Article citation info:
Laskowski P, Zimakowska-Laskowska M. The problem of emission of total particulate matter and heavy metals from tribological systems in vehicles. Combustion Engines. 2024;198(3):13-19. https://doi.org/10.19206/CE-183121

Piotr LASKOWSKI
Magdalena ZIMAKOWSKA-LASKOWSKA

Combustion Engines
Polish Scientific Society of Combustion Engines

The problem of emission of total particulate matter and heavy metals from tribological systems in vehicles

ARTICLE INFO

Received: 5 September 2023
Revised: 20 January 2024
Accepted: 25 January 2024
Available online: 13 April 2024

The article presents the problem of particulate matter and heavy metal emissions from the tribological systems (road abrasion, brake and tyre wear) road of cars equipped with internal combustion engines (ICEs), battery electric vehicles (BEVs), hybrids and plug-in vehicles (PHEVs). The results of mathematical modelling carried out for obtaining of the emissions of particulate matter and heavy metals, such as As, Cd, Cr, Cu, Ni, Pb, Se and Zn, resulting from road abrasion, brakes and tyre wear, are presented. Emissions are shown depending on the average speed and type of traffic (traffic in the city (urban), outside the city (rural) and on the highway) and the type of vehicle.

Key words: *BEV, ICE, heavy metals, particulate matters, emission*

1. Introduction

According to the source, the particles emitted due to the automobile's operation can be divided into spent traffic-related particles and unused traffic-related particles emitted due to the incomplete combustion of fuel and lubricants during combustion. trial. They are either generated from unused traffic-related sources or exist as materials already deposited in the environment, only to be disturbed again by traffic-induced turbulence. Particulate matter emissions have been well studied and characterized, and technological improvements have led to significant emission reductions [4, 5, 17]. On the other hand, decommissioning processes are still insufficiently studied and several questions remain unanswered regarding the physicochemical properties, emission factors and harmful health effects of wear particles [4, 5, 17]. The most important wear processes leading to direct particulate matter (PM) and heavy metals emissions are tire, brake, clutch and road wear. Other potential causes include engine wear, worn wheel bearings, corrosion of other vehicle parts, street furniture and fences [4, 5, 17].

Airborne particles are generated when the tyres of a car interact with the road and when the brakes are used to reduce the speed. The main factor responsible for this is the shear forces created by the friction between the surfaces. Additionally, when the surfaces become hot due to contact, the evaporation of material from the surfaces can also contribute to particle production [13].

Tyre wear

Vehicle tyres carry the load of the vehicle and passengers, provide traction and steering, and absorb changes in the road surface, improving the ride quality. The tyre consists of a complex rubber mixture, though the precise ingredients used in commercially available tyres are usually not made publicly available for commercial reasons. According to a study by Camatini et al. [2], the typical composition of passenger car tyres is 75% styrene butadiene rubber, 15% natural rubber, and 10% polybutadiene. Different types of elements are blended into the mixture to achieve the desired characteristics during the manufacturing process and to ensure the expected road conditions. One of the most important additives is zinc oxide (ZnO), which acts as a vulcanizer. According to Smolders and Degryse [16], the typical concentration of ZnO in the tyre tread ranges from 1.2% (passenger cars) to 2.1% (trucks) [13].

The friction created between the tyre tread and the road surface is the source of complex physical and chemical process that affect the wear of the tyre. As a result, the particles released from the tyre and those on the road surface are connected, and wear particles on the road surface are inextricably linked [13].

The amount your tyres wear down is based on a various parameter like what type of tyres you have, where they're located, what they're made of, their condition and age, the weight of your vehicle and its frame, the way of driving (speeding, starting and stopping, taking corners), what the road surface type is like, and meteorological conditions, mainly the air temperature and moisture. The way you drive affects how quickly your car wears down. Even when the car is going at a steady speed, the tyre still has a tiny amount of slipping on the road – this is what gives it a grip. As the driving dynamics increase (cornering, braking, acceleration) in response to greater forces generated at the surface-tyre interface, slippage occurs, which may cause additional wear of both the tyre and the road surface. Therefore, 'smooth' driving extends the life of the tyre and *vice versa*. The tyre's lifetime decreases as the intensity of intense or transient vehicle operation increases [13].

Brake wear

Currently, two brake system designs are being employed: disc brakes, in which flat brake pads press against a spinning metal disc, and drum brakes, in which curved pads press against the interior of a spinning cylinder. Disc brakes are typically installed in more diminutive vehicles (passenger cars and motorcycles) as well as the front wheels of light trucks. Drum brakes, which have been in use for a longer period of time, are more common in larger vehicles, though disc brakes are becoming more prevalent in newer heavy-duty vehicles.

Currently are used the two main brake system configurations: disc brakes, where flat brake pads are pressed against a rotating metal disc, and drum brakes, where curved pads are pressed against the inside surface of a rotating cylinder. Disc brakes are typically used on smaller vehicles (cars and motorcycles) and the front wheels of light trucks. Traditionally, the drum brakes are used on heavier vehicles, although disc brakes are increasingly used on newer heavy-duty vehicles [3, 13].

The components of brake linings consist of binders, fibers, fillers, and friction modifiers which can all be thermoresistant. The binders are modified phenol-formaldehyde resins and the fibers come in metallic, mineral, ceramic, and aramid varieties like steel, copper, brass, potassium titanate, glass, asbestos, organic material, or Kevlar. Fillers are usually inexpensive materials such as barium and antimony sulphate, kaolinite clays, magnesium and chromium oxides, or metal powders. Friction modifiers can be organic, inorganic, or metallic and graphite is the most commonly used modifier, but cashew dust, ground rubber, and soot are also used. Asbestos fibers were once used in brake pads, but have been completely banned in the European fleet [14].

The brake wear material's chemical composition depends on the manufacturer, the application used (car, truck, etc.), and the targeted properties of the brake pads. Studies from Legret and Pagotto [11] and Hildemann et al. [7] suggest the pads are generally composed of primarily metals coupled with silicon composites. Iron typically contributes up to 46%, copper up to 14%, organic material around 13%, and then a few other metals such as lead (~4%), zinc (~2%), calcium, and barium [15].

The abrasion of tyres and brakes leads to the emission of particulate matter (PM) and heavy metals, such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), selenium (Sn) and zinc (Zn). This article, in particular, focuses on the air quality assessment of particulate matter, lead, arsenic, cadmium and nickel, since there are national regulations and EU directives that set limits for such substances to ensure human and plant health is protected.

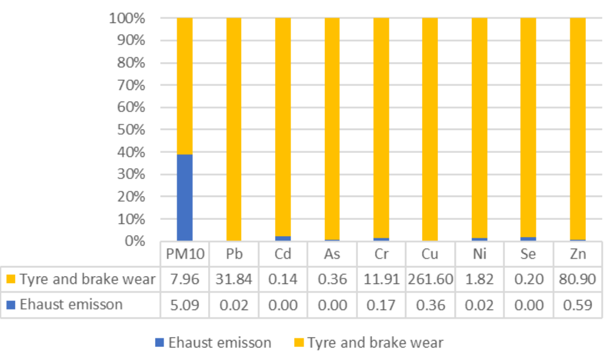

Fig. 1. Percentage of emissions from tyre and brake wear (as a sum) and exhaust system

For road traffic, it is expected to assume that most primary particulates are emitted from exhaust gases and that most coarse particles originate from sources other than exhaust gases. This is not accurate, as there is much evidence to suggest that non-exhaust particles contribute to both fine and coarse PM10. While there are a number of studies that report that the contribution of exhaust and non-exhaust sources to total traffic-related PM10 emissions is roughly equal, it is expected that the contribution of non-exhaust sources will increase in the future due to continued reductions in emissions [4, 5, 17]. The National Centre for Emissions Management (KOBiZE) [12] has estimated that the emission of particulate matter and heavy metals from abrasion in 2021 was greater than that from exhaust systems, which is illustrated in Fig. 1.

2. Materials and methods

For modelling purposes, COPERT software was used for implementing the Tier 3 methodology [13]. COPERT is a software tool, coordinated by the EEA, and widely used for the mathematical modelling of air pollutant emissions from mobile sources.

The COPERT model was utilized for the mathematical air emissions estimation by employing the EMEP Guidebook [13] recommendations. This general equation was used for separate calculations of the emissions from tyre wear and brake wear:

$$T_E = \sum_j N_j \times M_j \times EF_{TSP,s,j} \times f_{s,i} \times S_s(V) \qquad (1)$$

where: T_E – the total amount of emissions released within a certain time period and geographical area [g], N_j – the number of cars in category j within the specified region, M_j – the distance in kilometres that each vehicle of category j travelled during the pre-designated time frame, $EF_{TSP,s,j}$ – the mass emission factor for total suspended particulates (TSP) for vehicles in category j [g/km], $F_{s,I}$ – mass fraction of TSP that can be attributed to particle size class i, $S_s(V)$ – the adjustment needed for an average vehicle travelling at speed V.

The index j is associated with the type of vehicle, while the index s indicates where the particulate matter (PM) originated from, either tyre (T) or brake (B) wear. The particle size classes i include TSP, PM10, PM2.5, PM1 and PM0.1.

For their math modelling, the authors employed the COPERT software to calculate emissions. They followed the directions in the EMEP Guidebook 2019 [13] which is a standard of air pollutant emission inventories.

Based on the applied methodology, driving is split into three types due to the most frequent driving conditions: urban, rural, and highway.

In this section, the authors used COPERT (Computer Programme to Calculate Emissions from Road Traffic), a complex modelling software tool for calculating air pollutant emissions from road transport. The applied methodology followed d the EMEP (European Monitoring and Evaluation Programme) Guidebook 2019 [13] guidelines.

Using the COPERT model made estimating emissions following international and EU law requirements possible. Road transport emissions estimates were based on the following:

– fuel consumption
– engine size
– number of vehicles per category

- vehicle weight
- emissions control technology
- mileage per vehicle class
- share per road class (urban, rural, and highway)
- average speed per vehicle type and per road class
- monthly temperature (minimum and maximum)
- fuel characteristics.

In the case of the simulation presented in the article, the most important input data are the vehicle mass, mileage per vehicle class, share per road class (urban, rural, and highway); average speed per vehicle type and road class.

The mathematical approach included in the COPERT software is classified as a "Tier 3" approach for quantitative emissions assessment. It should be emphasized that all of the emissions factors included in the COPERT model were determined based on laboratory testing under the WLTP driving cycle [13, 20].

The estimations were conducted based on the following basic assumptions: the estimates were made assuming that one vehicle travelled 10,000 km. Equal shares of vehicle traffic in the urban, rural and highway were assumed. It was also assumed that cars drive at average speeds type of traffic: urban, rural and highway of 31.5 km/h, 70 km/h and 120 km/h, respectively.

Based on the mathematical modelling, the authors want to check the following dependencies:

- the influence of the type of vehicles on tyre and brake wear particulate matter and heavy metals emissions; to simulation only passenger cars were used for the simulation (internal combustion engines (ICE) with various types of fuel, hybrid, plug-in (PHEV) and battery electric vehicles (BEV)) on emissions
- the influence of the type of traffic (urban, rural and highway) on the on tyre and brake wear particulate matter and heavy metals emission
- the influence of the average velocity on tyre and brake wear particulate matter and heavy metals emissions.

Simulations were carried out for two types of emissions: brake wear and tyre wear.

3. Results

This method enabled the simulations depicted in Fig. 2 through 9, which demonstrate the effect of the vehicle type on tyre and brake wear emissions. In the simulations, only passenger cars such as internal combustion engine, hybrid, plug-in, and battery electric vehicles were utilized for tyre and brake wear emissions.

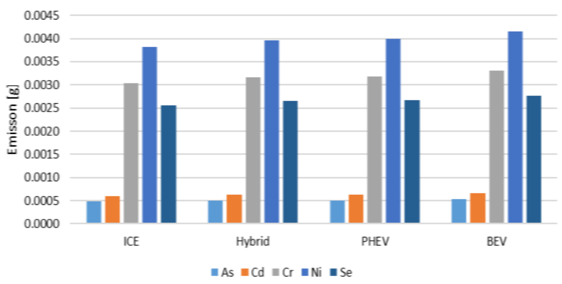

Fig. 2. The influence of vehicle type on tyre wear heavy metals (arsenic, cadmium, chromium, nickel and selenium) emissions

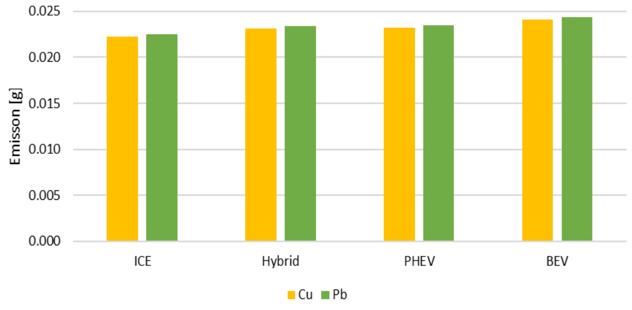

Fig. 3. The influence of vehicle type on tyre wear heavy metals (copper, lead) emissions

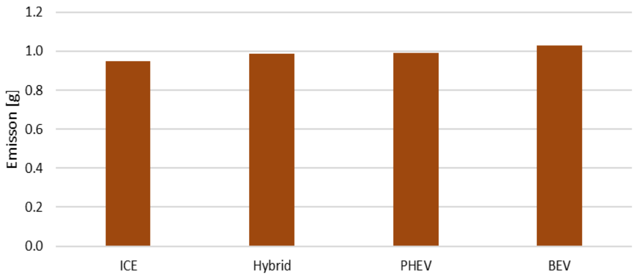

Fig. 4. The influence of vehicle type on tyre wear heavy metals (zinc) emissions

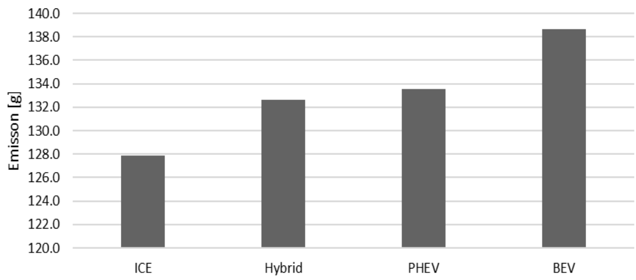

Fig. 5. The influence of vehicle type on tyre wear particulate matter emissions

The Fig. 2–5 shows that the emission of heavy metals particulate matter from tyre wear, the emission from BEV is the highest, and in the case of ICEV – the lowest. There is a slight difference in emissions from Hybrid and PHEV for the heavy metals emission simulated. The weight of the vehicles most likely causes this relationship; BEVs are the heaviest of the vehicles tested.

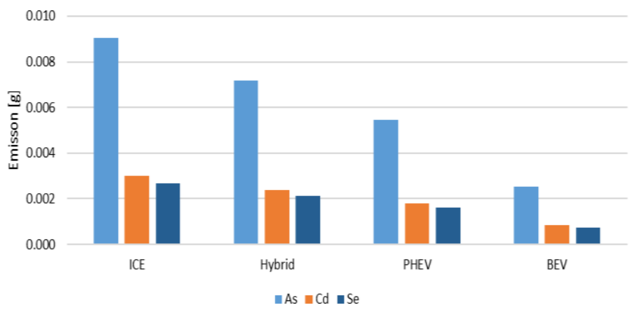

Fig. 6. The influence of vehicle brake wear on tyre wear heavy metals (arsenic, cadmium, selenium) emissions

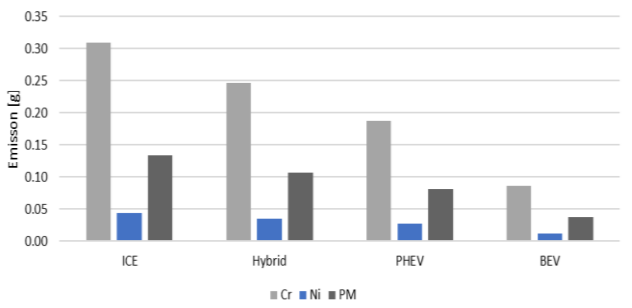

Fig. 7. The influence of vehicle brake wear on tyre wear heavy metals (chromium, nickel) and particulate matter emissions

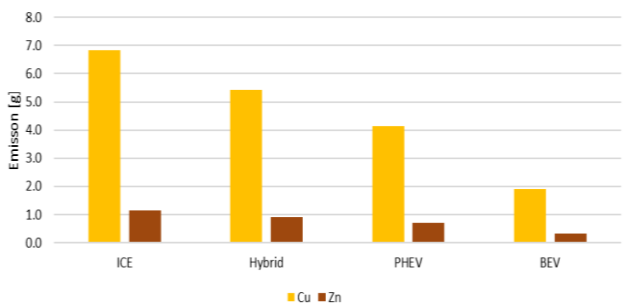

Fig. 8. The influence of vehicle brake wear on tyre wear heavy metals (copper, zinc) emissions

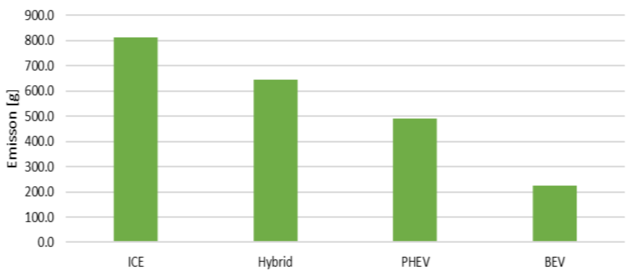

Fig. 9. The influence of vehicle brake wear on tyre wear heavy metals (lead) emissions

In contrary to the case of emissions from tyre abrasion, emissions from brake abrasion are the highest for ICE cars and the lowest for BEVs. There is also a noticeable difference in particulate matter and heavy metal emissions for hybrid and PHEV, with lower emissions for PHEV. The lower emissions for BEV, PHEV and hybrid than for ICEv are due to the use of regenerative braking in electric and hybrid vehicles (Fig. 6–9).

The particulate matter emissions from tyre wear shown in Fig. 5 are higher for BEVs, with significantly lower emissions for ICE cars. In the case of heavy metals (Fig. 2 and 9), there is no significant difference in tyre abrasion emissions, but there is a noticeable relationship that these emissions are higher for BEV.

On the other hand, the relationship is reversed in the case of brake wear. For BEV, attrition emissions for all pollutants tested are lower than for ICE, hybrid and plug-in (Fig. 6–9).

Figures 10 to 18 show the influence of the type of traffic (urban, rural and highway) on the tyre and brake wear emission.

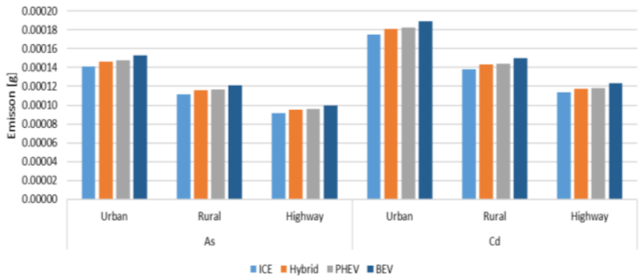

Fig. 10. The influence of the type of traffic (urban, rural and highway) on the tyre wear heavy metals (arsenic, cadmium) emission

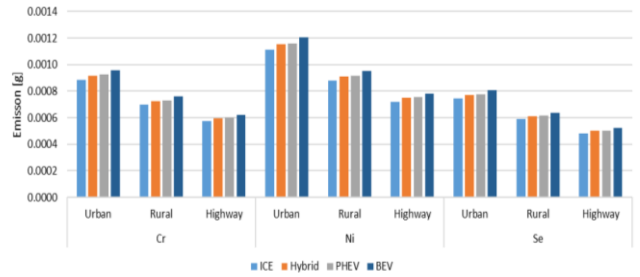

Fig. 11. The influence of the type of traffic (urban, rural and highway) on the tyre wear heavy metals (chromium, nickel, selenium) emission

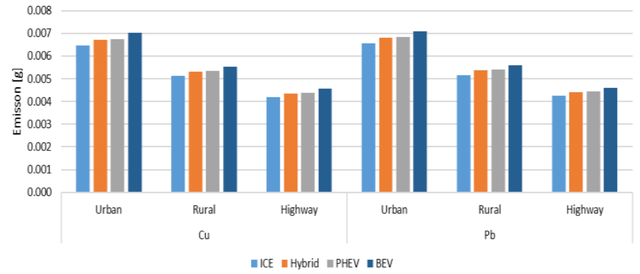

Fig. 12. The influence of the type of traffic (urban, rural and highway) on the tyre wear heavy metals (copper, lead) emission

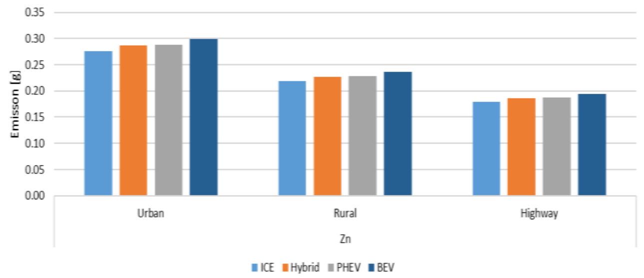

Fig. 13. The influence of the type of traffic (urban, rural and highway) on the tyre wear heavy metals (zinc) emission

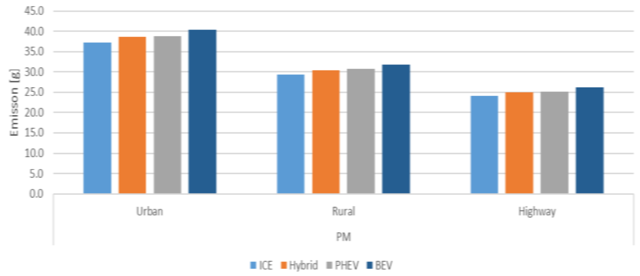

Fig. 14. The influence of the type of traffic (urban, rural and highway) on the tyre wear particulate matter emission

There is a visible dependency that emissions from tyre abrasion are highest in cities, where vehicles constantly brake while driving in traffic congestion, which causes higher abrasion.

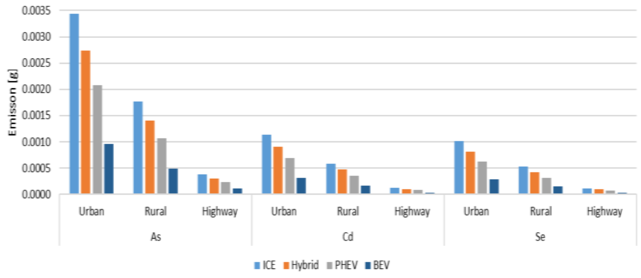

Fig. 15. The influence of the type of traffic (urban, rural and highway) on the brake wear heavy metals (arsenic, cadmium, selenium) emission

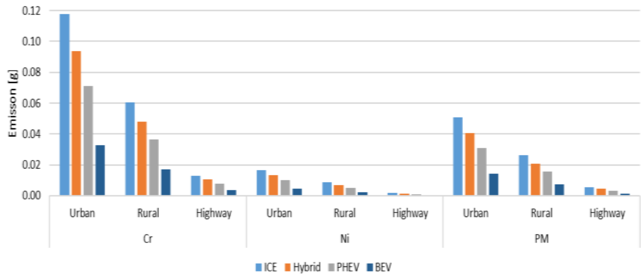

Fig. 16. The influence of the type of traffic (urban, rural and highway) on the brake wear heavy metals (chromium, nickel) and particulate matter emission

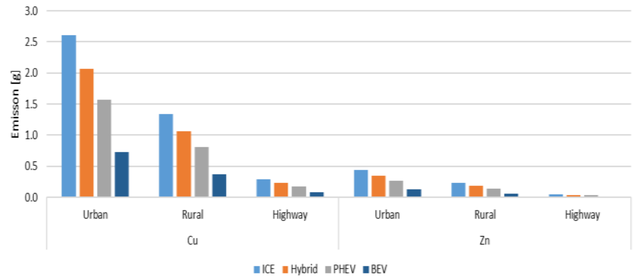

Fig. 17. The influence of the type of traffic (urban, rural and highway) on the brake wear heavy metals (copper, zinc) emission

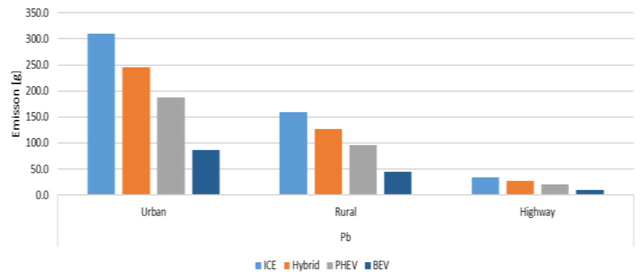

Fig. 18. The influence of the type of traffic (urban, rural and highway) on the brake wear heavy metals (lead) emission

Figures 10 to 18 show a noticeable relationship between higher emissions from abrasion of tyres and brake wear in urban areas and significantly lower highway emissions. In the case of this simulation, there also occurs a dependency between higher emissions from tyre wear for BEV compared to other types of drive and lower emissions from brake wear for this type of vehicle.

Figures 19 to 22 show the influence of the average velocity on the tyre and brake wear emissions.

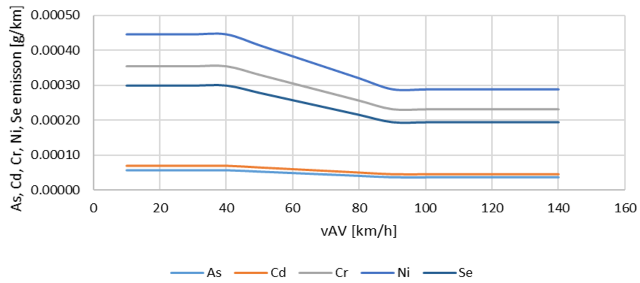

Fig. 19. The influence of the average velocity on the tyre heavy metals (arsenic, cadmium, chromium, nickel, selenium) emissions

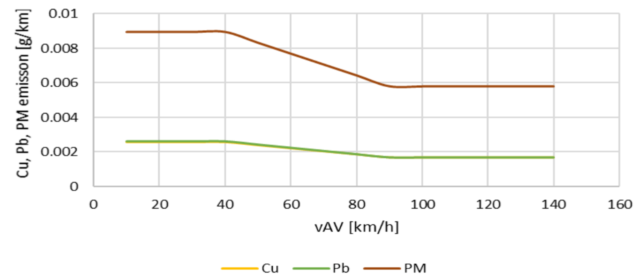

Fig. 20. The influence of the average velocity on the tyre heavy metals (chromium, lead) and particulate matter emissions

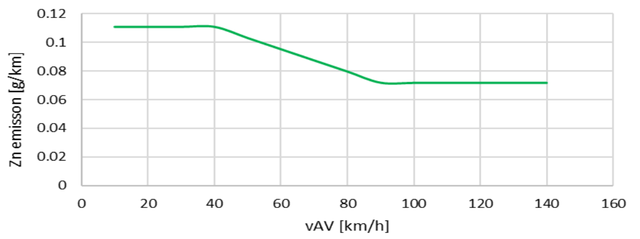

Fig. 21. The influence of the average velocity on the tyre heavy metals (zinc) emissions

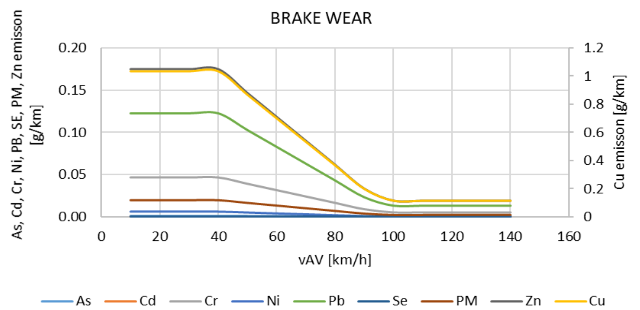

Fig. 22. The influence of the average velocity on the break wear heavy metals (arsenic, cadmium, chromium, copper, nickel, lead, selenium and zinc) and particulate matter emissions

Similarly, to the simulations presented in Fig. 10 to 18, and in Fig. 19 to 22, it can be seen that the higher the speed, the lower the emission of heavy metals and particulate matter from tyre and brake abrasion.

4. Discussion

The weight of a BEV is greater than that of an ICE vehicle, resulting in an impact on tyre wear. Figures 2 to 9 illustrate that BEVs, hybrids, and plug-ins all have higher emissions for all pollutants. This finding is supported by other studies, such as by Timmers and Achten [19], which found that electric vehicles are 24% heavier than their non-electric counterparts, weighing an additional 280 kg.

Beddows and Harrison [1] recently conducted a study that compared battery electric and combustion engine vehicles based on power output. On average, electric cars had a weight increase of 258 kg and 314 kg in comparison to petrol and diesel cars, resulting in an increase of 7–10% for PM10 and PM2.5 emissions from tyre wear.

The studies by Beddows & Harrison [1], and by Liu et al. [11] both indicated a similar rise in tyre wear. The study [11] also revealed the differences between small, medium and large internal combustion engine vehicles, with an average of 10–20% variation between the segments. Woo et al. [21] analysed that a 20% increase in vehicle weight would lead to a 15–20% growth in tyre wear emissions. Tests conducted by the Emissions Analytics in real-world conditions demonstrated that for a 500kg increase in vehicle weight, tyre wear emissions increased by 21%. Lastly, Oroumiyeh and Zhu [14] measured the tyre wear of small, medium and large vehicles, finding that the tyre wear was proportional to the vehicle weight.

It has been observed that the correlation between tyre abrasion and emissions is not observable for emissions from brake wear. This has been corroborated in various studies, including by Beddows & Harrison [1], which demonstrated that a heavier vehicle weight in electric vehicles leads to a 10–15% increase in brake wear, and consequently, non-exhaust emissions.

The research [20] resulted in the same conclusion about the influence of body mass on brake wear emissions. They discovered that a 20% rise in the weight of a vehicle caused a 15–20% increase in emissions. The research resulted in the same conclusion about the influence of body mass on brake wear emissions. Moreover, they discovered that a 20% rise in the mass of a vehicle caused a 15–20% increase in emissions.

The findings showed that there was a 9–17% reduction in the emission rates of PM10 and PM2.5 from brakes when the weight of the battery electric vehicle was increased. It is also worth noticing that electric vehicles typically come with regenerative braking which is a system that takes the energy from braking and turns it into electricity, which can then be used to power the vehicle and aid in acceleration.

More research is necessary to understand the emission reduction potential of brakes [12]. However, preliminary measurements by Hagino et al. [6], Stanard et al. [18], and Koupal et al. [8] suggest that the brakes can reduce emissions significantly.

5. Conclusion

It is expected that vehicles will brake more frequently in congested areas, leading to higher emissions from abrasion. This fact is supported by mathematical modelling, which is illustrated in Fig. 10 to 18. Emissions from tyres and brake wear in urban areas are significantly higher than on the highways.

As demonstrated by Fig. 19 to 22, the faster average driving speed, the less the tyre wear, likely due to the fact that city driving usually involves more braking and turning than highway driving does.

It is anticipated that decarbonizing and advocating for BEV will result in the elimination of emissions from exhaust systems. However, this may create further issues with particulate matter and heavy metal emissions due to tyre and brake abrasion. This may lead to people inhaling heavy metal dust, which can result in future severe health consequences.

Acknowledgements

This work was supported by the Faculty of Automotive and Construction Machinery Engineering Warsaw University of Technology.

Nomenclature

As	arsenic
BEV	battery electric vehicle
Cd	cadmium
Cr	chrome
Cu	copper
ICE	internal combustion engine
Ni	nickel
Pb	lead
PHEV	plug-in
PM	particulate matter
Se	selenium
Zn	zinc

Bibliography

[1] Beddows DCS, Harrison RM. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles. Atmos Environ. 2021;244:117886. https://doi.org/10.1016/j.atmosenv.2020.117886

[2] Camatini M, Crosta GF, Dolukhanyan T, Sung C, Giuliani G, Corbetta GM et al. Microcharacterization and identification of tyre debris in heterogeneous laboratory and environmental specimens. Mater Charact. 2001;46:271-283. https://doi.org/10.1016/S1044-5803(00)00098-X

[3] CEPMEIP, 2003. Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance. http://www.air.sk/tno/cepmeip/ (accessed on 19 July 2019).

[4] Dimopoulos Eggenschwiler P, Schreiber D, Habersatter J. Brake particle PN and PM emissions of a hybrid light duty vehicle measured on the chassis dynamometer. Atmosphere. 2023;14(5):784. https://doi.org/10.3390/atmos14050784

[5] Grigoratos T, Martini G. Brake wear particle emissions: a review. Environ Sci Pollut. 2015;22:2491-2504. https://doi.org/10.1007/s11356-014-3696-8
[6] Hagino H. Sensitivity and reproducibility of brake wear particle emission measurements using JARI system. PMP 50th Meeting. 2019.
[7] Hildemann LM, Markowski GR, Cass GR. Chemical composition of emissions from urban sources of fine organic aerosol. Envir Sci Tech. 1991;25:744-759. https://doi.org/10.1021/es00016a021
[8] Koupal J, Denbleyker A, Kishan S, Vedula R, Agudelo C. Brake wear particulate matter emissions modelling. Eastern Research Group, Inc., LINK Engineering Company 2021. CA21-3232. https://rosap.ntl.bts.gov/view/dot/60273
[9] Laskowski PP, Zimakowska-Laskowska M, Zasina D, Wiatrak M. Comparative analysis of the emissions of carbon dioxide and toxic substances emitted by vehicles with ICE compared to the equivalent emissions of BEV. Combustion Engines. 2021;187(4):102-105. https://doi.org/10.19206/CE-141739
[10] Legret M, Pagotto C. Evaluation of pollutant loadings in the runoff waters from a major rural highway. Sci Total Environ. 1999;235:143-150. https://doi.org/10.1016/s0048-9697(99)00207-7
[11] Liu Y, Chen H, Gao J, Li Y, Dave K, Chen J et al. Comparative analysis of non-exhaust airborne particles from electric and internal combustion engine vehicles. J Hazard Mater. 2021;420:126626. https://doi.org/10.1016/j.jhazmat.2021.126626
[12] Ministry of Climate and Environment. 2023. Poland's Informative Inventory Report. Submission under the UNECE CLRTAP and NEC Directive. https://cdr.eionet.europa.eu/pl/eu/nec_revised/iir/envyei5sq/
[13] Ntziachristos L, Boulter P. Road transport. In: EMEP/EEA – 1.A.3.b.vi-vii Road tyre and brake wear. 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-vi/view
[14] Oroumiyeh F, Zhu Y. Brake and tire particles measured from on-road vehicles: effects of vehicle mass and braking intensity. Atmos Environ. 2021;12:100121. https://doi.org/10.1016/j.aeaoa.2021.100121
[15] Rauterberg-Wulff A. Determination of emission factors for tire wear particles by tunnel measurements. 8th International Symposium 'Transport and Air Pollution'. 1999. Graz.
[16] Smolders E, Degryse F. Fate and effect of zinc from tire debris in soil. Envir Sci Tech. 2002;36:3706-3710. https://doi.org/10.1021/es025567p
[17] Sommer F, Dietze V, Baum A, Sauer J, Gilge S, Maschowski C et al. Tire abrasion as a major source of microplastics in the environment. Aerosol Air Qual. 2018;18: 2014-2028. https://doi.org/10.4209/aaqr.2018.03.0099
[18] Stanard A, Tim D, Palacios C, Kishan S. Brake and tire wear emissions. Report for CARB Project 17RD016. 2021. https://ww2.arb.ca.gov/sites/default/files/2021-04/17RD016.pdf
[19] Timmers VRJH, Achten PAJ. Non-exhaust PM emissions from electric vehicles. Atmos Environ. 2016;134:10-17. https://doi.org/10.1016/j.atmosenv.2016.03.017
[20] Wiśniowski P, Gis M. Representativeness of emissions of toxic substances in bench tests reflecting the road traffic conditions of a vehicle. Combustion Engines. 2019;177(2): 88-90. https://doi.org/10.19206/CE-2019-215
[21] Woo SH, Jang H, Lee SB, Lee S. Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: an experimental analysis. Sci Total Environ. 2022;842:156961. https://doi.org/10.1016/j.scitotenv.2022.156961

Piotr Laskowski, DEng. – Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Poland.
e-mail: *piotr.laskowski@pw.edu.pl*

Magdalena Zimakowska-Laskowska, DEng. – Environment Protection Centre, Motor Transport Institute, Poland.
e-mail: *magdalena.zimakowska-laskowska@its.waw.pl*