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EMISSION CHARACTERISTICS OF A PASSENGER CAR SPARK-IGNITION ENGINE DETERMINED FROM REAL DRIVING EMISSIONS TEST

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Abstract

This paper presents a method for determining characteristics of exhaust emission from a passenger car engine on the basis of empirical research outcomes from the Real Driving Emissions test, i.e. under real-world driving conditions. The emission characteristics were described as the relationship between specific distance pollutant emissions (carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide) and the number of road particulate matter particles as a function of the vehicle's average velocity. Mass specific distance fuel consumption was also examined. Specific distance emissions, the particulate matter number and mass road fuel consumption were defined as their derivatives in relation to vehicle's travelled distance. The determination of the characteristics was carried out using Monte Carlo simulations, i.e. under random conditions based on empirical research results from actual vehicle operating conditions. The determined characteristics demonstrate significant regularity and can be used for simulation analyses of emissions under various driving conditions.

Keywords: emission characteristics, pollutant emission, spark-ignition engine, passenger car, Real Driving Emissions, Monte Carlo Method

List of Symbols/Acronyms

AV – average value
ARTEMIS – Assessment and Reliability of Transport Emission Models and Inventory Systems
b – specific distance emission
CO – carbon monoxide
CO_2 – carbon dioxide
COPERT – Calculations of Emissions from Road Transport
E – intensity of pollutant emission (of particulate number)
HBEFA – The Handbook Emission Factors for Road Transport, INFRAS AG
M_{er} – relative engine torque
MZA – Miejskie Zakłady Autobusowe w Warszawie (Warsaw City Bus Company)
n – engine speed
N_{er} – relative engine power
NOx – nitrogen oxides
PN – particulate number
q – intensity of fuel mass consumption
Q – specific distance fuel mass consumption
RDE – Real Driving Emissions
SORT – Standardised On-Road Tests Cycles
UITP – Union Internationale des Transports Publics
v – velocity
WLTC – Worldwide Harmonized Light Vehicle Test Cycle
WLTP – Worldwide Harmonized Light Vehicle Test Procedure.

1. INTRODUCTION

The functional properties of objects are determined by their characteristics, including operating materials, operating states of the objects, and external conditions.

For internal combustion engines in road vehicles, both pollutant emissions and fuel consumption depend not only on external conditions but primarily on operating parameters, including:

– engine speed,
– engine load, typically expressed in terms of torque, net power (or alternatively relative torque and power), engine controlling, fuel injection, and in spark-ignition engines, vacuum in the intake manifold,
– thermal state – understood as the temperature distribution of engine parts and consumables; usually the temperature of a selected operating medium is used, e.g. engine oil or coolant in the case of indirect engine cooling.

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Apart from environmental influences, the operating conditions of car engines are largely depended on vehicle speed. For this reason, the performance characteristics of cars are tested in road tests that simulate real-world use and under comparable environmental conditions. Such standards are applied in type-approval procedures [4, 14, 31].

The criteria for type-approval tests of light vehicles (passenger cars, light trucks and minibuses) in terms of pollutant emissions are the specific distance emissions of pollutants and the number of particulate matter. Distance specific emissions and particulate matter number are expressed as their derivatives with respect to the vehicle's travelled distance. Since November 2017, the WLTP procedure has been used for light vehicles with the WLTC test [4, 14, 31]. From March 2016 to November 2018, the RDE (Real Driving Emissions) procedure, established in the European Union for vehicles in Europe (Annex IIIA to Regulation (RC) 692/2008), was introduced for Euro 6 vehicles [2 – 4, 14, 17, 20, 31]. The RDE procedure is carried out in actual driving conditions with the use of portable PEMS Testing equipment (Portable Emissions Measurement Systems) [24] and Semtech-DS (On-Board Vehicle Emissions Analyzer) [27] and TSI 3090 EEPS™ (Engine Exhaust Particle Sizer™) [28] analyzers to confirm compliance with the results of road NOx emissions and the particulate matter number in the WLTP procedure [4, 14, 31].

RDE tests are characterised by a certain degree of uncertainty compared to measurements performed on a chassis dynamometer. Therefore, RDE testing is, in a sense, a random process [6, 7, 23].

In the countries of America, Asia, Africa and Australia, numerous homologation tests are used, described in the literature [4, 14, 31].

Specifically dedicated tests are also used for testing heavy-duty vehicles, mainly buses. For testing fuel and energy consumption of city buses in road conditions a standardized protocol developed by UITP (Union Internationale des Transports Publics) is used: SORT 1 for heavy urban, SORT 2 for mixed/easy urban and SORT 3 for easy suburban [29, 30], as well as the MZA (Warsaw City Bus Company) test [9, 11].

Special tests are also used, e.g. those developed as part of the European ARTEMIS project [1, 4, 14, 31] – the so-called CADC tests (Common Artemis Driving Cycles), designed to reflect real-world driving patterns, but are optimized for passenger cars and light commercial vehicles [1, 4, 14, 31].

2. LITERATURE REVIEW

Article [1] describes tests for testing light vehicles, developed as part of the ARTEMIS program. These tests are designed for testing vehicles in urban, rural, and highway conditions. Article [2] presents an analysis of operating states of a passenger car internal combustion engine under RDE test, while article [3] focuses on the results of pollutant emissions measurements conducted under the same RDE conditions. This publication presents test results that significantly exceed the RDE test standards: emissions of all exhaust gas components were tested, and the tests were performed in various dynamic states.

Publication [5] presents a method for estimating emissions used in the emission inventory procedures in line with the standards defined in [15, 16]. This procedure is based on road traffic models covering urban, rural, and expressway driving conditions.

In emission models, specific distance emissions are assumed to be a function of average speed [8]. Another way for linking specific distance emissions with traffic conditions is to express them as a function of the mean value of the product of vehicle speed and acceleration modulus [8]. Example results of road transport emission inventory are presented in [25].

The paper [10] presents the results of pollutant emissions and fuel consumption tests in the form of sets of realizations in conditions simulating the movement of a passenger car in congestion, in cities outside congestion, outside cities and on fast roads: expressways and highways. The stochastic test implementations were determined based on empirical studies. Pollutant emissions and fuel consumption were measured using a chassis dynamometer using test equipment meeting homologation requirements. The obtained results demonstrate a relationship between specific distance pollutant emissions and average speed of vehicles, which is consistent with HBEFA INFRAS AG [19] and COPERT [13] software standards.

3. RESARCH METHOD

To determine the characteristics of pollutant emissions and fuel consumption of a passenger car engine, results from empirical RDE test were used, as they reflect conditions closer to real-world operation than those obtained from chassis dynamometer measurements.

The technical specifications of the examined passenger car are presented in Table 1.

Table 1. Technical specification of the examined vehicle

Parameters	Vehicle
Engine type	Gasoline, turbocharged, R4, 16 V
Fuel system	Direct injection
Engine displacement	1984 cm^3
Maximum power	195 kW at 5000 rpm
Maximum torque	370 Nm/(1600 ÷ 4200) rpm
Transmission	Automatic, 7-speed
Curb weight	1770 kg
Specific power output	9.1 kg/kW
Average CO_2 emissions	228 g/km (WLTC)
Emission standard	Euro 6

The tests were carried out using portable equipment – PEMS Testing [24] and Semtech-DS [27] and TSI 3090 EEPS™ [28].

The following process trajectories were recorded:

- vehicle velocity – v(t),
- engine speed – n(t),
- engine controlling signal – s(t),
- relative engine torque – $M_{er}(t)$,
- relative engine power – $N_{er}(t)$,
- emission intensity of: carbon monoxide – $E_{CO}(t)$, hydrocarbons – $E_{HC}(t)$, nitrogen oxides – $E_{NOx}(t)$, carbon dioxide – $E_{CO2}(t)$, particulate number – $E_{PN}(t)$,
- intensity of fuel mass consumption – q(t).

The registered processes were filtered using a five-point Savitzky-Golay low-pass filter [6, 7, 22, 26] with a second-order polynomial approximation to minimize high-frequency noise component. Next, the relative net power was determined based on the engine speed and relative torque. The specific distance emission – b was determined as the quotient of the intensity of emission – E and the vehicle velocity – v:

$$b = \frac{E}{v} \quad (1)$$

The particulate number emission – b_{PN} is the quotient of the intensity of the particulate number emission – E_{PN} and the vehicle velocity – v:

$$b_{PN} = \frac{E_{PN}}{v} \quad (2)$$

Fuel mass consumption – Q is equal:

$$Q = \frac{q}{v} \quad (3)$$

Pollutant emission and fuel consumption characteristics are generated using the Monte Carlo method [12, 18, 21] by averaging within randomly selected limits:

- specific distance emissions, particulate number, and fuel mass consumption,
- vehicle velocity.

The Monte Carlo method is employed to simulate a pseudorandom reality, in which the generation of pseudorandom numbers constituting a key component of the method. This article uses a pseudorandom number generator, which generates values in the range from 0 to 1 according to a uniform probability distribution. The pseudorandom number generator used produces values following a uniform distribution. Such generators are standard functions available in Excel spreadsheets.

In this article 130 pseudorandom experiments were generated for specific distance emissions of all pollutants, for the fuel mass consumption and particulate number. The relationship between these values and the averaged speed is approximated using power functions available in the software. The accuracy of this approximation is measured by the coefficient of determination.

4. RESULTS OF THE REAL DRIVING EMISSIONS TEST

Figures 1-12 present the results of filtered empirical data obtained from vehicle tests conducted under RDE test. The vehicle velocity curve and engine control curve are shown in Figures 1 and 2.

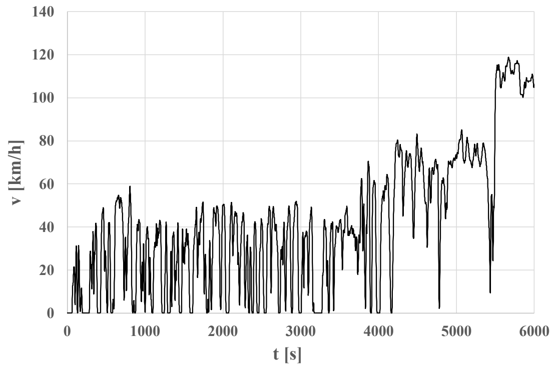

Fig. 1. Vehicle velocity – v in the Real Driving Emissions in the time domain – t

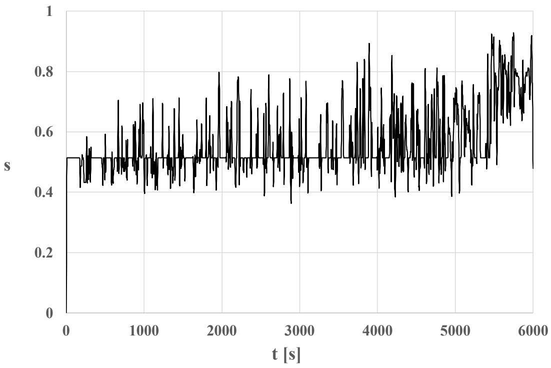

Fig. 2. Engine control – s in the Real Driving Emissions in the time domain – t

The following figures (3-5) shows respectively: engine speed, relative engine torque and relative engine power.

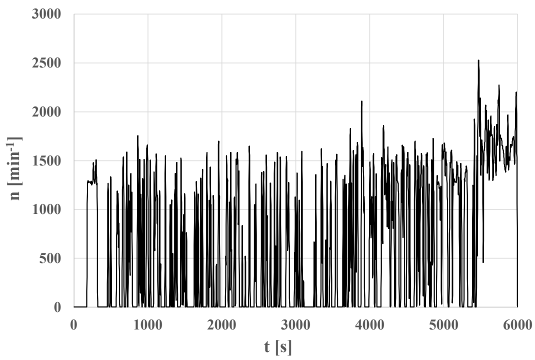

Fig. 3. Engine speed – n in the Real Driving Emissions in the time domain – t

Figure 6 presents the distribution of points in coordinates defined by engine controlling signal – s and vehicle velocity – v. The point corresponding to the average values of these coordinates (AV[s] – AV[v]) is also indicated in the figure.

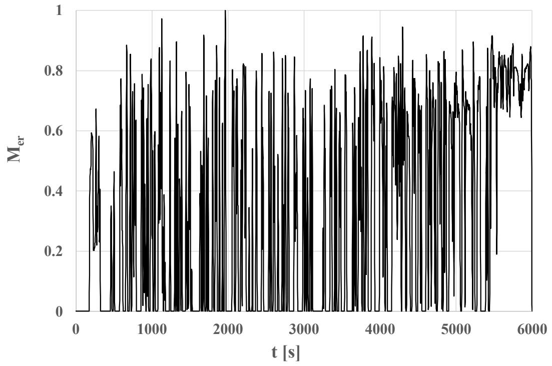

Fig. 4. Relative engine torque – M_{er} in the Real Driving Emissions in the time domain – t

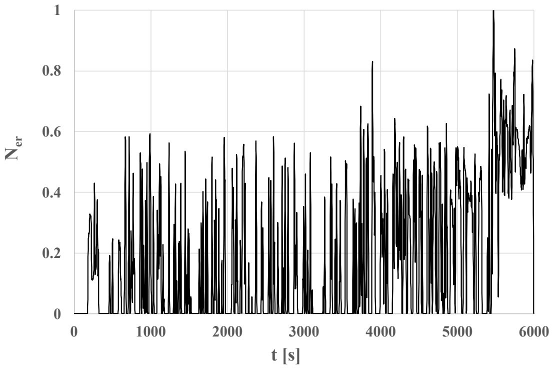

Fig. 5. Relative engine power – N_{er} in the Real Driving Emissions in the time domain – t

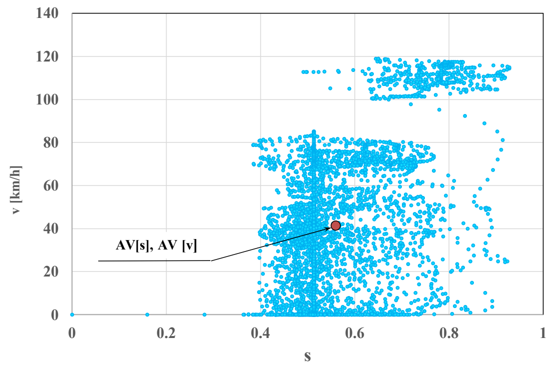

Fig. 6. The set of engine control parameters – s and vehicle velocity – v and the average value of engine control parameters – AV[s] and vehicle velocity – AV[v] in the RDE test

Figures 7 – 10 show the pollutant emission intensity curves in the RDE test.

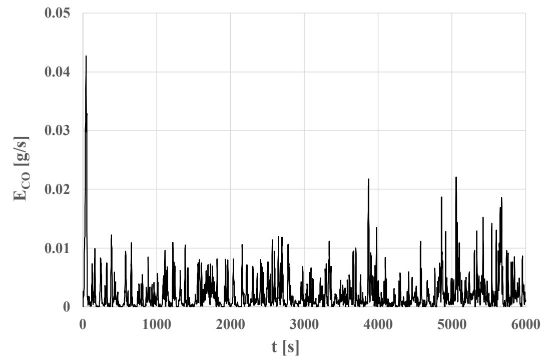

Fig. 7. Intensity of carbon monoxide emission – E_{CO} in the Real Driving Emissions in the time domain – t

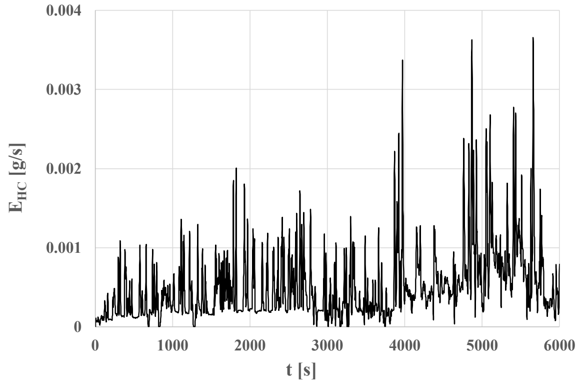

Fig. 8. Intensity of hydrocarbon emission – E_{HC} in the Real Driving Emissions in the time domain – t

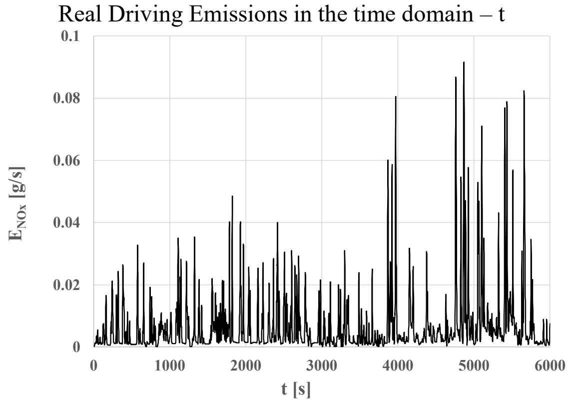

Fig. 9. Intensity of nitrogen oxides emission – E_{NOx} in the Real Driving Emissions in the time domain – t

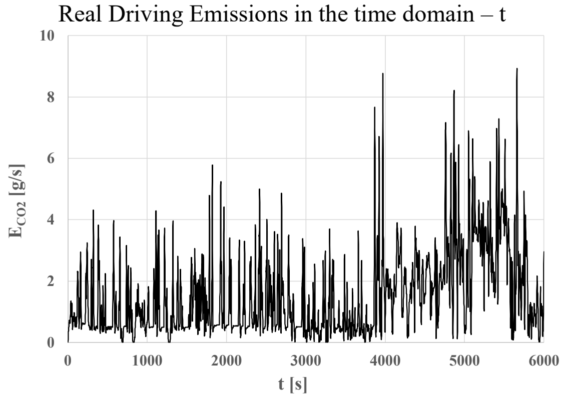

Fig. 10. Intensity of carbon dioxide emission – E_{CO2} in the Real Driving Emissions in the time domain – t

Figures 11 and 12 shows the course of the particle number intensity and fuel consumption in this test.

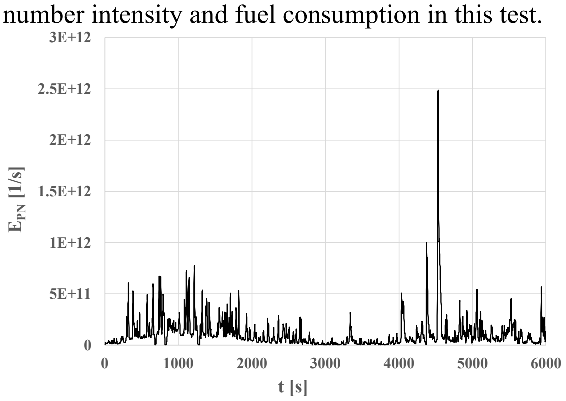

Fig. 11. Intensity of particulate number – E_{PN} in the Real Driving Emissions in the time domain – t

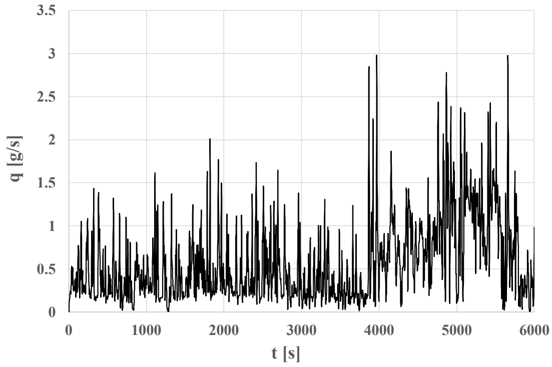

Fig. 12. Intensity of fuel consumption – q in the Real Driving Emissions in the time domain – t

5. EMISSION CHARACTERISTICS BASED ON THE RESULTS OBTAINED FROM RDE TEST

Figures 13 – 18 show the determined characteristics of pollutant emissions and fuel consumption in the average velocity domain. The characteristics were determined by approximating a set of points with power function. The criterion for selecting functions approximating these data sets was to maximize the coefficient of determination of the characteristic models to the empirical data.

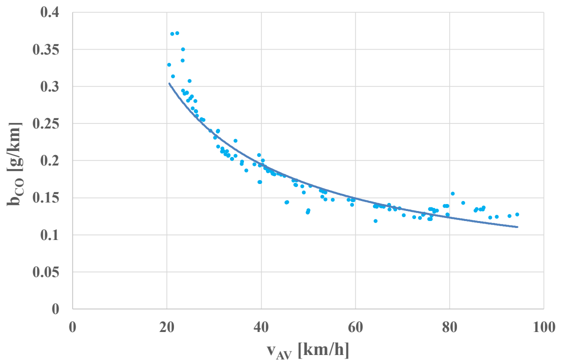

Fig. 13. Characteristic of carbon monoxide emission: specific distance carbon monoxide emission – b_{CO} in the average velocity domain – v_{AV}

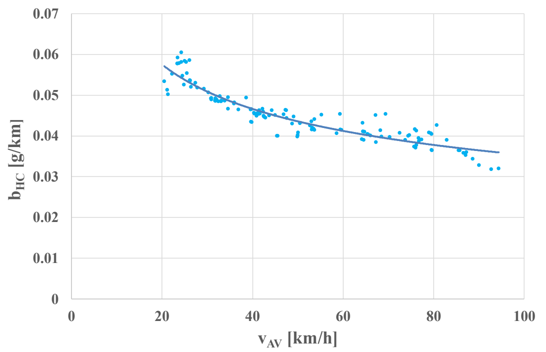

Fig. 14. Characteristic of hydrocarbons emission: specific distance hydrocarbons emission – b_{HC} in the average velocity domain – v_{AV}

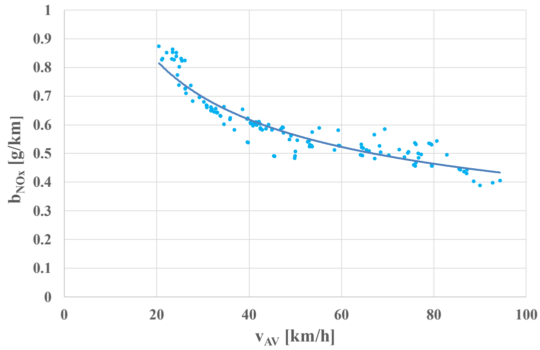

Fig. 15. Characteristic of nitrogen oxides emission: specific distance nitrogen oxides emission – b_{NOx} in the average velocity domain – v_{AV}

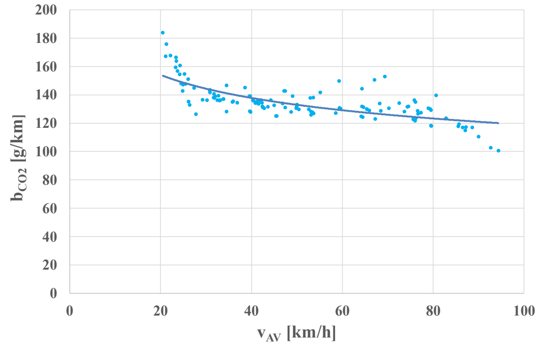

Fig. 16. Characteristic of carbon dioxide emission: specific distance carbon dioxide emission – b_{CO2} in the average velocity domain – v_{AV}

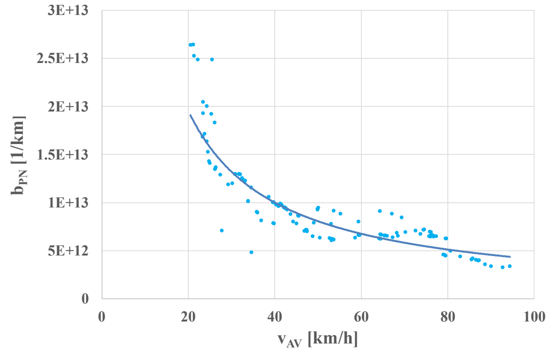

Fig. 17. Characteristic of particulate number: specific distance particulate number – b_{PN} in the average velocity domain – v_{AV}

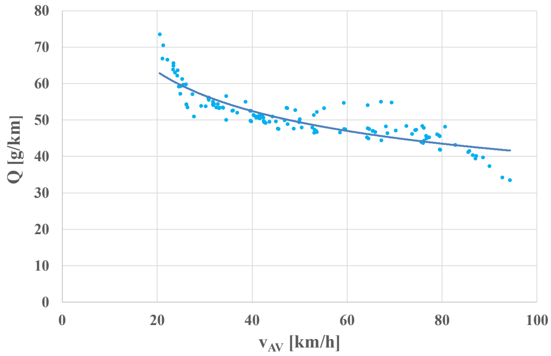

Fig. 18. Characteristic of mass fuel consumption: specific distance mass fuel consumption – Q in the average velocity domain – v_{AV}

Table 2 presents the characteristics of pollutant emissions and mass fuel consumption as well as the determination coefficients of the characteristic models for empirical data.

Table 2. Characteristics of pollutant emissions and mass fuel consumption and determination coefficients of characteristic models for empirical data – R^2

	R^2	Characteristics
CO	0.9058	$b_{CO} = 2.2526 \cdot v_{AV}$^(-0.663)
HC	0.8641	$b_{HC} = 0.1426 \cdot v_{AV}$^(-0.303)
NOx	0.8701	$b_{NOx} = 2.8429 \cdot v_{AV}$^(-0.414)
CO2	0.5424	$b_{CO2} = 249.22 \cdot v_{AV}$^(-0.161)
PN	0.8133	$b_{PN} = 4.0E14 \cdot v_{AV}$^(-0.967)
Q	0.7639	$Q = 142.09 \cdot v_{AV}$^(-0.270)

Figure 19 presents the coefficients of determination – R^2 of the models of pollutant emission characteristics and fuel mass consumption for empirical data. Among the analyzed characteristics, the lowest coefficient of determination was obtained for carbon dioxide emissions, while the highest for carbon monoxide.

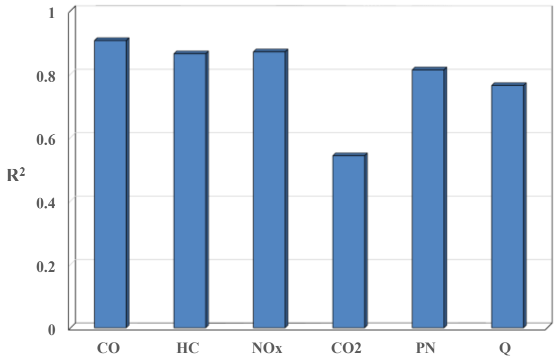

Fig. 19. Determination coefficients of pollutant emission and mass consumption characteristic models for empirical data – R^2

6. SUMMARY

The results of the conducted studies allow for the formulation of the following conclusions:

1. Vehicle operating conditions under RDE testing are defined by a wide range of vehicle velocity, engine speed, and engine load. This high variability in engine operating conditions is confirmed by the wide range of recorded pollutant emission intensities, particulate number intensities and mass fuel consumption rates. Such variability enables the use of empirical pollutant emission and fuel consumption test results to determine characteristics applicable to a wide range of vehicle operating conditions.
2. Empirical research confirms how sensitive vehicle exhaust emissions are to engine operating states determined by vehicle velocity. The sensitivity of pollutant emissions to engine operating states is significantly greater than that of fuel consumption. This justifies examining pollutant emissions under conditions reflecting real-world vehicle use.
3. The use of the Monte Carlo method to study object properties allows for the simulation of a pseudo-random reality. This allows for the avoidance of highly labour-intensive, multi-sample studies. The effectiveness of the Monte Carlo method for determining pollutant emission characteristics is confirmed by their consistency with characteristics that can be determined based on data contained in software used for pollutant emission and fuel consumption modeling, such as HBEFA INFRAS AG [19] or COPERT [13].
4. The sets of specific distance pollutant emissions, particulate matter numbers, and specific distance mass fuel consumption determined using the Monte Carlo method are characterized by significant scatter, despite the general nature of the dependence of the determined values on average velocity being unambiguous. This finding confirms the high sensitivity of pollutant emission and fuel consumption to random vehicle operating conditions.
5. The determined pollutant emission and fuel consumption characteristics are in good agreement with the empirical data used. This is confirmed by the high values of the coefficients of determination obtained for both models and the empirical data.
6. It is advisable to test pollutant emissions in various engine operating conditions, e.g. in various driving tests, including non-homologation tests, as well as in test fragments with different operating states, including those with different dynamic properties.
7. Repeating the tests multiple times is recommended in order to evaluate the repeatability of the obtained results.

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