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PM_{10} 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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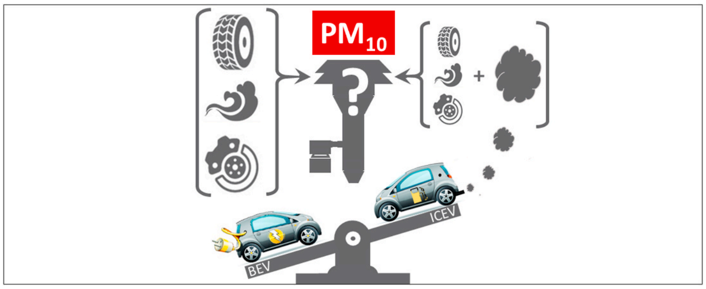
HIGHLIGHTS

- F020 Emission factors estimated for brake, tyre and road surface wear.
- F020 Emission factors estimated for road dust resuspension.
- F020 Vehicle weight dependence of emission factors modelled.
- F020 Vehicle weight increase of battery electric vehicles evaluated.
- F020 Emissions differences between electric and conventional vehicles calculated.

GRAPHICAL ABSTRACT



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ABSTRACT

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

1. Introduction

Road vehicles emit particulate matter from sources other than their exhaust. Such sources include brake wear, tyre wear, road surface wear and resuspension of road surface dusts (Thorpe and Harrison, 2008; Amato et al., 2014; Amato, 2018). Emissions inventory estimates indicate that non-exhaust emissions well exceed exhaust emissions by a large margin, both for PM_{10} and $PM_{2.5}$, in the current vehicle fleet

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(AQEG, 2019).

Many governments now have policies to steadily incentivise electrification of the vehicle fleet, and hence emissions from BEV are a matter of concern. For example, in Britain EVs are exempt from annual road taxes and there are subsidies available for electric and hybrid vehicles with carbon dioxide emissions below 50 g km^{-1} and range above 70 miles in electric mode. In America, there are subsidies for EVs of 10% of the purchase price (<$4000) and California implements a zero-emission policy that requires all car manufacturers to produce a certain percentage of zero-emission vehicles; otherwise, manufacturers will receive a huge penalty. Similar schemes have also been implemented in Norway, Netherlands, France and Germany, amongst many countries (Li et al., 2019). Timmers and Achten (2016, 2018) have suggested that as battery electric vehicles would typically be heavier than their internal combustion engine equivalent and, even allowing for far lower emissions from regenerative braking (i.e. cutting power to the motor so that it acts as a generator), the non-exhaust emissions from a BEV might exceed all particle emissions from an equivalent ICEV. This study seeks to evaluate available data concerning BEV in relation to non-exhaust emissions from ICEV and to make projections where firm data are not available. Total emissions from both ICEV and BEV passenger cars are evaluated to form a view as to whether electrification of cars will reduce PM emissions within the fleet. The analysis is limited to passenger cars, as those are currently on sale, while battery-powered heavy duty vehicles are still under development, and vehicle weight statistics are not yet available.

2. Methods

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

- Adopting a set of emission factors for PM_{10} and $PM_{2.5}$ for different vehicle types and road types which are widely used in national inventories.
- Associating a vehicle mass with each vehicle type.
- Determining separate relationships between emission factor and vehicle mass for each of brake wear, tyre wear and road surface abrasion.
- Estimating the typical masses of light duty BEVs and gasoline and diesel ICEVs from data on BEVs and ICEVs paired on the basis of engine power output.
- Using the typical vehicle masses to estimate emission factors for each vehicle type for brake, tyre and road surface wear.
- Estimating particle resuspension emission factors for BEVs, and gasoline and diesel ICEVs using the USEPA AP42 algorithm.
- Summing the emission factors for each vehicle type and road type, together with exhaust emission factors for the ICEVs to compare total emissions for typical light duty BEVs and gasoline and diesel ICEVs.

3. Results

3.1. Emission factors

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

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 of the EMEP Corinair Emissions 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).

Table 1

Emission factors $EF_{PM_{10}}$ and EF $EF_{PM_{2.5}}$ 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. [Units: mg PM veh^{-1} 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	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	14.0	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 and Coaches	*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	3.0
	Rural	2.0	2.9	1.1	2.8		
	Motorway	1.7	2.5	0.3	0.7		

Table 2
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.

Vehicle Category	Num. of axles	Num. of wheels	Estimated weight range (t)	Estimated ave. weight W (t)
Motorcycles	2	2	-	0.2
Cars	2	4	≤2.5	1.2
LGVs	2	6	≤3.5	3
Rigid HGVs	2–3	6–10	3.5–32	14
Artic HGVs	3–6	14–18	14–44	30
Buses	6–10	6–10	3.5–32	14

3.2. *Vehicle category mass W*

3.2.1. *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.

3.2.2. *Values relevant to the current vehicle fleet*

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

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

The change in vehicle weight △W due to electrification is mainly due to the increased weight of the battery pack used to drive the electric motors in the BEV. While this may not be fully mitigated by the substitution of the fossil fuel engine, transmission and sundries in the vehicle design, further weight saving can be made by the choice of weight saving parts and materials which otherwise would make △W much larger. To estimate a change in emission factor due to the overall increase in vehicle mass due to the electrification of cars, BEV-ICEV car pairs were chosen with the same make and model from an internet database (encyCARpedia) built up from various press materials and consumer brochures by Chapple and Chapple (2017). For each of the

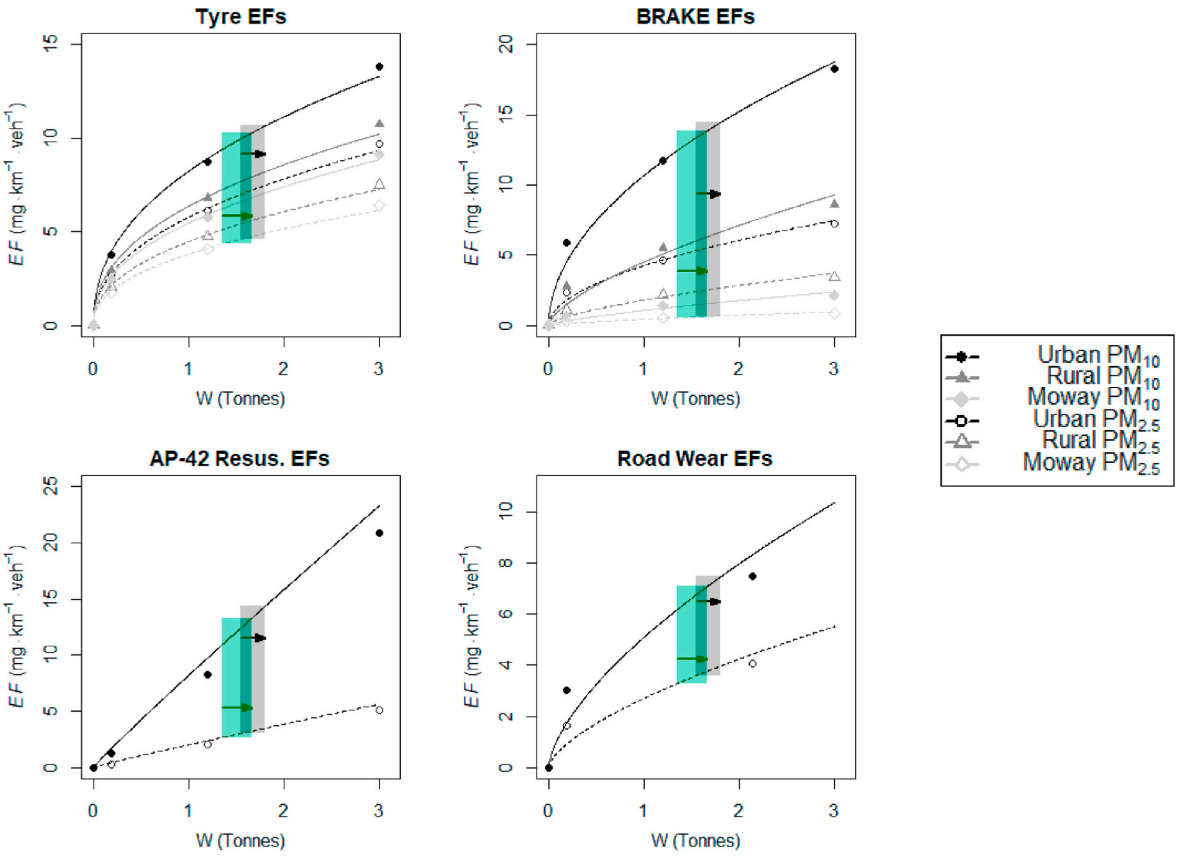

Fig. 1. Regression of tyre, brake and road wear EF_{PM} emission factors against vehicle mass (Tables 1 and 2). The shaded green and black rectangles highlight the increase EF_{be} - EF_{ice} for comparisons with petrol and diesel fuelled engines respectively. Nonlinear Least Squares fit of $EF = bW_{ref}^{\frac{1}{c}}$ shown by black solid and dashed lines: dashed lines signifying the 3σ limits. (see Table 3 for fitted values of *b* and *c* and Figs. SI 1 and 2 for the individual plots with error bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Regression coefficient used to fit the $EF_{PM_{2.5/10}}$ vs W curves in the plots of Fig. 1. $[EF = bW_{rel}^{\frac{1}{c}}$; b (mg veh^{-}1 km^{-1}); c (no unit); $W_{rel} = \frac{W}{1000} kg]$

		Urban	
		b	*c*
Tyre	PM_{10}	5.8 ± 0.5	2.3 ± 0.4
	$PM_{2.5}$	8.2 ± 0.6	2.3 ± 0.4
Brake	PM_{10}	4.2 ± 1.1	1.9 ± 0.2
	$PM_{2.5}$	11 ± 2.7	1.9 ± 0.2
		Rural	
		b	*c*
Tyre	PM_{10}	4.5 ± 0.3	2.3 ± 0.4
	$PM_{2.5}$	6.4 ± 0.5	2.3 ± 0.4
Brake	PM_{10}	1.8 ± 0.9	1.5 ± 0.3
	$PM_{2.5}$	4.5 ± 2.4	1.5 ± 0.3
		Motorway	
		b	*c*
Type	PM_{10}	3.8 ± 0.3	2.3 ± 0.4
	$PM_{2.5}$	5.5 ± 0.4	2.3 ± 0.4
Brake	PM_{10}	0.4 ± 0.4	1.3 ± 0.4
	$PM_{2.5}$	1.0 ± 1.0	1.3 ± 0.4
		Urban/Rural/Motorway	
		b	*c*
Road	PM_{10}	2.8 ± 0.5	1.5 ± 0.1
	$PM_{2.5}$	5.1 ± 0.9	1.5 ± 0.1
Resuspension	PM_{10}	2.0 ± 0.8	1.1 ± 0.4
	$PM_{2.5}$	8.2 ± 3.2	1.1 ± 0.4

chosen internal combustion engine and battery electric vehicle pairs, their engine specifications were matched as closely as possible according to power output (selected to be within 15% of each other) and their masses duly noted as W_{icev} and W_{bev} respectively. Furthermore, owing the large number of matches on enCARpedia, an increase in mass due to both the electrification of either petrol or diesel engines could be calculated. Table S1 shows 20 such matches for petrol and 9 for diesel giving an average mass difference of 318 ± 145 kg and 258 ± 125 kg respectively. As expected, there is less of an increase from the heavier diesel engine cars compared to petrol.

Data from the assessment of Faria et al. (2012), of electric vehicles gave a difference of kerb weight of 256 kg (an increase of 20%) for ICEV and BEV vehicles and likewise, Timmers and Achten (2016) reported a value of 280 ± 45 kg for their increase in weight from ICEV to BEV, (24% heavier).

The increased mass due to electrification of our whole vehicle sample is 300 ± 140 kg, corresponding to a 21% increase which is in line with the aforementioned literature values. Accounting for diesel and petrol engines, petrol engine vehicles have an average mass of 1349 kg which rises by 318 kg when compared to their electric equivalent ($^{\mathrm{petrol}}\mathrm{W}_{bev} = 1349 + 319$ kg). Likewise, diesel engine vehicles have an average mass of 1550 kg which rises by 257 kg when compared to their electric equivalent ($^{\mathrm{diesel}}\mathrm{W}_{bev} = 1550 + 257$ kg).

3.4. Main calculation

3.4.1. Regression of emission factors with vehicle mass

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

$$EF = b \cdot W_{ref}^{\frac{1}{c}} \tag{1}$$

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

For tyre wear and brake wear, there are emission factors for all of the six vehicle categories whereas for road wear the number of data points was less. For road abrasion, a distinction between the 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).

3.5. 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 μm diameter); *L*: Surface material loading, defined as mass of particles per unit area of the travel surface (g/m^2); *b*: an exponent to which *sL* is raised ($sL_{rel} = sL/1g.m^{-2}$); *k*: base emission factor (g/VKT); W_{rel}: vehicle mass ($W_{rel} = W/1000\, Kg$) and *p*: a dimensionless exponent – the particulate emission factor (g/VKT) has been parameterised by Eq. (2).

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

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 Eq. (2) with $k = 0.54$ 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 (Eq. (3)). A *k* value of 0.62 g km^{-1} is used for the PM_{10} fraction (scaled by a $PM_{2.5}/PM_{10}$ mass fraction ratio of 0.24 for $PM_{2.5}$), and the term (1-P/4N) accounts for the number of wet days P in a total of N measurement days.

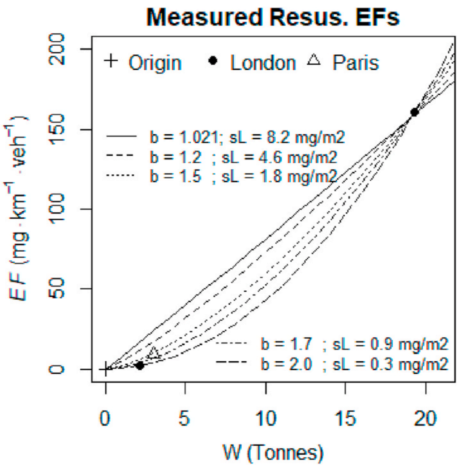

Fig. 2. Effect on the AP-42 curve by the setting of the values of *b* and *sL* using Eq. (2). $EF^{resus} = 0.62(sL)^{0.912} W_{rel}$.

Table 4

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

	Roadside Increment X_{pol} [µg/m^3]	At Source Emission $EF_{Tail.Pol}$ [mg PM$_{coarse}$ 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

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

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

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

To consider the applicability of the AP-42 model to European roads, measurements carried out in London and Paris were considered where PM$_{10}$ resuspension emission factors were calculated at roadside for LGV, HGV and for the fleet. To evaluate the response of PM$_{10}$ resuspension to vehicle mass, the LGV and HGV emission factors estimated by Thorpe et al. (2007) from measurements on Marylebone Road, London were allocated to aggregated LGV and HGV vehicle weights (Table 2) and the vehicle weight dependence of AP-42 fitted to these values using Eq. (2). An additional point was included from the Paris work of Amato et al. (2016), who derive a value of 9.2 mg km^{-1} for the mixed vehicle fleet. The three data points are plotted in Fig. 2 and used together with the origin as a fourth point to fit Eq. (2). This shows the plot of data for different values of the exponent, 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 Eq. (2), using a value of p = 0.91.

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

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

Estimation of the PM$_{10}$ Emission Factor for Battery Electric Cars

Using the regressions presented in Fig. 1, the increase in the emission factors are calculated due to the increase in car mass in converting from an internal combustion engine to a battery electric car $\Delta W = W_{bev} - W_{icev}$; these are shown in Table 6, and a comparison can be made with the work of 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 Fig. 1 and Table 7 giving the resultant calculated increase in EF due to the electrification.

The increases in PM$_{10}$ tyre, brake and road wear emission factors for urban, rural and motorway UK roads range from 9.5 to 22% for petrol vehicles and 6.8–11% 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$_{2.5}$ 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

Table 5

Dust loading reported for European paved roads[a]. [Units: mg PM$_{10}$ 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)

[a] 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 regressions shown in Figs. 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				*Urban*	*Rural*	*Motorway*	Timmers and Achten (2016)
ICEV	EF^{brake}_{icev}	Petrol	PM_{10}	6.6 ± 0.7	5.1 ± 0.6	4.3 ± 0.5	2.9
			$PM_{2.5}$	9.4 ± 1.0	7.2 ± 0.8	6.2 ± 0.7	6.1
		Diesel	PM_{10}	7.0 ± 0.7	5.4 ± 0.5	4.6 ± 0.5	2.9
			$PM_{2.5}$	10.0 ± 1.0	7.7 ± 0.8	6.6 ± 0.7	6.1
BEV	EF^{brake}_{bev}	Petrol-eq	PM_{10}	7.2 ± 0.8	5.6 ± 0.6	4.8 ± 0.5	3.7
			$PM_{2.5}$	10.3 ± 1.2	7.9 ± 0.9	6.8 ± 0.8	7.2
		Diesel-eq	PM_{10}	7.5 ± 0.8	5.8 ± 0.6	5.0 ± 0.5	3.7
			$PM_{2.5}$	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^{brake}_{icev}	Petrol	PM_{10}	5.0 ± 0.6	2.2 ± 0.4	0.5 ± 0.1	2.2
			$PM_{2.5}$	12.4 ± 1.6	5.5 ± 0.9	1.3 ± 0.2	9.3
		Diesel	PM_{10}	5.3 ± 0.6	2.4 ± 0.4	0.6 ± 0.1	2.2
			$PM_{2.5}$	13.4 ± 1.6	6.0 ± 0.9	1.5 ± 0.2	9.3
BEV	EF^{brake}_{bev}	Petrol-eq	PM_{10}	5.5 ± 0.7	2.5 ± 0.4	0.6 ± 0.1	0
			$PM_{2.5}$	13.9 ± 1.9	6.3 ± 1.1	1.5 ± 0.3	0
		Diesel-eq	PM_{10}	5.8 ± 0.7	2.6 ± 0.4	0.6 ± 0.1	0
			$PM_{2.5}$	14.5 ± 1.8	6.6 ± 1.1	1.6 ± 0.3	0
Resuspension				***Urban***	***Rural***	***Motorway***	Timmers and Achten (2016)
ICEV	EF^{brake}_{icev}	Petrol	PM_{10}		2.7 ± 0.6		3.1
			$PM_{2.5}$		11.0 ± 1.6		7.5
		Diesel	PM_{10}		3.0 ± 0.6		3.1
			$PM_{2.5}$		12.5 ± 1.6		7.5
BEV	EF^{brake}_{bev}	Petrol-eq	PM_{10}		3.2 ± 0.7		3.8
			$PM_{2.5}$		13.4 ± 1.9		8.9
		Diesel-eq	PM_{10}		3.5 ± 0.7		3.8
			$PM_{2.5}$		14.4 ± 1.8		8.9
Road Wear				***Urban***	***Rural***	***Motorway***	Timmers and Achten (2016)
ICEV	EF^{brake}_{icev}	Petrol	PM_{10}		3.3 ± 0.5		12.0
			$PM_{2.5}$		6.1 ± 1.0		40.0
		Diesel	PM_{10}		3.6 ± 0.5		12.0
			$PM_{2.5}$		6.8 ± 1.0		40.0
BEV	EF^{brake}_{bev}	Petrol-eq	PM_{10}		3.8 ± 0.6		14.9
			$PM_{2.5}$		7.0 ± 1.2		49.6
		Diesel-eq	PM_{10}		4.0 ± 0.6		14.9
			$PM_{2.5}$		7.4 ± 1.2		49.6

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^{-2}, the resuspension model suggests that the increase in weight of a passenger car $W_{bev} - W_{icev}$ will increase the PM_{10} resuspension emission factor by 16% and 22% (12.5–14.4 mg/VKT for diesel and 11.0–13.4 mg/VKT for petrol; for $\triangle W = 318$ and 257 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_{10} 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.

3.7. *Tail pipe emissions*

In order to make a full assessment of the change in PM_{10} and $PM_{2.5}$ 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 and 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).

3.8. *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 Eqs. (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. $EF^{brake}_{bev} = 0$) 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 $0\% \times EF^{fric}_{bev}$ and $100\% \times EF^{fric}_{bev}$. 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 ($frac_{brake} = 10\%$).

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

Table 7
Increase (and percentage increase) in Emission Factor due to the increase of the weight of the average UK car of 318 and 257 kg for petrol and diesel cars respectively (and 300 kg across petrol and diesel) (Timmers and Achten, 2016) [eq – equivalent, units: mg PM veh^{-1} km^{-1}].

			Urban	Rural	Motorway	Timmers and Achten (2016)
Tyre	*Petrol to Petrol-eq*	PM_{10}	0.6(9.7%)	0.5(9.8%)	0.4(9.7%)	0.8(30.7%)
		$PM_{2.5}$	0.9(9.7%)	0.7(9.5%)	0.6(9.8%)	1.1(18.0%)
	Diesel to Diesel-eq	PM_{10}	0.7(6.9%)	0.4(7.0%)	0.3(7.0%)	0.8(30.7%)
		$PM_{2.5}$	0.7(6.9%)	0.5(6.8%)	0.5(7.0%)	1.1(18.0%)
Brake	*Petrol to Petrol-eq*	PM_{10}	0.6(11.5%)	0.3(15.0%)	0.1(17.1%)	–
		$PM_{2.5}$	1.4(11.5%)	0.8(15.0%)	0.2(17.1%)	
	Diesel to Diesel-eq	PM_{10}	0.4(8.2%)	0.3(10.6%)	0.1(12.1%)	
		$PM_{2.5}$	1.1(8.2%)	0.6(10.6%)	0.2(12.1%)	
			Urban/Rural/Motorway			Timmers and Achten (2016)
Road Wear	Petrol to Petrol-eq	PM_{10}		0.5(14.8%)		0.7(22.5%)
		$PM_{2.5}$		0.9(14.8%)		1.4(18.7%)
	Diesel to Diesel-eq	PM_{10}		0.4(10.5%)		0.7(22.5%)
		$PM_{2.5}$		0.7(10.4%)		1.4(18.7%)
Resuspension	Petrol to Petrol-eq	PM_{10}		0.6(22.0%)		2.9(24.1%)
		$PM_{2.5}$		2.4(22.0%)		9.6(24.0%)
	Petrol to Diesel-eq	PM_{10}		0.5(15.6%)		2.9(24.1%)
		$PM_{2.5}$		1.9(15.5%)		9.6(24.0%)

Table 8
Exhaust emission factors EURO 6 for cars (mg km^{-1}·veh^{-1}) (from Ricardo Energy and Environment, 2018). The NAEI currently uses the fraction of PM_{10} emitted as $PM_{2.5}$ of 1.0 for exhaust emissions, taken from EMEP (2016), implying that all the PM exhaust emissions are in the $PM_{2.5}$ size range.

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

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

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

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

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

- The uncertainties associated with each of these total emission factors are a large fraction of the calculated values themselves. This uncertainty is by virtue of the variability of the values in the literature used in this study. More measurements are required together with studies to understand how to best parameterise each emission component.
- The total emission factors for all road types from the BEVs are ~7–12% greater than their euro 6 diesel and petrol equivalent (Fig. 3) for PM_{10} and, ignoring the petrol motorway, ~1–5% greater for $PM_{2.5}$. This is a marked difference from the case for pre-Euro 5 passenger cars where the particulate emissions from diesels are significantly higher than those for petrol engine cars.
- There is a significant increase from the total PM_{10} emissions of an ICEV car to the heavier BEV car supporting 100% friction brakes. This suggests that in order to bring total BEV cars emissions in line with the emissions of a petrol equivalent ICE, regenerative braking needs to reduce brake dust emissions to 70% (i.e. 30% regen.) for urban roads and 43% (i.e. 57% regen.) for rural roads. In comparison, the critical values are higher for diesel equivalent BEV emissions. Regenerative braking needs to reduce brake dust emissions of diesel equivalent BEV to 80% (i.e. 20% regen.) for urban roads and 60% (i.e. 40% regen) for rural roads.
- The total PM_{10} emission factor on rural roads is less than that of urban. Likewise, the total PM_{10} emission on motorways is again lower than urban and rural roads and consequently, no amount of regeneration will bring the total PM_{10} emissions of BEV cars in line with their ICEV equivalent cars, i.e. even with 100% regenerative braking the total emissions are still higher for BEV cars.
- For the total $PM_{2.5}$, the increase in emissions of the heavier BEV cars supporting 100% friction brakes is marginal (Fig. 3). In order to decrease the total $PM_{2.5}$ 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 $PM_{10.}$ 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_{10}, 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_{10} emissions might be expected ranges from 43% to 70% for petrol and 60–80% for diesel equivalent BEV. For $PM_{2.5}$ we might expect $frac_{brake}$ to be in the range 74%–85% and 86%–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_{10} by at least 20–57% and $PM_{2.5}$ by at least 5–26%. On motorways there remains a positive increase in the total EF of PM_{10} relative to both petrol and diesels even using 100% regen. Removal of friction braking (e.g. through 100% regenerative

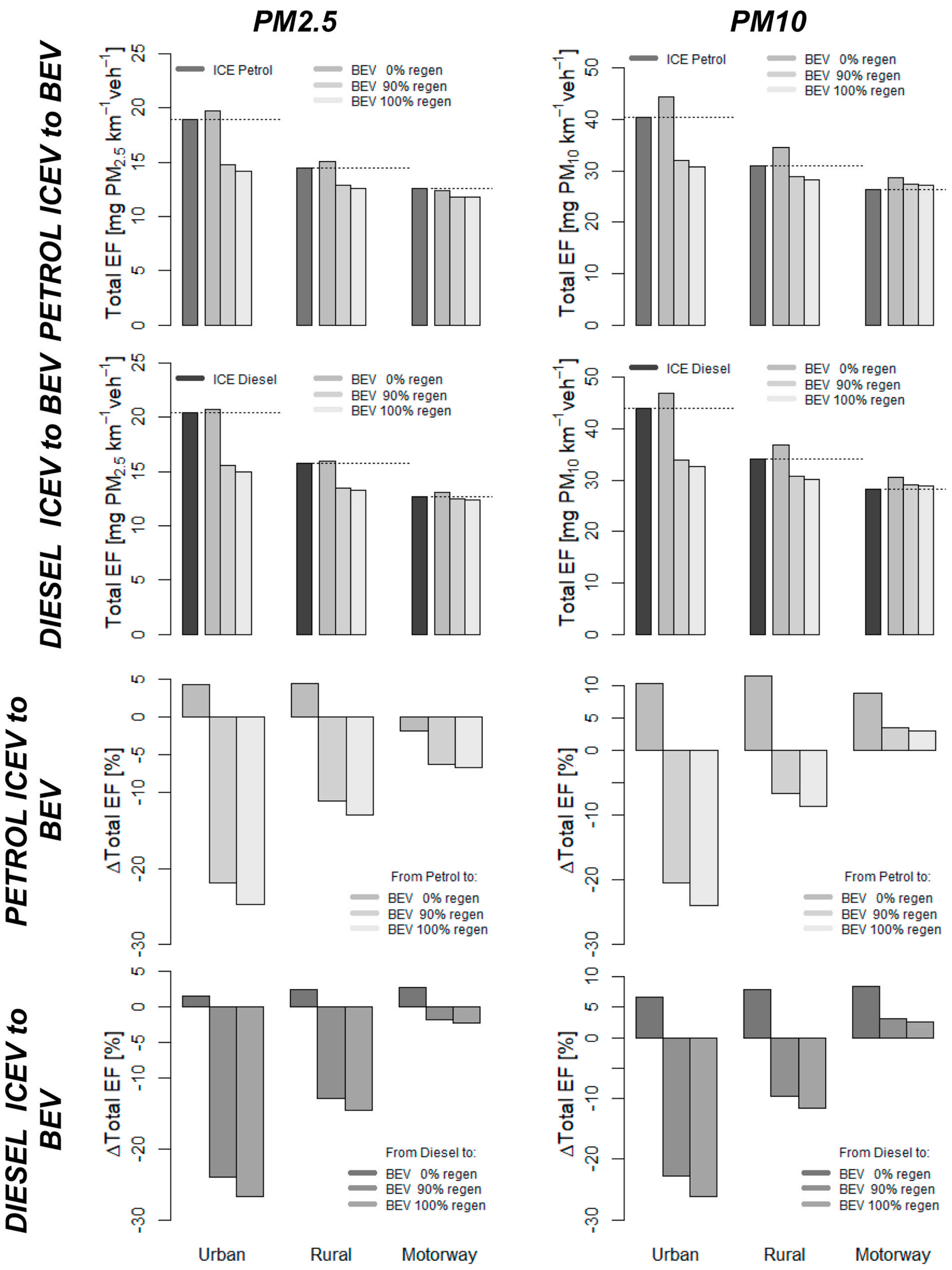

Fig. 3. Absolute and percentage change in the total emission factors shown in *without/with* regenerative braking. The upper panel shows the absolute values of total emission factor estimated for petrol, diesel and battery electric vehicles, the latter with 0%, 90% and 100% regenerative braking on different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

braking) can provide up to 25–27% reduction of PM$_{10}$ emissions in the urban environment (24–26% for PM$_{2.5}$). With a realistic regenerative braking (using 10% friction brakes) we might expect up to 22–24% (21–23% for PM$_{2.5}$) 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, $^{p}W_{bev}$ (and 93% for our diesel-equivalent BEV, $^{d}W_{bev}$) 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 mg km^{-1}. This compares well with an average emission factor for battery electric vehicles of 22.3 mg km^{-1} introduced to COPERT in 2020.

4. 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.*

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

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

Data availability

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

CRediT authorship contribution statement

David C.S. Beddows: Methodology, Software, Formal analysis, Writing - original draft, Visualization. **Roy M. Harrison:** Conceptualization, Writing - review & editing, Methodology, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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