE (2003)	65	22.5	
	Rauterberg-Wolff (2003)	195		
	LUT (2004)	62		
	NBI (2004)	67		
	Noordermeer (2006)	47 90	112	
	Hofstra (2006)	33	14	
	Rogge et al. (1993)			200
Pyrene	Nilsson et al. (2005)	24.2	15	
	Baumann and Ismeier (1997)	14.0	3.5	
	LUT (2004)	17.0		
	NBI (2004)	23.5		
	Gadd and Kennedy (2000)	10.8-69.7	6.3	
	Rogge et al. (1993)			54.1
	DeMarini et al. (1994)			34-452
	Reddy and Quinn (1997)			41.4
	Kennedy et al. (2002)			42.6
	Values used in this study	13.9	4.9	
Benzo(a) pyrene	Nilsson et al. (2005)	1.3	2.5	
	Baumann and Ismeier (1997)	3.0	0.4	
	LUT (2004)	3.0		
	NBI (2004)	2.1		
	Rogge et al. (1993)			3.9
	VROM (1997)			6.4
	DeMarini et al. (1994)			85-114
	Values used in this study	2.35	1.45	

*average concentrations are quoted where available; highlighted values have been disregarded in the calculation of the values to be used in this study

b) PAHs

The benzo(a)pyrene and pyrene emission factors for tyre wear solids are calculated in the same way as for metals using the concentrations in Table 11. The calculated values are compared with the ranges of emission factors for benzo(a)pyrene and pyrene reported by Siopi (2015) in Table 12. The calculated values in this study are consistently at the lower end of the ranges reported by Siopi (2015) which is appropriate given the recently introduced legislation regarding the use of HA extender oils. It is also noticeable that the emission factors for tyre wear are 2 to 3 orders of magnitude greater than those for PAHs produced by brake lining wear.

Table 12. Ranges of calculated benzo(a)pyrene and pyrene emission factors for tyre wear for all vehicles compared with data provided by Siopi (2015).

PAH	Emission factors for tyre wear (µg/vkm)	
	EF ranges calculated for this study	EF ranges reported by Siopi et al. (2015)
Benzo(a)pyrene	0.141-1.233	0.038-12.00
Pyrene	0.830-4.170	0.317-132.0

2.4 Road surface wear emissions

A range of asphalt-based and concrete-based road surfacings are used in the UK. Concrete surfacings are composed of coarse aggregate, sand and cement. The majority of road surfaces are asphaltic in nature. Asphalts are mixtures of mineral aggregates (stone material), filler and bitumen binder in which the stone content is on average 95% with the bituminous binder constituting 5%. Bitumen is a complex substance based on organic compounds as well as traces of many different metals. The organic fraction constitutes a viscous hydrocarbon material containing two major components, maltenes (which are soluble in n-heptane) and asphaltenes (molecular weight of up to 1000; which are not soluble in n-heptane), in a medium of saturated hydrocarbons (oils) and polycyclic aromatic hydrocarbons (resins). The complexity of bitumen makes it very difficult to characterise (Lindgren, 1996), and its precise composition varies according to the source of the crude oil from which it originates, and any subsequent modification (Whiteoak, 1990). Fauser (1999) has suggested that asphaltenes and maltenes from bitumen can be used as tracers for road surface wear.

2.4.1 Road surface wear emission factors

Boulter (2006) reports that a wide range of road surface wear factors have been determined in a small number of studies. Values vary from 3.8 mg/vkm (Muschack, 1990) to 440 mg/vkm (Kennedy et al., 2002) where the surface contained a high proportion (e.g. 50%) of bitumen. Where the bitumen comprised only 10% of the road surface material, this reduced to 90 mg/vkm. However, in Nordic and Alpine countries where there is extensive use of road sanding and studded tyres during the winter, the road surface wear can be considerably higher with values of between 4 and 24 g/vkm (Lindgren, 1996). Carlsson et al. (1995) found that the introduction of softer studded tyres and more durable asphalt reduced this to 11 g/vkm.

The above values are summarised in Table 13 although unfortunately they do not discriminate between the impact of the different types of vehicles. However, more recent reports by EMEP/EEA (2016) and Klein (2017) do provide this important discrimination as shown in Table 13.

Table 13. Road surface wear emission factors (total particulates) for different vehicle types.

Vehicle type	Road surface wear emission factors (mg/vkm)			
	Review of literature values	EMEP/EEA (2016)	Klein et al. (2017)	Value used in this study
Passenger cars	3.8-440	150	180	165
LDVs		150	180	165
HGVs		760	922	840
Motorcycles			74	74
Taxis		150	180	165
Buses			922	840
Coaches				550

2.4.2 Pollutant concentrations in road surface wear material

a) Metals

Lindgren (1996) has reported the metal concentrations in the stone aggregate and bitumen constituents of asphalt. The two types of stone aggregate identified are gabbro and porphyry. The former has coarser grains, is softer and generally has a higher content of most metals as shown in Table 14. This Table also identifies the estimation of metal contents in new asphalt based on a content of 95% stone aggregate (gabbro or porphyry) and 5% bitumen. These combined values for Cd, Cu and Zn, which are used in the spreadsheets (see Appendices 1, 2 and 3) are listed in Table 14.

Table 14. Selected metal concentrations (mg/kg) in asphalt road surfacings

	Metal concentration (mg/kg) Lindgren (1996)				
	Stone aggregate (95%)			Bitumen (5%)	Combined asphalt value used in this study
	Gabbro	Porphyry	Average value		
Cd	0.127	0.136	0.132	0.09[1]	0.13
Cu	70.5	21.9	46.2	<17 (use 15)	44.6
Zn	149	36.3	92.7	<17 (use 15)	88.8

[1] Alloway (1990)

b) PAHs

Concentrations of specific organic compounds in road surface material have not been reported in detail. Gadd and Kennedy (2000) found that the mass composition of raw bitumen was dominated (86%) by high-molecular weight n-alkanes (>C_{29}), with C_{15}-

C_{28} n-alkanes contributing 13%, and C_{10}-C_{14} n-alkanes contributing only 1%. Elvebakken (1991) used PAHs as bitumen tracers, and noted that more than 300 different PAHs are present in bitumen. However, each compound could only be found in a concentration of less than 0.1%. Gadd and Kennedy (2000) reported a total PAH concentration in New Zealand 180/200+P bitumen of 9.2 mg/kg. Brandt and Groot (2001) observed a total PAH concentration in bitumen of 6.4 -15.2 mg/kg

Bitumen typically contains 3-4 ring PAHs with approximately five side chains (aliphatic and alicyclic), with an average of seven carbon atoms. However, only small amounts of individual PAHs are present in bitumen compared to the initial crude oil. The vacuum distillation processing of bitumen removes most PAHs, leaving a total concentration commonly between 0.0012 to 0.0020% (12 to 20 mg/kg). Although there are likely to be some variations in the concentration of individual PAH compounds in bitumen, the total PAH (estimated based on detected PAHs) and measured by Gadd and Kennedy (2000) at 10 mg/kg is considered to represent an appropriate contribution of bitumen wear to total PAH loading on road surfaces. Table 15 also provides details of reported pyrene and benzo(a)pyrene concentrations in bitumen which can also be seen to be highly variable. The values selected for use in this study have been derived by averaging the values remaining after the extremes (high and low) have been removed. It is important to note that these concentrations are for bitumen which only represents 5% of the composition of asphalt aggregates. The individual PAH concentrations in the total asphalt are shown in Tables 16a and 16b together with the previously used emission factors for asphalt road wear for different vehicle classes.

Table 15. Reported concentrations of benzo(a)pyrene, pyrene and total PAHs in bitumen.

Pollutant	Reference details	Concentration in bitumen (mg/kg)
Total PAHs	Gadd and Kennedy (2000)	9.2
	Brandt and De Groot (2001)	15.2, 13.3, 6.4 [11.63]
	Ifenna and Osuji (2013)	170.7, 164.6, 119.3, 190.9, 103.8 [149.9]
Pyrene	Gadd and Kennedy (2000)	2.1
	Brandt and De Groot (2001)	0.9, 1.0, 0.3 [0.73]
	Lundgren (1998)	2.9, 4.9, 7.2 [5.0]
	Fernandes et al. (2009)	8.0
	Pinhiero et al. (2009)	0.06
	Ifenna and Osuji (2013)	6.46, 2.38, 7.68, 14.55, 2.35 [6.68]
	Values used in this study	3.63
Benzo(a) pyrene	Gadd and Kennedy (2000)	<0.2
	Brandt and De Groot (2001)	0.7, 0.5 [0.6]
	Herrington et al.(1993)	0.15
	Lundgren (1998)	5.0, 6.0, 8.0 [6.33]
	Fernandes et al. (2009)	10.0
	Pinhiero et al. (2009)	0.145
	Ifenna and Osuji (2013)	8.05, 11.98, 7.74, 8.06, 5.11 [8.19]
	Values used in this study	1.81

Highlighted values have been disregarded in the calculation of the values to be used in this study

Table 16a. Values used in spreadsheet (see Appendix 5) for the calculation of emission factors for benzo(a)pyrene arising from asphalt surface wear.

Vehicle type	EF for asphalt surface wear (mg/vkm)	Bz(a)Py concentration in asphalt (µg/mg)	EF for Bz(a)Py from asphalt surface wear (mg/vkm)
Motorcycles	74	0.0000905	6.7×10^{-6}
All cars, all LDVs, taxis	165	0.0000905	14.9×10^{-6}
Coaches	550	0.0000905	49.8×10^{-6}
HGVs, buses	840	0.0000905	76.0×10^{-6}

Table 16b. Values used in spreadsheet (see Appendix 4) for the calculation of emission factors for pyrene arising from asphalt surface wear.

Vehicle type	EF for asphalt surface wear (mg/vkm)	Py concentration in asphalt (µg/mg)	EF for Py from asphalt surface wear (mg/vkm)
Motorcycles	74	0.00001815	13.4×10^{-6}
All cars, all LDVs, taxis	165	0.00001815	29.9×10^{-6}
Coaches	550	0.00001815	99.8×10^{-6}
HGVs, buses	840	0.00001815	$^{152.5} \times 10^{-6}$

2.4.3 Calculation of pollutant emissions per vehicle-kilometre travelled due to road surface wear

The calculation of pollutant emissions from road surface wear per vehicle-kilometre is carried out using the following equation:

Pollutant emissions per vehicle-kilometre (µg/vkm) = pollutant emission factor (mg/vkm) x pollutant concentration in road surface wear material (µg/mg)

a) Metals

Using the emission factors and metal concentrations reported in Tables 13 and 14, representative calculations are shown below for Zn emissions from passenger cars and for Cu emissions from HGVs. The values used in the spreadsheets (see Appendices 1, 2 and 3) were determined using similar appropriate calculations.

For passenger cars:

Emissions of Zn per kilometre = 165 x 0.0888
= 14.7 µg/vkm
= 0.0147 mg/vkm

For heavy goods vehicles (rigid axle and articulated):

Emissions of Cu per kilometre = 840 x 0.0446

= 37.46 µg/vkm
= 0.0375 mg/vkm

b) PAHs

The benzo(a)pyrene and pyrene emission factors for asphalt surface wear are calculated in the same way with the results being shown in Tables 16a and 16b. Previously published emission factor ranges arising from asphalt surface wear are 15.0×10^{-6} - 64.0×10^{-6} for benzo(a)pyrene and 8.7×10^{-6} – 57.6×10^{-6} for pyrene (Siopi et al., 2015). These are in good agreement with the values derived in this study (Tables 16a and 16b).

2.5 Oil leakage emissions

Motor lubricating oils consist mainly of mineral oils (derived from refining crude petroleum) and are characterised as paraffinic or naphthenic hydrocarbons. Lubricating oils are used in a vehicle engine to lubricate the moving engine parts to reduce friction, to minimise wear and tear and to maximise performance. They also maintain engine cleanliness, protect against engine rust and corrosion, cool engine parts, seal combustion gases and permit easy starting (Denton, 2007).

USDOE (1987) reports that the principle contaminants in used oil are aromatics (benzene, toluene and xylenes), PAHs (benz(a)anthracene, benzo(a)pyrene, naphthalene and others) and chlorinated organics (dichlorodifluoromethane, trichlorotrifluorethane, 1,1,1-trichloroethane, trichloroethylene, tetrachloro-ethylene and polychlorinated biphenyls). The amount of PAHs in lubricating motor oil increases during use due to pyrolysis and pyrosynthesis at the high temperatures in the engine and consequently further contamination of the lubricant by fuel combustion products (Wong and Wang, 2000). In a study performed on petrol engine vehicles it was found that the total PAH content peaked at around 4,000 miles while the more toxic five ring PAHs continued to increase up to 5,800 miles. However, not all engines have the same effect on the lubricating oil with petrol engines being capable of producing more carcinogenic compounds than higher operating temperature diesel engines (Clonfero et al., 1996).

Most lubricating oils contain additives to influence properties such as viscosity, volatility, stability, cleanliness and cold flow. These additives include organic compounds as well as inorganic salts. Examples of additives which incorporate metals, normally as salts, include anti-oxidants (to prevent the build-up of engine deposits), detergents and dispersants (to maintain engine cleanliness) and anti-wear agents. New motor oils may contain metals such as calcium, magnesium, barium and zinc (Zieba-Palus 1998; Zieba-Palus and Kocielniak 2000) with used oils additionally containing aluminium, antimony, arsenic, cadmium, chromium, cobalt, copper, lead, manganese, mercury and nickel (US DOE 1987).

2.5.1 Oil leakage emission factors

Oil loss rates due to leakage of 2.8 mL/1,000 km for cars and LDVs and 2.1 mL/1,000 km for HGVs and buses have been reported (Kennedy et al., 2002). Given an average value for the specific gravity of motor oil of 0.89 kg/L, these correspond to oil leakage values of 2.49 mg/km for cars and LDVs and 1.87 mg/km for HGVs and buses.

2.5.2 Pollutant concentrations in engine oil

a) Metals

Table 17 summarises the reported concentrations of zinc, copper and cadmium in new and used oils (5000-6000 km). There is a considerable variability between the different studies. Those values which are deemed to be extremes (either high or low) are highlighted in Table 17 and have not been used to calculate the value to be used in this study. The data suggests that the concentrations of copper and cadmium in engine oil increase with usage most probably due to wear processes. In contrast, zinc levels remain effectively unchanged possibly due to the higher initial concentrations with variations being due to breakdown derivatives of the original additives. Oil leakage will occur regardless of level of usage and since one value is required, the average of reported values for new and used oils has been chosen for use in the spreadsheets.

b) PAHs

The reported concentrations of total PAHs, pyrene and benzo(a)pyrene from used engine oil are shown in Table 18. It is possible that these values overestimate the PAH levels in engine oil loss as they generally represent analyses of used oil collected during oil changes (and therefore with maximum contamination), whereas oil leakage occurs through the life of the oil, including when PAH concentrations are lower.

The values reported in Table 18 for total PAHs are fairly consistent apart from one low value (10.3 mg/kg) and an extremely high range (2516-4605 mg/kg) for unleaded petrol cars. The latter value appears unreasonably high compared to diesel engine values when assessed against individual PAH concentrations in used oil. All reported concentrations for pyrene are of the same order with the values proposed by Kingett-Mitchell being preferred. Unfortunately, these do not fully discriminate between petrol and diesel engines but in the absence of any other available data have been adopted for this application. The same reasoning is applied to the benzo(a)pyrene data with the elevated 144.1 mg/kg value being ignored. The lower values will also result in emission factors for used oil loss which are consistent with those published (see Tables 20a and 20b).

Table 17. Reported concentrations of cadmium, copper and zinc in new and used motor lubricating oil.

Pollutant	Reference details	Concentration in new engine oil (mg/kg)	Concentration in used engine oil (mg/kg)
Zinc	Zieba-Palus (1998) (Lotos 15W/40 engine oil)	2117	2011
	Zieba-Palus (1998) (Castrol GTX engine oil)	1320	1020
	Roslan et al. (2016)	46.1-65.2	
	Values used in this study	1719	1516
	Average value for use in spreadsheet	1618	
Copper	Zieba-Palus (1998) (Lotos 15W/40 engine oil)	0.46	34.7
	Zieba-Palus (1998) (Castrol GTX engine oil)	0.5	2.5
	MfE (2000)		105
	Roslan et al. (2016)	0.028-0.416 [0.222]	
	Values used in this study	0.39	2.5
	Average value for use in spreadsheet	1.45	
Cadmium	Zieba-Palus (1998) (Lotos 15W/40 engine oil)	0.15	1.29
	Kingett and Mitchell (1994)		<1
	MfE (2000		1
	Roslan et al. (2016)	0.24-0.61 [0.43]	
	Values used in this study	0.29	1.15
	Average value for use in spreadsheet	0.72	

[ ] indicates average values derived from ranges of values; highlighted values have been disregarded in the calculation of the values to be used in this study

Table 18. Reported concentrations of benzo(a)pyrene, pyrene and total PAHs in used motor lubricating oil.

Pollutant	Reference details	Concentration in used engine oil (mg/kg)
Total PAHs	Colwill et al. (1984)	110
	Denton (2007)	10.3
	Kingett-Mitchell (1994)	369-750 (petrol car) [560] 344 (mixed petrol/diesel car)
	MfE (2000)	204
	Clonfero et al. (1996)	2516-4605 (unleaded petrol car) 27-197 (diesel car) 27-291 (diesel HGV)
Pyrene	Kingett-Mitchell (1994)	50-61 (petrol car) [55.5] 52 (mixed petrol/diesel car)
	Wong and Wang (2000)	0-95.8 [47.9]
	Values used in this study	55.5 (petrol car) 52 (diesel car)
Benzo(a) pyrene	Kingett-Mitchell (1994)	5-6 (petrol car) [5.5] 4 (mixed petrol/diesel car)
	Wong and Wang (2000)	0-144.1 [72.1]
	Values used in this study	5.5 (petrol car) 4 (diesel car)

2.5.3 Calculation of pollutant emissions per vehicle-kilometre travelled due to oil leakage

The calculation of pollutant emissions from oil leakage per vehicle-kilometre is carried out using the following equation:

Pollutant emissions per vehicle-kilometre (µg/vkm) = pollutant emission factor (mg/vkm) x average pollutant concentration in used/unused engine oil (µg/mg)

a) Metals

The data used in the calculation of the emission factors for zinc, copper and cadmium due to oil leakage are collected in Table 19. Representative calculations are shown below for Zn emissions from passenger cars and for Cu emissions from HGVs. The values used in the spreadsheets (see Appendices 1, 2 and 3) were determined using similar appropriate calculations.

For passenger cars:

Emissions of Zn per kilometre = 2.49 x 1.618
= 4.03 µg/vkm
= 0.00403 mg/vkm

For heavy goods vehicles (rigid axle and articulated):

Emissions of Cu per kilometre = 1.87 x 0.00145
= 0.00271 µg/vkm
= 2.71 x 10^{-6} mg/vkm

In addition to the calculated metal emission factors for engine oil leakage, Table 19. also shows previously reported emission factors (Kennedy et al., 2002). There is good agreement between both sets of values.

Table 19. Values used in the spreadsheets (see Appendices 1, 2 and 3) for the calculation of emission factors for zinc, copper and cadmium arising from engine oil leakage

	Vehicle type	EF for engine oil leakage (mg/vkm)	Metal concentration in engine oil (µg/mg)	EF for zinc from engine oil leakage (mg/vkm)	Values reported by Kennedy et al. (2002) (mg/vkm)
Zinc	Cars and LDVs	2.49	1.618	4.03 x 10^{-3}	2.9 x 10^{-3}
	HGVs and buses	1.87	1.618	3.03 x 10^{-3}	2.1 x 10^{-3}
Copper	Cars and LDVs	2.49	0.00145	3.61 x 10^{-6}	2.5 x10^{-6}
	HGVs and buses	1.87	0.00145	2.71 x 10^{-6}	1.9 x 10^{-6}
Cadmium	Cars and LDVs	2.49	0.00072	1.79 x 10^{-6}	3.2 x 10^{-6}
	HGVs and buses	1.87	0.00072	1.35 x 10^{-6}	2.4 x 10^{-6}

b) PAHs

The relevant data used for the calculation of emission factors for benzo(a)pyrene and pyrene for different vehicle types are shown in Tables 20a and 20b, respectively. There is good agreement between the calculated emission factors (µg/vkm) and those reported by Kennedy et al. (2002).

Table 20a. Values used in spreadsheet (see Appendix 5) for the calculation of emission factors for benzo(a)pyrene arising from engine oil leakage

Vehicle type	EF for engine oil leakage (mg/vkm)	Bz(a)Py concentration in used engine oil (µg/mg)	EF for Bz(a)Py from engine oil leakage (mg/vkm)	Values reported by Kennedy et al. (2002) (mg/vkm)
Petrol cars and LDVs	2.49	0.0055	13.7×10^{-6}	14.0×10^{-6}
Diesel cars and LDVs	2.49	0.004	12.5×10^{-6}	
HGVs and buses (diesel)	1.87	0.004	7.5×10^{-6}	7.0×10^{-6}

Table 20b. Values used in spreadsheet (see Appendix 4) for the calculation of emission factors for pyrene arising from engine oil leakage.

Vehicle type	EF for engine oil leakage (mg/vkm)	Py concentration in use engine oil (µg/mg)	EF for Py from engine oil leakage (mg/vkm)	Values reported by Kennedy et al. (2002) (mg/vkm)
Petrol cars and LDVs	2.49	0.0555	138×10^{-6}	140×10^{-6}
Diesel cars and LDVs	2.49	0.052	129×10^{-6}	
HGVs and buses (diesel)	1.87	0.052	152.5×10^{-6}	97×10^{-6}

3. Spreadsheet construction

The following sections describe the different components of the spreadsheet and include material which is additional to that discussed in Section 2 above.

3.1 Road characteristics

The following sub-sections identify the information required for incorporation in the relevant columns of the spreadsheet (see Appendices 1, 2, 3, 4, 5 and 6).

3.1.1 Average annual daily traffic (AADT)

For each section of road being considered, the AADT values (derived from TfL statistics) are included for the following categories of vehicles:

Petrol passenger cars
Diesel passenger cars
Petrol LDVs
Diesel LDVs
Diesel rigid axle HGVs
Diesel articulated HGVs
Motorcycles
Electric car
Electric LDVs
Taxis
Buses
Coaches

3.1.2 Road length (km)

Road lengths given in the spreadsheet represent the distances between intersections for which the AADT values are available from TfL monitoring data and which are also representative of particular drainage sections.

3.1.3 Road width

Road widths are based on the number of lanes in the carriageway and using the recommended lane width of 3.65 m (DMRB, 2005).

3.1.4 Road area

This should include all contributing drainage areas to the surface runoff from the identified section of road. In addition to the carriageway this may also include impervious central reservations, cycle lanes, laybys and pavements (where present).

3.1.5 Daily vehicle kilometre travelled

This is calculated in the spreadsheet by multiplying the average daily traffic flow (for each vehicle type) by the length of the road section under consideration.

3.2 Daily engine emissions

The calculation of exhaust emissions per vehicle-kilometre (mg/vkm) for each vehicle category has been described in Section 2.1. The pollutants in the exhaust emissions are concentrated in the particulate fractions.

Where there is no data specifically available for a particular vehicle type, emission factors and/or pollutant concentrations appropriate to the nearest equivalent class of vehicle (in terms of size and usage characteristics) are used e.g. HGV data for buses; diesel passenger cars for taxis. This applies to all the emission processes described in Sections 3.2, 3.3, 3.4, 3.5 and 3.6.

3.2.1 Exhaust emissions on a particular road section

This is calculated by multiplying the exhaust emissions per vehicle-kilometre (mg/vkm) by the daily vehicle-kilometres travelled for each category of vehicle.

3.2.2 Exhaust emissions deposited

Diesel engine emissions are known to produce more particulates than petrol engines but in both cases, the majority of the particulates are in the PM_{10} size fraction i.e. possessing an aerodynamic diameter less than 10 µm. There is now increasing attention directed at the $PM_{2.5}$ fraction (referred to as the fine fraction of PM_{10}) with the coarse fraction comprising particles with diameters in the size range between 2.5 µm and 10 µm. It is now believed that vehicle exhaust emissions are concentrated in the $PM_{2.5}$ fraction (Thorpe et al., 2007) with a large proportion of the particles emitted from vehicles lying in the ultra-fine region (< 100 nm diameter or $PM_{0.1}$).

Particles emitted within the fine size range of the PM_{10} fraction (<2.5 µm) are likely to remain airborne for long periods and potentially travel hundreds of miles. The coarser particles (> 2.5 µm but <10 µm) will remain airborne for shorter periods but will still tend to be deposited some distance downwind of the vehicle emission source. Particle coarser than 10 µm will have more potential to be deposited by gravitational forces in the immediate area following their emission i.e. on the road surface although this may take several hours. However, given that the aerodynamic mass median diameters of particles emitted by heavy duty diesel engines have been found to be in the range 0.3 to 0.5 µm (e.g. McCain and Drehmel, 1981) it is unlikely that these particles will be readily deposited in the road environment. Given the predicted preference for vehicle emitted particles to remain airborne, a value of only 10% has been applied in the spreadsheets (see Appendices 1, 2, 3, 4, 5 and 6) to the amount being deposited on the immediate road surface. It is acknowledged that this may be an optimistically high value although it would also allow for vehicle emissions in neighbouring roads which are ultimately deposited on the road section under consideration.

3.3 Daily brake wear emissions

The calculation of brake wear emissions per vehicle-kilometre (mg/vkm) for each vehicle category has been described in Section 2.2.

3.3.1 Brake wear emissions on a particular road section

This is calculated by multiplying the brake wear emissions per vehicle-kilometre (mg/vkm) by the daily vehicle-kilometres travelled for each category of vehicle.

3.3.2 Brake wear emissions deposited

Brake wear particles are emitted as a result of a predominantly mechanical process and therefore are expected to lie within the coarser size fractions but there are also studies which report high particle concentrations in the fine and ultrafine fractions (Iijima et al., 2007; Riediker et al., 2008; Kukutschová et al., 2011). It is estimated that between 40-50% by mass of generated brake wear particles are emitted as PM10 (Garg et al., 2000; Sanders et al., 2003; Mosleh et al., 2004; Iijima et al., 2008; Wik and Dave, 2009; Kukutschová et al., 2011; Harrison et al., 2012; Kumar et al., 2013) and are retained in the atmosphere. The rest may initially remain attached to the vehicle or be deposited on the road or nearby (adjacent soils and/or surface waters). These figures are confirmed by EMEP/EEA (2016) and Klein (2017) who report that, on average, 50% of brake wear emissions are available for deposition on the road surface. Therefore a value of 50% has been applied in the spreadsheet to calculate the amount of brake wear material deposited on the road surface.

3.4 Daily tyre wear emissions

The calculation of tyre wear emissions per vehicle-kilometre (mg/vkm) for each vehicle category has been described in Section 2.3.

3.4.1 Tyre wear emissions on a particular road section

This is calculated by multiplying the tyre wear emissions per vehicle-kilometre (mg/vkm) by the daily vehicle-kilometres travelled for each category of vehicle.

3.4.2 Tyre wear emissions deposited

Tyre wear particles are generated either by shear forces between the tread and the road pavement or by volatilization (Kreider et al., 2010). The former are mainly distributed in the coarse size fraction whereas volatilization of the tyre contents results in the generation of much finer particles as a consequence of thermo-mechanical processes where local hot spots develop on the tyre tread and reach temperatures of up to 180°C (Mathissen et al., 2011). The result is the airborne generation of very small particles in the fine and sometimes ultrafine mode (Fauser, 1999; Boulter, 2006; Mathissen et al., 2011) but this typically represents less than 10% by weight of tyre wear particles (Barlow et al., 2007).

The abraded rubber generated mechanically is released as relatively large particles (>20 μm), and therefore is deposited on the road or very close to it. Kreider et al. (2010) tested summer and friction tyres on asphalt based pavements on a road simulator and found that the size distribution by volume of collected tyre wear particles ranged between 5.0 μm and 220 μm with a clear mode at 70-80 μm. The corresponding size distribution of on-road generated wear particles collected under normal driving conditions was similar with the mode centred at 50 μm. Similar observations were made by Smolders and Degryse (2002), who found roadside tyre debris with a mean diameter of 65 µm for passenger vehicles and 80 µm for trucks. All these findings suggest that most of the material emitted during the tyre wear process will be deposited fairly rapidly and amounts have been estimated to be between 90 and 99.9% of the generated tyre wear particles (Fauser, 1999; Rauterberg-Wulff, 1999; Boulter, 2006; Barlow et al., 2007; Wik and Dave, 2009; Panko et al., 2013; Kwak et al., 2013). Klein et al. (2017) confirm these figures with a 95% deposition rate whereas EMEP/EEA (2016) suggest that, on average 80-90% of tyre wear emissions will end up not being released to the atmosphere. For the purposes of this study, the spreadsheets (see Appendices 1, 2, 3, 4, 5 and 6) apply a value of 85% for the amount of tyre wear deposited on the road surface.

3.5 Daily road surface wear emissions

The calculation of road surface wear emissions per vehicle-kilometre (mg/vkm) for each vehicle category has been described in Section 2.4.

3.5.1 Road surface wear emissions on a particular road section

This is calculated by multiplying the road surface wear emissions per vehicle-kilometre (mg/vkm) by the daily vehicle-kilometres travelled for each category of vehicle.

3.5.2 Road surface wear emissions deposited

There is very little published information relating to the distribution between the atmosphere and the road surface itself of particles derived from road surface wear. EMEP/EEA (2016) states that, on average, approximately 10% of road surfaces wear can be expected to be airborne. Klein et al. (2017) puts this lower at 5% indicating that 95% of road wear particles are available for immediate deposition. The lower of the two estimates (90%) has been selected for use in the spreadsheet used in this study.

3.6 Oil leakage deposits

The calculation of oil leakage emissions per vehicle-kilometre (mg/vkm) for each vehicle category has been described in Section 2.5.

3.6.1 Oil leakage emissions on a particular road section

This is calculated by multiplying the oil leakage emissions per vehicle-kilometre (mg/vkm) by the daily vehicle-kilometres travelled for each category of vehicle.

3.6.2 Oil leakage emissions deposited

The majority of oil leaking from the engine sump is expected to be deposited directly on to the road surface. A small amount may be retained on the lower parts of the engine with some being transferred to the chassis through turbulence effects beneath the vehicles. In addition, there may be some volatilisation of the lost oil due to the high operating temperatures in the engine compartment. However, only in the region of 10% of leaked oil is expected to be vaporised or retained on the vehicle with 90% being deposited on the road surface.

3.7 Overall emissions deposited

The overall emissions in the spreadsheets are represented as both daily and monthly emissions. The daily overall emissions are calculated as the sum of daily exhaust emissions deposited (Section 3.2.2), the daily brake wear emissions deposited (Section 3.3.2), the daily tyre wear emissions deposited (Section 3.4.2), the road surface wear emissions deposited (Section 3.5.2} and the oil leakage deposits (Section 3.6.2). This value is multiplied by 30 to obtain the monthly overall emissions deposited.

The selection of one month as the time period for pollutant deposition on the road surface is based on the established pattern of pollutant accumulation on road surfaces which is used in modelling processes. Although a wide range of mathematical models have been used to describe the temporal build-up process the most widely employed predictive relationships for urban surfaces are the exponential function (e.g. Deletic et al., 1997) and the power function (e.g. Egodawatta et al., 2013). Both these models indicate a build-up process which decreases gradually after an initial high accumulation rate and eventually reaches an almost constant value after a time in excess of 14 days. In the UK, a typical prolonged dry period is unlikely to exceed one month and therefore this has been chosen as the time period during which the maximum accumulation of pollutants on a road surface is likely to occur. After this time the application of the monthly average rainfall volume will provide a run-off concentration which is representative of a typical maximum monthly average runoff concentration (see Section 3.8).

3.8 Monthly average runoff concentration

3.8.1 Amount of deposited pollutant removed in runoff

Vehicle derived pollutants which have been deposited on road surfaces are subject to a number of different removal pathways including runoff, splash/spray and dispersion (Folkeson et al., 2009). This project is concerned solely with the runoff process and the pollutants which are contained in the drainage water. Previous investigations have assessed the distribution of pollutants in the different removal pathways. From a study of several roads, Best et al. (2002) found that 46-92% of the pollutants were removed via drift while 8-54% of the pollutants were removed via runoff. For the same removal processes, Steiner et al. (2006) observed that 36% of water and associated pollutants were removed from a road via runoff compared to 64% being removed via drift and spray. The POLMIT-model (POLMIT, 2002) applies 35% to the proportion of pollutants transported by run-off with the larger fraction of 65% probably being re-emitted to air. Based on the latter two studies, a figure of 35% is applied in the spreadsheet to the proportion of pollutants removed from the road surface in runoff during rainfall events.

3.8.2 Monthly rainfall

Rainfall data need to be obtained from the most recent annual records provided by the meteorological site closest to the road site being investigated. Monthly rainfall volumes shown in the spreadsheets are determined by dividing the annual values (expressed in metre) by 12.

3.8.3 Runoff coefficient

The runoff coefficient is a dimensionless coefficient, with a value between 0 and 1, defining the proportion of rainfall landing on a surface that is converted into runoff. A value of 0 corresponds to a situation where all of the water falling on the surface infiltrates through it and a value of 1 indicates that all rainfall is converted into runoff. The range of runoff coefficients quoted for asphalt surfaced roads is 0.75 – 0.95 with values towards the higher end of this range for good quality surfaces. A value of 0.90 has been used in the spreadsheets (see Appendices 1, 2, 3, 4, 5 and 6) and has been selected to represent the 'worst case scenario' in terms of the volume of runoff produced.

3.8.4 Monthly runoff volume

The monthly runoff volume is calculated by multiplying the monthly rainfall (m) by the surface area (m^2) upon which the rainfall is incident and taking into account the runoff coefficient (0.9). In addition to the road surface this should include any other surfaces which contribute to the drainage of this section of road (see Section 3.1.4). The originally calculated volume in m^3 is converted into litres.

3.8.5 Monthly average pollutant runoff concentration

The monthly average pollutant runoff concentration is calculated by dividing the monthly amount of pollutant removed by runoff (mg) (Section 3.8.1) by the monthly runoff volume (L) (Section 3.7.4) and converted to µg/L by multiplying by 1000.

4. Conclusions

By considering the deposition of pollutants derived from vehicle exhaust emissions, brake wear, tyre wear, road surface erosion and oil leakage it has been possible to predict the runoff concentrations for 3 metals (Cd, Cu and Zn), 2 PAHs (pyrene and benzo(a)pyrene) as well as total suspended solids. The road under consideration is a 134 m dual carriageway section of the North Circular Road. The calculations are based on the accumulation of surface deposits. over a one month period and their removal by the monthly average rainfall. Therefore, the reported monthly average runoff concentrations are representative of the potentially maximum amounts of accumulated pollutants. Ideally it would be preferential to calculate runoff concentrations for a specific storm event (event mean concentration) and to compare these values with monitored values. This would enable calibration of the proposed calculation routine. It is hoped to do this when the required monitoring data for relevant stretches of urban London roads becomes available.

The highest predicted metal pollutant runoff concentration is for Zn with a monthly average value of 601.5 µg/L. By far the major contributor to this elevated concentration is tyre wear (91.4%) followed by brake wear (6.7%). Within the tyre wear category, rigid axle HGVs represent the main input (39.3%). The monthly average runoff concentration of Cu is estimated to be 58.6 µg/L to which brake wear is the major contributor (91.2%) followed by road surface wear (8.4%). 53.6% of the brake wear input to this particular road section is estimated to be produced by passenger cars. The predicted average monthly runoff concentration for Cd (0.098 µg/L) is nearly three magnitudes lower than the predicted Cu concentration indicating the limited sources of this metal within the highway environment. Tyres provide the highest input (69.8%) to this low concentration and passenger cars represent the major vehicle source (66.1%). Clearly, Zn and Cu are the metals likely to pose the greatest impact in the receiving stream. Analysis of the data in terms of both vehicular and material sources provides information on where control procedures need to be directed to reduce the concentrations of these metals. For total suspended solids, an average monthly runoff concentration of 193.1 mg/L is predicted. However, this may represent an under-estimation as vehicle derived sources do not necessarily dominate the production of solids in the highway environment as other sources, such as surface soils, will also make important contributions.

The monthly average runoff concentrations for pyrene and benzo(a)pyrene are predicted to be 1.98 µg/L and 0.25 µg/L, respectively. Although these exceed the predicted concentration for cadmium they indicate that the sources of these polyaromatic hydrocarbons are limited in the highway environment particularly when compared to copper and zinc. The major origins of both the studied PAHs are exhaust emissions and tyre wear although the relative amounts differ. Pyrene is predominantly produced by fuel consumption (53.6%) with 41.5% being derived from tyre wear. Benzo(a)pyrene is predominantly produced by tyre wear (63.6%) with 26.5% being derived from exhaust emissions. For both PAHs the exhaust emissions are predominantly from diesel vehicles with only around 14% of the total being produce by petrol engine vehicles (passenger cars and light duty vehicles).

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APPENDICES

Appendix 1. Spreadsheet for the calculation of zinc concentrations in road runoff

Appendix 2. Spreadsheet for the calculation of copper concentrations in road runoff

Appendix 3. Spreadsheet for the calculation of cadmium concentrations in road runoff

Appendix 4. Spreadsheet for the calculation of pyrene concentrations in road runoff

Appendix 5. Spreadsheet for the calculation of benzo(a)pyrene concentrations in road runoff

Appendix 6. Spreadsheet for the calculation of total suspended solids concentrations in road runoff

Appendix 1. Spreadsheet for the calculation of zinc concentrations in road runoff

Zn	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road length (km)	Road width (km)	Road area (km2)	Daily vehicle km travelled	EF for exhaust emissions (mg/kg/ veh)	Fuel density (kg/L)	Fuel consumtion (L/km)	Emission per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 10%	EF for brake wear solids (mg/vkm)	Zn concn in brake dust ug/mg	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 50%	EF for tyre wear solids (mg/vkm)	Zn concn in tyre wear deposits (ug/mg)	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45	0.036	0.74	0.074	0.00197	4.295	0.4295	14.0	7.5	0.105	228.738	114.369	100	5.5	0.550	1198.150	1018.427
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68	0.019	0.83	0.057	0.00090	1.668	0.1668	14.0	7.5	0.105	194.846	97.423	100	5.5	0.550	1020.622	867.528
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54	0.036	0.74	0.128	0.00341	0.046	0.0046	26.0	7.5	0.195	2.641	1.321	159	2.4	0.382	5.168	4.393
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50	0.019	0.83	0.102	0.00161	1.135	0.1135	26.0	7.5	0.195	137.573	68.786	159	2.4	0.382	269.219	228.836
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82	0.019	0.83	0.309	0.00487	1.378	0.1378	55.0	7.5	0.4125	116.662	58.331	850	11	9.350	2644.338	2247.687
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43	0.019	0.83	0.317	0.00500	0.437	0.0437	55.0	7.5	0.4125	36.066	18.033	850	11	9.350	817.500	694.875
Motorcycles	311	0.1341	0.0146	0.001958	41.71	0.036	0.74	0.0355	0.00095	0.039	0.0039	8.0	7.5	0.06	2.502	1.251	60	5.5	0.330	13.763	11.698
Electric car	166	0.1341	0.0146	0.001958	22.26	0	0	0	0.00000	0.000	0.0000	14.0	7.5	0.105	2.337	1.169	100	5.5	0.550	12.243	10.407
Electric LGVs	143	0.1341	0.0146	0.001958	19.18	0	0	0	0.00000	0.000	0.0000	26.0	7.5	0.195	3.739	1.870	159	2.4	0.382	7.318	6.220
Taxis	3132	0.1341	0.0146	0.001958	420.00	0.019	0.83	0.0633	0.00100	0.419	0.0419	14.0	7.5	0.105	44.100	22.050	100	5.5	0.550	231.001	196.351
Buses	220	0.1341	0.0146	0.001958	29.50	0.019	0.83	0.475	0.00749	0.221	0.0221	75.0	7.5	0.5625	16.595	8.297	415	11	4.565	134.677	114.475
Coaches	79	0.1341	0.0146	0.001958	10.59	0.019	0.83	0.26	0.00410	0.043	0.0043	52.0	7.5	0.39	4.132	2.066	250	5.5	1.375	14.567	12.382
											0.9682					394.966					5413.280
											0.02					6.67					91.35

Daily road surface wear emissions					**Daily oil leakage emissions**					**Overall emissions**		**Monthly average runoff concentrations**					
EF for road surface wear (mg/vkm)	Zn concn in asphalt (ug/mg)	Emissions per vehicle km (mg/vkm)	Emissions on this road (mg)	Amount deposited (mg) 90%	Oil loss rate (mg/vkm)	Zn concn in oil (ug/mg)	Zn emissions per vehicle km (mg/vkm)	Emissions on this road (mg)	Amount deposite (mg 90%	Daily emissions on this road (mg)	Monthly emissions on this road (mg)	Amont remove runoff (mg) 35%	Monthly rainfall (m)	Runoff coeff	Monthly runoff volume (L)	Monthly average runoff concentration ug/L	
165	0.089	0.0147	31.991	28.792	2.49	1.618	0.00403	8.777	7.899	1169.92	35097.5	12284.121	0.0587	0.9	103448.428	118.75	Passenger car petrol
165	0.089	0.0147	27.251	24.526	2.49	1.618	0.00403	7.476	6.729	996.37	29891.2	10461.909	0.0587	0.9	103448.428	101.13	Passenger car diesel
165	0.089	0.0147	0.199	0.179	2.49	1.618	0.00403	0.055	0.049	5.95	178.4	62.438	0.0587	0.9	103448.428	0.60	LGV petrol
165	0.089	0.0147	10.360	9.324	2.49	1.618	0.00403	2.842	2.558	309.62	9288.5	3250.990	0.0587	0.9	103448.428	31.43	LGV diesel
840	0.089	0.0748	21.143	19.029	1.87	1.618	0.00303	0.856	0.770	2325.96	69778.7	24422.531	0.0587	0.9	103448.428	236.08	HGV rigid axle
840	0.089	0.0748	6.537	5.883	1.87	1.618	0.00303	0.265	0.238	719.07	21572.2	7550.268	0.0587	0.9	103448.428	72.99	HGV articulated
74	0.089	0.0066	0.275	0.247	1.25	1.618	0.00202	0.084	0.076	13.28	398.3	139.403	0.0587	0.9	103448.428	1.35	Motorcycles
165	0.089	0.0147	0.327	0.294	0	1.618	0.00000	0.000	0.000	11.87	356.1	124.632	0.0587	0.9	103448.428	1.20	Electric cars
165	0.089	0.0147	0.282	0.253	0	1.618	0.00000	0.000	0.000	8.34	250.3	87.603	0.0587	0.9	103448.428	0.85	Electric LGVs
165	0.089	0.0147	6.168	5.551	2.49	1.618	0.00403	1.692	1.523	225.52	6765.5	2367.922	0.0587	0.9	103448.428	22.89	Taxis
840	0.089	0.0748	2.206	1.985	1.87	1.618	0.00303	0.089	0.080	124.86	3745.8	1311.030	0.0587	0.9	103448.428	12.67	Buses
550	0.089	0.0490	0.519	0.467	1.87	1.618	0.00303	0.032	0.029	14.95	448.4	156.947	0.0587	0.9	103448.428	1.52	Coaches
				96.530					19.951	5925.69	177770.8	62219.794				601.46	

Appendix 2. Spreadsheet for the calculation of copper concentrations in road runoff

Cu	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road	Road	Road	Daily vehicle	EF for exhaust	Fuel	Fuel	Emission per	Emission	Amount	EF for brake	Cu concn	Emissions per	Emission	Amount	EF for tyre	Cu concn in tyre	Emissions per	Emission	Amount
		length	width	area	km	emissions	density	consumtion	vehicle km	on this	deposited (mg)	wear solids	in brake dust	vehicle km	on this	deposited (mg)	wear solids	wear deposits	vehicle km	on this	deposited (mg)
		(km)	(km)	(km2)	travelled	(mg/kg/ veh)	(kg/L)	(L/km)	(mg/vkm)	road (mg)	10%	(mg/vkm)	ug/mg	(mg/vkm)	road (mg)	50%	(mg/vkm)	(ug/mg)	(mg/vkm)	road (mg)	85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45	0.004	0.74	0.074	0.00022	0.477	0.0477	14.0	10.0	0.14	304.984	152.492	100	0.0028	0.00028	0.610	0.518
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68	0.0073	0.83	0.057	0.00035	0.641	0.0641	14.0	10.0	0.14	259.795	129.897	100	0.0028	0.00028	0.520	0.442
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54	0.004	0.74	0.128	0.00038	0.005	0.0005	26.0	10.0	0.26	3.521	1.761	159	0.002	0.00032	0.004	0.004
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50	0.0073	0.83	0.102	0.00062	0.436	0.0436	26.0	10.0	0.26	183.430	91.715	159	0.002	0.00032	0.224	0.191
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82	0.0073	0.83	0.309	0.00187	0.529	0.0529	55.0	10.0	0.55	155.549	77.775	850	0.0018	0.00153	0.433	0.368
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43	0.0073	0.83	0.317	0.00192	0.168	0.0168	55.0	10.0	0.55	48.088	24.044	850	0.0018	0.00153	0.134	0.114
Motorcycles	311	0.1341	0.0146	0.001958	41.71	0.004	0.74	0.0355	0.00011	0.004	0.0004	8.0	10.0	0.08	3.336	1.668	60	0.0028	0.00017	0.007	0.006
Electric car	166	0.1341	0.0146	0.001958	22.26	0	0	0	0.00000	0.000	0.0000	14.0	10.0	0.14	3.116	1.558	100	0.0028	0.00028	0.006	0.005
Electric LGVs	143	0.1341	0.0146	0.001958	19.18	0	0	0	0.00000	0.000	0.0000	26.0	10.0	0.26	4.986	2.493	159	0.002	0.00032	0.006	0.005
Taxis	3132	0.1341	0.0146	0.001958	420.00	0.0073	0.83	0.0633	0.00038	0.161	0.0161	14.0	10.0	0.14	58.800	29.400	100	0.0028	0.00028	0.118	0.100
Buses	220	0.1341	0.0146	0.001958	29.50	0.0073	0.83	0.475	0.00288	0.085	0.0085	75.0	10.0	0.75	22.127	11.063	415	0.0018	0.00075	0.022	0.019
Coaches	79	0.1341	0.0146	0.001958	10.59	0.0073	0.83	0.26	0.00158	0.017	0.0017	52.0	10.0	0.52	5.509	2.754	250	0.002	0.00050	0.005	0.005
											0.2524					526.621					1.776

Daily road surface wear emissions					**Daily oil leakage emissions**					**Overall emissions**		**Monthly average runoff concentrations**					
EF for road	Cu concn in	Emissions per	Emissions on	Amount	Oil loss	Cu concn in	Cu emissions per	Emissions on	Amount	Daily emissions	Monthly emissions	Amount in	Monthly	Runoff	Monthly	Monthly average	
surface wear	asphalt	vehicle km	this road	deposited (mg)	rate	oil	vehicle km	this road	deosited (mg)	on this road	on this road	runoff (mg)	rainfall	coeff	runoff	runoff concentration	
(mg/vkm)	(ug/mg)	(mg/vkm)	(mg)	90%	(mg/vkm)	(ug/mg)	(mg/vkm)	(mg)	90%	(mg)	(mg)	35%	(m)		volume (L)	ug/L	
165	0.0446	0.0074	16.031	14.428	2.49	0.0145	0.0000361	0.07865	0.07079	167.56	5026.7	1759.348	0.0587	0.9	103448.428	17.01	Passenger car petrol
165	0.0446	0.0074	13.656	12.290	2.49	0.0145	0.0000361	0.06700	0.06030	142.75	4282.6	1498.914	0.0587	0.9	103448.428	14.49	Passenger car diesel
165	0.0446	0.0074	0.100	0.090	2.49	0.0145	0.0000361	0.00049	0.00044	1.86	55.7	19.478	0.0587	0.9	103448.428	0.19	LGV petrol
165	0.0446	0.0074	5.192	4.673	2.49	0.0145	0.0000361	0.02547	0.02292	96.64	2899.3	1014.771	0.0587	0.9	103448.428	9.81	LGV diesel
840	0.0446	0.0375	10.595	9.536	1.87	0.0145	0.0000271	0.00767	0.00690	87.74	2632.1	921.251	0.0587	0.9	103448.428	8.91	HGV rigid axle
840	0.0446	0.0375	3.276	2.948	1.87	0.0145	0.0000271	0.00237	0.00213	27.12	813.7	284.810	0.0587	0.9	103448.428	2.75	HGV articulated
74	0.0446	0.0033	0.138	0.124	1.25	0.0145	0.0000181	0.00076	0.00068	1.80	54.0	18.891	0.0587	0.9	103448.428	0.18	Motorcycles
165	0.0446	0.0074	0.164	0.147	0	0.0145	0.0000000	0.00000	0.00000	1.71	51.3	17.965	0.0587	0.9	103448.428	0.17	Electric cars
165	0.0446	0.0074	0.141	0.127	0	0.0145	0.0000000	0.00000	0.00000	2.63	78.8	27.564	0.0587	0.9	103448.428	0.27	Electric LGVs
165	0.0446	0.0074	3.091	2.782	2.49	0.0145	0.0000361	0.01516	0.01365	32.31	969.3	339.271	0.0587	0.9	103448.428	3.28	Taxis
840	0.0446	0.0375	1.105	0.995	1.87	0.0145	0.0000271	0.00080	0.00072	12.09	362.6	126.902	0.0587	0.9	103448.428	1.23	Buses
550	0.0446	0.0245	0.260	0.234	1.87	0.0145	0.0000271	0.00029	0.00026	2.99	89.8	31.445	0.0587	0.9	103448.428	0.30	Coaches
				48.373					0.17879	577.20	17316.0	6060.609				58.59	

Appendix 3. Spreadsheet for the calculation of cadmium concentrations in road runoff

Cd	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road	Road	Road	Daily vehicle	EF for exhaust	Fuel	Fuel	Emission per	Emission	Amount	EF for brake	Cd concn	Emissions per	Emission	Amount	EF for tyre	Cd concn in tyre	Emissions per	Emission	Amount
		length	width	area	km	emissions	density	consumtion	vehicle km	on this	deposited (mg)	wear solids	in brake dust	vehicle km	on this	deposited (mg)	wear solids	wear deposits	vehicle km	on this	deposited (mg)
		(km)	(km)	(km2)	travelled	(mg/kg/ veh)	(kg/L)	(L/km)	(mg/vkm)	road (mg)	10%	(mg/vkm)	ug/mg	(mg/vkm)	road (mg)	50%	(mg/vkm)	(ug/mg)	(mg/vkm)	road (mg)	85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45	0.00029	0.74	0.074	0.00002	0.035	0.0035	14.0	0.0026	0.0000364	0.079	0.040	100	0.0013	0.000	0.283	0.241
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68	0.00005	0.83	0.057	0.00000	0.004	0.0004	14.0	0.0026	0.0000364	0.068	0.034	100	0.0013	0.000	0.241	0.205
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54	0.00029	0.74	0.128	0.00003	0.000	0.0000	26.0	0.0026	0.0000676	0.001	0.000	159	0.0006	0.000	0.001	0.001
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50	0.00005	0.83	0.102	0.00000	0.003	0.0003	26.0	0.0026	0.0000676	0.048	0.024	159	0.0006	0.000	0.067	0.057
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82	0.00005	0.83	0.309	0.00001	0.004	0.0004	55.0	0.0026	0.000143	0.040	0.020	850	0.00042	0.000	0.101	0.086
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43	0.00005	0.83	0.317	0.00001	0.001	0.0001	55.0	0.0026	0.000143	0.013	0.006	850	0.00042	0.000	0.031	0.027
Motorcycles	311	0.1341	0.0146	0.001958	41.71	0.00029	0.74	0.0355	0.00001	0.000	0.0000	8.0	0.0026	0.0000208	0.001	0.000	60	0.0013	0.000	0.003	0.003
Electric car	166	0.1341	0.0146	0.001958	22.26	0	0	0	0.00000	0.000	0.0000	14.0	0.0026	0.0000364	0.001	0.000	100	0.0013	0.000	0.003	0.002
Electric LGVs	143	0.1341	0.0146	0.001958	19.18	0	0	0	0.00000	0.000	0.0000	26.0	0.0026	0.0000676	0.001	0.001	159	0.0006	0.000	0.002	0.002
Taxis	3132	0.1341	0.0146	0.001958	420.00	0.00005	0.83	0.0633	0.00000	0.001	0.0001	14.0	0.0026	0.0000364	0.015	0.008	100	0.0013	0.000	0.055	0.046
Buses	220	0.1341	0.0146	0.001958	29.50	0.00005	0.83	0.475	0.00002	0.001	0.0001	75.0	0.0026	0.000195	0.006	0.003	415	0.00042	0.000	0.005	0.004
Coaches	79	0.1341	0.0146	0.001958	10.59	0.00005	0.83	0.26	0.00001	0.000	0.0000	52.0	0.0026	0.0001352	0.001	0.001	250	0.0006	0.000	0.002	0.001
											0.0049					0.137					0.675

Daily road surface wear emissions					**Daily oil leakage emissions**					**Overall emissions**		**Monthly average runoff concentration**							
EF for road	Cd concn in	Emissions per	Emissions on	Amount	Oil loss	Cd concentration	Cd emissions	Cd emissions	Amount	Daily emissions	Monthly emissions	Amont removed in	Monthly	Runoff	Monthly	Monthly average			
surface wear	asphalt	vehicle km	this road	deposited (mg)	rate	in oil	per vehicle km	on this road	deposited (mg)	on this road (mg)	on this road (mg)	runoff (mg)	rainfall	coeff	runoff	runoff concentration			
(mg/vkm)	(ug/mg)	(mg/vkm)	(mg)	90%	(mg/vkm)	(ug/mg)	(mg/vkm)	(mg)	90%			35%	(m)		volume (L)	ug/L			
165	0.00013	0.0000	0.047	0.042	2.49	0.00072	1.7928E-06	0.003906	0.003515	0.33	9.9	3.459	0.0587	0.9	103448.428	0.0334	Passenger car petrol		
165	0.00013	0.0000	0.040	0.036	2.49	0.00072	1.7928E-06	0.003327	0.002994	0.28	8.3	2.920	0.0587	0.9	103448.428	0.0282	Passenger car diesel		
165	0.00013	0.0000	0.000	0.000	2.49	0.00072	1.7928E-06	0.000024	0.000022	0.00	0.1	0.020	0.0587	0.9	103448.428	0.0002	LGV petrol		
165	0.00013	0.0000	0.015	0.014	2.49	0.00072	1.7928E-06	0.001265	0.001138	0.10	2.9	1.009	0.0587	0.9	103448.428	0.0098	LGV diesel		
840	0.00013	0.0001	0.031	0.028	1.87	0.00072	1.3464E-06	0.000381	0.000343	0.13	4.0	1.413	0.0587	0.9	103448.428	0.0137	HGV rigid axle		
840	0.00013	0.0001	0.010	0.009	1.87	0.00072	1.3464E-06	0.000118	0.000106	0.04	1.2	0.437	0.0587	0.9	103448.428	0.0042	HGV articulated		
74	0.00013	0.0000	0.000	0.000	1.25	0.00072	0.0000009	0.000038	0.000034	0.00	0.1	0.038	0.0587	0.9	103448.428	0.0004	Motorcycles		
165	0.00013	0.0000	0.000	0.000	0	0.00072	0	0.000000	0.000000	0.00	0.1	0.035	0.0587	0.9	103448.428	0.0003	Electric cars		
165	0.00013	0.0000	0.000	0.000	0	0.00072	0	0.000000	0.000000	0.00	0.1	0.027	0.0587	0.9	103448.428	0.0003	Electric LGVs		
165	0.00013	0.0000	0.009	0.008	2.49	0.00072	1.7928E-06	0.000753	0.000678	0.06	1.9	0.661	0.0587	0.9	103448.428	0.0064	Taxis		
840	0.00013	0.0001	0.003	0.003	1.87	0.00072	1.3464E-06	0.000040	0.000036	0.01	0.3	0.108	0.0587	0.9	103448.428	0.0010	Buses		
550	0.00013	0.0001	0.001	0.001	1.87	0.00072	1.3464E-06	0.000014	0.000013	0.00	0.1	0.029	0.0587	0.9	103448.428	0.0003	Coaches		
				0.141					0.008878	0.97	29.0	10.154				0.098			

Appendix 4. Spreadsheet for the calculation of pyrene concentrations in road runoff

Py	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road length (km)	Road width (km)	Road area (km2)	Daily vehicle km travelled	EF for exhaust emissions (mg/kg/ veh)	Fuel density (kg/L)	Fuel consumtion (L/km)	Emission per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 10%	EF for brake wear solids (mg/vkm)	Py concn in brake dust ug/mg	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 50%	EF for tyre wear solids (mg/vkm)	Py concn in tyre wear deposits (ug/mg)	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45				0.00690	15.031	1.5031	14.0	0.0035	0.000049	0.107	0.053	100	0.0139	0.00139	3.028	2.574
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68				0.02563	47.561	4.7561	14.0	0.0011	0.0000154	0.029	0.014	100	0.0139	0.00139	2.579	2.192
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54				0.00690	0.093	0.0093	26.0	0.0011	0.0000286	0.000	0.000	159	0.0139	0.00221	0.030	0.025
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50				0.02563	18.082	1.8082	26.0	0.0011	0.0000286	0.020	0.010	159	0.0139	0.00221	1.559	1.325
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82				0.03085	8.725	0.8725	55.0	0.0011	0.0000605	0.017	0.009	850	0.0049	0.00417	1.178	1.001
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43				0.03085	2.697	0.2697	55.0	0.0011	0.0000605	0.005	0.003	850	0.0049	0.00417	0.364	0.310
Motorcycles	311	0.1341	0.0146	0.001958	41.71				0.00690	0.288	0.0288	8.0	0.0011	0.0000088	0.000	0.000	60	0.0139	0.00083	0.035	0.030
Electric car	166	0.1341	0.0146	0.001958	22.26				0.00000	0.000	0.0000	14.0	0.0011	0.0000154	0.000	0.000	100	0.0139	0.00139	0.031	0.026
Electric LGVs	143	0.1341	0.0146	0.001958	19.18				0.00000	0.000	0.0000	26.0	0.0011	0.0000286	0.001	0.000	159	0.0139	0.00221	0.042	0.036
Taxis	3132	0.1341	0.0146	0.001958	420.00				0.02563	10.765	1.0765	14.0	0.0011	0.0000154	0.006	0.003	100	0.0139	0.00139	0.584	0.496
Buses	220	0.1341	0.0146	0.001958	29.50				0.03085	0.910	0.0910	75.0	0.0011	0.0000825	0.002	0.001	415	0.0049	0.00203	0.060	0.051
Coaches	79	0.1341	0.0146	0.001958	10.59				0.03085	0.327	0.0327	52.0	0.0011	0.0000572	0.001	0.000	250	0.0049	0.00123	0.013	0.011
											10.4479					0.095					8.078

Daily road surface wear emissions					**Daily oil leakage emissions**					**Overall emissions**		**Monthly average runoff concentration**						
EF for road surface wear (mg/vkm)	Py concn in asphalt (ug/mg)	Emissions per vehicle km (mg/vkm)	Emissions on this road (mg)	Amount deposited (mg) 90%	Oil loss rate (mg/vkm)	Py concn in used oil (ug/mg)	Emissions per vehicle km (mg/vkm)	Emissions on this road (mg)	Amount deposited (mg) 90%	Daily emissions on this road (mg)	Monthly emissions on this road (mg)	Amont removed runoff (mg) 35%	Monthly rainfall (m)	Runoff coeff	Monthly runoff volume (L)	Monthly average runoff concentration ug/L		
165	0.0001815	0.0000299	0.065	0.0587	2.49	0.0555	0.0001382	0.301	0.27095	4.46	133.8	46.830	0.0587	0.9	103448.428	0.4527	Passenger car petrol	
165	0.0001815	0.0000299	0.056	0.0500	2.49	0.052	0.0001295	0.240	0.21625	7.23	216.9	75.906	0.0587	0.9	103448.428	0.7338	Passenger car diesel	
165	0.0001815	0.0000299	0.000	0.0004	2.49	0.0555	0.0001382	0.002	0.00168	0.04	1.1	0.389	0.0587	0.9	103448.428	0.0038	LGV petrol	
165	0.0001815	0.0000299	0.021	0.0190	2.49	0.052	0.0001295	0.091	0.08221	3.24	97.3	34.071	0.0587	0.9	103448.428	0.3294	LGV diesel	
840	0.0001815	0.0001525	0.043	0.0388	1.87	0.052	0.0000972	0.028	0.02475	1.95	58.4	20.431	0.0587	0.9	103448.428	0.1975	HGV rigid axle	
840	0.0001815	0.0001525	0.013	0.0120	1.87	0.052	0.0000972	0.009	0.00765	0.60	18.0	6.316	0.0587	0.9	103448.428	0.0611	HGV articulated	
74	0.0001815	0.0000134	0.001	0.0005	1.25	0.0555	0.0000694	0.003	0.00260	0.06	1.8	0.647	0.0587	0.9	103448.428	0.0063	Motorcycles	
165	0.0001815	0.0000299	0.001	0.0006	0	0	0.0000000	0.000	0.00000	0.03	0.8	0.284	0.0587	0.9	103448.428	0.0027	Electric cars	
165	0.0001815	0.0000299	0.001	0.0005	0	0	0.0000000	0.000	0.00000	0.04	1.1	0.387	0.0587	0.9	103448.428	0.0037	Electric LGVs	
165	0.0001815	0.0000299	0.013	0.0113	2.49	0.052	0.0001295	0.054	0.04894	1.64	49.1	17.180	0.0587	0.9	103448.428	0.1661	Taxis	
840	0.0001815	0.0001525	0.004	0.0040	1.87	0.0555	0.0001038	0.003	0.00276	0.15	4.5	1.575	0.0587	0.9	103448.428	0.0152	Buses	
550	0.0001815	0.0000998	0.001	0.0010	1.87	0.0555	0.0001038	0.001	0.00099	0.05	1.4	0.483	0.0587	0.9	103448.428	0.0047	Coaches	
				0.1969					0.65879	19.48	584.3	204.499				1.98		

Appendix 5. Spreadsheet for the calculation of benzo(a)pyrene concentrations in road runoff

Bz(a)Py	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road length (km)	Road width (km)	Road area (km2)	Daily vehicle km travelled	EF for exhaust emissions (mg/kg/ veh)	Fuel density (kg/L)	Fuel consumtion (L/km)	Emission per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 10%	EF for brake wear solids (mg/vkm)	Bz(a)Py concn in brake dust ug/mg	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 50%	EF for tyre wear solids (mg/vkm)	Bz(a)Py concn in ty wear deposits (ug/mg)	Emissions per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45				0.00040	0.871	0.0871	14.0	0.00370	0.0000518	0.113	0.056	100	0.00235	0.000235	0.512	0.435
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68				0.00174	3.229	0.3229	14.0	0.00074	0.00001036	0.019	0.010	100	0.00235	0.000235	0.436	0.371
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54				0.00040	0.005	0.0005	26.0	0.00074	0.00001924	0.000	0.000	159	0.00235	0.000374	0.005	0.004
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50				0.00174	1.228	0.1228	26.0	0.00074	0.00001924	0.014	0.007	159	0.00235	0.000374	0.264	0.224
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82				0.00080	0.226	0.0226	55.0	0.00074	0.0000407	0.012	0.006	850	0.00145	0.001233	0.349	0.296
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43				0.00080	0.070	0.0070	55.0	0.00074	0.0000407	0.004	0.002	850	0.00145	0.001233	0.108	0.092
Motorcycles	311	0.1341	0.0146	0.001958	41.71				0.00040	0.017	0.0017	8.0	0.00074	0.00000592	0.000	0.000	60	0.00235	0.000141	0.006	0.005
Electric car	166	0.1341	0.0146	0.001958	22.26				0.00000	0.000	0.0000	14.0	0.00074	0.00001036	0.000	0.000	100	0.00235	0.000235	0.005	0.004
Electric LGVs	143	0.1341	0.0146	0.001958	19.18				0.00000	0.000	0.0000	26.0	0.00074	0.00001924	0.000	0.000	159	0.00235	0.000374	0.007	0.006
Taxis	3132	0.1341	0.0146	0.001958	420.00				0.00174	0.731	0.0731	14.0	0.00074	0.00001036	0.004	0.002	100	0.00235	0.000235	0.099	0.084
Buses	220	0.1341	0.0146	0.001958	29.50				0.00080	0.024	0.0024	75.0	0.00074	0.0000555	0.002	0.001	415	0.00145	0.000602	0.018	0.015
Coaches	79	0.1341	0.0146	0.001958	10.59				0.00080	0.008	0.0008	52.0	0.00074	0.00003848	0.000	0.000	250	0.00145	0.000363	0.004	0.003
											0.6409					0.084					1.540

Daily road surface wear emissions					**Daily oil leakage emissions**					**Overall emissions**		**Monthly average runoff concentration**							
EF for road surface wear (mg/vkm)	Bz(a)Py concn in asphalt (ug/mg)	Emissions per vehicle km (mg/vkm)	Emissions on this road (mg)	Amount deposited (mg) 90%	Oil loss rate (mg/vkm)	BzPy concn in used oil (ug/mg)	Emissions per vehicle km (mg/vkm)	Emissions this road (mg)	Amount deposited (mg) 90%	Daily emissions on this road (mg)	Monthly emissions on this road (mg)	Amont removed runoff (mg) 35%	Monthly rainfall (m)	Runoff coeff	Monthly runoff volume (L)	Monthly average runoff concentration ug/L			
165	0.0000905	0.0000149	0.0325	0.029	2.49	0.0055	0.0000137	0.02983	0.02685	0.6348	19.045	6.666	0.0587	0.9	103448.428	0.0644	Passenger car petrol		
165	0.0000905	0.0000149	0.0277	0.025	2.49	0.004	0.0000100	0.01848	0.01663	0.7447	22.342	7.820	0.0587	0.9	103448.428	0.0756	Passenger car diesel		
165	0.0000905	0.0000149	0.0002	0.000	2.49	0.0055	0.0000137	0.00019	0.00017	0.0053	0.160	0.056	0.0587	0.9	103448.428	0.0005	LGV petrol		
165	0.0000905	0.0000149	0.0105	0.009	2.49	0.004	0.0000100	0.00703	0.00632	0.3694	11.083	3.879	0.0587	0.9	103448.428	0.0375	LGV diesel		
840	0.0000905	0.0000760	0.0215	0.019	1.87	0.004	0.0000075	0.00212	0.00190	0.3459	10.378	3.632	0.0587	0.9	103448.428	0.0351	HGV rigid axle		
840	0.0000905	0.0000760	0.0066	0.006	1.87	0.004	0.0000075	0.00065	0.00059	0.1069	3.208	1.123	0.0587	0.9	103448.428	0.0109	HGV articulated		
74	0.0000905	0.0000067	0.0003	0.000	1.25	0.0055	0.0000069	0.00029	0.00026	0.0070	0.211	0.074	0.0587	0.9	103448.428	0.0007	Motorcycles		
165	0.0000905	0.0000149	0.0003	0.000	0	0	0.0000000	0.00000	0.00000	0.0049	0.146	0.051	0.0587	0.9	103448.428	0.0005	Electric cars		
165	0.0000905	0.0000149	0.0003	0.000	0	0	0.0000000	0.00000	0.00000	0.0065	0.196	0.069	0.0587	0.9	103448.428	0.0007	Electric LGVs		
165	0.0000905	0.0000149	0.0063	0.006	2.49	0.004	0.0000100	0.00418	0.00376	0.1686	5.057	1.770	0.0587	0.9	103448.428	0.0171	Taxis		
840	0.0000905	0.0000760	0.0022	0.002	1.87	0.004	0.0000075	0.00022	0.00020	0.0205	0.615	0.215	0.0587	0.9	103448.428	0.0021	Buses		
550	0.0000905	0.0000498	0.0005	0.000	1.87	0.004	0.0000075	0.00008	0.00007	0.0049	0.146	0.051	0.0587	0.9	103448.428	0.0005	Coaches		
				0.098					0.05676	2.4195	72.586	25.405				0.25			

Appendix 6. Spreadsheet for the calculation of total suspended solids concentrations in road runoff

TSP	**Road characteristics**					**Daily engine emissions**						**Daily brake emissions**					**Daily tyre emissions**				
	AADT	Road length (km)	Road width (km)	Road area (km2)	Daily vehicle km travelled				EF for PM10 per vehicle km (mg/vkm)	Emission on this road (mg)	Amount deposited (mg) 10%	EF for brake wear solids (mg/vkm)			Emission on this road (mg)	Amount deposited (mg) 50%	EF for tyre wear solids (mg/vkm)			Emission on this road (mg)	Amount deposited (mg) 85%
Petrol passenger cars	16245	0.1341	0.0146	0.001958	2178.45				1.00000	2178.455	217.8455	14.0			30498.363	15249.182	100			217845.450	185168.633
Diesel passenger cars	13838	0.1341	0.0146	0.001958	1855.68				11.00000	20412.434	2041.2434	14.0			25979.461	12989.731	100			185567.580	157732.443
Petrol LGVs	101	0.1341	0.0146	0.001958	13.54				1.00000	13.544	1.3544	26.0			352.147	176.073	159			2153.512	1830.485
Diesel LGVs	5261	0.1341	0.0146	0.001958	705.50				15.00000	10582.502	1058.2502	26.0			18343.003	9171.501	159			112174.516	95348.339
Diesel rigid axle HGVs	2109	0.1341	0.0146	0.001958	282.82				35.00000	9898.592	989.8592	55.0			15554.930	7777.465	850			240394.365	204335.210
Diesel articulated HGVs	652	0.1341	0.0146	0.001958	87.43				33.00000	2885.296	288.5296	55.0			4808.826	2404.413	850			74318.220	63170.487
Motorcycles	311	0.1341	0.0146	0.001958	41.71				9.00000	375.346	37.5346	8.0			333.641	166.820	60			2502.306	2126.960
Electric car	166	0.1341	0.0146	0.001958	22.26				0.00000	0.000	0.0000	14.0			311.648	155.824	100			2226.060	1892.151
Electric LGVs	143	0.1341	0.0146	0.001958	19.18				0.00000	0.000	0.0000	26.0			498.584	249.292	159			3049.032	2591.677
Taxis	3132	0.1341	0.0146	0.001958	420.00				11.00000	4620.013	462.0013	14.0			5880.017	2940.008	100			42000.120	35700.102
Buses	220	0.1341	0.0146	0.001958	29.50				52.00000	1534.104	153.4104	75.0			2212.650	1106.325	415			12243.330	10406.831
Coaches	79	0.1341	0.0146	0.001958	10.59				52.00000	550.883	55.0883	52.0			550.883	275.441	250			0.000	0.000
											5305.1167					52662.076					760303.317

Daily road surface wear emissions					**Overall emissions**		**Monthly average runoff concentration**							
EF for road surface wear (mg/vkm)			Emissions on this road (mg)	Amount deposited (mg) 90%	Daily emissions on this road (mg)	Monthly emissions on this road (mg)	Amont removed runoff (mg) 35%	Monthly rainfall (m)	Runoff coeff	Monthly runoff volume (L)	Monthly average runoff concentration mg/L			
165			359444.993	323500.493	524136.15	15724084.6	5503429.603	0.0587	0.9	103448.428	53.20	Passenger car petrol		
165			306186.507	275567.856	448331.27	13449938.2	4707478.369	0.0587	0.9	103448.428	45.51	Passenger car diesel		
165			2234.777	2011.299	4019.21	120576.4	42201.723	0.0587	0.9	103448.428	0.41	LGV petrol		
165			116407.517	104766.765	210344.85	6310345.6	2208620.976	0.0587	0.9	103448.428	21.35	LGV diesel		
840			237566.196	213809.576	426912.11	12807363.3	4482577.161	0.0587	0.9	103448.428	43.33	HGV rigid axle		
840			73443.888	66099.499	131962.93	3958887.9	1385610.752	0.0587	0.9	103448.428	13.39	HGV articulated		
74			3086.177	2777.560	5108.87	153266.2	53643.185	0.0587	0.9	103448.428	0.52	Motorcycles		
165			3672.999	3305.699	5353.67	160610.2	56213.580	0.0587	0.9	103448.428	0.54	Electric cars		
165			3164.090	2847.681	5688.65	170659.5	59730.819	0.0587	0.9	103448.428	0.58	Electric LGVs		
165			69300.198	62370.178	101472.29	3044168.7	1065459.044	0.0587	0.9	103448.428	10.30	Taxis		
840			24781.680	22303.512	33970.08	1019102.3	356685.818	0.0587	0.9	103448.428	3.45	Buses		
550			5826.645	5243.981	5574.51	167235.3	58532.357	0.0587	0.9	103448.428	0.57	Coaches		
				1084604.099	1902874.61	57086238.2	19980183.386				193.14			