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Meta-Analysis as Early Evidence on the Particulate Emissions Impact of EURO VI on Battery Electric Bus Fleet Transitions

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Abstract: The current generation of Zero Emission Vehicle (ZEV) policies are designed to accelerate the transition away from conventional internal combustion engine (ICE) petrol and diesel vehicle fleets. However, the current focus on zero exhaust emissions and the lack of more detailed guidance regarding Non-Exhaust Emissions (NEEs) may mean that some of the trade-offs in transitioning to, e.g., Battery Electric Vehicle (BEV) fleets may be missed by many in the commercial sector. Here, as part of early work on the scoping of the First Bus EURO VI Diesel Vehicle (E6DV) to BEV fleet upgrades, we estimate E6DV total particulate emissions to be ca. 62–85 and 164–213 mg.veh^{-1}.km^{-1} for $PM_{2.5}$ and PM_{10}, respectively, and that the majority, typically 93–97%, are NEEs. We also discuss the complex interaction between E6DV/BEV properties and estimate potential changes resulting from the transition to BEVs as ranging from a decrease of ca. 2–12% to an increase of ca. 12–50% depending on a combination of weight difference, regenerative brake performance and journey type. Finally, we propose metrics that would allow fleet operators more insight into a wider range of emission outcomes at the scoping stage of a fleet upgrade.

Keywords: heavy-duty vehicles; electric vehicles; bus emissions; non-exhaust emissions; air quality; particulates

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1. Introduction

Alongside numerous local and regional authorities, automotive manufacturers, fleet owners and operators and investors, the UK government was one of 38 national governments to sign the Glasgow Declaration committing themselves to rapid acceleration of the transition to 'Zero Emission Vehicles' (ZEVs) [1]. A combination of focused regulatory action, associated local and national air quality management activities and the step-wise introduction of increasingly aggressive emission abatement technologies (e.g., the EURO, TIER and CHINA programmes in Europe, the US and China, respectively) have resulted in a significant decrease in vehicle tailpipe emissions in recent decades (see e.g., [2–4]). Seen in this historical context, the transition to ZEVs policy and the associated increase in electric vehicle (and other alternative fuel) fleet numbers, is an obvious step in on-going efforts to deliver cleaner vehicle fleets [5,6]. Although less pronounced than exhaust emission reductions, previous iterations of abatement technology have also generated measurable air quality benefits [7,8], and it is widely anticipated that both hybrid electric and electric vehicles will provide further air quality improvements for tailpipe emissions, such as oxides of nitrogen (NO, NO_2 and NOx), when deployed on-scale in existing urban pollution hotspots [6].

It is, however, just as important to recognise this as a step in an ongoing process rather than an end-goal and to acknowledge the incoming electric vehicles as cleaner rather than clean vehicles.

A growing body of evidence indicates that while vehicle exhaust emissions have been reduced in recent years, Non-Exhaust Emissions (NEEs) have increased over similar time scales. Both source apportionment and chemical tracer studies show that NEEs are already significant sources of transport-related particulates and that levels of NEEs now very likely exceed those of tailpipe emissions in many countries [9–11]. This trend is attributed to a combination of factors, including increasing vehicle numbers and weights and changing brake and tyre technologies (see e.g., [12,13]). Given that the first generation electric vehicles are already in service and significantly heavier than equivalent petrol and diesel vehicles in contemporary fleets, predictions suggest that this trend will continue [14] unless lighter weight battery technologies or mitigations can be deployed sooner rather than later.

Despite significant efforts to characterise and quantify NEEs, they are neither as well understood nor as effectively managed as exhaust emissions [9,10,12]. Here, the vehicle emissions regulators face multiple challenges: NEEs are more complex and more diffuse than exhaust emissions; they are less easily measured; and, given the rapid mixing of brake, tyre and road dust contributions and their subsequent resuspension, they are not always confidently attributed to specific sources. In addition, exposure to airborne particulate matter (PM) is widely recognised as a source of increased morbidity and mortality associated with cardiovascular respiratory diseases, diabetes and lung cancer (see e.g., [12,15]). Whilst there remains uncertainty as to the differential health impacts of PM arising from exhaust compared to non-exhaust sources, consistent epidemiological evidence indicates health impacts of low exposure levels [16] and that full mortality benefits of concentration reductions are unlikely to be realised immediately [17]. So, regardless of the challenges, there is an urgent need to match the current commitment to achieve zero emissions at the tailpipe with a complementary programme of NEE mitigation activities if we intend to deliver not just on the current Net Zero policy agenda but also more completely on the potential public health, air quality and climate benefits of the transition to cleaner vehicle fleets [18].

As part of that work programme, we report here on a meta-analysis study of bus fleet NEEs, undertaken as early scoping work to identify potential sources of excess NEEs associated with a fleet transition from conventional EURO VI Diesel Vehicle (E6DV) to equivalent Battery Electric Vehicle (BEV) bus services and (ideally) identify options to mitigate any anticipated negative impacts. This work, led by First Bus and funded by the TRANSITION Clean Air Network as part of the UK's Natural Environment Research Council's Clean Air Programme [19], has already started to gather activity data from the on-road bus fleet. Here, we focus on the potential divergence between regulatory metrics, conventional emission factors and inventory model predictions and what the early evidence indicates will actually happen as we migrate our vehicle fleets to what we need to be significantly cleaner technologies.

For many commercial fleet operators, such scoping work is an important element of the case they build when upgrading their rolling stock. However, formal guidance on impact assessment can often be very crude. For example, the UK National Atmospheric Emissions Inventory (NAEI) provides aggregate NEE particulate emission factors (EFs) for PM_{10}, the particulate mass fraction $\leq$10 µm, for brake emissions of 53.6, 27.1 and 8.4 mg.km^{-1} and for tyre emissions of 21.2, 17.4 and 14.0 mg.km^{-1} for all buses, regardless of weight, on urban, rural and motorway routes, respectively [20]. By comparison, bus exhaust PM EFs are reported by EURO classification (Pre-EURO to EURO VI) and sub-categorised according to both weight (<15, 15–18 and >18 tonnes) and bus type (urban, articulated and coach). Applying these EFs to any fleet upgrade would obviously be insensitive to, for example, the influence of vehicle weight on NEEs and arguably generate a misleadingly positive impression of the PM impact of the E6DV-to-BEV transition. Consequently, approaches and methods described here are proposed as an option for fleet operators looking to undertake more robust early impact assessments as part of similar exercises.

2. Studied Buses and Methods

2.1. Studied Buses

The studied subset of the First Bus fleet comprises 10 double-decker buses operated from First's York Bus Depot on routes in the surrounding city and region. Five were conventional internal combustion engine (ICE) diesel EURO VI buses (Volvo B9TLs), and five were lithium-ion BEV buses (Optare Metrodecker M1110EVs) purchased as ZEV equivalents (Table 1). Estimated weights were calculated as weight of bus, driver (75 kg) and 50 passengers (65 kg each) following Schoemaker [21] and indicated an 11% (bus plus driver and 50 passengers) to 15% (bus plus driver) operating weight increase for BEVs compared to E6DVs. This is smaller than the ca. 25% differences commonly cited for smaller vehicles [22] and if typical of the incoming fleets, indicates a ca. 2000 kg increase in urban bus weights.

Table 1. First York Bus Fleet Upgrade.

Make	Model	Estimated Weight [1]	Fuel or Battery	Engine	Power Output	Emission Class	Emission Control [2]	Exhaust Filter [3]	Regenerative Braking
Volvo	B9TL	15,925 kg	ULS Diesel	ICE Diesel	260PS (194 kW)	EURO VI [4]	Adblue SCRT	EATS	no
Volvo	B9TL	15,925 kg	ULS Diesel	ICE Diesel	260PS (194 kW)	EURO VI [4]	Adblue SCRT	EATS	no
Volvo	B9TL	15,925 kg	ULS Diesel	ICE Diesel	260PS (194 kW)	EURO VI [4]	Adblue SCRT	EATS	no
Volvo	B9TL	15,925 kg	ULS Diesel	ICE Diesel	260PS (194 kW)	EURO VI [4]	Adblue SCRT	EATS	no
Volvo	B9TL	15,925 kg	ULS Diesel	ICE Diesel	260PS (194 kW)	EURO VI [4]	Adblue SCRT	EATS	no
Optare	Metrodecker M1110EV	17,425 kg	Lithium Ion Battery	Electric Motor	300 kW	ZEV	-	-	yes
Optare	Metrodecker M1110EV	17,725 kg	Lithium Ion Battery	Electric Motor	300 kW	ZEV	-	-	yes
Optare	Metrodecker M1110EV	17,725 kg	Lithium Ion Battery	Electric Motor	300 kW	ZEV	-	-	yes
Optare	Metrodecker M1110EV	17,725 kg	Lithium Ion Battery	Electric Motor	300 kW	ZEV	-	-	yes
Optare	Metrodecker M1110EV	17,725 kg	Lithium Ion Battery	Electric Motor	300 kW	ZEV	-	-	yes

[1] Estimated operational weight, vehicle + driver (assumed 75 kg) + 50 passengers (assumed 65 kg each); [2] SCRT—Selective Catalytic Reduction with Continuous Regeneration Trap; [3] EATS—Exhaust After-Treatment System; [4] strictly EURO V with EATS retrofit, so classified as EURO VI equivalent.

2.2. Methods

As part of the first round of data gathering and literature review for the meta-analysis, Beddows and Harrison [14] methods previously applied to BEV, gasoline and diesel passenger cars were selected as the starting point for the estimation of bus emissions. We also report exhaust PM EFs as a point-of-reference for discussion of trade-offs between conventional ICE and BEV vehicles and discuss proposed modifications to Beddows and Harrison [14] for use in E6DV/BEV bus PM emissions scoping exercises to extend weight-based corrections to weight- and route-based corrections.

Summarising briefly, the main methods were:

- Select PM_{10} and $PM_{2.5}$ (the particulate mass fraction ≤2.5 µm) emission factors for different vehicle and route types from national inventories. So, for UK buses, EFs as reported in the UK NAEI [20], which are in turn based on European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) emission inventory guidebook recommendations [23].
- Use weight-based emission factor calculation methods for brake, tyre and road dust from Beddows and Harrison [14] and compare with public evidence on these.

- Estimate particle resuspension *EFs* using the USEPA AP42 method [24].
- Compare work completed during regulatory test cycles and test cycle urban, rural and motorway phases and during more typical journeys to estimate real-world emissions for these vehicles.
- Sum *EFs* were then calculated for each vehicle and road type to provide a comparison of estimated NEEs for BEV and diesel ICE buses.

Our results and a critique of our findings based on the external evidence identified during the literature review, are presented in Sections 3 and 4 of this paper.

3. Results

The overall EF, $EF^{100\%}$, is estimated in the conventional form:

$$EF^{100\%} = EF^{exhaust} + EF^{brake} + EF^{tyre} + EF^{road} + EF^{resusp} \quad (1)$$

where $EF^{exhaust}$, EF^{brake}, EF^{tyre}, EF^{road} and EF^{resusp} are the EFs for exhaust, brake, tyre, road and resuspended particulate, respectively, all (and $EF_{100\%}$) in units of mg.veh^{-1}.km^{-1}.

3.1. Exhaust Particulate Emission Factors, $EF^{exhaust}$

Exhaust PM EFs were determined for E6DV buses on urban, rural and motorway routes using UK NAEI methods, i.e., using the COPERT 5 (https://www.emisia.com/utilities/copert/ (accessed on 20 November 2022) PM emissions speed profiles via VEIN [25] and typical bus speeds (as reported in Brown et al. [26]; 32, 62 and 82 km.h^{-1}, respectively), assuming 0% road slope, to give $EF^{exhaust}_{urban}$, $EF^{exhaust}_{rural}$ and $EF^{exhaust}_{motorway}$ of 4.7, 3.2 and 3.1 mg.veh^{-1}.km^{-1}, respectively. PM exhaust emissions are predominately much smaller than 2.5 µm, especially for modern vehicles such as the E6DV buses considered here, so we assume, in line with NAEI practices:

$$EF(PM)^{exhaust} = EF(PM_{2.5})^{exhaust} = EF(PM_{10})^{exhaust} \quad (2)$$

Although there is some evidence that exhaust PM emissions may be higher and/or varying in size distribution under different operating conditions, e.g., during cold start [27], exhaust filter regeneration [28] or when emissions control systems have been tampered with [29], on-road surveillance indicates that these PM EFs are similar to those observed for real-world bus fleets (see, e.g., [30,31], Euro VI Bus $EF(PM)$ ca. 5 mg.veh^{-1}.km^{-1}).

Obviously, all BEV bus exhaust emissions were set to zero.

3.2. Brake Particulate Emission Factors, EF^{brake}

Brake dust is typically produced as the result of mechanical action during breaking events, and a range of factors have been associated with instantaneous emission rates, including composition brake pads, design of braking mechanism, vehicle mass, brake temperature and driving conditions (see, e.g., [12,32,33]). NAEI methods provide initial estimates of EF^{brake} of 53.6, 27.1 and 8.4 mg.km^{-1} for PM_{10} on urban, rural and motorway routes, respectively, and 21.4, 10.8 and 3.4 mg.km^{-1} for $PM_{2.5}$ on urban, rural and motorway routes, respectively [34]. In a conventional assessment, the same factors would be applied to all E6DV and BEV buses regardless of age, weight or brake technology used by the bus or the traffic conditions, e.g., free-flow or congested.

Beddows and Harrison [14] propose an alternative EF estimator based on vehicle weight in the form:

$$EF^j_i = b^j_i\left(\frac{W}{1000}\right)^{\frac{1}{c^j_i}} \quad (3)$$

where i and j are the emission type descriptors, e.g., urban and brake, respectively; W is the weight of the vehicle; and b and c are constants derived in [14] and summarised in Table 2.

Table 2. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Brake Emission Factors, EF^{brake} calculated using Equation (3), weights from Table 1 and b and c brake constants from [14].

Contribution	b	c	EF^{brake} mg.veh^{-1}.km^{-1}
E6DV			
Urban $PM_{2.5}$	4.2 ± 1.1	1.9 ± 0.2	18 (12–27)
Rural $PM_{2.5}$	1.8 ± 0.9	1.5 ± 0.3	11 (4.2–27)
Motorway $PM_{2.5}$	0.4 ± 0.4	1.3 ± 0.4	3.4 (0–17)
Urban PM_{10}	11 ± 2.7	1.9 ± 0.2	47 (31–70)
Rural PM_{10}	4.5 ± 2.4	1.5 ± 0.3	28 (9.8–69)
Motorway PM_{10}	1.0 ± 1.0	1.3 ± 0.4	8.4 (0–43)
BEV			
Urban $PM_{2.5}$	4.2 ± 1.1	1.9 ± 0.2	19 (12–29)
Rural $PM_{2.5}$	1.8 ± 0.9	1.5 ± 0.3	12 (4.4–30)
Motorway $PM_{2.5}$	0.4 ± 0.4	1.3 ± 0.4	3.7 (0–20)
Urban PM_{10}	11 ± 2.7	1.9 ± 0.2	50 (33–74)
Rural PM_{10}	4.5 ± 2.4	1.5 ± 0.3	31 (10–76)
Motorway PM_{10}	1.0 ± 1.0	1.3 ± 0.4	9.1 (0–49)

$PM_{2.5}^{brake}/PM_{10}^{brake}$ ratios for all routes and vehicle types are ca. 0.4, consistent with those estimated for brake emissions in UK NAEI guidance [26], and EF^{brake} values are in the approximate range 10–50 mg.veh^{-1}.km^{-1}, with highest and lowest emissions estimated for urban and motorway routes, respectively.

As would be expected based on the use of this weight-based model, EF^{brake} values are higher for (heavier) BEVs in comparison to E6DVs (here, ca. 7%). Although there is currently little direct surveillance data on the brake dust levels associated with BEVs, these and E6DVs estimates are both broadly consistent with those reported in the literature for heavy duty vehicles (cf. 20–80 mg.veh^{-1}.km^{-1} for HDV $EF(PM_{10})^{brake}$ in [33] and references therein). Brake PM emissions are associated with elevated airborne metal concentrations (most notably of barium, copper, iron, manganese, titanium and zinc) [12], and this has been linked with adverse health affects which some claim may be comparable in severity to diesel exhaust particle exposure.

The BEVs studied here have regenerative braking systems. These use engine braking rather than convectional frictional braking as their main slowing/stopping system and can re-coop expended electric energy.

Beddows and Harrison [14], as part of their study, assigned a 90% EF^{brake} saving for regenerative brakes on smaller vehicles. However, here it is important to note that regenerative braking cannot be used to completely stop a vehicle, that conventional friction brakes are still employed as part of regenerative brakes and that the proportion of conventional (versus regenerative) braking is expected to be significantly larger for bigger (higher-inertia) vehicles such as trucks and buses fitted with regenerative brakes (see, e.g., [35]). We, therefore, adopt a more conservative approach for BEV buses and attribute a provisional 25 to 75% range for EF^{brake} savings associated with the use of regenerative brakes (Equation (4)):

$$EF^{regen.brake.low} = EF^{brake} \times (1 - 0.25); EF^{regen.brake.high} = EF^{brake} \times (1 - 0.75) \quad (4)$$

As even the lower estimate offsets the weight-related increases in EF^{brake}, this is likely to be a beneficial addition, assuming no impact on other aspects of performance, e.g., safety, reliability or running costs.

3.3. Tyre Particulate Emission Factors, EF^{tyre}

Tyre dust is produced as a result of tyre wear during general operation, and rates of wear are commonly associated with both tyre and road composition and condition, the use of grip-enhancements such as studded tyres or tyre chains and driving conditions. There is some debate regarding the proportions of worn material that enter the atmosphere, although estimates are generally low, e.g., ca. 1% [12]. NAEI guidance provides initial estimates of EF^{tyre} of 21.2, 17.1 and 14.0 mg.km^{-1} for PM_{10} on urban, rural and motorway routes, respectively, and 14.9, 12.0 and 9.8 mg.km^{-1} for $PM_{2.5}$ on urban, rural and motorway routes, respectively [34]. As with brake emissions assessment, the same factors would be applied to all E6DV and BEV buses regardless of age, weight or brake technology used by the bus or the traffic conditions, e.g., free-flow or congested.

Applying the Beddows and Harrison [14] method, Equation (3), weights from Table 1 and tyre constants from [14], weight-based tyre PM emissions are estimated as reported in Table 3.

Table 3. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Tyre Emission Factors, EF^{tyre}, calculated using Equation (3), weights from Table 1 and b and c tyre constants from [14].

Contribution	b	c	EF^{tyre} mg.veh^{-1}.km^{-1}
E6DV			
Urban $PM_{2.5}$	5.8 ± 0.5	2.3 ± 0.4	19 (15–27)
Rural $PM_{2.5}$	4.5 ± 0.3	2.3 ± 0.4	15 (12–21)
Motorway $PM_{2.5}$	3.8 ± 0.3	2.3 ± 0.4	13 (9.8–18)
Urban PM_{10}	8.2 ± 0.6	2.3 ± 0.4	27 (21–38)
Rural PM_{10}	6.4 ± 0.5	2.3 ± 0.4	21 (16–30)
Motorway PM_{10}	5.5 ± 0.4	2.3 ± 0.4	18 (14–25)
BEV			
Urban $PM_{2.5}$	5.8 ± 0.5	2.3 ± 0.4	20 (15–29)
Rural $PM_{2.5}$	4.5 ± 0.3	2.3 ± 0.4	16 (12–22)
Motorway $PM_{2.5}$	3.8 ± 0.3	2.3 ± 0.4	13 (10–19)
Urban PM_{10}	8.2 ± 0.6	2.3 ± 0.4	29 (22–40)
Rural PM_{10}	6.4 ± 0.5	2.3 ± 0.4	22 (17–31)
Motorway PM_{10}	5.5 ± 0.4	2.3 ± 0.4	19 (15–27)

$PM_{2.5}^{tyre}/PM_{10}^{tyre}$ ratios for all routes and vehicle types are ca. 0.7, consistent with those estimated for tyre emissions in UK NAEI guidance [26]. Again, as would expect based on the use of this weight-based model, EF^{tyre} values are higher for (heavier) BEVs in comparison to E6DVs (here, ca. 4%), and EF^{tyre} values tend to be more similar, 13–29 mg.veh^{-1}.km^{-1} in comparison to brake emissions, but the highest emissions are also predicted for buses on urban routes. As with BEV brake emissions, there is currently little direct surveillance data to confirm these predictions, and what little evidence there is from conventional toxicity testing suggests that airborne tyre emissions may be relatively benign in comparison to PM for many other sources [12]. However, some studies have identified tyre wear as a major source of environmental micro-plastics [36], and others have linked specific tyre additives and their breakdown products to higher mortality rates in fish [37], highlighting the need for more work on the composition, source apportionment and the long-term fate of NEEs once emitted.

3.4. Road Particulate Emission Factors, EF^{road}

Road dust is produced as the result of road surface wear and tear. Both vehicle and environmental action contribute to emission rates, and rates can be more pronounced in areas where studded tyres and/or tyre chains are commonly used. NAEI guidance provides estimates of EF^{road} of 38.0 mg.veh^{-1}.km^{-1} for PM_{10} and 20.5 mg.veh^{-1}.km^{-1} for $PM_{2.5}$, irrespective of road type [34]. So, in a conventional assessment, the same factors would be applied to all E6DV and BEV buses regardless of road type, age, weight or brake technology used by the bus or the traffic conditions, e.g., free-flow or congested, making it one of the least sensitive contributions in the model.

Applying the Beddows and Harrison [14] method, Equation (3), weights from Table 1 and road constants from [14], weight-based road dust PM emissions are estimated as reported in Table 4.

$PM_{2.5}^{road}/PM_{10}^{road}$ ratios for both vehicle types are ca. 0.55, consistent with those estimated for road PM emissions in UK NAEI guidance [26], and the model predicts a ca. 7% increase in related road dust as a result of the investigated E6DV-to-BEV bus transition.

As would be expected, road wear products and related airborne emissions tend to be very similar, composition-wise, to asphalt, rock aggregates, binding agents and additives used for road surfacing, and road dust emissions typically associate with mineral element enrichment by, e.g., silicon, aluminum, calcium, potassium, iron and titanium, and bitumen-related enrichment by sulphur and chlorides. Both toxicological and epidemiological studies have reported adverse health effects associated with road dust exposure, although the relative contribution of road-wear-derived material is rarely easily quantified [12].

Table 4. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Road Emission Factors, EF^{road}, calculated using Equation (3), weights from Table 1 and *b* and *c* road dust constants from [14].

Contribution	*b*	*c*	EF^{road} mg.veh^{-1}.km^{-1}
E6DV			
$PM_{2.5}$ (all roads)	2.8 ± 0.5	1.5 ± 0.1	18 (13–24)
PM_{10} (all roads)	5.1 ± 0.9	1.5 ± 0.1	32 (24–43)
BEV			
$PM_{2.5}$ (all roads)	2.8 ± 0.5	1.5 ± 0.1	19 (14–26)
PM_{10} (all roads)	5.1 ± 0.9	1.5 ± 0.1	35 (25–47)

3.5. Road Particulate Resuspension Emission Factors, EF^{resusp}

Particulate deposited on road surfaces and studied fractions of these, e.g., RD_{10} (road dust ≤10 µm), tend to be dominated by the coarser PM emissions of vehicles, and for modern vehicles with very fine exhaust PM emissions, also NEE PM [12,38]. Other sources can also make significant contributions, e.g., road-salting in winter, dust from construction work around building sites, and wind-blown dust in arid areas [39]. The rate of resuspension of road dust, arguably better envisioned as re-emission than emission, is dependent on multiple factors, including the amount and composition of the deposited material [40], weather conditions, most notably humidity, rainfall, temperature and wind speed [13,41], and traffic volume, composition, vehicle speeds and driver behaviours [38]. Mechanisms for resuspension are also diverse; e.g., dry particulate can be picked up and released from wheel surfaces and grips or entrained in the turbulent air about the body of passing vehicles or in street canyons, while wet particulate can be nebulised as the result of both vehicle and wind action at water surfaces [38]. Given the complex nature of resuspended road dust and the challenges in attributing without 'double counting', many relevant authorities, including EMEP/EEA, do not recommend calculation methods or include EF^{resusp} in emission inventories. Therefore, we, like Beddows and Harrison [14], use the US EPA AP42 method [24]. Beddows and Harrison [14] rationalised the function by refitting it in the form of Equation (3) in their own work. However, here, we retain the AP42 form and refer back to this in later discussion of real-world emissions:

$$EF^{resusp} = k(sL)^d \times (\frac{W}{1000})^e \times [1 - \frac{1}{4}\frac{P}{N}] \tag{5}$$

where k is a weighting constant, 0.62 for PM_{10}; sL is the surface loading of road dust (g.m^{-2}); W is again the weight of the vehicle (kg); d and e are scaling terms derived empirically; and P is the number of wet days in the sampling period of N days.

Applying the Beddows and Harrison [14] method, Equation (3), weights from Table 1, resuspension constants from [14], and weight-based resuspended PM emissions are estimated as reported in Table 5.

Table 5. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) resuspended PM Emission Factors, EF^{resusp}, calculated using Equation (3), weights from Table 1 and *b* and *c* constants from [14].

Contribution	*b*	*c*	EF^{resusp} mg.veh^{-1}.km^{-1}
E6DV			
$PM_{2.5}$ (all roads)	2.0 ± 0.8	1.1 ± 0.4	25 (7.6–150)
PM_{10} (all roads)	8.2 ± 3.2	1.1 ± 0.4	100 (32–590)
BEV			
$PM_{2.5}$ (all roads)	2.0 ± 0.8	1.1 ± 0.4	27 (8.2–170)
PM_{10} (all roads)	8.2 ± 3.2	1.1 ± 0.4	110 (34–690)

$PM_{2.5}^{resusp}/PM_{10}^{resusp}$ ratios for both vehicle types are ca. 0.24, consistent with a relatively coarse PM source in comparison to both exhaust and other non-exhaust emissions, although, given the nature of resuspended PM, it is perhaps better regarded as a reservoir because of its sink/source behaviour. In the form derived by Beddows and

Harrison [14], the model predicts a 10% increase in related resuspended PM as the result of the investigated E6DV-to-BEV bus transition. It also suggests that this has the potential to be the largest source of additional PM_{10} associated with this transition. The Beddows and Harrison [14] model assumes a fixed surface loading of previously deposited PM (sL in Equation (5)). The fitting strategy they adopted allowed them to estimate typical values for $k(sL)^d$ for the UK for up-scaling to fleet and national levels for inventorying. Considered on smaller scales and, e.g., in environments where higher levels of street cleaning might be employed as part of an air quality management plan, it may not always be the major source of PM_{10}. Based on Equation (5), d typically being ca. 1, and obviously assuming the models are representative, we would predict a reduction in resuspended PM levels to be roughly proportionate to reductions in sL. So, air quality management plans that target already deposited dust may be particularly effective in reducing PM if, e.g., levels remain high or increase after a local ICE-to-BEV bus fleet intervention has been implemented. As would be expected, the composition of resuspended PM typically reflects the composition of other local PM sources [38,39]. As with PM^{road}, the impact of PM^{resusp} is not readily separated from that of initial PM sources [12].

3.6. Total Particulate Emissions Factors, $EF^{100\%}$

Total emission factors $EF^{100\%}$ were calculated for E6DV and BEV buses according to Equation (1) and the above methods and summarised in Figure 1 and Table 6.

The largest total $PM_{2.5}$ and PM_{10} emissions are predicted for buses on urban routes. This trend associates with higher amounts of stop/start driving and therefore braking and braking emissions. For the studied E6DV-to-BEV bus transition, there is likely to be a small PM penalty for the move from a diesel ICE engine to a zero exhaust emissions electric motor because of the heavier vehicle weight regardless of route type for both $PM_{2.5}$ and PM_{10} (We compare E6DV and BEV bus total emissions in all panels in Figure 1.)

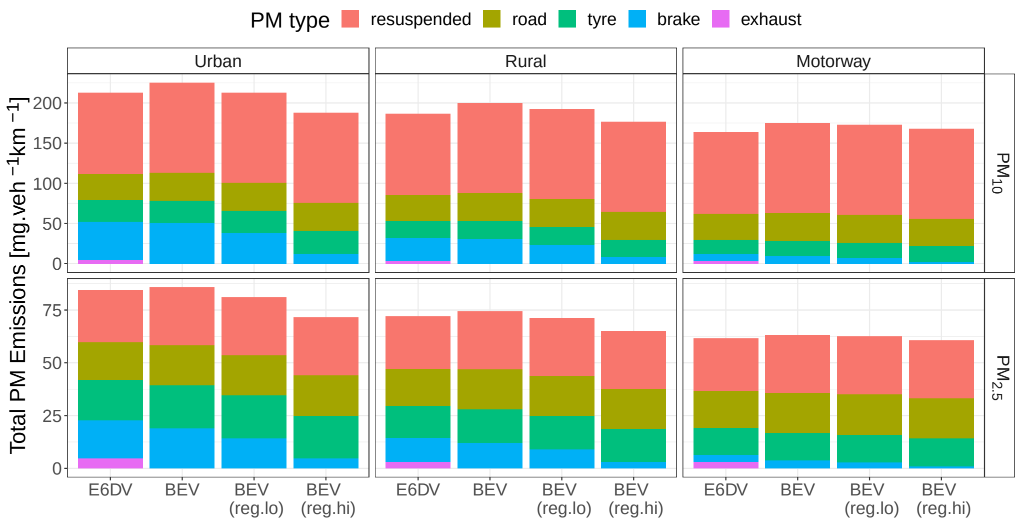

Figure 1. Euro VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total PM emissions, calculated for urban, rural and motorway bus routes. BEV emissions are calculated for BEV without regenerative brakes; BEV with regenerative brakes offsets 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes offsets 75% of brake emissions (BEV reg.hi).

Table 6. Euro VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total PM emissions, calculated for urban, rural and motorway bus routes. BEV emissions are calculated for BEV with regenerative brakes; BEV with regenerative brakes offset 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes offset 75% of brake emissions (BEV reg.hi).

Total PM Emissions	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (reg.lo) mg.veh^{-1}.km^{-1}	BEV (reg.hi) mg.veh^{-1}.km^{-1}
Urban $PM_{2.5}$	84.5 (51.6–229)	85.6 (49.6–253)	80.9 (46.5–246)	71.3 (46.5–246)
Rural $PM_{2.5}$	72.1 (39.7–221)	74.3 (38.7–247)	71.2 (37.5–240)	65.1 (37.5–240)
Motorway $PM_{2.5}$	61.6 (33.4–208)	63.2 (32.2–234)	62.3 (32.2–229)	60.5 (32.2–229)
Urban PM_{10}	213 (112–750)	225 (114–854)	213 (106–835)	188 (106–835)
Rural PM_{10}	187 (84.8–740)	200 (86.8–847)	192 (84.2–828)	177 (84.2–828)
Motorway PM_{10}	164 (72.7–710)	175 (74.1–815)	173 (74.1–803)	168 (74.1–803)

Calculated ranges, reported in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. See Table A1 in Appendix A for full breakdown of $PM_{2.5}$ and PM_{10} emissions by source.

However, current predictions suggest that this should be largely offset by the use of regenerative braking, assuming the reduction in conventional (friction) brake use is more than 50%. (In Figure 1, the break-even point for benefits is estimated at or near the lower performance case of a 25% reduction in conventional brake use for four of the six modelled cases and all motorway PM_{10} with a 75% reduction.) It is also important to note that the uncertainties, as indicated by the ranges reported in Table 6, are large in this type of study and that results need to be treated as indicative. However, they do suggest that PM emissions savings are at best modest (2–10% for 5/6 cases analysed here). The error bands on the weight functions, shown in the Appendices in Figures A1–A4, indicate that the largest uncertainties are likely to be associated with brake emissions and resuspended road dust.

4. Discussion and Model Refinements

The Beddows and Harrison [14] models provide multiple insights into the likely PM impacts of ICE-to-BEV transitions. Strictly, their functions were intended to provide UK-representative values of modelling parameters for scaling-up to provide emission inventory contributions. However, as observed above, it would also be useful to consider how the models could be refined to provide bus fleet managers with tools to inform fleet upgrade plans and associated maintenance and mitigation plans.

One example, based on the use of the US EPA AP42 (here reported as Equation (5)) and discussed in Section 3.5, would be to reincorporate the deposited road dust measurement sL into the EF^{resusp} weight function, so estimates of the effectiveness of local road cleaning activities could be assessed, e.g., using established European certification test procedures (DIN EN 15429-3; https://www.en-standard.eu/din-en-15429-3-sweepers-part-3-efficiency-of-particulate-mattercollection-testing-and-evaluation/ (accessed on 20 November 2022)).

It is, however, important to acknowledge that current research indicates that standard road sweeping is only likely to be effective on the coarsest PM and that active methods, e.g., high suction and/or road washing may be required to deliver clear benefits in all but the dustiest environments. There may also be hidden energy consumption penalties and financial cost implications that would need to be carefully considered (e.g., [12] and references therein, [42,43]).

Other examples include:

- *Using average speed to estimate emissions on other similar routes.* The use of urban, rural and motorway EFs provides a useful general description of emissions. It does not, however, provide a fleet manager with a measure of impacts on the routes they operate on or about the potential to reduce impacts through route planning or other traffic management strategies. EMEP/EEA guidance identifies associations between emissions and average vehicle speed for both EF^{brake} and EF^{tyre} [23]. Applying this to the Beddows and Harrison [14] EF^{brake} and EF^{tyre} models and assuming average speeds on the urban, rural and motorway routes for $EF^{exhaust}$ in

Section 3.1, we derive speed modifiers (Appendix A, Figures A5 and A6) by linear regression (Equation (6)):

$$EF^{j} = l_1 + l_2(avg.speed) \tag{6}$$

where EF^{j} is either the brake or tyre dust emission factor, and l_1 and l_2 are conventional linear regression intercept and gradient terms applied to average vehicle speed, $avg.spd$, (km.h^{-1}).

We then apply these to the three phases of the UK Bus Test Cycle (UKBC; Figure 2; Outer London, Inner London and rural, average speeds 16.9, 10.0 and 31.3 km.h^{-1}) to estimate associated EF^{brake} and EF^{tyre} values (Table 7) and total emissions for the three test phases as described in Table A2 in Appendix A and summarised in Figure 3 and Table 8. Comparing Figures 1 and 3 (or Tables A1 and A2 in Appendix A), again we see higher PM on the slower routes. Again, the models suggest that trends are likely to more pronounced at the lower speeds associated with Inner London driving, and outcomes are even more dependent on the trade-offs between vehicle weight and regenerative brake performance. This associates with the shape of the EF^{brake} and EF^{tyre} average speed functions (Figure A5 and A6 in Appendix A) which are linear and only increase associated PM ca. 10% between 30 and 15 km.h^{-1}. By comparison, the $EF^{exhaust}$ speed curve from COPERT, which has a pronounced upward curve, doubles exhaust contributions over the same range and significantly affects trends for PM_{25} in Inner London.

- *Extrapolating to routes with different characteristics.* Equation (6) assumes a strong association between EFs and speed at an aggregated level, i.e., speeds averaged across several minutes or kilometers. Elsewhere, researchers have identified other statistical measures of driving as better proxies for EF^{brake}, e.g., the US EPA used acceleration ≤ -2 miles.h^{-1}.s^{-1} or vehicle specific power (VSP) ≤ -4 kW.tonne^{-1} in their motor vehicle emission simulator (MOVES) model [44], and Wei et al [32] identified brake energy intensity (BEI) in their more recent machine learning study. Alternative EF^{tyre} parameters are less commonly cited although elevated emissions are associated with a range of driving activities, including both acceleration and braking [45]. We therefore propose the following functions:

$$B = \frac{(-avg.dec \times brk_{t.prop})}{avg.spd}; EF^{brake} = m_1 + m_2(B) \tag{7}$$

$$T = \frac{(-avg.dec \times brk_{t.prop}) + (avg.acc \times acc_{t.prop})}{avg.spd}; EF^{tyre} = n_1 + n_2(T) \tag{8}$$

where B and T are proxies for the amount of brake and tyre work performed per km travelled, $avg.dec$ and $avg.acc$ are the negative and positive components of acceleration, and $brk_{t.prop}$ and $acc_{t.prop}$ are the proportions of journey time the bus is braking and accelerating, respectively.

While these are simplifications, all these parameters can be readily calculated from a drive cycle test or GPS speed profiles using, e.g., ART.KINEMA methods [46]. The parameters are estimated for the urban, rural and motorway cases (Table 9), associated EFs calculated using Equation (3) and Tables 2 and 3 parameters, and these fit the brake and tyre work proxies using linear regression (B and T in Equations (7) and (8)) to generate provisional response terms (Figures A7 and A8 in Appendix A summarised in Table 9). Calculating through (Table 10), we produce associated brake and tyre proxy-based estimates (Figure 4, Table 11, and expanded in Table A3 in Appendix A). This indicates an even more pronounced effect under Inner London conditions, mainly associated with higher levels of braking and therefore brake emissions.

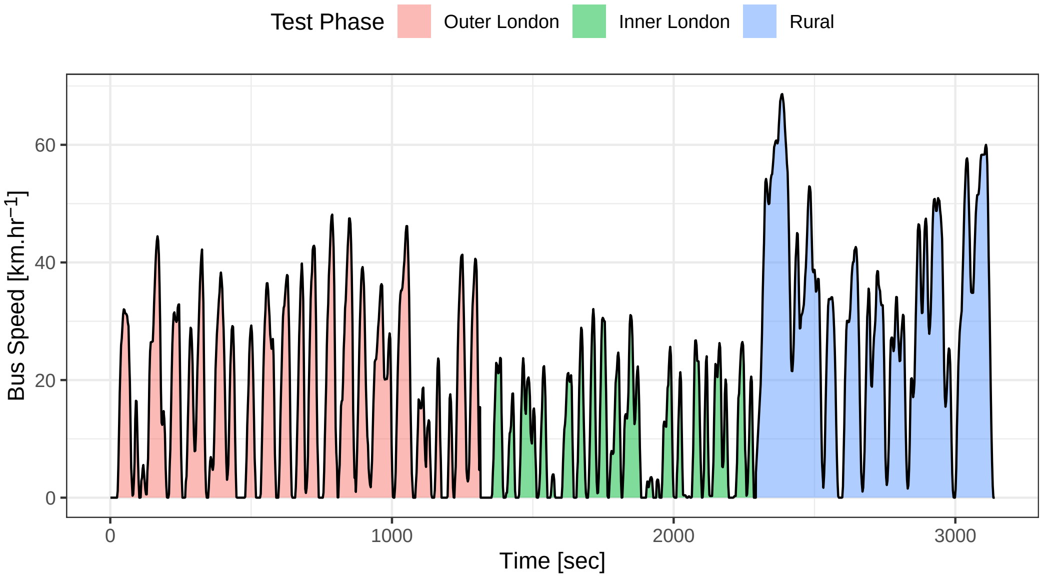

Figure 2. UK Bus Test Cycle (UKBC), comprising Outer London, Inner London and rural phases. The Outer and Inner London phases of the cycle were developed by Millbrook as the Westminster London Bus Cycle and extended to include a rural driving phase, and the combination is widely considered more representative of urban buses in the UK than the conventional urban, rural and motorway designations used in NAEI guidance.

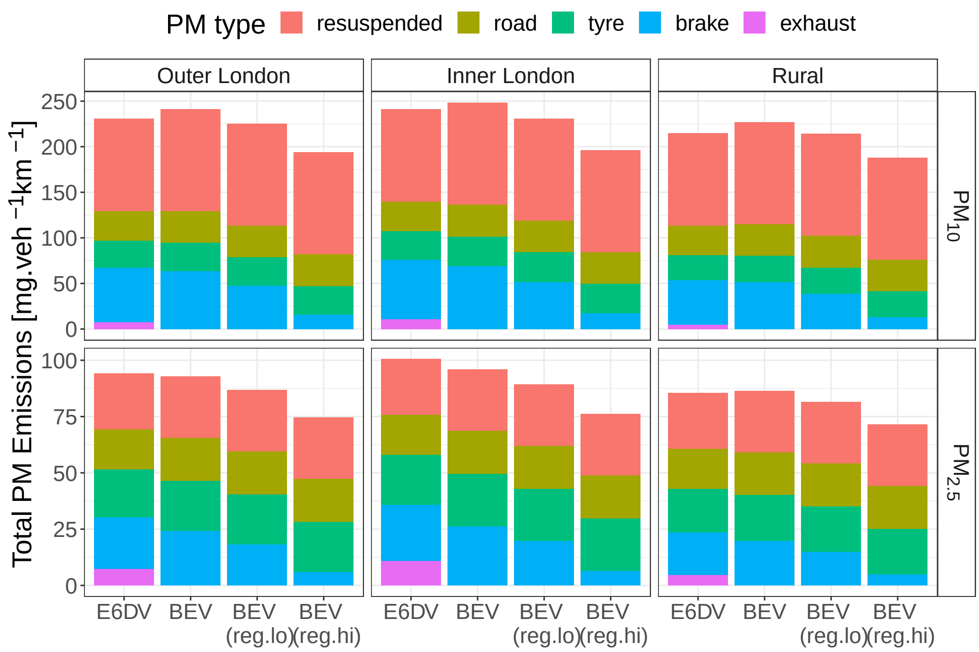

Figure 3. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total *PM* emissions, calculated for UK Bus Test Cycle (UKBC) Outer London, Inner London and rural phases, calculated using average speed model (Equation (6); MODEL 01). BEV emissions are calculated for BEV without regenerative brakes; BEV with regenerative brakes offsets 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes offsets 75% of brake emissions (BEV reg.hi).

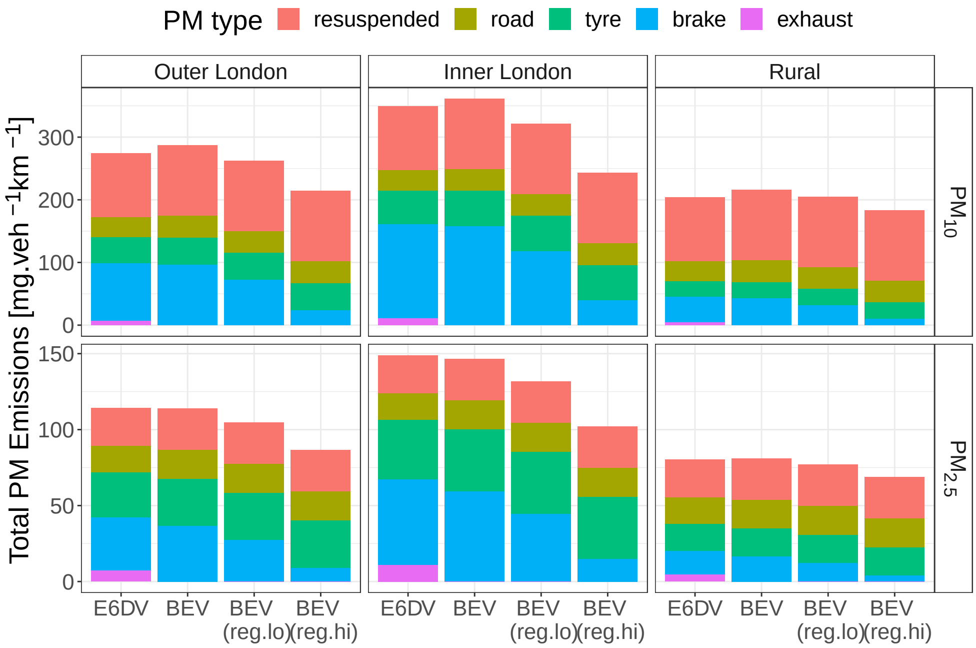

Figure 4. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total PM emissions, calculated for UK Bus Test Cycle (UKBC) Outer London, Inner London and rural phases, calculated using brake and tyre work proxies (Equations (7) and (8); MODEL 03). BEV emissions are calculated for BEV without regenerative brakes; BEV with regenerative brakes offsets 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes offsets 75% of brake emissions (BEV reg.hi).

Table 7. Average speed-based prediction of EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) brake and tyre PM emission factors, EF^{brake} and EF^{tyre}, for Outer London, Inner London and rural phases of the UK Bus Test Cycle (UKBC; Figure 2) calculated using the average speed correction (Equation (6); MODEL 01).

Contribution	l_1	l_2	EF^{brake} mg.veh^{-1}.km^{-1}
E6DV			
Outer London $PM_{2.5}$	10.9 ± 9.28	−10.2 ± 0.977	23 (15–31)
Inner London $PM_{2.5}$	10.9 ± 9.28	−10.2 ± 0.977	25 (17–32)
Rural $PM_{2.5}$	10.9 ± 9.28	−10.2 ± 0.977	19 (12–29)
Outer London PM_{10}	28 ± 23.6	−27.2 ± 2.46	60 (40–81)
Inner London PM_{10}	28 ± 23.6	−27.2 ± 2.46	65 (44–85)
Rural PM_{10}	28 ± 23.6	−27.2 ± 2.46	49 (31–74)
BEV			
Outer London $PM_{2.5}$	11.7 ± 10.2	−10.7 ± 1.37	24 (16–33)
Inner London $PM_{2.5}$	11.7 ± 10.2	−10.7 ± 1.37	26 (17–34)
Rural $PM_{2.5}$	11.7 ± 10.2	−10.7 ± 1.37	20 (12–31)
Outer London PM_{10}	29.9 ± 26	−28.6 ± 3.43	63 (42–86)
Inner London PM_{10}	29.9 ± 26	−28.6 ± 3.43	69 (46–89)
Rural PM_{10}	29.9 ± 26	−28.6 ± 3.43	52 (32–79)
Contribution	l_1	l_2	EF^{tyre} mg.veh^{-1}.km^{-1}
E6DV			
Outer London $PM_{2.5}$	15.7 ± 4.83	−4.77 ± 1.61	21 (16–30)
Inner London $PM_{2.5}$	15.7 ± 4.83	−4.77 ± 1.61	22 (17–31)
Rural $PM_{2.5}$	15.7 ± 4.83	−4.77 ± 1.61	19 (15–27)
Outer London PM_{10}	22.3 ± 6.81	−6.46 ± 1.96	30 (23–41)
Inner London PM_{10}	22.3 ± 6.81	−6.46 ± 1.96	31 (24–43)
Rural PM_{10}	22.3 ± 6.81	−6.46 ± 1.96	27 (21–38)
BEV			
Outer London $PM_{2.5}$	16.4 ± 5.22	−5.00 ± 1.73	22 (17–31)
Inner London $PM_{2.5}$	16.4 ± 5.22	−5.00 ± 1.73	23 (18–33)
Rural $PM_{2.5}$	16.4 ± 5.22	−5.00 ± 1.73	20 (15–29)
Outer London PM_{10}	23.4 ± 7.36	−6.77 ± 2.11	31 (24–44)
Inner London PM_{10}	23.4 ± 7.36	−6.77 ± 2.11	33 (25–46)
Rural PM_{10}	23.4 ± 7.36	−6.77 ± 2.11	29 (22–40)

Ranges calculated by extrapolating errors reported in [14] using Equation (6) and weight-specific speed functions (Figures A5 and A6).

Table 8. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total PM emissions, calculated for Outer London, Inner London and rural phases of the UK Bus Test Cycle (UKBC; Figure 2) calculated using the average speed correction Equation (6) (MODEL02). BEV emissions are calculated for BEV with regenerative brakes; BEV with regenerative brakes that offset 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes that offset 75% of brake emissions (BEV reg.hi).

Total PM Emissions	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (reg.lo) mg.veh^{-1}.km^{-1}	BEV (reg.hi) mg.veh^{-1}.km^{-1}
Outer London $PM_{2.5}$	94.1 (59.2–238)	92.9 (54.7–260)	86.8 (50.8–252)	74.7 (50.8–252)
Inner London $PM_{2.5}$	100 (65–244)	95.9 (57.1–263)	89.3 (52.8–254)	76.2 (52.8–254)
Rural $PM_{2.5}$	85.4 (51.8–230)	86.5 (49.7–255)	81.5 (46.6–247)	71.6 (46.6–247)
Outer London PM_{10}	231 (126–768)	241 (125–869)	225 (115–848)	194 (115–848)
Inner London PM_{10}	241 (134–776)	248 (131–874)	231 (119–852)	196 (119–852)
Rural PM_{10}	215 (112–755)	227 (114–859)	214 (106–839)	188 (106–839)

Ranges calculated by extrapolating errors reported in [14] using Equation (6). See Table A2 in Appendix A for full breakdown of $PM_{2.5}$ and PM_{10} emissions by source.

Table 9. Driving condition statistics: average speed ($avg.spd$), average acceleration ($avg.acc$), proportion of time acceleration ($acc_{t.prop}$), average deceleration ($avg.dec$), proportion of time braking ($brk_{t.prop}$) and brake and tyre work proxies (B and T).

Classification	$avg.spd$ km.h^{-1}	[1] $avg.acc$ km.h^{-1}.s^{-1}	$acc_{t.prop}$	[1] $avg.dec$ km.h^{-1}.s^{-1}	$brk_{t.prop}$	[2] B km.h^{-1}.s^{-1}	[2] T km.h^{-1}.s^{-1}
NAEI Route							
Urban	32	0.530	0.295	−0.469	0.334	0.00489	0.0104
Rural	62	0.508	0.299	−0.514	0.299	0.00248	0.00493
Motorway	82	0.388	0.384	−0.466	0.307	0.00174	0.00319
UKBC Phase							
Outer London	17	0.442	0.4188	−0.619	0.2384	0.0087	0.0197
Inner London	10	0.4181	0.3574	−0.647	0.2154	0.0139	0.0289
Rural	31	0.2877	0.4038	−0.5912	0.2201	0.0042	0.0079

[1] Calculated using ART.KINEMA methods as described in [46]. [2] Break and tyre work proxies calculated using Equations (7) and (8).

While these parameters should be considered provisional and are likely to be subject to some refinement as part of ongoing work (see also Conclusions), their inclusion highlights the complexity of the situation and the trade-offs between driving conditions, E6DV-to-BEV weight incr ease and regenerative braking technology performance. To illustrate the point, two further cases are considered, both based on the brake and tyre models. First is the case where the incoming BEV bus is the same weight as the equivalent E6DV bus (Figure A7a and Table A4 in the Appendix A), and, second is the case where the incoming BEV bus is 22% heavier than the E6DV bus (Figure A7b and Table A5 in the Appendix A). The emissions trends for the E6DV-to-BEV transition are then compared for buses on the Outer London, Inner London and rural phases of the UKBC using the average-speed modification (Equation (6); MODEL 01), the brake and tyre work modification (Equations (7) and (8); MODEL 02) and the lighter and heavier alternatives to MODEL 02 (MODEL 03 and 04, respectively) as Figure 5. These indicate that PM impacts will be highly dependent on both local driving conditions and the weight of the incoming vehicle fleet.

At this stage, we do not propose either EF^{road} or EF^{resusp} modifiers because, like Beddows and Harrison [14]) before us, we lack sufficient data to reliably differentiate associated EF_i^js. Similarly, we note that other modifiers could also be considered, e.g., a bad weather correction, such as the $1 - (1/4) \times (P/N)$ component of the US EPA AP42 [24]. We did not include this or other similar options, e.g., based on rainfall, temperature or wind speed, in the current method because our objective here was to a develop of a desk-based method for bus fleet operators considering the E6DV-to-BEV bus fleet transition, and our focus was inputs they can measure and manage.

Table 10. Brake and tyre proxy-based prediction of EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) brake and tyre PM emission factors, EF^{brake} and EF^{tyre}, for Outer London, Inner London and rural phases of the UK Bus Test Cycle (UKBC; Figure 2) calculated using brake and tyre work proxies (Equations (7) and (8); MODEL 03).

Contribution	m_1	m_2	EF^{brake} mg.veh^{-1}.km^{-1}
E6DV			
Outer London $PM_{2.5}$	10.9 ± 9.28	9.75 ± 1.43	35 (25–37)
Inner London $PM_{2.5}$	10.9 ± 9.28	9.75 ± 1.43	57 (44–49)
Rural $PM_{2.5}$	10.9 ± 9.28	9.75 ± 1.43	16 (9.2–26)
Outer London PM_{10}	28.0 ± 23.6	26.1 ± 3.74	92 (68–97)
Inner London PM_{10}	28.0 ± 23.6	26.1 ± 3.74	150 (120–130)
Rural PM_{10}	28.0 ± 23.6	26.1 ± 3.74	41 (24–68)
BEV			
Outer London $PM_{2.5}$	11.7 ± 10.2	10.2 ± 1.85	37 (27–38)
Inner London $PM_{2.5}$	11.7 ± 10.2	10.2 ± 1.85	59 (46–49)
Rural $PM_{2.5}$	11.7 ± 10.2	10.2 ± 1.85	17 (9.7–28)
Outer London PM_{10}	29.9 ± 26.0	27.3 ± 4.81	97 (72–100)
Inner London PM_{10}	29.9 ± 26.0	27.3 ± 4.81	160 (120–130)
Rural PM_{10}	29.9 ± 26.0	27.3 ± 4.81	43 (26–73)
Contribution	n_1	n_2	EF^{tyre} mg.veh^{-1}.km^{-1}
E6DV			
Outer London $PM_{2.5}$	15.7 ± 4.83	4.73 ± 1.63	30 (22–42)
Inner London $PM_{2.5}$	15.7 ± 4.83	4.73 ± 1.63	39 (29–55)
Rural $PM_{2.5}$	15.7 ± 4.83	4.73 ± 1.63	17 (13–24)
Outer London PM_{10}	22.3 ± 6.81	6.43 ± 1.93	41 (32–57)
Inner London PM_{10}	22.3 ± 6.81	6.43 ± 1.93	54 (42–75)
Rural PM_{10}	22.3 ± 6.81	6.43 ± 1.93	25 (19–34)
BEV			
Outer London $PM_{2.5}$	16.4 ± 5.22	4.96 ± 1.76	31 (23–44)
Inner London $PM_{2.5}$	16.4 ± 5.22	4.96 ± 1.76	41 (31–58)
Rural $PM_{2.5}$	16.4 ± 5.22	4.96 ± 1.76	18 (14–26)
Outer London PM_{10}	23.4 ± 7.36	6.74 ± 2.08	43 (33–60)
Inner London PM_{10}	23.4 ± 7.36	6.74 ± 2.08	57 (44–79)
Rural PM_{10}	23.4 ± 7.36	6.74 ± 2.08	26 (20–36)

Ranges calculated by extrapolating errors reported in [14] using Equation (6) and weight-specific speed functions (Figures A5 and A6).

Table 11. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total PM emissions, calculated for Outer London, Inner London and rural phases of the UK Bus Test Cycle (UKBC; Figure 2) calculated using brake and tyre work proxies (Equations (7) and (8); MODEL 03). BEV emissions are calculated for BEV with regenerative brakes; BEV with regenerative brakes that offset 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes that offset 75% of brake emissions (BEV reg.hi).

Total PM Emissions	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (reg.lo) mg.veh^{-1}.km^{-1}	BEV (reg.hi) mg.veh^{-1}.km^{-1}
Outer London $PM_{2.5}$	114 (75.7–256)	114 (72–278)	105 (65.4–269)	86.5 (65.4–269)
Inner London $PM_{2.5}$	149 (105–285)	147 (98.6–303)	132 (87.1–291)	102 (87.1–291)
Rural $PM_{2.5}$	80.4 (48–225)	81.2 (45.7–250)	77.1 (43.3–243)	68.8 (43.3–243)
Outer London PM_{10}	274 (163–799)	287 (164–900)	262 (146–875)	214 (146–875)
Inner London PM_{10}	349 (226–854)	361 (227–950)	322 (196–917)	243 (196–917)
Rural PM_{10}	204 (104–745)	216 (105–849)	205 (98.5–831)	183 (98.5–831)

Ranges calculated by extrapolating errors reported in [14] using Equation (6). See Table A2 in Appendix A for full breakdown of $PM_{2.5}$ and PM_{10} emissions by source.

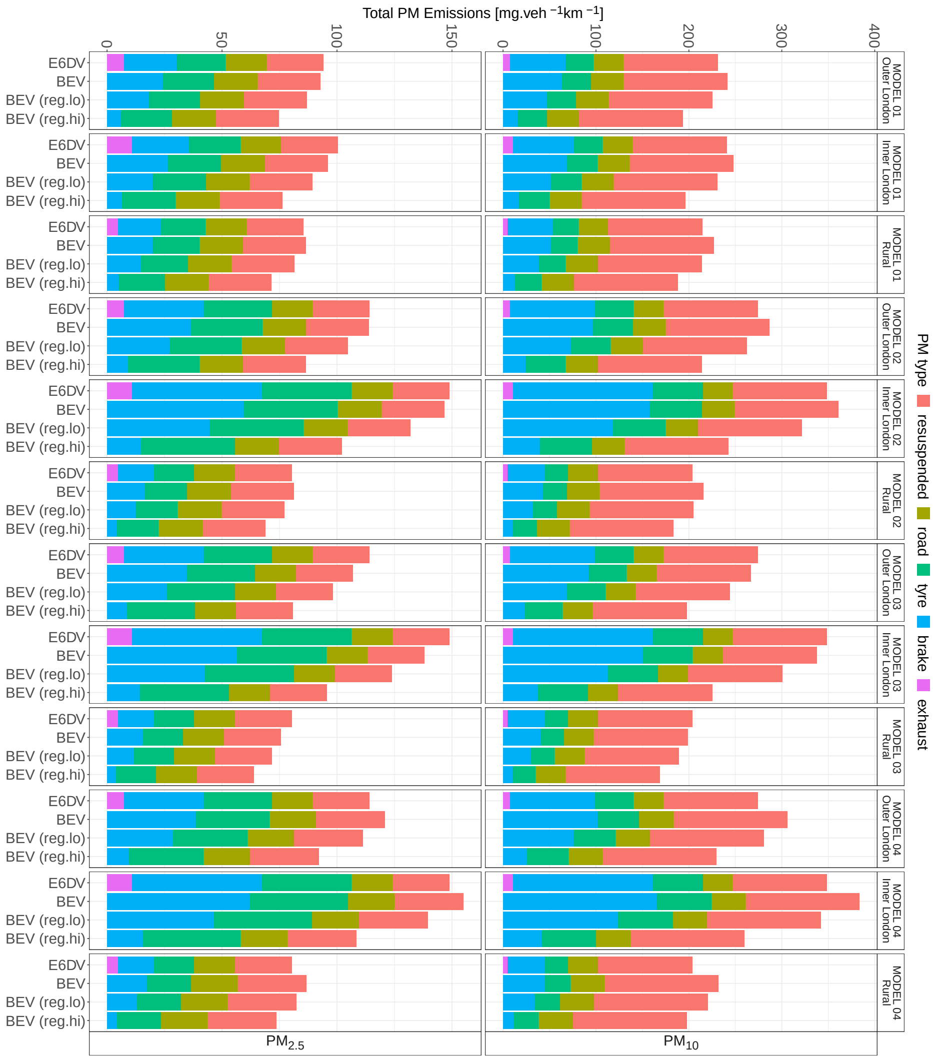

Figure 5. Comparison of EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total *PM* emissions on Outer London, Inner London and rural phases of the UK Bus Test Cycle (UKBC). BEV emissions are calculated for BEV with regenerative brakes; BEV with regenerative brakes that offset 25% of brake emissions (BEV reg.lo) and BEV with regenerative brakes that offset 75% of brake emissions (BEV reg.hi). Models are MODEL 01 average speed (Equation (6)), MODEL 02 brake and tyre work proxy (Equations (7) and (8)), MODEL 03 brake and tyre work proxy for BEV same weight as E6DV, and MODEL 04 brake and tyre work proxy for BEV 23% heavier than E6DV (twice current weight difference).

5. Conclusions and Future Work

Although this study, like any scoping exercise of its nature, is subject to significant uncertainties, we still provide some useful insights regarding the trade-offs between driving conditions, E6DV-to-BEV weight increase and regenerative braking technology performance, e.g.:

- All analyses confirm that NEEs are likely to be the major source of E6DV bus-related PM (approximately 97% and 93% for $PM_{2.5}$ and PM_{10}, of studied E6DV bus PM emissions, respectively) and that, while the transition is a clear benefit in terms of urban NO_x pollution, it is unlikely to have a major effect on local PM pollution levels.
- All analyses indicate that an E6DV-to-BEV bus fleet transition, such as that currently being undertaken by First Bus, is likely to have a small effect on bus-related PM but that outcomes (benefits or penalties) are likely to be highly dependent on the trade-offs between E6DV/BEV weight difference and regenerative braking efficiency, e.g., 1–3%

and 2–6% increases for $PM_{2.5}$ and PM_{10}, respectively, for a BEV without regenerative braking, to a 2–5% and 4–12% decreases for $PM_{2.5}$ and PM_{10}, respectively, for a BEV with regenerative braking that is 75% effective in offsetting brake emissions.

- However, both average-speed and brake and tyre work proxy-based corrections suggest that PM emissions could be significantly higher on routes with driving characteristics, such as the Inner London phase of the UKBC, where all vehicle types produced 13–50% more PM depending on model (average-speed or brake and tyre work modifier, E6DV/BEV weight difference and regenerative brake performance), in comparison to the urban set point defined in NAEI guidance.

Although there is still relatively little source apportionment evidence regarding the NEE impact of the transition to BEV bus fleets, these findings are broadly consistently with other public evidence: for example, the amounts of NEE PM in comparison to exhaust PM for modern (post-EURO V) vehicle fleets (see, e.g., [23,34]), bus NEEs of the order of 50–100 and 150–350 mg.veh^{-1}.km^{-1} for $PM_{2.5}$ and PM_{10}, respectively (see, e.g., [9,13]), and the impact of heavier vehicles more generally [22].

We note that many urban bus fleets are likely to be operating outside the conventional urban, rural and motorway set points employed by the NAEI methods and highlight the value of not just weight corrections but also route-specific (e.g., speed or source proxies) corrections for driving on other routes (or under other driving conditions). We also acknowledge the value of the NAEI set points when, e.g., rescaling for national inventories, but also highlight the value of being able to fine-tune outputs for local routes when used by, e.g., a fleet manager accessing options for bus upgrades. As noted above, parameters proposed here are likely to be subject to some refinement as part of on-going work as we gather data from the E6DV-to-BEV Bus Fleet Transition Evaluation and similar real-world initiatives. Here, we also highlight road slope as a likely significant contributor to differing on-route NEEs outside the scope of the current meta-analysis and hope to contribute to associated EF modifiers as part of the ongoing project.

Elsewhere, researchers have highlighted that future battery technologies will most likely be lighter and that this may be a short-term issue. However, the current generation of BEV buses are heavier than E6DV equivalents and are likely to be on the road for ca. 10 years. So, fleet managers, local government and highway authorities all need to thinking not just about fleet transitions but also the longer-term management of the incoming fleets to ensure best performance from technologies, such as e.g., regenerative braking, and retrofitting plans for early adopter fleets if/when integratable lighter battery systems become available to ensure that we benefit sooner rather than later from this effort and investment. Likewise, manufacturers need to be actively working to address the full life-cycle costs, both financial and environmental, of these incoming vehicle and battery technologies if we want to re-position ourselves as a truly circular economy, and tools such as the methods presented here can help fleet managers and policy makers facing a marketplace full of choices.

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Data Availability Statement: Code developed for this study is available under General Public License at: https://github.com/karlropkins/embrs (accessed on 9 November 2023).

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Abbreviations

$acc_{t.propr}$	Proportion of Time Vehicle Accelerating
$avg.acc$; $avg.dec$; $avg.spd$	Average Acceleration, Deceleration and Speed
b; c	Scaling constants from [14]; See e.g., Equation (3)
B	Brake Work Proxy (proposed here)
BEV(s)	Battery Electric Vehicle(s)
BEI	Brake Energy Intensity
$brake$	Airborne Brake (Wear) Particulate
$brk_{t.propr}$	Proportion of Time Vehicle Braking
COMEAP	(UK) Committee on the Medical Effects of Air Pollutants
d; e; k	Scaling constants from [24]; see e.g., Equation (5)
E6DV(s)	Euro VI Diesel Vehicle(s)
EATS	Exhaust After-Treatment System
EMEP	(EC) European Monitoring and Evaluation Programme
EEA	(EC) European Environment Agency
EF; EF_i^j	Emission Factor where i and j are application and type descriptors e.g., EF_{urban}^{brake} is emission factor for brake particulate on urban routes
ICE(s)	Internal Combustion Engine(s)
$InnerLondon$	Inner London Driving/Route (UKBC definition)
l_1; l_2	Average Speed scaling constants (proposed here); see Equation (6)
m_1; m_2	Brake Work Proxy scaling constants (proposed here); see Equation (7)
$motorway$	Urban Driving/Route (NAEI definition)
MOVES	Motor vehicle emission simulator
n_1; n_2	Tyre Work Proxy scaling constants (proposed here); see Equation (8)
NAEI	(UK) National Atmospheric Emissions Inventory
NO_x; NO; NO_2	Oxides of nitrogen; nitric oxide; nitrogen dioxide
$OuterLondon$	Outer London Driving/Route (UKBC definition)
P/N	Proportion of Wet Days; from [24], see Equation (5)
PM; PM_{10}; $PM_{2.5}$	Particulate Matter; $PM \leq 10$ µm; $PM \leq 2.5$ µm
$resusp$	Resuspended Airborne Particulate
$regen$	Regenerative Braking
$road$	Airborne Road (Wear) Particulate
$rural$	Urban Driving/Route (NAEI and UKBC definitions)
RD_{10}	Road Dust ≤ 10 µm
SCRT	Selective Catalytic Reduction with Continuous Regeneration Trap
sL	Road Surface Particulate Loading
T	Tyre Work Proxy (proposed here)
$tyre$	Airborne Tyre (Wear) Particulate
$urban$	Urban Driving/Route (NAEI definition)
UKBC	UK Bus Test Cycle
US EPA	United States Environmental Protection Agency
VSP	Vehicle Specific Power
W	Vehicle Weight
ZEV(s)	Zero Emissions Vehicle(s)

Appendix A

Appendix A.1. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Total PM Emissions (BASE CASE)

Table A1. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) contribution and total emissions of $PM_{2.5}$ and $PM_{2.5}$, calculated for urban, rural and motorway bus routes.

PM Emissions	Contribution	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (regen.low) mg.veh^{-1}.km^{-1}	BEV (regen.high) mg.veh^{-1}.km^{-1}
Urban $PM_{2.5}$	exhaust	4.7 (4.7–4.7)	0	0	0
Urban $PM_{2.5}$	brake	18 (11.6–27)	19.1 (12.2–28.8)	14.3 (9.14–21.6)	4.77 (9.14–21.6)
Urban $PM_{2.5}$	tyre	19.3 (14.8–27)	20.2 (15.4–28.6)	20.2 (15.4–28.6)	20.2 (15.4–28.6)
Urban $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Urban $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Urban $PM_{2.5}$	Total	84.5 (51.6–229)	85.6 (49.6–253)	80.9 (46.5–246)	71.3 (46.5–246)
		Difference (%)	**1.11 (1.31%)**	**−3.66 (−4.33%)**	**−13.2 (−15.6%)**
Rural $PM_{2.5}$	exhaust	3.2 (3.2–3.2)	0	0	0
Rural $PM_{2.5}$	brake	11.4 (4.19–27.1)	12.2 (4.45–29.6)	9.18 (3.33–22.2)	3.06 (3.33–22.2)
Rural $PM_{2.5}$	tyre	15 (11.7–20.6)	15.7 (12.2–21.8)	15.7 (12.2–21.8)	15.7 (12.2–21.8)
Rural $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Rural $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Rural $PM_{2.5}$	Total	72.1 (39.7–221)	74.3 (38.7–247)	71.2 (37.5–240)	65.1 (37.5–240)
		Difference (%)	**2.2 (3.05%)**	**−0.858 (−1.19%)**	**−6.98 (−9.68%)**
Motorway $PM_{2.5}$	exhaust	3.1 (3.1–3.1)	0	0	0
Motorway $PM_{2.5}$	brake	3.36 (0–17.3)	3.65 (0–19.5)	2.74 (0–14.6)	0.913 (0–14.6)
Motorway $PM_{2.5}$	tyre	12.7 (9.76–17.6)	13.3 (10.2–18.6)	13.3 (10.2–18.6)	13.3 (10.2–18.6)
Motorway $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Motorway $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Motorway $PM_{2.5}$	Total	61.6 (33.4–208)	63.2 (32.2–234)	62.3 (32.2–229)	60.5 (32.2–229)
		Difference (%)	**1.64 (2.65%)**	**0.723 (1.17%)**	**−1.1 (−1.79%)**
Urban PM_{10}	exhaust	4.7 (4.7–4.7)	0	0	0
Urban PM_{10}	brake	47.2 (31–69.8)	50 (32.6–74.3)	37.5 (24.5–55.7)	12.5 (24.5–55.7)
Urban PM_{10}	tyre	27.3 (21.2–37.8)	28.6 (22–40)	28.6 (22–40)	28.6 (22–40)
Urban PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Urban PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Urban PM_{10}	Total	213 (112–750)	225 (114–854)	213 (106–835)	188 (106–835)
		Difference (%)	**12.1 (5.68%)**	**−0.378 (−0.177%)**	**−25.4 (−11.9%)**
Rural PM_{10}	exhaust	3.2 (3.2–3.2)	0	0	0
Rural PM_{10}	brake	28.5 (9.77–69.3)	30.6 (10.4–75.7)	22.9 (7.78–56.8)	7.65 (7.78–56.8)
Rural PM_{10}	tyre	21.3 (16.4–29.6)	22.3 (17.1–31.3)	22.3 (17.1–31.3)	22.3 (17.1–31.3)
Rural PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Rural PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Rural PM_{10}	Total	187 (84.8–740)	200 (86.8–847)	192 (84.2–828)	177 (84.2–828)
		Difference (%)	**12.7 (6.79%)**	**5.05 (2.7%)**	**−10.2 (−5.49%)**
Motorway PM_{10}	exhaust	3.1 (3.1–3.1)	0	0	0
Motorway PM_{10}	brake	8.41 (0–43.3)	9.13 (0–48.8)	6.85 (0–36.6)	2.28 (0–36.6)
Motorway PM_{10}	tyre	18.3 (14.2–25.3)	19.2 (14.8–26.8)	19.2 (14.8–26.8)	19.2 (14.8–26.8)
Motorway PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Motorway PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Motorway PM_{10}	Total	164 (72.7–710)	175 (74.1–815)	173 (74.1–803)	168 (74.1–803)
		Difference (%)	**11.3 (6.88%)**	**8.98 (5.49%)**	**4.42 (2.7%)**

Calculated ranges, in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. $EF^{exhaust}$ fixed calculated rate, so ranges are a measure of NEEs errors. BEV is BEV without regenerative brakes; BEV with regenerative brakes offsetting 25% and 75% of brake emissions, BEV reg.lo and BEV reg.hi, respectively.

Appendix A.2. Weight-Dependent Emissions EF Functions

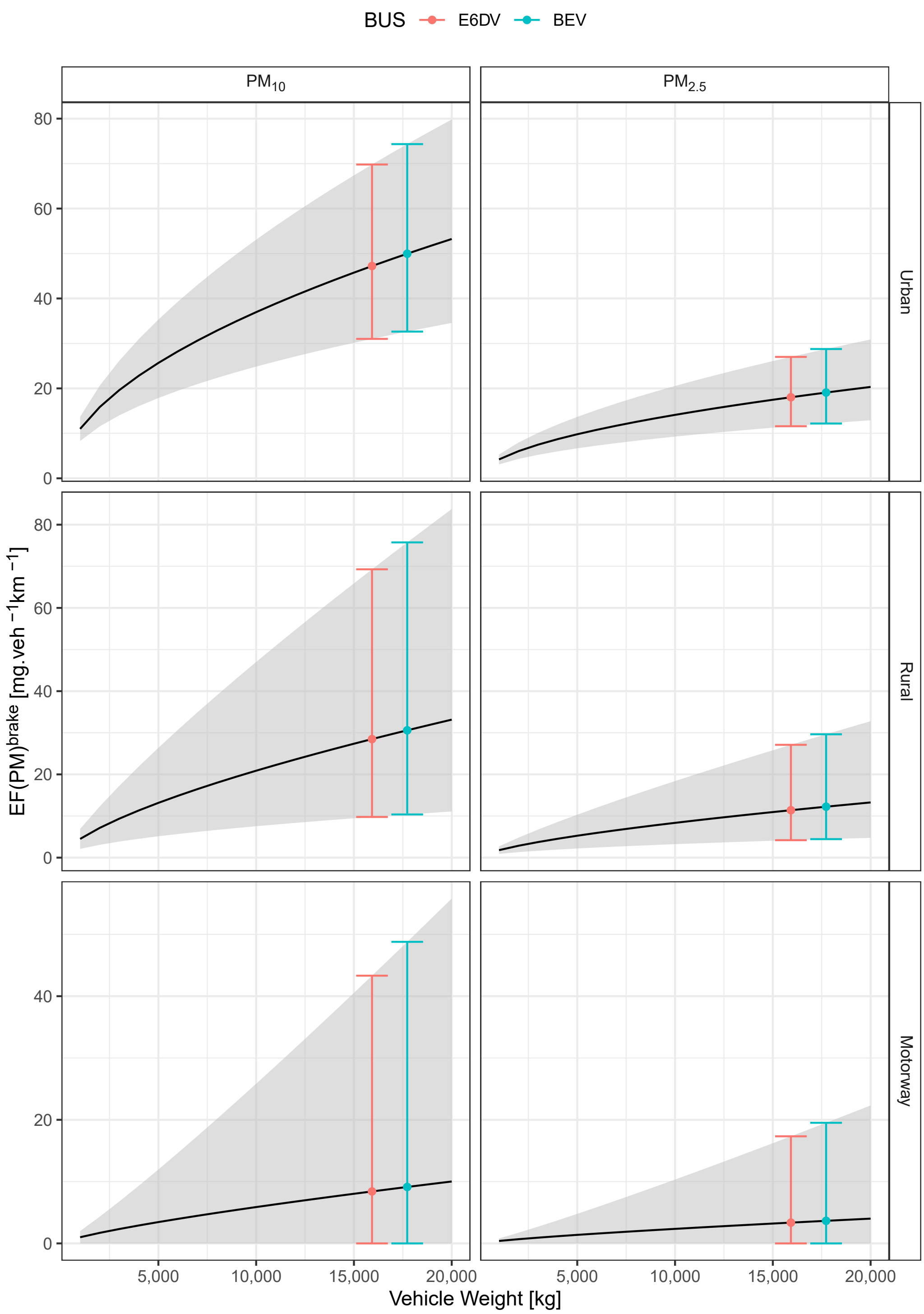

Figure A1. Weight-dependent brake emissions EF^{break} functions with predictions as a black line and error regions as grey bands. EURO VI Diesel Vehicle (E6DV; orange) and Battery Electric Vehicle (BEV; blue) PM emissions included as points and error bars for reference.

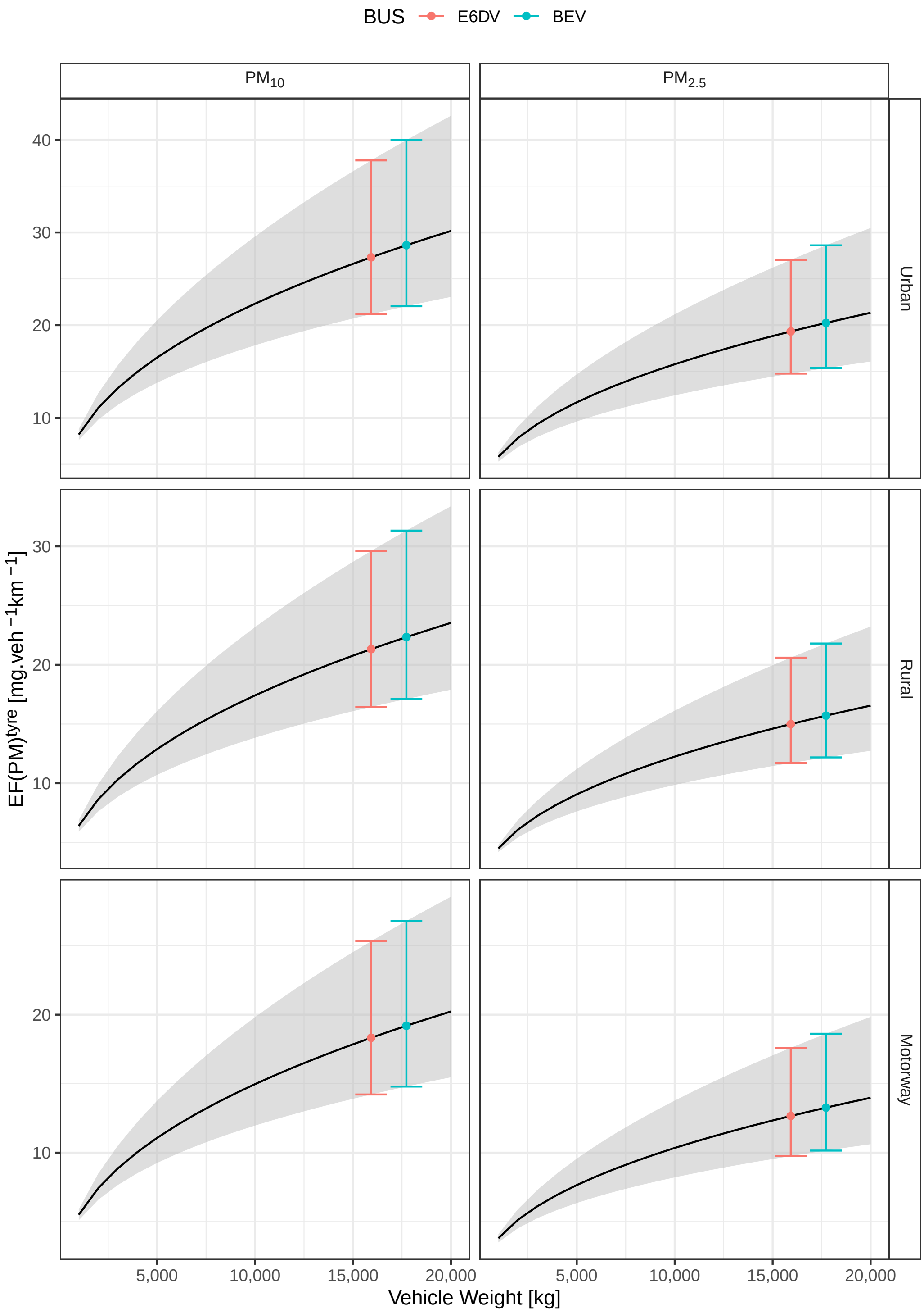

Figure A2. Weight-dependent tyre emissions EF^{tyre} functions with predictions as a black line and error regions as grey bands. EURO VI Diesel Vehicle (E6DV; orange) and Battery Electric Vehicle (BEV; blue) PM emissions included as points and error bars for reference.

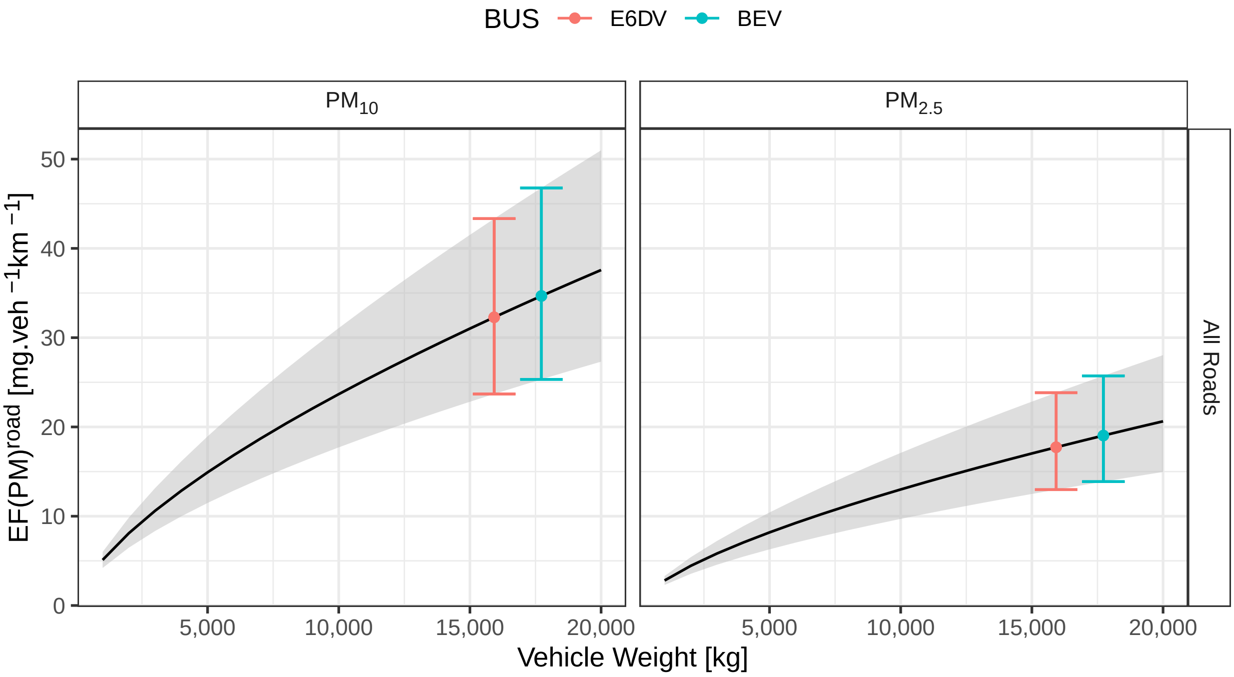

Figure A3. Weight-dependent road-dust emissions EF^{road} functions with predictions as a black line and error regions as grey bands. EURO VI Diesel Vehicle (E6DV; orange) and Battery Electric Vehicle (BEV; blue) PM emissions included as points and error bars for reference.

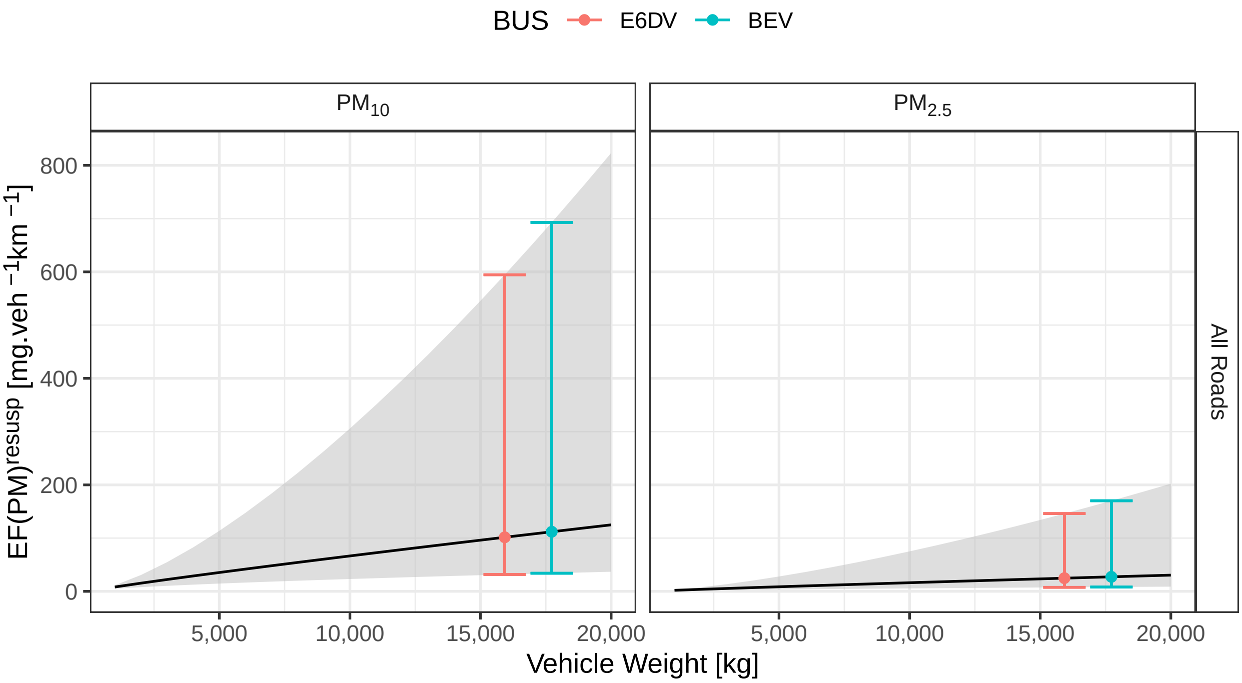

Figure A4. Weight-dependent resuspended road-dust emissions EF^{resusp} functions with predictions as a black line and error regions as grey bands. EURO VI Diesel Vehicle (E6DV; orange) and Battery Electric Vehicle (BEV; blue) PM emissions included as points and error bars for reference.

Appendix A.3. By-Weight, Average Speed-Dependent Emissions EF Functions

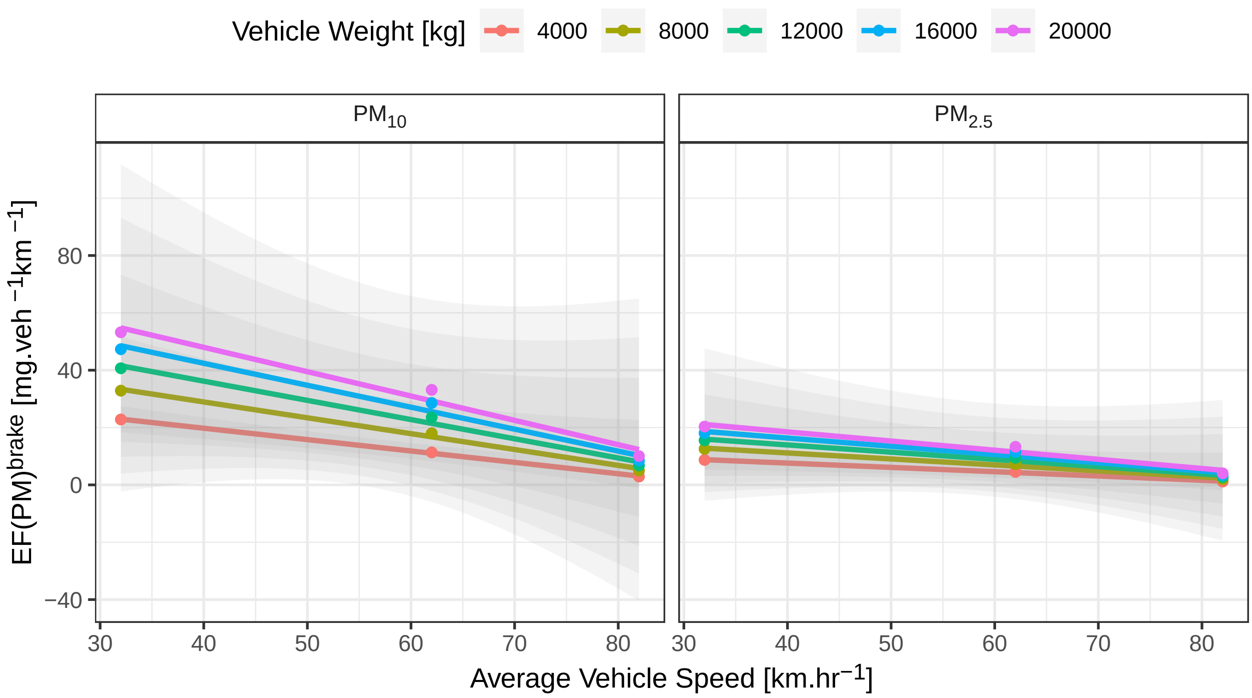

Figure A5. By-weight, average speed-dependent brake emissions EF^{break} functions.

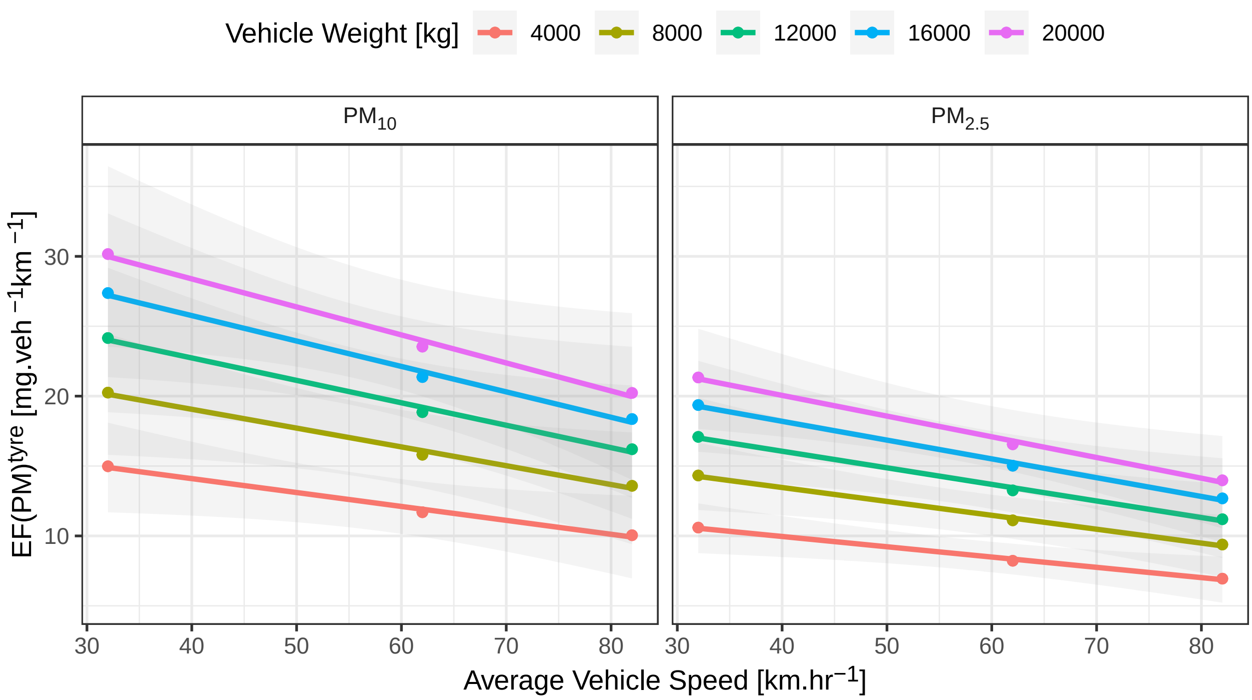

Figure A6. By-weight, average speed-dependent brake emissions EF^{break} functions.

Appendix A.4. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Total PM Emissions estimated using by-weight average speed-dependent functions (MODEL 01).

Table A2. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) contribution and total emissions of $PM_{2.5}$ and $PM_{2.5}$, calculated for Outer London, Inner London and rural phases of the UK Bus Test Cycle.

PM Emissions	Contribution	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (regen.low) mg.veh^{-1}.km^{-1}	BEV (regen.high) mg.veh^{-1}.km^{-1}
Outer London $PM_{2.5}$	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London $PM_{2.5}$	brake	22.9 (15–31.2)	24.3 (15.8–33)	18.2 (11.8–24.7)	6.07 (11.8–24.7)
Outer London $PM_{2.5}$	tyre	21.3 (16.3–29.7)	22.3 (16.9–31.4)	22.3 (16.9–31.4)	22.3 (16.9–31.4)
Outer London $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Outer London $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Outer London $PM_{2.5}$	Total	94.1 (59.2–238)	92.9 (54.7–260)	86.8 (50.8–252)	74.7 (50.8–252)
		Difference (%)	**−1.2 (−1.27%)**	**−7.26 (−7.72%)**	**−19.4 (−20.6%)**
Inner London $PM_{2.5}$	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London $PM_{2.5}$	brake	24.9 (16.6–32.5)	26.4 (17.5–34.1)	19.8 (13.1–25.6)	6.59 (13.1–25.6)
Inner London $PM_{2.5}$	tyre	22.2 (17–31)	23.2 (17.7–32.8)	23.2 (17.7–32.8)	23.2 (17.7–32.8)
Inner London $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Inner London $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Inner London $PM_{2.5}$	Total	100 (65–244)	95.9 (57.1–263)	89.3 (52.8–254)	76.2 (52.8–254)
		Difference (%)	**−4.57 (−4.55%)**	**−11.2 (−11.1%)**	**−24.3 (−24.2%)**
Rural $PM_{2.5}$	exhaust	4.77 (4.77–4.77)	0	0	0
Rural $PM_{2.5}$	brake	18.8 (11.6–28.7)	19.9 (12.2–30.6)	14.9 (9.18–22.9)	4.98 (9.18–22.9)
Rural $PM_{2.5}$	tyre	19.3 (14.8–27)	20.3 (15.4–28.5)	20.3 (15.4–28.5)	20.3 (15.4–28.5)
Rural $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Rural $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Rural $PM_{2.5}$	Total	85.4 (51.8–230)	86.5 (49.7–255)	81.5 (46.6–247)	71.6 (46.6–247)
		Difference (%)	**1.11 (1.31%)**	**−3.86 (−4.53%)**	**−13.8 (−16.2%)**
Outer London PM_{10}	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London PM_{10}	brake	60 (39.8–81.2)	63.4 (41.9–85.8)	47.6 (31.4–64.3)	15.9 (31.4–64.3)
Outer London PM_{10}	tyre	29.9 (23.2–41.4)	31.3 (24.1–43.8)	31.3 (24.1–43.8)	31.3 (24.1–43.8)
Outer London PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Outer London PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Outer London PM_{10}	Total	231 (126–768)	241 (125–869)	225 (115–848)	194 (115–848)
		Difference (%)	**10.3 (4.45%)**	**−5.57 (−2.41%)**	**−37.3 (−16.1%)**
Inner London PM_{10}	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London PM_{10}	brake	65.2 (44.1–84.6)	69 (46.4–89)	51.7 (34.8–66.8)	17.2 (34.8–66.8)
Inner London PM_{10}	tyre	31.2 (24.1–43.1)	32.6 (25.1–45.6)	32.6 (25.1–45.6)	32.6 (25.1–45.6)
Inner London PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Inner London PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Inner London PM_{10}	Total	241 (134–776)	248 (131–874)	231 (119–852)	196 (119–852)
		Difference (%)	**7.1 (2.94%)**	**−10.1 (−4.21%)**	**−44.6 (−18.5%)**
Rural PM_{10}	exhaust	4.77 (4.77–4.77)	0	0	0
Rural PM_{10}	brake	48.9 (30.8–74.2)	51.9 (32.4–79.1)	38.9 (24.3–59.3)	13 (24.3–59.3)
Rural PM_{10}	tyre	27.3 (21.1–37.8)	28.6 (22–40)	28.6 (22–40)	28.6 (22–40)
Rural PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Rural PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Rural PM_{10}	Total	215 (112–755)	227 (114–859)	214 (106–839)	188 (106–839)
		Difference (%)	**12.2 (5.69%)**	**−0.75 (−0.35%)**	**−26.7 (−12.4%)**

Calculated ranges, in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. $EF^{exhaust}$ fixed calculated rate, so ranges are a measure of NEEs errors. EF^{brake} and EF^{tyre} adjusted for average speed using Equation (6). BEV emissions are calculated for BEV without regenerative brakes; BEV with regenerative brakes offsetting 25% and 75% of brake emissions, BEV reg.lo and BEV reg.hi, respectively.

Appendix A.5. By-Weight, Brake and Tyre Proxy-Dependent Emissions EF Functions

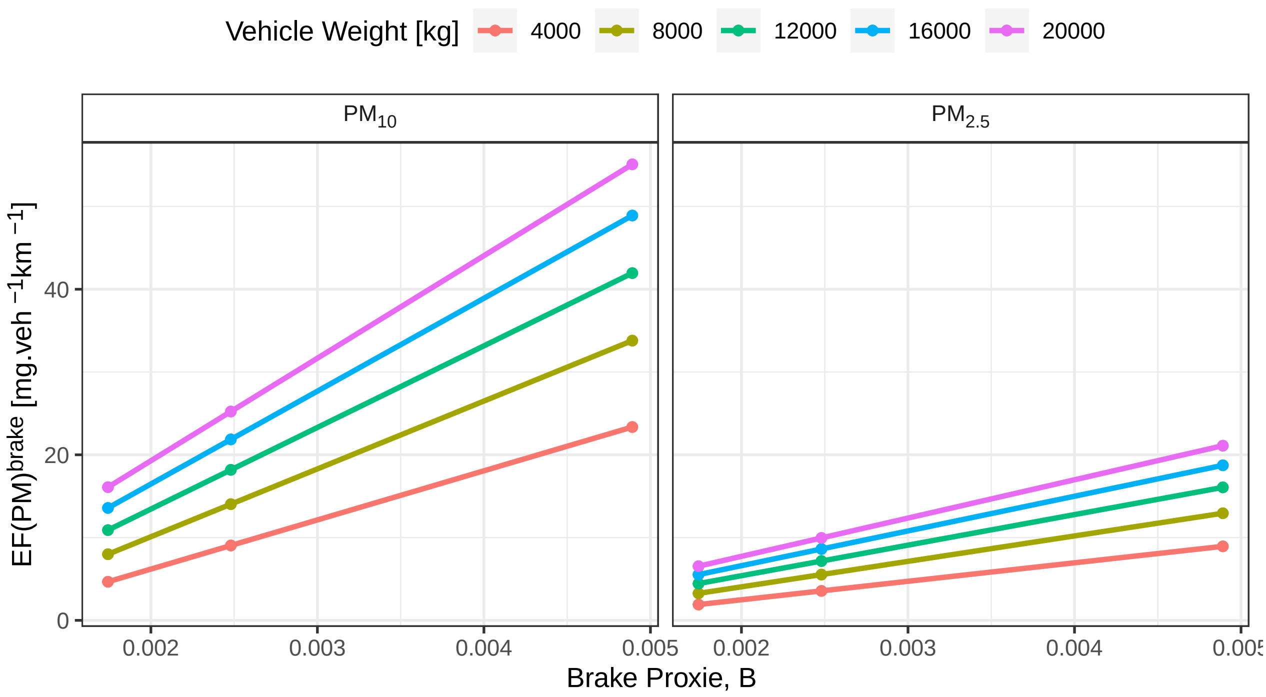

Figure A7. By-weight, brake proxy-dependent brake emissions EF^{break} functions.

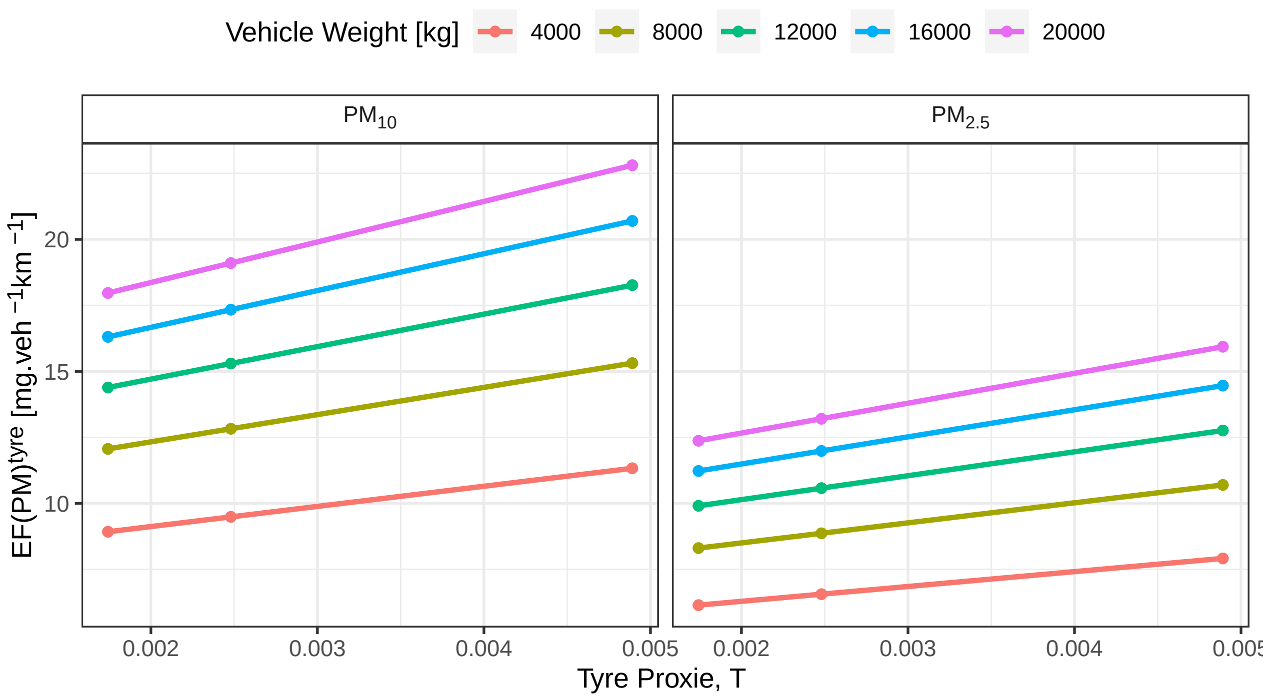

Figure A8. By-weight, tyre proxy-dependent brake emissions EF^{break} functions.

Appendix A.6. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Total PM Emissions Estimated Using by-Weight Brake and Tyre Work Proxy Functions (MODEL 02)

Table A3. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) contribution and total emissions of PM, calculated for Outer London, Inner London and Rural phases of the UK Bus Test Cycle using brake and tyre work proxies (Equations (7) and (8)).

PM Emissions	**Contribution**	**E6DV mg.veh^{-1}.km^{-1}**	**BEV mg.veh^{-1}.km^{-1}**	**BEV (regen.low) mg.veh^{-1}.km^{-1}**	**BEV (regen.high) mg.veh^{-1}.km^{-1}**
Outer London $PM_{2.5}$	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London $PM_{2.5}$	brake	34.8 (25.3–36.9)	36.6 (26.7–38)	27.5 (20–28.5)	9.16 (20–28.5)
Outer London $PM_{2.5}$	tyre	29.6 (22.4–41.7)	31 (23.3–44.1)	31 (23.3–44.1)	31 (23.3–44.1)
Outer London $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Outer London $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Outer London $PM_{2.5}$	Total	114 (75.7–256)	114 (72–278)	105 (65.4–269)	86.5 (65.4–269)
		Difference (%)	**−0.26 (−0.22%)**	**−9.41 (−8.24%)**	**−27.7 (−24.3%)**
Inner London $PM_{2.5}$	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London $PM_{2.5}$	brake	56.5 (43.7–48.9)	59.5 (45.9–49)	44.6 (34.5–36.8)	14.9 (34.5–36.8)
Inner London $PM_{2.5}$	tyre	39 (29.4–55.2)	40.9 (30.6–58.4)	40.9 (30.6–58.4)	40.9 (30.6–58.4)
Inner London $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Inner London $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Inner London $PM_{2.5}$	Total	149 (105–285)	147 (98.6–303)	132 (87.1–291)	102 (87.1–291)
		Difference (%)	**−2.27 (−1.53%)**	**−17.1 (−11.5%)**	**−46.9 (−31.5%)**
Rural $PM_{2.5}$	exhaust	4.77 (4.77–4.77)	0	0	0
Rural $PM_{2.5}$	brake	15.6 (9.2–26.4)	16.6 (9.69–28.3)	12.4 (7.27–21.3)	4.14 (7.27–21.3)
Rural $PM_{2.5}$	tyre	17.5 (13.4–24.4)	18.3 (14–25.8)	18.3 (14–25.8)	18.3 (14–25.8)
Rural $PM_{2.5}$	road	17.7 (13–23.8)	19 (13.9–25.7)	19 (13.9–25.7)	19 (13.9–25.7)
Rural $PM_{2.5}$	resuspended	24.8 (7.6–146)	27.3 (8.16–170)	27.3 (8.16–170)	27.3 (8.16–170)
Rural $PM_{2.5}$	Total	80.4 (48–225)	81.2 (45.7–250)	77.1 (43.3–243)	68.8 (43.3–243)
		Difference (%)	**0.86 (1.07%)**	**−3.28 (−4.09%)**	**−11.6 (−14.4%)**
Outer London PM_{10}	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London PM_{10}	brake	91.8 (68.2–97.1)	96.7 (71.8–100)	72.6 (53.8–75.2)	24.2 (53.8–75.2)
Outer London PM_{10}	tyre	41.2 (32–57)	43.2 (33.3–60.3)	43.2 (33.3–60.3)	43.2 (33.3–60.3)
Outer London PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Outer London PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Outer London PM_{10}	Total	274 (163–799)	287 (164–900)	262 (146–875)	214 (146–875)
		Difference (%)	**12.3 (4.49%)**	**−11.9 (−4.33%)**	**−60.2 (−22%)**
Inner London PM_{10}	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London PM_{10}	brake	150 (118–130)	158 (124–131)	118 (93.2–98.4)	39.5 (93.2–98.4)
Inner London PM_{10}	tyre	54 (42–74.6)	56.6 (43.7–78.9)	56.6 (43.7–78.9)	56.6 (43.7–78.9)
Inner London PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Inner London PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Inner London PM_{10}	Total	349 (226–854)	361 (227–950)	322 (196–917)	243 (196–917)
		Difference (%)	**12.3 (3.51%)**	**−27.2 (−7.8%)**	**−106 (−30.4%)**
Rural PM_{10}	exhaust	4.77 (4.77–4.77)	0	0	0
Rural PM_{10}	brake	40.6 (24.3–67.9)	43 (25.6–73)	32.3 (19.2–54.7)	10.8 (19.2–54.7)
Rural PM_{10}	tyre	24.8 (19.2–34.3)	26 (20–36.3)	26 (20–36.3)	26 (20–36.3)
Rural PM_{10}	road	32.3 (23.7–43.3)	34.7 (25.3–46.8)	34.7 (25.3–46.8)	34.7 (25.3–46.8)
Rural PM_{10}	resuspended	102 (31.6–595)	112 (34–693)	112 (34–693)	112 (34–693)
Rural PM_{10}	Total	204 (104–745)	216 (105–849)	205 (98.5–831)	183 (98.5–831)
		Difference (%)	**11.6 (5.71%)**	**0.89 (0.44%)**	**−20.6 (−10.1%)**

Calculated ranges, in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. $EF^{exhaust}$ fixed calculated rate, so ranges are a measure of NEEs errors. EF^{brake} and EF^{tyre} adjusted for brake and tyre work using Equations (7) and (8). BEV is BEV without regenerative brakes; BEV reg.lo and BEV reg.hi are BEV with regenerative brakes offsetting 25% and 75% of brake emissions, respectively.

Appendix A.7. Rerun of EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) Total PM Emissions Estimated Using by-Weight Brake and Tyre Work Proxy Functions and Different Weight BEVs (MODELS 03 and 04)

(**a**) BEV same weight as E6DV

(**b**) BEV 23% heavier than E6DV (twice current difference)

Figure A9. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) total *PM* emissions, calculated for UK Bus Test Cycle (UKBC) Outer London, Inner London and Rural phases, calculated using brake and tyre work proxies (Equations (7) and (8)) assuming different weights. BEV emissions are calculated for BEV without regenerative brakes; BEV with regenerative brakes offsets 25% of brake emissions (BEV reg.lo), and BEV with regenerative brakes offsets 75% of brake emissions (BEV reg.hi).

Table A4. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) contribution and total emissions of $PM_{2.5}$ and $PM_{2.5}$, calculated for Outer London, Inner London and Rural phases of the UK Bus Test Cycle using brake and tyre work proxies (Equations (7) and (8)) assuming BEV same weight as E6DV.

$PM_{2.5}$ Emissions	Contribution	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (regen.low) mg.veh^{-1}.km^{-1}	BEV (regen.high) mg.veh^{-1}.km^{-1}
Outer London $PM_{2.5}$	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London $PM_{2.5}$	brake	34.8 (25.3–36.9)	34.8 (25.3–36.9)	26.1 (19–27.7)	8.69 (19–27.7)
Outer London $PM_{2.5}$	tyre	29.6 (22.4–41.7)	29.6 (22.4–41.7)	29.6 (22.4–41.7)	29.6 (22.4–41.7)
Outer London $PM_{2.5}$	road	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)
Outer London $PM_{2.5}$	resuspended	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)
Outer London $PM_{2.5}$	Total	114 (75.7–256)	107 (68.3–248)	98.2 (62–239)	80.8 (62–239)
		Difference (%)	**−7.38 (−6.46%)**	**−16.1 (−14.1%)**	**−33.5 (−29.3%)**
Inner London $PM_{2.5}$	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London $PM_{2.5}$	brake	56.5 (43.7–48.9)	56.5 (43.7–48.9)	42.4 (32.8–36.7)	14.1 (32.8–36.7)
Inner London $PM_{2.5}$	tyre	39 (29.4–55.2)	39 (29.4–55.2)	39 (29.4–55.2)	39 (29.4–55.2)
Inner London $PM_{2.5}$	road	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)
Inner London $PM_{2.5}$	resuspended	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)
Inner London $PM_{2.5}$	Total	149 (105–285)	138 (93.7–274)	124 (82.8–262)	95.6 (82.8–262)
		Difference (%)	**−10.9 (−7.32%)**	**−25 (−16.8%)**	**−53.3 (−35.8%)**
Rural $PM_{2.5}$	exhaust	4.77 (4.77–4.77)	0	0	0
Rural $PM_{2.5}$	brake	15.6 (9.2–26.4)	15.6 (9.2–26.4)	11.7 (6.9–19.8)	3.9 (6.9–19.8)
Rural $PM_{2.5}$	tyre	17.5 (13.4–24.4)	17.5 (13.4–24.4)	17.5 (13.4–24.4)	17.5 (13.4–24.4)
Rural $PM_{2.5}$	road	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)	17.7 (13–23.8)
Rural $PM_{2.5}$	resuspended	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)	24.8 (7.6–146)
Rural $PM_{2.5}$	Total	80.4 (48–225)	75.6 (43.2–221)	71.7 (40.9–214)	63.9 (40.9–214)
		Difference (%)	**−4.77 (−5.94%)**	**−8.67 (−10.8%)**	**−16.5 (−20.5%)**
Outer London PM_{10}	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London PM_{10}	brake	91.8 (68.2–97.1)	91.8 (68.2–97.1)	68.8 (51.2–72.8)	22.9 (51.2–72.8)
Outer London PM_{10}	tyre	41.2 (32–57)	41.2 (32–57)	41.2 (32–57)	41.2 (32–57)
Outer London PM_{10}	road	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)
Outer London PM_{10}	resuspended	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)
Outer London PM_{10}	Total	274 (163–799)	267 (156–792)	244 (139–768)	198 (139–768)
		Difference (%)	**−7.38 (−2.69%)**	**−30.3 (−11.1%)**	**−76.2 (−27.8%)**
Inner London PM_{10}	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London PM_{10}	brake	150 (118–130)	150 (118–130)	113 (88.6–97.7)	37.5 (88.6–97.7)
Inner London PM_{10}	tyre	54 (42–74.6)	54 (42–74.6)	54 (42–74.6)	54 (42–74.6)
Inner London PM_{10}	road	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)
Inner London PM_{10}	resuspended	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)
Inner London PM_{10}	Total	349 (226–854)	338 (215–843)	300 (186–810)	225 (186–810)
		Difference (%)	**−10.9 (−3.12%)**	**−48.4 (−13.9%)**	**−123 (−35.4%)**
Rural PM_{10}	exhaust	4.77 (4.77–4.77)	0	0	0
Rural PM_{10}	brake	40.6 (24.3–67.9)	40.6 (24.3–67.9)	30.4 (18.2–51)	10.1 (18.2–51)
Rural PM_{10}	tyre	24.8 (19.2–34.3)	24.8 (19.2–34.3)	24.8 (19.2–34.3)	24.8 (19.2–34.3)
Rural PM_{10}	road	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)	32.3 (23.7–43.3)
Rural PM_{10}	resuspended	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)	102 (31.6–595)
Rural PM_{10}	Total	204 (104–745)	199 (98.9–740)	189 (92.8–723)	169 (92.8–723)
		Difference (%)	**−4.77 (−2.34%)**	**−14.9 (−7.31%)**	**−35.2 (−17.3%)**

Calculated ranges, in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. $EF^{exhaust}$ fixed calculated rate, so ranges are a measure of NEEs errors. EF^{brake} and EF^{tyre} adjusted for brake and tyre work using Equations (7) and (8). BEV is BEV without regenerative brakes; BEV reg.lo and BEV reg.hi are BEV with regenerative brakes offsetting 25% and 75% of brake emissions, respectively

Table A5. EURO VI Diesel Vehicle (E6DV) and Battery Electric Vehicle (BEV) contribution and total emissions of $PM_{2.5}$ and $PM_{2.5}$, calculated for Outer London, Inner London and Rural phases of the UK Bus Test Cycle using brake and tyre work proxies (Equations (7) and (8)) assuming BEV 23% heavier than E6DV (twice current difference).

$PM_{2.5}$ Emissions	Contribution	E6DV mg.veh^{-1}.km^{-1}	BEV mg.veh^{-1}.km^{-1}	BEV (regen.low) mg.veh^{-1}.km^{-1}	BEV (regen.high) mg.veh^{-1}.km^{-1}
Outer London $PM_{2.5}$	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London $PM_{2.5}$	brake	34.8 (25.3–36.9)	38.4 (27.9–39)	28.8 (20.9–29.2)	9.6 (20.9–29.2)
Outer London $PM_{2.5}$	tyre	29.6 (22.4–41.7)	32.3 (24.2–46.4)	32.3 (24.2–46.4)	32.3 (24.2–46.4)
Outer London $PM_{2.5}$	road	17.7 (13–23.8)	20.3 (14.7–27.6)	20.3 (14.7–27.6)	20.3 (14.7–27.6)
Outer London $PM_{2.5}$	resuspended	24.8 (7.6–146)	29.8 (8.7–195)	29.8 (8.7–195)	29.8 (8.7–195)
Outer London $PM_{2.5}$	Total	114 (75.7–256)	121 (75.5–308)	111 (68.6–299)	92 (68.6–299)
		Difference (%)	**6.63 (5.8%)**	**−2.97 (−2.6%)**	**−22.2 (−19.4%)**
Inner London $PM_{2.5}$	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London $PM_{2.5}$	brake	56.5 (43.7–48.9)	62.2 (48.1–48.9)	46.7 (36.1–36.7)	15.6 (36.1–36.7)
Inner London $PM_{2.5}$	tyre	39 (29.4–55.2)	42.6 (31.7–61.5)	42.6 (31.7–61.5)	42.6 (31.7–61.5)
Inner London $PM_{2.5}$	road	17.7 (13–23.8)	20.3 (14.7–27.6)	20.3 (14.7–27.6)	20.3 (14.7–27.6)
Inner London $PM_{2.5}$	resuspended	24.8 (7.6–146)	29.8 (8.7–195)	29.8 (8.7–195)	29.8 (8.7–195)
Inner London $PM_{2.5}$	Total	149 (105–285)	155 (103–333)	139 (91.2–321)	108 (91.2–321)
		Difference (%)	**6.02 (4.04%)**	**−9.54 (−6.4%)**	**−40.6 (−27.3%)**
Rural $PM_{2.5}$	exhaust	4.77 (4.77–4.77)	0	0	0
Rural $PM_{2.5}$	brake	15.6 (9.2–26.4)	17.5 (10.2–30.2)	13.1 (7.62–22.7)	4.37 (7.62–22.7)
Rural $PM_{2.5}$	tyre	17.5 (13.4–24.4)	19.1 (14.5–27.1)	19.1 (14.5–27.1)	19.1 (14.5–27.1)
Rural $PM_{2.5}$	road	17.7 (13–23.8)	20.3 (14.7–27.6)	20.3 (14.7–27.6)	20.3 (14.7–27.6)
Rural $PM_{2.5}$	resuspended	24.8 (7.6–146)	29.8 (8.7–195)	29.8 (8.7–195)	29.8 (8.7–195)
Rural $PM_{2.5}$	Total	80.4 (48–225)	86.7 (48.1–280)	82.3 (45.5–273)	73.6 (45.5–273)
		Difference (%)	**6.33 (7.88%)**	**1.96 (2.44%)**	**−6.78 (−8.43%)**
Outer London PM_{10}	exhaust	7.38 (7.38–7.38)	0	0	0
Outer London PM_{10}	brake	91.8 (68.2–97.1)	101 (75.1–103)	76.1 (56.3–77.1)	25.4 (56.3–77.1)
Outer London PM_{10}	tyre	41.2 (32–57)	45.1 (34.5–63.4)	45.1 (34.5–63.4)	45.1 (34.5–63.4)
Outer London PM_{10}	road	32.3 (23.7–43.3)	37 (26.9–50.1)	37 (26.9–50.1)	37 (26.9–50.1)
Outer London PM_{10}	resuspended	102 (31.6–595)	122 (36.3–795)	122 (36.3–795)	122 (36.3–795)
Outer London PM_{10}	Total	274 (163–799)	306 (173–1010)	280 (154–986)	230 (154–986)
		Difference (%)	**31.5 (11.5%)**	**6.11 (2.23%)**	**−44.6 (−16.3%)**
Inner London PM_{10}	exhaust	10.9 (10.9–10.9)	0	0	0
Inner London PM_{10}	brake	150 (118–130)	165 (130–131)	124 (97.5–98.5)	41.3 (97.5–98.5)
Inner London PM_{10}	tyre	54 (42–74.6)	59.1 (45.3–83.1)	59.1 (45.3–83.1)	59.1 (45.3–83.1)
Inner London PM_{10}	road	32.3 (23.7–43.3)	37 (26.9–50.1)	37 (26.9–50.1)	37 (26.9–50.1)
Inner London PM_{10}	resuspended	102 (31.6–595)	122 (36.3–795)	122 (36.3–795)	122 (36.3–795)
Inner London PM_{10}	Total	349 (226–854)	383 (238–1060)	342 (206–1030)	260 (206–1030)
		Difference (%)	**34.7 (9.94%)**	**−6.65 (−1.91%)**	**−89.3 (−25.6%)**
Rural PM_{10}	exhaust	4.77 (4.77–4.77)	0	0	0
Rural PM_{10}	brake	40.6 (24.3–67.9)	45.4 (26.8–77.8)	34 (20.1–58.4)	11.3 (20.1–58.4)
Rural PM_{10}	tyre	24.8 (19.2–34.3)	27.1 (20.7–38.2)	27.1 (20.7–38.2)	27.1 (20.7–38.2)
Rural PM_{10}	road	32.3 (23.7–43.3)	37 (26.9–50.1)	37 (26.9–50.1)	37 (26.9–50.1)
Rural PM_{10}	resuspended	102 (31.6–595)	122 (36.3–795)	122 (36.3–795)	122 (36.3–795)
Rural PM_{10}	Total	204 (104–745)	232 (111–962)	220 (104–942)	198 (104–942)
		Difference (%)	**27.7 (13.6%)**	**16.4 (8.03%)**	**−6.33 (−3.1%)**

Calculated ranges, in brackets after calculated value, are based on estimated NEEs ranges as reported in Tables 2–5. $EF^{exhaust}$ fixed calculated rate, so ranges are a measure of NEEs errors. EF^{brake} and EF^{tyre} adjusted for brake and tyre work using Equations (7) and (8). BEV is BEV without regenerative brakes; BEV reg.lo and BEV reg.hi are BEV with regenerative brakes offsetting 25% and 75% of brake emissions, respectively.

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