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AN EFFECTIVE METHOD OF CREATING DYNAMIC CHARACTERISTICS USING DRIVE TESTS

The paper presents a methodology for creating dynamic characteristics of fuel consumption and intensity of emission of toxic components of exhaust gas. The source of data is the result of modal analysis of fuel consumption and emission intensity obtained from experimental drive tests. Two certified tests have been used: European NEDC and American FTP-75. A general algorithm for obtaining dynamic characteristics in the form of approximated functions is formulated on the basis of measured data. Examples of characteristics obtained for a real car with spark ignition engine are presented. The results obtained from experimental measurements and numerical simulations are compared and discussed.

1. Introduction

Monitoring and forecasting emission and dispersion of traffic pollutants is an environmental imperative resulting from technological developments. It should be based on objective data connected with the region and sources of pollution. The main data useful for estimation are:

- Geographical characteristics of the region,
- Statistical meteorological conditions for each month of the year,
- Statistical characteristics of sources of pollution specific for the country or the region.

The two first groups of data are fairly accurately defined on the basis of long observations, while characteristics of sources of pollutions dependent on

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ecological characteristics of the vehicle class of the region are not well recognized. An ecological characteristic [1] means here dependence of the intensity of emission on average accelerations and velocities of a statistical vehicle typical of the region. Obtaining a representative ecological characteristics is a complex task. Apart from the problems with statistical representation, the main problem is obtaining mathematical relations describing intensity of emission and fuel consumption with respect to the momentary acceleration and velocity of a vehicle. This relationship, not averaged for the vehicle class, is called a dynamic characteristic [2], [3], [4].

We elaborate a methodology which enables us to create dynamic characteristics on the basis of modal analysis of fuel consumption and emission of gas exhaust components measured during drive tests. The results used in this paper were obtained from FTP-75 and NEDC tests, carried out as part of project KBN 8T12D 03221, in a certified laboratory for toxicity of exhaust gases of the Research and Development Centre BOSMAL in Bielsko-Biala for an actual class B passenger car.

2. Distribution of engine load of a passenger car during drive tests

Engine load means the engine power developed in given conditions of motion. Distribution of load can be defined as the proportion of time when the engine works with a certain power in the overall time of engine work. This kind of distribution depends on realization of a given motion, engine characteristics and vehicle parameters. For the purposes of comparison, various drive tests have been carried out in different regions of the world, which take into account traffic conditions specific for continents or even countries. Drive tests have been devised to accurately represent frequency features of the processes characterizing traction. Usually, drive tests begin with a "cold start", which is characterized by much higher fuel consumption and toxic emission than during other parts of the tests when catalyst works best [5].

In this paper, the analysis pertains to the results obtained when the temperature of the catalyst is above 350°. The author of [1] has pointed out that the most important factor determining engine performance is the velocity of the car, and thus the courses of velocity should be the basis for comprehensive analysis of dynamic processes. Bearing this in mind, we decided that the dynamic characteristics are obtained on the basis of drive tests and thus they are presented as functions of velocities and accelerations. Emission data of toxic exhaust components and fuel consumption data with respect to momentary vehicle velocity and acceleration are obtained from a continuous analysis of exhaust gas of a vehicle on an engine test bed.

Different drive tests carried out on an engine test bed, which reflect typical conditions of vehicle use, make it possible to define the emission matrix and fuel consumptions in all coordinate spectra. The intensity of emission of exhaust gas components and fuel consumption are often presented in a coordinate system of velocity and product of velocity and acceleration. Product of velocity and acceleration can be interpreted as the degree of engine load in dynamic conditions.

In practice, the information about emission and fuel consumption in relation to motion parameters is usually only gained during drive tests for official certifications [1]. Both European UDC and EUDC as well as American FTP-95 and motorway HWFET tests are used. Data obtained in this way are averaged for each matrix cell (element) (comprising velocity v and acceleration a) with a given intensity. The smaller the dimension of the element, the more precise the representation of real values. An example of a matrix, which can be obtained as a result of an FTP-75 test in a grid of 10 km/h for the coordinate v and 10 m^2/s^3 for the coordinate which is the product v·a, is shown in Fig. 1.

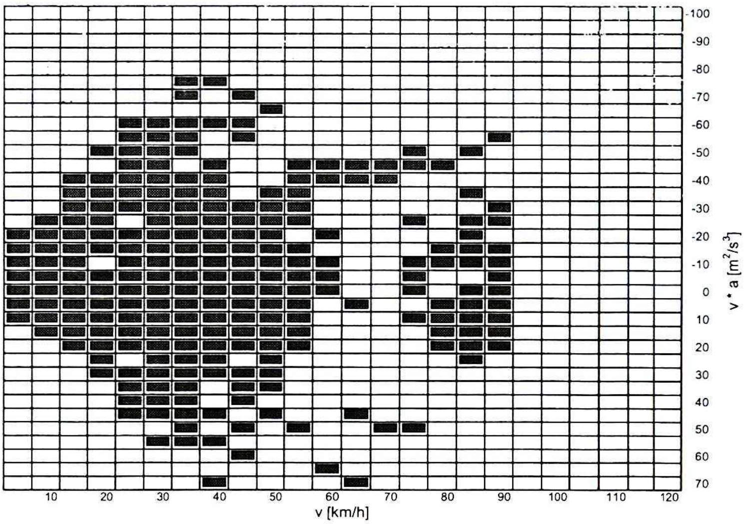

Fig. 1. Matrix of emission intensity or fuel consumption as a function of velocity and a product of velocity and acceleration, which can be obtained as a result of an FTP-75 drive test

For comparison, a matrix which can be obtained from an NEDC drive test is presented in Fig. 2.

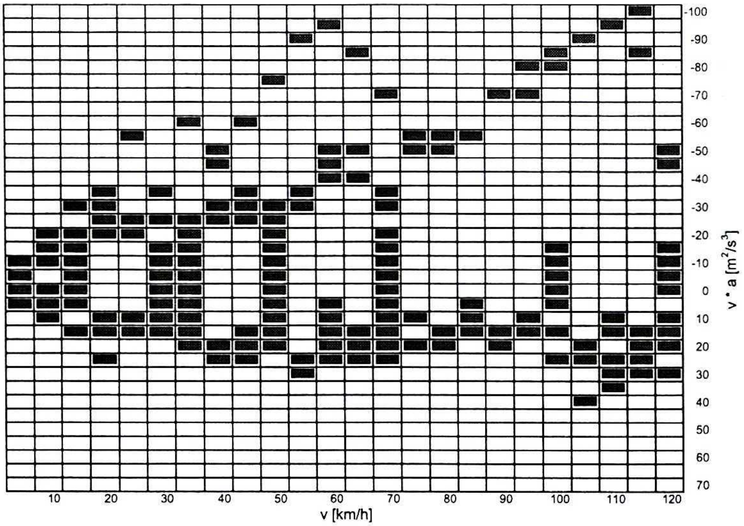

Fig. 2. Matrix of emission intensity or fuel consumption as a function of velocity and a product of velocity and acceleration, which can be obtained during an NEDC drive test

Having compared matrices from Figs 1 and 2, we decided that in order to create a data base about emission of exhaust gas components and fuel consumption the American FTP-75 test [6] will be used as a basis. In the European NEDC test [7] 40% of its duration is taken up by a run with constant velocity. The correctness of our approach can be confirmed by frequency analyses of velocities and time analyses of accelerations presented in [1]. This monograph demonstrates that the American tests have more dynamic features than the European ones. Thus the European test will be treated as a supplementary test.

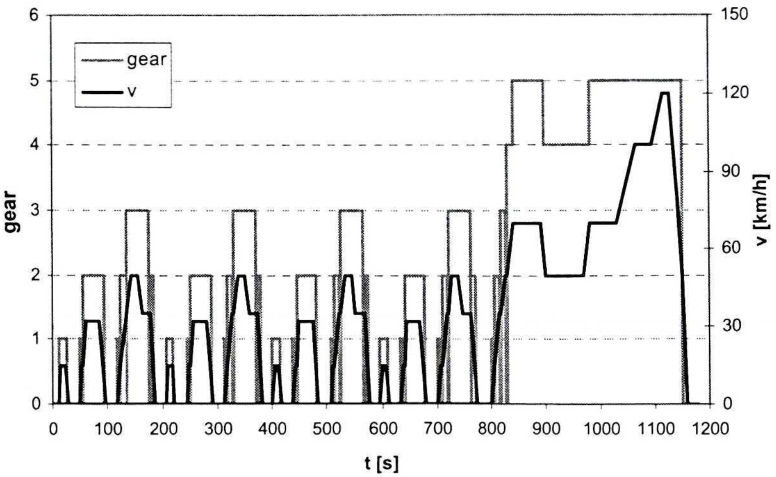

Fig. 3. European NEDC test

The European NEDC test projects statistical conditions of motion of a vehicle used in a European town of average size and consists of urban UDC and motorway EUDC parts. Fig. 3 presents the velocity course when carrying out such a test, together with changes in gear, while Table 1 and Fig. 4 illustrate proportions of time in each gear during the test.

Table 1

Proportion of time in each gear during NEDC test

	NEDC	UDC	EUDC
not in gear	364 s	77 s	56 s
1st gear	101 s	24 s	5 s
2nd gear	221 s	53 s	9 s
3rd gear	172 s	41 s	8 s
4th gear	99 s	0 s	99 s
5th gear	223 s	0 s	223 s
total	1180 s	195 s	400 s

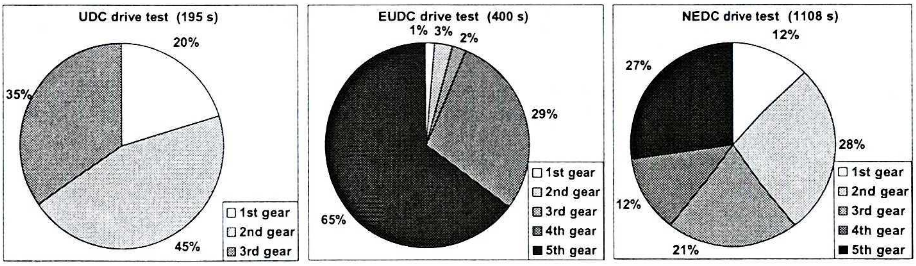

Fig. 4. Percentage of each gear during NEDC drive test (time when not in gear is neglected)

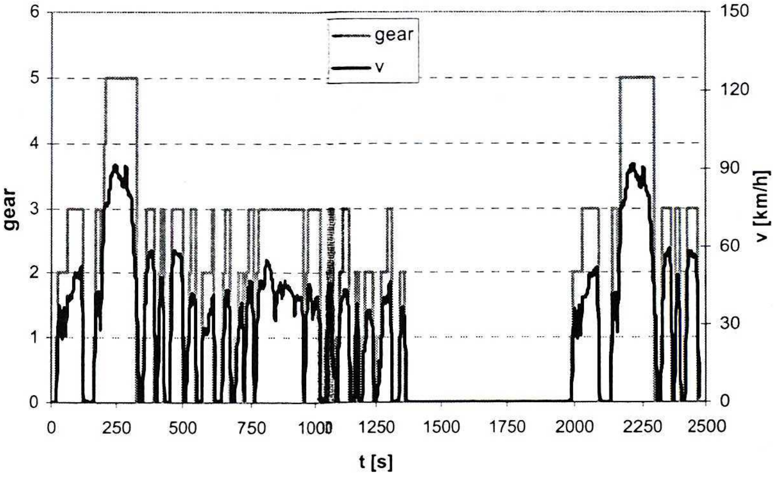

Fig. 5. American FTP-75 test realized for a mechanical gear box

Similarly, Fig. 5 shows the courses of velocity for the American FTP-75 test. Proportions of time of each gear are presented in Table 2 and in Fig. 6.

Table 2

Proportions of time of gears in each phase of FTP-75 test

	Whole test	Whole test without stationary phase	Transition phase	Stabilised phase
not in gear	1087 s	487 s	125 s	238 s
1st gear	156 s	156 s	25 s	105 s
2nd gear	296 s	296 s	56 s	184 s
3rd gear	690 s	690 s	175 s	340 s
4th gear	10 s	10 s	5 s	0 s
5th gear	238 s	238 s	119 s	0 s
total	2477 s	1877 s	505 s	867 s

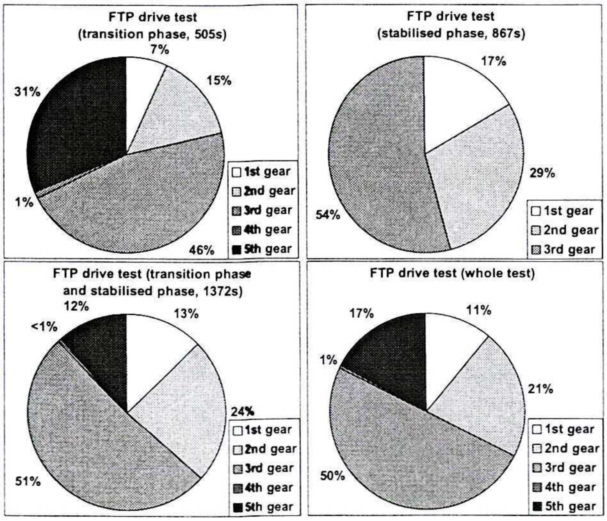

Fig. 6. Percentage of each gear during FTP-75 drive test (time when not in gear is neglected)

It should be underlined that realization of only UDC and FTP-75 tests does not allow us to obtain full dynamic characteristics of intensity of emission of an exhaust gas component or fuel consumption. This requires one of the following procedures:

- carrying out additional tests which would complete missing parts of the matrix with a given number of cells (elements) [8],
- completing the missing parts by using available information in the form of interpolation and approximation techniques.

Completing points of the characteristics by means of interpolation [8] is justified when data used is taken from different drive tests. In the paper, the dynamic characteristics are formulated using data from FTP-75 and NEDC drive tests by means of approximation.

In order to formulate dynamic characteristics, the conditions influencing their shapes have to be considered. A dynamic characteristic should contain only those values of accelerations, which are feasible in actual motion of a vehicle in a certain gear.

The starting point for such analyses can be the characteristic of the dynamic factor of a vehicle (a set of possible accelerations for each gear) created on the basis of a universal engine characteristic assuming constant friction in the power transmission system [9]. Assumption of a constant friction torque allows us to consider phenomena occurring during engine braking, and it is often used in German literature [10]. In paper [3] the authors show that during engine braking intensity of emission of gas exhaust components is relatively high and this should be taken into account in formulation of dynamic characteristics.

The characteristics of the dynamic factor of a vehicle enables us to present accelerations as a function of the velocity of different gears, because according to [11] the dynamic factor D can be connected with acceleration in the following relationship:

$$\frac{dv}{dt} = \frac{g}{\delta}(\vartheta \cdot D_b - f) \tag{1}$$

where: δ – coefficient of reduced masses,

ϑ – coefficient of decrease in engine power in unstable conditions,

D_b – dynamic factor for a given gear,

f – coefficient of rolling friction.

The value of the dynamic factor for a given gear b can be calculated as follows:

$$D_b = \frac{P_{nb} - P_p}{mg} \tag{2}$$

$$P_{nb} = \frac{(M - M_T) \cdot i_{cb}}{r_d} \tag{3}$$

$$D_b = \frac{M \cdot i_{cb}}{r_d \cdot mg} - \left(\frac{M_T \cdot i_{cb} + P_p}{r_d \cdot mg}\right) \tag{4}$$

where: P_{nb} – drive force for gear b,
P_p – air resistance,
M – engine torque,
M_T – friction torque,
i_{cb} – total ratio for gear b,
r_d – dynamic radius of driving wheels,
m – vehicle mass.

The negative part of relation (4) demonstrates the influence of friction torque and air resistance on the value of the dynamic factor. When the driver's foot is taken off the acceleration pedal, the engine torque is zero and the relationship presents a negative value of the dynamic factor and thus acceleration of a vehicle in a given gear. An example characteristic of a dynamic factor (area of changes in acceleration with respect to gear) for an actual car with five gears is presented in Fig. 7. D_+ denotes positive values calculated from (4) and D_- the negative values in the brackets.

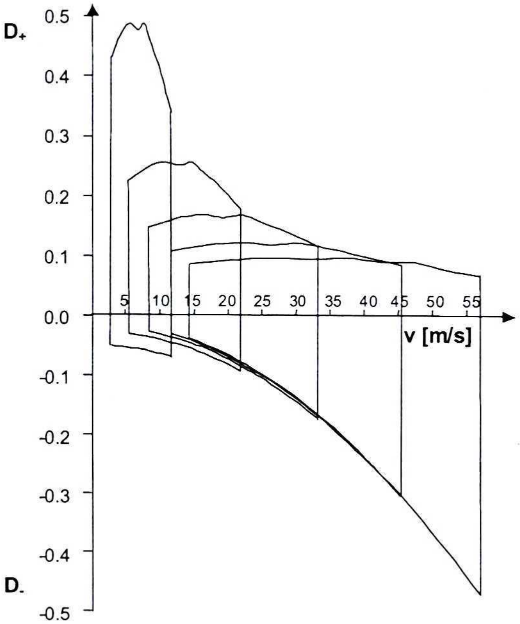

Fig. 7. Example characteristic of the dynamic factor with a constant friction torque for an actual passenger car of medium size

The characteristic of the dynamic factor (acceleration) presented in velocity and dynamic factor coordinates can be the basis for creating the dynamic characteristics when value E depends on velocity and acceleration. Value E can represent either intensity of emission of each component of exhaust gas or fuel consumption. Fig. 8 illustrates how to create the dynamic characteristic for a car with a mechanical gear box of four gears. Thus, on the plane *v*, *dv/dt* there are four curves of maximal accelerations for each gear. Surface graphs of changes in value *E* are presented only for the first and fourth gear.

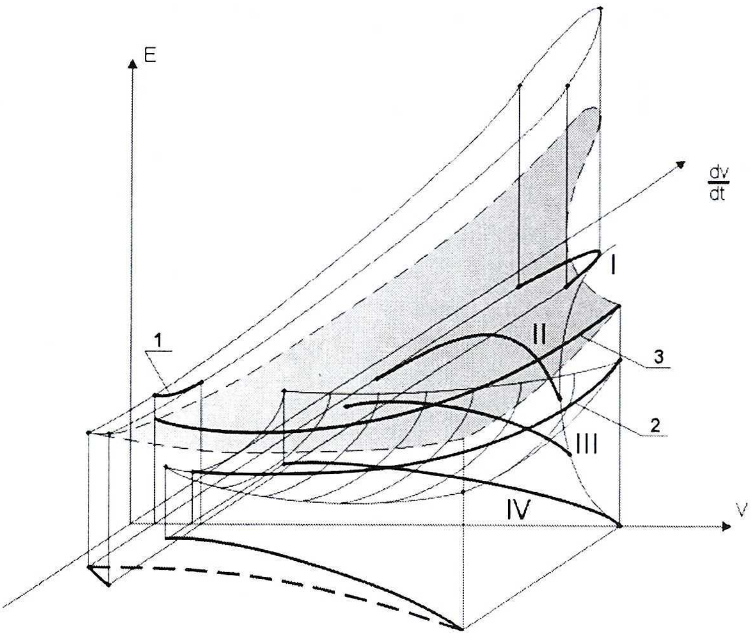

Fig. 8. Illustration of an averaged dynamic characteristic for a car with a gear box of four gears

Those surfaces make trace on plane *v*, *E* denoted by 1 and 2 for the first and fourth gear respectively. The shaded surface presents the change in *E* averaged for the whole range of engine work. The shape of this surface can be obtained during a drive test by introducing weight coefficients with respect to time proportions of each gear (including proportion when not in gear) during the whole time of the test. For example, 50% of time during an FTP-75 test (Fig. 6) is in the third gear, and the values of E obtained from modal analysis for this gear can be assumed to be predominant.

In order to create the averaged dynamic characteristic with respect to gear, the values *E* obtained from modal analysis for each gear can be modified with a coefficient resulting from time proportion of this gear over the total time of the test. As a result, curve 3 (Fig. 8) presents the trace of an averaged surface on plane *v*, *E*, and thus it can be treated as a static characteristic (defining change in *E* with respect to velocity only) close to that assumed in COPERT and HBEFA models [2], [12].

3. Formulation of the approximation task

In general, the task is to define two variable function (velocity and acceleration or velocity and the product of velocity and acceleration) approximating the intensity of emission of a given exhaust component or fuel consumption.

Because of limitations of experimental measurements and specification of the tests made on the engine test bed, the gathered information is discrete. Thus, in the first step of approximation, one assumes the density of net cells which allows determination of components (cells) of the matrix, for example as in Fig. 1. When data available are only from one drive test, this division should result in too many elements, since the measurement information will be missing for too many elements of the matrix. Fig. 9 presents the percentage of elements without information as a result of the increase in density of the net for the range of coordinates obtained in the FTP-75 test.

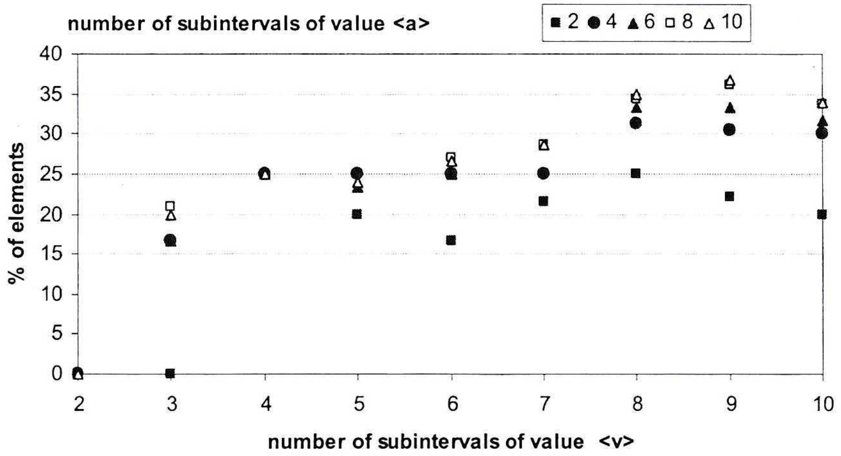

Fig. 9. Percentage of matrix elements without measurement information with respect to density of coordinate division in system of v and a obtained from the FTP-75 test

Having analysed relationships presented in Fig. 9, we can see that in the case considered the division which guarantees that 65% of elements are filled with averaged measurement information should be in the range between two and six subintervals for the measured range of accelerations. In [3] it is said that in the case of coordinates of velocity and the product of velocity and acceleration greater density of the matrix can be achieved with measurement information of at least 65% of elements. Thus, dynamic characteristics obtained using various methods are often presented as a function of velocity and the product of velocity and acceleration. Such a coordinate system also eliminates the problem of conditioning the characteristic shape described in the previous section.

Fig. 10 shows the relationship defining the percentage of elements without measurement information for the range of coordinates obtained in the NEDC test with respect to density of division.

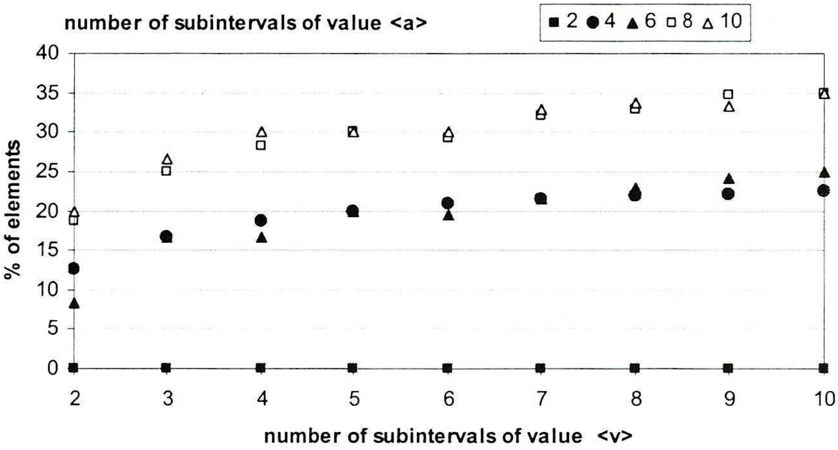

Fig. 10. Percentage of matrix elements without measurement information with respect to density of coordinate division in system of v and a obtained from the NEDC test

Determination of a sufficient number of averaged measurements for a given element is another problem. Some research in this field was carried out in the framework of European projects [8].

Having divided the matrix into elements, we can average the measured values for each element. The average value in a given element is a weighted mean in the form:

$$f_e = \frac{\sum_{i=1}^{n} \alpha_i f_{e,i}}{\sum_{i=1}^{n} \alpha_i} \tag{5}$$

where: α_i – weighted coefficient dependent on the gear for which the measurement was taken,

$f_{e,i}$ – value measured.

Weighted coefficients α_i reflect real time proportion of drive with a given gear during the drive test.

The averaged values are used for approximation of a function with two variables in the way described below.

It is assumed that the approximating function takes the general form:

$$W(x,y) = \sum_{i=0}^{n_x} \alpha_i x^i \cdot \sum_{j=0}^{n_y} b_j y^j, \tag{6}$$

with $(n_x + 1) \cdot (n_y + 1)$ coefficients.
Introducing denotation $c_{ij} = a_i \cdot b_j$ into (6), the following is obtained:

$$W(x,y) = \sum_{i=0}^{n_x} \sum_{j=0}^{n_y} c_{ij} x^i y^i. \tag{7}$$

The task of formulation of the approximating function in form (3) can be defined as searching for such values of parameters c_{ij}, for which functional Ω defined in (8) is minimized by means of a sum of least squares:

$$\Omega\,(c_{00} \dots c_{n_x n_y}) = \sum_{e=0}^{m} \left(\sum_{i=0}^{n_x} \sum_{i=0}^{n_y} c_{ij} x_e^i y_e^j - f_e \right)^2, \tag{8}$$

where $(m + 1)$ is the number of matrix elements for which values f_e (intensity of emission or fuel consumption) are known.

The sufficient and necessary condition for $\Omega(c_{ij})$ to achieve the minimum is:

$$\frac{\partial \Omega}{\partial c_{ij}} = 0. \tag{9}$$

Taking into account (8) from equations (9) one can obtain:

$$\sum_{s=0}^{n_x} \sum_{r=0}^{n_y} c_{sr} \sum_{e=0}^{m} x_e^{s+i} y_e^{r+j} = \sum_{k=0}^{m} f_e x_e^i y_e^j, \tag{10}$$

for $i = 0,\dots,n_x$; $j = 0,\dots,n_y$.

Solution of the set of equations (10) enables us to calculate the coefficients c_{ij} and to construct approximating surfaces of emission intensity of exhaust components and fuel consumption. The choice of coefficients n_x and n_y, which do not need to be identical, is another problem.

4. Verification of dynamic characteristics obtained by means of approximation

In order to determine optimal choice of approximation coefficients and achieve acceptable concordance of approximating surfaces with real values, an additional numerical experiment has been carried out. This was numerical simulation of drive tests and calculations, on the basis of the characteristic obtained by means of approximation, of the sum of each exhaust component and the amount of fuel consumed. Then, the simulation results were compared with the experimental measurement results, and thus a comparison of both numerical and measurement results was made.

The data for the dynamic characteristics presented below were obtained from three FTP-75 and NEDC tests carried out at a Certified Laboratory of Exhaust Gas Toxicity at the Research & Development Centre BOSMAL. Threefold repetition of both tests enabled us to average the results of experimental measurements and eliminate accidental errors. A class B passenger car with a mass of 1200 kg and petrol engine was used for experimental measurements. The data of emission intensity and fuel consumption were obtained by means of modal analysis with a time step of one second.

The approximation algorithm presented has been used for formulation of the dynamic characteristic of intensity of emission of carbon monoxide (CO), nitrogen oxide (NO_x) and carbon dioxide (CO_2) as well as the dynamic characteristic of fuel consumption. First, approximation of dynamic characteristics on the basis of only one test is considered. The data obtained from the NEDC test were limited to those of the same range of velocity as in the FTP-75 test. For the intervals of parameters v and a, the same division is carried out, so that for both tests 70% of elements contain averaged information. Possible values of parameters n_x, n_y for approximation for each test are presented in Table 3.

Table 3

Approximation parameters (n_x, n_y) with respect to the drive test

	(n_x, n_y)
FTP-75	(1,1); (1,2); (1,3); (2,1); (2,2); (2,3); (3,1); (3,2); (3,3)
NEDC	(1,1); (1,2)

Juxtaposition of possible values of approximation parameters (Table 3) illustrates the limitations of data from the NEDC test. In the next step, the class of approximating surface of the dynamic characteristic of a given dependent parameter (CO, NO_x etc) was chosen. The criterion of choice was the following relation:

$$\min |S_{n_x,n_y} - S_e| \tag{11}$$

where S_{n_x,n_y} is total emission or fuel consumption during the whole test calculated using the characteristic, S_e is total emission or fuel consumption respectively, measured experimentally.
For the car analysed, the results of criterion (11) are presented in Table 4.

Table 4

Approximation parameters (n_x, n_y) for each test according to the criterion assumed

	CO	NO_x	CO_2	Fuel
FTP-75	(3,3)	(2,3)	(2,2)	(2,3)
NEDC	(1,1)	(1,1)	(1,2)	(1,1)

By analyzing values of parameters for which (11) gives the minimal value for the FTP-75 test, one can see a clear difference in the approximation class for each dependent value.

Further analysis also includes the results of approximation of data obtained by averaging data from both test. Criterion (11) has also been used in this case for the choice of approximation class; however, parameters (n_x, n_y) were determined for each test separately by comparing results of approximation with results of experimental measurements. The optimal parameters, according to the criterion assumed, are presented in Table 5.

Table 5

Approximation parameters (n_x, n_y) chosen for averaged data of both test with respect to criterion (11)

	CO	NO_x	CO_2	Fuel
FTP-75	(1,2)	(2,3)	(1,3)	(2,3)
NEDC	(3,1)	(3,3)	(3,3)	(3,3)

Figs 11 and 12 present the percentage differences between the total sum obtained for the approximation class assumed for each dependent parameter according to tables 4 and 5, and the experimental results (which are assumed as 100%) for the FTP-75 and NEDC tests.

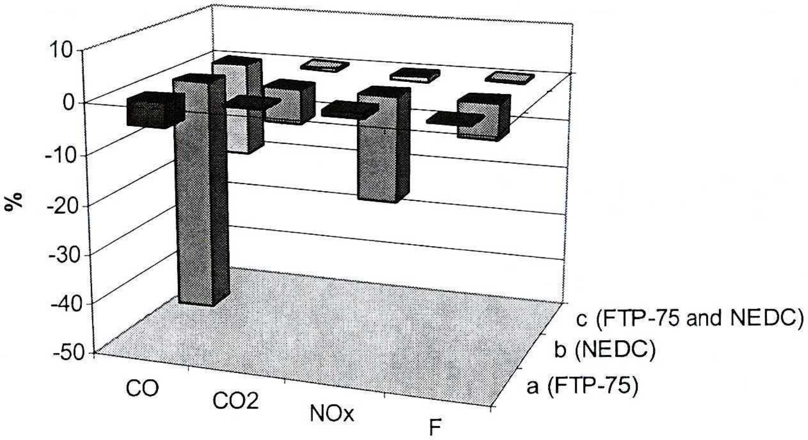

Fig. 11. Percentage difference between S_{n_x,n_y} and S_e for FTP-75 test when the dynamic characteristics are assumed on the basis of a) only FTP-75 test, b) only NDEC test, c) both tests

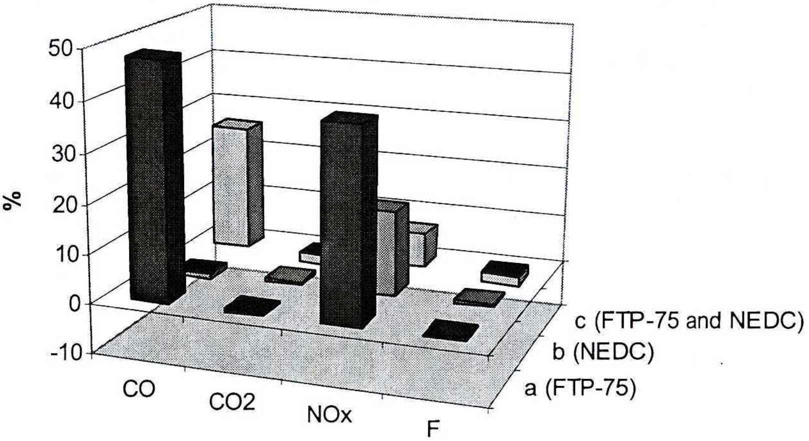

Fig. 12. Percentage difference between S_{n_x,n_y} and S_e for NDEC test when the dynamic characteristics are assumed on the basis of a) only FTP-75 test, b) only NDEC test, c) both tests

The analysis of data presented in Figs 11 and 12 demonstrates certain regularities. By using the dynamic characteristic obtained by means of approximated data from a different test, divergence of even 50% can be obtained. However, use of the characteristic obtained from the FTP-75 test ensures compatibility in total emission of carbon dioxide and fuel consumption. In the opposite case, using the characteristic obtained on the basis of NEDC test, the divergence for the components emitted and fuel consumed in the FTP-75 test are smallest for carbon dioxide and fuel. This leads to the conclusion that CO_2 emission and fuel consumption in both tests are well projected. Much better compatibility of results has been obtained using the data averaged from both tests. It is clear that emission of CO and NO_x calculated become smaler when one uses data obtained from a test with lower dynamics (Fig. 11b) and larger for data from test with higher dynamics (Fig. 12a).

The next graphs present dynamic characteristics of emission of the components of exhaust gas and of fuel consumption using the averaged data from both test. For the approximation it has been assumed that $n_x = n_y = 2$, and the respective characteristics are shown in Fig. 13.

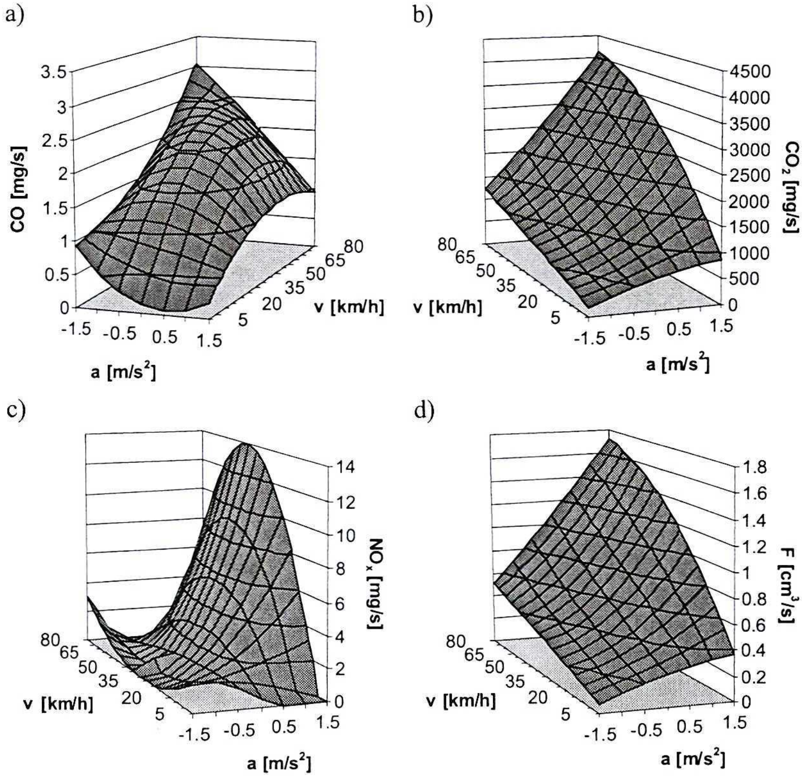

Fig. 13. Dynamic characteristics of: a) intensity of emission of CO, b) intensity of emission of CO_2, c) intensity of emission of NO_x, d) fuel consumption

5. Final remarks

A method of creating dynamic characteristics using data obtained from drive tests is presented. A procedure of averaging results when information about gears is taken into account is described, and problems associated with division of the coordinates into elements which are approximation nodes are discussed. The methodology presented is then used for formulation of dynamic characteristics of intensity of emission of some components of exhaust gas and fuel consumption for a car with an SI engine. A congruence of information obtained from two drive tests, FTP-75 and NDEC, was analysed and verified with respect to the results obtained experimentally. The conclusions are as follows:

- Data obtained from the European NEDC test can be included in a data base for approximation of dynamic characteristics,
- Approximation of intensity of emission of CO_2 and fuel consumption gives correct results regardless of the test used for data,
- Approximation parameters can vary for every toxic component of exhaust gas and also for a specific car.

The methodology presented can be used in formulation of models of emission of toxic components of exhaust gas. These models, together with the models of diffusion of pollution, enable us to estimate the influence of traffic on the environment.

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O pewnej metodzie tworzenia charakterystyk dynamicznych w oparciu o testy jezdne

Streszczenie

W artykule przedstawiono metodykę tworzenia charakterystyk dynamicznych zużycia paliwa i natężenia emisji związków szkodliwych spalin. Jako źródło danych wykorzystano wyniki analizy modalnej natężenia emisji i zużycia paliwa uzyskane podczas realizacji hamownianych testów jezdnych. Wykorzystano dwa legislacyjne testy jezdne: europejski NEDC i amerykański FTP-75. Opisano ogólny algorytm tworzenia charakterystyk dynamicznych w postaci funkcji aproksymujących dane pomiarowe. W artykule przedstawiono również przykłady uzyskanych charakterystyk dynamicznych dla rzeczywistego samochodu z silnikiem o zapłonie iskrowym. Porównano i skomentowano wyniki otrzymane z badań rzeczywistych i symulacyjnych.