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PM₁₀ and PM_{2.5} Emission Factors for Non-Exhaust Particles from Road Vehicles: Dependence Upon Vehicle Mass and Implications for Battery Electric Vehicles

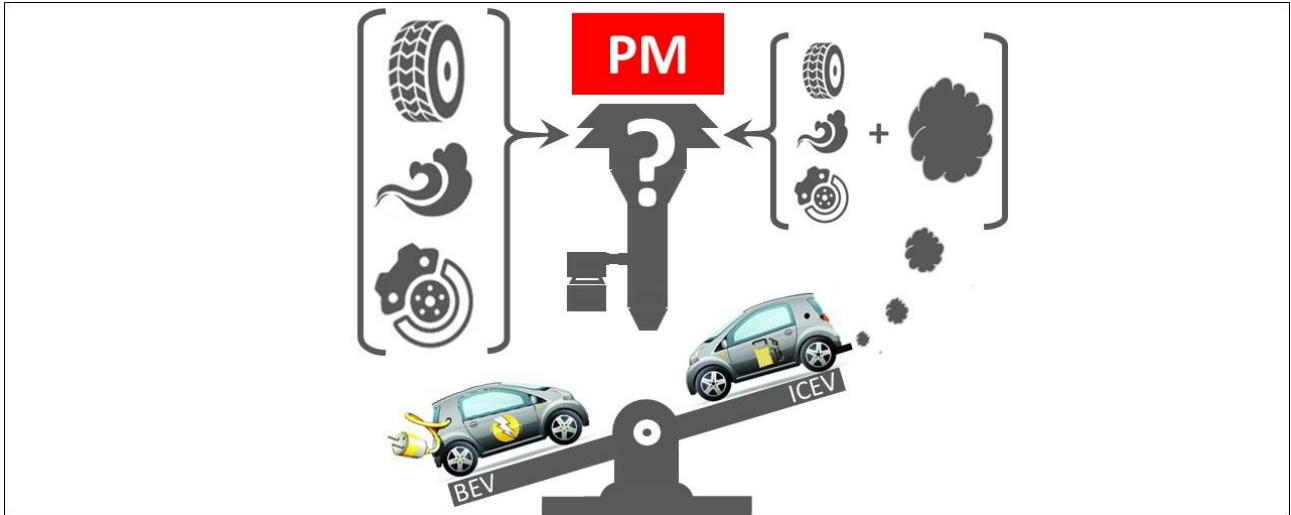
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22 **GRAPHICAL ABSTRACT:**



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CAPTION: Question: Will the electrification of passenger cars reduce total PM emissions?

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

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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 will exceed exhaust emissions by a large margin, both for PM₁₀ and PM_{2.5}, 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 PM₁₀ and PM_{2.5} 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

95 Table 1 provides emission factors for tyre, brake and road wear published in the EMEP/EEA
96 emission inventory guidebook, 2013 (Ntziachristos and Boulter, 2019). The values are for the six
97 aggregated vehicle classes (Two Wheeled Motor Vehicles - motorcycles, Cars, Light Goods
98 Vehicles - LGVs, both Rigid and Articulated Heavy Goods Vehicles – HGVs and Buses/Coaches)
99 for a UK road fleet. These values are derived from emission factors reported in the literature and a
100 deeper understanding of their derivation can be sought from the Automobile Tyre and Brake Wear
101 website which supports the development of chapter B770 (SNAP 0707) of the EMEP/Corinair
102 Emission Inventory Guidebook [<https://www.eng.auth.gr/mech0/lat/PM10/>]. We use these to
103 estimate a dependence of these aggregate emission factors (EF) on an estimated vehicle mass. The
104 means by which the values in Table 1 are calculated, including dependence on, vehicle speed, mass,
105 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*

109 In order to evaluate the effect of changing vehicle masses, it is first necessary to estimate the masses
110 of vehicles used in the estimation of our base emission factors in Table 1. These appear to derive
111 predominantly from data collected on vehicles around the year 2000 (Ntziachristos and Boulter, 2013,
112 2019). To assign a vehicle mass to each of the classes in Table 1, an aggregated vehicle mass was
113 selected based on the estimated values of Boulter et al. (2006). For motorcycles and cars, Boulter et
114 al. (2006) use values of 0.2 and 1.2 tonnes respectively. The car mass is roughly 200 kg less than the
115 mass used for our ICEV value which represents car weights closer to the year 2020. The LGV mass
116 was taken as 3 tonnes, whereas the rigid HGV, articulated HGV and bus masses were calculated as
117 the average across several categories. For example, the rigid HGV and bus masses were both taken
118 as the average of vehicle *HGV, buses and coach* categories with 2 or 3 axles. Similarly, the articulated
119 HGV mass was taken as the average of the HGV categories with 4 or more axles. Estimated mass
120 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 cm³ 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 ΔW 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 ΔW 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 ± 145 kg and 258 ± 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 ± 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 ± 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

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

176

177 **Resuspension Emission Factors EF^{resus}**

178 Resuspension is the term used to describe particles of road surface dust raised into the air by passing
179 traffic, due either to shear forces at the tyre/road surface interface, or air turbulence in the wake of a
180 moving vehicle. The EMEP/EEA Guidebook does not include the calculation of resuspended road
181 dust, and estimates are often not included in emissions inventories. However, resuspension emission
182 factors EF^{resus} can be calculated using the USEPA guidance in AP-42 and a review of past and
183 current paved road emission factors is given by the USEPA (2011). Based on various parameters –
184 s : surface material content silt ($< 75 \mu\text{m}$ diameter); L : Surface material loading, defined as mass of
185 particles per unit area of the travel surface (g/m^2); b : an exponent to which sL is raised ($sL_{rel} =$
186 $sL/1\text{g}\cdot\text{m}^{-2}$); k : base emission factor (g/VKT); W_{rel} : vehicle mass ($W_{rel} = W/1000 \text{Kg}$) and p : a
187 dimensionless exponent – the particulate emission factor (g/VKT) has been parameterised by
188 equation 2.

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

189 The extent to which resuspension emissions are related to vehicle mass is uncertain, and Venkatram
190 (2000) critiqued the US EPA AP42 model for emission from paved roads (AP-42 paved road section
191 2011); (then equation 2 with $k = 0.54 \text{ g km}^{-1}$; $b = 0.65$; $p = 1.5$). This has since been updated by
192 similar models in 1995, 2002, 2003, and most recently in 2011 (equation (3)). A k value of 0.62 g
193 km^{-1} is used for the 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
194 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 of both sL and
 204 W_{rel} produce $\sim 10\%$ variation in EF_{resus} whereas a 10% variation in the ration 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 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 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 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 PM_{10} of 10
228 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 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 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 mg m^{-2} translates approximately to a
237 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 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

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

248

249 The increases in PM₁₀ tyre, brake and road wear emission factors for urban, rural and motorway UK
250 roads range from 9.5 to 22% for petrol vehicles and 6.8 to 11% for diesels. Diesel vehicles have a
251 smaller increase due to the fact that the diesel vehicles are heavier than petrol and hence less of an
252 increase emission factor can be expected when compared to their BEV equivalent. This is also shown
253 in the percentage increase of the PM_{2.5} emission factors for petrol and diesel vehicles 8.6-17% and
254 6.8-12% respectively. As expected, the values reduce from high to low for urban to rural to motorway
255 although this is not reflected in the relative values which show a consistent increase for tyre emission
256 factors and increasing percentage for brake emission factors. There is very rough agreement between
257 our values and the ICEV values presented by Timmers and Achten (2016) for tyre and brake
258 emissions (Table 6). On average, both our tyre and brake wear emission factors are slightly higher,
259 whereas our resuspension values are notably higher. Conversely, Timmers and Achten (2016) has
260 significantly higher values for road wear. Comparison of the increases in the non-exhaust emission
261 factors in Table 7 are closer for road wear and resuspension although our tyre emission factors are
262 roughly half those of Timmers and Achten (2016).

263

264 Using a value for sL of 8 mg m⁻², the resuspension model suggests that the increase in weight of a
265 passenger car $W_{bev} - W_{icev}$ will increase the PM₁₀ resuspension emission factor by 16% and 22%
266 (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
267 respectively). The overall magnitude of these emission factors can be compared with those of
268 Bukowiecki et al. (2010), Ketzler et al. (2007), Amato et al. (2010; 2016; 2017) and Gehrig et al.
269 (2004) who derive fleet PM₁₀ emission factors (Table S2). Although the European LGV and HGV
270 emission factors of Gehrig et al. (2004) are in line with the London measurements, the fleet average

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

273

274 **Tail Pipe Emissions**

275 In order to make a full assessment of the change in PM₁₀ and PM_{2.5} due electrification of passenger
 276 cars, a tail pipe emission factor is also required. For this, we used Euro 6 engine emissions as used
 277 in the UK National Atmospheric Emissions Inventory (Ricardo Energy & Environment, 2018) (Table
 278 8). From this, the harmonisation in Euro 6 of previously higher diesel emissions to those of their
 279 counterpart petrol engine cars can be seen. Interesting to note is the lower emission for diesel cars
 280 under conditions of higher speed (rural and motorway).

281

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

283 The total emission factor for cars either powered by internal combustion engines or battery electric
 284 motors are given by the sums in equations (4) and (5). The ICEV and BEV emission factors simply
 285 differ by the inclusion of the exhaust emissions and the degree to which the brake emission factor
 286 contributes. By specifying for BEV, a 0% (fully inductive brake, i.e. $EF_{bev}^{brake} = 0$) and 100% (fully
 287 friction brake) contribution to the brake emission factor, we define a range of possible values within
 288 which a regenerative braking system might operate: between $0\% \times EF_{bev}^{fric}$ and $100\% \times EF_{bev}^{fric}$. But
 289 in this work, we assume that a BEV using regenerative brakes will emit a 10% fraction $frac_{brake}$ of
 290 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 PM₁₀ and, ignoring the petrol motorway, ~1-5% greater
 303 for PM_{2.5}. 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 PM₁₀ 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 PM₁₀ emission factor on rural roads is less than that of urban. Likewise, the total PM₁₀
 313 emission on motorways is again lower than urban and rural roads and consequently, no amount
 314 of regeneration will bring the total PM₁₀ 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_{2.5}, 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_{2.5} emissions of BEV cars to be

318 in line with their petrol equivalent ICE cars, regenerative braking needs to play a lesser role than
319 for the case of PM₁₀. For petrol and diesel cars, the brake emissions need to be reduced
320 respectively to 85% and 95% (i.e. 15% and 5% regen.) for urban roads and 74% and 86% (i.e.
321 26% and 14% regen.) respectively for petrol and diesel roads on rural roads. As with PM₁₀,
322 motorways are a special case, requiring a reduction to 47% for diesel equivalent BEV on
323 motorways, and no requirement for the petrol equivalent BEV cars to lower their total emissions
324 below those of ICEV cars.

325 • Focusing on urban and rural roads, in order to achieve any reduction in PM emissions in the
326 electrification of vehicles, regenerative braking plays a significant part in the reduction of vehicle
327 speed when used in place of friction braking. Hall (2017) compared the braking behaviour of a
328 BEV with that of an ICEV in Los Angeles in city driving conditions. Due to changes in driving
329 style, the number of braking events for the BEV was reduced by as much as a factor of 8. The
330 energy dissipation by the friction brakes in the BEV was lower by a factor as large as 20-fold.
331 As alluded to in the previous point, using the model in this work, the critical $frac_{brake}$ value
332 below which an overall reduction in total PM₁₀ emissions might be expected ranges from 43% to
333 70% for petrol and 60 to 80% for diesel equivalent BEV. For PM_{2.5} we might expect
334 $frac_{brake}$ to be in the range 74% to 85% and 86% to 95% respectively for petrol and diesel.
335 This means in order to expect a reduction in PM emissions of a fleet of ICEV cars on urban and
336 rural roads by electrification, inductive braking has to reduce the brake emissions of PM₁₀ by at
337 least 20 – 57% and PM_{2.5} by at least 5 – 26%. On motorways there remains a positive increase
338 in the total EF of PM₁₀ relative to both petrol and diesels even using 100% regen. Removal of
339 friction braking (e.g. through 100% regenerative braking) can provide up to 25-27% reduction
340 of PM₁₀ emissions in the urban environment (24-26% for PM_{2.5}). With a realistic regenerative
341 braking (using 10% friction brakes) we might expect up to 22-24% (21-23% for PM_{2.5}) reduction
342 in overall emissions (Tables S3 and S4). This potential reduction is less for motorway roads,

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

- 345 • The increase in total PM₁₀ emissions for BEVs on motorways with full regenerative braking may
346 be recouped by weight saving measures. By reducing the weight of petrol-equivalent BEVs by
347 4% (3.5% for diesel-equivalent BEVs) the difference in total PM₁₀ emissions is reduced to zero,
348 thus lowering the total urban and rural emissions further by ~2%. Similarly, for a petrol-hybrid
349 with 90% regenerative braking, if it is assumed that the PM exhaust emissions are reduced by
350 80% (Lijewski, 2020) then it must be at most 88% of the weight of our petrol-equivalent BEV,
351 ${}^pW_{\text{bev}}$ (and 93% for our diesel-equivalent BEV, ${}^dW_{\text{bev}}$) for the increase in motorway emission to
352 be brought down to zero. In other words, a balance has to be found between the combined weight
353 of a light internal combustion engine and the weight of a reduced battery pack such that the
354 overall weight of the car is reduced to 88% of a petrol-equivalent BEV (and 93% for a diesel-
355 equivalent BEV). Similar gains in the reduction of PM_{2.5} are expected due to the reduction of
356 weight. By reducing both the petrol and diesel-equivalent BEVs by 4%, the total PM_{2.5} can also
357 be expected to be reduced by 2% on either urban, rural or motorway roads.
- 358 • The PM₁₀ emission factor averaged across different road types for the BEV without regenerative
359 braking including brake, tyre and road surface wear without resuspension is 20.7 mg km⁻¹. This
360 compares well with an average emission factor for battery electric vehicles of 22.3 mg km⁻¹
361 introduced to COPERT in 2020.

362

363 CONCLUSIONS

364 In this study, published emission factors to model PM₁₀ and PM_{2.5} emissions from brake, tyre and
365 road wear and resuspension have been used to estimate the change in total emissions due to the
366 electrification of cars. The question is addressed of *whether there is a reduction of total PM₁₀ and*
367 *PM_{2.5} emissions by electrification of cars or whether the gains made by removal of tailpipe emissions*
368 *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 PM₁₀ and 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 PM₁₀ 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 mg·km⁻¹·veh⁻¹ in the
376 urban environment, i.e. ~ 26% reduction in PM₁₀ 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 mg·km⁻¹·veh⁻¹, which is nonetheless a ~12% reduction. For motorway environments, our model
379 shows no level of regenerative braking can mitigate against the increase in PM₁₀ 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 PM_{2.5}, a reduction of up to 5.5 mg·km⁻¹·veh⁻¹ in the urban environment, i.e.
382 ~ 27% reduction can be achieved. Unlike for PM₁₀ emissions, there is a reduction of 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

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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

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532 **TABLE LEGENDS**

533

534 **Table 1:** Emission factors $EF_{PM_{10}}$ and $EF_{PM_{2.5}}$ for brake and tyre wear by vehicle type and
 535 road type (from AQEG, 2019, derived from the EMEP/EEA emission inventory
 536 guidebook 2019). These are the values used in the calculation of national inventories
 537 and in numerical models for prediction of air quality.

538

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

542

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

544

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

547

548 **Table 5:** Dust loading reported for European paved roads*. [Units: mg PM₁₀ m⁻²].

549 **Table 6:** Emission factors for petrol and diesel ICEVs and their petrol and diesel equivalent
 550 BEVs. For BEV, the regressions shown in Figures 1 and 2 are used to estimate the
 551 emission factors based on the increase in the mass of BEV of 318 and 258 kg for
 552 petrol and diesel cars respectively. Values from Timmers and Achten (2016) are
 553 given for comparison. [Units: mg PM veh⁻¹].

554

555 **Table 7:** Increase (and percentage increase) in Emission Factor due to the increase of the weight
 556 of the average UK car of 318 and 258 kg for petrol and diesel cars respectively (and
 557 300 kg across petrol and diesel) (Timmers and Achten, 2016) [eq – equivalent, units:
 558 mg PM veh⁻¹ km⁻¹].

559 **Table 8:** Exhaust emission factors EURO 6 for cars (mg·km⁻¹·veh⁻¹) (from Ricardo Energy &
 560 Environment 2018). The NAEI currently uses the fraction of PM₁₀ emitted as PM_{2.5} of
 561 1.0 for exhaust emissions, taken from EMEP (2016), implying that all the PM exhaust
 562 emissions are in the PM_{2.5} mass range.

563

564 **FIGURE LEGENDS**

565

566 **Figure 1:** Regression of tyre, brake and road wear EF_{PM} emission factors against vehicle mass
 567 (Table 1 and 2). The shaded green and black rectangles highlight the increase EF_{be}
 568 - EF_{ice} for comparisons with petrol and diesel fuelled engines. Nonlinear Least
 569 Squares fit of $EF = bW_{ref}^{\frac{1}{c}}$ shown by black solid and dashed lines: dashed lines
 570 signifying the 3σ limits. (see Table 3 for fitted values of b and c and Figures SI 1 and
 571 2 for the individual plots with error bars).

572

573 **Figure 2:** Effect on the AP-42 curve by the setting of the values of b and sL using equation 2.
 574 $EF^{resus} = 0.62(sL)^{0.912}(W)^b$.

575

576 **Figure 3:** Absolute and percentage change in the total emission factors shown in *without / with*
 577 regenerative braking. The upper panel shows the absolute values of total emission
 578 factor estimated for petrol, diesel and battery electric vehicles, the latter with 0%,
 579 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 ⁻¹	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		
	Rural	4.8	6.8	2.2	5.5	4.2	7.5
	Motorway	4.1	5.8	0.5	1.4		
LGVs	Urban	9.7	13.8	7.3	18.2		
	Rural	7.5	10.7	3.4	8.6	4.1	7.5
	Motorway	6.4	9.2	0.8	2.1		
Rigid HGVs	Urban	14.5	20.7	13.0	51		
	Rural	12.2	17.4	27.1	27.1	20.5	38
	Motorway	9.6	14	4.2	8.4		
Articulated HGVs	Urban	33.0	47.1	13.0	51		
	Rural	27.8	38.2	27.1	27.1	20.5	38
	Motorway	22.0	31.5	4.2	8.4		
Buses	Urban	14.8	21.2	21.3	53.6		
	Rural	12.2	17.4	13.7	27.1	20.5	38
	Motorway	9.8	14	4.4	8.4		
Motorcycles	Urban	2.6	3.7	2.3	5.8		
	Rural	2.0	2.9	1.1	2.8	1.6	3
	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 ($\text{mg}\cdot\text{veh}^{-1}\cdot\text{km}^{-1}$); c (no unit); $W_{rel} = \frac{w}{1000} \text{kg}$								597
								598
		Urban		Rural		Motorway		
		b	c	b	c	B	c	599
Tyre	PM _{2.5}	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 ₁₀	8.2 ± 0.6	2.3 ± 0.4	6.4 ± 0.5	2.3 ± 0.41	5.5 ± 0.42	2.3 ± 0.4	
Brake	PM _{2.5}	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 ₁₀	11 ± 2.7	1.9 ± 0.2	4.5 ± 2.4	1.5 ± 0.3	1.0 ± 1.0	1.3 ± 0.4	
Urban / Rural / Motorway								602
		B		c				
Road	PM _{2.5}	2.8 ± 0.5		1.5 ± 0.1				603
	PM ₁₀	5.1 ± 0.9		1.5 ± 0.1				604
Resus.	PM _{2.5}	2.0 ± 0.8		1.1 ± 0.4				
	PM ₁₀	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} [$\mu\text{g}/\text{m}^3$]	At Source Emission $EF_{Tail.Pol}$ [$\text{mg PM}_{\text{coarse}} \text{km}^{-1}$]
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: $\text{mg PM}_{10} \text{m}^{-2}$].

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

Table 6: 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>
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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⁻¹]. **Tyre**

Wear

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

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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⁻¹ km⁻¹].

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

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621 **Table 8:** Exhaust emission factors EURO 6 for cars (mg·km⁻¹·veh⁻¹) (from Ricardo Energy &
622 Environment 2018). The NAEI currently uses the fraction of PM₁₀ emitted as PM_{2.5} of 1.0 for exhaust
623 emissions, taken from EMEP (2016), implying that all the PM exhaust emissions are in the PM_{2.5} size
624 range.

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

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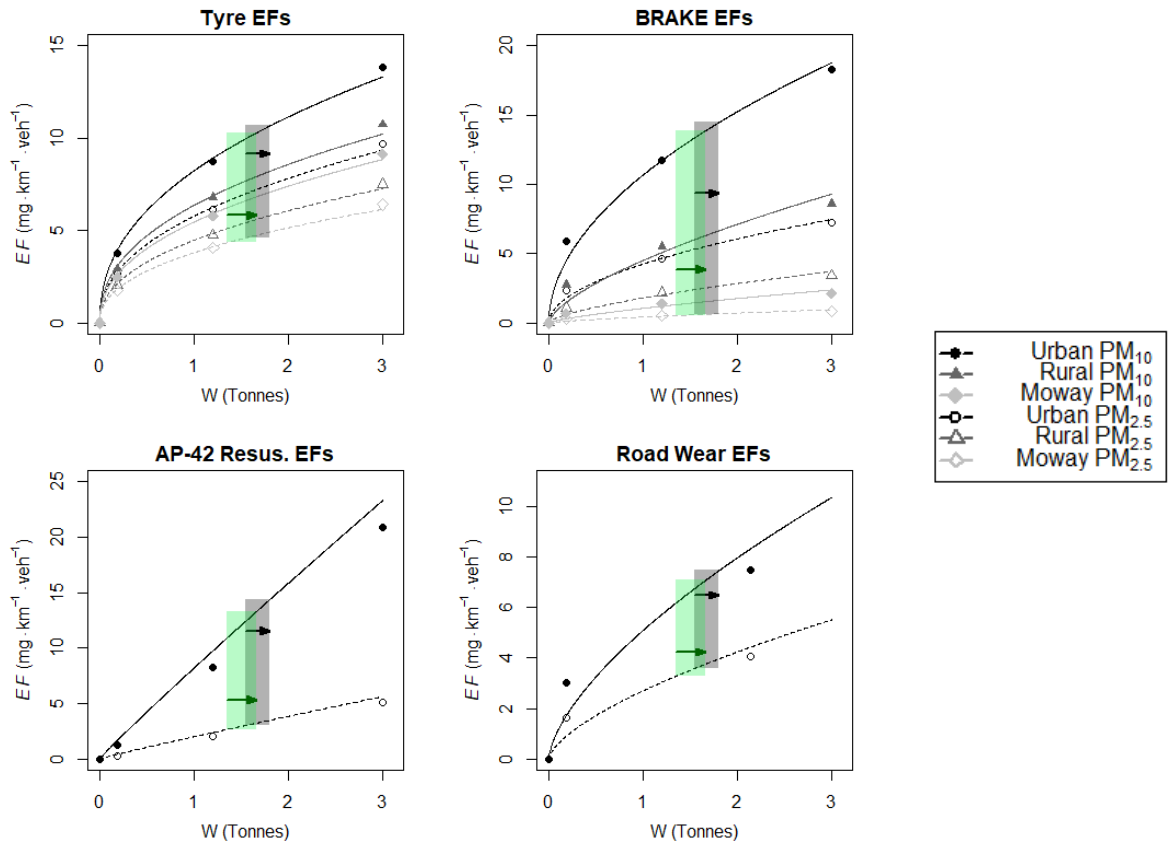
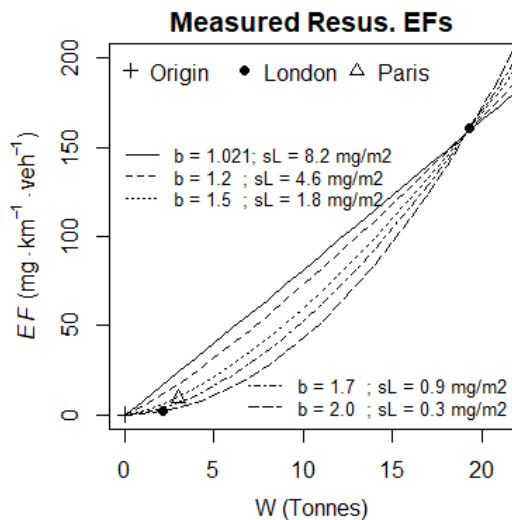


Figure 1: Regression of tyre, brake and road wear EF_{PM} emission factors against vehicle mass (Table 1 and 2). The shaded green and black rectangles highlight the increase $EF_{be} - EF_{ice}$ for comparisons with petrol and diesel fuelled engines. Nonlinear Least Squares fit of $EF = bW_{ref}^{\frac{1}{c}}$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

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Figure 2. Effect on the AP-42 curve by the setting of the values of b and sL using equation 2.

629 $EF^{resus} = 0.62(sL)^{0.912}(W)^b.$

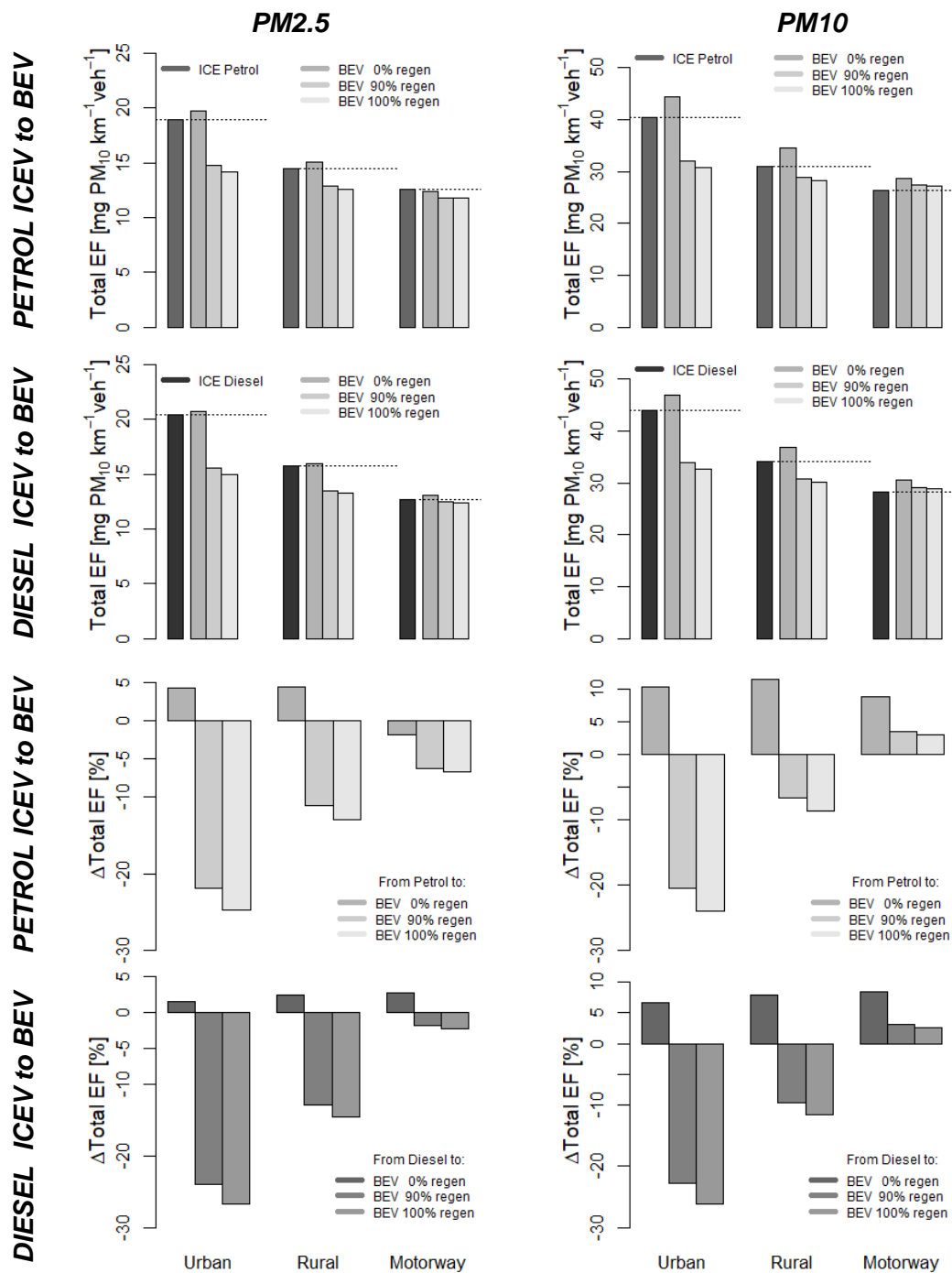


Figure 3: Absolute and percentage change in the total emission factors shown in *without* / *with* regenerative braking. The upper panel shows the absolute values of total emission factor estimated for petrol, diesel and battery electric vehicles, the latter with 0%, 90% and 100% regenerative braking 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.