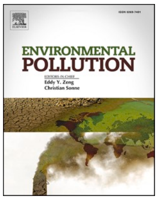
Environmental Pollution 336 (2023) 122400

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol



Quantifying the change of brake wear particulate matter emissions through powertrain electrification in passenger vehicles☆

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ARTICLE INFO

Keywords:
Brake wear
Electrification
PM_{10}
$PM_{2.5}$
Non-exhaust emissions

ABSTRACT

With vehicle fleets transitioning from internal combustion engines (ICE) to electric powertrains, we have used friction brake power simulations, for different vehicle classes and driving styles, to predict the impact of regenerative braking systems (RBS) on brake wear particulate matter emissions (PM_{10} and $PM_{2.5}$). Under the same powertrain, subcompact (SC) vehicles were predicted to require between 38 and 68% less friction brake power than heavier sports utility vehicles (L-SUV). However, despite electric and hybrid vehicles being heavier than ICE vehicles, the results show that RBS would reduce brake wear by between 64 and 95%. The study highlights the effect of aggressive braking on the amount of friction brake power required, with electric powertrains more likely to require friction braking to perform short, but aggressive braking compared with longer, slower braking events. Brake wear reductions varied under different driving conditions, as the level of mitigation depends on the complex interaction of several variables, including: vehicle speed, deceleration rate, regenerative braking technology and vehicle mass. Urban brake wear emission factors for electric powertrains ranged from 3.9 to 5.5 mg PM_{10}/km and 1.5–2.1 mg $PM_{2.5}$/km, providing an average reduction in PM emission factors of 68%. Rural and motorway driving conditions had lower brake wear emission factors, with plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) emitting negligible PM_{10} and $PM_{2.5}$ brake wear. Although electric powertrain uptake, vehicle mileage driven and driving styles are dependent upon national policies and strategies, by 2035, we project that total UK brake wear PM emissions would reduce by up to 39% compared with 2020 levels. This analysis supports the transition towards electric and hybrid vehicle fleets to reduce brake wear emissions, however increases in tyre wear, road wear, and resuspension due to increased vehicle mass may offset these benefits.

1. Introduction

Airborne particulate matter, including PM_{10} (particles with an aerodynamic diameter less than or equal to 10 μm) and $PM_{2.5}$ (particles with an aerodynamic diameter less than or equal to 2.5 μm), originating from the abrasion of vehicle brake pads and discs, plays a significant role in global road transport emissions (Harrison et al., 2021; Garg et al., 2000; Fussell et al., 2022). Due to stricter exhaust regulatory standards, brake wear emissions represent an increasingly large share of overall PM traffic emissions (up to 49% of PM_{10} emissions in urban areas) (Grigoratos and Martini, 2015; Amato et al., 2014; Oroumiyeh et al., 2022; Harrison et al., 2012; Hicks et al., 2021). Governments have proposed banning the sale of pure internal combustion engine (ICE) vehicles, leading to the adoption of electric and hybrid vehicles that reduce fuel consumption and CO_2 emissions (Wappelhorst, 2021; SMMT, 2022).

Electric and hybrid vehicles are heavier than their ICE counterparts, which may increase non-exhaust emissions (Timmers and Achten, 2016; Beddows and Harrison, 2021; OECD, 2020). While it is complex to directly compare the mass of different vehicles due to the different specifications and materials used, Liu et al. (2021) found that the difference in mass between electric and ICE vehicles increased with the size of vehicle. For example, electric vehicles (EVs) of small, medium, and large sizes respectively weigh, on average, 191-197 kg (15-18%), 232-313 kg (17-23%), and 362-433 kg (19-24%) more than their petrol and diesel equivalents. This corresponds to an average 20% increase in vehicle mass (Liu et al., 2021). This finding is consistent with other

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☆ This paper has been recommended for acceptance by Admir Créso Targino.
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https://doi.org/10.1016/j.envpol.2023.122400
Received 9 March 2023; Received in revised form 30 July 2023; Accepted 15 August 2023

estimates that suggest a weight increase ranging from 20 to 25% (Timmers and Achten, 2016; Beddows and Harrison, 2021; Faria et al., 2012).

Whilst ICE vehicles primarily rely on hydraulic friction brake systems to decelerate, electric and hybrid powertrains benefit from the introduction of regenerative braking systems (RBS), an energy recovery system which involves cutting power to the electric motor which then continues to rotate due to the inertia of the vehicle. The magnetic resistance in the electric motor provides the braking force and the energy is stored in a high-voltage battery (Bosch, 2018). Since regenerative braking does not rely on frictional wear of brake materials to slow the vehicle it is expected to substantially reduce the need for conventional friction brake systems and reduce the PM emissions from them. To maximise the benefits of RBS, it is therefore desirable to recuperate kinetic energy during deceleration events at as high a power level as possible (FraserBerger et al., 2021). However, when more braking torque is required than the generator alone can provide, additional braking is provided by friction brakes. As heavy-duty vehicles generally have excessive brake torque requirements beyond the capabilities of current regenerative braking technology (due to their mass), friction braking would still be expected for most deceleration events. However, for electric and hybrid passenger vehicles, friction braking is typically only still required during rapid deceleration, during a quick change from acceleration to braking, at very low speeds and when the vehicle is stationary.

Despite growing research on non-exhaust PM emissions, minimal published research has assessed the impact of RBS on brake wear emissions (Hooftman et al., 2016; Liu et al., 2021; Beddows and Harrison, 2021; Fussell et al., 2022). To address this gap, an integrated simulation-based approach has been used to assess the impact of regenerative braking on abrasive brake wear emissions. Passenger vehicle dynamics and driving characteristics are simulated to predict and analyse real-life performance, which is essential for optimising car performance and safety (Liermann, 2012; Kleisch et al., 2021; Bellman, 1957).

For this study, simulations have been used to determine the friction brake power requirements for ICE and hybrid electric vehicles to perform the World Harmonized Light Vehicle Test Procedure (WLTP) and Transport for London (TfL) Urban Inter-Peak (UIP) drive cycles. The TfL UIP was selected as the cycle is based on real-world driving in London, combining very low average speeds (14 km/h) with multiple fast transients, making it a challenging cycle for vehicles to utilise regenerative braking. The results have been used to determine electric and hybrid brake wear PM_{10} and $PM_{2.5}$ emission factors. Future trends in total passenger vehicle brake wear emissions in the UK have been projected based on the UK's Department for Transport (DfT) forecasts of vehicle distance and uptake of electric vehicles.

2. Materials and methods

2.1. Vehicle class

The size and mass of a vehicle has an important role in the rate of acceleration and deceleration needed for the drive train to carry out the drive cycles. Therefore, in this study, two vehicle classes have been assessed: a subcompact vehicle (SC) and a large sport utility vehicle (L-SUV). These two vehicle classes have been assessed under four powertrains (see Table 1).

Table 1
Simulated automotive classes and example models.

Automotive Classes	Powertrain Types	Examples of Models
Subcompact (SC)	ICE/HEV/PHEV	Vauxhall Corsa Volkswagen Polo Peugeot 208
Large-sports utility vehicle (L-SUV)	ICE/HEV/PHEV	Mitsubishi Outlander Volvo XC90 Skoda Kodiaq

2.2. Vehicle powertrain

The SC and L-SUV vehicle classes have undergone testing with three distinct powertrains: conventional ICE and two different types of hybrid electric powertrains. While a driver has the flexibility to adjust the level of regenerative braking, for the scope of these simulations, we have based our predictions on the highest possible level of regenerative braking for each vehicle type.

Conventional ICE vehicles are powered solely by an internal combustion engine and therefore have no RBS. 48-volt hybrid electric vehicles (HEV), also known as mild-hybrid systems, combine an ICE with a small, electrified motor that provides up to 48 V for acceleration. HEV use one or more electric motors that use energy stored in batteries, but do not need to plug in to recharge the battery. The HEV simulation used a conventional vacuum brake booster along with a regenerative braking modular system (i.e. electronic stability program (ESP®) HEV (Bosch, 2020)). The ESP® HEV system has internal control unit limitations which result in a generative deceleration potential of 0.2 g [-force] at the maximum regenerative braking level. On the other hand, 280 V plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) are powered solely by an electric motor. For PHEV, the ICE engine can generate electricity to power the electric motor when the battery charge runs out. The PHEV simulations use an electromechanical brake booster (i.e. 'iBooster') combined with a regenerative braking modular system (i.e. ESP® HEV (Bosch, 2020)). The iBooster actuates the brake pedal and sends information to the control unit, which determines the control signals for the electric motor. Due to the controllable support force of the iBooster, the recuperation potential of the ESP® HEV system is less limited, leading to a generative deceleration potential of 0.3 g [-force] at the maximum regenerative braking level.

2.3. Changes to brake wear emissions due to vehicle mass

The impact of increased vehicle mass of ICE, HEV, PHEV, and BEV powertrains on brake wear emissions has been calculated using a regression approach first described in Beddows and Harrison (2021) using the following steps.

- 'Base' PM_{10} and $PM_{2.5}$ brake EFs for urban, rural and motorway driving were obtained from the European Monitoring and Evaluation Programme (EMEP)/European Economic Area (EEA) Guidebook (Ntziachristos and Boulter, 2019). The 'base' brake wear emission factors were derived from laboratory studies and are comparable to emission factors generated in real-world atmospheric measurement studies (Hicks et al., 2021).
- The mass of each vehicle class and powertrain has been obtained from a GT Suite industry database (Table S1);
- The correlation coefficient between brake wear EF and vehicle mass was used to generate weight-dependent EFs for SC/L-SUV with ICE, HEV, and PHEV powertrains, under urban, rural and motorway road conditions, using equation (1):

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

Where EF is the brake wear emission factor (for the assessed road type) corrected for vehicle mass, W_{ref} is the vehicle mass (g) of the assessed vehicle category (presented in Table S1), b is the EMEP/EEA Guidebook EF (mg/km) for the assessed road type and c (no unit) is the EMEP/EEA brake wear correlation parameter (Beddows and Harrison, 2021).

Table S1 summarises the assessed vehicle class, powertrain, mass, and their regenerating braking technology and recouperation potential.

2.4. Simulations

The impact of regenerative braking has been evaluated using a dynamic simulation model to predict vehicle dynamics and energy performance. This model comprises of GT Suite and Matlab/Simulink software and is grounded in fundamental physics. It has been extensively employed by manufacturers to conduct simulations evaluating vehicle performance, braking systems and efficiency outcomes (Kleisch et al., 2021; Rizzo et al., 2017; Zhao and Luo, 2018; Xue et al., 2020; Kim et al., 2016). The model is employed to minimise the hybrid vehicle's electricity consumption (equivalent to fuel consumption) in the most efficient way possible, taking into account the vehicle's dynamic inertia (Kleisch et al., 2021). We have used this model to determine the driving characteristics and brake power for ICE, HEV, and PHEV over the WLTP and TfL UIP drive cycles every 0.1 s. The driving resistances and losses are modelled under the vehicle dynamics equation (2):

$$P_e = P_{loss} + P_S + P_R + P_{DR} + P_{CR} + P_a \tag{2}$$

Where P_e: = Effective propulsive power, P_{loss}: Drive train losses, P_S: Slip losses, P_R: Rolling resistance, P_{DR}: Drag resistance, P_{CR}: Climbing resistance, and P_a: Acceleration resistance.

Eq. (2) represents the power needed for a vehicle to maintain a defined operating condition and is composed of the driving resistance and power losses (Kleisch et al., 2021). For ICE vehicles, the drive train losses are caused by friction. For hybrid vehicles, an electric motor is integrated into the drive train which can cause new operating states of the combustion engine, such as load point boosting/reduction, pure electric driving, and energy recuperation. This provides varying degrees of propulsion and recuperation wheel forces which are dependent upon the basic dynamic effects of each other. The evaluation criteria for the model is described in Kleisch et al. (2021). The model has undergone validation using test SC/LSUV vehicles under the WLTP and TfL UIP drive cycles. The model aligns with measured data from the test vehicles under the drive cycles in the real world, exhibiting a maximum accuracy deviation of under 5%. This deviation, calculated as the highest disparity between simulated and experimental values across all test cases and parameters, is within an acceptable range for such simulations. This suggests that the model reliably simulates vehicle dynamics and energy performance. The model's wide use and rigorous validation within the vehicle industry further enhances its reliability for the purpose of our assessment. The input parameters for the SC and LSUV vehicle-level resistances, as used in the simulations, can be found in Table 2.

The WLTP drive cycle is used for vehicle manufacturers and regulators to measure average fuel consumption, exhaust pollutants and CO_2 emissions, providing an equivalence for testing. It is split into four sections (urban, suburban, rural and motorway). The TfL drive cycle is based on congested urban driving conditions in London during the period between the peak periods i.e. 10:00 to 16:00 daytime (Williams et al., 2021). It comprises a relatively low average velocity (14 kmh^{-1}), but is highly dynamic and features regular, harsh braking, presenting an interesting test for the influence of RBS. Table S2 summarises the key metrics and provides a comparison of the TfL and WLTP test cycles. The TfL drive cycle is 8 min 30 s longer than the WLTP drive cycle. However, the WLTP covers a distance 14 km greater than the TfL drive cycle, with the route segmented into urban, suburban, rural, and motorway driving conditions. Both drive cycles provide varied, but repeatable test cycles, to determine the impact of regenerative braking.

Table 2
Simulation input parameters for SC and LSUV vehicle-level resistances.

	Vehicle Type	
	SC	LSUV
Vehicle Frontal Area (m^2)	2.1	2.8
Vehicle Drag Coefficient	0.26	0.308
Tyre Rolling Radius (mm)	306.5	330
Tyre Rolling Resistance Factor	0.008	0.0094
Friction coefficient between tyres and road	0.9	0.9
Ambient Air Temperature (°C)	14	14
Ambient Air Pressure (bar)	1.013	1.013
Relative Humidity	0.6	0.6
Initial oil temperature (°C)	14	14

2.5. Hybrid/electric vehicle emission factors

For each electric/hybrid powertrain simulation, the relative change in brake power has been compared with the equivalent ICE simulation to determine the changes relative to friction braking. The average reductions in friction brake power for electric and hybrid powertrains have been used to determine changes in brake wear emissions. The average reductions due to electric motor regenerative braking have been applied to the mass-based emission factors to provide electric and hybrid emission factors.

2.6. Traffic forecasts

The UK DfT's National Transport Model projects that passenger vehicle mileage is expected to grow year-on-year (DfT, 2018). The predicted changes in future brake wear emissions will depend upon the forecast passenger vehicle mileage and electric vehicle uptake rates. Three scenarios have been considered from 2015 (e.g. base year) to 2035, which incorporate different rates of electric vehicle uptake along with different vehicle distance forecasts derived from the UK DfT's projections (Table 3).

- 'No electrification': DfT reference (Scenario 1) traffic projections assuming no electrification of the vehicle fleet.
- 'National Atmospheric Emissions Inventory (NAEI) EV uptake' – DfT reference (Scenario 1) traffic projections + 'moderate' update of electric vehicles.
- 'Road to zero' – DfT shift to zero emission vehicles (Scenario 7) traffic projections + 'high' uptake of electric vehicles.

3. Results and discussion

3.1. Powertrain simulations

Friction brake power depends upon a combination of vehicle class, technology (e.g., generative deceleration potential), driving styles (velocity/deceleration rates), and road conditions (urban/suburban/rural/motorway). The total (MW) and normalised (MW/km) friction brake power needed to carry out the WLTP and TfL drive cycles have been calculated for the urban (Table S3), suburban (Table S4), rural (Table S5) and motorway (Table S6) segments. The cumulative brake power simulations are shown in Fig. 1 (WLTP) and Fig. 2 (TfL UIP). For both drive cycles, the main figure illustrates the cumulative friction brake work (kWh), split by vehicle class and powertrain. The drive cycle

Table 3
Total projected passenger vehicle distance per annum (billion km/yr) and fleet % EV for the three assessed scenarios.

	No Electrification		NAEI EV Uptake		Road to Zero	
	Vehicle distance (billion km/yr)	EV (%)	Vehicle distance (billion km/yr)	EV (%)	Vehicle distance (billion km/yr)	EV (%)
2015	364	0	364	0.1	364	0.1
2020	390	0	390	0.6	390	0.6
2025	409	0	409	2.5	411	10
2030	426	0	426	9.2	434	30
2035	445	0	445	17.5	463	55

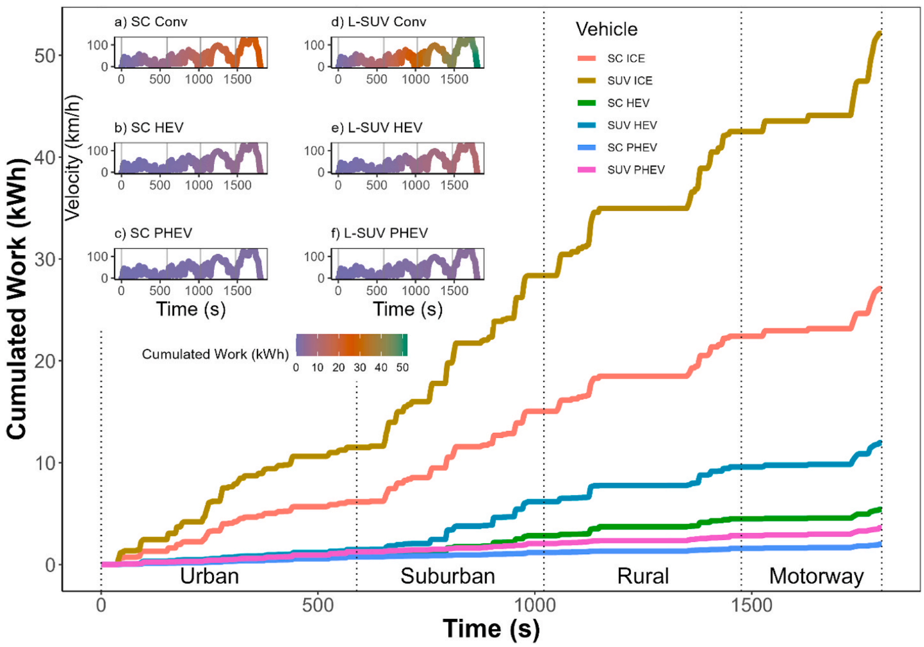

Fig. 1. Cumulated friction brake work (kWh) for the assessed vehicle types under the WLTP drive cycle. The WLTP drive cycle has been separated into the urban, suburban, rural and motorway segments, split by the vertical dotted lines. The drive cycle inserts plot the velocity (km/h) by time (s) and cumulative brake work (kWh) required for each individual vehicle class: SC (a–c) and L-SUV vehicles (d–f); ICE powertrains (a,d), HEV powertrains (b,e), and PHEV powertrains (c,f). Brake power during the WLTP drive cycle ranged from 0.05 MW/km (motorway) for a SC PHEV to 3.5 MW/km for a L-SUV ICE (suburban).

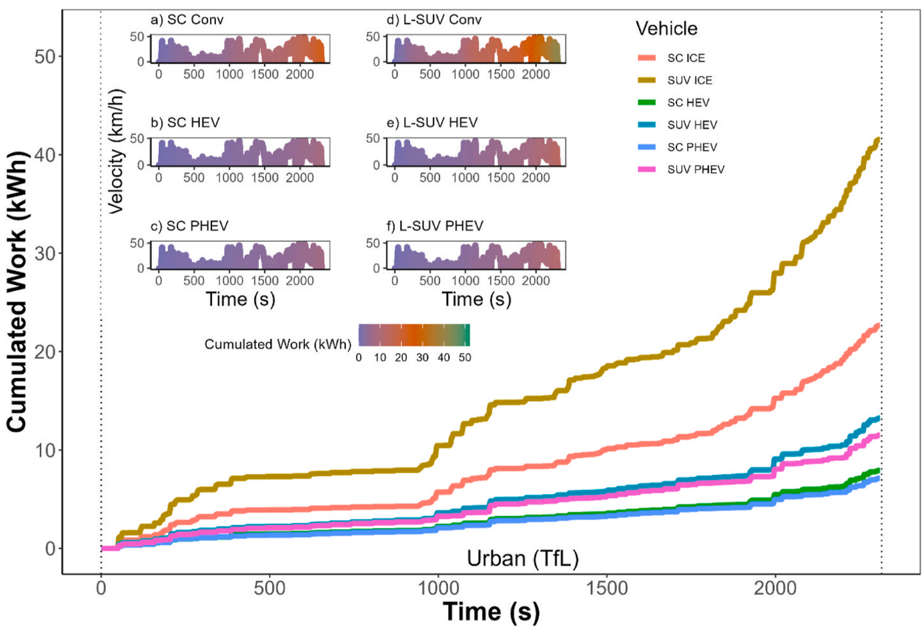

Fig. 2. Cumulated friction brake work (kWh) for the assessed vehicle types under the urban TfL UIP drive cycle. The drive cycle inserts plot the velocity (km/h) by time (s) and cumulative brake power (kWh) required for each individual vehicle class: SC (a–c) and L-SUV vehicles (d–f); ICE powertrains (a,d), HEV powertrains (b,e), and PHEV powertrains (c,f). The SC PHEV requires the least brake power whereas the L-SUV ICE requires the most. Average friction brake power ranged from 0.8 MW/km for a SC PHEV to 4.7 MW/km for a L-SUV ICE.

inserts plot the velocity and brake power required for each individual vehicle class: SC (a-c) and L-SUV vehicles (d-f); ICE powertrains (a,d), HEV powertrains (b,e), and PHEV powertrains (c,f). The colour scale portrays the cumulative friction brake power needed for each vehicle to carry out the WLTP and TfL drive cycles.

Average friction brake power during the TfL UIP drive cycle ranged from 0.8 MW/km for a SC PHEV to 4.7 MW/km for a L-SUV ICE. Brake power during the WLTP drive cycle ranged from 0.05 MW/km for a SC PHEV driving on the motorway to 3.5 MW/km for a L-SUV ICE on the suburban component.

In terms of vehicle class, more friction brake power is needed for the assessed L-SUVs to carry out the TfL and WLTP drive cycles compared with SC vehicles, although the extent depends on powertrain, speed and drive cycle segment. For example, to carry out the TfL UIP drive cycle, L-SUVs require 41.6 MW (L-SUV ICE), 13.2 MW (L-SUV HEV), and 11.5 MW (L-SUV PHEV) whereas SC vehicles require 22.6 MW (SC ICE), 7.9 MW (SC HEV), 7.1 MW (SC PHEV), corresponding to a reduction in friction brake power of 46% (ICE), 40% (HEV), and 38% (PHEV). During the WLTP urban segment, SCs require 47% (ICE), 43% (HEV), and 40% (PHEV) less friction brake power than L-SUVs. This suggests that whilst all powertrains would benefit from reducing mass under urban driving condition, ICE vehicles incur the greatest benefits both in relative (%) and absolute (MW) levels. However, for the WLTP suburban, rural and motorway segments, SCs require between 47 and 52% (ICE), 52-61% (HEV) and 46-48% (PHEV) less brake power than L-SUVs. This reduction in friction brake power is greatest for HEV during motorway driving because of the high brake torque requirements at faster speeds, in which the energy requirements of heavier L-SUV regularly exceed the HEV's recouperation potential. Previously, significant differences in PM_{10} and $PM_{2.5}$ brake wear emissions from a compact and L-SUV were found under real-world driving conditions, although the level depended on the deceleration rate (Oroumiyeh and Zhu, 2021). These results further establish that heavier vehicles require more friction brake power than lighter vehicles under the same powertrain due to the additional energy requirements, but the extent varies depending on the powertrain technology, speed and driving style.

Indeed, ICE vehicles (averaged by class) require less friction brake power during drive cycle segments which incorporate higher average speeds. The lower number of deceleration events during these segments is reflected by the trend in normalised brake power, where ICE vehicles require 2.8–3.6 MW/km (WLTP – TfL urban), 2.7 MW/km (suburban), 1.5 MW/km (rural), and 0.9 MW/km (motorway). However, the relationship is more complex for vehicles with RBS. HEV need 0.4–1.2 MW/km (WLTP – TfL urban), 0.7 MW/km (suburban), 0.4 MW/km (rural), 0.2 MW/km (motorway), whilst PHEV require 0.3–1.0 MW/km (urban) and 0.1 MW/km (suburban/rural/motorway). The HEV friction brake power requirements are strongly dependent upon speed and driving style due to the powertrain's maximum generative potential of 0.2 g (g $= 9.81\ m/s^2$). This difference is highlighted by a comparison of the HEV and PHEV powertrains, the latter of which has a generative potential of 0.3 g. Despite having a slightly higher mass than their HEV equivalents (due to the bigger battery), PHEV require, on average, 68% less friction brake power to carry out the WLTP drive cycle, with the greatest differences occurring during suburban driving as this type of driving combines higher speeds (than urban driving) with a higher number of deceleration events (than rural/motorway driving). On average, PHEVs require 77% (rural), 63% (motorway), 13% (WLTP urban), and 12% (TfL urban) less brake power than HEVs to carry out their respective segments. Despite having a higher number of deceleration events, urban driving tends to occur at relatively low speeds, in which both HEV and PHEV require the use of friction brakes. The relationship between the hybrid (PHEV/HEV averaged) and ICE powertrains also offers an interesting comparison between the powertrains and drive cycles. Due to regenerative braking, the hybrids require 88% (WLTP urban), 85% (suburban), 86% (rural), 85% (motorway), and 69% (TfL urban) less brake power than ICE to carry out the drive cycle segments. These suggests large reductions in brake power, although interestingly, there are noteworthy discrepancies between the urban segments of the WLTP and TfL drive cycles, which is a result of the variation in deceleration rates needed to carry out the drive cycles.

The frequent and aggressive braking characteristic of the TfL drive cycle mirrors the higher count of step changes within this cycle, providing a more accurate reflection of real-world city driving conditions (Fig. 2). The TfL drive cycle incorporates greater average brake power than during the WLTP drive cycle for all powertrains and vehicle types. Averaged at 0.1s time interval, the upper deceleration rates for the urban TfL drive cycle are $-4.8\ m/s2$ (maximum) and $-2.2\ m/s2$ (99th percentile) whereas the WLTP urban segment are $-1.6\ m/s2$ (maximum) and $-1.5\ m/s2$ (99th percentile). The upper range of instantaneous brake power for the TfL drive cycle is 44.1 kW (maximum) and 15.7 kW (99th percentile) whereas for the WLTP urban drive cycle, the upper range is 14.7 kW (maximum) and 10.7 kW (99th percentile).

Furthermore, the relationship between brake power (kW) and rate of deceleration ($m\ s^{-2}$) has been evaluated in two distinct speed categories: very low speeds and speeds exceeding 12kph for the WLTP (Fig. S1) and TfL UIP (Fig. S2). The differences in friction brake power between the ICE powertrains occur in the higher speed categories. Interestingly, the ICE, HEV and PHEV powertrains share a strong linear relationship between friction brake power and the rate of deceleration under the WLTP ($R^2 = 0.61$–0.66) and TfL ($R^2 = 0.72$–0.76) drive cycles below 12kph, with up to 2% additional friction brake power needed for the heavier hybrid vehicles. However, when moving at higher speeds, the PHEV typically only need to engage friction brakes during instances of aggressive deceleration (at or below $-1.5\ ms^{-2}$) whereas the HEV typically require friction braking for moderate deceleration events (at or below $-0.75ms^{-2}$). It's important to note that the rate of deceleration can also be influenced by the speed and class of the vehicle. This highlights the importance of smooth driving in reducing hybrid and electric brake wear emissions. It has been suggested that ICE friction braking events with higher deceleration rates take less time, and therefore PM is produced for a shorter period of time (Oroumiyeh and Zhu, 2021). However, these simulations indicate that electric powertrains would be more likely to require friction braking to perform short, but aggressive braking compared with longer, slower braking events.

The simulations used in this study to determine the potential impact of electric and hybrid friction braking is a novel methodology. The results demonstrate that ICE vehicles require the most amount of friction braking, and regenerative braking reduces friction brake power by 65–87% for HEV powertrains and by 69–95% for PHEV powertrains (compared with ICE). The results highlight that brake power is influenced by a complex interaction between vehicle mass, speed, rate of deceleration, and powertrain technology on carrying out the WLTP and TfL drive cycles. However, the stopping power of RBS may also be dependent upon the state of charge which could influence the results at the start of a drive cycle as regenerative braking is less efficient at recouperation when the state of charge is above approximately 80–90% (as there is less capacity to store excess energy) (Hamatschek et al., 2022; Agudelo, 2022). Further simulations should be developed which incorporate the state of charge in the time domain of a drive cycle, as well as incorporating additional drive cycles (e.g., California Unified Cycle/Japanese JC08 Cycle) and a greater range of vehicle classes. Further simulations should evaluate the emissions of specific models of hybrid and electric vehicle brands in real-world driving conditions, which would provide more varied data under different scenarios.

Notwithstanding, the simulation results are comparable to published studies which have assessed regenerative braking, for example, Althaus and Gauch (2010) compared data on a VW Golf VI with different ICE and electric powertrains and suggest that the electric and hybrid powertrains result in a 90% (60-95%) reduction in emissions. Hooftman et al. (2016) compared the service time of brake linings from ICE and EVs in an urban setting and proposed that electric powertrains reduce friction brake wear emissions by up to 66% (Hooftman et al., 2016). Hall (2017) assessed the impact of regenerative braking under the Los Angeles City Traffic Brake Test Schedule, and found the frequency of friction braking was up to eight times lower due to regenerative braking. Other estimates of friction brake wear reductions range from 25 to 95% (Nopmongcol et al., 2017; OECD, 2020; Beddows and Harrison, 2021; Liu et al., 2021).

3.2. Brake wear emission factors

Brake wear emissions in the real world are influenced by a number of important variables, which can be averaged by distance-based emission factors (mg PM/km). The results of the vehicle mass regressions and drive train simulations have been applied to the base EMEP/EEA Guidebook emission factors to develop SC and L-SUV PM_{10} and $PM_{2.5}$ brake wear emission factors which are dependent upon powertrain generative deceleration, mass and driving conditions (urban/rural/motorway) (Fig. 3). The horizontal red bars show brake wear emissions without regenerative braking (PM_{10} and $PM_{2.5}$ brake wear emission factors increase with the greater mass of L-SUVs and electric powertrains); the green and blue bars illustrate the effects of RBS on emission factors under the TFL and WLTP drive cycles respectively.

Without regenerative braking, urban emission factors range from 12.0 to 18.9 mg PM_{10}/km and 4.6–7.2 mg $PM_{2.5}$/km; rural emission factors range from 4.6 to 8.9 mg PM_{10}/km and 2.0–3.6 mg $PM_{2.5}$/km; motorway emission factors range from 1.1 to 2.2 mg PM_{10}/km and 0.5–0.9 mg $PM_{2.5}$/km. However, the introduction of RBS substantially reduces these emission factors. Based on the TfL drive cycle simulations, urban brake wear emission factors for the electric powertrains range from 3.9 to 5.5 mg PM_{10}/km and 1.5–2.1 mg $PM_{2.5}$/km which corresponds to an average reduction in PM emission factors of 68%. On the

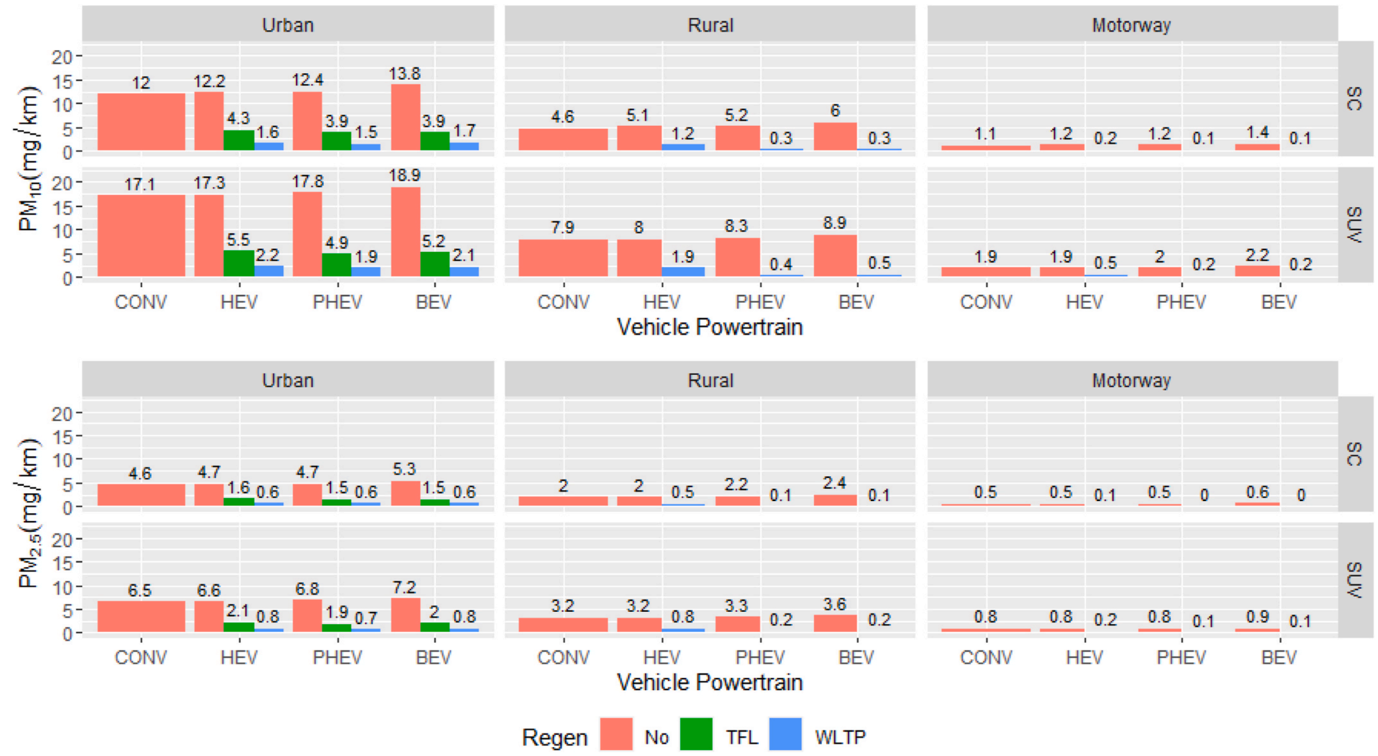

Fig. 3. Urban, rural and motorway PM_{10} and $PM_{2.5}$ brake wear emission factors for SC and SUV vehicle class under conventional, HEV, PHEV, and BEV powertrains. A vehicle mass EF regression approach was used to determine the impact of powertrain mass on emission factors (red), whilst reductions from regenerative braking were calculated using brake force simulations for passenger vehicles under the TfL (green) and WLTP (blue) drive cycles. The red bars demonstrate increasing PM_{10} and $PM_{2.5}$ brake wear emission factors with the heavier mass of the hybrid and electric vehicles. The highest brake wear emission factors are associated with SUVs under urban driving conditions.

other hand, based on the WLTP drive cycle simulations, emission factors range from 1.5 to 1.7 mg PM_{10}/km and 0.6–0.8 mg $PM_{2.5}$/km which provides an average reduction in emission factor of 88%. Regenerative braking is expected to reduce the average temperature of the friction brakes during urban driving, which should also avoid the generation of ultrafine particle matter, caused by the evaporation–condensation processes (Gramstat, 2018; Mamakos et al., 2019). In high-income nations, areas along city roads usually have the most receptors, along with the highest rates of air pollution emission per unit area (Beevers and Williams, 2020; Beevers et al., 2013; Hicks et al., 2021). Among these emissions, brake wear from traffic is the most significant source of PM (Hicks et al., 2021). To maximise the benefits of RBS, urban policies should focus on adopting vehicles which incorporate high regenerative braking potential, reduce vehicle mass, and encourage smooth driving behaviour. Increasing the number of electric charging stations should enable manufacturers to design vehicles which have smaller, lighter batteries in urban areas, which would further reduce urban brake wear emissions.

Compared with urban driving, rural and motorway driving conditions have lower brake wear emission factors (Fig. 3). Based on the WLTP simulations, rural brake wear emission factors (with regenerative braking) range from 0.3 to 1.9 mg PM_{10}/km, which is up to 76% (HEV) - 95% (PHEV/BEV) less than ICE vehicles. For motorway driving, emission factors range from 0.1 to 0.5 mg PM_{10}/km, which corresponds to a reduction of up to 83% (HEV) - 93% (PHEV/BEV). For PHEV and BEV, it is expected that rural and motorway driving styles will emit (near) negligible PM_{10} and $PM_{2.5}$ brake wear This demonstrates the benefits of powertrain electrification for brake wear emissions under rural and motorway driving conditions. However, it should be noted that the reduced load on the friction brake (due to RBS) can lead to build up of corrosion, which has been associated with increases in brake wear emissions (Gramstat, 2018). The specific challenges for vehicles which just drive under rural and (especially) motorway driving could be mitigated using more abrasive braking materials (but which are associated with higher wear rates), a cleaning function which temporarily stops the use of regenerative braking, and/or the re-introduction of drum brake/enclosed systems in passenger vehicles.

The EFs can be used to update the simplified guidebook NAEI EFs, which currently lack specific factors for hybrid and electric vehicles and can enhance the accuracy of national and local NEE projections. A key challenge in quantifying the health effects of brake wear PM is the lack of accurate exposure assessments (Fussell et al., 2022). The developed EFs can be combined with traffic and meteorological data to model NEE dispersion in the atmosphere, taking into account factors such as weather conditions, population density, and pollution sources. Incorporating these EFs in atmospheric dispersion models, whilst accounting for variations in rainfall, relative humidity, and wind speed, would enable more accurate human exposure estimates to brake wear, providing detailed spatial and temporal profiles of emissions near residential and commuting areas.

3.3. *Future emissions trends*

The PM_{10} and $PM_{2.5}$ emission factors have been implemented with three UK traffic forecast scenarios in which we assume varying EV uptake rates (Table 3). The total passenger vehicle PM_{10} and $PM_{2.5}$ brake wear emissions have been projected in Fig. 4. This shows that a ‘no uptake in EVs’ scenario would result in higher future $PM_{2.5}$ and PM_{10} brake wear emissions due to the projected increase in vehicle distance travelled and vehicle mass. From 2020 to 2035, PM emissions would increase by 14%, which would correspond to an increase of 0.16 Kt $PM_{2.5}$ and 0.41 Kt PM_{10}. The forecasts illustrate that without RBS, brake wear PM emissions would also increase under the ‘average electrification’ scenario by 17% and the ‘Road to Zero’ scenario by 29% during this

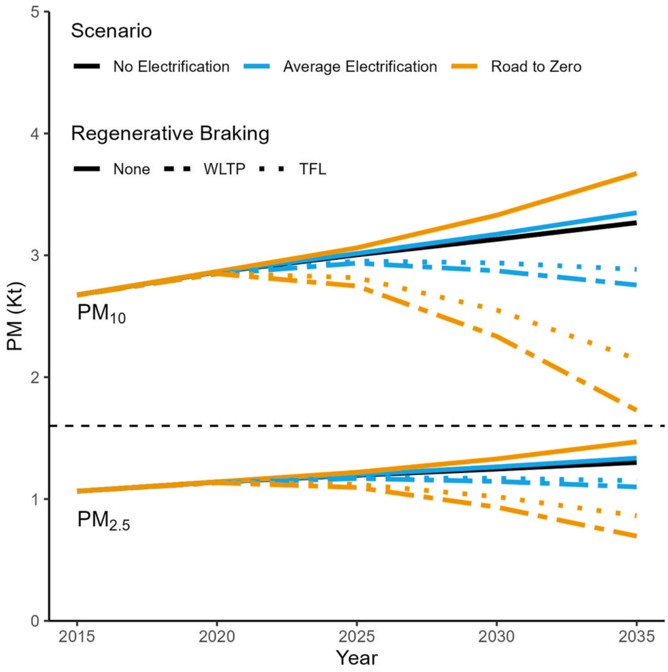

Fig. 4. Projected $PM_{2.5}$ and PM_{10} brake wear emission estimates for passenger cars in the UK based on changes in DfT (2018) modelled traffic volume and BEV uptake (vehicle mass, and regenerative braking). The dotted line type signifies the TFL regenerative braking forecast, and the dash-dot signifies the WLTP regenerative braking forecast. Three uptake scenarios have been considered: 'No Electrification'' (black), 'Average Electrification uptake' (blue), and '*Road to zero*' (high electrification uptake) (orange). Without regenerative braking, brake wear PM emissions would increase fastest under the road to zero scenario due to the higher mass of electric powertrains and increased projected mileage. However, despite the added mass of electric powertrains, the simulations indicate that overall brake wear emissions in the UK should reduce under average and high electrification scenarios thanks to regenerative braking.

time frame. Due to lower costs of running electric vehicles, the Road to Zero scenario incorporates more mileage and a higher uptake in electric vehicles than the other scenarios. This, combined with the higher EV (without regenerative braking) emission factors, would lead to substantial increases in PM emissions without regenerative braking. However, despite the added mass of electric powertrains, the 'road to zero' projections indicate that overall brake wear emissions in the UK should reduce if regenerative braking is in operation. In 2035, the Road to Zero scenario predicts that total PM emissions would reduce by 24% (TfL) to 39% (WLTP) compared with 2020. The average electrification scenario would see a levelling off in brake wear emissions from 2025 to 2030, and a small reduction from 2030 to 2035. Compared with 2020, this represents a reduction of 3% (WLTP) but an increase by 1% (TfL) in 2035. The variations in emission forecasts emphasise the combined importance that road traffic levels and future electric vehicle uptake policy will have on determining future brake wear emissions. There is uncertainty associated with the long-term traffic forecasts and rates in EV uptakes, both of which are likely to be influenced by future taxation strategies and broader economic pressures. However, the UK's traffic growth and EV uptake scenarios are comparable to the US and EU, suggesting similar trends in these regions (Bernard et al., 2021; US Department of Transportation, 2021).

More real-world PM measurements are also required to reduce the uncertainties associated with the different types of brake wear emission factors, such as those which incorporate the development of low-wear brake coatings and to validate these projections (Hesse et al., 2021). Further research should be undertaken to assess the net impact of powertrain electrification on other non-exhaust emissions such as tyre and road wear, as well as the resuspension of road dust, which are expected to increase because of the electrification of the vehicle fleet. There are no ready-made solutions for electric vehicles to offset the potential impact of increased mass on these other sources.

Promoting the adoption of electric powertrains represents an important step to reduce greenhouse gas emissions and mitigate the impacts of climate change due to their absence of exhaust emissions. This study highlights the potential of RBS to harness kinetic energy, which would be dissipated and lost in an ICE vehicle, and instead convert it into storable energy for the vehicle's battery. Further, our research reveals the substantial influence of both driving style and vehicle class on the energy recuperation potential of RBS. Considered in conjunction with the rates of EV uptake and the imperative of renewable energy sourcing, these factors significantly shape the prospective contribution of vehicular fleet electrification to climate change mitigation. Moreover, they serve to enhance the energy efficiency and comprehensive environmental performance of EVs.

4. Conclusion

As vehicle electrification gains momentum, this study highlights the importance of addressing brake wear PM_{10} and $PM_{2.5}$ emissions. Our findings reveal that vehicle mass, powertrain technology, driving style, and deceleration rates significantly impact brake power requirements and therefore brake wear emissions. Electrified powertrains which feature RBS substantially reduce brake power requirements and brake wear emissions, with the greatest reductions occurring during urban driving conditions. This study highlights the potential benefits of transitioning to electric and hybrid vehicle fleets in terms of reducing brake wear PM_{10} and $PM_{2.5}$ emissions, with average reductions in PM emission factors of 88% under the WLTP drive cycle and 68% under the TfL drive cycle. However, the extent of mitigation depends on driving style, vehicle speed, and vehicle mass.

To optimise the benefits of RBS in reducing brake wear emissions, policies should prioritise the adoption of vehicles with high regenerative braking potential, reduction of vehicle mass, and promotion of smooth driving behaviour. Additionally, increasing the number of electric charging stations could allow manufacturers to design vehicles with smaller, lighter batteries for urban areas, further reducing brake wear emissions. Future research should incorporate the state of charge in drive cycle simulations, analyse additional drive cycles, and investigate a broader range of vehicle classes.

While our analysis supports the transition towards electric and hybrid vehicle fleets as a means of reducing brake wear emissions, it is essential to also consider other wear-related emissions from tyres, road surfaces, and resuspension of road dust, as these sources could potentially increase due to vehicle mass.

Author statement

William Hicks: Conceptualisation, Methodology, Formal analysis, Visualization, Writing - Original Draft. David Green: Conceptualisation, Methodology, Supervision, Project administration, Visualization, Writing - Review & Editing, Funding Acquisition. Sean Beevers: Conceptualisation, Methodology, Supervision, Project administration, Visualization, Writing - Review & Editing, Funding Acquisition.

Funding sources

Natural Environment Research Council (NERC)/Bosch (NE/S013342/2). National Institute for Health and Care Research (NIHR).

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.

Data availability

Data will be made available on request.

Acknowledgements

This research is part funded by DfT/NERC PhD Grant (NE/S013342/2) and Robert Bosch GmbH as part of William Hicks' PhD studentship.

This study is part funded by the National Institute for Health Research (NIHR) Health Protection Research Unit in Environmental Exposures and Health, a partnership between UK Health Security Agency (UKHSA) and Imperial College London. The views expressed are those of the authors and not necessarily those of the NIHR, UKHSA or the Department of Health and Social Care.

Abbreviations

BEV	Battery Electric Vehicle
DfT	UK Department for Transport
EEA	European Economic Area
EF	Emission Factor
EMEP	European Monitoring and Evaluation Programme
ESP®	Electronic stability program
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal combustion engine
kW	Kilowatt
L-SUV	Large Sports Utility Vehicle
MW	Megawatt
NAEI	National Atmospheric Emission Inventories
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric vehicle
PM10	Particulate matter less than 10 μm in diameter
PM2.5	Particulate matter less than 2.5 μm in diameter
RBS	Regenerative braking system
SC	Subcompact
TfL	Transport for London
UIP	Urban Inter-Peak
WLTP	World Harmonized Light Vehicle Test Procedure

Appendix A. Supplementary data

Supplementary data to this article can be found online at.https://doi.org/10.1016/j.envpol.2023.122400

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