EVALUATION OF THE AIR POLLUTION IMPACT OF THE HEAVY GOODS, DIESEL VEHICLES ALONG, THE A1 HIGHWAY IN NORTH MACEDONIA

Nikola Manev[1*], Dame Dimitrovski[1], Elenior Nikolov[2], Drage Petreski[2], Zoran Markov[2]

[1*]Mechanical Engineering Faculty – Skopje, Ruger Boshkovik nmb.18, North Macedonia;
[2]Military Academy "General Mihailo Apostolski", Skopje, Vasko Karangeleski, North Macedonia;

[*]E-mail: manev.nikola@yahoo.com

ABSTRACT

Road traffic is a major source of air pollution due to emissions of a range of pollutants but most notably particulate matter (PM) emissions, which have a strong association between their concentration and respiratory system diseases. Diesel engines have the highest emission rates of PM as they dominate heavy-duty applications due to their greater fuel efficiency, power output and ability to haul bigger loads. This also means higher quantities of non-exhaust emissions per vehicle, as the load distribution, and the size of the vehicle, factor in the quantity of brake and tire wear emissions. This implies that the presence of exhaust and non-exhaust PM and their impact to the environment has been exacerbated by the presence of heavy goods vehicles (HGVs). Multiple reports on North Macedonia's air pollution management claim that national emissions inventories report all key sources of pollution but need to strengthen inputs for the transport sector as there is a need to validate the consistency of transport data used in the inventory and further capture context-specific features of important local emission sources. Consequently, since the average emissions of HGVs vary significantly as a result of the different mission profiles, payloads, mileage and vehicle age of an HGV, this paper defines a typical HGV model for North Macedonia and then provides an analysis and an estimate on the emissions footprint of the HGVs transiting the Macedonian A1 highway, thereby gathering a significant part of the aforementioned specific data on the air pollution impact of transport in the country.

Key words: HGVs, diesel, air pollution, impact, emissions, evaluation

INTRODUCTION & RELATED WORK

Road traffic has long been recognized as a major source of air pollution (AQEG, 2019) due to a range of emissions that can be distinguished according to their source into two main categories: exhaust traffic related emissions, which are a result of incomplete fuel combustion and lubricant volatilization during the combustion process, and non-exhaust traffic related emissions, which are actually particles produced by abrasion from brakes and tire wear, or already exist in the environment as deposited material and become resuspended due to traffic induced turbulence. (Grigoratos & Martini, 2014; Teixeira et al., 2018) All of these emissions are the cause for a range of pollutants but most notably carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC) and particulate matter (PM) (Amato et al., 2011; Hooftman, 2018) which have been proven to have an association between their concentration and significant adverse health effects in humans. (Valavandis et al., 2008; Cassee et al., 2013; Fedotov et al., 2014; Al-Thani et al., 2020)

Considerable attention has been paid in research toward diesel vehicles since they traditionally have the highest emission rates of exhaust pollutants. (Boulter, 2005; Petrovic, 2008) At the same time, diesel engines dominate heavy-duty applications because of their greater fuel efficiency and torque output which also means higher quantities of non-exhaust emissions per vehicle, as the load distribution, and the size of the vehicle, factor in the quantity of brake and tire wear emissions. This means that the presence of the abovementioned pollutants (with the exception of NMVOC) and their contribution to air pollution, overall negative impact to the environment and general quality of life have been exacerbated by the presence of heavy freight vehicles, otherwise known as heavy goods vehicles (HGVs).

Multiple reports (World Bank, 2019; UNECE, 2019) on North Macedonia's air pollution management claim that national emissions inventory reports all key sources of pollution but needs to strengthen inputs, notably for the transport sectors. There is a need to validate the consistency of transport data used in the inventory, cover all pollutants, and further advance inventory development methods to capture context-specific features of important local emission sources. Based on a thorough review of the related available literature (World Bank, 2019; UNECE, 2019) that addresses the topic of air pollution in North Macedonia, we concluded that CO and NMVOC are the least reported on, along with tire and break wear PM emissions. In this context, since the average emissions of HGVs vary significantly as a result of the very different mission profiles, payloads, mileage and vehicle age, this paper finds it important to define a typical HGV model, on account of its emissions of CO, NMVOC and non-exhaust PM for North Macedonia and then provide an analysis and an estimate on the emissions footprint of the HGVs transiting the Macedonian A1 highway, thereby contributing in capturing a significant part of the aforementioned specific data on transport in the country.

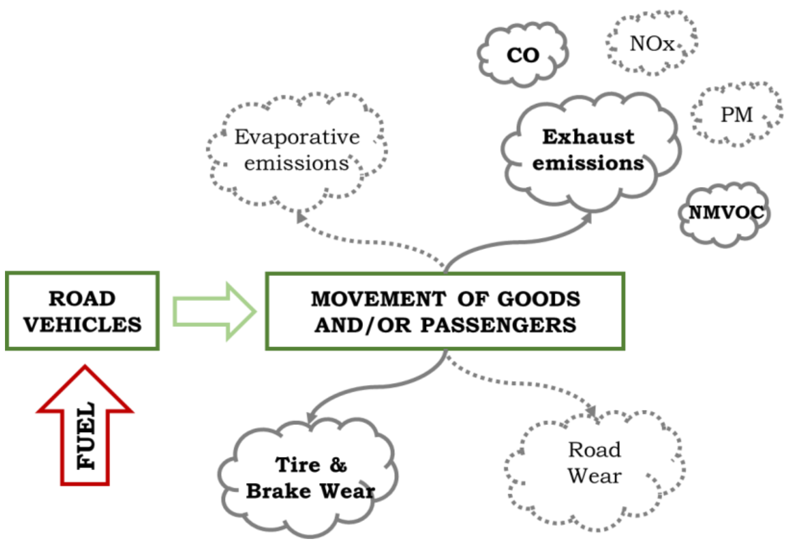

Figure 1. Road Transport emissions (full line, the ones covered in this paper)

MATERIALS AND METHODS

Materials

The annual Technical Fidelity Inspection of vehicles includes a number of systems checks that are used to identify if a vehicle abides by all of the operational, safety and environmental standards as set by eithernational or international legislation. Since the goal of this paper is to identify the HGVs ability to pollute, we looked to define a typical HGV model, using rigid lorry and road tractor non-exhaust (tire and brake wear) PM emissions, based on the available, existing regulative and using the equipment, devices and facilities found in a certified Technical Fidelity Inspection Service operating in North Macedonia (obtained through the project STRASS).

Additionally, we heavily relied on the revised 2019 edition of the EMEP/EEA air pollutant emission inventory guidebook, and its 1.A.3.b Road transport Chapter, with its 1.A.3.b.iii (Heavy-duty vehicles including busses) EEA, (2019b) and 1.A.3.b.vi (Road transport: Automobile tire and break wear) sub-chapters. EEA, (2019c) The guidebook supports the 'Guidelines for Reporting Emissions and Projections Data' under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP Convention), EEA, (2019a).

Finally, a vital part of the research data was supplied by the government owned, Public enterprise for state roads, and its Traffic Counting Section which provided us with an overview on the traffic frequency along the A1 highway. This included an Average Annual Daily Traffic Report for the year 2020, which consists of an average number of vehicles (by categories) transiting the A1 highway starting from International border crossing (IBC) Tabanovce on the north border, and all the way to IBC Bogorodica on the south border. According to this data, HGVs fall under three categories (based on their chassis type, laden vehicle mass and number of axles) **K5** Rigid Lorry, 3.5t-16t, 2 and 3 axles; **K6** Rigid Lorry and Trailer, 16t-32t, 4 axles; and **K7** Road tractor and semi-trailer, >32t, 4 and 5 axles. The distance covered equals 166 km along the A1 highway, which a vehicle driving with a mean speed of 100km/h would pass in roughly 1 hour and 40 minutes.

Methods

To calculate the exhaust emissions of interest to this paper (CO and NMVOC), along with the non-exhaust emissions that result from tire and brake wear, we used the tiered methodology proposed by the European environmental agency and found within their 2019 edition of the EMEP/EEA air pollutant emission inventory guidebook. The Guidebook describes a tiered methodology for estimating emissions. Simple (Tier1) methods are given for all the sources and substances that the countries that have ratified Convention protocols need to report. More advanced (Tier 2) methods are given for key categories. Further information is given for advanced (Tier 3) approaches for key categories where suitable methods are available. EEA, (2019a)

Tier 1 methods assume a simple linear relation between activity data (for example, fuel consumption) and emission factors. The activity data are derived from readily available statistical information (energy statistics, production statistics, traffic counts, population sizes, etc.). The default Tier 1 emission factors are chosen to represent 'typical' or 'averaged' process conditions - they tend to be technology independent. Tier 2 methods use the same or similar activity data to Tier 1 methods, but apply country-specific emission factors; country-specific emission factors need be developed, using country-specific information on process conditions, fuel qualities, abatement technologies, etc. It is exactly the Tier 2 methodology that we found most suited for the scope of this paper.

Exhaust Emissions

Calculating the amount of exhaust emissions, using Tier 2 methodology requires the number of vehicles and the annual mileage per technology (or the number of vehicle-km per technology). These vehicle-km data are multiplied by the Tier 2 emission factors. (EEA, 2019b) Hence, the algorithm used is:

$$E_{i,j} = \sum_k < M_{j,k} > * EF_{i,j,k} \quad \text{or} \quad E_{i,j} = N_{j,k} * M_{j,k} * EF_{i,j,k} \qquad (1) \text{ and } (2)$$

Where: $< M_{j,k} >$ is the total annual distance driven by all vehicles of category j and technology k [veh-km], $EF_{i,j,k}$ is technology-specific emission factor of pollutant i for vehicle category j and technology k [g/veh-km], $M_{j,k}$ stands for the average annual distance driven per vehicle of category j and technology k [km/veh], and $N_{j,k}$ is the number of vehicles in nation's fleet of category j and technology k. The vehicle category j is heavy-goods vehicles and the vehicle technologies k are Euro IV, V, and VI seeing as the HGV fleet in North Macedonia consists of roughly 20% Euro IV, 50% Euro V, and 30% Euro VI HGVs, and an insignificant portion of the remaining categorizations (Conventional to Euro III).

The emission factor for CO, for HGVs with a laden mass of less than 16 tones (7.5t-16t), for technology Euro IV,V and VI is $EF_{CO,HDVK5} = 0.071\ g/km$, for HGVs with a mass of more than 16 and less than 32 tones (16t-32t) $EF_{CO,HDVK6} = 0.105\ g/km$, and for HGVs with a mass of more than 32 tones (>32t) $EF_{CO,HDVK7} = 0.121\ g/km$.

On the other hand, the emission factor for NMVOCs, for HGVs with a laden weight of less than 16 tones (7.5t-16t), for technology Euro IV,V and VI is $EF_{NMVOC,HDVK5} = 0.008\ g/km$, for HGVs with a mass of more than 16 and less than 32 tones (16t-32t) $EF_{NMVOC,HDVK6} = 0.010\ g/km$, and for HGVs with a mass of more than 32 tones (>32t) $EF_{NMVOC,HDVK6} = 0.012\ g/km$.

Non-Exhaust Emissions

The following general equation is used to estimate emissions from tire wear and brake wear separately:

$$TE = \sum_j N_j * M_j * EF_{TSP,s,j} * f_{s,i} * S_s(V) \quad (3)$$

Where TE is total emission for the defined time period and spatial boundary [g], N_j is the number of vehicles in category j within the defined spatial boundary, M_j is the mileage [km] driven by each vehicle in category j during the defined time period, $EF_{TSP,s,j}$ is the TSP mass emission factor for vehicles in category j [g/km], $f_{s,i}$ is the mass fraction of TSP that can be attributed to particle size class i, and $S_s(V)$ is the correction factor for a mean vehicle travelling speed V. The index j relates to the vehicle category Heavy-goods vehicles. The index s refers to the source of PM, i.e. tire (T) or brake (B) wear. The particle size classes i are TSP (suspended particulates), PM10, PM2.5, PM1 and PM0.1.TSP emission factors are based on available experimental data. EEA, (2019c)

Tire wear emissions

With regard to tire wear, it should be noted that the TSP emission factors do not assume that all tire wear material is transformed into suspended particulate, as a large fraction of tire rubber may be produced as dust fall particles or larger shreds (e.g. under heavy braking). For HGVs the emission factor needs to take vehicle size (by the number of axles) and load into account. These are introduced by equation 4:

$$EF_{TSP,T,HGV} = \frac{N_{axle}}{2} * LCF_T * EF_{TSP,T,PC} \quad (4)$$

$EF_{TSP,T,HGV}$ is the TSP emission factor [g/km] for tire wear from heavy-duty vehicles, N_{axle} is the number of truck axles, LCF_T is the load correction factor for tire wear, $LCF_T = 1.41 + (1.38 * LF)$, LF is the load factor, ranging from 0% for an empty truck to 100% for a fully laden one (all of the HGVs are linearly given 80% laden capacity throughout this paper), and $EF_{TSP,T,PC}$ is the TSP emission factor for tire wear from passenger cars (0.0107 g/km).

A typical size profile for the TSP emitted by tire wear has been obtained by combining information from the available literature. Based on this information, the mass fraction of TSP in the different particle size classes is shown in Table 5. A value of 0.6 has been selected as the PM10/TSP ratio for tire wear in order to derive TSP values where only PM10 emission factors are available in the literature.

Table 1 Size distribution of tire wear particles

Particle size class (i)	**Mass fraction $f_{T,i}$ of TSP**
TSP	1.000
PM_{10}	0.600
$PM_{2.5}$	0.420
PM_1	0.060
PM_{01}	0.048

A speed correction is required to account for the different wear factors of the tire depending on the vehicle speed. It should be noted that, vehicle speed corresponds to mean trip speed and not constant travelling speed. Tire wear decreases as mean trip speed increases, because braking and cornering are less frequent in motorway driving. The mathematical expression is:

$$\begin{aligned} &V < 40\ km/h: && S_T(V) = 1.39 \\ &40\ km/h \le V \le 90\ km/h: && S_T(V) = -0.00974 * V + 1.78 \\ &V > 90\ km/h: && S_T(V) = 0.902 \end{aligned} \quad (5)$$

Brake wear emissions
The brake wear, HGV TSP emission factor is calculated by the following formula:

$$EF_{TSP,B,HGV} = 3.13 * LCF_B * EF_{TSP,B,PC} \quad (6)$$

In equation 6, 3.13 is an empirical factor derived from experimental data and LCF_B is defined in a similar way to LCF_T and can be determined again by linear regression on experimental data by the equation:

$$LCF_B = 1 + 0.79 * LF \quad (7)$$

We already know that LF has the value of 0% for an empty vehicle and 100% for a fully laden one, and again all of the HGVs are linearly given 80% laden capacity and the TSP emission factor ($EF_{TSP,B,PC}$) for brake wear from passenger cars equals 0.0075 g/km.
The mass fraction of TSP in the different particle size classes is shown in Table 2.

Table 2. Size distribution of brake wear particles

Particle size class (i)	**Mass fraction $f_{B,i}$ of TSP**
TSP	1.000
PM_{10}	0.980
$PM_{2.5}$	0.390
PM_1	0.100
PM_{01}	0.080

The mathematical expression of the speed correction factor for the case of brake wear $S_B(V)$ is given in equation 8:

$V < 40\ km/h$: $S_B(V) = 1.67$
$40\ km/h \leq V \leq 90\ km/h$: $S_B(V) = -0.0270 * V + 2.75$ (8)
$V > 90\ km/h$: $S_B(V) = 0.185$

RESULTS

Here follows the amount of exhaust (CO and NMVOC) and non-exhaust (Brake and Tire Wear PM) emissions as calculated using the Tier 2 Methodology:

Table 3. Daily amount of CO (a) and NMVOC (b) emissions (g) from HGVs along the A1 highway in the year 2020

Cat	N_j	M_j	$E_{CO,EuroIV,V,VI}$	$E_{i,j}$
K5	268	166	0.071	3158.65
K6	25	166	0.105	435.75
K7	734	166	0.121	14743.1
Total	1027	166	/	18337.5

a)

Cat	N_j	M_j	$E_{NMVOC,EuroIV,V,VI}$	$E_{i,j}$
K5	268	166	0.008	355.904
K6	25	166	0.01	41.5
K7	734	166	0.012	1462.13
Total	1027	166	/	1859.53

b)

Using the Average Annual Daily Traffic Report for the year 2020, and the average number of HGVs in each of the K5, K6 and K7 categories passing through the traffic counting points along the A1 highway, we were able to calculate the daily quantity of CO and NMVOC emissions of these vehicles. The numbers show that the CO emissions are higher than the NMVOC emissions by a factor of almost 10. Curiously enough, the Euro IV, V and VI regulations, are the same in regard to these pollutants, which means that ever since 2005 (Euro IV) there has not been a change in the requirements for lower emitting HGVs.

Table 4. Daily amount of Tire wear emissions for HGVs along the A1 highway in the year 2020 (g)

Cat	N_j	M_j	N_{axle}	LF	LCF_T	$EF_{TSP,T,PC}$	$EF_{TSP,T,HGV}$	$f_{T,TSP}$	t(min)	V	$S_T(V)$	TE(TSP)	TE(PM10)	TE(PM2.5)	TE(PM1)	TE(PM01)	TE(T)
K5	268	166	3	0.8	2.514	0.0107	0.0403497	1	100	100	0.902	1619.16	971.496	680.047	97.1496	77.7197	3445.57
K6	25	166	4	0.8	2.514	0.0107	0.0537996	1	100	100	0.902	201.388	120.833	84.583	12.0833	9.66663	428.554
K7	734	166	5	0.8	2.514	0.0107	0.0672495	1	100	100	0.902	7390.94	4434.56	3104.2	443.456	354.765	15727.9
Total	1027	166	12	0.8	/	/	/	/	/	100	/	9211.49	5526.89	3868.83	552.689	442.151	19602

Table 5. Daily amount of Brake wear emissions for HGVs along the A1 highway in the year 2020 (g)

Cat	N_j	M_j	N_{axle}	LF	LCF_B	$EF_{TSP,B,PC}$	$EF_{TSP,B,HGV}$	$f_{B,TSP}$	t(min)	V	$S_B(V)$	TE(TSP)	TE(PM10)	TE(PM2.5)	TE(PM1)	TE(PM01)	TE(B)
K5	268	166	3	0.8	1.632	0.0075	0.0383112	1	100	100	0.185	315.312	309.006	122.972	31.5312	25.225	804.045
K6	25	166	4	0.8	1.632	0.0075	0.0383112	1	100	100	0.185	29.4134	28.8252	11.4712	2.94134	2.35307	75.0042
K7	734	166	5	0.8	1.632	0.0075	0.0383112	1	100	100	0.185	863.578	846.307	336.795	86.3578	69.0862	2202.12
Total	1027	166	12	0.8	/	/	/	/	/	100	/	1208.3	1184.14	471.238	120.83	96.6643	3081.17

Since there is only limited braking at high motorway speeds, the results for emitted particles from brake wear logically show that brake wear is negligible along the A1 highway. However, depending primarily on the number of axles and the mass of each HGV, tire wear particles make up for a significant amount in comparison. In both cases fine $PM_{2.5}$, PM_1 and ultrafine $PM_{0.1}$, account for roughly 20-25% of the emitted mass of particles. This is a substantial contribution in mass especially since associations between chemical compositions and particle toxicity tend to be stronger for the fine and ultrafine PM size fractions as these are the sizes most likely to make their way into humans' respiratory systems.

CONCLUSION

Road traffic has long been recognized as a major source of air pollution that has a significant impact on the deterioration of air quality and general quality of life. Exhaust and non-exhaust emissions have directly contributed to the matter, as they cause severe health defects, and a range of diseases which have resulted in an increase in the morbidity and mortality rates in humans. Seeing as North Macedonia's air pollution management lacks data on the amount of pollutants from the transport sector, following a thorough review of the related scientific literature we identified that CO and NMVOC are the least reported on, along with tire and break wear PM emissions. Subsequently we calculated the daily quantity of emissions coming from HGVs transiting the A1 highway in North Macedonia using the advanced Tier 2 methodology of the EEA.

Previous research has showed that there is a general decreasing tendency of engine exhaust emissions due to the use of catalytic converters, diesel particulate filters (DPF) and improved fuels and engines, especially in diesel driven vehicles such as HGVs. However, whilst regulations set by the European Union have led to progressive reductions in the emissions of the regulated gaseous pollutants and of particulate matter from the exhausts of new vehicles, the non-exhaust emissions are not currently targeted by emissions regulations. Therefore, as the exhaust emissions have fallen, the proportion of non-exhaust emissions to the total emissions from road traffic has increased, with a number of sources stating that it is expected that the relative contribution of brake and tire wear particles to the total PM levels will rise in the forthcoming years. (Denier Van der Gon et al., 2012; Denier Van der Gon et al., 2013)

Knowing this, our paper succeeded in analyzing the individual quantity of exhaust CO and NMVOC emissions, and tire and brake wear PM emissions in HGVs using the A1 highway as a defined spatial boundary, since it is a vital transport corridor that traverses the entire country. Every piece of available data that came out of this paper and research can later be used to feed into a model that is going to take into account emissions such as exhaust NOx and PM emissions and further contribute to completing the picture of the impact that motorway, goods transport has on air pollution. We used the Macedonian transport fleet as a reference, however, in all likelihood the air pollution impact might be even smaller as a significant chunk of the HGVs transiting Macedonia as part of TIR would abide by much stricter UNECE regulations in terms of their emissions, so we can mostly expect Euro V and newer technologies.

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