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Assessment of Methods for Determining Vehicle Emission Characteristics

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This paper presents an analysis of pollutant emissions (carbon monoxide, hydrocarbons, nitrogen oxides, methane, non-methane volatile organic compounds and carbon dioxide) from a passenger car, particularly under real-world driving conditions, to more accurately model the impact of transport on the environment. These pollutants were selected due to their regulatory relevance and significant environmental and health impacts. A mathematical model developed in this study was used to estimate emissions, with vehicle speed identified as a key parameter influencing emission levels. Various speed ranges and their impact on emission levels were considered during parametric identification. Since the relationship between pollutants and speed is nonlinear, the least squares method was applied to estimate model parameters for the different pollutants. The model developed in the paper allows for precise emission prediction for various vehicle use scenarios. The scenarios analyzed include urban driving conditions with vehicle speeds not exceeding 60 km/h. The selected speed profile was first recorded in real-world traffic using a portable emissions measurement system (PEMS) and subsequently reproduced on a chassis dynamometer to ensure test repeatability under controlled laboratory conditions.

Keywords: pollutant emissions; emission modeling; road emissions; parametric estimation.

1. Introduction

The contemporary development of road transport and the growing number of vehicles on the road significantly affect air quality and climate. Research on pollutant emissions from combustion engines and their actual fuel consumption is gaining importance due stricter air quality regulations and the intensified use of vehicles in road transport [8, 11, 14, 26]. The term "emission characteristics" refers to the relationship between engine operating conditions and the amount of pollutants emitted. Understanding these emission characteristics is especially crucial for harmful substances released during driving, such as nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbons (HC). These emissions negatively impact the environment and public health, especially in large cities, where high vehicle concentrations and traffic congestion result in increased emissions due to longer travel times and lower average speeds [2, 3, 27].

Many decision-making bodies responsible for the state of our environment would like to receive instant data indicating actual pollutant emissions from combustion engines and fuel consumption; however, obtaining such data is challenging [5, 13]. One approach to improving the accuracy of emission measurements is to conduct driving tests simulating real routes or based on statistically determined traffic profiles. Alternatively, synthetic driving tests (i.e., laboratory-based chassis dynamometer tests or statistically reconstructed drive cycles) can be used. These methods account for the representativeness of different traffic conditions, allowing for the parameterization of tests and better adjustment to a vehicle's maximum speed and efficiency. In addition, mobile measurement systems (PEMS) and algorithms analyzing emissions based on real road traffic data are being increasingly used, enabling the calibration of emission models while considering variable factors.

Combustion engines show high sensitivity of their properties to their operating states, both static and dynamic states. Testing combustion engines solely utilizing an engine dynamometer do not provide a complete picture of emissions under real-world conditions, especially during transient engine operation. Measurements taken on a dynamometer are insufficient for analyzing pollutant emissions and fuel consumption in actual operating conditions of use [4]. This limitation has led to the dynamic worldwide growth of so-called driving tests, which simulate real operating conditions. In order to bring measurement conditions closer to reality, tests have been developed that replicate selected segments of actual speed profiles recorded over time, as confirmed by both previous studies and new research. In this study, a real-world speed profile was recorded during an actual urban drive using a PEMS device and then reproduced on a chassis dynamometer, allowing for precise and repeatable measurements under standardized conditions. Additionally, synthetic tests have been created to statistically reflect speed and acceleration patterns typical of specific vehicle use conditions [6, 19, 22].

Thanks to advanced measurement tools and statistical methods, it is possible to create comprehensive emission models that support regulatory processes and the development of technologies aimed at reducing the impact of transport on air quality [7, 13, 16, 25].

Developing and improving existing emission models (such as COPERT [17] or HBEFA [10]) to better account for real engine operating conditions is one of the main challenges. Traditional homologation and laboratory tests do not provide a complete picture of pollutant emissions under the dynamic conditions of real vehicle use. In particular, the lack of correlation between a single test and all the different road conditions highlights the need for more advanced methods that consider the variability of parameters such as speed, load and environmental conditions during operation.

Therefore, emission models that accurately reflect real vehicle use conditions and enable adaptation to different operating scenarios are essential [9, 18, 28]. In recent years, technologies such as advanced computer models, PEMS, and real-world driving tests have allowed for better calibration and verification of emission models. Developing accurate emission models is a key solution that enables governments and organizations to implement effective emission regulations and standards, supporting decision-making processes in sustainable transport development [9, 19, 28].

By continually improving emission measurement tools and developing new modeling techniques, it becomes possible to predict emissions more accurately based on driving style, road type, and weather conditions. In this way, research in this area contributes to a better understanding of the environmental impact of transport emissions and helps design more effective reduction policies that promote public health and align with sustainable development goals.

Therefore, despite numerous studies on pollutant emissions from combustion engines and progress in this field over recent decades, there are still many challenges inaccurately determining actual emissions under real vehicle operating conditions. As rightly noted in [1, 3, 6, 7, 12, 22, 25], while engine dynamometer tests provide valuable information, they do not fully reflect the complexity of processes occurring during real driving. Variations in engine load, speed, temperature and other factors influencing combustion process mean that laboratory test results may significantly differ from actual emissions. Understanding the impact of road transport on air quality and searching for effective methods to reduce pollutant emissions remain some of the most important challenges in modern science and policy. Accurate assessment of vehicle emission characteristics is crucial for developing effective regulations, new technologies, and improving air quality modeling.

The aim of this article was to identify the dependence of road emissions on vehicle speed under real operating conditions, with the goal of improving the accuracy of models assessing the impact of cars on the natural environment. An innovative aspect of the research was finding the scale of emission values based on engine operating parameters derived from real road traffic data. This approach made it possible to precisely represent dynamic variables, such as speed and engine load, significantly increasing the representativeness and accuracy of emission analysis.

The research presented in this paper introduced a novel method for identifying the synthesis dependence of reference emission tests, which allows for better alignment of laboratory conditions with actual road conditions. The variability of conditions in driving tests provided a realistic reflection of a wide range of operating conditions, enabling more accurate emission prediction and optimization of test methodologies.

The novelty of this study lies in the development of an emission prediction model based solely on vehicle speed, enabling simplified yet effective urban emission assessments.

2. Research problem

Introducing test scenarios that simulate driving conditions helps ensure representativeness of emission measurements. The valuable performance properties of an engine depend not only on its operating state, but also on the course of this state [3, 5, 13, 20, 24]. Therefore, the ecological properties of motor vehicle engines under dynamic conditions may differ from those observed under static conditions [3, 5, 13, 24]. Road emissions depend on the engine's operating state curves, which can be described by parameters such as engine load (e.g., torque), rotational speed, the engine's thermal state vector, and a vector containing information on ambient conditions [3, 5, 13, 24].

The engine operating conditions depend, among others, on vehicle speed, motion resistance, vehicle weight, gear ratios in the drivetrain, the dynamic radius of the drive wheels, and overall vehicle and engine design. The speed profile (i.e., time-dependent speed variation) is a decisive factor affecting emissions of substances, especially given the significant standardization of vehicle construction in comparable vehicle categories [3, 5, 13, 24].

A fundamental measure characterizing the ecological properties of vehicles is the road emission of pollutants, defined as the mass of pollutants emitted per distance traveled by the vehicle [13, 24]. The road emission of pollutants from a vehicle, treated as a dynamic value, depends on the engine's operating processes. As mentioned, the operating state of a combustion engine during traction operation depends on, among others, vehicle speed, motion resistance, and vehicle-specific parameters, including the gear ratios in the drivetrain [3, 5, 13, 24].

For a constant thermal state of the engine and comparable traffic conditions, considering the advanced structural standardization of motor vehicles, the factor determining the emission of pollutants is the vehicle speed [3, 5, 13, 24].

Therefore, the emission of road pollutants strictly depends on the specific profile of vehicle speed. To create a more general understanding of pollutant emissions in relation to varying speed profiles for which the emission is determined, it is necessary to characterize these speed profiles.

Homologation tests are particular cases of vehicle operation. However, actual operating conditions may differ significantly from those defined in homologation procedures.

2.1. Description of the methodology

The dependence of average road pollutant emission on speed is characterized by a uniform distribution of data points corresponding to individual pseudorandom experiments, representing both average speed and average pollutant emission. It is possible to approximate the relationship between pollutant emissions and vehicle speed. Determining these relationships and taking into account their structural parameters enables the identification of road emissions generated while driving a car with an internal combustion engine [3, 5, 13, 24, 25].

Therefore, this study used the vehicle speed data recorded under urban conditions, where the vehicle speed did not exceed 60 km/h. Although the legal urban speed limit in Poland is 50 km/h, a higher limit of 60 km/h was applied for technical reasons and to reflect the realistic urban driving variability (e.g., during acceleration or downhill movement).

A passenger car equipped with a spark-ignition engine with a displacement of 1798 cm^3 was used for the tests (Fig. 1). The measurements were performed using the Semtech DS research equipment. Figure 2 shows the mounting setup of the emission analyzer from Sensors Inc., type Semtech DS, designed for measuring emissions under real road traffic. The Semtech DS includes a gas analyzer, a set of flow meters for exhaust gases, and integrated GPS tracking to correlate vehicle speed with emission data. The system is designed for in-situ testing during real-world driving conditions and complies with current standards

Fig. 1. Test vehicle equipped with Semtech DS testing equipment.

for on-road vehicle emission testing. The set of flow meters in the device enable measurement of exhaust emissions from most engines that power motor vehicles.

Although the measurement setup resembles chassis dynamometer equipment, all tests were conducted in real-world urban traffic using a PEMS.

The recorded vehicle velocity over time is shown in Fig. 2.

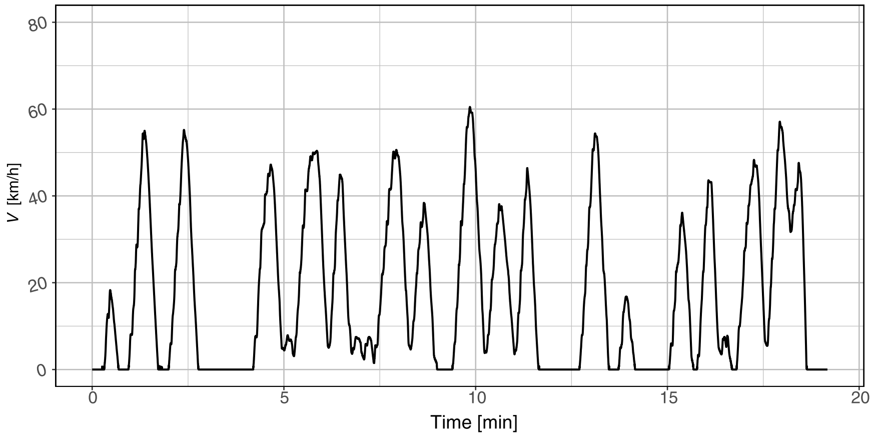

FIG. 2. Speed profile of the tested car over time.

2.2. Dependence of road emissions on speed

Based on the readings from the analyzer, measurements were taken for pollutants including CO, HC, CH_4, NMHC, NO_x, NO, and CO_2. For each type of pollutant, the data set analyzed was $D = \{(v_t, x_t) : 1 \leq t \leq n, v_t \geq 2\}$, where v_t represents the vehicle speed at time t, and x_t is the pollutant emission rate at that time, with $1 \leq t \leq n$. The study investigates the relationship between pollutant emissions and vehicle speed. Only readings where the vehicle speed exceeded 1 km/h ($v_t > 1$) were used in the analysis. Data obtained from the measuring equipment are expressed in grams per second [g/s]. Then, for each pollutant at time t the road emission rate expressed in grams per kilometer [g/km] was determined using the formula:

$$y_t = \frac{x_t}{v_t} 3600,$$

for $1 \leq t \leq n$.

The relationship between road emissions y and speed v is presented as:

$$y = \alpha_0 + \alpha_1 v + \alpha_2 \left(\frac{v}{\alpha_3}\right)^{\alpha_4 - 1} e^{-\left(\frac{v}{\alpha_3}\right)^{\alpha_4}} + \varepsilon, \tag{2.1}$$

where ε is a random variable with a normal distribution $N\left(0,\sigma^2\right)$. In Eq. (2.1), the component $\alpha_0+\alpha_1 v$ represents the scale of pollutant emissions associated with higher vehicle speed (having smaller effect at lower speeds), while the component $\alpha_2\left(\frac{v}{\alpha_3}\right)^{\alpha_4-1}e^{-\left(\frac{v}{\alpha_3}\right)^{\alpha_4}}$ represents the scale of pollutant emissions associated with lower vehicle speed (having smaller effect at higher speeds). The parameter α_2 is responsible for controlling the scale of pollutant emissions generated by the vehicle, whereas parameters α_3 and α_3 govern the scale and shape of the impact of speed on the pollutant emission curve (they are mainly responsible for emission decrease with increasing speed) [21, 23].

Based on the sequence $\{(y_t,v_t)\}_{1\le t\le n}$ the structural parameter $\alpha=(\alpha_0,\alpha_1,\alpha_2,\alpha_3,\alpha_4)$ were estimated by solving the following optimization problem:

$$\min_{\alpha\in S}F(\alpha), \tag{2.2}$$

where the objective function is given by the formula:

$$F(\alpha)=\sum_{t=1}^{n}\left(y_t-\alpha_0-\alpha_1 v_t-\alpha_2\left(\frac{v_t}{\alpha_3}\right)^{\alpha_4-1}e^{-\left(\frac{v_t}{\alpha_3}\right)^{\alpha_4}}\right)^2, \tag{2.3}$$

and the set of acceptable solutions is

$$S=\left\{(\alpha_0,\alpha_1,\alpha_2,\alpha_3,\alpha_4)\in\mathbb{R}^5:\alpha_0,\alpha_1,\alpha_2,\alpha_3\ge 0,\ 0<\alpha_4<1\right\}.$$

To solve the task (2.2), we use the Newton–Raphson algorithm [2, 15]. At iteration step $k+1$, the values of the parameter estimates are calculated using the following formula:

$$\alpha(k+1)=\alpha(k)-H_F^{-1}\left(\alpha(k)\right)\nabla F\left(\alpha(k)\right), \tag{2.4}$$

where $\alpha(k)=(\alpha_0(k),\alpha_1(k),\alpha_2(k),\alpha_3(k),\alpha_4(k))$, $\nabla F(\alpha)$ and $H_F(\alpha)$ denote the gradient and Hessian of the objective function (2.3), respectively.

3. Data analysis

An innovative aspect of this research is the development of a road emission dependence model that considers only vehicle speed as the key parameter. Such a model allows for a more straightforward and computationally efficient approach to emission analysis while maintaining good representativeness of the results. The model's structural parameters (2.1), describing the dependence of road emission on vehicle speed, were estimated using the least squares method. The research was conducted under real operating conditions. Table 1 presents

TABLE 1. Structural parameter values α_0, α_1, α_2, α_3, α_4 and standard deviation σ_ε of residuals for different pollutants.

	α_0	α_1	α_2	α_3	α_4	σ_ε
CO	5.5916	0.0512	14.1624	11.0376	$7.247 \cdot 10^{-4}$	4.13
HC	0.4696	0.0183	3.3673	13.3436	$7.825 \cdot 10^{-6}$	0.4606
CH_4	0.0139	0.0023	0.3218	14.7657	0.0039	0.0485
NMHC	0.4472	0.0158	2.9497	13.3813	$5.876 \cdot 10^{-6}$	0.42
NO_x		0.0115	1.8097	2.2878	0.872	0.1259
NO		0.0264	4.3705	2.1984	0.8459	0.2844
CO_2	140.8901	0.0135	423.9039	14.7496	$6.585 \cdot 10^{-8}$	41.7618

the values of the parameters of the structural model (2.1) and the standard deviations of the residuals. The parameters presented in Table 1 indicate the variability in emission characteristics depending on the type of pollutants. This dependence emphasizes the need for adopting an individualized modeling approach for each emission component when assessing their environmental impact.

The dependence of road emissions on speed obtained in this way, along with the fitted trend curves, is presented in Figs. 3–9.

Figure 3 shows the apparent effect of vehicle speed on carbon monoxide (CO) emissions. At low speeds, emissions are high, which can be attributed to incomplete fuel combustion during idling or frequent braking and acceleration. As speed increases, CO emissions drop significantly, reaching their lowest levels in the 30–50 km/h range, indicating more efficient combustion.

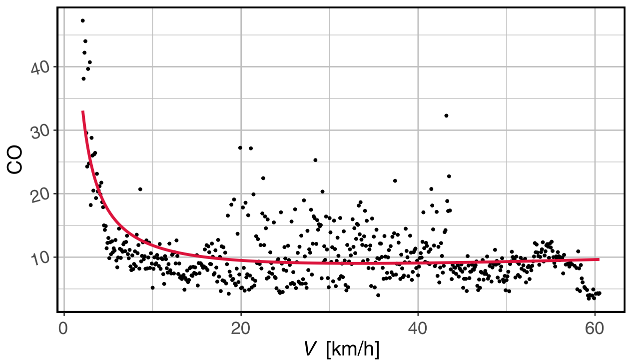

FIG. 3. Road emission values and trend function fit for CO.

Figure 4 shows hydrocarbon (HC) emissions as a function of speed. Similar to CO, HC emissions are high at lower speeds and decrease between 20 and 40 km/h, suggesting that engines operate more efficiently within this speed range.

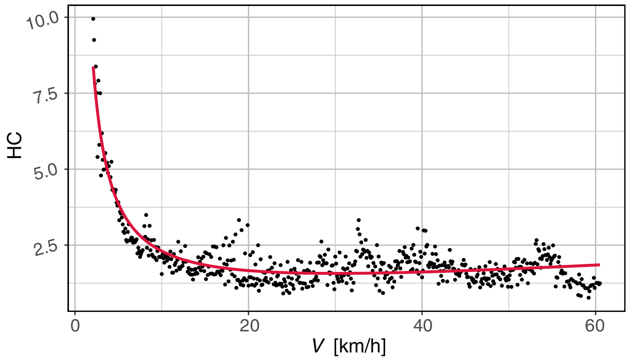

FIG. 4. Road emission values and trend function fit for HC.

Figure 5 shows methane (CH_4) emissions, which remain low between 20 and 40 km/h. Emissions are stable and minimal in this speed range, indicating optimal engine operating conditions for CH_4 reduction in this range.

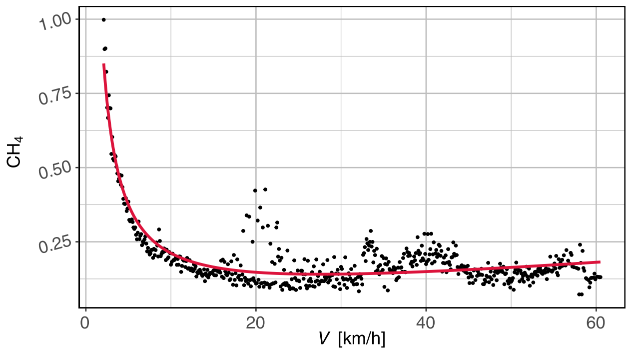

FIG. 5. Road emission values and trend function fit for CH_4.

Figure 6 illustrates the emissions of non-methane hydrocarbons (NMHC), which exhibit a decreasing trend as speed increase. The lowest emissions were

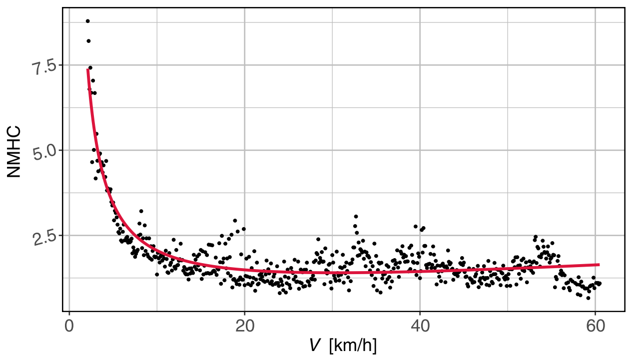

FIG. 6. Road emission values and trend function fit for NMHC.

recorded in the range of 20–50 km/h, highlighting the importance of smooth driving in minimizing NMHC emissions.

Figure 7 shows nitrogen oxide (NO_x) emissions, which show an increase at higher speeds due to higher combustion temperatures. The lowest NO_x emission values are observed at speeds below 30 km/h.

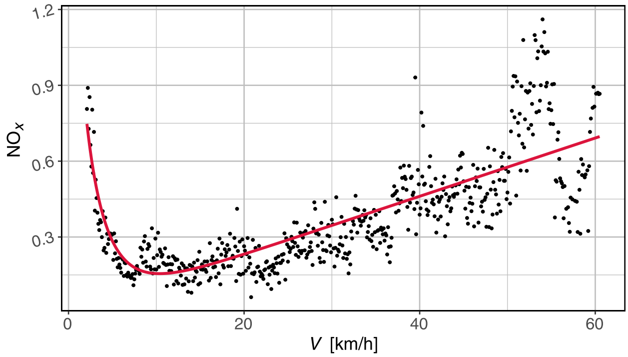

FIG. 7. Road emission values and trend function fit for NO_x.

Figure 8 shows nitrogen oxide (NO) emissions, which, like NO_x, increase with speed, reaching higher values above 50 km/h. This is due to more intensive combustion processes at high engine loads.

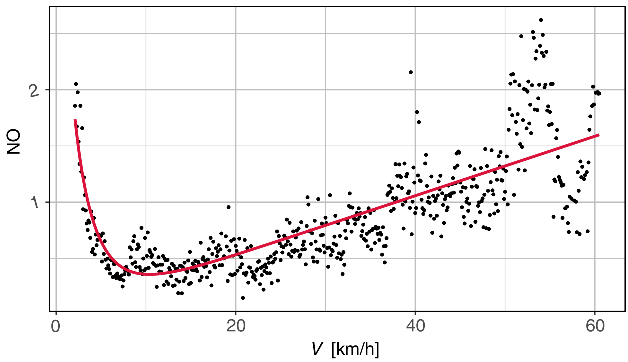

FIG. 8. Road emission values and trend function fit for NO.

Figure 9 shows carbon dioxide (CO_2) emissions as a function of speed. Unlike other pollutants, CO_2 emissions increase with increasing speed, reaching a maximum at the highest speeds, which is logical due to higher fuel consumption.

Figures 3–9 clearly show that the optimal speed range for minimizing the emissions of many pollutants lies between 20–40 km/h. They also indicate the variation in emission release depending on the chemical compound type and the dynamics of engine operation dynamics. These results provide a the basis for de-

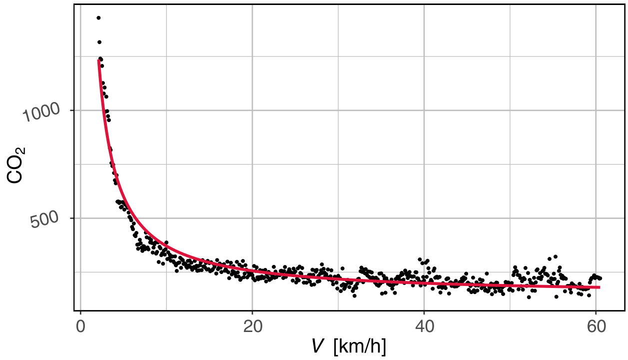

Fig. 9. Road emission values and trend function fit for CO_2.

veloping more effective emission reduction strategies in both urban and highway traffic contexts.

4. Conclusions

Based on the literature review presented in the introduction, it can be concluded that while laboratory tests of combustion engines provide valuable information, they are insufficient to fully understand vehicle emissions under real-world operating conditions. Therefore, increased emphasis is given to driving tests, which better simulate real-world vehicle operating conditions.

Homologation tests do not reflect all variables, such as speed fluctuations, engine load variations or changing environmental conditions, encountered during real-world driving. Research indicates the need for more flexible measurement methods that consider the dynamic operating states of vehicles and various usage scenarios.

Our research confirms that vehicle speed has a significant impact on the volume of road emissions. The conclusions from the presented studies show that, based on emission intensity readings from the analyzer and vehicle speed measurements, the dependence of road emissions on vehicle speed can be established. Thanks to this, it is possible to determine emissions for specific conditions and to predict them for future scenarios.

The model's structural parameters for each pollutant were estimated using the least squares method. The model presented in this paper allowed us to determine the dependence of road emissions on vehicle speed in urban driving conditions.

A innovative element of the research is the development of a road emission model based solely on vehicle speed as a key parameter. This approach simplifies and increases the efficiency of computational emission analysis while maintaining high reliability of results. The structural parameters obtained in this study depend on the type of pollutants, which indicates the need for an individualized approach to modeling and assessing specific emission components in terms of their impact on environment.

However, to increase the accuracy of the model in the future, it is planned to incorporate additional variables, such as vehicle acceleration, engine speed, as well as readings of other parameters, such as system temperature and engine torque. Including these factors will enable a more precise representation of real-world operating conditions and an even better prediction of emissions in different vehicle use scenarios. Such expansion will also allow for the calibration of models in a wide range of driving dynamics, from stop-and-go urban driving to smooth motorway traffic.

In addition, the study results highlight the benefits of using real-world tests, particularly during driving in urban conditions, to better reflect actual operating conditions. These tests enable a realistic representation of the impact of driving dynamics and urban traffic conditions on emissions, factors that are difficult to replicate in laboratory conditions. Variables related to vehicle frequent stops and accelerations play a significant role and generate a significant share of emissions in urban conditions.

In developing forecasting models and tools to support environmental policy decisions, the presented studies make an important contribution to the calibration of emission models such as COPERT and HBEFA. They also enable more precise emission forecasting across various operational scenarios, which is crucial for developing effective regulations.

In summary, the research confirms the need to continue developing dynamic measurement and modeling methods that consider the actual conditions of vehicle usage. Advanced tools, such PEMS or data analysis algorithms allow for further improvements of emission models and enhance their representativeness in the context of actual operating conditions. At the same time, the planned integration of the model with additional variables and readings of dynamic vehicle operating parameters is a promising direction for further research, contributing to more precise estimation of the environmental impact of road transport.

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