FACULTY OF MECHANICAL AND CIVIL ENGINEERING
IN KRALJEVO
UNIVERSITY OF KRAGUJEVAC

X Triennial
International Conference

HEAVY MACHINERY HM 2021

Proceedings

VRNJAČKA BANJA, SERBIA
June 23 - June 25 2021

FACULTY OF MECHANICAL AND CIVIL ENGINEERING KRALJEVO
UNIVERSITY OF KRAGUJEVAC
KRALJEVO – SERBIA

THE TENNTH INTERNATIONAL TRIENNIAL CONFERENCE

HEAVY MACHINERY
HM 2021

PROCEEDINGS

ORGANIZATION SUPPORTED BY:

Ministry of Education, Science and Technological Development, Republic of Serbia

Vrnjačka Banja, June 23–25, 2021

FACULTY OF MECHANICAL AND CIVIL ENGINEERING KRALJEVO
UNIVERSITY OF KRAGUJEVAC
KRALJEVO – SERBIA

PUBLISHER:
Faculty of Mechanical and Civil Engineering in Kraljevo

EDITOR:
Prof. dr Mile Savković

PRINTOUT:
TERCIJA d.o.o., Bor

TECHNICAL COMMITTEE

Doc. dr Aleksandra Petrović – CHAIRMAN
Bojan Beloica – VICE-CHAIRMAN
Jovana Bojković
Goran Bošković
Vladimir Đorđević
Marina Ivanović
Vladimir Mandić
Mladen Manojlović
Saša Marinković
Stefan Mihajlović
Miloš Nikolić
Đorđe Novičić
Anica Pantić
Vladimir Sinđelić
Nenad Stojić
Marko Todorović
Tanja Miodragović
Mladen Rasinac
Dragiša Šimunović
Jovana Perić
Branislav Prokić
Slobodan Bukarica

No. of copies: 80

ISBN 978-86-81412-09-1

REVIEWS:
All papers have been reviewed by members of scientific committee

CONFERENCE CHAIRMAN

Prof. dr Mile Savković, FMCE Kraljevo, Serbia

INTERNATIONAL SCIENTIFIC PROGRAM COMMITTEE

CHAIRMAN

Prof. dr Milan Kolarević, FMCE Kraljevo, Serbia

VICE-CHAIRMAN

Prof. dr Milan Bižić, FMCE Kraljevo, Serbia

MEMBERS

1. Prof. dr M. Alamoreanu, TU Bucharest, Romania
2. Prof. dr S. Arsovski, FME Kragujevac, Serbia
3. Prof. dr D. Atmadzhova, VTU "Todor Kableshkov", Sofia, Bulgaria
4. Prof. dr M. Berg, Royal Institute of Technology-KTH, Sweden
5. Prof. dr H. Bogdevicius, Technical University, Vilnus, Lithuania
6. Prof. dr N. Bogojević, FMCE Kraljevo, Serbia
7. Prof. dr S. Bošnjak, FME Belgrade, Serbia
8. Prof. dr A. Bruja, TU Bucharest, Romania
9. Prof. dr Z. Bučevac, FME Belgrade, Serbia
10. Prof. dr R. Bulatović, FMCE Kraljevo, Serbia
11. Prof. dr S. Ćirić-Kostić, FMCE Kraljevo, Serbia
12. Prof. dr M. Dedić, FMCE Kraljevo, Serbia
13. Prof. dr I. Despotović, FMCE Kraljevo, Serbia
14. Prof. dr R. Durković, FME Podgorica, Montenegro
15. Prof. dr M. Đapić, FMCE Kraljevo, Serbia
16. Prof. dr Z. Đinović, ACMIT, Wiener Neustadt, Austria
17. Prof. dr K. Ehmann, Northwestern University, Chicago, USA
18. Prof. dr I. Emeljanova, HGTUSA Harkov, Ukraine
19. Prof. dr O. Erić Cekić, FMCE Kraljevo, Serbia
20. Prof. dr V. Filipović, FMCE Kraljevo, Serbia
21. Prof. dr D. Golubović, FME East Sarajevo, Bosnia and Herzegovina
22. Prof. dr B. Jerman, FME Ljubljana, Slovenia
23. Prof. dr Z. Jugović, Technical Faculty Čačak, Serbia
24. Prof. dr V. Karamarković, FMCE Kraljevo, Serbia
25. Prof. dr R. Karamarković, FMCE Kraljevo, Serbia
26. Prof. dr M. Karasahin, Demirel University, Istanbul, Turkey
27. Prof. dr I. Kiričenko, HNADU Kiev, Ukraine
28. Prof. dr K. Kocman, Technical University of Brno, Czech Republic
29. Prof. dr S. Kolaković, Faculty of Technical Sciences, Novi Sad, Serbia
30. Prof. dr M. Kostic, Northern Illinois University, DeKalb, USA
31. Prof. dr M. Králik, FME Bratislava, Slovakia
32. Prof. dr M. Krajišnik, FME East Sarajevo, Bosnia and Herzegovina
33. Prof. dr E. Kudrjavcev, MGSU, Moscow, Russia
34. Prof. dr Đ. Lađinović, Faculty of Technical Sciences, Novi Sad, Serbia

35. Prof. dr LJ. Lukić, FMCE Kraljevo, Serbia
36. Prof. dr Z. Marinković, FME Niš, Serbia
37. Prof. dr G. Marković, FMCE Kraljevo, Serbia
38. Prof. dr N. Mešćerin, MGSU, Moscow, Russia
39. Prof. dr A. Milašinović, FME Banja Luka, Bosnia and Herzegovina
40. Prof. dr D. Milković, FME Belgrade, Serbia
41. Prof. dr B. Milošević, FMCE Kraljevo, Serbia
42. Prof. dr G. Minak, University of Bologna, Italy
43. Prof. dr D. Minić, FME Kosovska Mitrovica, Serbia
44. Prof. dr N. Nedić, FMCE Kraljevo, Serbia
45. Prof. dr V. Nikolić, FME Niš, Serbia
46. Prof. dr E. Nikolov, Technical University, Sofia, Bulgaria
47. Prof. dr M. Ognjanović, FME Belgrade, Serbia
48. Prof. dr J. Peterka, FMS&T, Trnava, Slovakia
49. Prof. dr D. Petrović, FMCE Kraljevo, Serbia
50. Prof. dr J. Polajnar, BC University, Prince George, Canada
51. Prof. dr D. Pršić, FMCE Kraljevo, Serbia
52. Prof. dr N. Radić, FME East Sarajevo, Bosnia and Herzegovina
53. Prof. dr V. Radonjanin, Faculty of Technical Sciences, Novi Sad, Serbia
54. Prof. dr M. Rajović, FMCE Kraljevo, Serbia
55. Prof. dr D. Sever, Maribor, Civil Engineering, Slovenia
56. Prof. dr M. Stefanović, FME Kragujevac, Serbia
57. Prof. dr M. A. Stepanov, MGSU, Moscow, Russia
58. Prof. dr I. S. Surovcev, VGSU, Voronezh, Russia
59. Prof. dr S. Šalinić, FMCE Kraljevo, Serbia
60. Prof. dr Z. Šoškić, FMCE Kraljevo, Serbia
61. Prof. dr LJ. Tanović, FME Belgrade, Serbia
62. Prof. dr D. Todorova, VTU "Todor Kableshkov", Sofia, Bulgaria
63. Prof. dr S. Trifunović, FMCE Kraljevo, Serbia
64. Prof. dr J. Vladić, Faculty of Technical Sciences, Novi Sad, Serbia
65. Prof. dr M. Vukićević, FMCE Kraljevo, Serbia
66. Prof. dr K. Weinert, University of Dortmund, Germany
67. Prof. dr N. Zdravković, FMCE Kraljevo, Serbia
68. Prof. dr N. Zrnić, FME Belgrade, Serbia
69. Prof. dr D. Živanić, Faculty of Technical Sciences, Novi Sad, Serbia

ORGANIZING COMMITTEE

CHAIRMAN:

Prof. dr Slaviša Šalinić, FMCE Kraljevo

VICE-CHAIRMAN:

Prof. dr Goran Marković, FMCE Kraljevo, Serbia

MEMBERS:

Doc. dr M. Bjelić, FMCE Kraljevo, Serbia
Doc. dr V. Grković, FMCE Kraljevo, Serbia
Doc. dr Lj. Dubonjić, FMCE Kraljevo, Serbia
Doc. dr M. Maraševič, FMCE Kraljevo, Serbia
Doc. dr A. Nikolić, FMCE Kraljevo, Serbia
Doc. dr A. Petrović, FMCE Kraljevo, Serbia
Doc. dr B. Radičević, FMCE Kraljevo, Serbia
Doc. dr B. Sredojević, FMCE Kraljevo, Serbia
Doc. dr V. Stojanović, FMCE Kraljevo, Serbia
Dr N. Pavlović, FMCE Kraljevo, Serbia
Dr M. Bošković, FMCE Kraljevo, Serbia
Dr J. Tomić, FMCE Kraljevo, Serbia

PLENARY SESSION

SESSION A: EARTH-MOVING AND TRANSPORTATION MACHINERY

SESSION B: PRODUCTION TECHNOLOGIES

SESSION C: AUTOMATIC CONTROL AND FLUID TECHNIQUE

SESSION D: APPLIED MECHANICS

SESSION E: RAILWAY ENGINEERING

SESSION F: THERMAL TECHNIQUE AND ENVIRONMENT PROTECTION

SESSION G: CIVIL ENGINEERING

Non-Exhaust PM Emissions from Heavy-Duty Vehicles

Jasna Glišović[1*], Saša Vasiljević[2], Nenad Miloradović[1], Nadica Stojanović[1], Ivan Grujić[1]
[1]Faculty of Engineering/Department for Motor Vehicles and Motors, University of Kragujevac, Kragujevac (Serbia)
[2]High Technical School of Professional Studies, Kragujevac (Serbia)

The important technological improvements have been made for reducing particulate matter (PM) emissions from exhaust sources, but no actions are currently in place to reduce the non-exhaust part of emissions such as those from brake wear, road wear, tyre wear and road dust resuspension. In the future these emissions will become increasingly important in relative terms. However, as exhaust emissions are set to steadily decline, in 2030, total non-exhaust emissions will be an estimated 1.6 times greater than total exhaust emissions. Non-exhaust emissions are more difficult to quantify than exhaust emissions owing to the strong influence of not only the type of vehicle and traffic conditions, but also the material properties and meteorological factors. Most studies indicate that emission factors for PM from brake wear are significantly larger from heavy-duty vehicles (HDVs) than from light-duty vehicles (LDVs). This would be due to the larger number or size of brakes on heavy-duty vehicles and the fact that the larger vehicle weight releases more kinetic energy in the process of slowing the vehicle down. HDVs contributed five to ten times more resuspended road dust than LDVs. One of the objectives of this paper is to overcome significant gaps still exist in our understanding of the participation of HDVs in total non-exhaust emissions.

Keywords: Heavy-Duty Vehicles, Non-Exhaust Emission, Particle Matter, Road Traffic

1. INTRODUCTION

Whilst exhaust emissions of PM are becoming heavily regulated, non-exhaust sources of PM emissions remain largely uncontrolled. Manufacturers have strict emission standards to adhere to and the majority of diesel vehicles on roads are now equipped with a particulate traps. Therefore attention is now focussing on emission sources such as non-exhaust emissions (NEE), which have been found to contribute significantly to particulate concentrations. Non-exhaust emissions are generated through the resuspension of road dust or road surface wear as the vehicle travels over the road surface, corrosion of vehicle components or during the mechanical friction processes associated with driving, such as brake, clutch or tyre wear (Table 1) [1]. Grigorators and Martini [2] noted that as exhaust emissions controls become stricter, relative contributions of non-exhaust sources to traffic related emissions will become more significant.

Table 1: Mechanisms for non-exhaust particle emission

Emission type	Mechanism	Includes
Direct	Abrasion and wear and tear	Tyre, brake, clutch, road surface
	Corrosion	Vehicle, street furniture
Indirect	Resuspension (due to tyre shear, wind and vehicle turbulence)	

Key reasons for needing to understand non-exhaust emissions include their inherent toxicity including their tendency to act as carriers of heavy metals and carcinogenic components [4] and their contribution to exceedances of air quality guidelines and standards [5]. Many studies have aimed to distinguish between the different non-exhaust particulate emissions by identifying particular chemical components. While the constituents of brake material may vary among manufacturers, iron, copper, antimony, and barium have been associated with the particulate matter released from brake operation. Road surfaces are generally composed of either concrete or aggregate with a bituminous binder and abrasion of such a surface is likely to result in particulate matter of mineral origin. Tire wear is likely to result in predominantly carbonaceous particles, although small quantities of metals, in particular zinc which is used as a vulcanization activator, may be present. Material resuspended from the road surface may include all types of vehicle abrasion debris, in addition to material from non-road sources which has been deposited on the road surface. This may include mineral dust from the local environment, typically including silicon, aluminium, calcium, and iron particularly in arid locations [6].

Most countries follow the methodology for estimating emissions from tyre and brake wear and road surface wear given in the 2016 version of the EMEP/EEA Air Pollutant Emissions Inventory Guidebook [7]. This provides a fairly simple approach which combines PM emission factors in milligrams emitted per kilometre (mg/km) for passenger cars, light goods vehicles, heavy-duty vehicles (HDVs and buses) and two-wheelers, with vehicle kilometres travelled per year. The method and emission factors in the Guidebook [7] have not been updated for nearly 15 years and are based on the information available at the time, mostly on wear rates, and a number of assumptions.

Some countries have used emission factors based on their own literature search (e.g. the Netherlands) or have used evidence from country-specific information and research. These are generally based on the total mass loss of tyre or brake material resulting from the wear process and estimates on the amount that remain airborne in the PM_{10} and $PM_{2.5}$ range. The Scandinavian countries have been particularly active in this area and, for example, have taken account of the effect of studded tyres resulting in higher emissions from road wear.

* Corresponding author: Jasna Glišović: 6 Sestre Janjic Str., Kragujevac, jaca@kg.ac.rs

The UK’s National Atmospheric Emissions Inventory (NAEI) for tyre and brake wear and road abrasion uses the Tier 2 inventory method and emission factors in the EMEP/EEA Emissions Inventory Guidebook [7]. This approach provides mg/km emission factors for Total Suspended Particulates (TSP) for passenger cars, LDVs, HDVs and two-wheeled vehicles, together with PM_{10} and $PM_{2.5}$ mass fractions to combine with the TSP factors. The TSP factors for tyre and brake wear are used with an average speed correction factor which implies higher emission factors at lower speeds, on the basis of greater braking and cornering per km at lower speeds. For heavy-duty vehicles, a further correction factor is applied to take account of the load carried by the truck and in the case of tyre wear on the number of wheel axles. No such speed and load correction factors are provided for road surface wear emissions [8].

Nearly one-third of the traffic-related source contributions were associated with non-exhaust emissions from brake and tyre wear and road dust resuspension in the urban environment. Elevated levels of non-exhaust sources were correlated with the number of heavy-duty vehicles, rather than total traffic volume.

There are 6.6 million trucks on the EU’s roads. With more than 1.1 million trucks, Poland has the largest truck fleet, followed closely by Germany (946,541) and Italy (904,308).

Table 2: Medium and heavy commercial vehicles [10]

	2014	2015	2016	2017	2018
European Union	6,103,698	6,214,936	6,337,504	6,472,374	6,621,641
Norway	89,746	88,659	86,757	86,154	85,661
Switzerland	60,602	60,076	58,507	60,438	61,989
EFTA	150,348	148,735	145,264	146,592	147,650
Russia	3,738,145	3,690,032	3,703,635	3,733,711	3,759,152
Turkey	814,459	850,051	876,152	898,817	908,821
EUROPE	10,806,650	10,903,754	11,062,555	11,251,494	11,437,264

The EU motor vehicle fleet is getting older year-on-year. Passenger cars are now on average 11.1 years old, vans 11 years and heavy commercial vehicles 12 years. Trucks are on average 12.4 years old in the European Union. Among the EU’s five major markets, Spain has the oldest truck fleet (14.4 years), followed closely by Italy (14.0 years).

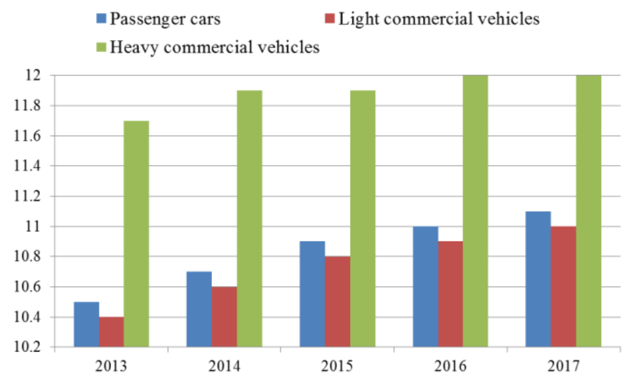

Figure 1: Average age of the EU fleet by vehicle type[10]

Emissions of heavy metals vary with the fleet composition, with higher emissions reported for some of the elements for heavy-duty vehicles (HDVs) so the aim of this paper is to highlight the share of this category in non-exhaust emission.

2. NON-EXHAUST EMISSION

Different non-exhaust particle sources contribute to both fine and coarse particles as well as ultrafine particles. Figure 2 presents an overview of the processes (flows) and deposits of road dust particles as a system diagram. It also summarizes factors affecting the processes and flows.

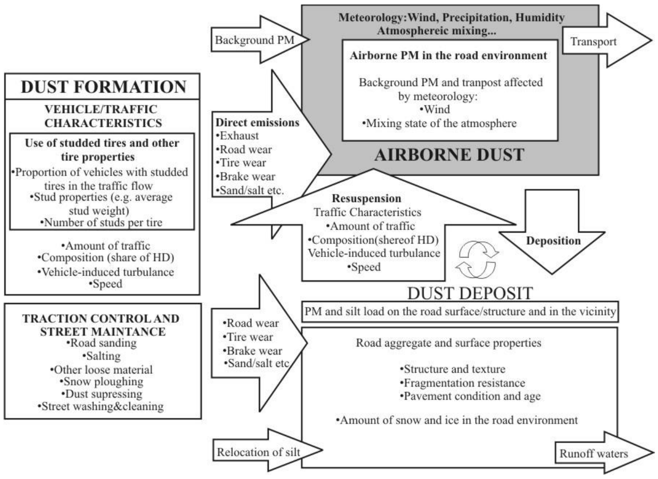

Figure 2: Material flows of road dust particles, with the main factors affecting the source strengths [11]

Particulate matter is present in a range of sizes in the atmosphere. Combustion processes generally result in smaller particles, which over time will agglomerate into the accumulation mode. Abrasive processes result in particles with aerodynamic diameters larger than the accumulation mode which are lost from the atmosphere largely by sedimentation. Size distribution of the particles measured by Harrison et al. [6] at the Marylebone Road site in London is show in Figure 3. The red line shows brake wear, the purple line shows tyre wear, and the green line shows resuspension.

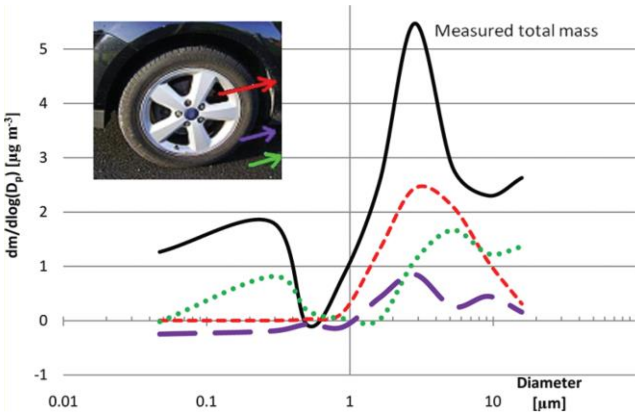

Figure 3: Size distribution of the particles measured at the Marylebone Road site in London [6]

However, emissions of trace metal markers are reported to vary with the fleet composition, with higher emissions reported for some of the elements for heavy-duty vehicles (HDVs). In addition, the profile of trace metal concentrations in non-exhaust particulate matter is unique for every region and varies based on parameters such as traffic volume and pattern, vehicle fleet characteristics, driving and traffic patterns and climate and geology of the. Another important aspect is the variability of tyre and brake composition depending on the manufacturer which makes it very difficult to ascertain fleet-wide composition other than from environmental measurements. Several factors are reported to affect non-exhaust emissions including increase in vehicle speed reported a non-linear relationship between traffic volume and non-exhaust emissions. Metal emissions due to road dust show a low correlation to metal emissions due to abrasion/brake wear and combustion. One of the major problems in analysis of non-exhaust PM using field data has been the difficulty in distinguishing between wear and tear emissions and road dust since the chemical composition is often very similar [12]. This may, in any case, not be a clear distinction as wear emissions may deposit to the road surface, only to be resuspended subsequently [3].

The factors in Table 3 are averages for different road types and can be seen to be greater on urban roads, followed by rural roads and then motorways. This reflects the greater amount of braking done on urban roads, although this may be partially offset by the fact that the intensity of braking when it does occur would be higher on motorways where the vehicles are slowing down from greater velocities [9].

Table 3: Emission factors for PM_{10} from tyre and brake wear for road transport vehicles as used in the UK's National Atmospheric Emissions Inventory [7,9]

mg PM_{10}/km		Tyre	Brake
Cars	Urban	8.7	11.7
	Rural	6.8	5.5
	Motorway	5.8	1.4
LDVs	Urban	13.8	18.2
	Rural	10.7	8.6
	Motorway	9.2	2.1
Rigid HDVs	Urban	20.7	51.0
	Rural	17.4	27.1
	Motorway	14.0	8.4
Artic HDVs	Urban	47.1	51.0
	Rural	38.2	27.1
	Motorway	31.5	8.4
Buses	Urban	21.2	53.6
	Rural	17.4	27.1
	Motorway	14.0	8.4
Motorcycles	Urban	3.7	5.8
	Rural	2.9	2.8
	Motorway	2.5	0.7

Table 4 shows the average PM_{10} emission factors for road abrasion taken from the Guidebook [7] for all road types and speeds.

Table 4: Emission factors for PM_{10} from road abrasion [8]

mg PM_{10}/km	Road abrasion
Cars	7.5
LDVs	7.5
HDVs	38.0
Buses	38.0
Motorcycles	3.0

There are two general approaches for determining emission factors (EFs) from non-exhaust sources:

i. Direct measurements from the sources, either under real world test conditions or in the laboratory.

ii. Receptor modelling where ambient pollutant concentration data are sub-divided according to its different sources and EFs are derived using mass-balance techniques.

Both methods have advantages and limitations. In particular, the first method provides emission factors of a relatively small number of vehicles, but for very well controlled conditions. However, tyre, brake and road surface wear are difficult to simulate in controlled tests. Speed, acceleration/deceleration, tyre material, temperature and parameters such a road surface construction and curvature are all important considerations. Sampling problems have also been noted. Further, resuspension fluxes are difficult to measure directly because the space around a vehicle does not form a "closed" system with obvious air inlets and outlets. Receptor modelling method requires knowledge of source composition and assumes that the sources specified are responsible of the species measure at the receptor. Beyond that source apportionment and quantification of airborne PM measured in the vicinity of roads is a rather complex task, road traffic contribution can be small compared with the background concentrations. Measurements in tunnels tend to overestimate pollutant concentrations due to limited dispersion and dilution, not to mention that influences of meteorology are reduced.

Non-exhaust EFs included in the database corresponds to tyre, brake, road wear and resuspension component is given for Heavy-Duty Vehicles in Table 5 and 6.

Table 5: EC (Elemental Carbon) Non-exhaust Emission Factors for Euro 7 diesel Heavy-Duty Vehicles [11]

Vehicle	Urban	Rural	Highway
HDV Rigid<=7.5t	0.008	0.005	0.003
HDV Rigid 7.5-12t	0.008	0.005	0.003
HDV Rigid 12-14t	0.008	0.005	0.003
HDV Rigid 14-20t	0.008	0.005	0.003
HDV Rigid 20-26t	0.009	0.006	0.004
HDV Rigid 26-28t	0.009	0.006	0.004
HDV Rigid 28-32t	0.009	0.006	0.004
HDV Rigid >32t	0.009	0.006	0.004
Articulated 20-28t	0.010	0.007	0.004
Articulated 28-34t	0.010	0.007	0.004
Articulated 34-40t	0.011	0.007	0.005

Table 6: OM (Organic Matter) Non-exhaust Emission Factors for Euro 7 diesel Heavy-Duty Vehicles [11]

Vehicle	Urban	Rural	Highway
HDV Rigid<=7.5t	0.018	0.012	0.007
HDV Rigid 7.5-12t	0.018	0.012	0.007
HDV Rigid 12-14t	0.018	0.012	0.007
HDV Rigid 14-20t	0.018	0.012	0.007
HDV Rigid 20-26t	0.021	0.014	0.009
HDV Rigid 26-28t	0.021	0.014	0.009
HDV Rigid 28-32t	0.021	0.014	0.009
HDV Rigid >32t	0.021	0.014	0.009
Articulated 20-28t	0.023	0.016	0.010
Articulated 28-34t	0.023	0.016	0.010
Articulated 34-40t	0.023	0.016	0.010

2.1. Tyre Wear

The surface of a tyre when in contact with the road is steadily abraded by contact with the road surface. This leads to release of large quantities of small rubber particles which cover a wide range of sizes. The larger particles will typically remain on the road surface until washed off in drainage water. However, the size range extends into sizes below 10 micrometres diameter and hence contributes to PM_{10} (and to $PM_{2.5}$). The smaller abraded particles are liable to become airborne contributing to non-exhaust particles in the atmosphere [8].

It is estimated that an average passenger vehicle tyre lasts for 40,000-50,000 km before it is worn out, with approximately 10-30% of its tread rubber emitted into the environment. The wear factor (defined as the total amount of material lost per kilometre) varies enormously depending on several parameters such as: a) *tyre characteristics* with the most important being size (radius/width/depth), tread depth, construction, pressure and temperature, contact patch area, chemical composition, accumulated mileage and set-up; b) *vehicle characteristics* such as weight, distribution of load, location of driving wheels, engine power, electronic braking systems, suspension type and state of maintenance; c) *road surface characteristics* with the most important being material (bitumen/concrete), texture pattern and wavelength, porosity, condition, wetness and surface dressing; d) *vehicle operation* such as speed, linear acceleration, radial acceleration, frequency and extend of braking and cornering [14]. For instance, heavy-duty vehicles have been reported to emit approximately ten times higher tyre wear particles compared to light duty vehicles and passenger cars, while concrete pavements have been shown to produce lower wear emissions to PM_{10} compared to other types of pavements [15].

Tyre wear factors are substantially higher for HDVs than for LDVs. The wear factor per vkm will be dependent on the vehicle configuration, such as the number of axles and the load, and so a wide range of values is to be expected [13].

2.2. Brake Wear

There are two main 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 pads are forced against the inner surface of a rotating cylinder. The frictional process causes abrasion both of the brake pad and of the surface of the disc or drum leading to the release of particles, a substantial fraction of which become airborne [8]. Drum brakes tend to be a more enclosed system than disc brakes, which means that a greater proportion of the particles released do not get emitted to the atmosphere, instead, becoming trapped within the drum brake system. For this reason, emissions to the atmosphere from drum brakes tend to be lower than from disc brakes. Historically, drum brakes have tended to be more widely used in heavy-duty vehicles (HDVs), relative to light duty vehicles (LDVs), although HDVs are using disc brakes more now [7].

The effect on wear rate of the relative position of brakes on a vehicle is even more important than it is for tyres. With heavy trucks, the braking energy is more evenly distributed between the axles because of lower deceleration rates and the heavy load at the back of the vehicle. Wear rates also depend on brake actuation mechanism (pneumatic, electric), and hence it is more difficult to estimate lifetime of linings. It is expected that for trucks and coaches, the lifetime of brake linings is of the order of 60 000 km [13].

Abu-Allaban et al. [18] employed chemical mass balance receptor modelling and SEM techniques in order to determine brake wear EFs of light and heavy-duty vehicles at roadside locations in the U.S.A. They found PM_{10} EFs of 0-80 mg/km per vehicle for LDVs and 0-610 mg/km per vehicle for HDVs. The corresponding $PM_{2.5}$ EFs were 0-5 and 0-15 mg/km per vehicle. In general, high brake wear EFs were observed at freeway exit sites, while brake wear emissions in highways and tunnels were negligible.

There is very little literature on direct heavy-duty brake emissions measurements. To decelerate, heavy-duty vehicles employ technologies such as disc and drum as well as other braking methods including downshifting and engine (or "jake") braking. Due to the difficulty of differentiating a small brake emissions signal from the much larger signal coming from tailpipe, tire wear and road dust combined, there is much uncertainty in these measurements-yet another reason why adjusted laboratory measurements were favoured above [16].

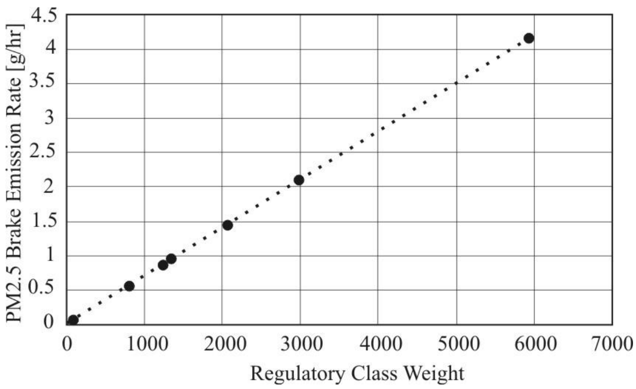

Figure 4: Interpolated Brake $PM_{2.5}$ Emission Rate by Regulatory Class Weight. Passenger Cars and Combination Heavy-duty Trucks Define the Slope [16]

Figure 5 presents the $PM_{2.5}$ emissions from brake wear in the UK split by vehicle type and road type. The emissions at this level of detail are derived by combining the vehicle and road type specific emission factors with vehicle kilometre data available for different vehicle and road types, as provided for the UK inventory by the UK Department for Transport (DfT). These data come from DfT's traffic census and traffic forecasts available at this level of detail. Note that the points of the lines are offset slightly to avoid overlapping (e.g. as occurs for Heavy-Duty Vehicles and Passenger cars on Motorways). It is clearly apparent from this figure how emissions from brake wear are more dominant on urban roads than on motorways and how emissions from passenger cars dominate over other vehicle types on urban roads. The dominance of passenger cars is less on rural roads and on motorways, passenger cars and heavy-duty vehicles make a similar small contribution [9].

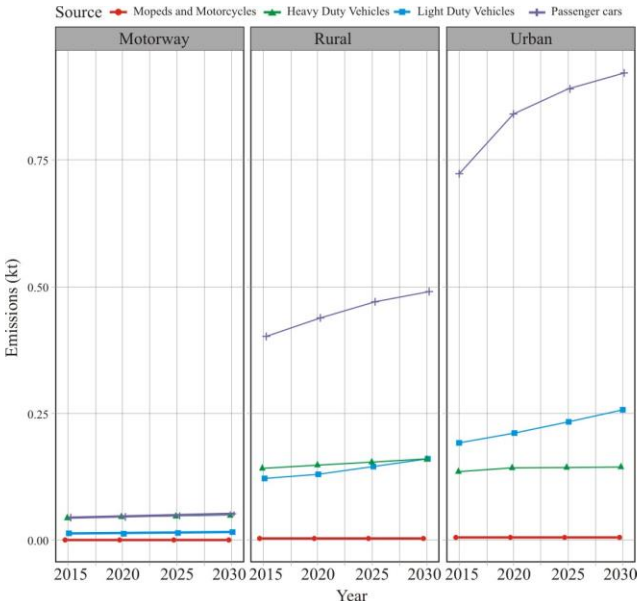

Figure 5: $PM_{2.5}$ emissions from brake wear in the UK split by vehicle type (coloured legend lines) and road type [9]

Most studies indicate that emission factors for PM from brake wear are significantly larger from HDVs than from LDVs [12] and [7]. This would be due to the larger number or size of brakes on heavy-duty vehicles and the fact that the larger vehicle weight releases more kinetic energy in the process of slowing the vehicle down. Garg et al. [19] also found a positive relationship between the weight of vehicles considered and the associated brake wear emission factors. Table 3 shows the emission factors for tyre wear and brake wear of road vehicles as used in the UK's National Atmospheric Emissions Inventory, submitted in 2017 [9]. These emission factors were developed based on a method Table in the EMEP/EEA Emissions Inventory Guidebook [7], a Guidebook for national emissions inventory compilation. This shows, amongst other things, that the brake wear emission factors for HDVs are around 5 times higher than those from passenger cars [9].

Figure 6 shows the average fractional size distribution of the LDV and HDV emission factors. The similar distribution for most of the considered elements suggests that these elements origin from the same source, i.e., from individual brake wear particles. Brake wear particles from light duty vehicles were distributed in the entire size range larger than 1 μm, while the contribution from the submicrometer mode was very low.

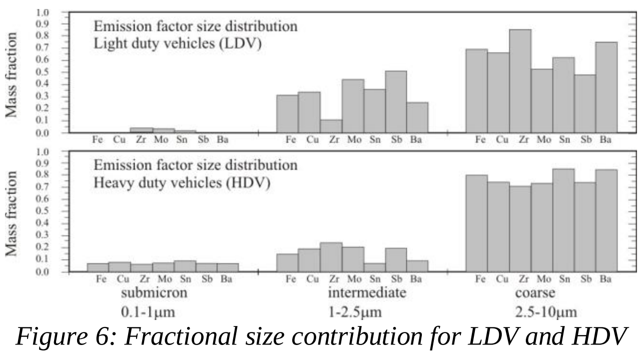

Figure 6: Fractional size contribution for LDV and HDV EFs determined for brake wear related trace elements [12]

In contrast, more than 75% of the brake wear emissions from heavy-duty vehicles were found in the coarse mode (2.5-10 μm). An explanation of these different size distributions remains difficult, but is likely due to the different design and operating conditions of LDV and HDV brake systems [12].

Total brake wear for light-duty vehicles appears to be around 10 to 20 mg/vkm, and around 50 to 80 mg/vkm for heavy goods vehicles. Typically 50% of brake wear debris from LDVs escapes the vehicle and enters the atmosphere, and more than 80% of airborne brake wear particles can be classified as PM_{10}. A substantial amount of the PM_{10} can also be present as $PM_{2.5.}$ There is considerable uncertainty regarding the amount of material which is lost from the brake linings, and the amount which is lost from the disc or drum [14].

2.3. Road surface wear

The friction between the tyre surface and the road surface which leads to tyre abrasion is also liable to abrade the road surface, especially where this is already fragmenting. Hence, road surface wear particles are also released to the atmosphere. Some studies have suggested that road wear particles are internally mixed with tyre rubber in the particles generated through this abrasion process [8].

With the increasing demands on road surfaces due to heavy traffic loads and extreme weather conditions, a range of modifiers are incorporated into the bituminous binder or asphalt mix. All serve to enhance the properties of the road surface material such that it is fit for its application and to consolidate the bonding between the binder and the mineral aggregate components. Various fillers and fibres may be added to reinforce binder-aggregate bonding. Glass, coal fly ash, and rubber tyres have been used as fillers, the latter becoming increasingly popular owing to problems relating to the disposal of used tyres. In order to harden the binder, sulphur may be added. An array of polymers, epoxy resins, and metal complexes have also been utilised as modifiers. Concrete road materials are a mixture of mineral aggregate, sand, and cement. There is little information in the literature on the precise chemical composition of the bulk road surface materials or PM generated by the wear of the road surface material, presumably due to the complexity of its composition and the range of different surface materials in use. Consequently, there exists no definitive molecular marker for road surface wear [20].

Some authors reported wear factors for LDVs and HDVs of 7.9 and 38 mg/vkm respectively, although these values also included tyre and brake wear. For New Zealand, Kennedy et al. [21] calculated a wear factor of 0.44 g/vkm for a road surface containing 50 % bitumen. In a situation where the bitumen comprises only 10 % of the worn surface, this figure would be reduced to 0.09 g/vkm. However, in areas where there is extensive use of studded tyres during the winter, the wear of the road surface, and the resulting PM concentrations due to resuspension, are considerably higher. Indeed, the wear when non-studded tyres are used is insignificant compared to when studded tyres are used. Winter maintenance procedures in cold climates, such as traction sanding (the dispersion of sand aggregate on the road surface) and the use of studded tyres, have been associated with high airborne particle concentrations through a formation process known as the "sandpaper effect". The wear of the road surface increases with moisture level, and is 2 to 6 times larger for a wet road than for a dry one. It also increases after salting of the road, since the surface remains wet for longer periods. Vehicle speed, tyre pressure and air temperature also affect road wear. As the temperature decreases the tyres become less elastic, with the result that the road surface wear rates increase [13].

2.4. Resuspension

Dusts from a number of sources accumulate on road surfaces. These originate from dry and wet deposition of airborne particles, especially coarser particles such as those deriving from soil. Additionally, abrasion products from the vehicle may deposit on the road contributing to the road surface dusts. Some of this material is in the PM10 size range when depositing to the road surface and the action of tyres on surface dusts may also cause some grinding leading to the creation of smaller particles from the coarser dusts. Studies of road surface dusts have shown a substantial fraction to be within the $PM_{2.5}$ and PM_{10} size ranges. Such particles are rather easily suspended from the road surface, both by shear forces at the tyre-road interface and by atmospheric turbulence in the wake of the vehicle. There is also evidence that elevated wind speeds contribute to the resuspension of surface dusts [8].

Heavy-duty vehicles (HDVs) are expected to contribute significantly more to road wear than light duty vehicles (LDV). In the literature the enhancement of road wear by HDV can be from 5 to 100 [14], though in many studies it is often difficult to distinguish between suspended and direct road wear. All LDV wear rates (*v=li*) have been enhanced by a factor of 5 to specify HDV wear rates (*v=he*). It is also worth noting that the percentage of studded tyres on HDV is often quite low, or none at all, and so the studded tyre contribution from HDV's may not be significant [17].

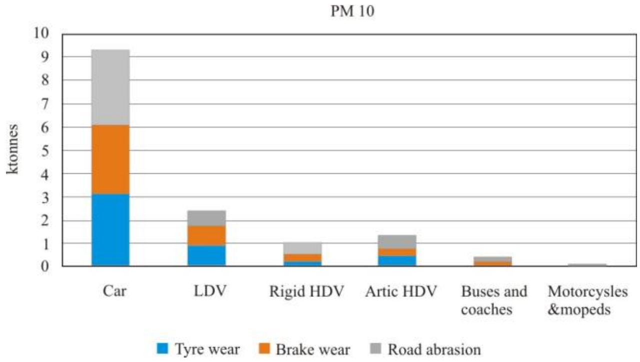

Figure 7: UK emissions of PM_{10} from road transport in 2016 by vehicle type [8]

3. FUTURE TRENDS IN NON-EXHAUST EMISSIONS OF PARTICULATE MATTER

The magnitude of non-exhaust emissions of PM as currently estimated has important implications for future PM emissions and air quality, because although current policies on exhaust emissions suggest that emissions of PM per vehicle, both light- and heavy-duty, will decrease significantly, as legislation and policy currently stand this is not necessarily the case for non-exhaust emissions. Three important issues determine the level and importance of non-exhaust emissions in future years, namely (i) the effect of future vehicle technology, in particular the effect of electric and hybrid vehicles on non-exhaust emissions, (ii) future trends in vehicle activity and (iii) the effect of any future legislation which could affect the level and chemical composition of non-exhaust emissions [8].

Using the Guidebook emission factors and vehicle activity data, the NAEI reports the trends in UK tyre wear, brake wear and road abrasion emissions of PM_{10} and $PM_{2.5}$ shown in Figure 8 and Figure 9. For comparison, emissions from vehicle exhausts are also shown. The emissions shown from 2000-2016 are from the latest version of the reported UK inventory representing actual vehicle activities, while emissions from 2017-2030 are projections in emissions based on DfT's traffic growth assumptions and in the case of exhaust emissions reflect the turnover in the vehicle fleet with the penetration of new vehicles meeting tighter Euro standards for PM emissions. Figures show how as vehicle exhaust emissions have declined, the non-exhaust emissions have been slowly increasing with increasing traffic levels and are becoming a much larger share of overall PM_{10} and $PM_{2.5}$ traffic emissions. The proportion of total NEE from brake wear, tyre wear, road surface wear has increased from 39% of total UK road transport emissions of PM_{10} in 2000 to 73% in 2016; for $PM_{2.5}$ the proportion of NEE has increased from 26% in 2000 to 60% in 2016.

Without any NEE abatement this trend is predicted to continue so that by 2030, the non-exhaust sources will contribute to 94% of total UK road transport emissions of PM_{10} and 90% of $PM_{2.5}$ [8].

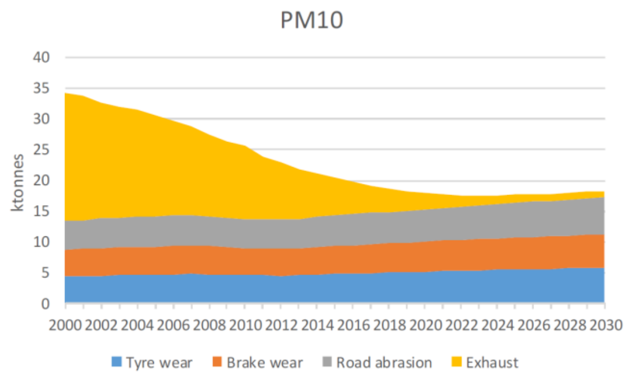

Figure 8: UK emissions of PM10 from road transport [8]

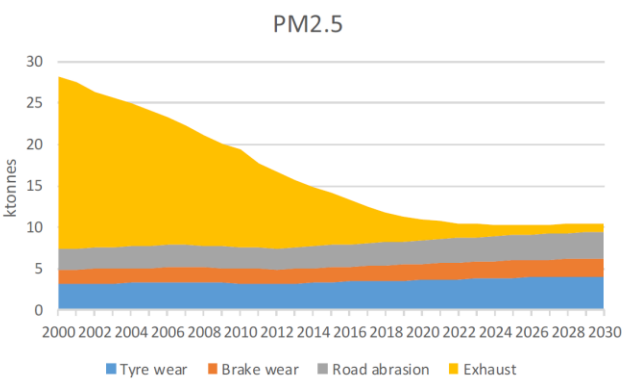

Figure 9: UK emissions of $PM_{2.5}$ from road transport [8]

4. CONSLUSIONS

Non-exhaust emissions from mobile sources make significant contributions to total PM emissions in the world today. The importance of this source will grow in the future since effective control programs are in place to reduce exhaust emission from transport.

In case of urban street canyon, the percentage of HDVs is lower than on the highway (10 compare to 15%). Compared to light duty vehicles, the absolute emission factors for heavy-duty vehicles were 15 times higher for total PM_{10} and 10 times higher for brake wear and the exhaust emissions. In contrast to light duty vehicles, the road dust resuspension capability of an individual heavy-duty vehicle was estimated to be substantial. More than half of the PM_{10} emissions of an individual heavy-duty vehicle were attributed to road dust resuspension and minor contributions of road wear and tire wear.

The average PM_{10} emission factor for highway was caused by exhaust emissions (≈40%) and very low contributions from brake wear emissions (3%). The remaining percentage of the traffic emissions were not directly identified, but probably represented contributions from road dust resuspension (and minor contributions from tire wear and road wear).

Significant gaps still exist in our understanding of traffic emissions, particularly:

1. Characterization and quantification of different non-exhaust sources.

2. Impacts of non-exhaust emissions upon human health: While there are many studies reporting links between exposure to air pollution and adverse health impacts, detailed information on the components that contribute to toxicity is missing.

3. Aerosol chemistry in high traffic environments, and the evolution of particles emitted from vehicles. Further, most of the reported analyses have been carried out in the USA or Europe, and there is a lack of reliable information on traffic emissions in areas with high population density in Africa, Asia and South America. The field offers much scope for future research, including the development of enhanced methods for quantification of non-exhaust contributions to airborne concentrations.

ACKNOWLEDGEMENTS

This paper was realized within the researching project "The research of vehicle safety as part of a cybernetic system: Driver-Vehicle-Environment" ref. no. TR35041, funded by Ministry of Education, Science and Technological Development of the Republic of Serbia.

REFERENCES

[1] S. Lawrence, R. Sokhi and K. Ravindra, "Quantification of vehicle fleet PM10 particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques", Environmental Pollution, Vol. 210, pp. 419-428, (2016)

[2] T. Grigoratos and G. Martini, "Brake wear particle emissions: a review" J. Environ. Sci. Poll. Res. pp.1-14, (2014)

[3] P. Pant and R.M. Harrison, "Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review", Atmospheric Environment, Vol 77, 78-97, (2013)

[4] K. Adachi, Y. Tainosho, "Characterization of heavy metal particles embedded in tire dust", Environment International Vol.30 (8), pp. 1009-1017, (2004)

[5] F. Amato, M. Pandolfi, M. Viana, X. Querol, A. Alastuey, T. Moreno, "Spatial and chemical patterns of PM10 in road dust deposited in urban environment", Atmospheric Environment, Vol.43 (9), pp. 1650-1659, (2009)

[6] R. M. Harrison, A. M. Jones, J. Gietl, J. Yin, D. C. Green, "Estimation of the contributions of brake dust, tire wear, and resuspension to nonexhaust traffic particles derived from atmospheric measurements", Environmental Science & Technology Vol.46, pp. 6523-6529, (2012)

[7] EMEP/EEA, Air Pollutant Emissions Inventory Guidebook, available at https://www.eea.europa.eu/publications/emep-eea-guidebook-2016, (2016)

[8] Non-Exhaust Emissions from Road Traffic, Air Quailty Expert Group, Crown copyright (2019)

[9] D. Wakeling, T. Murrells, D. Carslaw, J. Norris, L. Jones, "The Contribution of Brake Wear Emissions to Particulate Matter in Ambient Air", FORSCHUNGSVEREINIGUNG AUTOMOBIL TECHNIK E.V. FAT-SCHRIFTENREIHE

[10] ACEA Report Vehicles in use Europe 2019

[11] I. Vouitsis, L. Ntziachristos, Z. Samaras, "TRANSPHORM Report, Transport related Air Pollution and Health impacts-Integrated Methodologies for Assessing Particulate Matter, Methodology for the quantification of non-exhaust road transport PM emissions", (2013)

[12] N. Bukowiecki, R. Gehrig, P. Lienemann, M. Hill, R. Figi, B. Buchmann, M. Furger, A. Richard, C. Mohr, S. Weimer, A. Prévôt, and U. Baltensperger, "PM10 emission factors of abrasion particles from road traffic (APART)". Swiss Association of Road and Transportation Experts (VSS), (2009)

[13] L. Ntziachristos and P. Boulter, "EMEP/EEA emission inventory guidebook 2009, Road vehicle tyre and brake wear; Road surface wear", (2009)

[14] P.G. Boulter, "A review of emission factors and models for road vehicle non-exhaust particulate matter, TRL Report PPR065. TRL Limited, Wokingham (2006)

[15] F. Amato, M. Pandolfi, T. Moreno, M. Furger, J. Pey, A. Alastuey, N. Bukowiecki, A.S.H. Prevot, U. Baltensberger, and X. Querol, "Sources and variability of inhalable road dust particles in three European cities", Atmospheric Environment Vol. 45, pp. 6777-6787, (2011)

[16] Brake and Tire Wear Emissions from On-road Vehicles in MOVES2014, Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, (2014)

[17] B.R. Denby, I. Sundvor , C. Johansson, L. Pirjola, M. Ketzel, M. Norman, K. Kupiainen, M. Gustafsson, G. Blomqvist, G. Omstedt, "A coupled road dust and surface

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

621(082)
621.86/.87(082)
629.3/.4(082)
622.6(082)
681.5(082)

INTERNATIONAL Triennial Conference Heavy Machinery (10 ; 2021 ; Vrnjačka Banja)
Proceedings / The Tennth International Triennial Conference Heavy Machinery HM 2021, Vrnjačka Banja, June 23-25, 2021 ; [editor Mile Savković]. - Kraljevo : Faculty of Mechanical and Civil Engineering University of Kragujevac, 2021 (Bor : Tercija). - 1 knj. (razl. pag.) : ilustr. ; 29 cm

Tekst štampan dvostubačno. - Tiraž 80. - Str. [7]: Predgovor / Mile Savković. - Bibliografija uz svaki rad.

ISBN 978-86-81412-09-1

a) Машиноградња - Зборници b) Транспортна средства - Зборници c) Производно машинство - Зборници d) Шинска возила - Зборници e) Аутоматско управљање - Зборници

COBISS.SR-ID 41166089