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INFLUENCE OF FUELLING WITH PETROL AND LPG GAS ON OPTIMAL ECONOMICAL AND ECOLOGICAL CAR ACCELERATION

The paper presents methodology for calculating optimal drive torques which ensure reduced or minimal fuel consumption and emission of toxic components of exhaust gas during acceleration of a car. Data for fuel consumption and toxic emission in dynamic conditions (for a run with changeable speed) are obtained using experimental measurements during typical drive tests. A dynamic optimization problem for calculating a drive torque has been formulated using dynamic characteristics and a simple mat hematical model a vehicle when travelling in a straight line. The optimization problem has been solved for a drive with petrol and LPG. Results of numerical calculations followed by conclusions are presented.

1. Introduction

Scientific literature presents many publications showing the abilities of applications of algorithms of dynamic optimization for solving issues of cars movement. For example in [11] the authors optimized congested traffic flow, with a stochastic car-following model, by controlling traffic lights with the aim of minimizing the emission of CO_2. In [12] the authors looked at problems of using optimizing algorithms for controlling the flow of energy in hybrid car drive systems. The issues of modeling and optimizing the reduction of CO_2 emission from car engines are dealt with in paper [13].

The above-mentioned publications are merely examples of applications of optimizing methods, in which the issues of cars movement are based on static characteristics. In the following paper an attempt is made at optimizing

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car acceleration based on unique dynamic characteristics by the authors, presented in [2], [14].

Determination of an engine drive torque which ensures reduction or minimization of fuel consumption and toxic emission while accelerating a car is an interesting problem both in its practical and theoretical aspects. Acceleration of a car means here increase in speed of a certain value over a given time period. This was also a subject of the authors' previous research [1].

The solution of the problem requires:

- Definition of data for dynamic characteristics of fuel consumption and toxic emission
- Formulation of a dynamic model of a vehicle
- Solution of the optimization task

Considerations in paper [1] are limited to minimization of fuel consumption assuming a model of a car with one degree of freedom. This paper presents experimental and computational methods enabling us to formulate and solve the problem without limitations assumed in [1].

We suggest that the data of unit fuel consumption and intensity of toxic emission assumed are in the form of dynamic characteristics. By using experimental measurements and modal analysis of the measured results of fuel consumption and toxic emission during typical drive tests it is possible to define unit fuel consumption and toxic emission of gas exhaust components with respect to instant velocity and acceleration [2].

The model of a car (formulated with 9 degrees of freedom) enables the parameters of car motion for a given course of drive torque to be calculated; this model is then used in the optimization task.

The aim of the optimization is to determine parameters of the drive torque in order to reduce or minimize fuel consumption and toxic emission of exhaust gas components. Since a defined course of the drive torque results in a specific course of velocity and acceleration of a vehicle, it is possible to determine fuel consumption and toxic emission of exhaust gas components for a given drive torque on the basis of dynamic characteristics. Thus, the strategy of accelerating the car can be chosen according to the solution of the dynamic optimization task, in which it is necessary to integrate the equations of motion several times in order to calculate the value of the objective function and the constraints. Such an approach successfully used in [1], [3], [4], [5] is an effective tool for solving the optimization problem for ESP systems and is also used in this paper.

2. Dynamic characteristics

Dynamic (ecological) characteristics mean here dependencies of unit fuel consumption and intensity of toxic emissions on car velocity and accelerations [6]. The authors of [2] suggest defining such characteristics using the modal analysis of fuel consumption and emission of exhaust as components measured during drive tests. Encouraging results have been obtained using FTP-75 and NUDC tests carried out for a passenger car at a certified exhaust gas toxicity laboratory of the Research and Development Centre BOSMAL in Bielsko-Biała. Drive tests were created so that the frequency features of the processes characterizing traction are well mapped. Usually drive tests begin with a cold start and during this phase fuel consumption and emission of exhaust gas are much higher than during the remaining time of the drive test with nominal work of the catalyst [7]. In this paper the results analysed are those which were obtained when the catalyst temperature was above 350°C (at its nominal work stage). Test FTP-75 [8] is taken as the primary one, and this is justified by the frequency analysis of velocities and time analysis of accelerations described in [6]. The author points to more dynamic features of American tests in comparison with European tests. Paper [2] describes how to create an averaging dynamic characteristic that takes into account gear change in road cycles. Figs 1,2 and 3 present averaging dynamic characteristics of unit fuel consumption E_0 and emission intensities of carbon monoxide CO – E_1 and nitric oxide NO_x for engines using petrol or LPG.

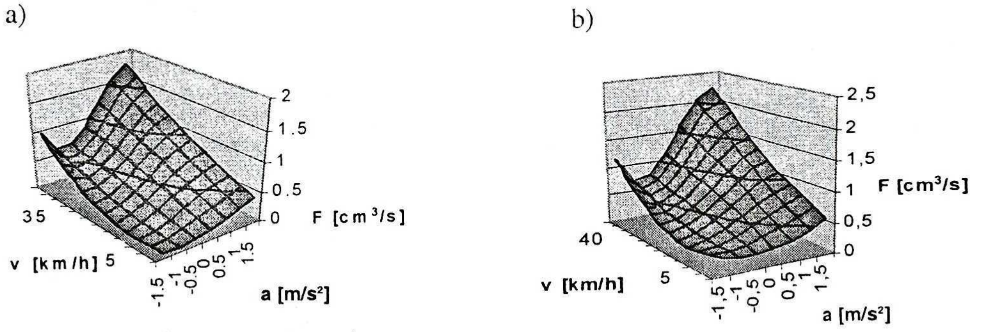

Fig. 1. Averaging dynamic characteristics of fuel consumption: a) petrol, b) LPG

The use of averaging characteristics eliminates the problem of gear changes from further considerations, thus simplifying of the optimization task. Universal dynamic characteristics shown in Figs 1, 2 and 3 are used in numerical calculations, the results of which will be presented below.

a) b)

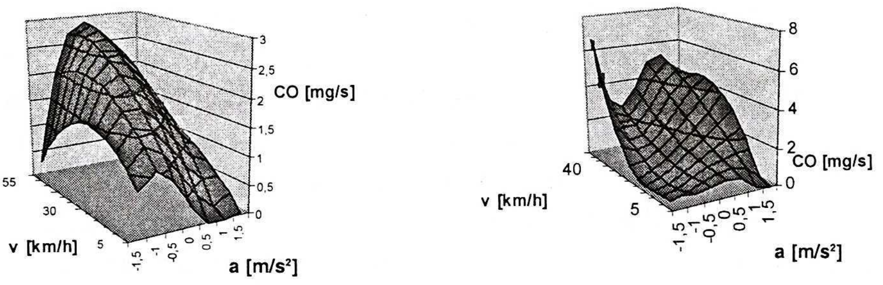

Fig. 2. Averaging dynamic characteristics of carbon monoxide emission: a) petrol, b) LPG

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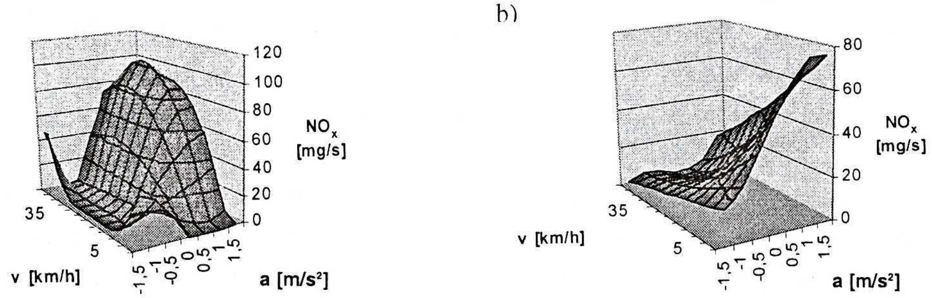

Fig. 3. Averaging dynamic characteristics of nitric oxide emission: a) petrol, b) LPG

3. Mathematical model of a car

After calculating kinetic and potential energies, the equations of motion are derived from the Lagrange equations. The Lagrange equations can be presented in the form:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{\mathbf{q}}} - \frac{\partial T}{\partial \mathbf{q}} + \frac{\partial V}{\partial \mathbf{q}} = \mathbf{Q} \tag{1}$$

where T – kinetic energy of the system,
V – potential energy of the system,
$\mathbf{Q}$ – vector of generalised forces,
$\mathbf{q}$ – vector of generalised coordinates.

The procedure of deriving the equations of motion according to (1) is presented below.

It is assumed that a car moves in a straight line, which allows us to consider its planar model. The car is treated as a system of 5 masses (Fig.4):

- car body n with three degrees of freedom; its position is described by coordinates x_n, z_n, θ;
- suspensions z_1 and z_2 are treated as lumped masses with two degrees of freedom, each describing the motion of the suspension with respect to

the car body (Δx_{z_1}, Δz_{z_1} and Δx_{z_2}, Δz_{z_2} respectively) and connected to the car body by spring-damping elements;
- wheels are rigidly connected to suspensions; φ_1, φ_2 are degrees of freedom describing the motion of the wheels with respect to the suspensions.

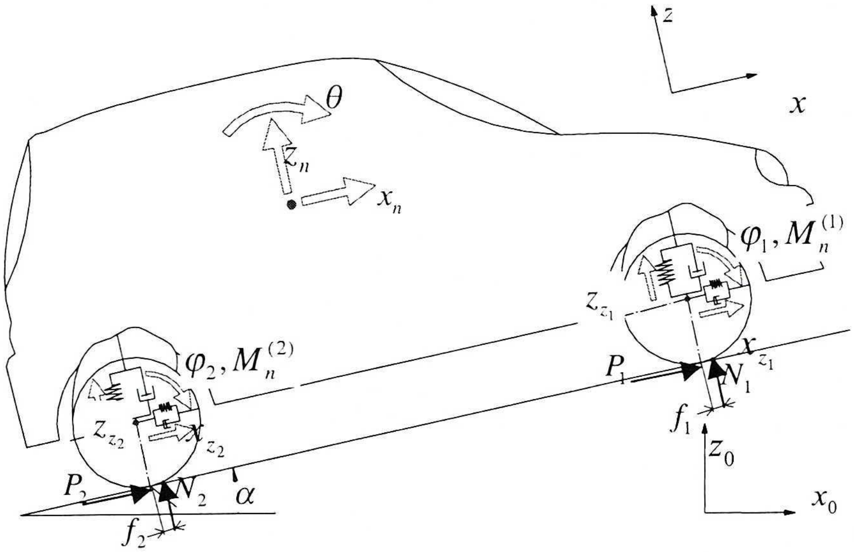

Fig. 4 Model of a car

In the case considered the vector of the generalized coordinates of the whole system has the following components:

$$\mathbf{q}_n = [x_n \;\; z_n \;\; \theta \;\; \Delta x_{z_1} \;\; \Delta z_{z_1} \;\; \varphi_1 \;\; \Delta x_{z_2} \;\; \Delta z_{z_2} \;\; \varphi_2]^T \tag{2}$$

and it can be written in a different form as:

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_n \\ \mathbf{q}_{z1} \\ \varphi_1 \\ \mathbf{q}_{z2} \\ \varphi_2 \end{bmatrix}, \tag{3}$$

where $\mathbf{q}_n = [x_n \;\; z_n \;\; \theta]^T$ – generalised coordinates of the car body,
$\mathbf{q}_{zk} = [x_{z_k} \;\; z_{z_k}]^T$ – generalised coordinates of suspension k,
φ_k – turning angle of wheel k.

The kinetic energy of the system is the sum of energies of all subsystems considered: car body, suspensions and wheels:

$$T = T_n + T_{z_1} + T_{z_2} + T_{k_1} + T_{k_2} \tag{3}$$

where T_n – kinetic energy of the car body,
T_{z_k} – kinetic energy of suspension k,
T_{k_k} – kinetic energy of wheel k,
$k = 1$ – front, $k = 2$ – rear.

Having carried out necessary calculations and transformations described in [9], we obtain the following:

$$\varepsilon(T) = \frac{d}{dt}\frac{\partial T}{\partial \dot{\mathbf{q}}} - \frac{\partial T}{\partial \mathbf{q}} = \mathbf{A}\ddot{\mathbf{q}} + \mathbf{h}, \tag{4}$$

where elements of matrix $\mathbf{A}$ and vector $\mathbf{h}$ are described in [9].

The sum of potential energies resulting from the gravity forces and spring deformations of suspensions is:

$$V = V_{gn} + \sum_{k=1}^{2} V_{gzk} + \sum_{k=1}^{2} V_{g\varphi k} + \sum_{k=1}^{2} V_{szk}, \tag{5}$$

where V_{gn} – potential energy of gravity of the car body,
V_{gzk} – potential energy of gravity of suspension k,
$V_{g\varphi k}$ – potential energy of gravity of wheel k,
V_{szk} – potential energy of spring deformation of suspension k.

After necessary transformations the following is obtained [9]:

$$\frac{\partial V}{\partial \mathbf{q}} = \mathbf{g} = \begin{bmatrix} \mathbf{g}_n^{(n)} + \sum_{k=1}^{2} \mathbf{g}^{(z_k)} \\ \hline \mathbf{g}_{z_1}^{(z_1)} + \mathbf{c}_{z_1}^{(z_1)} \\ \hline 0 \\ \hline \mathbf{g}_{z_2}^{(z_2)} + \mathbf{c}_{z_2}^{(z_2)} \\ \hline 0 \end{bmatrix} \tag{6}$$

The method of calculating the components of vector **Q** is also presented in [9]. Forces N_1, P_1 and N_2, P_2 (Fig.5), on which the generalised coordinates depend, are calculated according to the Dugoff-Uffelman model described in [4], which takes into account wheel spin.

The equations of motion are written in the form:

$$\mathbf{A}\ddot{\mathbf{q}} = \mathbf{F}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{Q} - \mathbf{h} - \mathbf{g}. \tag{7}$$

and consist of 9 ordinary differential equations of the second order. The Runge-Kuttv method of the fourth order is used for solving the equations of motion.

4. Dynamic optimization

Determination of characteristics of fuel consumption and toxic emission of exhaust gas and the mathematical model of the car make it possible to formulate the dynamic optimization task.

In this paper, it is assu med that the components of the following vector are the design variables which have to be found:

$$\mathbf{X} = \begin{bmatrix} X_0 \\ \dots \\ X_i \\ \dots \\ X_p \end{bmatrix}, \tag{8}$$

where $X_i = M_n^{(i)}(t_i)$, $t_i = t_0 + i \cdot h$, $h = \dfrac{t_k - t_0}{p}$,

t_0, t_k – start and end time of the movement of the car,

$p+1$ – the number of points at wkich the values of the drive torque are sought (Fig.5).

It is also assumed that the drive torque is interpolated by cubic splines of the third order:

$$\begin{gathered} M_n^{(1)}(t) = a_i(t - t_{i-1})^3 + b_i(t - t_{i-1})^2 + c_i(t - t_i) + d_i \\ \text{for } t \in \langle t_{i-1}, t_i \rangle, i = 1,..,p. \end{gathered} \tag{9}$$

This ensures continuity of the function and its first and second derivatives. The characteristics of fuel consumption and toxic emission discussed in section 2 enable the following relation to be defined:

$$E = E_i(v_n, a_n) = E_i(\dot{q}, \ddot{q}), \tag{10}$$

where $v_n = \dot{q}$, $a = \ddot{q}$, q – defined in (3),
E_0 – intensity of fuel consumption,
E_i – emission of the i-th component of the exhaust gas ($i = 1, ..., S$).

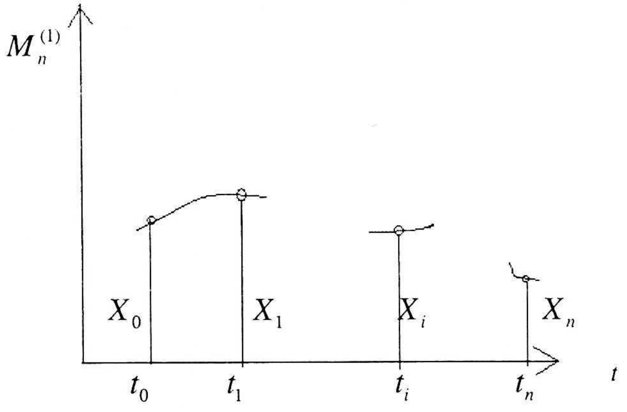

Fig. 5. Interpretation of the design variables $X_i = M_n^{(1)}(t_i)$

The relation between the vector of design variables **X** and the vector of generalized coordinates is defined in (7), with additional initial conditions which form an initial value problem for a set of ordinary differential equations in the form:

$$\mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} = \mathbf{F}(t, \mathbf{X}, \mathbf{q}, \dot{\mathbf{q}}) \tag{11.1}$$

$$\mathbf{q}(t_0) = \mathbf{q}^{(0)}, \tag{11.2}$$

$$\dot{\mathbf{q}}(t_0) = \mathbf{q}^{(1)}, \tag{11.3}$$

where $\mathbf{q}^{(0)}$, $\mathbf{q}^{(1)}$ are known initial values of generalised coordinates and velocities.
The optimisation task is formulated as follows:
Minimise

$$\Omega = \Omega(X) = \sum_{i=0}^{S} c_i \int_{t_0}^{t_k} E_i(\dot{\mathbf{q}}, \ddot{\mathbf{q}})\,dt, \tag{12}$$

where c_i – coefficients,

when the following constraints are satisfied:

$$v_n(t_0) = v_0, \tag{13.1}$$
$$v_n(t_k) = v_k, \tag{13.2}$$

which means that a car with velocity v_0 at t_0 will attain velocity v_k at t_k. Functional (12) is also subject to the following constraints:

$$N_i(\mathbf{X}, \mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \le 0, \quad i = 1,...,r. \tag{14}$$

Solving (12), (13) and (14) is difficult because in order to calculate values $\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$ for a given $\mathbf{X}$ the equations (11) have to be integrated. This means that at each optimization step the initial problem (11) has to be solved. Thus the model describing the dynamics of the car should not be too complicated. In this paper the downhill simplex method [10] is used for solving the optimization problem. This method has been successfully used for similar problems connected with ESP systems [3], [4].

5. Results of calculations and analysis

The characteristics presented in Figs 1, 2 and 3 are assumed for numerical calculations. Parameters of the car are those of a Seicento Fiat with an engine 1200 cc. The parameters of tires in the Dugoff-Ufflman method are taken as in [4], [9]. The characteristics in Figs 1,2 and 3 are averaging characteristics which do not require the gear to be defined. However, in order to solve the optimization task for car acceleration it is necessary to determine the gear because some of the constraints (14) concerning drive torques and thus moment $M_n^{(1)}$ and design variables $X_0,...,X_p$ depend on the gear. Fig. 6 presents limitations of the drive moment $M_n^{(1)}$ for the second and third gear with respect to the speed of the car.
Below two tasks are considered.

Task 1: $t_0 = 0$, $v_0 = 5$ m/s, $t_k = 20$ s, $v_k = 15$ m/s, 2nd gear

The optimization method assumed, like most other methods, is sensitive to the initial values of design variables; in this case the values of the drive moment $M_{n.0}^{(1)}(t)$. For numerical calculations it has been assumed that $M_n^{(1)}(t) = M_{n.0}^{(1)}(t) = X_i = 277\ Nm$ (for $i = 0,...,p$). Such a moment ensures that $v_k(t_k) = 15\ m/s$. Then the numerical calculations were carried out and the optimal courses of moments $M_n^{(1)}$ were calculated using spline functions through points $(t_i, X_i)(i = 0,...,p)$ for the following cases:

P1. $c_0 = 1, c_1 = 0, c_2 = 0,$

P2. $c_0 = 0, c_1 = 1, c_2 = 0,$

P3. $c_0 = 0, c_1 = 0, c_2 = 1,$

P4. $c_0 = \frac{1}{I_{0C}}, c_1 = \frac{1}{I_{1C}}, c_2 = \frac{1}{I_{2C}},$

where I_{0C} – fuel consumption, I_{1C} – CO emission, I_{2C} – NO_x emission, taken for a constant value of drive torque assumed for the initial approximation.

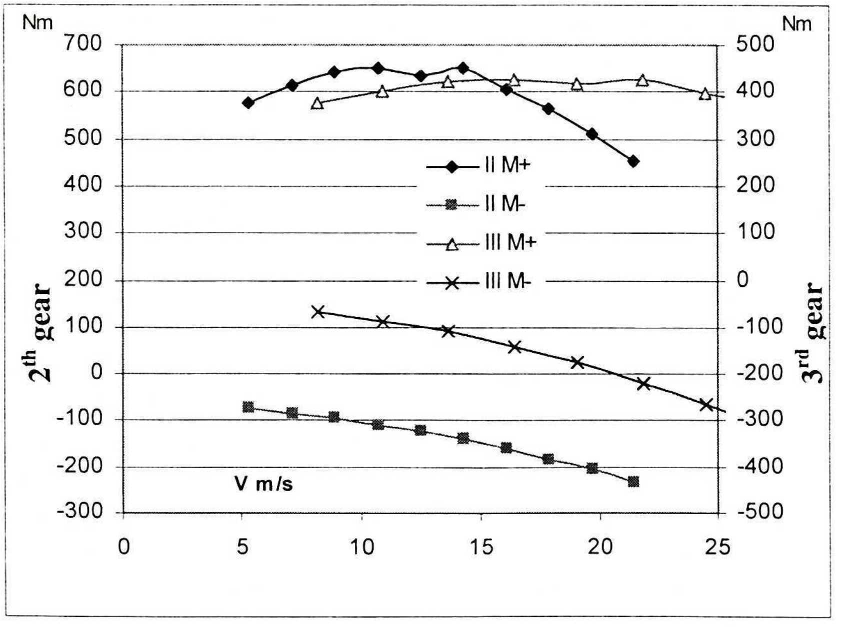

Fig. 6. Limitations of the drive moments for the second (II) and third (III) gear
M+ – positive value, M- – negative value

Cases P1, P2, P3 refer to the optimization problem when only one factor is minimized, either fuel consumption or carbon monoxide or nitric oxide emission. P4 is the case when all three factors are minimized at the same time. Courses of drive torques (for the cases considered) when petrol is the fuel are presented in Fig.7. In this figure percentage values of $I_0, I_{0C}, I_1, I_{1C}, I_2, I_{2C}$ are also presented (values I_{0C}, I_{1C}, I_{2C} are assumed to be 100 %). The measurement units are as follows: for I_{0C}, I_0 – cm^3, for I_{1C}, I_1 – mg, for I_{2C}, I_2 – ppm. The largest reduction has been achieved for cases P3 and P4 (minimization of NO_x emission and polyoptimisation).

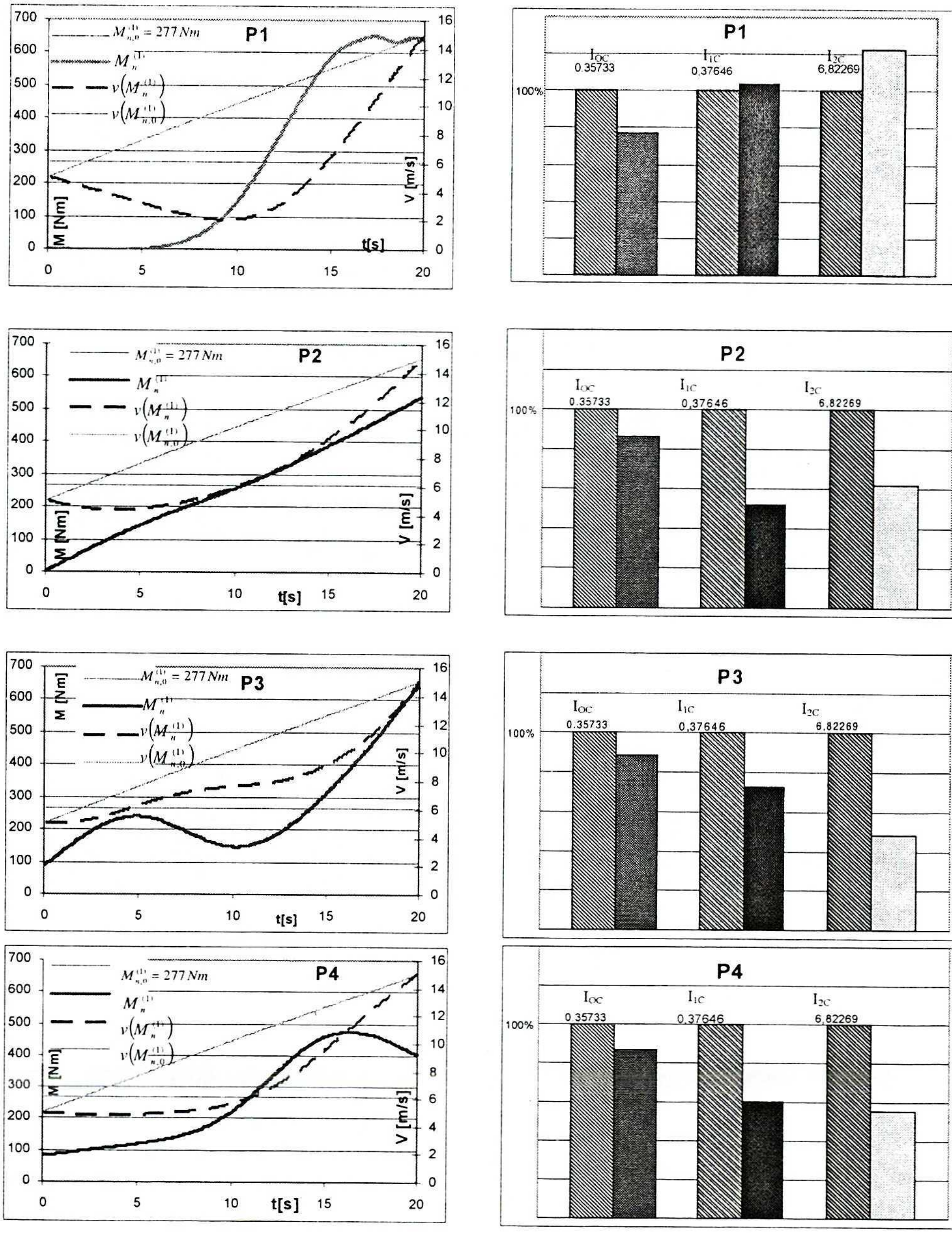

Fig. 7 Courses of drive moment and velocity of the car for the task 1, cases P1, P2, P3, P4. Petrol feed

Fig. 8 shows the results of calculations with LPG fuel. Reductions in fuel consumption and emissions of CO and NO_x are not as significant as in the case of petrol.

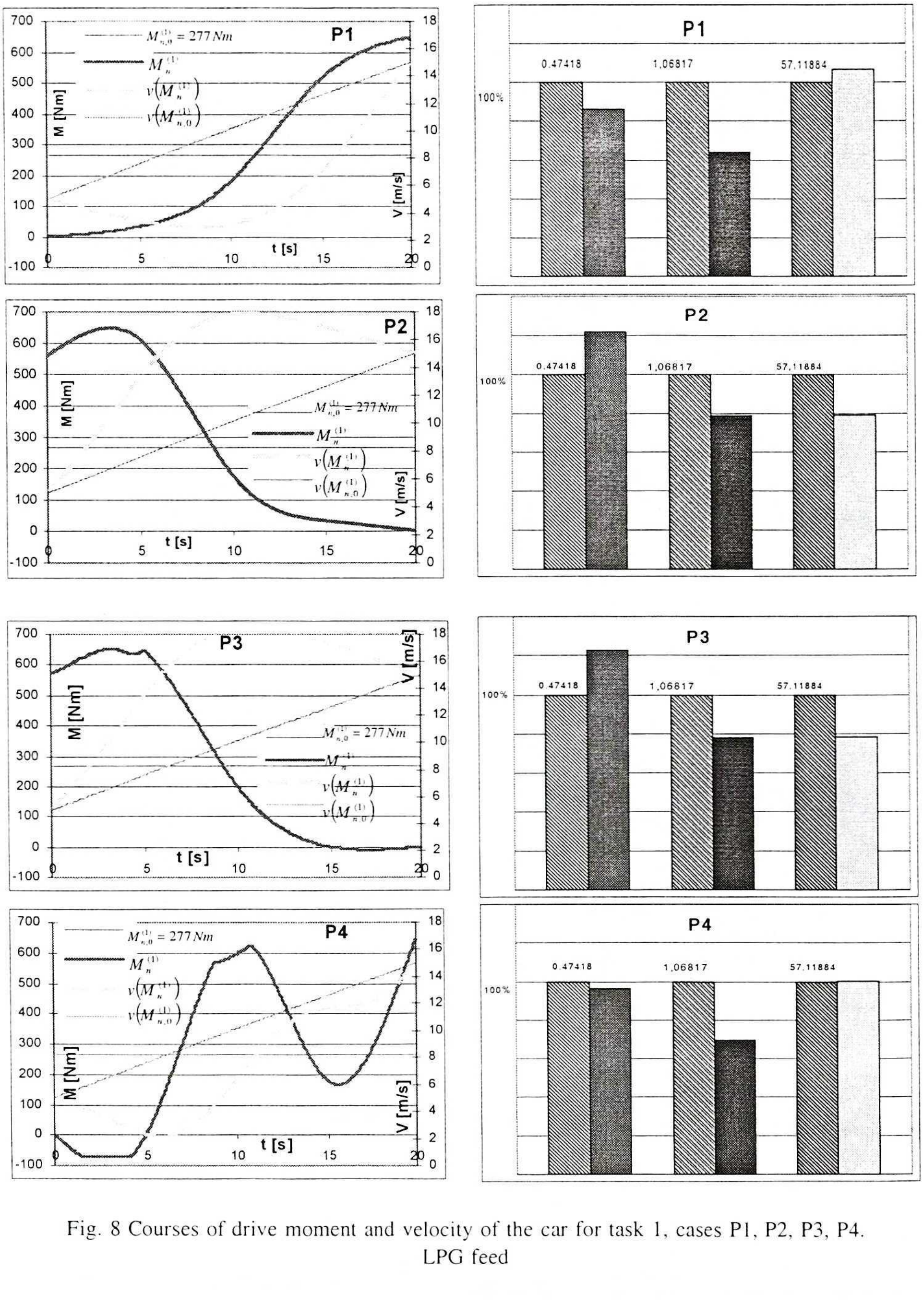

Fig. 8 Courses of drive moment and velocity of the car for task 1, cases P1, P2, P3, P4. LPG feed

In Fig. 9 comparison of the drive moment and velocity of the car for both fuels and in all cases are presented. The differences in the courses of drive torques are significant for all cases.

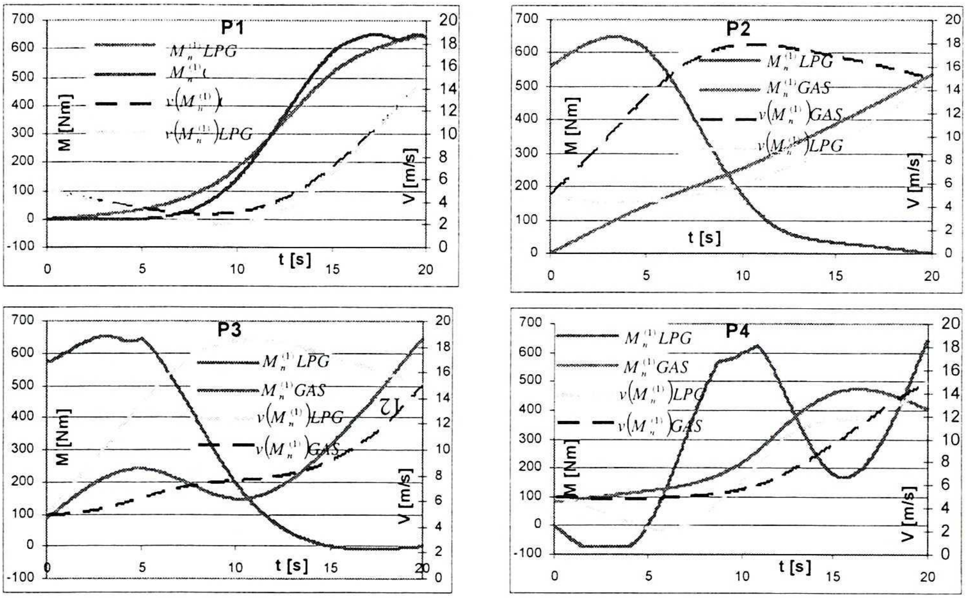

Fig. 9 Influence of fuel on the courses of $M_n^{(1)}$ and v_n in cases P1, P2, P3, P4 task 1

Task 2: $t_0 = 0$, $v_0 = 15$ m/s, $t_k = 20$ s, $v_k = 22{,}5$ m/s, 3rd gear.
In this case the constant value of the drive moment which ensures the condition $v_k(t_k) = 22.5 m/s$, is $M_{n,0}^{(1)}(t) = X_i = 253\ Nm$ $(i = 0,...,p)$. Fig. 10 presents the results of calculations for cases P1, P2, P3, P4 when petrol is the fuel, while in Fig.11 the results are presented when LPG is the fuel. Comparison of optimal drive torques $M_n^{(1)}$ and velocities of the car is shown in Fig. 12.

Whereas the kind of fuel used does not influence the optimal courses of the drive moment in cases P1 and P2, significant differences can be seen for cases P3 and P4. For the calculations discussed it has been assumed that $p = 4$.

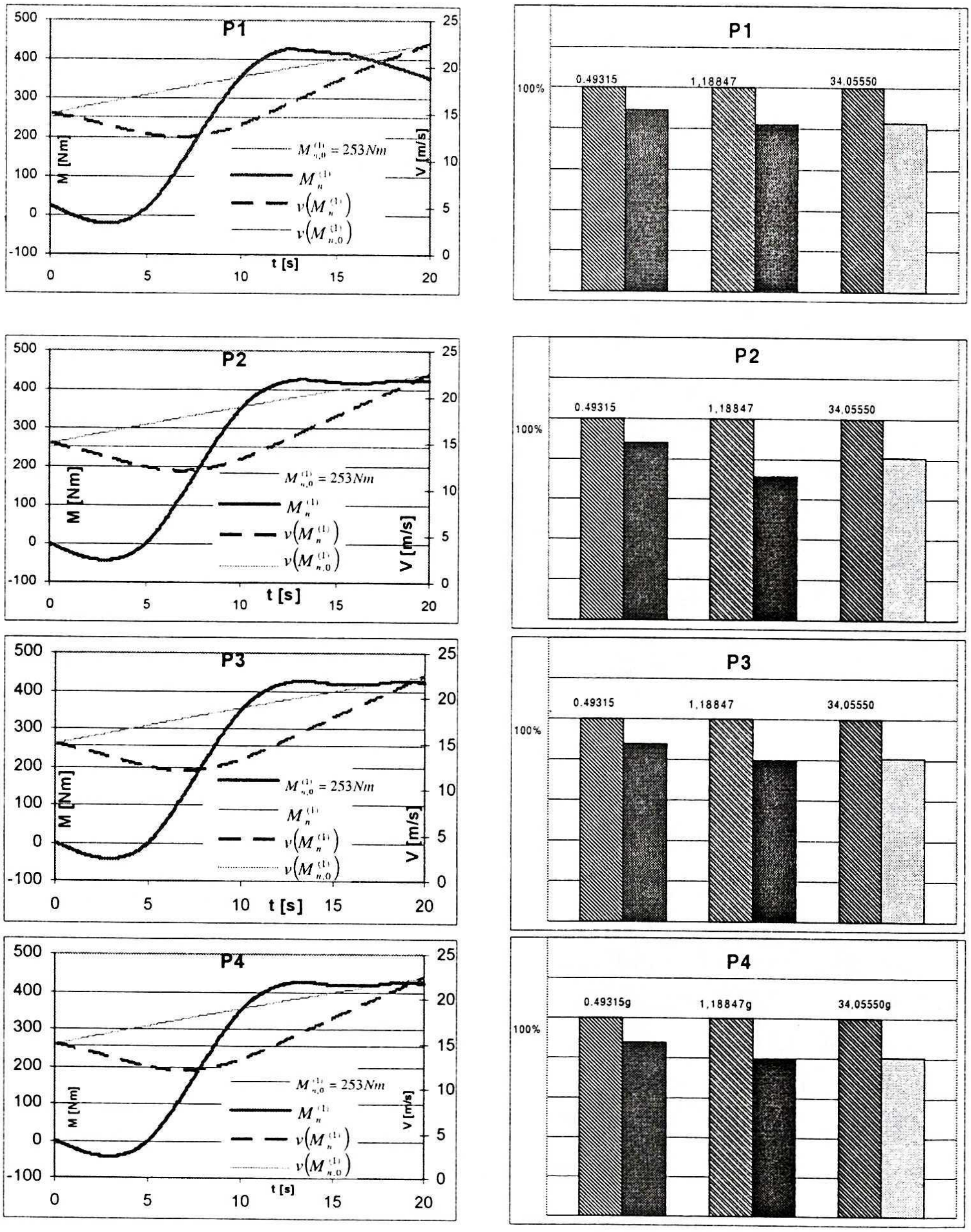

Fig. 10 Courses of drive moment and velocity of the car for task 2, cases P1, P2, P3, P4. Petrol feed

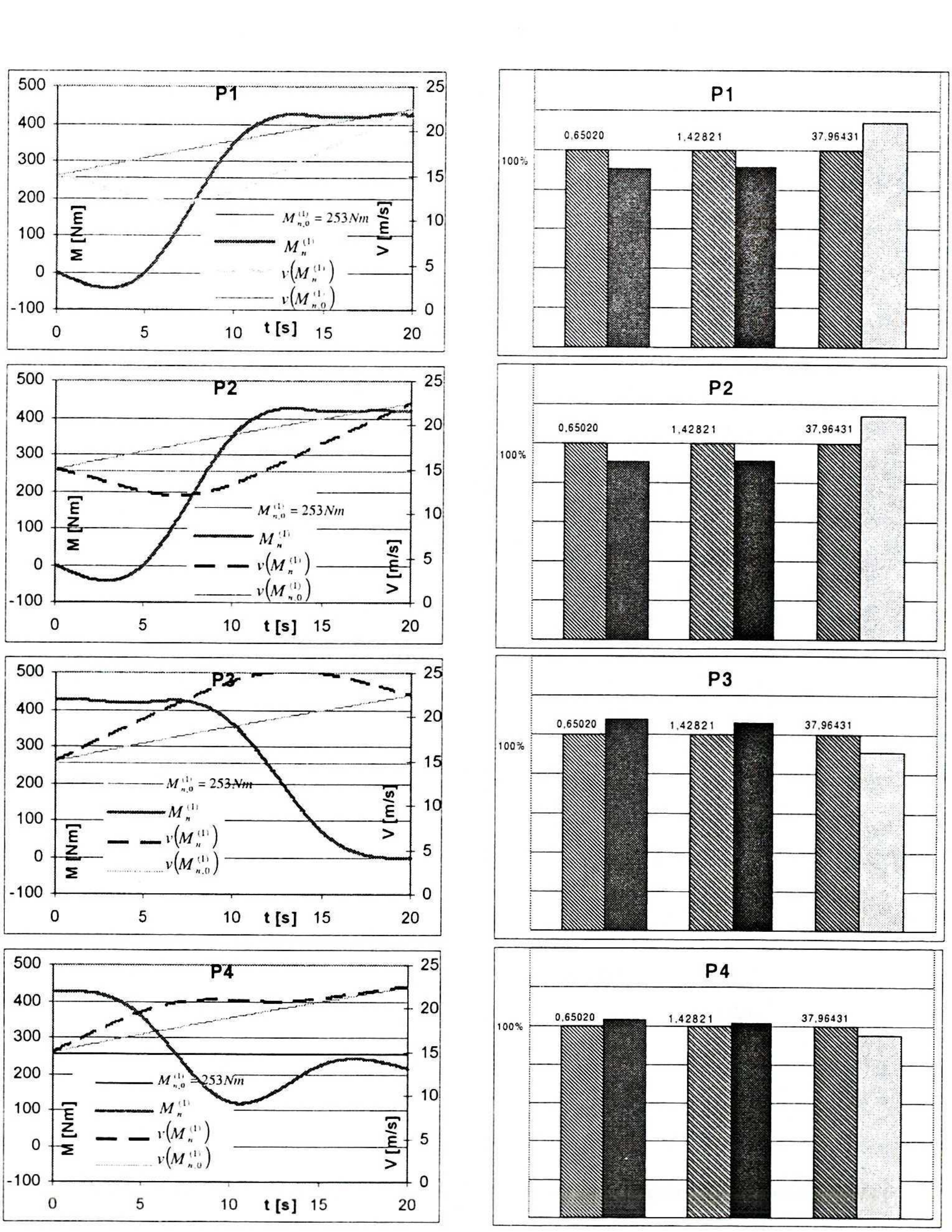

Fig. 11. Courses of drive moment and velocity of the car for task 2, cases P1, P2, P3, P4. LPG feed

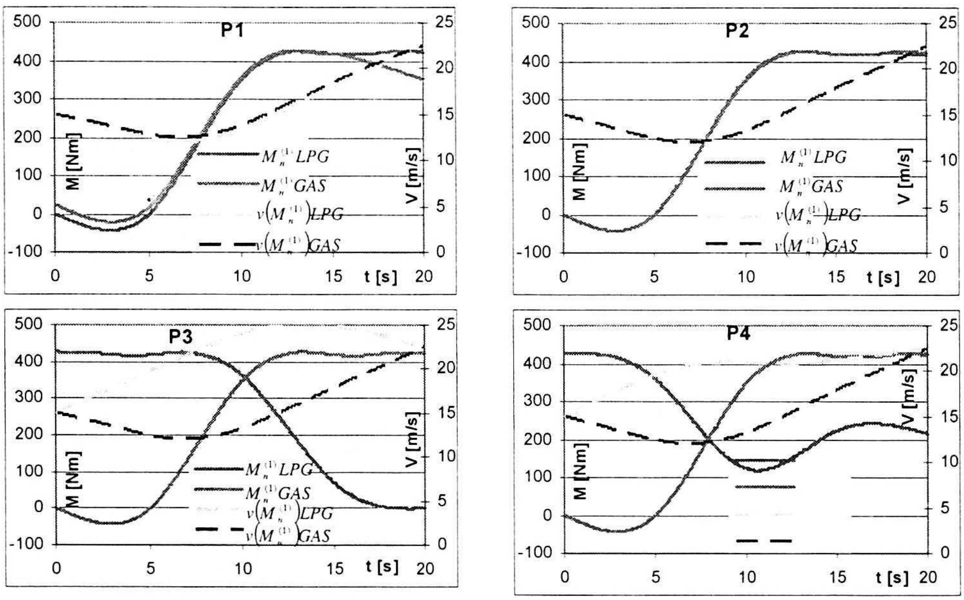

Fig. 12 Influence of fuel on courses $M_n^{(1)}$ and v_n in cases P1, P2, P3, P4, task 2

6. Conclusions

The paper presents an algorithm which enables us to define a strategy of accelerating a car with front-wheel drive in an economical and ecological manner. The dynamic characteristics of fuel consumption and toxic emission of exhaust gas components are obtained from the experimental measurements. A simplified model of a car is presented and the dynamic optimization task is formulated.

Numerical calculations have been carried out and they prove that it is possible to determine a strategy of accelerating a car (course of drive torque) which ensures significant reduction in pollutants compared to that when a constant drive torque is applied. These reductions can be significant.

The time of calculations for a single case does not exceed 20 sec. on an IBM PC 2.4 GHz.

Test calculations have shown that optimal courses of the drive torque $M_n^{(1)}$ are sensitive to the initial approximation. Thus the authors believe in the use of genetic algorithms and they are conducting such research presently.

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REFERENCES

[1] Romaniszyn K., Wojciech S.: Optimization of a vehicles acceleration process. The Archive of Mechanical Engineering, 1996, Vol XLIII/1, pp. 19÷28.

[2] Brzozowski K., Romaniszyn K.: O pewnej metodzie tworzenia charakterystyk ekologicznych pojazdów w oparciu o testy jezdne (in print).

[3] Grzegożek W., Wojciech S.: Time-domain optimisation of braking torque in the EPS system. The Archive of Mechanical Engeneering, 2002, Vol XLIX/1, pp. 65÷79.

[4] Grzegożek W.: Modelowanie dynamiki samochochodu przy stabilizującym sterowaniu siłami hamowania. Scientific Papers in Mechanics 275, 2002, Cracow TU Press.

[5] Grzegożek W., Adamiec I., Wojciech W.: Komputerowe modelowanie pojazdów (in print).

[6] Chłopek Z.: Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej. Scientific Papers in Mechanics 175, 1999, Warsaw TU Press.

[7] Bielaszyc P., Merkisz J., Pielecha J.: Stan cieplny silnika spalinowego a emisja związków szkodliwych. 2001, Poznań TU Press.

[8] Codes of Federal Regulations, Protection of Environment, Title 40, Part 86, Revised as of July 1, 2000. U.S. Government Printing Office Washington 2000.

[9] Adamski W., Romaniszyn K.: Ocena modeli samochodów pod kątem ich przydatności w analizie rozpędzania. XVII Polish Scientific Conference on TMM, Wrocław, 2002, pp. 27÷34.

[10] Wit R.: Programowanie nieliniowe. WNT 1987, Warsaw.

[11] Tomer E., Safanov L., Madar N., Havlin S.: Optimisation of congested traffic by controlling stop-and-go wawes. Phys Rev E Stat Nonlin Matter Phys. Jun 2002.

[12] Ercole G., Brahma A., Guenzennec Y., Rizzoni G.: General supervisory control policy for the energy optimization of charge-sustaining hybrid electric vehicles. JSAE Review Science B. V., Oct. 2001.

[13] Nakata T.: Energy modeling on cleaner vehicles for reducing CO2 emissions in Japan. Journal of Cleaner Production. Jun 2003.

[14] Brzozowski K., Romaniszyn K.: An effective method of creating dynamic characteristics using drive test. The Archive of Mechanical Engineering, Vol. L, 4/2003, pp. 391÷408.

Wpływ paliwa na ekonomiczne i ekologiczne rozpędzanie samochodu

S t r e s z c z e n i e

W pracy przedstawiono metodykę postępowania zmierzającego do obliczeniowego wyznaczenia optymalnych przebiegów momentów napędowych, zapewniających ograniczenie bądź minimalizację zużycia paliwa i emisji składników toksycznych spalin, przy rozpędzniu pojazdu. Dane dotyczące zużycia paliwa i emisji zanieczyszczeń w warunkach dynamicznych (a więc jazdy ze zmienną prędkością) opracowano na podstawie badań stanowiskowych, związanych z analizą modalną zużycia paliwa i emisji spalin przy realizaji typowych testów jezdnych. W oparciu o charakterystki dynamiczne oraz prosty model matematyczny opisujący dynamikę pojazdu przy jeździe na wprost, sformułowano zadanie optymalizacji dynamicznej którego rozwiązanie umożliwia dobór momentu napędowego. Zadanie optymalizacji rozwiązano dla napędu benzyną i LPG. Przedstawiono wyniki obliczeń komputerowych i sformułowano wnioski.