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Comparative analysis of non-exhaust airborne particles from electric and internal combustion engine vehicles

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ABSTRACT

This paper evaluates the effect of the electrification of the small, medium, and large internal combustion engine (ICE) passenger cars on the levels of total particulate matter (PM). The total mean PM_{10} and $PM_{2.5}$ emission factors (EFs) on urban, rural, and motorway roads are in the range of 26.13 – 39.57 mg km^{-1} veh^{-1} and 13.39 – 18.44 mg km^{-1} veh^{-1}, respectively, from small to large ICE passenger cars. Correspondingly, the total mean PM_{10} and $PM_{2.5}$ non-exhaust EFs on urban, rural, and motorway roads range from 27.76 to 43.43 mg km^{-1} veh^{-1} and 13.17 –19.24 mg km^{-1} veh^{-1} from equivalent small to large electric vehicles (EVs) without regenerative braking. These results show that the total non-exhaust PM from the equivalent EVs may exceed all PM from ICE passenger cars, including exhaust particle emissions, which are dependent mainly on the extent of regenerative braking, followed by passenger car type and road type. PM_{10} EFs for equivalent EVs without regenerative braking on urban, rural, and motorway roads are all higher than those from ICE cars. As for $PM_{2.5}$, most of the equivalent EVs require different extents of regenerative braking to reduce brake emissions to be in line with all particle emissions from relative ICE cars.

1. Introduction

The number of electric vehicles (EVs), especially electric passenger cars, has increased significantly recent years because the policies of many governments steadily incentive electrification of the vehicle fleet (AIRUSE, 2016; Li et al., 2019; Yang, 2016). The electrification of vehicles has been considered a solution to air pollution, which provides zero emissions and promising cleaner urban air (Calef and Goble, 2007; Murrells and Pang, 2013). These advocates often, however, neglect the particulate matter (PM) emissions from the non-exhaust emissions, including brake wear, tyre wear, road wear, and resuspension of road dust. In fact, non-exhaust emissions have been considered as a critical contributor to ambient PM as tailpipe emission standards for internal combustion engine vehicles (ICEVs) have become more and more stringent (Amato et al., 2014; Grigoratos and Martini, 2014; Ho et al., 2006; Hong et al., 2020). Squizzato et al. (2016) and Rexeis and Hausberger (2009) revealed that non-exhaust emissions would contribute up to 90% to total PM emissions from traffic.

Compared to ICEVs, the advantage of EVs is that they have no exhaust emissions, but EVs will emit abundant non-exhaust emissions due to the heavier weight than ICEVs (Hooftman et al., 2018). This implies that the increasing popularity of EVs might not trigger a remarkable reduction in PM levels and no significant improvement in air quality. Soret et al. (2014) evaluated the effect of EVs on air quality and revealed that the electrification of vehicle fleet would not considerably reduce PM emissions due to the generation of substantial non-exhaust emissions. Timmers and Achten (2016) pointed out that as EVs were generally heavier than the ICE equivalents, the non-exhaust emissions generated from EVs, even with 100% regenerative braking, may exceed all particle emissions generated from equivalent ICEVs.

Exhaust and non-exhaust PMs emitted from passenger cars are one of the significant contributors to ambient PM, especially in urban areas (Goel and Kumar, 2014). These PMs are composed of agglomerated particles with absorbed organic and inorganic species on their surfaces, which affects human health visibility and climate change (Peng et al., 2016; Ubando et al., 2021; Woo et al., 2021; Zazouli et al., 2021). For

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instance, PM was considered as a short-lived climate forcer with a high global warming potential (Prasad and Bella, 2010). Previous toxicological and epidemiological studies have identified that PM could accumulate in the respiratory system and even penetrate the cell membranes to induce inheritable mutations (Amato et al., 2014; Riedl and Diaz-Sanchez, 2005). In addition, PM was one of Europe's most problematic pollutants in terms of harm to human health based on the European Environmental Agency (EEA), which was responsible for thousands of premature deaths in the European Region every year (EEA, 2014). GBD 2015 Risk Factors Collaborators (2016) revealed that exposure to PM pollution was the sixth leading risk factor worldwide with both short-term and long-term health effects.

In this context, this study aims to evaluate total PM emissions from small, medium, and large conventional passenger cars and the equivalent EVs to form a view as to how electrification of various types of passenger cars will affect the PM emissions within the fleet. The mean PM emission factors (EFs) of various types of ICEVs and EVs within the fleet are beneficial for the regulatory authorities and policy makers to design the mitigation strategies and to compute their individual contributions and impacts on public health and local air quality (Timmers and Achten, 2016; Tran et al., 2021; Wang et al., 2021). The non-exhaust PM_{10} and $PM_{2.5}$ emissions from tyre wear, brake wear, road wear, and road dust resuspension on urban, rural and motorway roads were calculated according to the method recently reported by Beddows and Harrison (2020). The present analysis is only concerned with passenger cars on sale because the statistics of these vehicle weight are available.

2. Methods

ICE passenger cars are classified into three types based on the difference in vehicle kerb weight: small (< 1200 kg), medium (between 1200 kg and 1600 kg), and large (> 1600 kg) passenger cars (Simons, 2016). To evaluate the additional non-exhaust emissions due to the electrification of cars causing an increase in vehicle weight, a comparative estimation is needed between the weights of various types of ICE cars and corresponding EVs. Various types of ICEV-EV pairs were selected from an internet database (Chapple, 2017). For each pair of selected either petrol or diesel passenger cars and equivalent EVs, their output power was matched within 15%. Non-exhaust EFs of these ICE passenger cars and their corresponding EVs were calculated based on the approach recently reported by Beddows and Harrison (2020). This approach includes the following steps: (1) 2995 $PM_{2.5}$ EFs and 2933 PM_{10} EFs including tyre wear, brake wear, road wear and road dust resuspension were adopted for various vehicle types and road types employed in national inventories; (2) the vehicle mass with each vehicle type was associated with these EFs; (3) the separate correlations between EFs and vehicle mass for each tyre wear, brake wear, road wear and resuspension of road dust were determined, as shown in Eq. (1), and the square of each correlation coefficient (R^2) is listed in Table 1; (4) the masses of various types of passenger cars and the equivalent EVs were estimated; (5) the EFs for various types of ICE passenger cars and the equivalent EVs on urban, rural, motorway roads were evaluated.

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

where W_{ref} is the vehicle mass divided by 1000 kg, the b (mg km^{-1} veh^{-1}) and c (no unit) are regression coefficients and are listed in Table 1.

Compared to ICEVs, regenerative braking of EVs is another feature, which could lower effectively brake wear emissions (DeLuchi et al., 1989; Hawkins et al., 2013). Few experimental studies, however, have been done to quantify the reduction in brake emissions so far, and only several researchers have provided some predictions (Barlow, 2014; Del Duce et al., 2014; Hooftman et al., 2016; Ligterink et al., 2014; Van Zeebroek and De Ceuster, 2013). For instance, Barlow (2014) implied that regenerative braking of EVs could produce nearly no brake wear emissions. A report by Ligterink et al. (2014) suggested that up to 95% reduction in brake emissions could be achieved by means of regenerative braking. In the study by Van Zeebroek and De Ceuster (2013), they pointed out that the 50% brake wear emissions were reduced with 50% regenerative braking. Hooftman et al. (2016) revealed that there was a 66% reduction in brake emissions through the 66% regenerative braking. Based on the estimation of braking regenerative above, the EVs with 0%, 50%, and 100% regenerative braking were evaluated in this work. Regenerative braking slows down vehicle speed by converting the kinetic energy into a form that can be either used immediately or stored till needed. As a result, no brake wear emission would be emitted when regenerative braking is used to slow down vehicle speed. That is, the EVs with 60% regenerative braking can reduce 60% brake wear emissions. The total EFs for the ICEVs (EF_{ICEV}) and equivalent EVs with 0% ($EF_{EV}^{0\%RB}$), 50% ($EF_{EV}^{50\%RB}$), and 100% ($EF_{EV}^{100\%RB}$) regenerative braking were calculated by the following Eqs. (2), (3), (4), and (5).

$$EF_{ICEV} = EF_{ICEV}^{TYRE} + EF_{ICEV}^{BRAKE} + EF_{ICEV}^{ROAD} + EF_{ICEV}^{RESUS} + EF_{ICEV}^{EXHAUST} \quad (2)$$

$$EF_{EV}^{0\%RB} = EF_{EV}^{TYRE} + EF_{EV}^{ROAD} + EF_{EV}^{RESUS} + 1.0 \times EF_{EV}^{BRAKE} \quad (3)$$

$$EF_{EV}^{50\%RB} = EF_{EV}^{TYRE} + EF_{EV}^{ROAD} + EF_{EV}^{RESUS} + 0.5 \times EF_{EV}^{BRAKE} \quad (4)$$

$$EF_{EV}^{100\%RB} = EF_{EV}^{TYRE} + EF_{EV}^{ROAD} + EF_{EV}^{RESUS} + 0.0 \times EF_{EV}^{BRAKE} \quad (5)$$

3. Results and discussion

3.1. Weight evaluation of EVs and ICEVs

Non-exhaust airborne particles from traffic are generated from tyre wear, brake wear, and road surface wear and from the resuspension of deposited material that already existed on-road owing to vehicle-induced turbulence (Amato et al., 2011). Each of the sources of non-exhaust airborne particles is closely related to vehicle weight (Timmers and Achten, 2016, 2018). Friction between the tyre tread and road surface results in road abrasion and tyre wear, which is closely

Table 1
Regression coefficient (b and c) used to fit the EFs vs. vehicle weight and the square of each correlation coefficient (Beddows and Harrison, 2020).

		Urban			Rural			Motorway		
		b	c	R^2	b	c	R^2	b	c	R^2
Tyre	$PM_{2.5}$	5.8	2.3	0.89	4.5	2.3	0.90	3.8	2.3	0.87
	PM_{10}	8.2	2.3	0.94	6.4	2.3	0.91	5.5	2.3	0.90
Brake	$PM_{2.5}$	4.2	1.9	0.90	1.8	1.5	0.89	0.4	1.3	0.90
	PM_{10}	11.0	1.9	0.92	4.5	1.5	0.87	1.0	1.3	0.86
		Urban/Rural/Motorway								
		b				c				R^2
Road wear	$PM_{2.5}$	2.8				1.5				0.89
	PM_{10}	5.1				1.5				0.86
Resuspension	$PM_{2.5}$	2.0				1.1				0.87
	PM_{10}	8.2				1.1				0.85

associated with to friction coefficient between them and the normal force against the road (Muller et al., 2003; Rajamani et al., 2010). This normal force is proportional to the vehicle mass, meaning that increasing vehicle mass enhances the wear rates of tyre tread and road surface and thereby generates more non-exhaust emissions. Friction between the brake pad and brake disc leads to brake wear. The friction energy requires to reduce vehicle momentum is proportional to the vehicle speed and weight (Archard, 1953; Kakad et al., 2017). Accordingly, more energy is required to decelerate vehicle speed with the increase of vehicle weight, resulting in worse brake wear. Vehicle-induced turbulence causes the resuspension of deposited material on road, which is highly dependent on vehicle size, mass, and aerodynamics. Heavier vehicles trigger stronger turbulence, leading to increased resuspension (Timmers and Achten, 2016).

The effect of vehicle weight on non-exhaust emissions has been reported by several researchers. Simons (2016) calculated the PM_{10} EFs of brake, tyre, and road surface wear and found that these emissions factors from a medium car with 1600 kg increased by about 50% than those from the small car with 1200 kg. Large cars with 2000 kg generated more than twice the amount of PM_{10} relative to corresponding small cars. Wang et al. (2017) studied the correlations between contact properties of tyre and tyre wear and revealed that there was an almost linear correlation between vertical load and tyre wear. In the study by Garg et al. (2000), brake emissions were evaluated from small cars, large cars, and large pickup trucks. They found that the brake emissions of large cars and large pickup trucks emitted more than 55% and twice the quantity of suspended particles relative to the small car. Amato et al. (2012) studied the effect of vehicle weight on resuspension of deposited material on road. They pointed out that resuspension emissions exhibited a strong linear correlation with the vehicle weight and resuspension rates of PM_{10} from passenger cars were 10 times higher than those from motorcycles.

The electrification of cars leads to an increase in vehicle weight primarily because of the increment in the weight of the battery pack that is used to drive the motors of EVs. Various types of ICE cars switch to equivalent EVs, however, cause a significant difference in percentage increase of vehicle weight. Accordingly, the weight of small, medium, and large ICE passenger cars as well as their equivalent EVs was evaluated according to the method mentioned above. Tables 2 and 3 show weight comparison between various types of ICE passenger cars and their equivalent EVs. The average weight of small, medium and large petrol ICE cars are 1037, 1333, and 1827 kg, and the average weights of their equivalent EVs are 191 (18%), 313 (23%), and 433 kg (24%) heavier than them, respectively. The average weight difference from small, medium and large diesel cars to the EV counterparts is 197, 232, and 362 kg, respectively, corresponding to the increase of 15%, 17%, and 19%. Compared with the various types of petrol ICE cars, the electrification of diesel engine cars shows less increase in average weight. In addition, it is interesting to note that whether it is petrol or diesel passenger cars, from small cars to large cars, the percentage increases in average vehicle weight all exhibit rising trend.

In the evaluation of Faria et al. (2012), they reported that the average weight difference was 256 kg from ICEVs and EVs, and the percentage increase was 20%. Timmers and Achten (2016) revealed that, on average, EVs are 280 kg (24%) heavier than their ICE equivalents. Beddows and Harrison (2020) reported that the electrification of passenger cars caused a 300 kg increase in vehicle average mass, and the percentage increase was 21%. In the present study, the average weight difference for all the vehicle samples is 282 kg with a corresponding increase of 20%, in agreement with the preceding literature data.

3.2. Emission factors of EVs and ICEVs

3.2.1. Non-exhaust emission factors

Non-exhaust EFs for different types of petrol and diesel ICE passenger cars and their equivalent EVs were calculated according to the method reported by Beddows and Harrison (2020), and the calculated results are shown in Figs. 1 and 2. It is obvious that PM_{10} and $PM_{2.5}$ EFs of all the non-exhaust emissions exhibit a gradually increasing trend from small ICE cars and equivalent EVs to large ICE cars and equivalent EVs. As expected, the $PM_{2.5}$ and PM_{10} EFs generated from tyre and brake wear for both ICE passenger cars and corresponding EVs on the urban environment are higher than those on both rural and motorway roads. Such behavior is mainly as a result of higher frequency of acceleration and

Table 2
Weight comparison between various types of petrol ICE passenger cars and equivalent EVs (https://www.encycarpedia.com/).

Passenger car type	EV name	Petrol ICE car name	Kerb weight, EV (kg)	Kerb weight, ICEV (kg)	Difference (kg)
Small size	Mitsubishi i-MiEV	Mitsubishi Mirage 1.0	1185	920	265
	BMW Mini Cooper SE 3 Door	BMW Mini Cooper S 3 Door	1365	1200	165
	Smart Fortwo Coupe Electric	Smart Fortwo Coupe 0.9 L	1095	995	100
	Citroën C-Zero	Citroën C3 PureTech 68	1140	1051	89
	SEAT Mii Electric	SEAT Mii 1.0 75	1130	929	201
	Peugeot e208	Peugeot 208 Pure Tech 130	1455	1158	297
	Volkswagen e-up	Volkswagen cross up	1229	1009	220
Average weight (EVs): 1228 kg Average weight (ICEVs): 1037 kg Average difference: 191 kg					
Medium size	Mercedes B 250 e	Mercedes B 250	1735	1495	240
	Ford Focus Electric	Ford Focus 1.8 125	1644	1288	356
	Nissan Leaf Acenta	Nissan Micra N-Sport	1995	1560	435
	Hyundai Kona Electric 39	Hyundai Kona 1.0 T-GDI 2WD	1535	1233	302
	Honda e Advance	Honda Jazz 1.5 i-MMD	1526	1228	298
	Vauxhall Corsa-e	Vauxhall Corsa Gsi	1530	1214	316
	Kia Soul EV	Kia Soul 1.6 GD	1593	1287	306
	Volkswagen ID.4 Pro	Volkswagen Polo GTI	1605	1355	249
Average weight (EVs): 1645 kg Average weight (ICEVs): 1333 kg Average difference: 313 kg					
Large size	Jaguar I-pace EV	Jaguar E-pace P300	2208	1894	314
	Mercedes SLS AMG Electric Drive	Mercedes SLS AMG Black Series	2110	1625	485
	Jaguar I-Pace EV400	Jaguar F-Pace	2185	1861	324
	Porche Tycan Turbo	Porche 911 Turbo S	2305	1640	665
	Audi e-tron 50 Quattro	Audi Q7 3.0 TFSI Quattro	2370	2045	325
	Volvo XC40 P8 AWD Recharge	Volvo V60 POLESTAR AWD	2150	1796	354
	Mercedes EQC 400 Estate 4MATIC	Mercedes E43 AMG Estate 4MATIC	2495	1930	565
Average weight (EVs): 2260 kg Average weight (ICEVs): 1827 kg Average difference: 433 kg					

Table 3
Weight comparison between various types of diesel ICE passenger cars and corresponding EVs (https://www.encycarpedia.com/).

Passenger car type	EV name	Diesel ICE car name	Kerb weight, EV (kg)	Kerb weight, ICEV (kg)	Difference (kg)
Small size	Smart Fortwo Coupe Electric	Smart Forfour Coupe cdi 95	1200	1085	115
	Volkswagen e-up	Volkswagen Cross Polo 1.2 70	1214	1053	161
	Citroën AX Electric	Citroën C3 BlueHDi 75 S/S	1380	1165	215
Average weight (EVs): 1298 kg Average weight (ICEVs): 1101 kg Average difference: 197 kg					
Medium size	Ford Focus Electric	Ford Focus 2.0 TDCi 136	1644	1378	266
	Renault Fluence Z.E.	Renault Fluence dCi 90 FAP	1605	1280	325
	Hyundai KONA Electric 39 KWh	Hyundai i30 1.6 CRDi 136	1535	1338	197
	Renault Zoe R110	Renault dCi 115	1502	1277	225
	Honda e	Honda Civic 1.6 i-DTEC	1531	1301	230
	DS DS 3 Crossback E-Tense	DS DS 4 BlueHDi 120	1523	1365	158
	Vauxhall Corsa-e	Vauxhall Corsa 1.7 CDTI 130	1530	1278	252
	Kia Soul EV	Kia Soul 1.6 CRDi	1593	1390	203
Average weight (EVs): 1558 kg Average weight (ICEVs): 1326 kg Average difference: 232 kg					
Large size	Volkswagen ID.4 Pro	Volkswagen Passat Alltrack 2.0 TDI	2124	1725	399
	Jaguar I-pace EV	Jaguar E-pace D240	2208	1926	282
	Audi e-tron 50 Quattro	Audi Q7 50 TDI Quattro	2370	2090	280
	Mercedes CLS 400 d 4MATIC	Mercedes CLS 400 d 4MATIC	2495	1935	560
	BMW iX3	BMW X3 xDrive30d	2185	1895	290
Average weight (EVs): 2276 kg Average weight (ICEVs): 1914 kg Average difference: 362 kg					

deceleration manoeuvres on the urban road compared to rural and motorway roads, leading to an increase in tyre and brake wear emissions (Kwak et al., 2013; Yang et al., 2018).

The EF values calculated in the present study are consistent with the data published in most literature (Beddows and Harrison, 2020; EEA, 2019a, 2019b; Luhana et al., 2004; NAEI, 2018; Piscitello et al., 2021). Table 4 summarizes the PM_{10} and $PM_{2.5}$ EFs from tyre, brake, road wear, and resuspension of road dust published in the literature and the results in the present work. In the present work, the mean PM_{10} and $PM_{2.5}$ EFs from tyre wear on urban, rural, and motorway roads are in the range of 6.81–8.71 mg km^{-1} veh^{-1} and 4.77–6.11 mg km^{-1} veh^{-1} from small to large petrol cars as well as in the range of 6.98 – 8.88 mg km^{-1} veh^{-1} and 4.90–6.23 mg km^{-1} veh^{-1} from small to large diesel cars, respectively. Beddows and Harrison (2020) evaluated the PM_{10} and $PM_{2.5}$ EFs of tyre wear using a receptor modelling method. They found and that the mean values of PM_{10} and $PM_{2.5}$ EFs from passenger cars on urban, rural and motorway roads were 7.1 mg km^{-1} veh^{-1} and 5.0 mg km^{-1} veh^{-1}, respectively. The updated emission inventory by EEA (2019a) obtained values of 6.4 mg km^{-1} veh^{-1} for PM_{10} and 4.5 mg km^{-1} veh^{-1} for $PM_{2.5}$. The UK National Atmospheric Emission Inventory (NAEI, 2018) confirmed that the tyre wear EFs of PM_{10} and $PM_{2.5}$ for passenger vehicles were 7 mg km^{-1} veh^{-1} and 5 mg km^{-1} veh^{-1}, respectively, which is in agreement with the current tyre wear EFs. As for the EFs from brake wear, the brake wear emissions of C-segment (medium) passenger cars were measured by our project partner (Brembo) in the brake dynamometer over the novel worldwide harmonised light-duty vehicles test procedure (WLTP)–brake cycle (Grigoratos et al., 2020; Mathissen et al., 2018), including 303 stops over a total distance of 192 km. The obtained mean values of PM_{10} and $PM_{2.5}$ EFs are 7.02 mg km^{-1} veh^{-1} and 2.26 mg km^{-1} veh^{-1}, respectively, which provides further evidence of the calculated mean PM_{10} and $PM_{2.5}$ EF values of 6.49 mg km^{-1} veh^{-1} and 2.52 mg km^{-1} veh^{-1} of medium cars in the present work. In addition, in the brake dynamometer tests performed by Garg et al. (2000), they obtained slightly lower PM_{10} and $PM_{2.5}$ EFs of 5.2 mg km^{-1} veh^{-1} and 2.3 mg km^{-1} veh^{-1}. The median PM_{10} and $PM_{2.5}$ brake wear EFs from EEA (2019a) were 7.4 mg km^{-1} veh^{-1} and 2.9 mg km^{-1} veh^{-1}. Compared to tyre and brake wear, few studies provided road wear and resuspension PM_{10} and $PM_{2.5}$ EFs. Road wear PM_{10} and $PM_{2.5}$ EFs of 7.5 mg km^{-1} veh^{-1} and 4.1 mg km^{-1} veh^{-1} were reported by EEA (2019b). Beddows and Harrison (2020) estimated the PM_{10} and $PM_{2.5}$ EFs of road wear and resuspension of road dust and obtained the corresponding PM_{10} and $PM_{2.5}$ EFs of 6.1 mg km^{-1} veh^{-1} and 3.3 mg km^{-1} veh^{-1} from road wear as well as 11 mg km^{-1} veh^{-1} and 2.7 mg km^{-1} veh^{-1} from resuspension of road dust, respectively, in agreement with the current results.

To further assess the impact of various types of petrol and diesel cars electrification on non-exhaust emissions, the increase and percentage increase in EFs were calculated from various types of ICE cars to corresponding EVs. The calculated results are summarised in Tables 5 and 6. There are increasing in the percentage increases in PM_{10} and $PM_{2.5}$ EFs of the tyre, brake, road wear, and resuspension of road dust on urban, rural and motorway from small ICE cars converting into the equivalent EVs to large ICE cars converting into the equivalent EVs, indicating that the large ICE cars switch to the equivalent EVs makes greater contributor to non-exhaust emissions. The percentage increases of non-exhaust EFs on urban, rural, and motorway are in the range of 7.62–21.33% for petrol ICE cars switch to the equivalent EVs and 6.21–17.06% for diesel ICE cars switch to the equivalent EVs. Compared to petrol ICE passenger cars, diesel ICE cars exhibit a smaller percentage increase because diesel ICE cars are heavier relative to petrol ICE cars and thereby the increase in EFs is less when compared to their equivalent EVs. In addition, it is visible that the increments in tyre and brake wear EFs for various types of ICE cars switch to their equivalent EVs reduce from urban to rural to motorway, whereas percentage increases in EFs for tyre wear EFs are equal, and the percentage increases for brake wear EFs rise gradually.

3.2.2. Exhaust emission factors

ICE passenger cars generate PM via exhaust and non-exhaust pathways. In order to fully assess the impact of passenger car electrification on PM_{10} and $PM_{2.5}$, PM EFs from the ICE car pipeline are also needed. Here, EFs from Euro 6 cars reported in UK's Road Transport Emissions Inventory are used (Brown et al., 2018). The ratio of PM_{10} to $PM_{2.5}$ in this inventory is 1.0, which indicates that all exhaust particle emissions are in the range of $PM_{2.5}$ size. EFs for petrol ICE cars on urban, rural, and motorway are 1.46, 1.24, and 1.80 mg km^{-1}·veh^{-1}, respectively. There are 1.49, 1.11, and 0.90 mg km^{-1}·veh^{-1} for EFs of diesel ICE cars on urban, rural, and motorway. Compared to particle emissions from petrol ICE cars, diesel ICE cars have higher emissions on urban roads and lower emissions on rural and motorway roads.

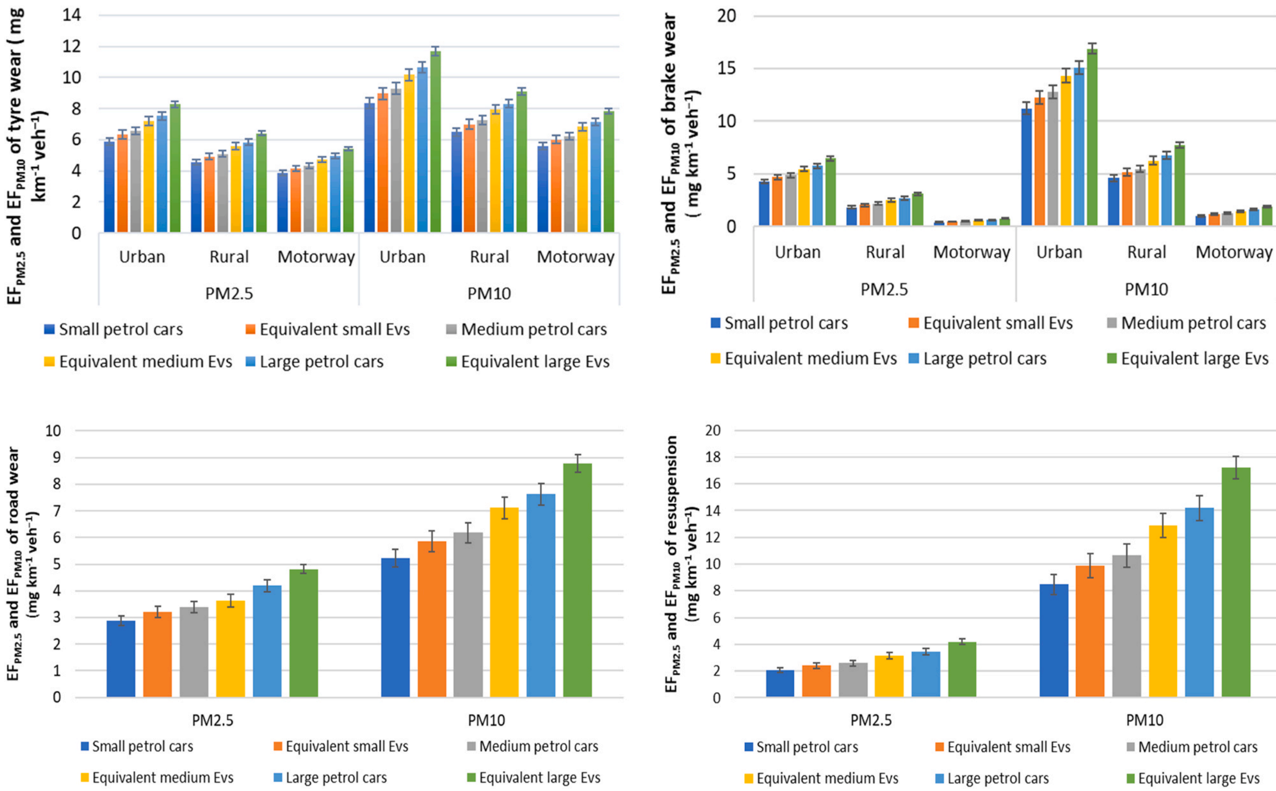

Fig. 1. Non-exhaust EFs for three types of petrol ICE passenger cars and their equivalent EVs. The error bars indicate the standard error.

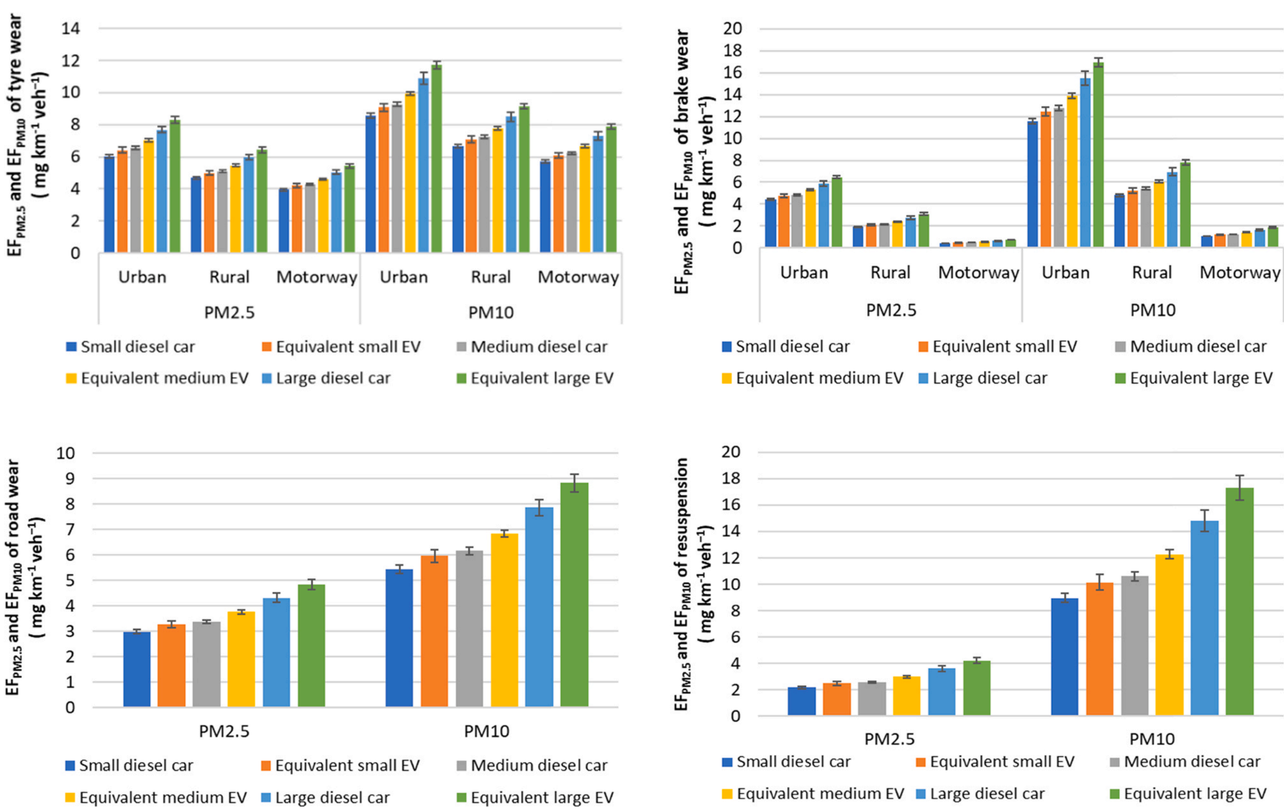

Fig. 2. Non-exhaust EFs for three types of diesel ICE passenger cars and their equivalent EVs. The error bars indicate the standard error.

Table 4
Summary of the PM_{10} and $PM_{2.5}$ EFs from tyre, brake, road wear, and resuspension of road dust.

Non-exhaust emissions	PM_{10} EF (mg km^{-1} veh^{-1})	$PM_{2.5}$ EF (mg km^{-1} veh^{-1})	Data sources	Reference
Tyre wear	6.81–8.71[a] 6.98–8.88[b]	4.77–6.11[a] 4.90–6.23[b]	Receptor modelling	Present work
	7.4	~	Receptor Modelling	(Luhana et al., 2004)
	7.1	5.0	Receptor Modelling	(Beddows and Harrison, 2020)
	6.1	2.9	Receptor Modelling	(Timmers and Achten, 2016)
	7	5	Emission inventory	(NAEI, 2018)
	6.4	4.5	Emission inventory	(EEA, 2019a)
Brake wear	5.62–7.81[a] 5.82–8.02[b]	2.18–3.03[a] 2.26–3.12[b]	Receptor modelling	Present work
	7.02[c]	2.26[c]	Brake dynamometer study	Present work
	5.8	~	Brake dynamometer study	(Iijima et al., 2008)
	5.2	2.3	Brake dynamometer study	(Garg et al., 2000)
	7.4	~	Receptor modelling	(Dahl et al., 2006)
	9.3	2.2	Receptor modelling	(Timmers and Achten, 2016)
	6.20	2.47	Receptor modelling	(Beddows and Harrison, 2020)
	7.4	2.3	Receptor modelling	(Piscitello et al., 2021)
	7.4	2.9	Emission inventory	(EEA, 2019a)
	7.0	3.0	Emission inventory	(NAEI, 2018)
Road wear	5.23–7.62[a] 5.44–7.86[b]	2.87–4.19[a] 2.99–4.32[b]	Receptor modelling	Present work
	7.5	3.1	Receptor modelling	(Timmers and Achten, 2016)
	6.1	3.3	Receptor modelling	(Beddows and Harrison, 2020)
	7.75	4.05	Receptor modelling	(Piscitello et al., 2021)
	7.5	4.1	Emission inventory	(EEA, 2019b)
Resuspension of road dust	8.48–14.18[a] 8.95–14.80[b]	2.07–3.46[a] 2.18–3.61[b]	Receptor modelling	Present work
	5.4–9.0	~	Roadside study	(Amato et al., 2016)
	9.4–36.9	~	Roadside study	(Amato et al., 2012)
	11	2.7	Receptor modelling	(Beddows and Harrison, 2020)

Note:
[a] Mean EFs for tyre, brake, road wear, resuspension on urban, rural and motorway roads from small to large petrol cars.
[b] Mean EFs for tyre, brake, road wear, and resuspension on urban, rural and motorway roads from small to large diesel cars.
[c] Mean EFs of brake wear were evaluated over the novel worldwide harmonised light-duty vehicles test procedure (WLTP)–brake cycle.

Table 5
Increase and percentage increase in non-exhaust EFs from three types of petrol cars to their equivalent EVs.

Non-exhaust emissions	Three types of petrol ICE cars switch to equivalent EVs	Emission factors (mg km^{-1} veh^{-1})	Urban road	Rural road	Motorway road
Tyre wear	Small petrol cars to equivalent EVs	$EF_{PM2.5}$	0.45 (7.62%)	0.35 (7.62%)	0.29 (7.62%)
		EF_{PM10}	0.64 (7.62%)	0.50 (7.62%)	0.43 (7.62%)
	Medium petrol cars to equivalent EVs	$EF_{PM2.5}$	0.63 (9.60%)	0.49 (9.60%)	0.41 (9.60%)
		EF_{PM10}	0.89 (9.60%)	0.70 (9.60%)	0.60 (9.60%)
	Large petrol cars to equivalent EVs	$EF_{PM2.5}$	0.73 (9.69%)	0.57 (9.69%)	0.48 (9.69%)
		EF_{PM10}	1.03 (9.69%)	0.81 (9.69%)	0.69 (9.69%)
Brake wear	Small petrol cars to equivalent EVs	$EF_{PM2.5}$	0.40 (9.30%)	0.22 (11.93%)	0.06 (13.88%)
		EF_{PM10}	1.04 (9.30%)	0.55 (11.93%)	0.14 (13.88%)
	Medium petrol cars to equivalent EVs	$EF_{PM2.5}$	0.57 (11.74%)	0.33 (15.10%)	0.09 (17.61%)
		EF_{PM10}	1.50 (11.74%)	0.82 (15.10%)	0.22 (17.61%)
	Large petrol cars to equivalent EVs	$EF_{PM2.5}$	0.68 (11.85%)	0.41 (15.24%)	0.11 (17.78%)
		EF_{PM10}	1.79 (11.85%)	1.02 (15.24%)	0.28 (17.78%)
			Urban/Rural/Motorway roads		
Road wear	Small petrol cars to equivalent EVs	$EF_{PM2.5}$	0.34 (11.93%)		
		EF_{PM10}	0.62 (11.93%)		
	Medium petrol cars to equivalent EVs	$EF_{PM2.5}$	0.51 (15.10%)		
		EF_{PM10}	0.93 (15.10%)		
	Large petrol cars to equivalent EVs	$EF_{PM2.5}$	0.64 (15.24%)		
		EF_{PM10}	1.16 (15.24%)		
Resuspension of road dust	Small petrol cars to equivalent EVs	$EF_{PM2.5}$	0.34 (16.61%)		
		EF_{PM10}	1.41 (16.61%)		
	Medium petrol cars to equivalent EVs	$EF_{PM2.5}$	0.55 (21.14%)		
		EF_{PM10}	2.25 (21.14%)		
	Large petrol cars to equivalent EVs	$EF_{PM2.5}$	0.74 (21.33%)		
		EF_{PM10}	3.03 (21.33%)		

3.3. Comparative analysis of EV and ICEV emissions

Figs. 3 and 4 show the total EFs for different types of ICE passenger cars and their equivalent EVs with 0%, 50%, and 100% regenerative braking on urban, rural, and motorway and percentage variation in EFs

Table 6
Increase and percentage increase in non-exhaust EFs from three types of diesel cars to their equivalent EVs.

Non-exhaust emissions	Three types of petrol ICE cars switch to equivalent EVs	Emission factors (mg km^{-1} veh^{-1})	Urban road	Rural road	Motorway road
Tyre wear	Small diesel cars to equivalent EVs	$EF_{PM2.5}$	0.38 (6.21%)	0.29 (6.21%)	0.25 (6.21%)
		EF_{PM10}	0.53 (6.21%)	0.41 (6.21%)	0.36 (6.21%)
	Medium diesel cars to equivalent EVs	$EF_{PM2.5}$	0.48 (7.26%)	0.37 (7.26%)	0.31 (7.26%)
		EF_{PM10}	0.67 (7.26%)	0.53 (7.26%)	0.45 (7.26%)
	Large diesel cars to equivalent EVs	$EF_{PM2.5}$	0.60 (7.83%)	0.47 (7.83%)	0.39 (7.83%)
		EF_{PM10}	0.85 (7.83%)	0.66 (7.83%)	0.57 (7.83%)
Brake wear	Small diesel cars to equivalent EVs	$EF_{PM2.5}$	0.33 (7.57%)	0.19 (9.68%)	0.05 (11.25%)
		EF_{PM10}	0.88 (7.57%)	0.46 (9.68%)	0.12 (11.25%)
	Medium diesel cars to equivalent EVs	$EF_{PM2.5}$	0.43 (8.86%)	0.25 (11.35%)	0.07 (13.21%)
		EF_{PM10}	1.13 (8.86%)	0.62 (11.35%)	0.16 (13.21%)
	Large diesel cars to equivalent EVs	$EF_{PM2.5}$	0.56 (9.55%)	0.34 (12.25%)	0.09 (14.26%)
		EF_{PM10}	1.48 (9.55%)	0.85 (12.25%)	0.23 (14.26%)
			Urban/Rural/Motorway roads		
Road wear	Small diesel cars to equivalent EVs	$EF_{PM2.5}$	0.29 (9.68%)		
		EF_{PM10}	0.53 (9.68%)		
	Medium diesel cars to equivalent EVs	$EF_{PM2.5}$	0.38 (11.35%)		
		EF_{PM10}	0.70 (11.35%)		
	Large diesel cars to equivalent EVs	$EF_{PM2.5}$	0.53 (12.25%)		
		EF_{PM10}	0.96 (12.25%)		
Resuspension of road dust	Small diesel cars to equivalent EVs	$EF_{PM2.5}$	0.29 (13.43%)		
		EF_{PM10}	1.20 (13.43%)		
	Medium diesel cars to equivalent EVs	$EF_{PM2.5}$	0.41 (15.79%)		
		EF_{PM10}	1.67 (15.79%)		
	Large diesel cars to equivalent EVs	$EF_{PM2.5}$	0.62 (17.06%)		
		EF_{PM10}	2.52 (17.06%)		

from various types of ICE passenger cars to their equivalent EVs. Without considering regenerative braking, the total PM_{10} EFs generated from corresponding small, medium and large EVs on all the road types are 3.94–7.40%, 9.06–11.72%, and 11.01–12.97% larger than the Euro 6 petrol counterparts as well as 4.77–6.16%, 6.92–8.62% and 8.83–10.74% larger than the Euro 6 diesel equivalents, respectively. As for $PM_{2.5}$ EFs, small, medium, and large petrol equivalent EVs without regenerative braking on all road types except for motorway roads have 0.11–0.44%, 4.11–4.26%, and 1.11–6.38% greater EFs than the petrol ICE passenger cars. Diesel equivalent medium and large EV counterparts have 1.11–2.31% and 3.57–5.05% greater EFs on all road types compared to medium and large ICE passenger cars, while small diesel EV equivalents exhibit 0.22–1.16% lower EFs relative to small diesel cars. However, considering the uncertainties for some cases, as shown in Figs. 3 and 4, there seems to be no apparent difference in the total PM EFs. To obtain the difference analysis results of the PM EFs, the *t*-test was carried out using IBM SPSS 25. Prior to performing the *t*-test, it is necessary to determine that the analysis data conform to normal distribution. The obtained results show that the analysis data conform to the normal distribution, and the *p* values for the total PM EFs from various types of ICE passenger cars and equivalent EVs on urban, rural and motorway roads are less than 0.05, indicating that such differences in the total PM EFs are significant at a 95% confidence level.

The total PM_{10} EFs are significantly increased from various types of ICE passenger cars to the corresponding heavier EV equivalents without regenerative braking. Accordingly, regenerative braking of EVs needs to reduce brake emissions in order to make total emissions of EVs that equal to the emissions of equivalent ICE cars. Compared to total PM_{10} EFs from petrol small, medium and large passenger cars, brake emissions of equivalent EVs require to be decreased respectively to 81.65%, 71.21% and 67.15% (i.e.18.35%, 28.79% and 32.85% regenerative braking) for urban roads as well as 64.41%, 44.81% and 38.35% (i.e. 35.59%, 55.19% and 61.65% regenerative braking) for rural roads. In comparison, diesel equivalent EVs need less extent of regenerative braking. Regenerative braking for small, medium, and large diesel equivalent EVs requires to reach respectively 13.21%, 19.33%, and 25.51% on urban roads as well as 28.45%, 39.74%, and 49.97% on rural roads. In addition, the total PM_{10} EFs for various types of ICE passenger cars and their equivalent EVs on all road types follows the sequence: on urban roads > on rural roads > on motorway roads. On motorways, the total PM_{10} EFs of equivalent EVs even with 100% regenerative braking are higher than the corresponding ICE passenger cars except for small petrol ICE cars, which indicates that regenerative braking cannot mitigate against the increment in PM_{10} caused by the increase in vehicle weight.

Compared to the total PM_{10} EFs, the total $PM_{2.5}$ emissions generated from the equivalent heavier EVs without regenerative braking exhibit a smaller increment, as shown in Figs. 3 and 4. Consequently, less extent of regenerative braking is needed to be in line with the emissions from equivalent ICE cars. For small, medium, and large petrol equivalent EVs, it is required regenerative braking to reduce braking emissions to 98.44%, 85.25%, and 79.39% for urban roads as well as 99.31%,74.52%, and 64.12% for rural roads. On a motorway environment, however, small and medium petrol equivalent EVs without regenerative braking are lower than those for corresponding petrol ICE cars. In line with the $PM_{2.5}$ emissions from diesel passenger cars, medium and large diesel equivalent EVs require regenerative braking to reduce brake emissions by 3.95% and 12.68% for urban roads as well as 12.30% and 27.01% for rural roads, whereas there is no requirement of regenerative braking for small diesel equivalent EVs on all road types due to the $PM_{2.5}$ EFs below that for small diesel cars.

Small, medium and large equivalent EVs with the various extent of regenerative braking on urban roads can reduce PM_{10} EFs up to 12.45, 14.30, and 16.96 mg km^{-1} veh^{-1}, i.e., ~31.30%, ~28.89%, and ~25.77% reduction. For rural roads, these reductions in PM_{10} EFs drop to 5.26, 6.27, and 7.79 mg km^{-1} veh^{-1}, corresponding to ~14.56%, ~12.39%, and ~10.23% reduction. For motorway roads, only small petrol equivalent EVs with fully regenerative braking can decrease 1.83% PM_{10} emissions, whilst other types of petrol and diesel equivalent EVs, even with 100% regenerative braking, cannot reduce the increment in PM_{10} caused by the increase in vehicle weight. In comparison, reductions of $PM_{2.5}$ EFs for small, medium, and large equivalent EVs with different extent of regenerative braking are up to 6.75, 6.45, and 6.48 mg km^{-1} veh^{-1} on urban roads, 2.11, 2.51, and 3.11 mg km^{-1} veh^{-1} on rural roads, and 0.48, 0.59 and 0.75 mg km^{-1} veh^{-1} on motorway roads.

The increase and percentage increase in vehicle weight and total non-exhaust EFs for the conversion of three types of ICEVs and

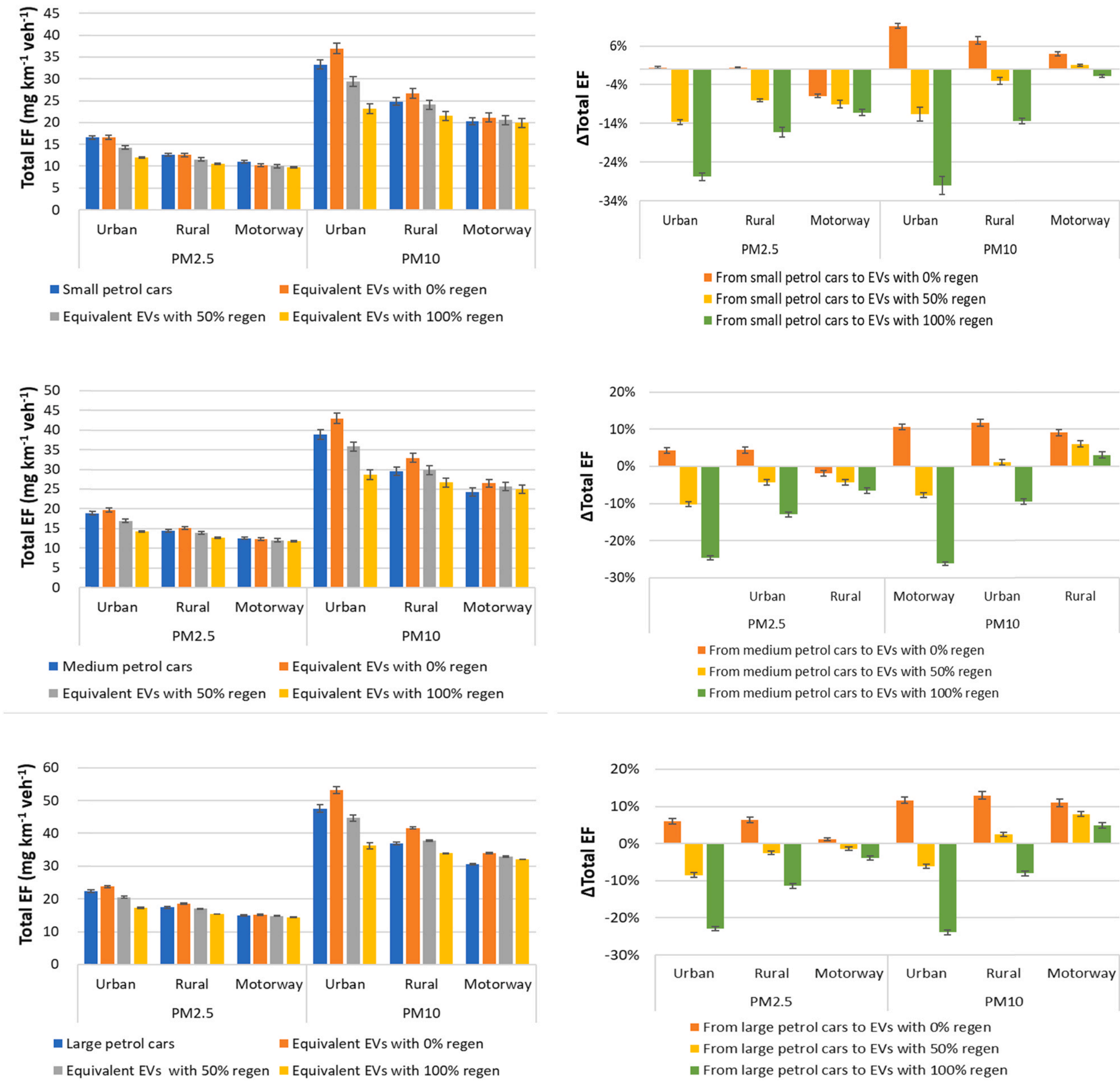

Fig. 3. Left panel presents total EFs for different types of petrol ICE passenger cars and equivalent EVs with 0%, 50%, and 100% regenerative braking on urban, rural, and motorway roads. Right panel presents percentage variation in EFs from various types of petrol ICE cars to their equivalent EVs with 0%, 50%, and 100% regenerative braking. The error bars indicate the standard error.

equivalent EVs were calculated and the obtained results are listed in Table 7. Compared to small petrol passenger cars, there are 28.54% and 76.18% increases in the weight for medium and large petrol passenger cars, respectively. Correspondingly, the total PM emissions of medium and large petrol passenger cars on urban, rural, and motorway roads increase by up to 15.17% and 38.34% for $PM_{2.5}$ as well as 19.57% and 50.31% for PM_{10} than that of small petrol passenger cars, respectively. In parallel, there are up to 20.55% and 25.46% increases in the total $PM_{2.5}$ and PM_{10} non-exhaust emissions for the conversion from the equivalent small EVs to medium EVs and up to 48.21% and 60.53% for the conversion from the equivalent small EVs to large EVs on the urban, rural and motorway roads. In the case of the conversion from small diesel cars to large diesel cars, there is 73.84% increase in vehicle weight, and the percentage increases in total $PM_{2.5}$ and PM_{10} emissions are in the range of 34.42%–38.84% and 42.04%–49.07% on urban, rural, and motorway roads. The total $PM_{2.5}$ and PM_{10} non-exhaust emissions for the equivalent small EVs to large EVs on urban, rural, motorway roads increase from 40.84% to 46.17% and from 47.54% to 55.50%, respectively. A similar finding was reported by Garg et al. (2000), who discovered that the $PM_{2.5}$ and PM_{10} emissions from brake wear of large passenger cars were 55% higher than that of small passenger cars. Lükewille et al. (2001) revealed that the light-duty vehicles would emit over two and a half times PM_{10} relative to passenger cars.

In the present study, the total $PM_{2.5}$ and PM_{10} EFs for the ICE petrol passenger cars and the equivalent EVs as functions of vehicle weight were also evaluated, as shown in Figs. 5 and 6. Compared to conventional petrol cars, the total $PM_{2.5}$ EFs for the EVs with the same vehicle weight various regenerative braking conditions are observed to be smaller on urban, rural and motorway roads, especially for urban roads and 100% regenerative braking. In the case of the PM_{10} EFs, the conventional petrol passenger cars and EVs with the same vehicle weight emit the same PM_{10} emissions, which is because all the exhaust particle emissions from Euro 6 passenger cars fall in the range of $PM_{2.5}$. However, the EVs with 50% and 100% regenerative braking would emit less

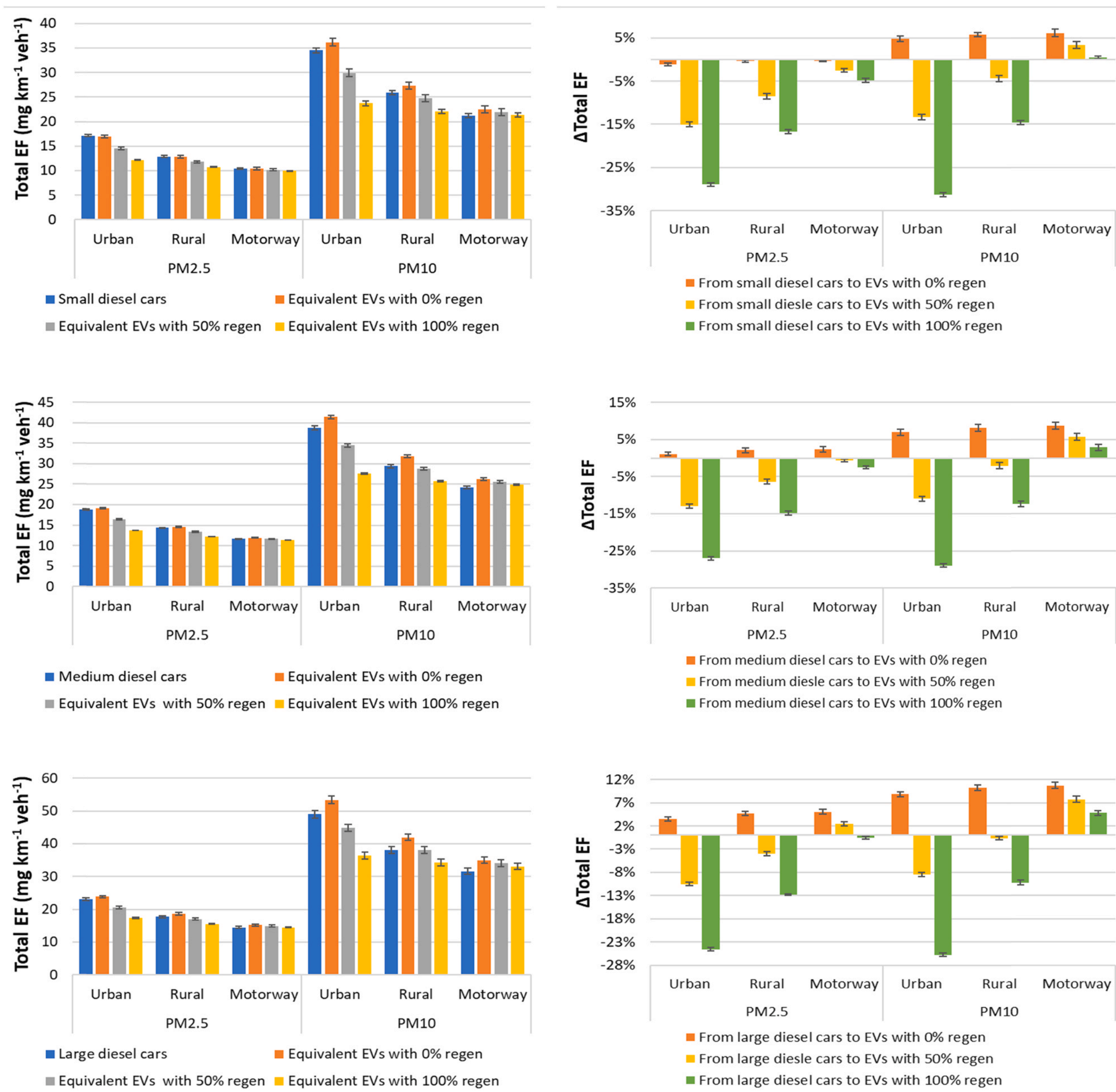

Fig. 4. Left panel presents total EFs for different types of diesel ICE passenger cars and their equivalent EVs with 0%, 50%, and 100% regenerative braking on urban, rural, and motorway roads. Right panel presents percentage variation in EFs from different types of diesel ICE cars to their equivalent EVs with 0%, 50%, and 100% regenerative braking. The error bars indicate the standard error.

PM_{10} emissions than the conventional cars with the same weight. These results identify that the EVs within the fleet would produce less PM emissions than the ICEVs with almost the same weight, which is beneficial to the improvement of air quality. In addition, it is found in Figs. 5 and 6 that the utility of regenerative braking can significantly reduce PM emissions on urban roads, followed by rural and motorway roads.

4. Conclusions

In this study, vehicle weights of small, medium and large ICE cars and their equivalent EVs were evaluated. The non-exhaust PM_{10} and $PM_{2.5}$ EFs for ICEVs and EVs on urban, rural and motorway environments were calculated according to the relationships between the EFs and vehicle weight to identify whether the electrification of these cars could effectively reduce levels of PM as much as expected. The current results indicate that non-exhaust particle emissions from the equivalent EVs are likely to be more than all particle emissions from ICE passenger cars, including exhaust particle emissions, which are dependent mainly upon the extent of regenerative braking, road type, and passenger car type. For instance, PM_{10} EFs from all the equivalent EVs without regenerative braking on all road types are all higher than the particle emissions from ICE passenger cars, including exhaust particles. Especially on motorway environment, all the equivalent EVs except for small petrol EVs even with fully regenerative braking still have larger EFs than the corresponding conventional petrol and diesel cars. As for $PM_{2.5}$, most of the equivalent EVs on most road types have to require different regenerative braking to reduce brake emissions to make total $PM_{2.5}$ in line with all particle emissions from relative ICE cars. Only small and medium petrol equivalent EVs on motorway roads and small diesel equivalent EVs on all road types without regenerative braking emit less PM relative to the ICE cars. The total $PM_{2.5}$ and PM_{10} EFs of the EVs with 0%, 50%, and 100% regenerative braking would reduce by up to 33.32%

Table 7
Increase and percentage increase in vehicle weight and total $PM_{2.5}$ and PM_{10} EFs for the conversion of three types of ICEVs and equivalent EVs.

	The conversion in three types of cars	Difference in vehicle weight (kg)	Emission factors (mg km^{-1} veh^{-1})	Urban road	Rural road	Motorway road
Total non-exhaust emissions	Small petrol cars to medium petrol cars	296 (28.54%)	$EF_{PM2.5}$	2.33 (14.06%)	1.91 (15.17%)	1.58 (14.36%)
			EF_{PM10}	5.65 (17.00%)	4.70 (18.94%)	3.98 (19.57%)
	Equivalent small EVs to medium EVs	417 (33.96%)	$EF_{PM2.5}$	2.54 (18.40%)	2.54 (20.11%)	2.11 (20.55%)
			EF_{PM10}	6.06 (16.39%)	6.33 (23.73%)	5.38 (25.46%)
	Medium petrol cars to large petrol cars	494 (37.06%)	$EF_{PM2.5}$	3.51 (18.56%)	2.92 (20.12%)	2.43 (19.29%)
			EF_{PM10}	8.67 (22.28%)	7.33 (24.83%)	6.25 (25.71%)
	Equivalent medium EVs to large EVs	615 (37.39%)	$EF_{PM2.5}$	4.03 (20.46%)	3.39 (22.40%)	2.83 (22.94%)
			EF_{PM10}	10.10 (23.48%)	8.65 (26.22%)	7.41 (27.96%)
	Small petrol cars to large petrol cars	790 (76.18%)	$EF_{PM2.5}$	5.84 (35.23%)	4.83 (38.34%)	4.01 (36.42%)
			EF_{PM10}	14.32 (43.07%)	12.03 (48.48%)	10.22 (50.31%)
	Equivalent small EVs to large EVs	1032 (84.04%)	$EF_{PM2.5}$	7.09 (42.62%)	5.93 (47.01%)	4.94 (48.21%)
			EF_{PM10}	16.16 (43.72%)	14.97 (56.17%)	12.79 (60.53%)
Total non-exhaust emissions	Small diesel cars to medium diesel cars	225 (20.44%)	$EF_{PM2.5}$	1.76 (10.27%)	1.44 (11.20%)	1.20 (11.43%)
			EF_{PM10}	4.27 (12.80%)	3.56 (13.96%)	3.01 (14.25%)
	Equivalent small EVs to medium EVs	260 (20.03%)	$EF_{PM2.5}$	2.17 (12.38%)	1.79 (13.76%)	1.49 (14.21%)
			EF_{PM10}	5.31 (14.70%)	4.47 (16.32%)	3.79 (16.86%)
	Medium diesel cars to large diesel cars	588 (44.34%)	$EF_{PM2.5}$	4.14 (21.90%)	3.44 (24.03%)	2.87 (24.60%)
			EF_{PM10}	10.23 (26.38%)	8.67 (29.46%)	7.39 (30.52%)
	Equivalent medium EVs to large EVs	718 (46.08%)	$EF_{PM2.5}$	4.75 (24.86%)	3.99 (27.26%)	3.33 (27.93%)
			EF_{PM10}	11.87 (28.64%)	10.15 (31.91%)	8.70 (33.06%)
	Small diesel cars to large diesel cars	813 (73.84%)	$EF_{PM2.5}$	5.89 (34.42%)	4.89 (37.93%)	4.06 (38.84%)
			EF_{PM10}	14.51 (42.04%)	12.23 (47.28%)	10.40 (49.07%)
	Equivalent small EVs to large EVs	978 (75.35%)	$EF_{PM2.5}$	6.91 (40.84%)	5.78 (45.02%)	4.82 (46.17%)
			EF_{PM10}	17.19 (47.54%)	14.62 (53.44%)	12.49 (55.50%)

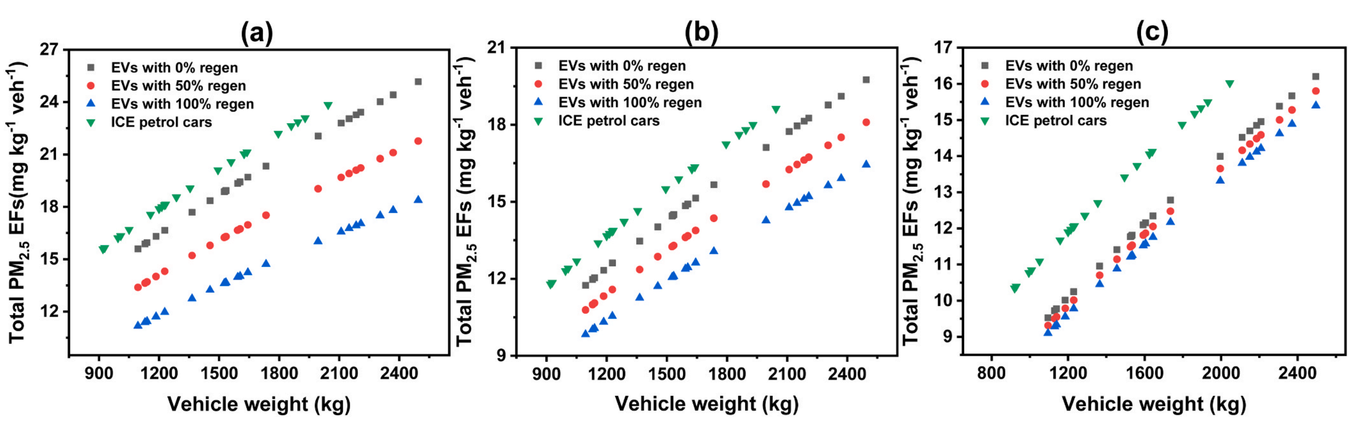

Fig. 5. Total $PM_{2.5}$ EFs for the ICE petrol passenger cars and EVs on urban (a), rural (b) and motorway roads (c) as functions of vehicle weight.

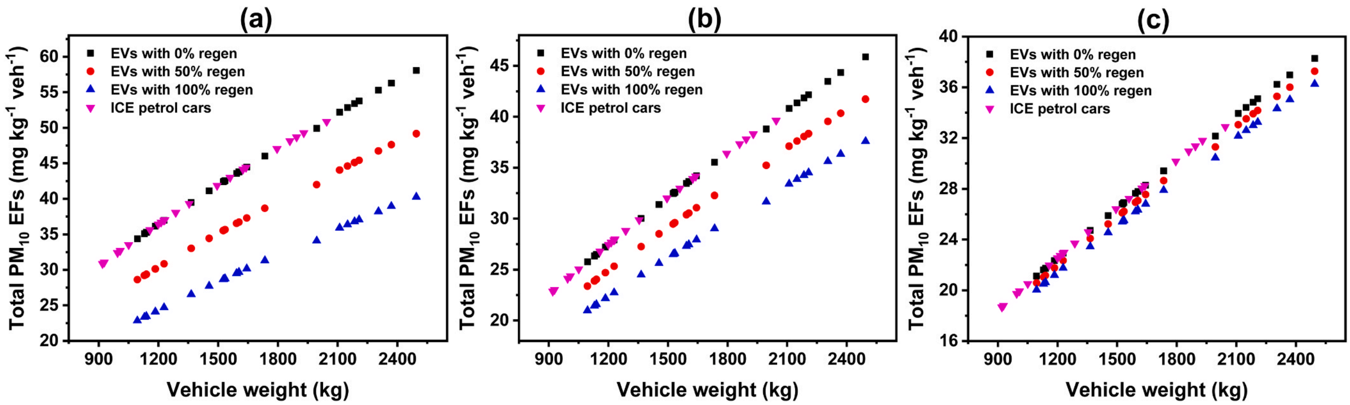

Fig. 6. Total PM_{10} EFs for the ICE petrol passenger cars and EVs on urban (a), rural (b) and motorway roads (c) as functions of vehicle weight.

and 32.33% than those of the ICEVs when the ICEVs and EVs have the almost same weight of 1130 kg within the fleet. The present data are useful for the regulatory authorities and policy makers to design the mitigation strategies and to compute their individual contributions and impacts on public health and local air quality.

CRediT authorship contribution statement

Ye Liu: Investigation, Methodology, Data visualisation, Writing – original draft. **Haibo Chen**: Conceptualisation, Investigation, Funding acquisition, Project management. **Jianbing Gao**: Methodology, Writing – review & editing. **Ying Li**: Methodology, Writing – review & editing. **Kaushali Dave**: Investigation, Writing – review & editing. **Junyan Chen**: Writing – review & editing. **Matteo Federici:** Investigation, Validation, Writing – review & editing. **Guido Perricone:** Investigation, Writing – review & editing.

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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