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Review

Light-Duty Vehicle Brake Emission Factors

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Abstract: Particulate Matter (PM) air pollution has been linked to major adverse health effects. Road transport still contributes significantly to ambient PM concentrations, but mainly due to the non-exhaust emissions from vehicles. For the first time worldwide, limits for non-exhaust emissions have been proposed by the European Union for the upcoming Euro 7 step. For these reasons, interest in brake emissions has increased in the past few years. Realistic emission factors are necessary to accurately calculate the contribution of brake emissions to air pollution but also to estimate the emissions reduction potential of new or existing technologies and improved brake formulations. This paper reviews emission factors from light-duty vehicles reported in the literature, with a focus on those that followed the recently introduced Global Technical Regulation (GTR 24) methodology on brakes in light-duty vehicles. Reduction efficiencies of non-asbestos organic (NAO) pads, brake dust filters, ceramic discs, coated discs, and regenerative braking are also discussed. Finally, the emission factors are compared with roadside measurements of brake emissions and emission inventories worldwide. The findings of this study can be used as an input in emission inventories to estimate the contribution of brakes to air pollution.

Keywords: non-exhaust; Euro 7; air pollution; brake pads; disc; filters; PM; PN; GTR 24

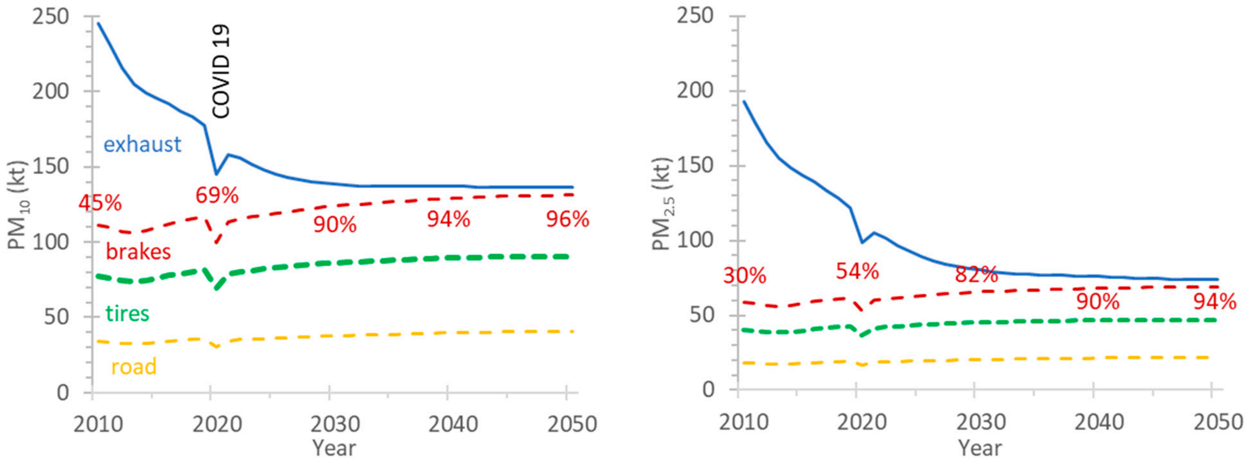
Citation: Giechaskiel, B.; Grigoratos, T.; Dilara, P.; Karageorgiou, T.; Ntziachristos, L.; Samaras, Z. Light-Duty Vehicle Brake Emission Factors. *Atmosphere* **2024**, *15*, 97. https://doi.org/10.3390/atmos15010097

Academic Editors: Shan Huang and Wei Wei Hu

Received: 20 December 2023
Revised: 7 January 2024
Accepted: 10 January 2024
Published: 11 January 2024

1. Introduction

Particulate Matter (PM) is a pollutant with adverse health effects. In 2019, exposure to PM with aerodynamic diameter < 2.5 µm ($PM_{2.5}$) was responsible for 7% of total global mortality (4.1 million deaths) [1]. In Europe, the contribution of road transport to ambient PM has decreased in the last decades from over 20% [2] to around 10% [3]. This can be largely attributed to the reduction of vehicle exhaust emissions, in particular due to the addition of Diesel particulate filters (DPFs) at the vehicles' aftertreatment systems since 2011 with Euro 5b. Although exhaust PM emissions are continuously decreasing over time due to fleet electrification, non-exhaust PM emissions (i.e., emissions from brakes, tires, and road) have slightly increased. The recent Euro 7 Impact Assessment study [4] has highlighted this issue by illustrating the expected evolution of PM emissions from exhaust and non-exhaust sources in the European Union (EU27) until 2050, assuming no emission control technologies are implemented for non-exhaust emissions (Figure 1). The increasing trend in non-exhaust emissions has also been demonstrated by data reported from the EU vehicle emission inventories until 2021 [5,6] and beyond [7,8]. National emission inventories primarily focus on primary particles, segregating PM emissions from tire and brake wear (nomenclature for reporting (NRF) 1A3bvi) and road abrasion (NRF 1A3bvii) from exhaust PM emissions [9]. Resuspended PM of the previously deposited material is not considered a primary source of emission and is not included in Figure 1 in order to avoid double-counting. Brakes contribute 30% ($PM_{2.5}$) to 40% (PM_{10}) to non-exhaust emissions. According to Figure 1, non-exhaust emissions accounted for 30% ($PM_{2.5}$) to 45% (PM_{10}) in 2010, 54% ($PM_{2.5}$) to 69% (PM_{10}) in 2020 (after introduction of DPFs), and will exceed 90% in 2040. This is the reason that the European Commission proposed to introduce limits for reducing brake and tire wear with Euro 7.



(**a**) (**b**)

Figure 1. Evolution and projections of exhaust, non-exhaust (brake, tire, and road wear), and total PM emissions from road transport in EU27 [4]: (**a**) PM_{10}; (**b**) $PM_{2.5}$. Percentages give contribution of non-exhaust to total PM at years 2010, 2020, 2030, 2040 and 2050. The decrease of emissions in 2020 was due to the COVID-19 restrictions.

Brake wear particles come mainly from the friction between the brake pad/shoe and disc/drum. A considerable part of the order, 40%, becomes airborne PM [10]. There are two main friction brake system configurations in current use: disc brakes, in which flat brake pads are forced against a rotating metal disc and drum brakes, in which curved brake shoes are forced against the inner surface of a rotating cylinder. Cars are usually equipped with front disc brakes and either rear disc or drum brakes. Commercial vehicles tend to be fitted with drum brakes, although disc brakes are being introduced by some manufacturers. Drum brakes in Europe are estimated to cover 10% of the brake market.

Gray (or grey) cast iron (GCI) is a popular automotive brake disc material due to its high melting point, good heat storage and damping capability, and good castability and machinability [11,12]. However, poor corrosion resistance and excessive wear result in high brake particle emissions. For example, a study found that the effect of corrosion inhibited braking performance by reducing the coefficient of friction and significantly increased both the number and mass of particle emissions by at least a factor of 2 and up to 30 times compared with the uncorroded disc under the same test conditions [13]. Various treatments (e.g., cryogenic, heat) can improve the tribological properties and reduce the wear [14]. Surface treatment in the form of a suitable coating (e.g., with hard metal coating (HMC) such as tungsten carbide, cobalt, chrome) is a promising solution [11,15]. Carbon–ceramic discs (CC) are another option, but more costly. The market penetration of CC and HMC discs is currently limited to high-performance sports cars and luxury class vehicles due to their high costs. However, it is becoming a very popular method for reducing the amount of particles formed. Replacing GCI with CC or coated discs reduces the emissions due to lower disc wear. The pads wear is also reduced (e.g., [16]), but in some cases, it can even increase [17]. For this reason, the use of such discs in vehicles is accompanied by research to develop the appropriate pads. It is noteworthy that some studies demonstrated low reductions from GCI replacement with CC or coated discs [18]. Even though the cost is quite high, the future cost of coated discs is estimated between 3.5 and 16 Euros per disc [19].

Brake pad materials can be categorized based on their friction material as organic, or metallic. Other categories include ceramic (expensive), carbon (only for high temperatures) and aluminum (only for light applications and rear brakes) but they are not widespread [20]. The metallic pads are sub-divided in low-metallic (LM) or low steel, semi-metallic (SM) or fully metallic (not common). Thus, in the literature, the pads are practically categorized as: non-asbestos organic (NAO), LM or SM [21,22]. Recently, non-metallic (NM) pads have been reported [12], but they refer to NAO pads [23]. The Economic Commission for Europe (ECE) refers to European performance brake pads (usually LM or SM). The United States of America (USA), Japan and Korea markets typically use NAO pads. Older and recent measurements indicated that replacing ECE with NAO pads can reduce PM from brakes [24,25].

As brake wear occurs mainly when braking, the highest concentrations of brake wear particles should be observed in urban areas, in particular at traffic lights, pedestrian crossings and corners. Particles may also be released from the brake mechanism or wheel housing sometime after the primary emission event. Finally, emissions due to the remaining drug force in non-braking events have been reported [26].

Various options exist for the reduction of brake emissions: Better pad and disc materials, vehicle light-weighting, capturing particles in the brake (e.g., drum brake or passive and active filters), reduced friction braking (e.g., regenerative braking or predictive braking) and reduction of drag torque [27,28].

Emission factors are based on specific brake measurements or on roadside measurements and source appointment. However, the experimental data on which the emission factors of the inventories are based on are limited and in some cases outdated. Even though the first studies on brake emissions date back in the 1980s [29], the topic was of low importance until the exhaust emissions decreased to levels comparable with the non-exhaust emissions.

For the determination of emission factors, measurements can be done in the laboratory (e.g., Pin-on-Disc (PoD), brake dynamometer) and on the vehicle (chassis dynamometer, on-road) using various instruments (gravimetric filter method, optical counters, electrical counters, etc.) and different driving cycles. Common cycles in the laboratory are the 3 h-Los Angeles City Traffic (3 h-LACT), Worldwide harmonized light vehicle test procedure cycle designed for exhaust emissions (WLTP-E) [30], or the one designed for brake emissions (WLTP-B) [31]. The various studies used different test conditions (ambient temperature, simulated vehicle weight), depending on their needs. The recent Global Technical Regulation (GTR 24) on brake emissions from light-duty vehicles standardized the measurement procedures. This UN GTR defines the test cycle, minimum system requirements, test conditions, and equipment preparation to execute the WLTP-B cycle using brake dynamometers. The Euro 7 proposal with brake limits is based on this methodology. The GTR 24 was developed by the Particle Measurement Programme (PMP) informal working group under the auspices of the United Nations Economic Commission for Europe (UNECE) Working Party on Pollution and Energy (GRPE), which started working on the topic in 2013. Until that period, there were only a few reviews [32], but since 2011 there have been numerous studies on brake emissions [22,33–43].

Aim of this comprehensive review is to summarize all studies on brake emissions and, in particular, those recent studies following the GTR 24 standardized methodology. The ultimate goal is to provide up-to-date $PM_{2.5}$, PM_{10} and particle number (PN) emission factors for light-duty vehicles and reduction potential of pads, discs and regenerative braking.

2. Background

Table 1 summarizes in chronological order the experimental studies that provided emission factors based on direct measurements. Most of them have been mentioned in previous reviews. Additional information regarding the test cycles and the instrumentation that was used is given. Studies that gave results in volume units (e.g., mg/m^3) and did not express the results per distance (i.e., mg/km) are not included. These studies are summarized elsewhere (e.g., [43]). It is evident that due to the methodological differences, test cycles, and instrumentation, a direct comparison is difficult. Nevertheless, emission inventories emission factors are based partly on these data.

Table 1. Emission factors of full friction brakes at vehicle level for mass (mg/km/V) or particle number (#/km/V).

Year	Ref.	Type	Pad	Vehicle or Mass	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN × 10^9 #/km/V	Comments
1983	[29]	D	Asbestos	n/a	7.8	-	-	Dyno, urban
2000	[44]	D	SM × 5	PCs	3.1–5.2	2.1–3.5	-	Estim. from pad life
2000	[44]	D + Drum	SM × 2	PT	7.5	5.5	-	Estim. from pad life
2002	[45]	all	all	all	7.0	-	-	Estim. from 40% of wear rate
2003	[46]	D	LM	Mid PC	8.2 mg/stop/B	-	-	
2003	[46]	D	SM	PT	2.0 mg/stop/B	-	-	Wind tunnel, urban driving
2003	[46]	D	NAO	Large PC	1.8 mg/stop/B	-	-	
2004	[32]	D	n/a	PC	1.8			Mass loss (Motorway)
2004	[32]	D + Drum	n/a	PC × 4	4.7–20.5			Mass loss (Urban − Motorw.)
2008	[47]	n/a	NAO × 3	2000	5.8 mg/stop/V	-	n/a	Estimated from pad life
2015	[48]	D	NAO	PC	0.67	0.53	n/a	Dyno, JC08 cycle
and	and	D	NAO	PC	1.38	1.00	n/a	Dust monitor
2016	[49]	Drum	NAO	Mid PT	0.16	0.11	n/a	
2017/18	[14,50]	D	NAO	1500	8.5–9.2 mg/stop/B		1530/stop/B	Dyno, SAE J2707, ELPI
2017/20	[36,50]	D	LM × 4	1500	13.7–46.4 mg/stop/B		80–910/stop/B	Dyno, SAE J2707, ELPI
2019	[51]	D + HMC	LM	Mid PC	4.0–6.0 **	-	570–3700 **	On road, LACT, DustTrak
2019	[52]	D + HMC	proto	1600	-	-	10	Chassis, LACT, CS + CPC_{10}
2019	[53]	D	n/a	Van 2286	-	-	5–20	On-road, $PEMS_{23}$
2021	[54]	D	n/a	1840	-	-	33	Dyno, WLTP-B, ELPI
2020	[55]	D	LM	n/a	1.9–3.1	-	-	Dyno, WLTP-E, OPC
2020	[55]	D	NM	n/a	0.2–2.3	-	-	Dyno, WLTP-E, OPC
2021	[56]	D	LM	n/a	7–21	-	7–30	Dyno, WLTP-E, ELPI
2021	[56]	D	NM	n/a	1.5–5.0	-	23–47	Dyno, WLTP-E, ELPI
2021	[57]	D	LM	Mid PC	7.4	-	-	Dyno, WLTP-E
2022	[58]	D	LM	1300 *	17.1 **	6.3	-	Dyno, WLTP-E, APS
2022	[58]	D	NAO	1300 *	3.3 **	2.3	-	Dyno, WLTP-E, APS
2022	[41]	D	LM	1400 *	7.0	-	-	Dyno, WLTP-B, ELPI
2022	[59]	D	ECE	2310	2.5–4.5	-	5.6–14	On road, chassis, ELPI
2023	[60]	D	ECE	1800	10.2 **	3.1 **	37 **	On road RDE, PM, CPC
2023	[61]	D	SM	n/a	9.3–15.3	2.0–3.5	-	Dyno, RDE braking, PM
2023	[61]	D	Ceramic	n/a	3.1	0.7	-	Dyno, RDE braking, PM

* estimated from rotational inertia. ** multiplied by 2.83 to convert front brake emissions to vehicle emissions. APS = aerodynamic particle sizer; B = brake; CPC_{10} = condensation particle counter > 10 nm; CS = catalytic stripper; D = disc (GCI); E = exhaust; ELPI = electrical low pressure impactor; GCI = gray cast iron; HMC = hard metal coated; LACT = Los Angeles City Traffic; LM = low metallic; NAO = non-asbestos organic; n/a = not available; NM = non-metallic; OPC = optical particle counter; PC = passenger car; $PEMS_{23}$ = portable emissions measurement system > 23 nm; PM = particulate matter (gravimetric method); PT = pick-up truck; RDE = real driving emissions; SM = semi-metallic; WLTP = worldwide harmonized light vehicles test procedure cycle.

The values of Table 1 refer to vehicle level. To convert front brake corner emissions to vehicle emissions, a factor of 2.83 was used, whenever no other information was provided. This value is based on the GTR 24 brake force distribution of front and rear axles of 77%/32%: if the emissions of the front brake are known, then the vehicle emissions can be calculated using the factor (77% + 32%)/(77%/2) = 2.83. Quite often the ratio 70%/30% is used, which results in a factor of (70% + 30%)/(70%/2) = 2.85, or sometimes the rounded value of 3 is used.

3. Research According to GTR 24

This section summarizes the research, following as closely as possible the light-duty vehicles Brakes GTR 24. The main requirements are: testing of a brake assembly in an enclosure, using a brake dynamometer, and following the WLTP-B (brake) cycle. Sampling from a tunnel using cyclonic separators is followed by filters for PM and condensation particle counters (CPC) for PN. Here, PN refers to total PN > 10 nm, but only when the measured values were close to the solid PN. Cases with high PN have been excluded (and will be discussed separately in the Discussion section).

When comparing pads, discs, or technologies, other studies deviating from the GTR are also included, as the relative difference is of interest.

The studies are those found in the literature, without any information regarding their representativeness or coverage of the market.

3.1. Emission Factors per Brake Corner

Table 2 summarizes the research that followed the Brakes GTR 24 (or very similar). The averages and different scenarios will be presented in Section 4.

Table 2. Emission factors of full friction brakes for mass (mg/km/B) or particle number (#/km/B) measured according to the Brakes GTR 24 for light-duty vehicles, i.e., with the WLTP-B (worldwide harmonized light vehicles test procedure brake cycle), unless otherwise specified. Values in brackets were assumed.

Year	Ref.	Axle	Type	Pad	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN × 10^9 #/km/B	Comments
2019	[62]	F	D	LM	1500	4.6	-	4.9	Mid-sized, LACT cycle
2019	[63]	F	D	ECE	1500	4.5	1.5	1.5	Mid-sized
2019	[64]	F	D	ECE	1200	2.5 *	1.2 *	0.8 *	City car
2019	[64]	F	D	NAO	1200	1.2 *	0.7 *	0.5 *	City car
2019	[64]	F	D	NAO	1200	0.4 *	0.2 *	0.1 *	City car
2020	[65]	F	D	ECE	1750	7.6	2.5	4.5	Also [66]
2020	[65]	F	D	ECE	2150	12.2	4.8	8.7	
2020	[67]	F	D	NAO	2500	1.2	0.5	1.1	Pick-up truck (8% payload)
2020	[67]	F	D	NAO	2500	0.7	0.4	0.6	Pick-up truck (8% payload)
2020	[67]	F	D	NAO	2950	0.8	0.5	0.8	Pick-up truck (67% payload)
2020	[67]	F	D	LM	2500	4.3	1.5	2.9	Pick-up truck (8% payload)
2020	[67]	F	D	LM	2950	7.1	2.1	3.2	Pick-up truck (67% payload)
2020	[67]	F	D	NAO	2182	2.2 *	1.0 *	-	Mini van
2020	[67]	F	D	NAO	1651	2.0 *	0.9 *	-	Class C
2020	[67]	F	D	NAO	1655	1.8	0.6	1.2	Class C
2020	[67]	F	D	NAO	1655	1.2	0.4	1.0	Class C
2020	[67]	F	D	LM	1655	2.3	0.7	2.4	Class C
2020	[67]	F	D	NAO	1347	3.2	1.3	-	Compact
2020	[68]	F	D	ECE	n/a	-	-	3.1	
2020	[68]	F	D	NAO	n/a	-	-	0.8	
2021	[23]	F	D	NAO	2000	0.1	0.05	-	
2021	[69,70]	F	D	ECE	(1700)	8.5	4.5	3.5	Medium sedan
2021	[69,70]	F	CC	ECE_{opt}	(1700)	2.2	1.1	1.5	Medium sedan
2021	[71]	F	D	LM	2250	4.7	2.4	1.0	Class J
2021	[71]	F	HMC	LM	2250	2.1	1.2	1.3	Class J
2021	[71]	F	CC	LM	2250	1.4	0.9	0.8	Class J
2021	[71]	F	D	LM	2250	12.4	6.0	4.6	Class J
2021	[71]	F	HMC	LM	2250	3.4	1.8	0.5	Class J
2021	[71]	F	CC	LM	2250	1.2	0.8	0.6	Class J
2022	[72]	F	D	ECE	1800	4.5	1.45	3.4	Luxury sedan
2022	[25]	F	D	LM	2000	4.2	2.1		
2022	[25]	F	D	NAO	2000	1.2	0.5	-	
2023	[10,73]	F	D	ECE	1600	6.0	2.0	2.2	Class C
2023	[10,73]	F	D	NAO	1600	2.3	0.7	1.0	Class C (as above)
2023	[10,73]	F	D	ECE	1668	10.7	3.8	8.6	Class J
2023	[10,73]	F	D	ECE	2623	9.1	3.1	3.3	SUV
2023	[10,73]	R	Drum	n/a	1253	0.5	0.3	1.7	Super mini
2023	[10,73]	F	D	ECE	2500	7.7	3.0	5.8	LCV (28% payload)
2023	[10,73]	F	D	ECE	3390	9.4	4.0	11.1	LCV (90% payload)
2023	[28]	F	D	LM	1660	5.3	2.8	4.3	Class C
2023	[28]	F	D	NAO	1660	3.9	2.2	1.8	Class C
2023	[28]	R	D	ECE	1660	1.5	0.9	5.1	Class C
2023	[28]	R	Drum	(LM)	2041	1.1	0.8	2.8	Class C
2023	[28]	R	Drum	(LM)	2041	0.7	0.6	1.1	Class C
2023	[28]	R	Drum	(NAO)	2041	0.3	0.3	0.5	Class C
2023	[28]	F	D	ECE	2113	7.6	3.5	3.9	Class J

Table 2. *Cont.*

Year	Ref.	Axle	Type	Pad	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN × 10^9 #/km/B	Comments
2023	[28]	F	HMC	ECE_{opt}	2113	1.6	1.0	1.4	Class J
2023	[60]	F	D	ECE	2027	4.1	1.2	2.1	Luxury sedan
2023	[74]	F	D	ECE	1840	6.5	1.8	0.5	Japanese market
2023	[75]	F	D	LM	1820	2.3	-	-	Corrected with ×0.7/2
2023	[75]	F	D	NAO	1820	1.1	-	-	Corrected with ×0.7/2
2023	[75]	F	D	LM	2250	1.3	-	-	Corrected with ×0.7/2
2023	[75]	F	D	HMC	2250	0.5	-	-	Corrected with ×0.7/2
2023	[76]	F	D	ECE	1500	7.3	-	-	Segment D
2023	[76]	F	D	ECE	1250	5.4	-	-	Segment B
2023	[76]	F	D	ECE	1200	6.9	-	-	Segment B
2023	[76]	F	D	ECE	1250	5.1	-	-	Segment B
2023	[61]	F	D	(SM)	n/a	5.7	1.2	-	Average of two
2023	[61]	F	D	Ceramic	n/a	3.2	0.8	-	Estimated from figure
2023	[77]	F	D	ECE	1240	3.7	1.3	-	-
2023	[77]	F	D	NAO	1240	1.4	0.6	-	-
2023	[78]	F	D	NAO	1533	0.8	0.2	0.1	-

* Divided by 2.83 to convert vehicle emission to brake corner. B = brake; CC = carbon ceramic; D = disc (GCI); ECE = Economic Commission for Europe; GCI = gray cast iron; HMC = hard metal coated discs; LACT = Los Angeles City Traffic; LCV = light-commercial vehicle; LM = low metallic; NAO = non-asbestos organic; SUV = sports utility vehicle.

3.2. Mass (Wear) Loss and Airborne Fraction

Not all mass (wear) that is lost from the pad and the disc becomes airborne. The airborne fraction, sometimes called the total suspended fraction, has been determined in some studies and is summarized in Table 3. On average, it is around 40%. Most of the airborne fraction is PM_{10} (typically ≫ 80%). For this reason, in some cases, airborne to mass loss or PM_{10} to mass loss ratios are used interchangeably. A few studies found ratios of PM_{10} to mass loss < 30%, but recent studies found ratios > 30%, on average 42%. This value should be lower than the airborne fraction, but it is based on different studies. Thus, the experimental conditions and the brakes were different. The three common studies reported that PM_{10} is 80–98% of total airborne PM. Combining the two numbers together, it can be concluded that the airborne and PM_{10} fractions account for on average 40–42% of the total wear. A study showed that theoretically, the 43% fraction corresponds to a mass median diameter of around 6.3 µm [79]. The same study summarized measured size distributions, and in agreement with other reviews [8,33] the mass peak is expected in the 3–6 µm range.

3.3. $PM_{2.5}$ to PM_{10}

Based on the studies of Table 2, the ratio of $PM_{2.5}$ to PM_{10} is 40% for ECE pads, 45% for NAO pads, 59% for CC and HMC discs, and 60–100% for drum brakes. The high percentage of drum brakes could be due to the low masses collected on the filters and the respective experimental uncertainty. A study found that while the ratio was 43% for the WLTP-B cycle, for other cycles the ratio varied from 33% to 70% [23]. Theoretically the 45% ratio corresponds to mass distribution with a peak at 3 µm [79].

3.4. ECE vs. NAO Pads

Many studies have demonstrated that the pad's composition has an impact on wear and particle formation (see studies in review [80]). From the previous section, it is evident that NAO pads have lower emissions than ECE (metallic) pads. This was demonstrated as early as 2000 [46]. An older study also showed that the disc mass loss can also be reduced by replacing LM with NAO pads [24]. NAO pads are typically used in USA, Japan and Korea, while ECE pads are typically used in Europe.

Table 3. Airborne and particulate matter PM_{10} fractions of total mass loss for gray cast iron disc brakes. Some information about the studies can be found in Table 2.

Year	Ref.	Airborne/ Mass Loss	PM_{10}/Mass Loss	Comment
1973	-	2–22%	-	Cited in [29]
1980	-	55%	-	Cited in [29]
1983	[29]	32%	-	-
2000	[44]	16–35% *	14–30%	86% from airborne
2003	[46]	50%	40%	80% from airborne
2008	[47]	63%	60–62%	95–98% from airborne
2016	[49]	2–29%	-	
2017	[50]	35–58%	-	
2019	[63]	-	57%	Based on recovered deposited mass
2020	[36]	37%	-	
2020	[67]	<10%	-	
2019	[62]	49%	-	
2021	[71]	-	24–51%	30–40% with CC and HMC
2022	[25]	-	28%	Both LM and NAO
2023	[10]	-	35–48%	21% for Drum
2023	[28]	-	40%	
2023	[76]	-	48–57%	
2023	[61]	-	66%	Six SM and ceramic pads
2023	[77]	-	35–40%	Both ECE and NAO
2023	[78]	-	25%	NAO

* correcting for particle losses, it arrives at 64% [46]. CC = carbon ceramic; HMC = hard metal coated discs; LM = low metallic; NAO = non-asbestos organic; SM = semi-metallic.

Table 4 summarizes the studies that investigated the impact of pad material on brake emissions. On average, the reduction is 62% for PM_{10}, 55% for $PM_{2.5}$ and 64% for PN when comparing NAO against ECE materials. However, the scatter of emission reductions is large due to the high variability of the (absolute) emission levels of the ECE pads. In other words, replacing a high-emitting ECE pad and a low-emitting ECE pad with the same NAO pad, will most likely result in different reduction efficiencies.

Table 4. Potential reduction of brake emissions with NAO (non-asbestos organic) pads compared to ECE pads.

Year	Ref.	PM_{10}	$PM_{2.5}$	PN	Comment
2003	[46]	78%	-	-	-
2018	[14]	65%	-	-	-
2019	[64]	52–84%	42–83%	40–88%	2 × NAO
2020	[67]	84–89%	73–76%	75–79%	Pickup truck
2020	[67]	22–48%	14–43%	50–58%	2 × NAO
2020	[68]	-	-	75%	-
2021	[69]	-	-	75%	-
2022	[58]	80%	64%	-	-
2022	[25]	72–77%	64–78%	-	3 cycles
2023	[10,73]	62%	65%	55%	-
2023	[28]	26%	22%	58%	-
2023	[75]	55%	-	-	-
2023	[81]	-	-	64%	-
2023	[77]	62%	55%	-	-

3.5. Advanced Discs

GCI discs are popular due to their advantages but, at the same time, are associated with high wear. In general, in GCI with ECE high-emitting brakes, the disc contributes around 60% to total mass loss [16,77,82,83]. With drum brakes, the contribution is lower;

one study found 37% [83]. However, with ceramic discs, the contribution of disc wear to total wear is much lower (<5%) [16].

Table 5 summarizes studies that investigated the impact of using carbon-ceramic (CC) or coated (HMC) discs instead of GCI discs on brake emissions. On average, the PM_{10} reduction is 81% for CC and 57% for HMC (70% for both CC and HMC) discs. The $PM_{2.5}$ reduction is 74% for CC and 60% for HMC (70% for both CC and HMC) discs. For PN the reduction is 61% for CC and 57% for HMC (59% for both CC and HMC) discs.

Table 5. Potential reduction of emissions replacing gray cast iron (GCI) disks with carbon-ceramic (CC) or hard metal coated (HMC) disks.

Year	Ref.	Wear	PM_{10}	$PM_{2.5}$	PN	Comment
2017	[84]	43–72%	38–57%		44–67%	HMC [1]
2019	[18]	32%	-	-	-	HMC [2]
2020	[85]	56%	-	-	-	HMC [3]
2020	[17]	21%	-	-	57%	HMC [4]
2021	[16]	78–84%	94% *	-	83–91%	CC
2021	[69]	-	74%	76%	57%	CC (+opt. pad)
2021	[71]	-	55%	50%	(30% incr.)	HMC [5]
2021	[71]	-	70%	63%	10%	CC
2021	[71]	-	73%	70%	89%	HMC [5]
2021	[71]	-	90%	87%	87%	CC
2023	[28]	-	79%	71%	64%	CC
2023	[75]		63%	-	-	HMC

[1] WC/CoCr; [2] Cr_2O_3-40%TiO_2; [3] 20NiCrBSi-WC12Co; [4] Ni-SF, SFTC; [5] WC; * determined with an electrical low pressure impactor (ELPI). CC = carbon ceramic; HMC = hard metal coated.

3.6. Brake Particle Filters or Collection Systems

In recent years, brake particle collection filters appeared in the market with promising results. The systems can be active (sucking) or passive. Table 6 summarizes the studies and the resulting brake particle filtration (collection) efficiencies. On average, passive systems have a PM efficiency of 50%, while active systems 75%. However, for more accurate estimates of filtration efficiency, more studies are necessary with commercially available systems. The relatively low collection efficiency with active systems, which are not operating for the whole cycle, has to do with the off-brake emissions due to drag torque and axial vibrations. A study found that during the full WLTP cycle, 40–53% of the particles were emitted outside braking (off-brake emissions) [76].

Table 6. Brake particles collection efficiency of various filters.

Year	Ref.	PM	PN		Comments
2016	[86]	92%	-	Passive	At ventilated disc
2020	[87]	68–95%	50–90%	Active	Grooved pad. 84% at WLTP-B
2020	[88]	75%	40–50%	Active	Grooved pad. Negligible improvement with passive
2021	[89]	20–39%	-	Passive	Can increase with smaller gap to the disc
2022	[90]	53%	-	Passive	Ceramic filter porosity 52%
2022	[91]	-	50–80%	Passive	Inertial separator. Above 2.2 µm. WLTP-B
2022	[91]	60–75%	>50%	Passive	Inertial separator and ESP. Above 0.5 µm. WLTP-B
2023	[92]	61%	-	Active	WLTP-B. Collection efficiency 80% with continuous sampling
2023	[76]	77%	-	Active	WLTP-B. Collection efficiency 84% with continuous sampling

ESP = electrostatic precipitator; PM = particulate matter; PN = particle number; WLTP-B = worldwide harmonized light vehicles test procedure brake cycle.

3.7. Electrified Vehicles

Electrified vehicles' sales and market share are increasing as EU is pacing to zero CO_2 tailpipe emissions by 2035. Brake emissions (as well as other non-exhaust emission) from electrified vehicles are expected to increase due to their higher mass, but on the other hand to decrease due to their regenerative braking and hence reduced use of friction brakes [93]. Most studies estimate weight increases of electric vehicles in the order of 15–25% (250–320 kg) [93,94]. However, due to the increasing sale shares of SUVs in the ICE fleet, the average masses of conventional and electrified vehicles may get closer [95]. A study estimated that due to the additional mass of electrified vehicles, regenerative braking of 20–60% was necessary to bring the PM_{10} emissions at the same levels with the full friction counterparts [94]. Many researchers have predicted the reduction of emissions due to regenerative braking, typically between 50% and 95% [58,96]. A study assumed that electric vehicles require about two-thirds less friction braking than internal combustion vehicles, based on the roughly two-thirds longer service times of brake pads than of diesel/petrol vehicles [97]. Another study measured 60% recuperation of braking kinetic energy at smooth braking but only 8% for hard braking from 97 to 0 km/h for mild and plug-in hybrid vehicles [98]. Based on the brakes GTR 24 the reduction of the emissions is expected to be proportional to the use of the friction brakes. Table 7 gives the expected regenerative braking based on the friction braking share coefficients c in the GTR $(1 - c)$. Furthermore, the fleet composition in 2020 is given based on European Commission's (EC) impact assessment study [4], which is in agreement with e.g., ACEA's report [99].

Table 7. Electrified vehicles stock and activity share in 2020′s fleet based on European Commission's (EC) impact assessment study [4], and expected use of friction brakes depending on the electrification level based on GTR 24. Activity is defined as the multiplication of vehicles and annual km travelled.

Category	PCs Share	PCs Activity	LCVs Share	LCVs Activity	Regenerative Braking
Petrol	53.0%	37.5%	7.7%	3.2%	0%
Diesel	41.1%	57.2%	90.5%	95.3%	0%
HEV	1.5%	2.0%	0.3%	0.4%	10–48%
PHEV	0.4%	0.6%	0.1%	0.1%	66%
BEV	0.4%	0.6%	0.3%	0.3%	83%
other	3.6%	2.0	1.2%	0.7%	0%

BEV = battery electric vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid vehicle.

The experimental studies on brake emission factors with electrified vehicles are limited and summarized in Table 8. The emission factors as absolute values are lower compared to Table 2, which were based on full friction braking. Also, compared to their ICE counterparts the reductions are typically > 60% (Table 8).

Table 8. Emission factors of electric vehicles for mass (mg/km/V) or particle number (#/km/V). Percentages in brackets give the emissions reductions compared to their internal combustion engine (ICE) counterpart with full friction braking (i.e., with regenerative braking de-activated).

Year	Ref.	Type	Pad	Vehicle or Mass	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN × 10^9 #/km/V	Comments
2020	[67]	Disc	NAO	1600	2.0–2.3	1.0–1.4	1.3–8.9	PHEV
2021	[100]	Disc	n/a	(1800)	0.9	-	-	BEV
2023	[28]	Disc	ECE	1660	5.7 (−62%)	3.4 (−57%)	7.3 (−40%)	PHEV
2023	[28]	Disc	ECE	1660	3.1 (−79%)	2.3 (−71%)	2.1 (−82%)	BEV
2023	[101]	Disc	ECE	1350	10.5	4.5	141	HEV, Chassis, WLTP-E
2023	[102]	Disc	ECE	1228	-	-	0.5 * (−4%)	Chassis, WLTP-B
2023	[102]	Disc	ECE	1228	-	-	0.5 * (−65%)	Chassis, WLTP-E
2023	[102]	Disc	ECE	1228	-	-	4 * (<90%)	Chassis, RDE
2023	[78]	Disc	NAO	1533	0.3 (−86%)	0.14 (−78%)	0.05 (−84%)	PHEV, WLTP-B **

* back-calculated to emissions without regenerative braking and multiplied with 2.83/0.83 to convert to total vehicle emissions from rear brake; ** multiplied by 2.83 to convert to vehicle emissions. n/a = not available.

4. Discussion

Section 2 summarized studies that provided emission factors following various methodologies. Section 3 summarized a large number of studies with brake emission factors following the recently introduced laboratory procedure of the GTR 24. Unfortunately, as it was mentioned, the market share of each brake is not known. Nevertheless, it can be assumed that the tested brakes are representative of the brakes in the market at the time of writing this paper. Differences of pad and disc materials, reductions with filters and regenerative braking were also summarized. Percentages of $PM_{2.5}$ and PM_{10} to airborne PM and total mass (wear) loss were also provided. This Section 4 will present emission factors estimations, and the data will be compared with other datasets, roadside studies and emission inventories.

4.1. Emission Factors and Vehicle Mass

In general brake wear and kinetic energy change or brake dissipation energy are correlated [23,51,74,103]. For the same braking events (i.e., cycles), the brake wear should correlate with the load (vehicle mass). The impact of vehicle mass on the brake emissions has been mentioned in previous studies, but has not been quantified (see review [104,105]). Figure 2 summarizes the data of Table 2 (red squares for ECE pads, open green circles for NAO pads) with the addition of three studies that examined the impact of mass on brake emissions for a passenger car (grey triangles, [106]), and two vans (large squares with black borders [10] and blue borders [67] connected with dotted blue lines for better visualization). Only gray cast-iron discs data were used (i.e., coated discs or drum brakes were not considered). As expected, the dedicated studies show a linear correlation (see grey triangles), but the slope is not the same for all studies. However, when considering all brakes, the results of Table 2 indicate no correlation for ECE or NAO pads, because any correlation is masked from the material impact on the emissions. For all ECE pads the average correlation factor is 3.1 mg/km/brake per 1000 kg of vehicle mass (note the low R^2 value).

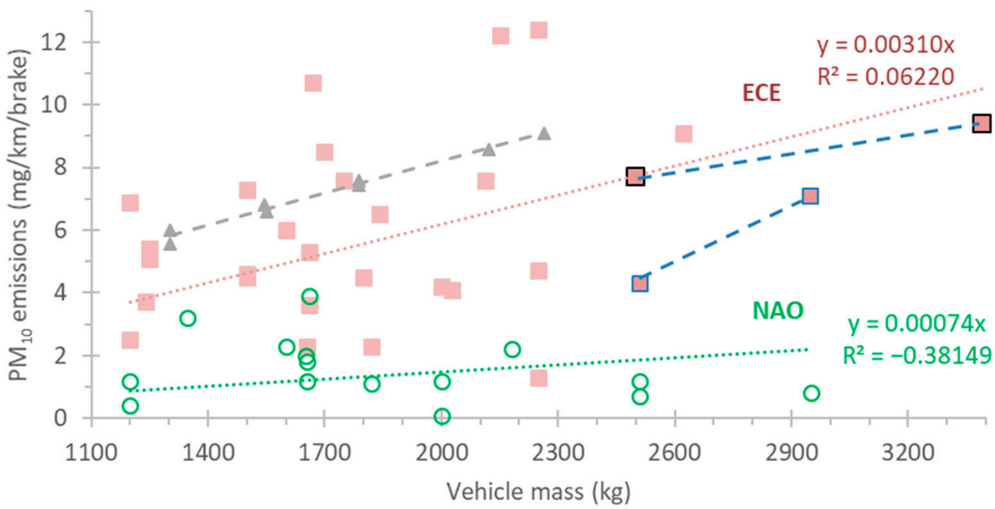


Figure 2. PM_{10} emissions in function of vehicle mass for ECE (squares) and NAO (circles) pads and gray cast iron discs. Grey triangles and bigger squares with border are three dedicated studies that modified the vehicle mass and the dashed lines show their trendline assuming linear correlation for each study. The dotted lines give the correlation line of the ECE and NAO brakes of Table 2.

Other researchers have suggested a non-linear (power) equation for the relation between brake emissions (mg/km/V) and vehicle mass (W_{ref} in t) [94].

$$EF = b\, W_{ref}^{(1/c)}, \tag{1}$$

where b (mg/km/V) and c (−) are constants. The constants for ECE pads of the data of Figure 2 were b = 12.7 and c = 1.87; values close to the urban emission factors of that study [94].

Table 9 gives the estimated emission factors per brake corner based on Table 2 or the correlation in Figure 2 for PM_{10} and based on Figures A1 and A2 in the Appendix A for $PM_{2.5}$ and PN, respectively.

Table 9. Summary of estimated emission factors per brake corner for mass (mg/km/B) and particle number (#/km/B).

Category	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN $\times 10^9$ #/km/B	Comment
ECE (all)	1902	6.0	2.5	3.9	Average Table 2
ECE (PCs)	1752	5.8	2.5	3.5	Average Table 2
ECE (LCVs)	2838	7.1	2.7	5.6	Average Table 2
ECE	1525	4.7	1.9	3.2	Based on Figure 2
ECE (N1-III)	1760	5.5	2.2	3.7	Based on Figure 2
ECE (N1-III)	2250	7.0	2.9	4.7	Based on Figure 2
NAO	1807	1.7	0.8	0.7	Average Table 2
CC and HMC	2152	1.8	1.1	1.0	Average Table 2
Drum	1844	0.7	0.5	1.5	Average Table 2

B = brake; CC = carbon-ceramic; ECE = Economic Commission for Europe; HMC = hard metal coated; LCV = light commercial vehicle; NAO = non-asbestos organic; PC = passenger car.

The average mass of all vehicles using ECE pads (with GCI discs), was 1902 kg, of all passenger cars 1752 kg, and of all LCVs 2838 kg. The mass of 1525 kg is the average mass in running order of passenger cars from 2020 plus half more passenger as defined in GTR 24 for testing [107], 1760 kg is the starting mass of N1 vehicles class III, while 2250 is the mass of N1-III vehicles with 28% payload. From Table 2, the average mass of all cars tested with NAO pads was 1807 kg, with CC and HMC discs 2152 kg and with drum brakes 1844 kg.

4.2. Comparison with International Organization of Motor Vehicle Manufacturers (OICA) Data

At the end of 2021, the OICA presented a large number of emission factors measured by its members [108]. The dataset included all typical brakes in use at that time, from small cars to SUVs and light commercial vehicles. The emission factors, expressed per vehicle, were transformed per brake by dividing by 3. Figure 3 presents the results as a function of vehicle mass. As with the previous data, there is no correlation between brake emission factors and vehicle mass when all brakes are considered and not the same material is used. The mean emission factor of the OICA dataset was 6.8 mg/km/brake, with a mean vehicle mass of 2200 kg. Separately, the LCVs had 5.7 mg/km/brake (mass 2465 kg). Forcing a linear trendline, the correlation factor would be 3 mg/km/brake per 1000 kg of vehicle mass, almost identical with the finding of Table 2 for ECE brakes (3.1 mg/km/brake per 1000 kg of vehicle mass). The data from Table 2 are also plotted for completeness. There is a high similarity in the scatter of the points, mainly with the ECE data, probably because the majority of brakes in Europe are ECE. The 62 cases in Table 2 and the 35 from OICA stress with high confidence the representativity of the reported emission factors in this paper.

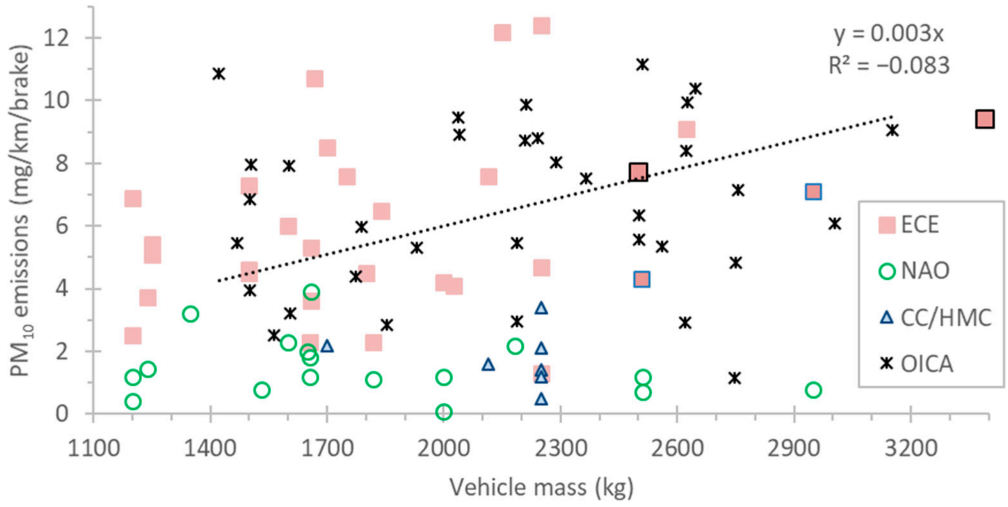


Figure 3. PM_{10} emission in function of vehicle mass for ECE or NAO pads and gray cast iron discs, or CC and HMC disks. With asterisks the OICA data (mix of brakes and vehicles). The dotted line is the correlation line of the OICA data.

4.3. Brake Emission Factors at Vehicle Level

Based on the emission factors per brake corner (Table 9), and multiplying them by 2.83, Table 10 presents the emission factors per vehicle for ECE pads. For vehicle masses between 1525 and 2250 kg the PM_{10} emissions are 13.4–19.7 mg/km/vehicle. Vehicles with ECE pads at the front wheels and drum brakes at the rear have PM_{10} emission levels between 12.2 (1760 kg) and 15.3 (2250 kg) mg/km/V. PM_{10} emission factors with NAO pads assuming that the emissions per brake corner are independent from the vehicle mass are 4.7 mg/km/V, while with the mass dependency of Figure 2, they are 5.4–7.9 mg/km/V. A last scenario with advanced discs at the front brakes and NAO pads at the rear brakes gives a PM_{10} of 6.9 mg/km/V for all vehicle masses. The 2020 fleet emission factors are only slightly lower compared to the scenario with a fleet without regenerative braking, due to the small share of electrified vehicles.

Table 10. Brake emission factors EF at vehicle level for mass (mg/km/vehicle) and particle number (#/km/V) for different disc and pad combinations. Emission factors per brake EF_B are given in Table 9. PC = passenger cars; LCV = light commercial vehicles.

Scenario	Mass kg	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN #/km/V	Comments
ECE	1525	13.4	5.5	9.1	$EF_{B,ECE} \times 2.83$
ECE	1760	15.4	6.3	10.5	$EF_{B,ECE} \times 2.83$
ECE	2250	19.7	8.1	13.4	$EF_{B,ECE} \times 2.83$
ECE + Drum	1760	12.2	5.5	10.5	$2 \times EF_{B,ECE} + 2 \times EF_{B,Drum}$
ECE + Drum	2250	15.3	6.7	12.5	$2 \times EF_{B,ECE} + 2 \times EF_{B,Drum}$
NAO	all	4.7	2.2	2.1	$EF_{B,NAO} \times 2.83$
NAO	1525–2250	5.4–7.9	2.5–3.6	4.1–6.0	−60% from ECE
CC/HMC + NAO	all	6.9	3.8	3.5	$2 \times EF_{B,CC} + 2 \times EF_{B,NAO}$
		Electrification share in fleet 2020			
PC	1525	13.1	5.4	8.9	Fleet activity Table 7
LCV	2250	19.6	8.0	13.4	Fleet activity Table 7

To put the estimations into perspective, the fleet emission factors can be compared with field studies and emission inventories.

4.4. Roadside and Tunnel Studies

Table 11 summarizes the brake emission factors from roadside and tunnel studies using metals as tracers to the source (brakes). Studies that calculated brake emissions using traffic data and emission factors given in databases (e.g., EMEP/CORINAIR [109]) were not included in the table. The overall average PM_{10}, considering the studies from 2004 on, is 5.9 mg/km/V. The average of the European studies gives 6.6 mg/km/V PM_{10} emissions. The values are much lower, almost half, compared to the emission factors estimated from measurements in the laboratories (Table 10).

Table 11. Light-duty vehicles brake emissions based on field studies and receptor modelling (mg/km/V). PC = passenger cars; HDV = heavy-duty vehicles.

Year	Ref.	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	Comments
2003	[110]	0–80	0–5	Freeway exits, North Carolina, USA
2004	[32]	6.9	-	Tunnel London, UK (13% HDV, incl. tire wear)
2010	[111]	8.0	-	Urban, Zurich, CH (9% vans)
2010	[111]	1.6	-	Interurban freeway, Zurich, CH (15% vans)
2016	[112]	1.6–6		Urban and ring road, Paris, France
2016	[113]	3.8–4.4	-	Tunnel, London, UK (8% HDVs)
2019	[114]	9.2	-	Grenoble, France (PC and HDV)
2020	[115]	0.3–1.0	0.1–0.5	Tunnels in four cities, China
2021	[116]	12.9	-	Urban, London, UK (3.2% HDV)
2023	[117]	4.4–7.4	-	Birmingham, UK (3% HDV)
2023	[118]	-	0.28	Urban tunnel, Tianjin, China (gasoline)

The reasons for this discrepancy need to be better understood. It is possible that the contribution of brake particles at the roadside measurements is lower due to fewer braking events. It could be that the laboratory method does not accurately capture the deposition of brake particles on the wheels. An experimental study found that around 10% of the brake wear mass deposited on the wheel. This percentage depends on many factors, such as the rim design, the brake disc ventilation, the trip characteristics and the braking events and the environmental conditions [119]. Simulations showed that, in terms of number concentration, the deposition is >30% up to 20 µm. This assumption needs to be investigated.

4.5. Emission Inventories

Table 12 summarizes the brake emission factors for PM_{10} and $PM_{2.5}$ of light-duty vehicles based on national emission inventories. The emission factors and methodology described in the European Monitoring and Evaluation Programme with European Environmental Agency (EMEP/EEA) Emissions Inventory Guidebook align with COPERT (Computer Programme to Estimate Emissions from Road Transport), the EU standard vehicle emissions calculator, widely utilized by most European countries for their inventories. The EMEP/EEA Emissions Inventory Guidebook [9] provides speed-dependent emission factors for estimating emissions from tire wear, brake wear and road abrasion. PM_{10} emission factors from the brake wear of passenger cars in COPERT range from 3.3 (BEV) to 12 mg/km (ICE). Correction factors are provided to account for different average speeds for mileages driven on urban, rural and highway roads, as brake wear decreases with increasing mean trip speed. This is because braking occurs more frequently in urban driving compared to highway driving, resulting in more brake wear [9,32]. Some European countries employ their own models to calculate emission inventories, like the UK, Netherlands, Denmark, and Sweden. However, in the context of non-exhaust emissions, almost all of them rely on the emission factors provided by the EMEP/EEA Emissions Inventory Guidebook. In the USA, brake wear emissions for passenger cars and vans are quoted as 13.8 and 15.3 mg/km, respectively, by the US EPA MOVES (Motor Vehicle Emission Simulator Tool) [120]. Lower values for brake wear emission factors are suggested by

CARB's EMFAC 2021 emissions model for California [121]. Regarding Australia, COPERT Australia is used to calculate the vehicle emission inventories, which is a special edition of COPERT designed to address the Australian fleet and driving conditions [95].

Table 12. Light-duty vehicles brake emissions based on emission inventories (mg/km/V).

Year	Ref.	PM_{10}	$PM_{2.5}$	Source
2022	[9]	12	4.8	EEA, COPERT (PC ICE)
2022		9.5	3.8	EEA, COPERT (PC HEV)
2022		6.5	2.6	EEA, COPERT (PC PHEV)
2022		3.3	1.3	EEA, COPERT (PC BEV)
2022		12	4.8	EEA, COPERT (LCV N1-I)
2022		17	6.7	EEA, COPERT (LCV N1-II/III)
2020	[122]	8.4	3.3	NAEI UK (PC)
2020		13.1	5.7	NAEI UK (LCV)
2020	[95]	6.2	2.4	Australia, COPERT Australia (ICE)
2020		4.3	1.6	Australia, COPERT Australia (BEV)
2020	[120]	13.8	1.7	US EPA, MOVES3 (PC)
2020		15.3	1.9	US EPA, MOVES3 (LCV)
2021	[121]	3–10	1–3	CARB, EMFAC (PC)
2021		14	4.5	CARB, EMFAC (LCV)
2021	[123]	9.1	3.6	DCE, CORPEM (PC)
2021	[124]	10	-	PBL NL (PC)

BEV = battery electric vehicle; HEV = hybrid electric vehicle; ICE = internal combustion engine; LCV = light commercial vehicle; PC = passenger car; PHEV = plug-in hybrid electric vehicle.

4.6. Total vs. Solid Particles

The emission factors presented refer to solid particles only (i.e., they do not evaporate at 350 °C) or, in a few cases, total particles, but without a separate nucleation mode. A volatile nucleation mode has been reported many times in the literature, when the temperature at the brake exceeds a critical temperature, typically in the range of 165 and 240 °C (see studies in [80] and discussion in [125]). This was already reported in 2000 [44] and confirmed by recent studies [52,71,103]. The increase of emissions can be orders of magnitude higher and it depends on the local super-saturation ratios. More studies are needed in this direction to confirm the reproducibility of the results, and most importantly, more studies are needed with the GTR 24 protocol. For this reason, no emission factors are presented for brakes exceeding their critical temperature.

5. Conclusions

In this study, we summarized brake wear emission factors from the literature. Approximately 30 studies were found in which non-standardized protocols were followed. Emission inventories are based partly on these studies. Another 62 additional emission factors were found in studies that followed the GTR 24 methodology, even if they were not fully compliant. The results were in good agreement with approximately 35 emission factors presented by OICA. The averages of these studies were compared with roadside measurements and emission inventories. Furthermore, the reduction potential of non-asbestos organic (NAO) pads, advanced discs, brake dust filters, and regenerative braking was calculated. The key findings are:

- The airborne and/or PM_{10} fraction to total wear is 40–45% on average.
- The $PM_{2.5}$ to PM_{10} ratio is in the order of 40–45%.
- ECE (i.e., low metal and semi metallic) pads with gray cast iron (GCI) discs emit on average around 3 mg/km/brake per 1000 kg of vehicle mass. However, there is a large variability and the exact value depends on the brake and/or disc combination. The emission factor at vehicle level is around 2.83 to 3 times higher.
- NAO pads can reduce the emissions by at least 60%.

- Advanced discs (coated GCI or carbon ceramic) can reduce the emissions by 60–80%. This may be further enhanced when appropriate pads are applied.
- Brake dust filter can reduce the emission from around 50% (passive systems) to 75% (active systems).
- The electrification of vehicles can reduce the emissions up to 60–80% due to regenerative braking. Lower reductions are observed with lower electrification levels.
- Roadside measurements of brake emissions estimate lower emission factors than those estimated in this review paper.
- The emission inventories are in quite good agreement with the emission factors of this review.

These conclusions should be considered a first approximation of the status of the market at the time of writing this paper. As the procedure has been standardized with GTR 24 since 2023, more accurate emission factors are expected in the future. Furthermore, the database is expected to get larger as the manufacturers will start type-approving their brakes in order to fulfil the upcoming Euro 7 regulation.

Author Contributions: Conceptualization, P.D., Z.S. and L.N.; formal analysis, B.G., T.G. and T.K; writing—original draft preparation, B.G.; writing—review and editing, T.G., P.D., T.K., L.N. and Z.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable. No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflict of interest. The information and views set out are those of the authors and do not necessarily reflect the official opinion of the European Commission and/or their universities and companies. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein. Mention of trade or commercial products does not constitute endorsement or recommendation by the authors or the European Commission.

Appendix A

Figures A1 and A2 present the correlation of ECE and NAO pads with vehicle mass for $PM_{2.5}$ and PN, respectively.

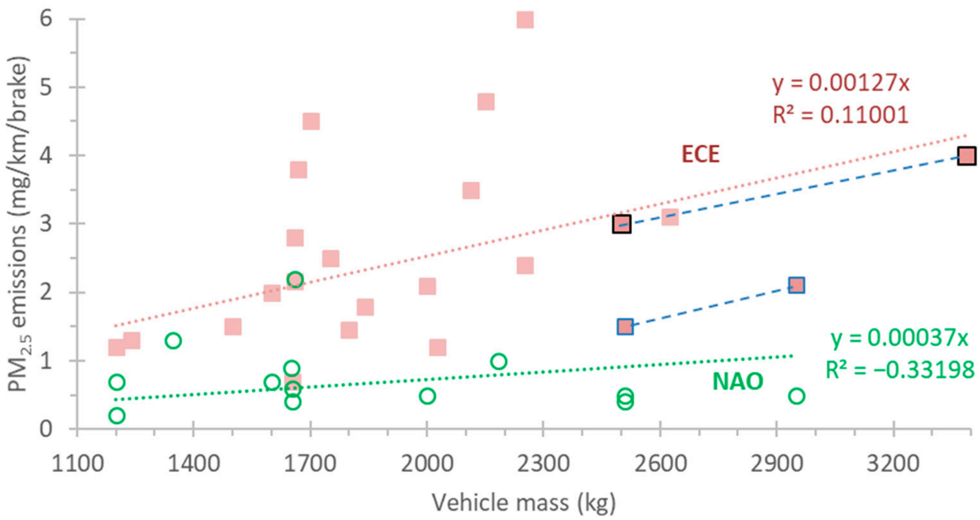


Figure A1. $PM_{2.5}$ emissions in function of vehicle mass for ECE (squares) and NAO (circles) pads and gray cast iron discs. Bigger squares with border are two dedicated studies that modified the vehicle mass and the dashed lines show their trendline assuming linear correlation for each study. The dotted line is the correlation line of the ECE and NAO brakes of Table 2.

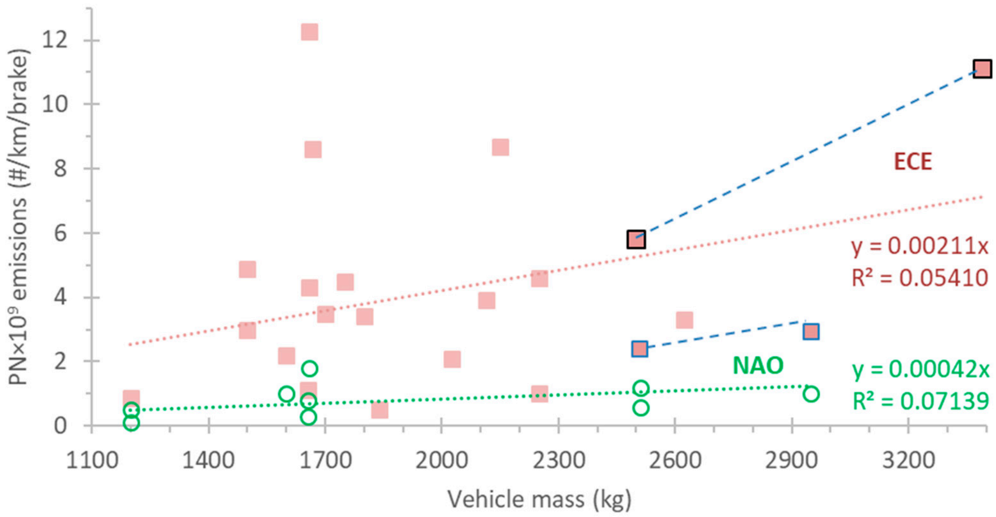


Figure A2. PN emissions in function of vehicle mass for ECE (squares) and NAO (circles) pads and gray cast iron discs. Bigger squares with border are two dedicated studies that modified the vehicle mass and the dashed lines show their trendline assuming linear correlation for each study. The dotted line is the correlation line of the ECE and NAO brakes of Table 2.

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