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NOVEL APPROACH TO MODEL PASSENGER CARS' URBAN EXHAUST EMISSIONS, AIR POLLUTION IMPACT: THE CASE OF THE CITY OF SKOPJE

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Abstract

With the problem of air pollution in mind, as well as the lack of reliable data for light passenger vehicles' (cars) share in the overall exhaust emissions in an urban setting, a novel, urban transportation, emissions model is derived based on the city of Skopje's (Republic of North Macedonia) traffic characteristics. For that purpose, the coefficients of emissions from mobile sources which are already derived by the European Environmental Agency were optimized and modified to comply with Skopje's traffic conditions and characteristics, and furthermore they were used in creating a unique length emission coefficient based on these urban driving conditions. The model considers different stages of the European emission standards (better known simply as EURO emission standards), average velocities and distances covered. Additionally, the model provides an insight into the urban emissions footprint, based on a future projection that considers the share of different alternative fuels and powertrains in light passenger vehicles in Skopje up to and including the year 2050.

Key words: optimization, length emission coefficient, precision, urban traffic characteristics

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1. Introduction

These days most everyday activities revolve on the basis of a well-developed transport sector. As a result, transport is one of the key elements that set the tone for a country's economic and social prosperity. At the same time, these economic and social benefits have long outweighed the concerns brought on by the environmental effects of transport (Manev et al., 2021). Conventional fossil fuels, while literally fuelling societies' progress, have been one of the major causes of air pollution and have led to a significant reduction in air quality and quality of life (Michalek et al., 2011; Tessum et al., 2014). This statement holds true for urban areas in the Western Balkans more than anywhere else, as the ill effects of transport are exacerbated by a greater concentration of people, motor vehicles and an infrastructure that does not necessarily support their daily migrations.

In fact, the capital cities of most Western Balkans states, have at one time or another found themselves on the roster of the world's most polluted capital cities (Balkan Insight, 2023; OBC Transeuropa, 2023). What is even more alarming about this whole situation is that it shows a tendency to worsen in the years to come, as these cities often lack long-term vision in terms of locating an efficient pollution-stopping capability. Looking at Skopje, the capital city of the Republic of North Macedonia, road transportation in particular, has been identified as one of the primary reasons behind the city's pollution, or otherwise having an old fleet of passenger cars (with

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an average age of 19.5 years as of 2021) (MakStat, 2023) and an urban infrastructure that does not support their large numbers (Dzinlev, 2016).

Multiple reports (World Bank, 2019; UNECE, 2019) on North Macedonia's air pollution management claim that the national emission inventory reports all major sources of pollution but needs to strengthen inputs, notably for the transport sector. At the same time, 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 transport related emission sources.

In this context, this paper focuses on the impact of passenger cars as they account for the most significant chunk of transport emissions in an urban setting. "A novel urban transportation exhaust emissions model is derived based on Skopje's traffic characteristics." The coefficients of emissions from mobile sources derived by the European Environmental Agency (EEA, 2019; EEA, 2020) are optimized and modified to comply with Skopje's traffic conditions, and furthermore they are used in creating a unique length emission coefficient based on urban driving conditions. The model considers different EURO emission standards, average velocities and distances covered. Additionally, the model provides an insight into the urban emissions footprint, based on a future projection that takes account of the share of different powertrains (AFPs) in passenger cars in passenger cars in Skopje up to and including 2050.

Thanks to the wide and encompassing nature of the model, the fact that it uses both theoretically derived and experimental data and the fact that it takes into account the future segment of passenger car development, sales and subsequently participation in traffic will contribute significantly in capturing a very important part of the aforementioned specific data on transport in North Macedonia.

The overarching motive behind writing this paper is that deriving suitable and applicable scenarios may help in devising policies that will lead to decreasing the emission of pollutants from mobile sources, which will also decrease the overall pollutant concentration and increase the urban air quality.

2. Materials and methods

2.1. European environmental agency tiered methodology

The 3-tiered methodology for estimating emissions proposed by the European environmental agency (EEA) found in the 2019 edition of the EMEP/EEA air pollutant emission inventory guidebook was used as a basis for the exhaust emission model (EEA, 2020). 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 and 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; fuel quality; abatement technologies, etc. Tier 2 methods also account for the year the vehicles' have been produced in the form of a EURO emissions standard and introduce a mean value of the most common speed profiles that occur under different driving conditions (urban and rural environments and highways).

While the calculation methods from the first two tiers provide a varying degree of precision, the Tier 3 method represents the most detailed and precise method for calculating traffic emissions. This methodology differs from the previous two in that combustion emission coefficients from internal combustion (IC) engines are not constant values derived in different driving modes, but the coefficients themselves represent polynomial expressions whose results change depending on the driving speed of the vehicles. For this purpose, polynomial emission factors have been developed for passenger cars, motorcycles, buses with minibuses, heavy and light trucks, divided according to the fuel they use and the EURO emission standard which allow the calculation of hot emissions, while the calculation of cold start engine emissions is far more complex and requires more data that usually has to be obtained in a laboratory setting. Furthermore, since vehicle emissions are heavily dependent on the engine operating conditions, a distinction is made between urban, rural and highway driving with different activity data and emission factors attributed to each driving situation. Hot exhaust emissions depend upon a variety of factors, including the distance that each vehicle travels, its speed (or road type), its age, its engine size and its weight. The basic formula for estimating hot emissions for a given time period, and using experimentally obtained emission factors (EF), can be found in (Eq. 1) (EEA, 2020):

$$emission\ [g] = EF\ [g/km] * number\ of\ vehicles\ [veh] * mileage\ per\ vehicle\ [km/veh] \quad (1)$$

Therefore, the formula to be applied for the calculation of hot emissions of pollutants (CO, NOx, (HC) VOCs, and PM) is found in Eq. (2):

$$E_{HOT;i,k,r} = N_{k*} M_{k,r*} e_{HOT;i,k,r} \quad (2)$$

where: $E_{HOT;i,k,r}$= hot exhaust emissions of the pollutant *i [g]*, produced in the period concerned by vehicles of technology k driven on roads of type *r*;
N_k= number of vehicles *[veh]* of technology *k* in operation in the period concerned;
$M_{k,r}$= mileage per vehicle *[km/veh]* driven on roads of type *r* by vehicles of technology *k*;

$e_{HOT;i,k,r}$= emission factor in *[g/km]* for pollutant *i*, relevant for the vehicle technology k, operated on roads of type *r*.

Vehicle speed, which is introduced into the calculation via the different driving modes, has a major influence on exhaust emissions, and to take this into account we are defining mean speed distribution curves $f_{j,k}(V)$ and integrate over the emission curves by using Eq. (3):

$$e_{HOT;i,k,r} = \int \left[e(V) * f_{k,r}(V) \right] dV \quad (3)$$

where:
V = speed of vehicles on the different road classes,
$e(V)$= expression of the speed-dependency of $e_{HOT;i,k,r}$,
$f_{k,r}(V)$= equation (e.g. formula of 'best fit' curve) describing the frequency distribution of the mean speeds which corresponds to the driving patterns of vehicles on road class 'urban'. The term $f_{k,r}(V)$ is a function of vehicle technology *k* and road type *r*.

Finally, the hot emission factor (EF) which is speed dependent and differs by fuel, vehicle class and engine technology can be calculated using Eq. (4). The reduction factor *(RF)* is applied where necessary.

$$EF = \left(Alpha * V^2 + Beta * V + Gamma + Delta / V\right) / \left(Epsilon * V^2 + Zeta * V + Eta\right) * (1 - RF) \quad (4)$$

The Tier 3 emission factors are experimentally calculated and therefore do not reflect a single specific parameter. For non-catalyst gasoline cars, they were developed by the Corinair Working Group (Eggleston et al., 1993), considering the results of comprehensive studies carried out in France, Germany, Greece, Italy, the Netherlands and the United Kingdom. In addition, some data measured in Austria, Sweden and Switzerland were incorporated. For gasoline catalyst-equipped cars, improved diesel cars and diesel heavy-duty vehicles, the emission factors are derived from the results of the Artemis project. Hot emission factors are speed dependent and are expressed in g/km. They differ by fuel, vehicle class and engine technology. A number of functions were already provided to calculate hot emission factors (Eqs. 2-3). These functions are now consolidated into a single equation, that is Eq. (4).

2.2. Readily available data

Data on the number of registered passenger cars per year of production (Euro emission standard) and the powertrain technology in use with them, on the territory of Skopje and North Macedonia (Tables 1-2) was primarily obtained using the Law on access to public information from the City of Skopje Mayor's Office and the Ministry of Interior, and data made available through the MakStat online database of the Macedonian Statistical Office.

Table 1. Number of total registered passenger cars per year of production (emission standard) and powertrain technology in North Macedonia

Macedonia				
Emission Standard	***Date of implementation***	***Powertrain technology***		
		Petrol	***Diesel***	***LPG****
Pre EURO	Prior to 1993	3888	2714	/
EURO 1	Approved in July 1992, first registration from 1993	23833	15939	11762
EURO 2	Approved in January 1996, first registration from 1996	23220	32971	/
EURO 3	Approved in January 2000, first registration from 2000	54222	94148	
EURO 4	Approved in January 2005, first registration from 2005	31915	79686	
EURO 5	Approved in September 2009, first registration from 2010	40788	28175	
EURO 6	Approved in September 2014, first registration from 2015	16523	17762	
Total by powertrain technology		194390	271394	11762
TOTAL		477546		

LPG stands for Liquified Petroleum Gas, a fuel gas used as a propellant in internal combustion engines, typically including a mixture of hydrocarbons gasses, but it is mostly propane or butane based.

Table 2. Number of total registered passenger cars per year of production (emission standard) and powertrain technology in Skopje

Skopje				
Emission standard	***Date of implementation***	***Powertrain technology***		
		Petrol	***Diesel***	***LPG***
Pre EURO	Prior to 1993	1632	820	/
EURO 1	Approved in July 1992, first registration from 1993	10006	4818	1773
EURO 2	Approved in January 1996, first registration from 1996	9749	9966	/
EURO 3	Approved in January 2000, first registration from 2000	22766	28458	
EURO 4	Approved in January 2005, first registration from 2005	13400	24086	
EURO 5	Approved in September 2009, first registration from 2010	17125	8516	
EURO 6	Approved in September 2014, first registration from 2015	6938	5369	
Total by powertrain technology		81618	82033	1773
TOTAL		165424		

2.3. Data acquisition setup

Applying the Tier 3 emission coefficients requires using the urban driving characteristics, the share of different fuel types and passenger car fleet age for the city of Skopje, Republic of North Macedonia. In order to determine the emission coefficients, the average speed, which is an input in this problem, is determined according to the instructions given by (Tian et al., 2009). In the absence of a more sophisticated way of measuring the average speed, as well as the city's traffic monitoring systems being inaccessible, this research was based on a video recording of a segment of one of the city's main boulevards that connects Skopje's suburbs to its central (or downtown) area being just 2 km short of the city centre (denoted by Skopje's Main Square). Furthermore, according to data provided by the Mayor's Office and the Ministry of Interior this boulevard acts as one of Skopje's main movement arteries and it gets the largest traffic frequency throughout the day.

The video recording of the traffic, i.e. the recording of a segment of Partizanski Odredi Boulevard in Skopje's Municipality of Karposh and the subsequent analysis of the video material made it possible to find the average speed of passenger cars participating in urban transport on the territory of Skopje. The video recording was carried out using a wide-angle lens camera, which allowed recording all six lanes of the boulevard at the same time, as shown in Fig. 1.

Determining the average speed of passenger cars was based on finding the time in which the vehicles cover a distance of 100 meters defined through two reference points located on the boulevard, as shown in Fig. 2. The results obtained from the video materials were verified using the geolocation systems built into the vehicle's or the owner's smart devices that have the ability to determine and record the speed of movement.

This additional method allowed us to determine the average speed along different roads in the city of Skopje over an observation period of 30 days. The results obtained from these observations point to the fact that the vehicles move at different speeds during the day, having the lowest average speed in the morning and afternoon hours, and the highest average speed was recorded in the evening hours.

Furthermore, we conducted a survey (whose template is attached in Appendix A) that included exactly 243 participants. Since the total number of registered passenger vehicles in the city of Skopje for 2021 equals 165424, this sample size has a sufficiently low margin of error at 6% and a high level of confidence with 95%. The survey was aimed at determining the most common method of transportation used amongst the participants, which straight away overwhelmingly pointed to passenger cars. An additional question of the survey was what is the average daily distance that the participants cover with their cars, with the average value coming around 25 km per day.

Fig. 1. The segment of the Partizanski Odredi Boulevard used to gather traffic data

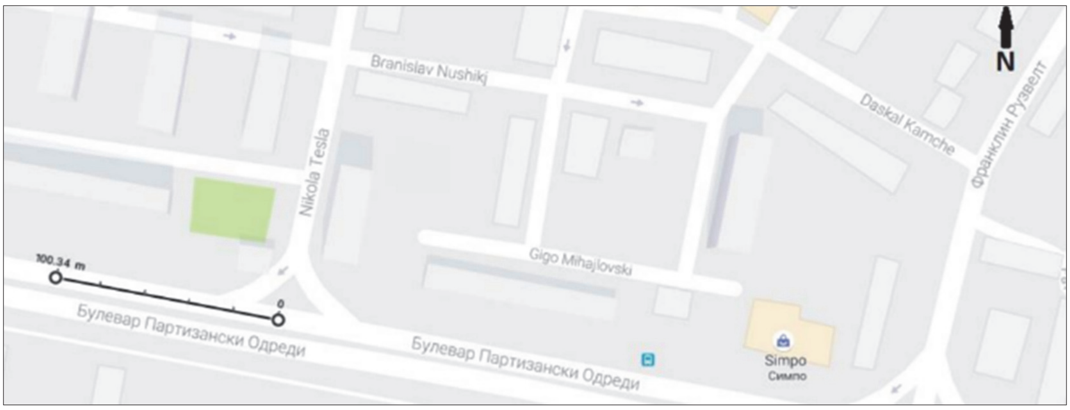

Fig. 2. Reference points along the Partizanski Odredi Boulevard (bottom left)

2.4. Optimization of the Tier 3 methods for Passenger Cars - Length emission coefficient

Passenger cars are the fastest growing category of vehicles in the world, whose share of the total pollution from mobile sources cannot be overlooked in any urban environment. The EEA has developed emission coefficients of passenger cars using different models of urban pollution, and these emission coefficients are divided according to the type of fuel (gasoline, diesel and liquefied petroleum gas - LPG), as well as according to the EURO emission standard, i.e. the year of production.

The observation of traffic in Skopje made it possible to define the average speed of passenger cars. In order to increase the accuracy of the results, three average speeds have been determined grouped by their frequency of occurrence in the analysed data. The average speeds and their frequency of occurrence for passenger cars in Skopje have been provided in Table 3.

Table 3. Average speed and frequency for passenger cars

Average speed	*15 km/h*	*35 km/h*	*55 km/h*
Frequency	1	3	1

Determining the average speeds and their frequency plays a significant role in the optimization of the emission coefficients of polluting substances in urban areas. This means, that the daily distance covered of 25 km covered, reported by the survey participants is covered in a manner, where 5 km are covered at a speed of 15 km/h, 15 km are covered at a speed of 35 km/h and finally, the remaining 5 km are covered at a speed of 55 km/h. However, performing the pollution calculation according to the Tier 3 methods is a long and comprehensive process and using three different average speeds with different frequency of occurrence would complicate the calculations significantly.

Therefore, it is necessary to simplify the procedure, that is, to define emission coefficients that would contain all three different average speeds. It is obvious that passenger cars move mostly at an average speed of 35 km/h, while the other two average speeds have a lower, albeit same frequency. Due to the nature of the equations for determining the coefficients of the emission of polluting substances, we cannot use an arithmetic mean value of the average speeds that will serve as input data in the pollution calculation. Hence the need for the definition of new emission coefficients of polluting substances, which will contain all three average velocities with the corresponding frequencies, and which due to their nature can be called length emission coefficients of pollutants (Eq.5).

$$EF_{length}\left[g/km\right] = 1/5 * emissions_{15\ km/h} + 3/5 * emissions_{35\ km/h} + 1/5 * emissions_{55\ km/h} \quad (5)$$

The length emission coefficient has the same unit as the previous emission coefficients. So, to determine the emission of polluting substances in urban environments that have the same driving characteristics as the analysed city area in Skopje, it will be necessary to multiply the corresponding length emission coefficient by the corresponding distance travelled. The length emission coefficients for passenger cars, for the city of Skopje are provided in Appendix B, C and D.

2.5. Future fleet share of alternative fuels and powertrains in the Western Balkans

Calculating the future urban air pollution footprint of passenger cars in Skopje required a projection on what the number of passenger cars will be in the designated timeframe (2050). This necessitated taking account of multiple criteria to be able to estimate the size of the passenger car fleet as well as its diversification on the account of vehicles driven by alternative fuels and powertrains.

The Global Transport Scenarios 2050 by the World Energy Council (WEC, 2011) state that there are two main directions of development of the automotive industry and hence of the passenger car fleet:

1. According to the Market-driven scenario the global car fleet will still be dominated by an 89% share for the conventional, liquid fuel, internal combustion (IC) Engine-driven vehicles and IC Engine Hybrids while only 6% share is captured by electric, fuel cells, and plug-in vehicles.

2. In the Regulation-driven scenario the global car fleet in 2050 will be very diverse, with shares of 26% for conventional, liquid fuel, IC Engine-driven vehicles (19% petrol and 7% diesel); 26% for liquid hybrids (18% petrol and 8% diesel); 18% plug-in hybrids; 16% battery-electric vehicles; 8% natural gas-driven vehicles; and 6% for others (Fig. 3).

Despite their names, both scenarios consider regulation that will facilitate and possibly speed up the transition of the passenger vehicle fleet such as lower taxation, maintenance discounts and other incentives for plug-in hybrid and battery-electric vehicles, as well as potential bans on the production of IC engine-driven, light passenger vehicles. In fact, such is the ban on new petrol/diesel passenger cars in the European Union by 2035 (Abnett, 2023).

The technology penetration in the Western Balkans however will follow the trend of the powertrain technology mix in the OECD countries (OECD countries stands for member countries of the Organisation for Economic Co-operation and Development) but due to the economic gap, the vehicle technology will be delayed by at least 5 to 10 years (OECD, 2021). This means that in 2050, the Western Balkans powertrain technology mix for passenger vehicles will likely be similar to the OECD powertrain technology mix in 2040.

Additionally, this paper also makes note of the insights from the Exxon Mobil Outlook for Energy 2014 (Exxon Mobil, 2014) which recently have been confirmed with newer energy data such as the one from BP's Energy Outlook (BP, 2023). These documents stress that the number of vehicles will grow as the income (GDP per capita) rises in a country. Furthermore, the results from the national censuses conducted in the period of 1948 to 2021 in North Macedonia (MakStat, 2002; MakStat, 2021a) which report a distinct negative population growth, were calculated into the projection, since this tendency will reflect the number of passenger vehicles in 2050.

According to (Dimitrovski et al, 2022) the number of passenger vehicles per 1000 inhabitants in North Macedonia for 2020 was 194, or a total of 403 316. Based on the assumed growth of the GDP as reported by the National Statistics Office and the 2021 Census results (MakStat, 2021b), the number of vehicles in North Macedonia in 2050 will follow a growth of 69.1% compared to 2020 and rise to 1 039 474. Finally, making out the number of passenger vehicles in Skopje in the same timeframe is just a matter of a simple fraction Equation.

3. Results and discussion

3.1. Results

Using the Optimized Tier 3 methodology updated with the use of the length emission coefficients for pollution from passenger cars which themselves are based on an analysis of the urban traffic characteristics of the city of Skopje, we were able to calculate the daily, monthly and yearly amount of pollutants that end up in Skopje's ambient air (Tables 5-7, respectively). When it comes to the monthly quantity of emissions, they were calculated for a 30-day month, but with a 20 % reduction of emissions considering the reduced daily migrations due to the weekends. Similarly, the yearly emissions were calculated as a sum of 365 days, with a reduction of 35 % due to weekends, holidays and annual leave and vacation days.

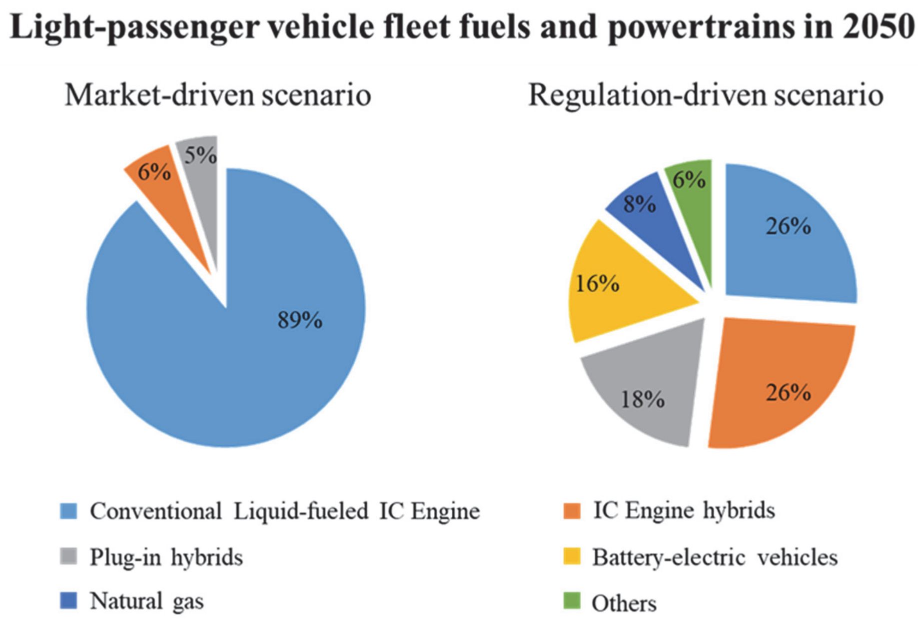

Fig. 3. Projected share of AFPs in the Western Balkans in 2050 according to both scenarios

Table 5. Daily pollutant exhaust emissions from passenger cars in the city of Skopje

	Pollutant	***[g]***	***[kg]***	***[t]***
Daily Exhaust Emissions	CO	5318706.06	5318.70606	5.31870606
	HC (VOC)	291831.6993	291.8316993	0.291831699
	NOx	1743434.373	1743.434373	1.743434373
	PM	1293635.233	1293.635233	1.293635233

Table 6. Monthly pollutant exhaust emissions from passenger cars in the city of Skopje

	Pollutant	***[g]***	***[kg]***	***[t]***
Monthly Exhaust Emissions	CO	111692827.3	111692.8273	111.6928273
	HC (VOC)	6128465.686	6128.465686	6.128465686
	NOx	36612121.82	36612.12182	36.61212182
	PM	27166339.88	27166.33988	27.16633988

Table 7. Yearly pollutant exhaust emissions from passenger cars in the city of Skopje

	Pollutant	***[g]***	***[kg]***	***[t]***
Yearly Exhaust Emissions	CO	1261863013	1261863.013	1261.863013
	HC (VOC)	69237070.66	69237.07066	69.23707066
	NOx	413629804.9	413629.8049	413.6298049
	PM	306914958.9	306914.9589	306.9149589

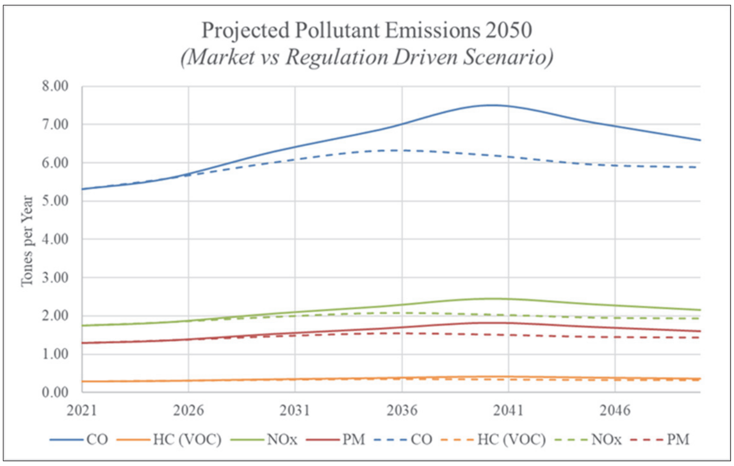

Fig. 4. Projected passenger car fleet yearly pollutant emissions 2020-2050 for the city of Skopje

The future, urban air pollution footprint of passenger cars for the city of Skopje was calculated based on multiple factors: the increase of the passenger car fleet, the fleet's share of alternative fuels and powertrains and the renewal trends of the existing passenger car fleet. Additionally, today's conventional ICE driven passenger car on average consumes 8 liters of fuel per 100 km of distance (BP, 2023) of urban driving. By implementing advanced fuel combustion technologies, parameter control, dual fuel technology and traffic optimization, this value could be lowered by as much as 40 % (Dimitrovski et al., 2022). Better catalytic and exhaust filtering solutions demanded by the implementation of the Euro 7 emissions standard starting in 2025 will also lead to exhaust emissions following this reduction trend. However, due to improvement of the economic status of the ordinary consumer, the daily mileage covered will increase by 30 % (Dimitrovski et al., 2022).

With this in mind and taking into account both the market-driven and the regulation-driven scenario, an emission reduction percentage was defined for 2050 (Fig. 4). The results show that in the Market-driven scenario (Fig. 4 - full line) the increase of the passenger car fleet and the small share of fully electric vehicles (with no local pollutants) will make for an increase of the total amount of exhaust pollutant emissions of 23.9 % compared to their levels in 2021. On the other hand, the Regulation-driven scenario (Fig. 4. - dashed line) is inclined toward a larger number of electric vehicles, and therefore, despite the increase of the annual mileage and the significant increase of the passenger car fleet, the amount of total exhaust pollutant emissions will only increase 11 %.

This disparity of the growth is a consequence of the improved fuel-metering and emissions reduction technologies in use with IC engine powered vehicles and the greater share of partially and fully electric vehicles as part of the passenger car fleet in the Western Balkans.

3.2. Discussion

Deriving suitable and precise scenarios is vital in creating efficient and real-world applicable policies that could potentially lead to decreasing the emission of pollutants from mobile sources, which will also decrease the overall pollutant concentration and increase the urban air quality. Along that line of thought, this paper provides a very significant input on the air pollution footprint of passenger cars in the city of Skopje as the largest contributor to the exhaust emissions quantity found in Skopje's ambient air.

To prove the accuracy of the new model, it was verified using annual emissions data from the National Road Transport Emission Inventory (UNDP, 2018) which in turn relies on the COPERT tool, a software used world-wide to calculate air pollutant and greenhouse gas emissions from road transport, whose development is coordinated by the European Environment Agency. The COPERT methodology is also a part of the EMEP/EEA air pollutant emission inventory guidebook for the calculation of air pollutant emissions. This was supplemented with data from a report funded by the Global Environment Facility (GEF) titled Transport in Skopje - Realities and Challenges (RCESD-MASA, 2017).

The model's results show very similar tendencies to the ones reported. Comparing both values, it was found that they differentiate by 5.4% for the annual CO emissions, 7.60% for the NOx emissions, 12.51% for the VOC emissions and 0.24 %

for the PM emissions. The rise in emissions depicted in the values derived from the model are attributed to the application of the length emission factor.

The approach taken here should foremost act as a strong foundation for the calculation and estimate of the air pollution impact of the remaining categories of mobile sources such as motorcycles, light and heavy-duty commercial vehicles, buses and minibuses. Additionally, although previous research reports on a progressive reduction of the quantity (between successive Euro emission technologies) of IC engine exhaust emissions and shows that regulations set by the European Union have been successful, the non-exhaust emissions are not currently targeted by emissions regulations.

While the quantity of exhaust emissions has been reducing, 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, 2013). Both of these insights will contribute to creating a more complete picture of transport's air pollution impact in an urban setting, and make for an important future research direction.

4. Conclusions

The aim of this paper was to quantify the air pollution impact of passenger cars' exhaust emissions on the ambient air in the city of Skopje. To achieve this, the paper builds on the European Environmental Agency Tiered Methodology for the calculation of the amount of exhaust pollutants from mobile sources and further considers the urban driving characteristics of the city of Skopje.

By using theoretically derived and experimental data which included an observation of Skopje's traffic, we were able to determine the average speed of passenger cars in traffic. This data was supplemented with data derived from a survey that included over 200 participants and allowed us to define the driving habits of Skopje's citizens, which among other things included the average daily distance each of them covers using their own personal passenger car. Both datasets were validated using the geolocation systems built into the vehicle's or the owner's smart devices that have the ability to determine and record the vehicle speed and mileage each vehicle covered on a daily basis.

In order to simplify and add to the accuracy of the EEA's Tier 3 calculation procedure, we defined an emission coefficient that would contain the influence of three different average speeds with three different frequencies of occurrence on the amount of exhaust emissions in Skopje. This length emission coefficient has the same unit as previous emission coefficients and is no longer speed dependent. So, to determine the emission of polluting substances in urban environments that have the same driving characteristics as the analyzed city area in Skopje, it will just be necessary to multiply the corresponding length emission coefficient by the corresponding distance traveled.

Finally, using readily available data on the number of registered passenger cars per year of production and the powertrain technology in use with them, on the territory of Skopje obtained primarily through the MakStat online database of the Macedonian Statistical Office and the newly defined length emission coefficients we calculated the daily, monthly and yearly quantity of pollutants that end up in Skopje's ambient air.

To complement these findings, the paper also includes a projection on the amount of emissions in 2050 that relies on a future mobility development scenario that takes account of the share of different alternative fuels and powertrains in passenger cars in 2050, the advancement in fuel metering, combustion, and emission reduction technologies, and the increase in the daily mileage of car users. Therefore, using the novel approach to estimate passenger cars' urban exhaust emissions, optimizes EEA's Tier 3 method through the introduction of a length emissions coefficient which significantly reduces the input requirements for a successful estimate. At the same time, this simplifies the process and increases the accuracy of the results which hopefully could lead to devising better and more suitable policies that could lead to decreasing the emission of pollutants from mobile sources in the urban cores of the Western Balkans.

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Appendix A. Survey template

URBAN TRANSPORT AS A SOURCE OF AIR POLLUTION IN THE CITY OF SKOPJE
(This survey is conducted as part of a research for the preparation of a Master thesis)

1. What mode of motorized transportation do you use on your ride to work? (Check the one most frequented)
   a. Passenger car
   b. Motorbike
   c. Public bus
   d. Taxi

(if you answered **a. passenger car** please continue with the following questions)

2. What year of production is your car?
   ____
3. What is the engine size (displacement)?
   ____
4. What type of fuel does your car use?
   ____
5. On average, what daily distance would you say you cover using your car?
   ____

Thank you for your time!

Appendix B. Length emission coefficient for petrol engine driven passenger cars

Vehicle type	*Fuel*	*Emission standard*	*Pollutant*	*EF_{length} [g/km]*	*Emission [g/km] at 15 km/h*	*Emission [g/km] at 25 km/h*	*Emission [g/km] at 55 km/h*
Passenger car	Petrol	Pre EURO	CO	32.6569	51.0233	29.9188	22.5049
Passenger car	Petrol	Pre EURO	HC (VOC)	2.8558	4.6450	2.5821	1.8877
Passenger car	Petrol	Pre EURO	NOx	1.7666	1.4790	1.7890	1.9870
Passenger car	Petrol	Euro 1	CO	11.0000	9.6440	10.7757	13.0290
Passenger car	Petrol	Euro 1	HC (VOC)	0.2196	0.3689	0.1962	0.1407
Passenger car	Petrol	Euro 1	NOx	0.3046	0.3961	0.2897	0.2581
Passenger car	Petrol	Euro 1	PM	0.0032	0.0032	0.0032	0.0032
Passenger car	Petrol	Euro 2	CO	0.8039	1.3118	0.7083	0.5829
Passenger car	Petrol	Euro 2	HC (VOC)	0.0930	0.1724	0.0792	0.0551
Passenger car	Petrol	Euro 2	NOx	0.1756	0.2395	0.1651	0.1433
Passenger car	Petrol	Euro 2	PM	0.0032	0.0032	0.0032	0.0032
Passenger car	Petrol	Euro 3	CO	0.5203	0.5097	0.5028	0.5833
Passenger car	Petrol	Euro 3	HC (VOC)	0.0178	0.0279	0.0159	0.0135
Passenger car	Petrol	Euro 3	NOx	0.0782	0.0872	0.0784	0.0684
Passenger car	Petrol	Euro 3	PM	0.0013	0.0013	0.0013	0.0013
Passenger car	Petrol	Euro 4	CO	0.1878	0.1533	0.1847	0.2317
Passenger car	Petrol	Euro 4	HC (VOC)	0.0118	0.0115	0.0117	0.0126
Passenger car	Petrol	Euro 4	NOx	0.0605	0.0839	0.0594	0.0406
Passenger car	Petrol	Euro 4	PM	0.0013	0.0013	0.0013	0.0013
Passenger car	Petrol	Euro 5	CO	0.2514	0.2396	0.2457	0.2804
Passenger car	Petrol	Euro 5	HC (VOC)	0.0067	0.0086	0.0064	0.0056
Passenger car	Petrol	Euro 5	NOx	0.0316	0.0436	0.0305	0.0230
Passenger car	Petrol	Euro 5	PM	0.0016	0.0020	0.0015	0.0014
Passenger car	Petrol	Euro 6	CO	0.2465	0.2370	0.2320	0.2997
Passenger car	Petrol	Euro 6	HC (VOC)	0.0068	0.0075	0.0068	0.0062
Passenger car	Petrol	Euro 6	NOx	0.0361	0.0496	0.0350	0.0259
Passenger car	Petrol	Euro 6	PM	0.0016	0.0020	0.0016	0.0014

Appendix C. Length emission coefficient for diesel engine driven passenger cars

Vehicle Type	*Fuel*	*Emission Standard*	*Pollutant*	*EF_length [g/km]*	*Emission [g/km] at 15 km/h*	*Emission [g/km] at 25 km/h*	*Emission [g/km] at 55 km/h*
Passenger car	Diesel	Pre EURO	CO	0.7593	1.1438	0.7033	0.5426
Passenger car	Diesel	Pre EURO	HC	0.1933	0.3645	0.1648	0.1079
Passenger car	Diesel	Pre EURO	NOx; <2	0.5679	0.7307	0.5517	0.4535
Passenger car	Diesel	Pre EURO	NOx; >2	0.8852	1.0909	0.8639	0.7433
Passenger car	Diesel	Pre EURO	PM	0.2293	0.3341	0.2201	0.1525
Passenger car	Diesel	Euro 1	CO	0.4890	0.7385	0.4715	0.2917
Passenger car	Diesel	Euro 1	HC (VOC); <2	0.0621	0.0951	0.0587	0.0389
Passenger car	Diesel	Euro 1	HC (VOC); >2	0.0897	0.1248	0.0877	0.0603
Passenger car	Diesel	Euro 1	NOx	0.7019	1.0335	0.6394	0.5581
Passenger car	Diesel	Euro 1	PM	10.2098	10.2301	10.2061	10.2002
Passenger car	Diesel	Euro 2	CO	0.4125	0.6587	0.3984	0.2083
Passenger car	Diesel	Euro 2	HC (VOC); <2	0.0423	0.0703	0.0385	0.0258
Passenger car	Diesel	Euro 2	HC (VOC); >2	0.1199	0.1986	0.1090	0.0739
Passenger car	Diesel	Euro 2	NOx	0.7539	1.1055	0.6969	0.5734
Passenger car	Diesel	Euro 2	PM	0.0516	0.0677	0.0499	0.0406
Passenger car	Diesel	Euro 3	CO	0.1216	0.2013	0.1135	0.0662
Passenger car	Diesel	Euro 3	HC (VOC); <2	0.0222	0.0369	0.0200	0.0138
Passenger car	Diesel	Euro 3	HC (VOC); >2	0.0448	0.0680	0.0434	0.0258
Passenger car	Diesel	Euro 3	NOx	0.7849	1.0195	0.7436	0.6741
Passenger car	Diesel	Euro 3	PM	0.0319	0.0401	0.0306	0.0277
Passenger car	Diesel	Euro 4	CO	0.1152	0.2234	0.1005	0.0509
Passenger car	Diesel	Euro 4	HC (VOC)	0.0081	0.0157	0.0067	0.0046
Passenger car	Diesel	Euro 4	NOx	0.6080	0.8403	0.5843	0.4467
Passenger car	Diesel	Euro 4	PM	0.0310	0.0377	0.0304	0.0259
Passenger car	Diesel	Euro 5	CO	0.1152	0.2234	0.1005	0.0509
Passenger car	Diesel	Euro 5	HC (VOC)	0.0081	0.0157	0.0067	0.0046
Passenger car	Diesel	Euro 5	NOx	0.7478	1.0336	0.7187	0.5494
Passenger car	Diesel	Euro 5	PM	0.0015	0.0019	0.0015	0.0013
Passenger car	Diesel	Euro 6	CO	0.0590	0.0738	0.0579	0.0475
Passenger car	Diesel	Euro 6	HC (VOC)	0.0113	0.0178	0.0104	0.0074
Passenger car	Diesel	Euro 6	NOx	0.2261	0.2936	0.2202	0.1763
Passenger car	Diesel	Euro 6	PM	0.0020	0.0032	0.0018	0.0014

Appendix D. Length emission coefficient for LPG fueled passenger cars

Vehicle type	*Fuel*	*Emission standard*	*Pollutant*	*EF_length [g/km]*	*Emission [g/km] at 15 km/h*	*Emission [g/km] at 25 km/h*	*Emission [g/km] at 55 km/h*
Passenger car	LPG	Euro 1 & >	CO	1.6558	2.7098	1.4798	1.1298
Passenger car	LPG	Euro 1 & >	NOx	0.3627	0.4423	0.3563	0.3023
Passenger car	LPG	Euro 1 & >	HC (VOC)	0.3006	0.5166	0.2846	0.1326