

# PM<sub>10</sub> and PM<sub>2.5</sub> emission factors for non-exhaust particles from road vehicles

Beddows, David; Harrison, Roy

DOI:

[10.1016/j.atmosenv.2020.117886](https://doi.org/10.1016/j.atmosenv.2020.117886)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

*Document Version*

Peer reviewed version

*Citation for published version (Harvard):*

Beddows, D & Harrison, R 2021, 'PM<sub>10</sub> and PM<sub>2.5</sub> emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles', *Atmospheric Environment*, vol. 244, 117886. <https://doi.org/10.1016/j.atmosenv.2020.117886>

[Link to publication on Research at Birmingham portal](#)

## General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

1  
2  
3  
4  
5  
6 **PM<sub>10</sub> and PM<sub>2.5</sub> Emission Factors for Non-Exhaust**  
7 **Particles from Road Vehicles: Dependence Upon**  
8 **Vehicle Mass and Implications for Battery Electric**  
9 **Vehicles**

10  
11  
12 **David C.S. Beddows and Roy M. Harrison<sup>\*†</sup>**

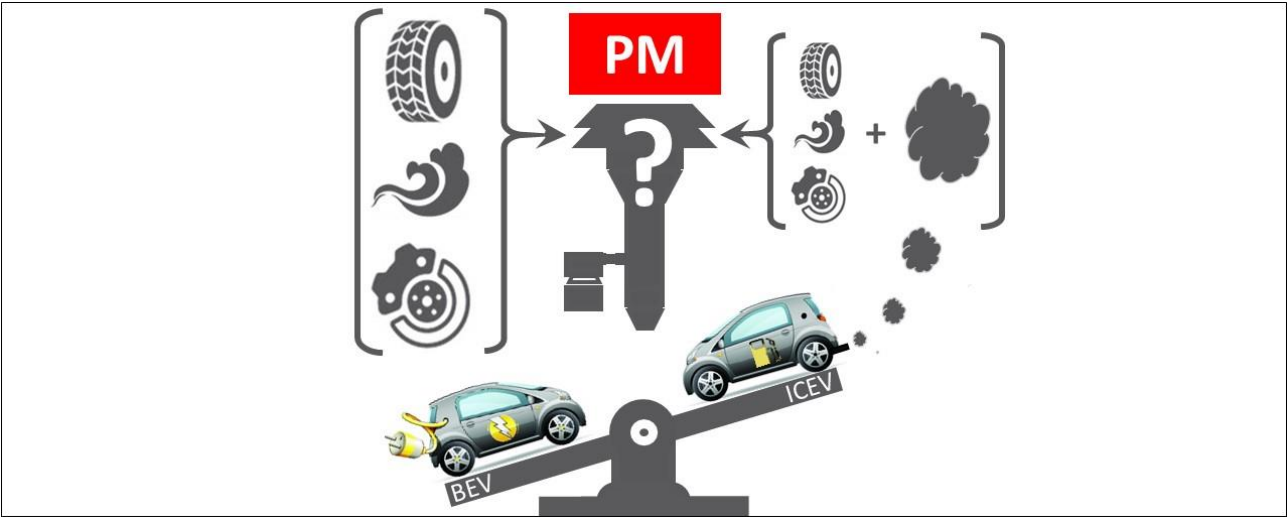
13  
14  
15 **National Centre for Atmospheric Science**  
16 **School of Geography, Earth and Environmental Sciences**  
17 **University of Birmingham**  
18 **Edgbaston, Birmingham B15 2TT**  
19 **United Kingdom**  
20  
21

---

<sup>\*</sup> To whom correspondence should be addressed (Email: [r.m.harrison@bham.ac.uk](mailto:r.m.harrison@bham.ac.uk))

<sup>†</sup>Also at: Department of Environmental Sciences / Center of Excellence in Environmental Studies, King Abdulaziz University, PO Box 80203, Jeddah, 21589, Saudi Arabia

22    **GRAPHICAL ABSTRACT:**



23    **CAPTION:** Question: Will the electrification of passenger cars reduce total PM emissions?  
24  
25  
26

27   **ABSTRACT**

28   Governments around the world are legislating to end the sale of conventionally fuelled (gasoline and  
29   diesel) internal combustion engine vehicles (ICEV) and it is assumed that battery-electric vehicles  
30   (BEV) will take their place. It has been suggested that due to their increased weight, non-exhaust  
31   emissions of particles from BEV may exceed all particle emissions, including exhaust, from an ICEV.  
32   This paper examines the vehicle weight-dependence of  $PM_{10}$  and  $PM_{2.5}$  emissions from abrasion  
33   (brake, tyre and road surface wear) and road dust resuspension and generates a comparison of the two  
34   vehicle types. The outcome is critically dependent upon the extent of regenerative braking relative to  
35   use of friction brakes on the BEV, but overall there will be only modest changes to the total local  
36   emissions of particles from a passenger car built to current emissions standards.

37  
38   **Keywords:** Vehicle emissions; non-exhaust; electric vehicle; regenerative braking  
39  
40  
41  
42

## 43 INTRODUCTION

44 Road vehicles emit particulate matter from sources other than their exhaust. Such sources include  
45 brake wear, tyre wear, road surface wear and resuspension of road surface dusts (Thorpe and Harrison,  
46 2008; Amato et al., 2014; Amato, 2018). Emissions inventory estimates indicate that non-exhaust  
47 emissions well exceed exhaust emissions by a large margin, both for PM<sub>10</sub> and PM<sub>2.5</sub>, in the current  
48 vehicle fleet (AQEG, 2019).

49  
50 Many governments now have policies to steadily incentivise electrification of the vehicle fleet, and  
51 hence emissions from BEV are a matter of concern. For example, in Britain EVs are exempt from  
52 annual road taxes and there are subsidies available for electric and hybrid vehicles with carbon  
53 dioxide emissions below 50 g/km and range above 70 miles in electric mode. In America, there are  
54 subsidies for EVs of 10% of the purchase price (<\$4000) and California implements a zero-emission  
55 policy that requires all car manufacturers to produce a certain percentage of zero-emission vehicles;  
56 otherwise, manufacturers will receive a huge penalty. Similar schemes have also been implemented  
57 in Norway, Netherlands, France and Germany, amongst many countries (Li et al., 2019). Timmers  
58 and Achten (2016, 2018) have suggested that as battery electric vehicles would typically be heavier  
59 than their internal combustion engine equivalent and, even allowing for far lower emissions from  
60 regenerative braking (i.e. cutting power to the motor so that it acts as a generator), the non-exhaust  
61 emissions from a BEV might exceed all particle emissions from an equivalent ICEV. This study  
62 seeks to evaluate available data concerning BEV in relation to non-exhaust emissions from ICEV and  
63 to make projections where firm data are not available. Total emissions from both ICEV and BEV  
64 passenger cars are evaluated to form a view as to whether electrification of cars will reduce PM  
65 emissions within the fleet. The analysis is limited to passenger cars, as those are currently on sale,  
66 while battery-powered heavy duty vehicles are still under development, and vehicle weight statistics  
67 are not yet available.

68

## 69    **METHODS:**

70    The approach to estimation of emission factors for BEV for comparison with both gasoline (petrol)  
71    and diesel fuelled ICEV involved the following stages.

- 72        • Adopting a set of emission factors for PM<sub>10</sub> and PM<sub>2.5</sub> for different vehicle types and road  
73        types which are widely used in national inventories.
- 74        • Associating a vehicle mass with each vehicle type.
- 75        • Determining separate relationships between emission factor and vehicle mass for each of  
76        brake wear, tyre wear and road surface abrasion.
- 77        • Estimating the typical masses of light duty BEVs and gasoline and diesel ICEVs from data on  
78        BEVs and ICEVs paired on the basis of engine power output.
- 79        • Using the typical vehicle masses to estimate emission factors for each vehicle type for brake,  
80        tyre and road surface wear.
- 81        • Estimating particle resuspension emission factors for BEVs, and gasoline and diesel ICEVs  
82        using the USEPA AP42 algorithm.
- 83        • Summing the emission factors for each vehicle type and road type, together with exhaust  
84        emission factors for the ICEVs to compare total emissions for typical light duty BEVs and  
85        gasoline and diesel ICEVs.

86  
87

## 88    **RESULTS**

### 89    **Emission Factors**

90    Current emission factors (EF) are listed according to vehicle type rather than vehicle mass. However,  
91    it was possible to derive relationships between EF and vehicle mass by attributing masses to the  
92    vehicle types for which EF are available. Our starting point was the six aggregated vehicle classes in  
93    the EMEP/EEA Guidebook as reported by AQEG (2019).

94

Table 1 provides emission factors for tyre, brake and road wear published in the EMEP/EEA emission inventory guidebook, 2013 (Ntziachristos and Boulter, 2019). The values are for the six aggregated vehicle classes (Two Wheeled Motor Vehicles - motorcycles, Cars, Light Goods Vehicles - LGVs, both Rigid and Articulated Heavy Goods Vehicles – HGVs and Buses/Coaches) for a UK road fleet. These values are derived from emission factors reported in the literature and a deeper understanding of their derivation can be sought from the Automobile Tyre and Brake Wear website which supports the development of chapter B770 (SNAP 0707) of the EMEP/Corinair Emission Inventory Guidebook [<https://www.eng.auth.gr/mech0/lat/PM10/>]. We use these to estimate a dependence of these aggregate emission factors (EF) on an estimated vehicle mass. The means by which the values in Table 1 are calculated, including dependence on, vehicle speed, mass, load, axle number, are summarised in the Supplementary Information (Ntziachristos et al. 2019).

106

#### 107 **Vehicle Category Mass, $W$**

##### 108 *Values relevant to the EMEP/EEA emission factors*

In order to evaluate the effect of changing vehicle masses, it is first necessary to estimate the masses of vehicles used in the estimation of our base emission factors in Table 1. These appear to derive predominantly from data collected on vehicles around the year 2000 (Ntziachristos and Boulter, 2013, 2019). To assign a vehicle mass to each of the classes in Table 1, an aggregated vehicle mass was selected based on the estimated values of Boulter et al. (2006). For motorcycles and cars, Boulter et al. (2006) use values of 0.2 and 1.2 tonnes respectively. The car mass is roughly 200 kg less than the mass used for our ICEV value which represents car weights closer to the year 2020. The LGV mass was taken as 3 tonnes, whereas the rigid HGV, articulated HGV and bus masses were calculated as the average across several categories. For example, the rigid HGV and bus masses were both taken as the average of vehicle *HGV, buses and coach* categories with 2 or 3 axles. Similarly, the articulated HGV mass was taken as the average of the HGV categories with 4 or more axles. Estimated mass values appear in Table 2.

121 *Values relevant to the current vehicle fleet*

122 For the car masses, the European Vehicle Market Statistic Pocketbook 2018/19 was used because it  
123 provides the average running order mass of vehicles in European countries which were weighted by  
124 the fleet number of vehicles for those countries (given by Eurostat) for the year 2000. Likewise, for  
125 motorcycles, Eurostat provided the fleet numbers of motorcycles with engine capacities less than and  
126 greater than 125 cm<sup>3</sup> which were then weighted by typical masses of these two categories, taken to  
127 be 78 and 240 kg respectively. These values are in close agreement with those of Boulter et al. (2006).

128

129 **Estimate of  $\Delta W = W_{bev} - W_{icev}$**

130 The change in vehicle weight  $\Delta W$  due to electrification is mainly due to the increased weight of the  
131 battery pack used to drive the electric motors in the BEV. While this may not be fully mitigated by  
132 the substitution of the fossil fuel engine, transmission and sundries in the vehicle design, further  
133 weight saving can be made by the choice of weight saving parts and materials which otherwise would  
134 make  $\Delta W$  much larger. To estimate a change in emission factor due to the overall increase in vehicle  
135 mass due to the electrification of cars, BEV-ICEV car pairs were chosen with the same make and  
136 model from an internet database (encyCARpedia) built up from various press materials and consumer  
137 brochures by Chapple and Chapple (2017). For each of the chosen internal combustion engine and  
138 battery electric vehicle pairs, their engine specifications were matched as closely as possible  
139 according to power output (selected to be within 15% of each other) and their masses duly noted as  
140  $W_{icev}$  and  $W_{bev}$  respectively. Furthermore, owing the large number of matches on enCARpedia, an  
141 increase in mass due to both the electrification of either petrol or diesel engines could be calculated.  
142 Table S1 shows 20 such matches for petrol and 9 for diesel giving an average mass difference of 318  
143  $\pm 145$ kg and  $258 \pm 125$  kg respectively. As expected, there is less of an increase from the heavier  
144 diesel engine cars compared to petrol.

145

146 Data from the assessment of Faria et al. (2012), of electric vehicles gave a difference of kerb weight

147 of 256 kg (an increase of 20%) for ICEV and BEV vehicles and likewise, Timmers and Achten  
 148 (2016), reported a value of  $280 \pm 45$  kg for their increase in weight from ICEV to BEV, (24% heavier).  
 149 The increase mass due to electrification of our whole vehicle sample is  $300 \pm 140$  kg, corresponding  
 150 to a 21% increase which is in line with the aforementioned literature values. Accounting for diesel  
 151 and petrol engines, petrol engine vehicles have an average mass of 1349 kg which rises by 318 kg  
 152 when compared to their electric equivalent ( $^{petrol}W_{bev} = 1349 + 319$  kg). Likewise, diesel engine  
 153 vehicles have an average mass of 1550 kg which rises by 257 kg when compared to their electric  
 154 equivalent ( $^{diesel}W_{bev} = 1550 + 257$  kg).

155

## 156 **Main Calculation**

### 157 *Regression of emission factors with vehicle mass*

158 The *EF* values in Table 1 were regressed against the *W* values in Table 2 and plotted in Figure 1  
 159 graphically for each road type (urban, rural and motorway) for tyre wear, brake wear and road wear.  
 160 Figures S1 and S2 show all 16 regressions on separate plots (including error bars) for  $PM_{10}$  and  $PM_{2.5}$ .  
 161 A non-linear least squares fit of the data was done using equation 1, where  $W_{ref} = W/1000$  kg and  
 162 *b* and *c* are parameters used to fit the equation (see Table 3).

$$EF = b \cdot W_{ref}^{\frac{1}{c}} \quad (1)$$

163

164 Parameters *b* and *c* do not have a physical significance however, regarding sensitivity, for a petrol car  
 165 on a rural road EF is more sensitive to the fitted value of *c* than *b* (e.g. a 10% variation in *b* will  
 166 produced a 10% variation in the value of EF, whereas a 10% variation in *c* will produce up to a 42%  
 167 variation in the value of EF).

168

169 For tyre wear and brake wear, there are emission factors for all of the six vehicle categories whereas  
 170 for road wear the number of data points was less. For road abrasion, a distinction between the  
 171 articulated, rigid and bus category was not made for the HGVs and hence an amalgamated emission

factor is used for both goods vehicles and buses. This approach was also applied to the LGV road wear emission factor in that the same value is used for both light goods vehicles and passenger cars. Hence an aggregated LGV emission factor and mass are used resulting in a 3-point fit (for the motorcycles, LGV and HGV data).

## **Resuspension Emission Factors $EF^{resus}$**

Resuspension is the term used to describe particles of road surface dust raised into the air by passing traffic, due either to shear forces at the tyre/road surface interface, or air turbulence in the wake of a moving vehicle. The EMEP/EEA Guidebook does not include the calculation of resuspended road dust, and estimates are often not included in emissions inventories. However, resuspension emission factors  $EF^{resus}$  can be calculated using the USEPA guidance in AP-42 and a review of past and current paved road emission factors is given by the USEPA (2011). Based on various parameters –  $s$ : surface material content silt ( $< 75 \mu\text{m}$  diameter);  $L$ : Surface material loading, defined as mass of particles per unit area of the travel surface ( $\text{g}/\text{m}^2$ );  $b$ : an exponent to which  $sL$  is raised ( $sL_{rel} = sL/1\text{g}\cdot\text{m}^{-2}$ );  $k$ : base emission factor ( $\text{g}/\text{VKT}$ );  $W_{rel}$ : vehicle mass ( $W_{rel} = W/1000 \text{ Kg}$ ) and  $p$ : a dimensionless exponent – the particulate emission factor ( $\text{g}/\text{VKT}$ ) has been parameterised by equation 2.

$$EF^{resus} = k (sL_{rel})^b W_{rel}^p \quad (2)$$

The extent to which resuspension emissions are related to vehicle mass is uncertain, and Venkatram (2000) critiqued the US EPA AP42 model for emission from paved roads (AP-42 paved road section 2011); (then equation 2 with  $k = 0.54 \text{ g km}^{-1}$ ;  $b = 0.65$ ;  $p = 1.5$ ). This has since been updated by similar models in 1995, 2002, 2003, and most recently in 2011 (equation (3)). A  $k$  value of  $0.62 \text{ g km}^{-1}$  is used for the  $\text{PM}_{10}$  fraction (scaled by a  $\text{PM}_{2.5}/\text{PM}_{10}$  mass fraction ratio of 0.24 for  $\text{PM}_{2.5}$ ), and the term  $(1-P/4N)$  accounts for the number of wet days  $P$  in a total of  $N$  measurement days.

$$EF_{resus} = 0.62(sL)^{0.91}W_{rel}^{1.021} \left[ 1 - \frac{1}{4} \frac{P}{N} \right] \quad (3)$$

195

196 This is an empirical equation, and a range of parameters is given by the USEPA (2011) report,  
 197 namely;  $k = 0.62 \text{ g km}^{-1}$ ;  $sL = 0.03\text{-}0.6 \text{ g/m}^2$ ;  $b = 0.85\text{-}1.19$ ;  $p = 0.677 - 1.14$ . These equations are  
 198 for vehicles of mean weight between 2.0 and 42 tonnes travelling between 1 and 88 kph and caution  
 199 is advised in using the equation outside of the range of variables and operating conditions specified.  
 200 Application to roadways or road networks with speeds above 88 kph and average vehicle weights of  
 201  $<2$  and  $>42$  tonnes, result in emission estimates with a higher level of uncertainty. With regards to  
 202 the sensitivity of equation 3 to the variables considered,  $EF_{resus}$  is marginally more sensitive to the  
 203 number of rain days in the year than the change of  $sL$  or  $W_{rel}$ , e.g. a 10% change of both  $sL$  and  
 204  $W_{rel}$  produce  $\sim 10\%$  variation in  $EF_{resus}$  whereas a 10% variation in the ratio of  $P/N$  produces a 14%  
 205 variation in  $EF_{resus}$ .

206

207 To consider the applicability of the AP-42 model to European roads, measurements carried out in  
 208 London and Paris were considered where  $PM_{10}$  resuspension emission factors were calculated at  
 209 roadside for LGV, HGV and for the fleet. To evaluate the response of  $PM_{10}$  resuspension to vehicle  
 210 mass, the LGV and HGV emission factors estimated by Thorpe et al. (2007) from measurements on  
 211 Marylebone Road, London were allocated to aggregated LGV and HGV vehicle weights (Table 2)  
 212 and the vehicle weight dependence of AP-42 fitted to these values using equation (2). An additional  
 213 point was included from the Paris work of Amato et al. (2016), who derive a value of  $9.2 \text{ mg km}^{-1}$  for  
 214 the mixed vehicle fleet. The three data points are plotted in Figure 2 and used together with the origin  
 215 as a fourth point to fit equation (2). This shows the plot of data for different values of the exponent,  
 216  $b$ . Values of  $b$  of 1.02, 1.2, 1.5 and 1.7 give  $sL$  values of 8.2, 4.6, 1.8 and  $0.9 \text{ mg m}^{-2}$  from equation  
 217 2, using a value of  $p = 0.91$ .

218

219 Harrison et al. (2012) reported the percentage of particle mass  $>0.9 \mu\text{m}$  attributable to brake wear,  
 220 tyre wear and resuspension on Marylebone Road, London. Using the method previously adopted by  
 221 Jones and Harrison (2006) to estimate emission factors by ratios of concentrations to  $\text{NO}_x$ , for which  
 222 an aggregate emission factor was calculated, the measured masses attributed to the different non-  
 223 exhaust source types were converted to emission factors listed in Table 4. The fleet-average emission  
 224 factors for resuspension for Marylebone Road estimated by difference of total non-exhaust particles  
 225 and brake, tyre and road surface wear reported by Thorpe et al. (2007) for years 2000-2003 ranged  
 226 from  $14.0\text{--}27.7 \text{ mg km}^{-1}$ , somewhat higher than the value of  $10.0 \pm 1.8 \text{ mg km}^{-1}$  in Table 4 derived  
 227 from measurement data from 2009. Using equation 3, a resuspension emission factor for  $\text{PM}_{10}$  of  $10$   
 228  $\text{mg km}^{-1}$  translates to a value of  $sL = 4.2 \text{ mg m}^{-2}$ , and the median of the values given by Thorpe et al.  
 229 (2007) gives a value of  $sL = 8.0 \text{ mg m}^{-2}$ .

230

231 In Table 5, road surface dust loadings derived from European studies are tabulated. These are very  
 232 variable. However, the values in Table 5 are for the  $\text{PM}_{10}$  size fraction, and silt loading as used in  
 233 the USEPA equations describes particles passing a 200 mesh sieve, and hence of  $<75 \mu\text{m}$ . There is  
 234 only a small literature describing the size distribution of particles in road dust, which suggests that  
 235 the  $\text{PM}_{10}$  size fraction is about 10-50% of the  $<75 \mu\text{m}$  fraction (Lanzerstorfer, 2018; Lanzerstorfer  
 236 and Logiewa, 2019; Padoan et al., 2017), and hence a  $sL$  of  $8 \text{ mg m}^{-2}$  translates approximately to a  
 237  $\text{PM}_{10}$  surface dust loading of  $1\text{--}4 \text{ mg m}^{-2}$ , which is line with many of the measured values in Table 5,  
 238 and consistent with the value estimated above.

239

#### 240 **Estimation of the $\text{PM}_{10}$ Emission Factor for Battery Electric Cars**

241 Using the regressions presented in Figure 1, the increase in the emission factors are calculated due to  
 242 the increase in car mass in converting from an internal combustion engine to a battery electric car  
 243  $\Delta W = W_{bev} - W_{icev}$ ; these are shown in Table 6, and a comparison can be made with the work of  
 244 Timmers and Achten (2016) using Table 7. Table 6 shows the non-exhaust (NEE) emission factors

for both BEV cars and their petrol- and diesel-equivalent ICEV calculated for our sample of cars using the regressions shown in Figure 1 and Table 7 giving the resultant calculated increase in EF due to the electrification.

The increases in PM<sub>10</sub> tyre, brake and road wear emission factors for urban, rural and motorway UK roads range from 9.5 to 22% for petrol vehicles and 6.8 to 11% for diesels. Diesel vehicles have a smaller increase due to the fact that the diesel vehicles are heavier than petrol and hence less of an increase emission factor can be expected when compared to their BEV equivalent. This is also shown in the percentage increase of the PM<sub>2.5</sub> emission factors for petrol and diesel vehicles 8.6-17% and 6.8-12% respectively. As expected, the values reduce from high to low for urban to rural to motorway although this is not reflected in the relative values which show a consistent increase for tyre emission factors and increasing percentage for brake emission factors. There is very rough agreement between our values and the ICEV values presented by Timmers and Achten (2016) for tyre and brake emissions (Table 6). On average, both our tyre and brake wear emission factors are slightly higher, whereas our resuspension values are notably higher. Conversely, Timmers and Achten (2016) has significantly higher values for road wear. Comparison of the increases in the non-exhaust emission factors in Table 7 are closer for road wear and resuspension although our tyre emission factors are roughly half those of Timmers and Achten (2016).

Using a value for sL of 8 mg m<sup>-2</sup>, the resuspension model suggests that the increase in weight of a passenger car  $W_{bev} - W_{icev}$  will increase the PM<sub>10</sub> resuspension emission factor by 16% and 22% (12.5 to 14.4 mg / VKT for diesel and 11.0 to 13.4 mg / VKT for petrol; for  $\Delta W = 318$  and 258 kg respectively). The overall magnitude of these emission factors can be compared with those of Bukowiecki et al. (2010), Ketzel et al. (2007), Amato et al. (2010; 2016; 2017) and Gehrig et al. (2004) who derive fleet PM<sub>10</sub> emission factors (Table S2). Although the European LGV and HGV emission factors of Gehrig et al. (2004) are in line with the London measurements, the fleet average

values are generally higher, although the large spread of these fleet values (i.e. 68% relative standard deviation) reflects site differences and/or measurement uncertainties.

273

## 274 Tail Pipe Emissions

In order to make a full assessment of the change in PM<sub>10</sub> and PM<sub>2.5</sub> due electrification of passenger cars, a tail pipe emission factor is also required. For this, we used Euro 6 engine emissions as used in the UK National Atmospheric Emissions Inventory (Ricardo Energy & Environment, 2018) (Table 8). From this, the harmonisation in Euro 6 of previously higher diesel emissions to those of their counterpart petrol engine cars can be seen. Interesting to note is the lower emission for diesel cars under conditions of higher speed (rural and motorway).

281

## 282 Comparison of the Total Emission from ICEV and BEV Cars

The total emission factor for cars either powered by internal combustion engines or battery electric motors are given by the sums in equations (4) and (5). The ICEV and BEV emission factors simply differ by the inclusion of the exhaust emissions and the degree to which the brake emission factor contributes. By specifying for BEV, a 0% (fully inductive brake, i.e.  $EF_{bev}^{brake} = 0$ ) and 100% (fully friction brake) contribution to the brake emission factor, we define a range of possible values within which a regenerative braking system might operate: between  $0\% \times EF_{bev}^{fric}$  and  $100\% \times EF_{bev}^{fric}$ . But in this work, we assume that a BEV using regenerative brakes will emit a 10% fraction  $frac_{brake}$  of the brake emissions occurring when the vehicle relies fully on friction brakes ( $frac_{brake} = 10\%$ ).

291

$$EF_{icev}^{petrol\ or\ diesel} = EF_{icev}^{tyre} + EF_{icev}^{road\ wear} + EF_{icev}^{resus} + EF_{icev}^{brake} + EF_{icev}^{exhaust} \quad (4)$$

292

$$EF_{bev}^{100\% \ fric} = EF_{bev}^{tyre} + EF_{bev}^{road\ wear} + EF_{bev}^{resus} + 1.0 \times EF_{bev}^{brake} \quad (5)$$

$$EF_{bev}^{10\% \ fric} = EF_{bev}^{tyre} + EF_{bev}^{road\ wear} + EF_{bev}^{resus} + 0.1 \times EF_{bev}^{brake}$$

$$EF_{bev}^{0\% \text{ fric}} = EF_{bev}^{tyre} + EF_{bev}^{road \text{ wear}} + EF_{bev}^{resus} + 0.0 \times EF_{bev}^{brake}$$

293

294 Figure 3 illustrates the total emission factors calculated for BEV and ICEV passenger cars, calculated  
 295 using equations (4) and (5) respectively, for which, the following points can be made (see value in  
 296 Table S3 and S4):

- 297 • The uncertainties associated with each of these total emission factors are a large fraction of the  
 298 calculated values themselves. This uncertainty is by virtue of the variability of the values in the  
 299 literature used in this study. More measurements are required together with studies to understand  
 300 how to best parameterise each emission component.
- 301 • The total emission factors for all road types from the BEVs are ~7-12% greater than their euro 6  
 302 diesel and petrol equivalent (Figure 3) for PM<sub>10</sub> and, ignoring the petrol motorway, ~1-5% greater  
 303 for PM<sub>2.5</sub>. This is a marked difference from the case for pre-Euro 5 passenger cars where the  
 304 particulate emissions from diesels are significantly higher than those for petrol engine cars.
- 305 • There is a significant increase from the total PM<sub>10</sub> emissions of an ICEV car to the heavier BEV  
 306 car supporting 100% friction brakes. This suggests that in order to bring total BEV cars  
 307 emissions in line with the emissions of a petrol equivalent ICE, regenerative braking needs to  
 308 reduce brake dust emissions to 70% (i.e. 30% regen.) for urban roads and 43% (i.e. 57% regen.)  
 309 for rural roads. In comparison, the critical values are higher for diesel equivalent BEV emissions.  
 310 Regenerative braking needs reduce brake dust emissions of diesel equivalent BEV to 80% (i.e.  
 311 20% regen.) for urban roads and 60% (i.e. 40% regen) for rural roads.
- 312 • The total PM<sub>10</sub> emission factor on rural roads is less than that of urban. Likewise, the total PM<sub>10</sub>  
 313 emission on motorways is again lower than urban and rural roads and consequently, no amount  
 314 of regeneration will bring the total PM<sub>10</sub> emissions of BEV cars in line with their ICEV equivalent  
 315 cars, i.e. even with 100% regenerative braking the total emissions are still higher for BEV cars.
- 316 • For the total PM<sub>2.5</sub>, the increase in emissions of the heavier BEV cars supporting 100% friction  
 317 brakes is marginal (Figure 3). In order to decrease the total PM<sub>2.5</sub> emissions of BEV cars to be

in line with their petrol equivalent ICE cars, regenerative braking needs to play a lesser role than for the case of PM<sub>10</sub>. For petrol and diesel cars, the brake emissions need to be reduced respectively to 85% and 95% (i.e. 15% and 5% regen.) for urban roads and 74% and 86% (i.e. 26% and 14% regen.) respectively for petrol and diesel roads on rural roads. As with PM<sub>10</sub>, motorways are a special case, requiring a reduction to 47% for diesel equivalent BEV on motorways, and no requirement for the petrol equivalent BEV cars to lower their total emissions below those of ICEV cars.

- Focusing on urban and rural roads, in order to achieve any reduction in PM emissions in the electrification of vehicles, regenerative braking plays a significant part in the reduction of vehicle speed when used in place of friction braking. Hall (2017) compared the braking behaviour of a BEV with that of an ICEV in Los Angeles in city driving conditions. Due to changes in driving style, the number of braking events for the BEV was reduced by as much as a factor of 8. The energy dissipation by the friction brakes in the BEV was lower by a factor as large as 20-fold. As alluded to in the previous point, using the model in this work, the critical  $frac_{brake}$  value below which an overall reduction in total PM<sub>10</sub> emissions might be expected ranges from 43% to 70% for petrol and 60 to 80% for diesel equivalent BEV. For PM<sub>2.5</sub> we might expect  $frac_{brake}$  to be in the range 74% to 85% and 86% to 95% respectively for petrol and diesel. This means in order to expect a reduction in PM emissions of a fleet of ICEV cars on urban and rural roads by electrification, inductive braking has to reduce the brake emissions of PM<sub>10</sub> by at least 20 – 57% and PM<sub>2.5</sub> by at least 5 – 26%. On motorways there remains a positive increase in the total EF of PM<sub>10</sub> relative to both petrol and diesels even using 100% regen. Removal of friction braking (e.g. through 100% regenerative braking) can provide up to 25-27% reduction of PM<sub>10</sub> emissions in the urban environment (24-26% for PM<sub>2.5</sub>). With a realistic regenerative braking (using 10% friction brakes) we might expect up to 22-24% (21-23% for PM<sub>2.5</sub>) reduction in overall emissions (Tables S3 and S4). This potential reduction is less for motorway roads,

because the amount of brake dust contributing to the total is small, and hence there is less gain in the reduction of total emission by lowering/removing brake dust emission.

- The increase in total  $PM_{10}$  emissions for BEVs on motorways with full regenerative braking may be recouped by weight saving measures. By reducing the weight of petrol-equivalent BEVs by 4% (3.5% for diesel-equivalent BEVs) the difference in total  $PM_{10}$  emissions is reduced to zero, thus lowering the total urban and rural emissions further by ~2%. Similarly, for a petrol-hybrid with 90% regenerative braking, if it is assumed that the PM exhaust emissions are reduced by 80% (Lijewski, 2020) then it must be at most 88% of the weight of our petrol-equivalent BEV,  $^PW_{bev}$  (and 93% for our diesel-equivalent BEV,  $^dW_{bev}$ ) for the increase in motorway emission to be brought down to zero. In other words, a balance has to be found between the combined weight of a light internal combustion engine and the weight of a reduced battery pack such that the overall weight of the car is reduced to 88% of a petrol-equivalent BEV (and 93% for a diesel-equivalent BEV). Similar gains in the reduction of  $PM_{2.5}$  are expected due to the reduction of weight. By reducing both the petrol and diesel-equivalent BEVs by 4%, the total  $PM_{2.5}$  can also be expected to be reduced by 2% on either urban, rural or motorway roads.

- The  $PM_{10}$  emission factor averaged across different road types for the BEV without regenerative braking including brake, tyre and road surface wear without resuspension is  $20.7 \text{ mg km}^{-1}$ . This compares well with an average emission factor for battery electric vehicles of  $22.3 \text{ mg km}^{-1}$  introduced to COPERT in 2020.

## CONCLUSIONS

In this study, published emission factors to model  $PM_{10}$  and  $PM_{2.5}$  emissions from brake, tyre and road wear and resuspension have been used to estimate the change in total emissions due to the electrification of cars. The question is addressed of *whether there is a reduction of total  $PM_{10}$  and  $PM_{2.5}$  emissions by electrification of cars or whether the gains made by removal of tailpipe emissions are replaced by the increased, non-exhaust emissions due to the increased weight of electric vehicles.*

369 There are still very high uncertainties which overshadow these findings, but the average values show  
370 that in order to make any reduction in  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  emissions from the electrification of vehicles,  
371 regenerative braking has to be operational in the vehicle design and/or a means of brake dust recovery  
372 used. Failing this, there is no reduction in  $\text{PM}_{10}$  in changing a euro 6 engine fleet to a fully electric  
373 drive chain and potentially an increase on motorways – so regenerative braking must be used.

374

375 The benefit a regenerative brake BEV is shown by the reduction of up to  $11.5 \text{ mg}\cdot\text{km}^{-1}\cdot\text{veh}^{-1}$  in the  
376 urban environment, i.e.  $\sim 26\%$  reduction in  $\text{PM}_{10}$  depending on the level of regenerative braking or  
377 brake dust capture. At higher speeds in rural environments this reduction falls to between 2.7-4.0  
378  $\text{mg}\cdot\text{km}^{-1}\cdot\text{veh}^{-1}$ , which is nonetheless a  $\sim 12\%$  reduction. For motorway environments, our model  
379 shows no level of regenerative braking can mitigate against the increase in  $\text{PM}_{10}$  due to increased  
380 vehicle weight and that additional strategies are required, e.g. reduction of vehicle weight by at least  
381  $22\%$ . In comparison, for  $\text{PM}_{2.5}$ , a reduction of up to  $5.5 \text{ mg}\cdot\text{km}^{-1}\cdot\text{veh}^{-1}$  in the urban environment, i.e.  
382  $\sim 27\%$  reduction can be achieved. Unlike for  $\text{PM}_{10}$  emissions, there is a reduction of  $\text{PM}_{2.5}$  (1.9 to  
383  $27\%$ ) on all road types with at least  $90\%$  regenerative braking.

384

## 385 DATA AVAILABILITY

386 Data supporting this publication are openly available from the UBIRA eData repository at  
387 <https://doi.org/10.25500/edata.bham.00000481>

388

## 389 ACKNOWLEDGEMENTS

390 This work was supported by the National Centre for Atmospheric Science funded by the U.K.  
391 Natural Environment Research Council (R8/H12/83/011).

392

## 393 SUPPORTING INFORMATION

394 Supporting Information provides further details of methods of estimation of emission factors and  
395 tables with additional information.

396

397    **CONFLICT OF INTERESTS**

398    The authors declare no competing financial interest.

399

## REFERENCES

- Amato, F. (Ed), 2018. Non-exhaust emissions. An urban air quality problem for public health; impact and mitigation measures, Academic Press.
- Amato, F., Bedogni, M., Padoan, E., Querol, X., Ealo, M., Rivas, I., 2017. Characterization of road dust emissions in Milan: impact of vehicle fleet speed, *Aerosol Air Qual. Res.*, 17, 2438–2449.
- Amato, F., Favez, O., Pandolfi, M., Alastuey, A., Querol, X., Moukhtar, S., Bruge, B., Verlhac, S., Orza, J.A.G., Bonnaire, N., Le Priol, T., Petit, J.-F., Sciare, J., 2016. Traffic induced particle resuspension in Paris: Emission factors and source contributions, *Atmos. Environ.*, 129 114-124.
- Amato, F., Cassee, F.R., Denier van der Gon, H.A.C., Gehrig, R., Gustafsson, M., Hafner, W., Harrison, R.M., Jozwicka, M., Kelly, F.J., Moreno, T., Prevot, A.S.H., Schaap, M., Sunyer, J., Querol, X., 2014. Urban air quality: The challenge of traffic non-exhaust emissions, *J. Hazard. Mater.*, 275, 31-36.
- Amato, F., Pandolfi, M., Alastuey, A., Lozano, A., Contreras González, J., Querol, X., 2013. Impact of traffic intensity and pavement aggregate size on road dust particles loading, *Atmos. Environ.*, 77, 711–717.
- Amato, F., Schaap, M., Denier van der Gon, H.A.C., Pandolfi, M., Alastuey, A., Keuken, M., Querol, X., 2012. Effect of rain events on the mobility of road dust load in two Dutch and Spanish roads, *Atmos. Environ.*, 62, 352–358.
- Amato, F., Pandolfi, M., Moreno, T., Furger, M., Pey, J., Alastuey, A., Bukowiecki, N., Prevot, A.S.H., Baltensperger, U., Querol, X., 2011. Sources and variability of inhalable road dust particles in three European cities, *Atmos. Environ.*, 45, 6777–6787.
- Amato, F., Nava, S., Lucarelli, F., Querol, X., Alastuey, A., Baldasano, J.M., Pandolfi, M., 2010. A comprehensive assessment of PM emissions from paved roads: real-world emission factors and intense street cleaning trials, *Sci. Total Environ.*, 408, 4309-4318.
- AQEG, 2019, Non-exhaust emissions from road traffic, Air Quality Expert Group, Department for Environment Food and Rural Affairs, London, [https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1907101151\\_20190709\\_Non\\_Exhaust\\_Emissions\\_typeset\\_Final.pdf](https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1907101151_20190709_Non_Exhaust_Emissions_typeset_Final.pdf) [last accessed: 13 Feb 2020].
- Boulter, P.G., Thorpe, A.J., Harrison, R.M., Allen, A.G., 2006. Road vehicle non-exhaust particle matter: Final Report on emission modelling, TRL Limited, Prepared for: Project Record: CPEA23. <https://trl.co.uk/reports/PPR110>, ISBN1-84608-923-8 [last accessed 13 Feb 2020].
- Bukowiecki, N., Lienemann, P., Hill, M., Furger, M., Richard, A., Amato, F., Prevot, Gehrig, R., 2010. PM<sub>10</sub> emission factors for non-exhaust particles generated by road traffic in an urban street canyon and along a freeway in Switzerland, *Atmos. Environ.*, 44, 2330-2340.
- Chapple, D and Chapple S., 2017. encyCARpedia database, <https://www.encycarpedia.com/>, [last accessed: 15 July 2020]
- Faria, R., Moura, R., Delgado, J., de Almeida, A. T., 2012. A sustainability assessment of electric vehicles as a personal mobility system, *Energ. Convers. Manage.*, 61, 19–30.

452 Gehrig, R., Hill, M., Buchmann, B., Imhof, D., Weingarter, E., Baltensprenger, U., 2004. Separate  
 453 determination of PM<sub>10</sub> emission factors of road traffic for tailpipe emissions and emissions from  
 454 abrasion and resuspension processes, *Int. J. Environ. Pollut.*, 22, 312-332.

455 Hall, T.J., 2017. A comparison of braking behavior between an IC engine and pure electric vehicle  
 456 in Los Angeles City during conditions, SAE Techn. Paper 2017-01-2518, doi 10.4271/2017-01-2518.

457

458 Harrison, R.M., Jones, A., Gietl, J., Yin J., Green, D.C., 2012, Estimation of the Contribution of  
 459 Brake Dust, Tyre Wear and Resuspension to Non-Exhaust Traffic Particles Derived from  
 460 Atmospheric Measurements, *Environ. Sci. & Technol.*, 46, 6523-6529.

461

462 Jones, A. and Harrison, R. M., 2006, Estimation of the emission factors of particle number and mass  
 463 fractions from traffic at a site where mean vehicle speeds vary over short distances, *Atmos. Environ.*,  
 464 40, 7125-7137.

465

466 Ketzel, M., Omstedt, G., Johansson, C., Düring, I., Pohjola, M., Oetl, D., Gidhagen, L., Wahlin, P.,  
 467 Lohmeyer, A. Haakana, M., Berkowicz, R., 2007. Estimation and validation of PM<sub>2.5</sub>/PM<sub>10</sub> exhaust  
 468 and non-exhaust emission factors for practical street pollution modeling, *Atmos. Environ.*, 41, 9370-  
 469 9385.

470

471 Lanzerstorfer, C., 2018. Heavy metals in the finest size fractions of road-deposited sediments,  
 472 *Environ. Pollut.*, 239, 522-531.

473

474 Lanzerstorfer, C., Logiewa, A., 2019. The upper size limit of the dust samples in road dust heavy  
 475 metal studies: Benefits of a combined sieving and air classification sample preparation procedure,  
 476 *Environ. Pollut.*, 245, 1079-1085.

477

478 Li, J., Jiao, J., and Tang, T., (2019) An evolutionary analysis on the effect of government policies on  
 479 electric vehicle diffusion in complex network, *Energy Policy*, Vol 129, 1-12.  
 480 <https://doi.org/10.1016/j.enpol.2019.01.070>

481

482 Lijewski, P., Kozak, M., Fuć, P., Rymaniak, L., Ziółkowski, A., 2020, Exhaust emissions generated  
 483 under actual operating conditions from a hybrid vehicle and an electric one fitted with a range  
 484 extender, *Transportation Research Part D*, 78, 102183.

485

486 Ntziachristos, L., Boulter, P., 2019. EMEP/EEA Emission Inventory Guidebook, 2019, Categories:  
 487 1.A.3.b.vi Road transport: Automobile tyre and brake wear; and 1.A.3.b.vii Road transport:  
 488 Automobile road abrasion. [[https://www.eea.europa.eu/publications/emep-eea-guidebook-  
 489 2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-vi/view](https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-vi/view) [last accessed 26  
 490 Mar 2020].

491

492 Ntziachristos, L., Boulter, P., 2013. EMEP/EEA Air Pollutant Emissions Inventory Guidebook 2013:  
 493 Road Vehicle Tyre and Brake Wear; Road Surface Wear [Internet]. European Environmental Agency,  
 494 Copenhagen [cited 11 August 2015]. Available from: [http://www.eea.europa.eu/publications/emep-  
 495 eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-tyre](http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-tyre).  
 496 [last accessed: 13 Feb 2020].

497

498 Padoan, E., Rome, C., Ajmone-Marsan, F., 2017. Bioaccessibility and size distribution of metals in  
 499 road dust and roadside soils along a peri-urban transect, *Sci. Tot. Environ.*, 601-602, 89-98.

500

501 Pant, P., Baker, S.J., Shukla, A., Maikawa, C., Pollitt, K.J. G., Harrison, R.M., 2015. The PM<sub>10</sub>  
 502 fraction of road dust in the UK and India: Characterization, source profiles and oxidative potential,  
 503 *Sci. Tot. Environ.*, 530-531, 445-452.

504  
 505 Ricardo Energy & Environment, 2018. Methodology for the UK's Road Transport Emissions  
 506 Inventory, Report for the Department for Business, Energy & Industrial Strategy, Version for the  
 507 2016 National Atmospheric Emissions Inventory, ED 59803130, Issue Number 1, 13/03/2018  
 508 [https://uk-](https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1804121004_Road_transport_emissions_methodology_report_2018_v1.1.pdf)  
 509 [air.defra.gov.uk/assets/documents/reports/cat07/1804121004\\_Road\\_transport\\_emissions\\_methodol](https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1804121004_Road_transport_emissions_methodology_report_2018_v1.1.pdf)  
 510 [ogy\\_report\\_2018\\_v1.1.pdf](https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1804121004_Road_transport_emissions_methodology_report_2018_v1.1.pdf) [last accessed: 13 Feb 2020]  
 511  
 512 Thorpe, A.J., Harrison, R.M., Boulter, P.G., McCrae, I.S., 2007. Estimation of particle resuspension  
 513 source strength on a major London Road, Atmos. Environ., 41, 8007-8020.  
 514 Thorpe, A., Harrison, R.M., 2008. Sources and properties of non-exhaust particulate matter from  
 515 road traffic: A Review, Sci Tot. Environ., 400, 270-282.  
 516  
 517 Timmers, V.R.J.H., Achten, P.A.J. 2016. Non-exhaust PM emissions from electric vehicles, Atmos.  
 518 Environ., 134, 10-16. Corrigendum to "Non-exhaust PM emissions from electric vehicles", Atmos.  
 519 Environ., 147, 492, 2016.  
 520  
 521 Timmers, V.R.G.H., and Achten, P.A.G., 2018. Chapter 12 - Non-Exhaust PM Emissions From Battery Electric  
 522 Vehicles, in Non-Exhaust Emissions- An Urban Air Quality Problem for Public Health; Impact and Mitigation  
 523 Measures, Pages 261-287, Academic Press.  
 524  
 525 USEPA, 2011. Emission Factor Documentation for AP-42, Section 13.2.1: Paved Roads.  
 526 Measurement Policy Group, Office of Air Quality Planning and Standards, U.S. Environmental  
 527 Protection Agency, January 2011, <https://www3.epa.gov/ttn/chief/ap42/ch13/bgdocs/b13s0201.pdf>  
 528 [last accessed: 13 Feb 2020].  
 529  
 530 Venkatram, 2000. A critique of empirical emission factor models: a case study of the AP-42 model  
 531 for estimating PM<sub>10</sub> emissions from paved roads, Atmos. Environ., 34 1-11.

## TABLE LEGENDS

<b>Table 1:</b>	Emission factors $EF_{PM_{10}}$ and $EF_{PM_{2.5}}$ for brake and tyre wear by vehicle type and road type (from AQEG, 2019, derived from the EMEP/EEA emission inventory guidebook 2019). These are the values used in the calculation of national inventories and in numerical models for prediction of air quality.
<b>Table 2:</b>	Selected masses used to represent the aggregate vehicle categories in Table 1; based on Table 2 of Boulter et al. (2006). These values are used in the estimation of the vehicle weight dependence of emission factors.
<b>Table 3:</b>	Regression coefficient used to fit the $EF_{PM_{2.5/10}}$ vs $W$ curves in the plots of Figure 1.
<b>Table 4:</b>	Mass increments and derived emissions factors calculated in Harrison et al. (2012) for: total mass, brake dust, tyre dust, and resuspension
<b>Table 5:</b>	Dust loading reported for European paved roads*. [Units: mg PM <sub>10</sub> m <sup>-2</sup> ].
<b>Table 6:</b>	Emission factors for petrol and diesel ICEVs and their petrol and diesel equivalent BEVs. For BEV, the regressions shown in Figures 1 and 2 are used to estimate the emission factors based on the increase in the mass of BEV of 318 and 258 kg for petrol and diesel cars respectively. Values from Timmers and Achten (2016) are given for comparison. [Units: mg PM veh <sup>-1</sup> ].
<b>Table 7:</b>	Increase (and percentage increase) in Emission Factor due to the increase of the weight of the average UK car of 318 and 258 kg for petrol and diesel cars respectively (and 300 kg across petrol and diesel) (Timmers and Achten, 2016) [eq – equivalent, units: mg PM veh <sup>-1</sup> km <sup>-1</sup> ].
<b>Table 8:</b>	Exhaust emission factors EURO 6 for cars (mg·km <sup>-1</sup> ·veh <sup>-1</sup> ) (from Ricardo Energy & Environment 2018). The NAEI currently uses the fraction of PM <sub>10</sub> emitted as PM <sub>2.5</sub> of 1.0 for exhaust emissions, taken from EMEP (2016), implying that all the PM exhaust emissions are in the PM <sub>2.5</sub> mass range.

## FIGURE LEGENDS

<b>Figure 1:</b>	Regression of tyre, brake and road wear $EF_{PM}$ emission factors against vehicle mass (Table 1 and 2). The shaded green and black rectangles highlight the increase $EF_{be} - EF_{ice}$ for comparisons with petrol and diesel fuelled engines. Nonlinear Least Squares fit of $EF = bW_{ref}^{\frac{1}{c}}$ shown by black solid and dashed lines: dashed lines signifying the $3\sigma$ limits. (see Table 3 for fitted values of $b$ and $c$ and Figures SI 1 and 2 for the individual plots with error bars).
<b>Figure 2:</b>	Effect on the AP-42 curve by the setting of the values of $b$ and $sL$ using equation 2. $EF^{resus} = 0.62(sL)^{0.912}(W)^b$ .
<b>Figure 3:</b>	Absolute and percentage change in the total emission factors shown in <i>without</i> / <i>with</i> regenerative braking. The upper panel shows the absolute values of total emission factor estimated for petrol, diesel and battery electric vehicles, the latter with 0%, 90% and 100% regenerative braking on different road types. The lower panels show

580 the change in emission factor from a diesel (left panel) or petrol (right panel) vehicle  
581 to a battery electric vehicle with 0%, 90% or 100% regenerative braking.  
582  
583

584 **Table 1:** Emission factors  $EF_{PM_{10}}$  and  $EF_{PM_{2.5}}$  for brake and tyre wear by vehicle type and road type  
585 (from AQEG, 2019, derived from the EMEP/EEA Emission Inventory Guidebook 2019). These are  
586 the values used in the calculation of national inventories and in numerical models for prediction of  
587 air quality.  
588

mg PM km <sup>-1</sup>	Road type	Tyre		Brake		Road abrasion	
		$EF_{PM_{2.5},T}$	$EF_{PM_{10},T}$	$EF_{PM_{2.5},B}$	$EF_{PM_{10},B}$	$EF_{PM_{2.5},A}$	$EF_{PM_{10},A}$
Cars	Urban	6.1	8.7	4.7	11.7	4.2	7.5
	Rural	4.8	6.8	2.2	5.5		
	Motorway	4.1	5.8	0.5	1.4		
LGVs	Urban	9.7	13.8	7.3	18.2	4.1	7.5
	Rural	7.5	10.7	3.4	8.6		
	Motorway	6.4	9.2	0.8	2.1		
Rigid HGVs	Urban	14.5	20.7	13.0	51	20.5	38
	Rural	12.2	17.4	27.1	27.1		
	Motorway	9.6	14	4.2	8.4		
Articulated HGVs	Urban	33.0	47.1	13.0	51	20.5	38
	Rural	27.8	38.2	27.1	27.1		
	Motorway	22.0	31.5	4.2	8.4		
Buses	Urban	14.8	21.2	21.3	53.6	20.5	38
	Rural	12.2	17.4	13.7	27.1		
	Motorway	9.8	14	4.4	8.4		
Motorcycles	Urban	2.6	3.7	2.3	5.8	1.6	3
	Rural	2.0	2.9	1.1	2.8		
	Motorway	1.7	2.5	0.3	0.7		

589

590 **Table 2:** Selected masses used to represent the aggregate vehicle categories in Table 1; based on  
591 Table 2 of Boulter et al. (2006). These values are used in the estimation of the vehicle weight  
592 dependence of emission factors.  
593

Vehicle Category	Num. of axles	Num. of wheels	Estimated weight range (t)	Estimated ave. weight W (t)
Motorcycles	2	2	-	0.187
Cars	2	4	≤ 2.5	1.2
LGVs	2	6	≤ 3.5	3
Rigid HGVs	2-3	6-10	3.5 – 32	14
Articulated HGVs	3-6	14-18	14 – 44	30
Buses	6-10	6-10	3.5 – 32	14

594

595

596 **Table 3:** Regression coefficient used to fit the  $EF_{PM_{2.5/10}}$  vs  $W$  curves in the plots of Figure 1.

$EF = bW_{rel}^{\frac{1}{c}}$ ; b (mg·veh <sup>-1</sup> ·km <sup>-1</sup> ); c (no unit); $W_{rel} = \frac{W}{1000} kg$								597
								598
		Urban		Rural		Motorway		
		b	c	b	c	B	c	599
Tyre	PM <sub>2.5</sub>	5.8 ± 0.5	2.3 ± 0.4	4.5 ± 0.3	2.3 ± 0.41	3.8 ± 0.3	2.3 ± 0.4	
	PM <sub>10</sub>	8.2 ± 0.6	2.3 ± 0.4	6.4 ± 0.5	2.3 ± 0.41	5.5 ± 0.42	2.3 ± 0.4	600
Brake	PM <sub>2.5</sub>	4.2 ± 1.1	1.9 ± 0.2	1.8 ± 0.9	1.5 ± 0.3	0.4 ± 0.4	1.3 ± 0.4	
	PM <sub>10</sub>	11 ± 2.7	1.9 ± 0.2	4.5 ± 2.4	1.5 ± 0.3	1.0 ± 1.0	1.3 ± 0.4	601
Urban / Rural / Motorway								602
		B		c				
Road	PM <sub>2.5</sub>	2.8 ± 0.5		1.5 ± 0.1				603
	PM <sub>10</sub>	5.1 ± 0.9		1.5 ± 0.1				604
Resus.	PM <sub>2.5</sub>	2.0 ± 0.8		1.1 ± 0.4				
	PM <sub>10</sub>	8.2 ± 3.2		1.1 ± 0.4				605

606 **Table 4.** Mass increments and derived emissions factors calculated in Harrison et al. (2012) for: total  
607 mass, brake dust, tyre dust, and resuspension.

	Roadside Increment $X_{pol}$ [µg/m <sup>3</sup> ]	At Source Emission $EF_{Tail.Pol}$ [mg PM <sub>coarse</sub> km <sup>-1</sup> ]
Brake wear	2.8 ± 0.5	14.6 ± 2.6
Tyre wear	0.5 ± 0.1	2.8 ± 0.5
Road surface		
Resuspension	1.9 ± 0.5	10 ± 1.8

608  
609 **Note:** Due to the method used, road surface wear is included in the resuspension category.

610  
611 **Table 5.** Dust loading reported for European paved roads\*. [Units: mg PM<sub>10</sub> m<sup>-2</sup>].

City	Road type	Dust loading (mean)	Reference
Zurich	Various	0.2-1.3	Amato et al. (2011)
Barcelona	Various	3.7-23.1	Amato et al. (2011)
Girona	Various	1.3-7.1	Amato et al. (2011)
Barcelona II	ring road	12.8-73.7	Amato et al. (2011)
Utrecht	residential, <50h after rain	2	Amato et al. (2012)
Barcelona	medium traffic, >50h after rain	3	Amato et al. (2012)
Cordoba	medium traffic, >26h after rain	2.4-20.1	Amato et al. (2013)
Seville	low to medium traffic, >100h after rain	1.9-11.2	Amato et al. (2013)
Algeciras Bay	low to medium traffic, >46h after rain	1.9-3.0	Amato et al. (2013)
Malaga	medium traffic, >242h after rain	4.3-5.9	Amato et al. (2013)
Granada	low to medium traffic, >246h after rain	5.9-18.1	Amato et al. (2013)
Birmingham	medium traffic	9.3	Pant et al. (2015)

612  
613 \* Excludes samples collected close to construction sites

<b>Table 6:</b> Emission factors for petrol and diesel ICEVs and their petrol and diesel equivalent BEVs. For BEV, the	<i>Urban</i>	<i>Rural</i>	<i>Motorway</i>	<i>Timmers and Achten (2016)</i>
--	--------------	--------------	-----------------	----------------------------------

regressions shown in Figures 1 and 2 are used to estimate the emission factors based on the increase in the mass of BEV of 318 and 258 kg for petrol and diesel cars respectively. Values from Timmers and Achten (2016) are given for comparison. [Units: mg PM veh<sup>-1</sup>]. **Tyre**

### Wear

ICEV	$EF_{icev}^{tyre}$	Petrol	PM <sub>2.5</sub>	6.6 ± 0.7	5.1 ± 0.6	4.3 ± 0.5	2.9
			PM <sub>10</sub>	9.4 ± 1.0	7.2 ± 0.8	6.2 ± 0.7	6.1
		Diesel	PM <sub>2.5</sub>	7.0 ± 0.7	5.4 ± 0.5	4.6 ± 0.5	2.9
			PM <sub>10</sub>	10.0 ± 1.0	7.7 ± 0.8	6.6 ± 0.7	6.1
BEV	$EF_{bev}^{tyre}$	Petrol-eq	PM <sub>2.5</sub>	7.2 ± 0.8	5.6 ± 0.6	4.8 ± 0.5	3.7
			PM <sub>10</sub>	10.3 ± 1.2	7.9 ± 0.9	6.8 ± 0.8	7.2
		Diesel-eq	PM <sub>2.5</sub>	7.5 ± 0.8	5.8 ± 0.6	5.0 ± 0.5	3.7
			PM <sub>10</sub>	10.7 ± 1.2	8.2 ± 0.9	7.1 ± 0.8	7.2
Brake Wear				Urban	Rural	Motorway	Timmers and Achten (2016)
ICEV	$EF_{icev}^{brake}$	Petrol	PM <sub>2.5</sub>	5.0 ± 0.6	2.2 ± 0.4	0.5 ± 0.1	2.2
			PM <sub>10</sub>	12.4 ± 1.6	5.5 ± 0.9	1.3 ± 0.2	9.3
		Diesel	PM <sub>2.5</sub>	5.3 ± 0.6	2.4 ± 0.4	0.6 ± 0.1	2.2
			PM <sub>10</sub>	13.4 ± 1.6	6.0 ± 0.9	1.5 ± 0.2	9.3
BEV	$EF_{bev}^{brake}$	Petrol-eq	PM <sub>2.5</sub>	5.5 ± 0.7	2.5 ± 0.4	0.6 ± 0.1	0
			PM <sub>10</sub>	13.9 ± 1.9	6.3 ± 1.1	1.5 ± 0.3	0
		Diesel-eq	PM <sub>2.5</sub>	5.8 ± 0.7	2.6 ± 0.4	0.6 ± 0.1	0
			PM <sub>10</sub>	14.5 ± 1.8	6.6 ± 1.1	1.6 ± 0.3	0
Resuspension				Urban / Rural / Motorway			Timmers and Achten (2016)
ICEV	$EF_{icev}^{resus}$	Petrol	PM <sub>2.5</sub>	2.7 ± 0.6			3.1
			PM <sub>10</sub>	11.0 ± 2.6			7.5
		Diesel	PM <sub>2.5</sub>	3.0 ± 0.6			3.1
			PM <sub>10</sub>	12.5 ± 2.7			7.5
BEV	$EF_{bev}^{resus}$	Petrol-eq	PM <sub>2.5</sub>	3.2 ± 0.8			3.8
			PM <sub>10</sub>	13.4 ± 3.3			8.9
		Diesel-eq	PM <sub>2.5</sub>	3.5 ± 0.8			3.8
			PM <sub>10</sub>	14.4 ± 3.3			8.9
Road Wear				Urban / Rural / Motorway			Timmers and Achten (2016)
ICEV	$EF_{icev}^{road\ wear}$	Petrol	PM <sub>2.5</sub>	3.3 ± 0.5			12.0
			PM <sub>10</sub>	6.1 ± 1.0			40.0
		Diesel	PM <sub>2.5</sub>	3.6 ± 0.5			12.0
			PM <sub>10</sub>	6.8 ± 1.0			40.0
BEV	$EF_{bev}^{road\ wear}$	Petrol-eq	PM <sub>2.5</sub>	3.8 ± 0.6			14.9
			PM <sub>10</sub>	7.0 ± 1.2			49.6
		Diesel-eq	PM <sub>2.5</sub>	4.0 ± 0.6			14.9
			PM <sub>10</sub>	7.4 ± 1.2			49.6

614

615

616

617 **Table 7:** Increase (and percentage increase) in Emission Factor due to the increase of the weight of  
618 the average UK car of 318 and 258 kg for petrol and diesel cars respectively (and 300 kg across petrol  
619 and diesel) (Timmers and Achten, 2016) [eq – equivalent, units: mg PM veh<sup>-1</sup> km<sup>-1</sup>].

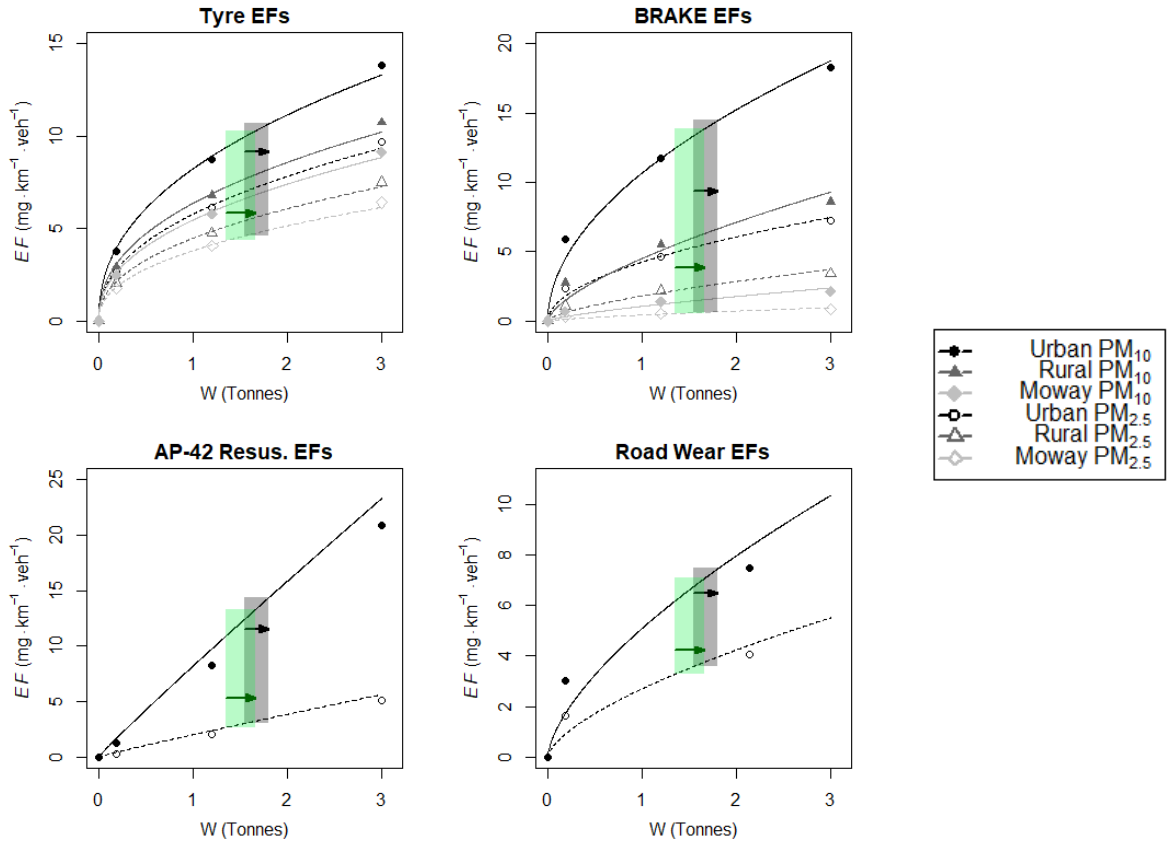
			<i>Urban</i>	<i>Rural</i>	<i>Motorway</i>	<i>T&amp;A(2016)</i>
<i>Tyre</i>	<i>Petrol to Petrol-eq</i>	<i>PM</i> <sub>2.5</sub>	0.6 (9.7%)	0.5 (9.8%)	0.4 (9.7%)	0.8 (30.7%)
		<i>PM</i> <sub>10</sub>	0.9 (9.7%)	0.7 (9.5%)	0.6 (9.8%)	1.1 (18.0%)
	<i>Diesel to Diesel-eq</i>	<i>PM</i> <sub>2.5</sub>	0.7 (6.9%)	0.4 (7.0%)	0.3 (7.0%)	0.8 (30.7%)
		<i>PM</i> <sub>10</sub>	0.7 (6.9%)	0.5 (6.8%)	0.5 (7.0%)	1.1 (18.0%)
<i>Brake</i>	<i>Petrol to Petrol-eq</i>	<i>PM</i> <sub>2.5</sub>	0.6 (11.5%)	0.3 (15.0%)	0.1 (17.1%)	-
		<i>PM</i> <sub>10</sub>	1.4 (11.5%)	0.8 (15.0%)	0.2 (17.1%)	
	<i>Diesel to Diesel-eq</i>	<i>PM</i> <sub>2.5</sub>	0.4 (8.2%)	0.3 (10.6%)	0.1 (12.1%)	
		<i>PM</i> <sub>10</sub>	1.1 (8.2%)	0.6 (10.6%)	0.2 (12.1%)	
<i>Urban/Rural/Motorway</i>						<i>T&amp;A(2016)</i>
<i>Road Wear</i>	<i>Petrol to Petrol-eq</i>	<i>PM</i> <sub>2.5</sub>	0.50 (14.8%)			0.7 (22.5%)
		<i>PM</i> <sub>10</sub>	0.9 (14.8%)			1.4 (18.7%)
	<i>Diesel to Diesel-eq</i>	<i>PM</i> <sub>2.5</sub>	0.4 (10.5%)			0.7 (22.5%)
		<i>PM</i> <sub>10</sub>	0.7 (10.4%)			1.4 (18.7%)
<i>Resus.</i>	<i>Petrol to Petrol-eq</i>	<i>PM</i> <sub>2.5</sub>	0.6 (22%)			2.9 (24.1%)
		<i>PM</i> <sub>10</sub>	2.4 (22.0%)			9.6 (24.0%)
	<i>Diesel to Diesel-eq</i>	<i>PM</i> <sub>2.5</sub>	0.5 (15.6%)			2.9 (24.1%)
		<i>PM</i> <sub>10</sub>	1.9 (15.5%)			9.6 (24.0%)

620

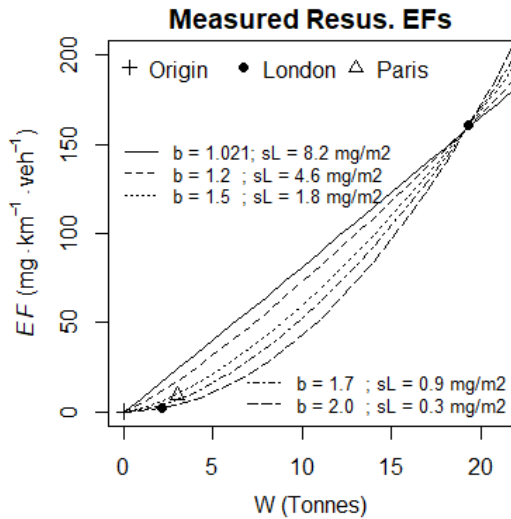
621 **Table 8:** Exhaust emission factors EURO 6 for cars (mg·km<sup>-1</sup>·veh<sup>-1</sup>) (from Ricardo Energy &  
622 Environment 2018). The NAEI currently uses the fraction of PM<sub>10</sub> emitted as PM<sub>2.5</sub> of 1.0 for exhaust  
623 emissions, taken from EMEP (2016), implying that all the PM exhaust emissions are in the PM<sub>2.5</sub> size  
624 range.

		<b>Urban</b>	<b>Rural</b>	<b>Motorway</b>
<i>ICEV</i> Petrol Cars	$EF_{icev}^{exhaust}$	1.46	1.24	1.80
<i>ICEV</i> Diesel Cars	$EF_{icev}^{exhaust}$	1.49	1.11	0.90

625

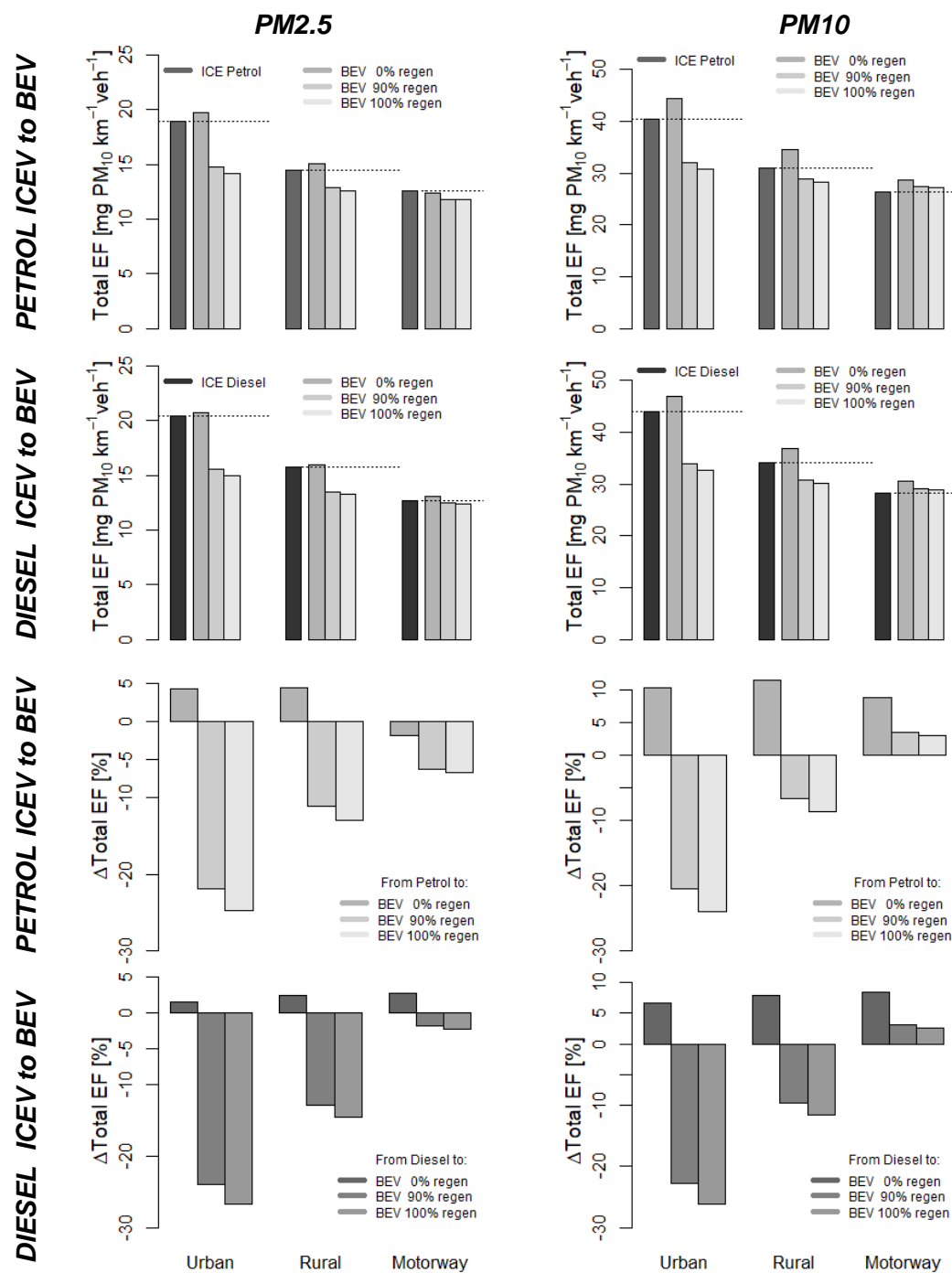


**Figure 1:** Regression of tyre, brake and road wear  $EF_{PM}$  emission factors against vehicle mass (Table 1 and 2). The shaded green and black rectangles highlight the increase  $EF_{be} - EF_{ice}$  for comparisons with petrol and diesel fuelled engines. Nonlinear Least Squares fit of  $EF = bW_{ref}^{\frac{1}{c}}$  shown by black solid and dashed lines: dashed lines signifying the  $3\sigma$  limits. (see Table 3 for fitted values of  $b$  and  $c$  and Figures SI 1 and 2 for the individual plots with error bars).



**Figure 2.** Effect on the AP-42 curve by the setting of the values of  $b$  and  $sL$  using equation 2.  $EF^{resus} = 0.62(sL)^{0.912}(W)^b$ .

630  
631



**Figure 3:** Absolute and percentage change in the total emission factors shown in *without* / *with* regenerative braking. The upper panel shows the absolute values of total emission factor estimated for petrol, diesel and battery electric vehicles, the latter with 0%, 90% and 100% regenerative braking on different road types. The lower panels show the change in emission factor from a diesel (left panel) or petrol (right panel) vehicle to a battery electric vehicle with 0%, 90% or 100% regenerative braking.

632