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THE POSSIBILITIES OF CONVERSION OF POLLUTION EMISSION VALUES FROM COMBUSTION ENGINES IN HEAVY-DUTY VEHICLES

Jerzy Merkisz, Jacek Pielecha

Poznan University of Technology
Institute of Combustion Engines and Transport
Piotrowo Street 3, 60-965 Poznan, Poland
tel.: +48 61 665 2207, fax: +48 61 665 2204
e-mail: jerzy.merkisz@put.poznan.pl
jacek.pielecha@put.poznan.pl

Abstract

The use of internal combustion engines as the drive for heavy-duty vehicles (with an unladen weight of over 3500 kg) forces these engines to be tested on an engine dynamometer. Thus, these engines operate under forced conditions, which are significantly different from their actual application. To assess the ecology of such vehicles (or more accurately the engine alone) the emission of pollution per unit of work done by the engine must be determined. However, obtaining the results of unit emissions (expressed in grams of the compound per a unit of performed work) does not give the grounds for determining the mass of pollutants on a given stretch of the road traveled by the vehicle. Therefore, there is a need to change the emission value expressed in units referenced to the engine work (g/kWh) into a value of road emissions (g/km). The paper presents a methodology of determining pollutant emissions of heavy-duty road vehicles on the basis of the unit emissions, as well as additional parameters determined on the basis of the algorithm presented in the article. A solution was obtained that can be used not only for heavy-duty vehicles, but was also extended to allow use for buses.

Keywords: pollutant emissions, heavy-duty vehicles

1. Introduction

The increasing number of vehicles in the world and the environmental pollution lead to rise in the requirements in terms of exhaust emissions. The problems tackled in this article applies to very important aspects in the ecological sense, as a part of the trend of environmental protection. The experiment conducted uses the available research potential in the form of mobile gas analyzers, which can measure harmful gaseous exhaust components. Use of data from on-board diagnostics system for measuring concentrations of toxic compounds for vehicles powered by natural gas enables the ecological assessment of means of transport during operation. Determination of the exhaust emission components from any vehicle or engine is possible in several ways [3, 4]:

a) based on engine dynamometer test – determines the concentration of the exhaust gas components; taking into account – in accordance with the standards – conversion methods with the characteristic values for the individual components, and using the measured values of engine power, it becomes possible to determine specific emissions (expressed in g/(kWh)) of the given exhaust component,

b) on the basis of tests on a chassis dynamometer – emissions in a particular test are determined, and also based on the standards and regulations it is possible to determine the road emissions (expressed in g/km or g/test) of the given exhaust component,

c) on the basis of road tests – the concentration of gaseous components and the weight and number of particles are determined, and taking into account the exhaust mass flow also the road emission of these components.

Recent research on pollutant emissions under real traffic conditions performed with the use of mobile devices [2, 7, 15] reflects the state of ecological vehicles very well. Most attention is paid to the possibility of using such tests to calibrate the engines [1], in such a way that allows to reduce emissions not only during the engine tests, but also in the entire range of engine operation [6]. Comparative studies conducted in laboratories [2] indicate that the emission limits during the operation of vehicles with petrol engines are met, while also indicating that vehicles with diesel engines far exceed the permissible emission limits of nitrogen oxides [8, 11, 12]. Attention is drawn to significant emissions of particulates predominantly in the range of nanoparticles for engines fed with alternative fuels (e.g. natural gas) [9, 14] and the dependence of the test results on the terrain topography [10]. The results of such studies are currently not separate, but are confirmed by articles which relate to several years of research [5] and comprehensive summaries of research on vehicles in real traffic conditions [13].

However, experience in measuring emissions from vehicles shows that it is possible to determine a mutual relationship between the obtained values of specific emissions and road emissions, which will be complemented by other additional features, characterizing the test engine or characteristics relating to the vehicle.

2. Aim and methodology

The aim of this study was to determine the relation between road pollutant emissions and unit emissions, as well as the generalization and expansion of the obtained results to other categories of vehicles (e.g. urban buses).

Comparative studies of the presented relations have been performed for a heavy-duty vehicle. The vehicle has an emission class of Euro IV and it was fitted with exhaust aftertreatment systems. The test route was divided into two main parts: the first – urban, and the second - suburban with elements of motorway driving and return in the opposite direction. The character of the tested section of road enabled the mapping of the conditions of everyday truck traffic with a maximum mass exceeding 16,000 kg (i.e. long haul) with the following characteristics:

– urban conditions – vehicle speed in the range 0–30 km/h,
– suburban conditions – vehicle speed in the range 30–60 km/h,
– motorway conditions – vehicle speed in the range 60–90 km/h.

Dividing the entire test route and all the measurement data obtained on it relations have been obtained, which show that 28% of the duration of the test was performed in urban conditions, 35% of the duration of the test was performed in suburban conditions and the remainder 37% is motorway driving (Fig. 1).

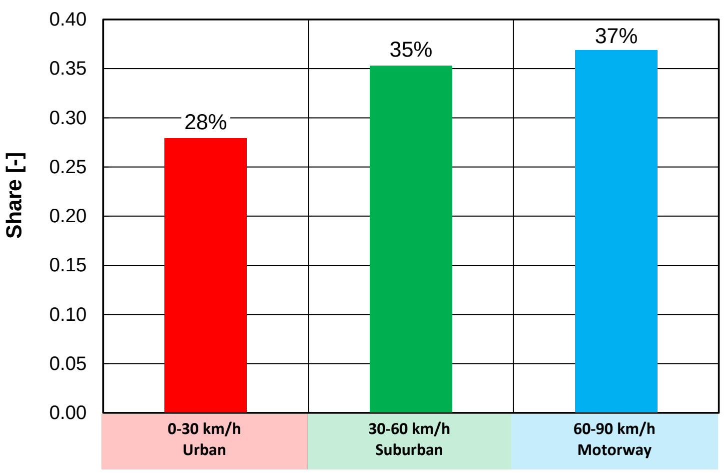

Fig. 1. Characteristics of the incidence of different traffic conditions for the vehicle

Emission measurements were done in real driving conditions; this approach requires the installation of the gas sampling apparatus on the vehicle in such a way that ensures its normal operation. Therefore a gas sampling system was prepared, which together with the system measuring the flow rate of the exhaust gas also performed partial sampling of the flue gas for the analyzers for the measurement (Figure 2 shows the wiring schematic of measuring equipment).

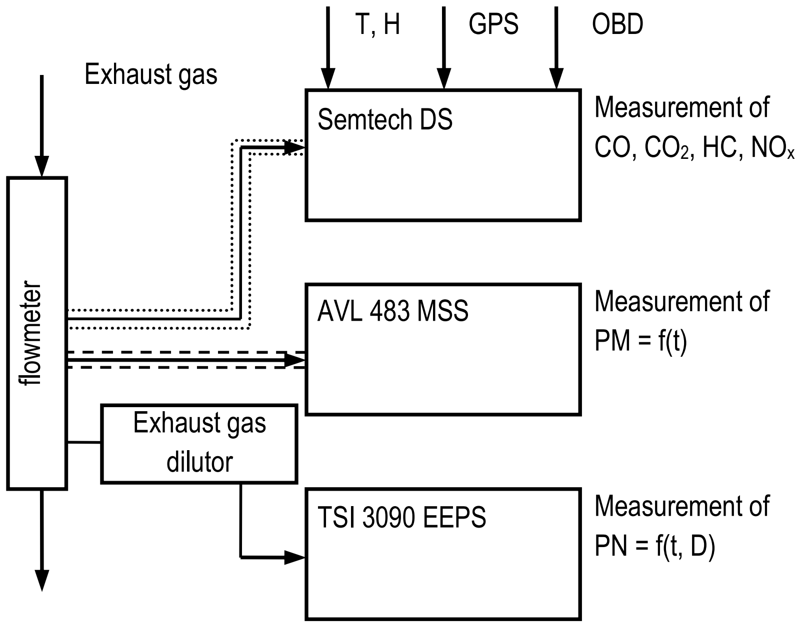

Fig. 2. Schematic diagram of measuring devices used for tests

For measuring the concentration of harmful substances in the exhaust gas the mobile Semtech DS Company Sensors (Sensors Emission Technology) analyzer was used (Table 1). It facilitated the measurement of harmful compounds – carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides. Further data directly transmitted from the vehicle's diagnostic system was sent to the central unit of the analyzer and a GPS was used. Information on the results from mobile gas analyzers in conjunction with the data recorded with the on-board diagnostic systems confirms the desirability of taking the assessment of emissions in real traffic conditions with the use of the measuring apparatus.

Table 1. Characteristics of mobile analyzer Semtech DS with the data transmission system

Parameter	Measurement method	Accuracy
1. Compound concentration in the exhaust gas		
CO	NDIR, range 0–10%	±3% of the measurement range
HC	FID, range 0–10,000 ppm	±2.5% of the measurement range
$NO_x = NO + NO_2$	NDUV, range 0–3000 ppm	±3% of the measurement range
CO_2	NDIR, range 0–20%	±3% of the measurement range
O_2	PMD, range 0–20%	±1% of the measurement range
2. Gas flow	mass flow rate	±2.5% of the measurement range
3. Warm-up time	900 s	
4. Response time	T90 < 1 s	
5. Diagnostic systems	SAE 1939	

3. Analysis of the emission results

The analysis of road emissions and unit emissions was done for carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides. Average values of emission of carbon dioxide in the various driving conditions are: 1968 g/km in urban conditions, 908 g/km in suburban conditions and 681 g/km in motorway driving (Fig. 3a). Analysis of the unit emissions of carbon dioxide allowed for determining the extent of variation: the value ranged from 100 g/kWh to about 800 g/kWh. Average unit emission values of carbon dioxide in different driving conditions are: 570 g/kWh in urban conditions, 308 g/kWh in suburban conditions and 261 g/kWh during motorway driving (Fig. 3b).

The instantaneous values of carbon monoxide emission in the various stages of the test exceed 50 g/km, however, the end values in the individual stages (the ratio of the total weight of the emitted compound and the total distance covered) produced significantly smaller values. Average values for the emissions of carbon monoxide in various driving conditions are: 5.03 g/km in urban conditions, 2.16 g/km in suburban conditions, and 1.16 g/km in motorway driving. Emission in motorway driving conditions was about 4 times less than in urban driving (Fig. 4a). Average unit value of carbon monoxide emissions in the various driving conditions are: 1.46 g/kWh in urban conditions, 0.73 g/kWh in suburban conditions, and 0.44 g/kWh during motorway driving (Fig. 4b). The resulting unit emissions of carbon monoxide are below the limit, which for these vehicles is 4 g/kWh.

a) *b)*

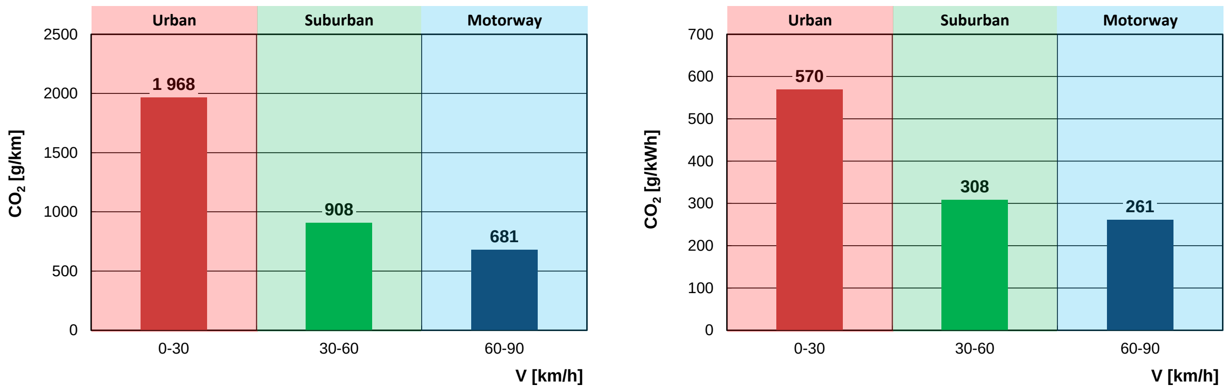

Fig. 3. Characteristics of carbon dioxide emissions: a) road emissions b) unit emissions

a) *b)*

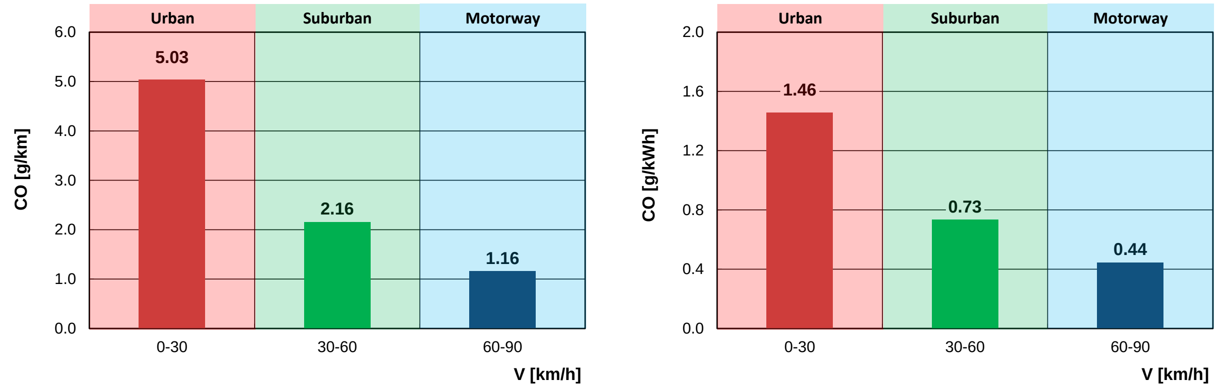

Fig. 4. Characteristics of carbon monoxide emissions: a) road emissions b) unit emissions

The instantaneous values of emission of hydrocarbons in various stages of the test exceed 30 g/km, but the end values in individual stages produced significantly smaller values. Average values of carbon monoxide emissions in the various driving conditions are: 3.31 g/km in urban conditions, 1.28 g/km in suburban conditions and 1 g/km in motorway driving. Emission in motorway driving conditions were more than 3 times less than in urban driving (Fig. 5a). While the average unit value of hydrocarbon emissions in different driving conditions are: 0.96 g/kWh in urban conditions, 0.44

g/kWh in suburban conditions and 0.38 g/kWh in motorway driving (Fig. 5b). The obtained values of hydrocarbons emissions are lower than the permissible limit (which for these vehicles is 0.55 g/kWh), but only for driving in rural and motorway conditions.

The instantaneous values of nitrogen oxides emission in the various stages of the vehicle exceed 100 g/km, but the end values in the individual stages produced smaller results. Average values for carbon monoxide emissions in the various driving conditions include: 14.36 g/km in urban conditions, 5.37 g/km in suburban conditions, and 2.05 g/km in motorway driving. Emission of nitrogen oxides in highway driving conditions was approximately 7 times lower than in urban driving (Fig. 6a). While the average unit value of nitrogen oxide emissions in the various driving conditions are: 4.16 g/kWh in urban conditions, 1.82 g/kWh in suburban conditions, and 0.787 g/kWh in motorway driving (Fig. 6b). The values of hydrocarbons emission are lower than the permissible limit (which for these vehicles is 2 g/kWh), but only for driving in rural and motorway conditions.

a) *b)*

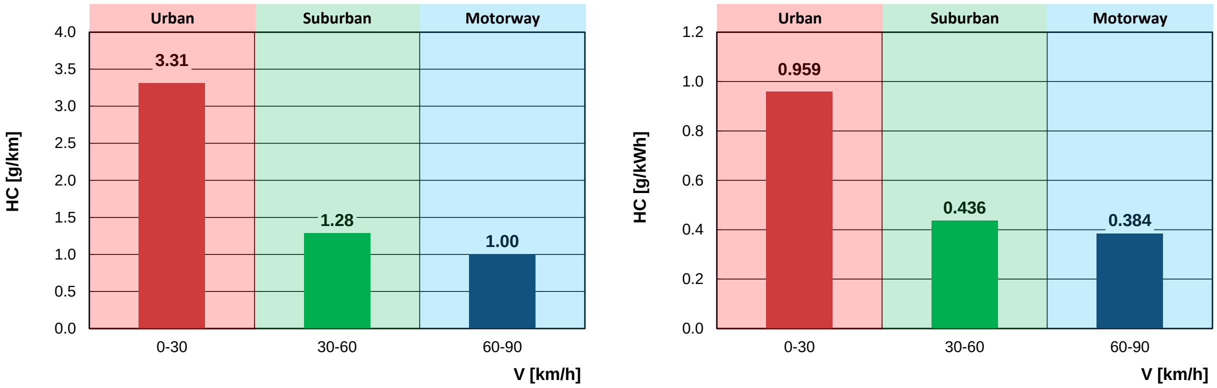

Fig. 5 Characteristics of hydrocarbons emissions: a) road emissions b) unit emissions

a) *b)*

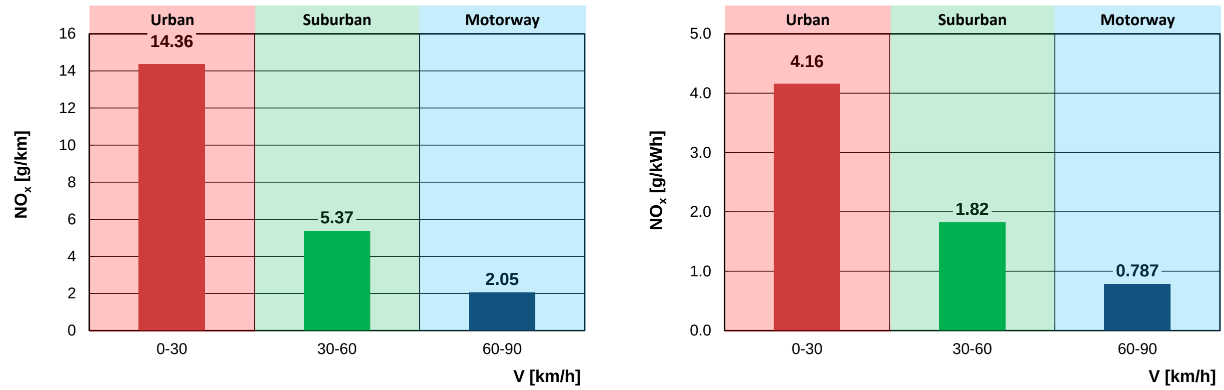

Fig. 6. Characteristics of nitrogen oxides emissions: a) road emissions b) unit emissions

The summary of the obtained research results are the average emissions generated for the entire test route, which are equal to (Fig. 7):

- for road emissions: carbon dioxide – 848 g/km, carbon monoxide – 1.77 g/km, hydrocarbons – 1.26 g/km and nitrogen oxides – 4.06 g/km,
- for unit emissions: carbon dioxide – 305 g/kWh, carbon monoxide – 0.64 g/kWh, hydrocarbons – 0.45 g/kWh, nitrogen oxides – 1.46 g/kWh.

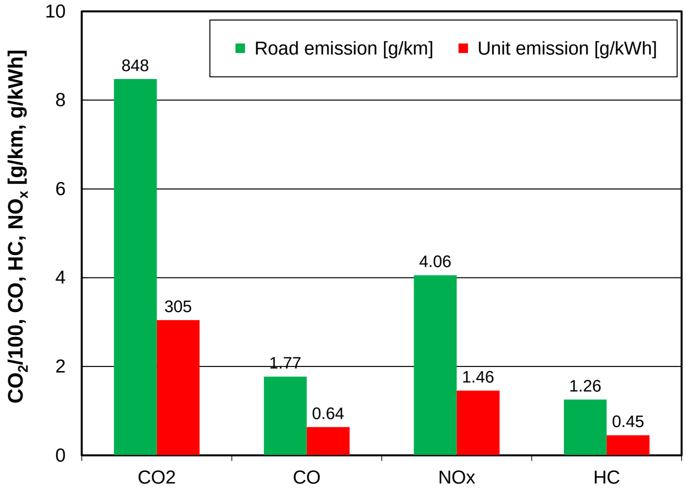

Fig. 7. The obtained average values of road emissions and unit emissions in the performed tests (the values for the entire route)

Expressing the obtained emission values of the road (b_d) and unit (e_j) emissions throughout the study (in various stages and also taking into account the end values), a ratio in the form of road emissions to unit emissions (b_d/e_j) of the given exhaust emission was determined (Fig. 8). A characteristic feature of the results is a constant value of this ratio for the various test route stages and their similarity as to the nature and value. Determining the relationship between the considered parameters (the road and unit emissions), the equation b_d = 3.164 e_j was defined (Fig. 9) on the basis of which the value of unit emissions can be determined knowing the value of road emissions (or vice versa).

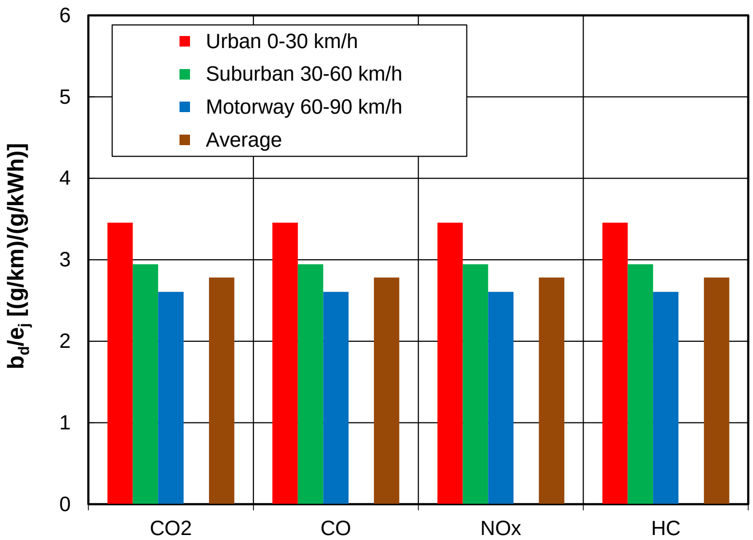

Fig. 8. The ratio of the values of road and unit emissions in various test route stages

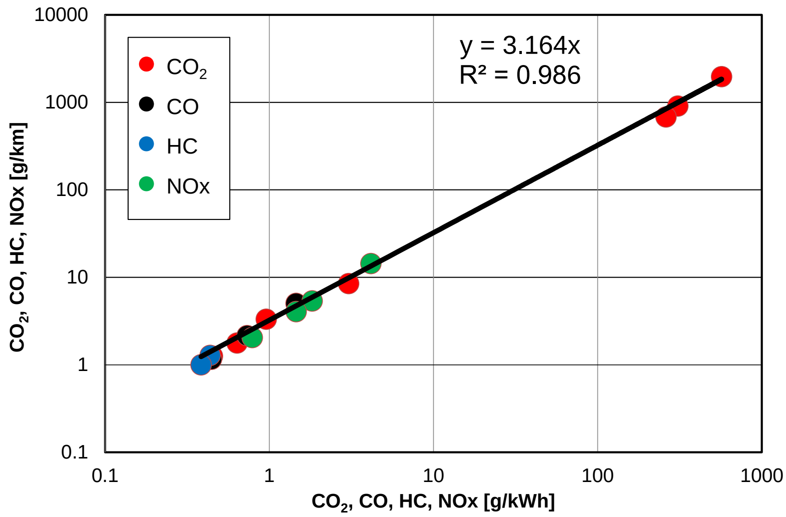

Fig. 9. Dependence of road emissions as a function of emission of pollutants in various stages of research

This relationship is valid for the conducted research (one case), but the resulting high value of the determination coefficient (0.986), hints on the nature of similarity between the work performed by the vehicle and the distance traveled. By plotting this dependence (Fig. 10), showing the impact of the distance travelled and the work done by the vehicle engine a linear relationship was obtained between the two quantities. The determination coefficient obtained with this relation is 0.993, therefore, it can be considered that the values of the road and unit emissions of pollutants are related.

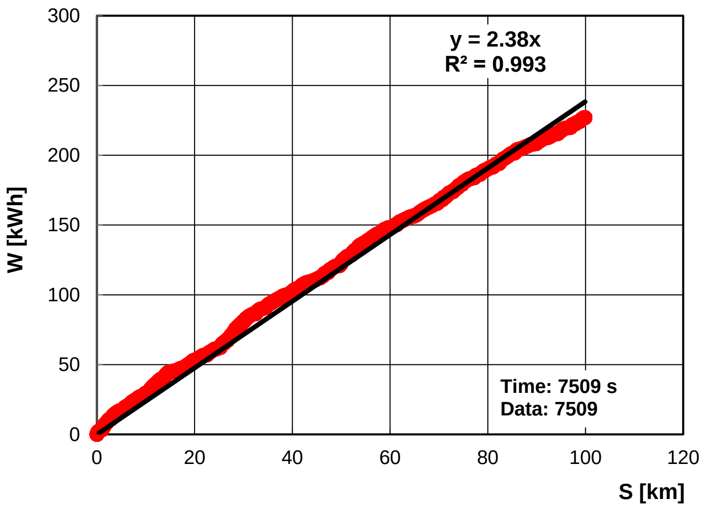

Fig. 10. Relation between road emissions as a function of unit emission of pollutants in various stages of research

The obtained results cannot be applied to tests of all types of heavy-duty vehicles. Therefore, the attempt to generalize these results to a larger group of heavy-duty vehicles. 12 tests were performed in various driving conditions, yielding the data presented in Table 2. These values are obtained for urban buses with different types of engines (SI and CI), varying maximum power and displacement, as well as different sizes (total weight range of 11,000–26,000 kg) and emission class.

The relationships between different values shown in Table 2 and the ratio of b_d/e_j, which reflects the relationship between road emissions and unit emissions of pollutants was investigated. The following relations were investigated:

– the impact of the maximum vehicle power on the ratio b_d/e_j:

$$b_d / e_j = f(N_e) \tag{1}$$

– the impact of the engine displacement on the ratio b_d/e_j:

$$b_d / e_j = f(V_s) \tag{2}$$

– the impact of the total mass of the vehicle on the ratio b_d/e_j:

$$b_d / e_j = f(m) \tag{3}$$

In the first step the relations between the ratio b_d/e_j and the maximum power (Fig. 11), the engine displacement (Fig. 12) and the mass of the vehicle (Fig. 13) were prepared. Maximum power affects the value of the work done by the engine, so the unit emission of pollutants will depend on the vehicle engine power.

Table 2. Example of data used to determine the relationship between the road emissions (b_d) and unit emissions (e_j) of heavy-duty vehicles

Test No.	b_d/e_j [(g/km)/(g/kWh)]	N_e [kW]	V_s [dm^3]	m [kg]
1	2.56	230	9.2	25,000
2	2.01	192	6.9	24,000
3	2.95	213	9.2	26,000
4	3.16	412	15.6	35,000
5	1.89	192	6.9	20,000
6	1.51	230	9.2	20,000
7	1,31	230	9.2	18,000
8	2.67	209	9.2	26,000
9	2.61	221	9.2	26,000
10	2.31	221	9.2	25,000
11	1.30	176	10.2	13,000
12	1.39	123	10.2	11,000

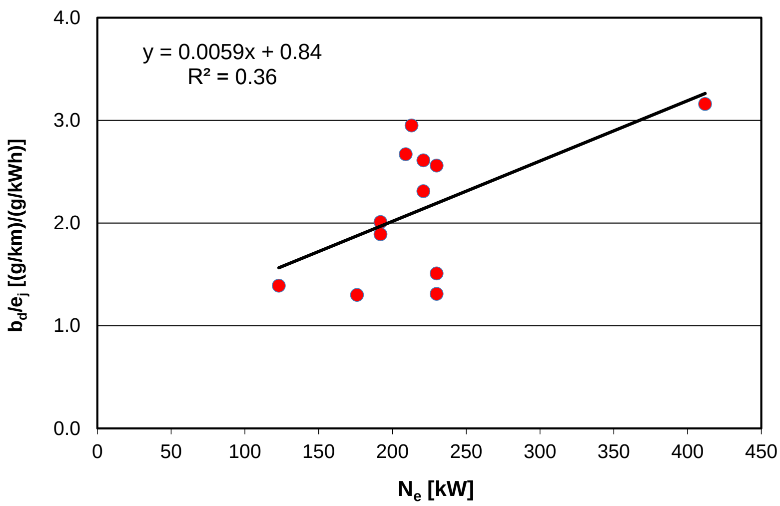

Fig. 11. The relation between the ratio of road to unit emissions and the maximum engine power of the vehicle

Equation (1) is characterized by a low value of the coefficient of determination (0.36), but the analysis of Figure 10 shows that this factor must be taken into account in further analysis (it has a clear impact). The impact of engine displacement on emissions can be assessed under the assumption that with increasing displacement the value of the road emission of pollutants (b_d) increases, while the respective value of unit emission may be unchanged. Generally speaking, an increase in engine displacement affects the value of the road emission, but not necessarily the value of the unit emission (Fig. 12).

The situation is similar with equation (2), where the resulting coefficient of determination value of 0.82, leads to the conclusion that this value can be used in the further analysis. Vehicle mass is a value with a significant impact on the value of the ratio b_d/e_j (Fig. 13).

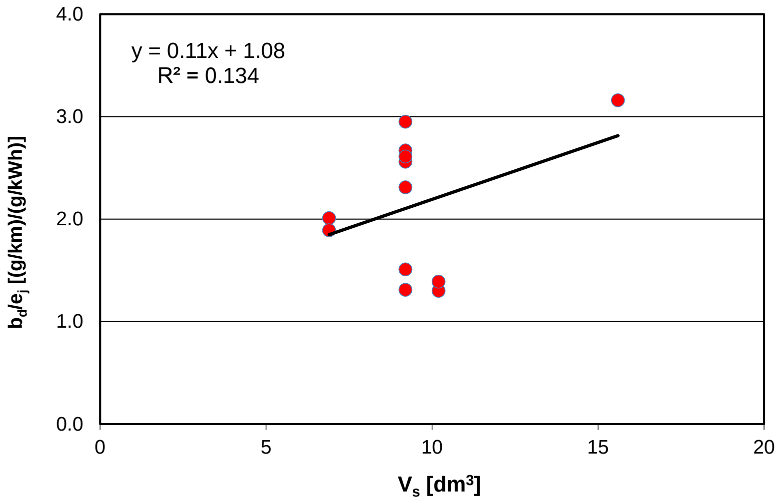

Fig. 12. The relation between the ratio of road to unit emissions and the engine displacement of the heavy-duty vehicle

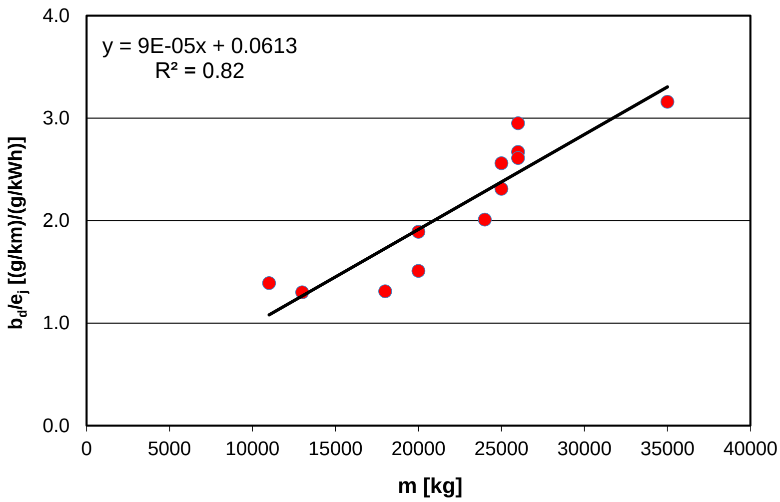

Fig. 13. The relation between the ratio of road to unit emissions and the total vehicle mass

Further steps were to use the obtained relations which was to result in a generalized equation, that could be used as a conversion method between the road emissions of pollutants and the unit emissions. The influence of the parameters previously taken for analysis was determined:

– the impact of the ratio of total vehicle mass and the engine displacement on the value of b_d/e_j:

$$b_d / e_j = f(m \cdot V_s) \tag{4}$$

– the impact of the ratio of total vehicle mass and the maximum engine power on the value of b_d/e_j:

$$b_d / e_j = f(m / N_e) \tag{5}$$

Equation (4) shown in Fig. 14, has a lower coefficient of determination (0.57), than the ratio $b_d/e_j = f(m)$, but higher than for the ratio $b_d/e_j = f(V_s)$. There is a significant range of the results of the product $(m \cdot V)$, which leads to the conclusion that other parameters presented in Table 2 should also be taken into account.

For equation (5) presented in Fig. 15 a coefficient of determination equal to 0.354 was obtained – a value close to the value of the coefficient of determination obtained for the relation $b_d/e_j = f(N_e)$, and less than for the relation $b_d/e_j = f(m)$.

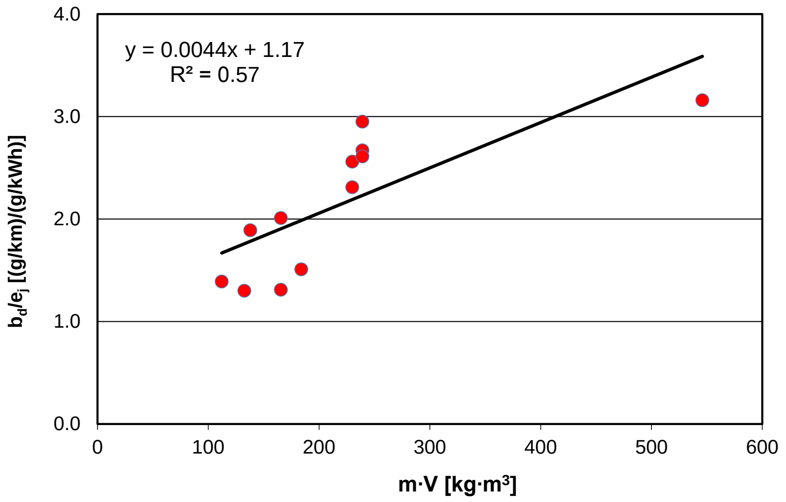

Fig. 14. The relation between the ratio of road to unit emissions and the ratio of total vehicle mass to the engine displacement

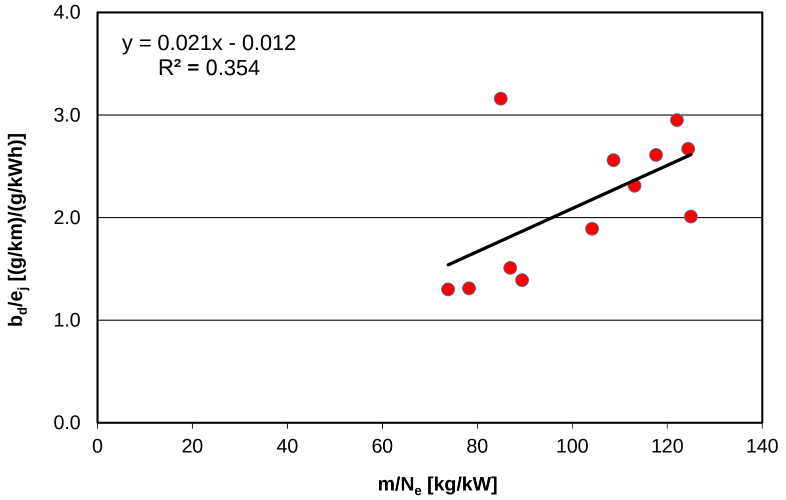

Fig. 15. The relation between the ratio of road to unit emissions and the ratio of total vehicle mass to the maximum engine power

The results presented in Fig. 14 and 15, allow for using these values to determine the relationship, which combines both of these values. The generalized solution can be written as:

$$b_d / e_j = f(m \cdot V_s / N_e) \tag{6}$$

Equation (6) has been shown graphically in Fig. 16, which has a coefficient of determination equal to 0.81, which is a very high value, given the small range of individual deviating points.

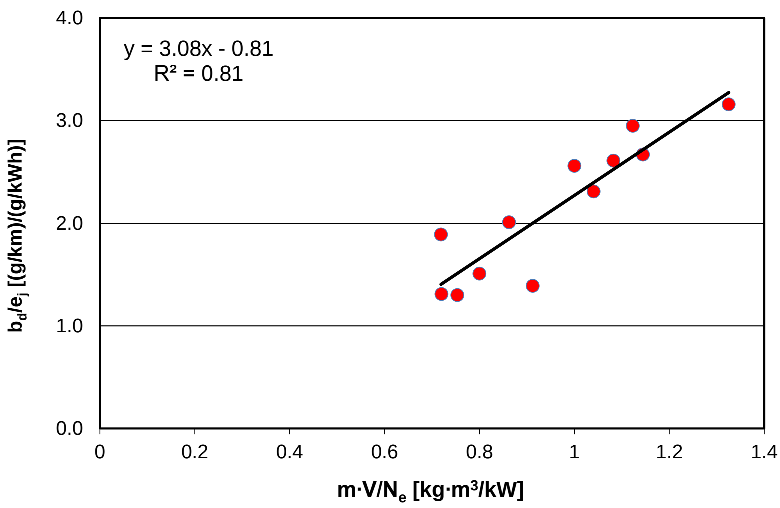

Fig. 16. The relation between the ratio of road to unit emissions and the ratio of total vehicle mass to the maximum engine power

The relationship shown in Fig. 16 can be expressed as:

$$b_d / e_j = 3.08 \frac{m \cdot V_s}{N_e} - 0.81 \tag{7}$$

and then convert to an expression that describes the relationship $b_d = f(e_j)$:

$$b_d = \left(3.08 \frac{m \cdot V_s}{N_e} - 0.81 \right) e_j \tag{8}$$

Equation (8) does not have a physical significance, and the units given are only used for the conversion of road emissions and unit emissions. The equation presented above is not final and may require further work, which will result in an increase in the number of parameters resulting in an increase in the accuracy of the data obtained. This procedure should be carried out for heavy-duty vehicles and buses with different operating parameters (including different vehicle mileage). However, this relationship can be used to convert the road and unit emissions, by utilizing the factors described earlier.

4. Conclusions

The method that reflects the real emissions of harmful compounds into the environment consists of studies of vehicles that are conducted in real driving conditions. Road emission testing of vehicles are considered innovative and necessary around the world. The main advantage of these tests is the measurement of the emissions and fuel consumption of the vehicle in real driving conditions, rather than on the test bench, with well specified and controlled conditions. The most critical in terms of emissions and fuel consumption are the conditions for transient operation of the vehicle (engine) as well as driving vehicles at maximum speeds. These elements of the test drive determine the load of the drive unit and the share of transient phases in the total time of engine operation. In addition, points of operation of the engine, i.e. the load range and speed of the engine crankshaft during actual operation, are significantly different from the operating points of the engine during the certification test. Moreover, in the case of real driving research, any route of travel and load of the test vehicle can be chosen. For these reasons, it seems necessary to develop an algorithm that allows for the conversion of road emission values and unit emissions.

Acknowledgments

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