TEKA Kom. Mot. Energ. Roln. – OL PAN, 2007, 7A, 23–34

APPLICATION OF THE TIME DENSITY CHARACTERISTICS IN OPTIMISATION OF PARAMETERS OF AN ENGINE WITH SEQUENTIAL TURBO-CHARGING

Krzysztof Danilecki

Faculty of Motor Vehicles Operation – Technical University of Szczecin,
Al. Piastów 19, 70-310 Szczecin, Poland. E-mail: kdanilecki@ps.pl, tel. +48 (91) 4494077

Summary. Reduced pollution of the natural environment with toxic compounds emitted by motor-vehicle engines is at present one of the most serious ecological issues. Not only the engine properties will decide on meeting these requirements but also the expected conditions of its operation that should be taken into consideration in the constructional and adjustment works. Attention was paid in this paper to the aspects of application of the optimisation procedure in the field of combustion engines. One of the possibilities of controlling the fuel consumption and concentration of toxic components in the exhaust gases was presented through optimum – as far as the set conditions are concerned – selection of constructional parameters of the turbo-charging system and methods of its adjustment. The results of the measurements of fuel consumption and the smoke opacity of the exhaust gases of the engine with compression-ignition of the SW-680 type with the sequential turbo-charging system were used in the calculations. An optimum configuration of the turbo-charging unit reduction of fuel consumption was obtained with keeping the smoke opacity of exhaust gases at the permissible level, which can be considered as a very promising result.

Key words: optimisation, sequential turbo-charging, emission of toxic compounds, fuel consumption.

INTRODUCTION

The requirements of high energetic properties ensuring adequate dynamics of a vehicle and economical operation are imposed on the modern traction engines. Equally important is to meet the constraints related to the toxicity of exhaust gases. As the result of fuel combustion, nitric oxides NO_X, carbon monoxide CO, hydrocarbons CH and particulate solids C are produced. They are the toxic compounds, the emission quantity of which is limited by the EURO standards. Apart from them, there is a whole series of other toxic compounds the concentrations of which have not been so far limited by any standards. The basic component of exhaust gases is carbon dioxide CO_2 that is not a toxic gas but its presence in the atmosphere is considered as the main source of the greenhouse effect. Hence, the standards in force at present also specify the permissible CO_2 emission. Reduction of this emission is thus equal to the reduction of average fuel consumption. In order to meet these goals it is necessary to intensify actions from the engine side, aiming at an improvement of efficiency of processes taking place in the cylinder.

One of the commonly used methods allowing for an improvement of properties of engines is turbo-charging. An increase of the maximum power of turbo-charged engines advantageously influences the improvement of dynamic properties of a vehicle and its ability to cope with inclinations without the necessity to reduce gears. However, it must be stressed that the traction engine operates at the full load very seldom. In the average operation conditions the majority of the overall operation time falls on the low and medium engine loads. Therefore not only the engine properties will decide on meeting the above mentioned requirements but also the conditions of its operation resulting from the character of the vehicle application. Hence the problem arises how to determine the engine operation parameters that should be taken into consideration in the construction and adjustment works.

The construction and adjustment issues related to matching the engine properties to the method of its operation is a task with a compromise solution, to the solution of which optimisation methods can be applied [1]. An optimisation problem includes adopting the engine operation quality criterion, so called objective function and determination of the set of construction and adjustment parameters deciding on the value of this criterion. The set of construction and adjustment parameters forms the W_d vector called the vector of decision variables. The adopted objective function makes the criterion value (e.g. minimising of fuel consumption, emission of toxic compounds) dependant on the selected constructional and operational parameters in the assumed engine operation conditions with simultaneous taking a series of constraints into consideration.

The optimisation actions are related to multiple determination of the objective function value that meets the assumed constraints. In cases where the mathematical formalisation of a problem is possible, this can be reached with the use of numerical methods by making the use of digital models of engine and operation conditions. In the remaining cases one should base on experimental tests, which are much more expensive, time consuming and limited to a finite number of discrete values of the optimised parameters. However, this does not exclude the use of experimental data for the creation of empirical models created by approximation of the sets of values obtained in tests in an engine test house.

In this paper attention the aspects of application of the optimisation procedure in the field of combustion engines. One of the possibilities was presented concerning controlling of fuel consumption and concentration of toxic compounds in the exhaust gases through optimum – for the assigned operation conditions – selection of the constructional parameters of a turbo-charging system and methods of its adjustment. The results of the fuel consumption measurements and the smoke opacity of the exhaust gases of the six cylinder engine with compression-ignition of the SW-680 type with sequential turbo-charging [6] were used. Narrowing of the problem to the reduction of consumption and the smoke opacity of the exhaust gases does not exclude the possibility to include a series of additional factors in the optimisation procedure.

PROBLEM DESCRIPTION

One of the commonly used methods used at present, allowing for an improvement of the engine properties is turbo-charging. The performance of turbo-charged engines mainly results from the efficiency of the turbo-charging system, determined by the possibility of a supply of an adequate quantity of air for the fuel combustion. The conventional turbo-charging with one turbo-charger does not ensure the required curve of the turbo-charging characteristic thus disadvantageously influencing the engine operation indicators. Matching the turbo-charging characteristics to changing conditions of a motor-vehicle engine operation is possible with the use of turbo-charging adjustment systems.

At present, the VGT turbo-chargers with variable geometry of the turbine are used more and more often. They enable an increase of the engine dynamics and the torque over the whole range of engine speeds, and matching the compressor output to the momentary engine load allows for a reduction of NO_x. Shaping of the turbo-charging characteristics is also possible by means of structurally less complex systems, out of which the sequential turbo-charging deserves a particular attention [14,16].

The sequential turbo-charging presented in the literature [11,12,15] consists in the use of at least two turbo-chargers, most often in two different sizes, reciprocally connected in parallel arrangement and equipped with the system of valves controlling their operation. According to the idea of the system operation at low engine loads, one turbo-charger is in operation. Engaging into operation of the second turbo-charger takes place only within the range of high engine speeds and engine loads and aims at its protection against excessive increase of mechanical loads [11,12].

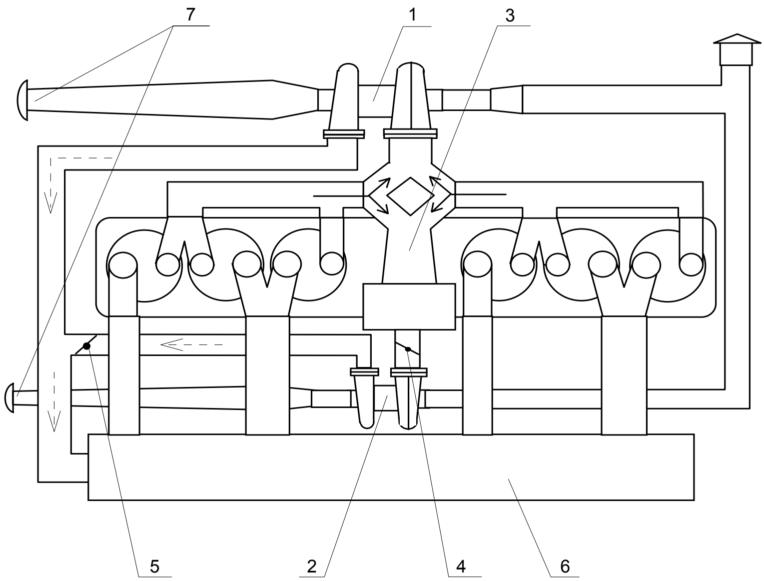

Fig. 1. Diagram of the sequential turbo-charging system of the SW-680 engine [6]
1 – larger turbo-charger of the 1st sequence , 2 – smaller turbo-charger of the 2nd sequence, 3 – branching with pulse exchanger, 4 – throttling valve between turbine and engine, 5 – throttling valve between turbo-charger and engine, 6 – inlet manifold, 7 – air intake

Application of two smaller turbo-chargers instead of one large turbo-charger allows for an increase of the mass of air supplied to the engine within the range of low engine speeds. The advantage of the tested turbo-charging system is the low modernisation cost as well as possibility of use of mass-produced turbo-chargers. The disadvantage of the sequential turbo-charging system resulting from the method of engaging of the second turbo-charger is the discontinuity of the turbo-charging pressure and the torque on the external characteristics of the engine. The diagram of the sequential turbo-charging was presented in Fig. 1. The detailed description of the system operation is contained in [6].

The research carried out by the author [8] has allowed for an assessment of the influence of the constructional parameters of the sequential turbo-charging on the SW 680 engine operation indicators showing significant advantages resulting from its application at the engine operation at high load. However, as indicated above, the actual distribution of loads taking place in the average operational conditions shows the necessity to optimise the constructional and adjustment parameters of the engine within these fields of the characteristics where it is in operation for the longest period of time [13]. Thus, there arises the problem of selection of turbo-chargers and determination of the functional properties of the control system for turbo-chargers that will enable matching the turbo-charging output to the momentary load of the engine with meeting the imposed requirements in accordance with the adopted optimisation criterion.

ASSUMED MODEL OF ENGINE OPERATION

The operational fuel consumption as well as the size of emission of toxic components produced by an engine with turbo-charging are dependant not only on the applied turbo-charging unit but significantly – as indicated above – are strictly related to the conditions of its operation (load and engine speed). The selection of a turbo-charging unit to the engine may take place for any engine speeds and loads. Most often these are the nominal ratings, under which the engine operates only for a few percent of the whole operation time. The results of the operational tests unambiguously show that the traction engine most often operates at low and medium loads and rotational speeds. Therefore, optimisation of the engine operation for the nominal rating departs from the purpose and seems to be of more advertising than of rational character. This results from the fact that optimisation of the engine operation for the range, in which the engine operates most of the time seems to be the most legitimate.

By applying the optimisation procedure it is easy to determine the optimum values of decision parameters for one point of the engine operation. However, the selection of a decision parameter vector for the whole area of the engine operation is a problem.

The engine operation conditions may be unambiguously determined by the torque values M_0 and the engine speed n. The momentary changes $M_0(t)$ and $n(t)$ in the field of the general characteristic of the engine obtained during the vehicle driving will be determining the engine operation model, and the $t <0,T>$, where T means the total observation time.

The $M_0(t)$ and $n(t)$ values may be determined by the direct measurement of the torque and the engine speed on the engine crankshaft during driving on the route specified by the research programme. However, this requires adequate equipment and long-term measurements as well as proper statistical processing of the obtained results. At present, for testing of vehicles engine test houses are used more and more often that enable a detailed simulation of strictly specified driving conditions of a vehicle on the road in the control tests executed according to the so called driving cycles. Such a cycle considered as the driving being the most representative for the movement of a given vehicle in actual operation conditions is used at the time of testing of emission of toxic components in the exhaust gases and at measurements of fuel consumption by a vehicle (CO_2 emission).

The $M_0(t)$ and $n(t)$ values may be rearranged to the form of so called time density (TD) [2,3,5]. The general characteristic of the engine i.e. the field of its operation in the M_0, n co-ordinates may be divided into i-segments with the dimensions of ΔM and Δn (Fig. 2). For the elementary i-segment, the time density is defined by the quotient:

$$TD_i = t_i/T \tag{1}$$

By *ti*, the operation time in the elementary i-segment of the operation field with the torque and the engine speed belonging to this segment are determined.

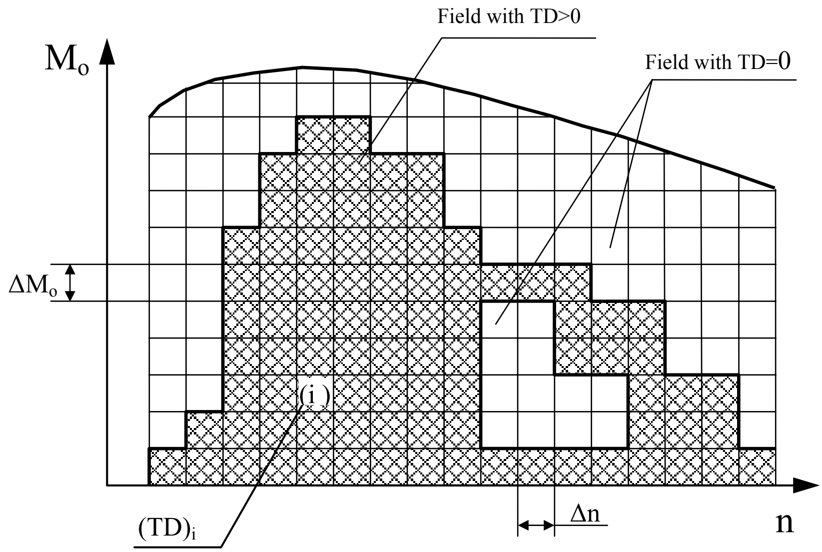

Fig. 2. Diagram of division of the characteristic into the *Mo* and n sections [5]

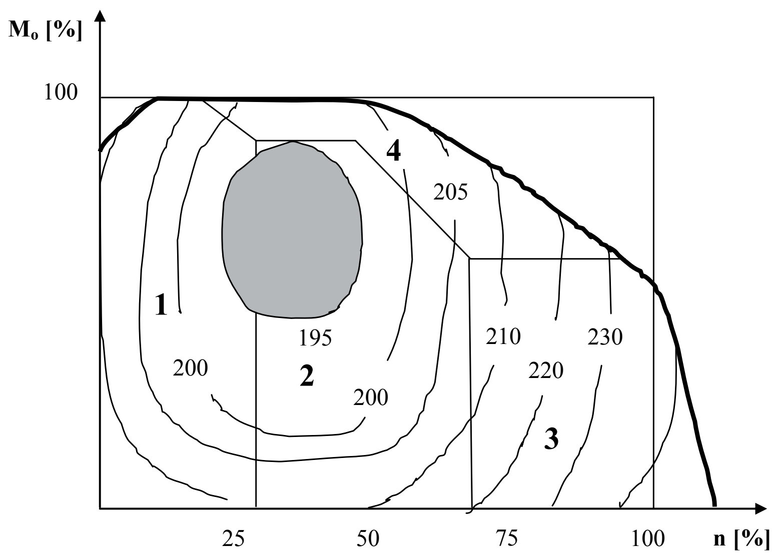

Fig. 3. Characteristic of time density of the Scania DC 11 01 340 engine [17]

The characteristic of the time density (TD) that constitutes the model of the engine operation may be the basis for determination of the value of the engine operation indicators taken into consideration in the objective function and constraints used in optimisation. In order to simplify the optimisation procedure it is recommended to replace several segments (TD) and their participations with a smaller number of representative fields with weighted factors (u_i participations) presenting replacement values of the time density (TD). The values of the engine operation indicators obtained during this must be the same during one cycle. According to the research results of the Scania company, division of the characteristics into 4 fields is sufficient (Fig. 3). As an example, the characteristic of the time density of the Scania DC 11 01 340 engine may be used, representing the group of turbo-charged engines designed for driving of lorries of high carrying capacity. On this characteristic, fields determining the characteristic areas of operation of the engine for road applications were marked. The percentage participations u_j of usage of particular fields under the torque curve of the utility vehicles engines according to Scania are [17]:

- field 1 – 9 %
- field 2 – 60%
- field 3 – 6%
- field 4 – 25%

It results from the character of operation of engines designed for driving of lorries of high carrying capacity. In such case of lorries of heavy weight, the field of the characteristic close to the maximum value of torque within the area of medium engine speeds is much more used, which – apart from the improvement of the dynamic properties of the engine – gives relatively low values of specific fuel consumption, and thus high general efficiency. Regardless of the total weight of the described vehicles the field No. 2 is the most used one (within the limits of 50-60% of the operation time) that covers the areas of the lowest specific fuel consumption. A significant use of the field No. 4 (25-35% of the operation time) by the engines of lorries of high carrying capacity is possible at driving on motorways with full load and constant driving speed, which is typical for such types of roads and heavy weight of transported load. Generally, one aims at the maximum use of the grey field, i.e. corresponding to the lowest fuel consumption, which is fully understandable when bearing in mind the previous operational experience.

A similar character of the JELCZ lorry operation shows that it is purposeful to carry out an assessment of the adopted constructional solutions of the SW 680 engine with sequential turbo-charging on the basis of the characteristic of time density (TD) for the Scania engines, presented in Fig. 3.

USE OF THE OPERATION MODEL IN THE OPTIMISATION PROCEDURE

Connecting of the anticipated operation conditions (TD) with the general characteristic of the engine provides the operation model with the versatility feature. It may be used in all types of problems where the assessment criterion should take into consideration the anticipated distribution of loads taking place during the operation. It may be the problems that are related to the selection of an engine with given properties to a vehicle, selection of an optimum driving method for a specified route section or determination of optimum gears in the power transmission system. It may be also the problems aiming at an improvement of the engine properties related to the actions of adjustment and constructional character, and in particular the tasks of selection of engine elements. In case of the engine with sequential turbo-charging it will be mainly the selection of turbo-chargers and determination of the fields of characteristics where the engine should operate with one or two turbo-chargers engaged. The adopted quality coefficient (objective function value) related to the adopted operation model should finally decide on the selection of a solution of this problem with the use of optimisation methods.

The method of connecting of the operation model with the quality coefficient may be different, selected individually depending on the executed problem, the computational possibilities, etc. Most often it is a parameter that determines the economy of the engine operation, being a known function of the optimised parameters. The requirement of economical operation happens to be supplemented with additional criteria that may take place in the form of constraints imposed on the parameters under optimisation. For example, it may be required to keep the emission of toxic components of exhaust gases or the noise emission at the permitted level.

In the executed optimisation problem for the SW 680 engine driving the JELCZ lorry of high carrying capacity, driven in the conditions described by the density characteristic presented in Fig. 3., one must determine the constructional and adjustment parameters of the turbo-charging unit, ensuring the best economy of operation at the emission of soot contained in the exhaust gases not exceeding the permissible value. For the assessment of economy, one may make use of the method for determination of the value of the equivalent fuel consumption on the basis of the time density characteristic. In this method, the percentage participations u_j of particular fields of the characteristic (TD) are the weights of the specific fuel consumption g_e.

$$g_{e.equiv.} = \sum (g_{e,j} \cdot u_j) \tag{2}$$

The optimisation problem with taking the time density into consideration was solved for the following vector of decision variables that determine the constructional and adjustment parameters of the system:

$$W_d = [d_1, d_2, d_3, d_4, d_5] \tag{3}$$

The decision variable d_1 was defined by the set of turbo-chargers of the 1st sequence being at disposal, manufactured by WSK Rzeszów, of the B3A series of types, with the catalogue numbers of the rotors of 259K, 279K, and the B3C series of types with the rotor number of 309K, whereas the variable d_2 defined the set of turbo-chargers of the 2nd sequence of the B65 series of types with the catalogue numbers of the rotors of 50 and 60. The quantity of turbo-chargers defined by the d_1 and d_2 variables gave 6 sets of turbo-chargers that required consideration.

The decision variable d_3 was defined by the set of turbo-chargers of the 1st sequence being at disposal, with the intersections of the inlet box A_T equal to 14 and 17 cm^2. The variable d_4 defined the set of turbo-chargers of the 2nd sequence with the intersections of the inlet box A_T equal to 3.31 and 5.65 cm^2. The used turbo-chargers have got replaceable bodies of turbines with unified dimensions of fastening flanges. After taking the number of sets of turbo-chargers into consideration it was possible to obtain as many as 24 variants of sets of the turbo-charging unit.

The decision variable d_5 defined the characteristic of controlling of the turbo-charger of the 2nd sequence. Two solutions are possible here. In the first one, engaging into operation of the turbo-charger of the 2nd sequence takes place only within the range of high engine speeds and loads and mainly aims at the protection of the engine against an excessive increase of mechanical loads resulting from too high supercharging pressures. Such approach may be encountered in the solutions presented in the literature [12]. Fig. 4. presents an example universal characteristics of the SW-680 engine for one of the tested sets of turbo-chargers controlled according to this concept. There is a boundary line plotted on the characteristics, above which engaging of the second turbo-charger into operation takes place, resulting from exceeding of the permissible supercharging pressures. It results from the research carried out by the author [10] that certain improvement of the economy of the tested SW-680 engine may be obtained through engaging of the second turbo-charger into operation already at low engine speeds and loads, however at the cost of an increased smoke opacity of the exhaust gases (Fig. 5.). Above the visible boundary line, switching into engine operation with one turbo-charger takes place. The purposefulness of such solution will be therefore dependant on the degree of use of the engine operation fields with reduced fuel consumption and it is directly connected with the adopted operation model whereas in Figures 6 and 7 the universal characteristics was presented in the bar chart arrangement with marked participations of particular fields with established specific fuel consumption g_e. These characteristics – after taking the time density (TD) into consideration – formed the basis for calculation of the value of the criterion function.

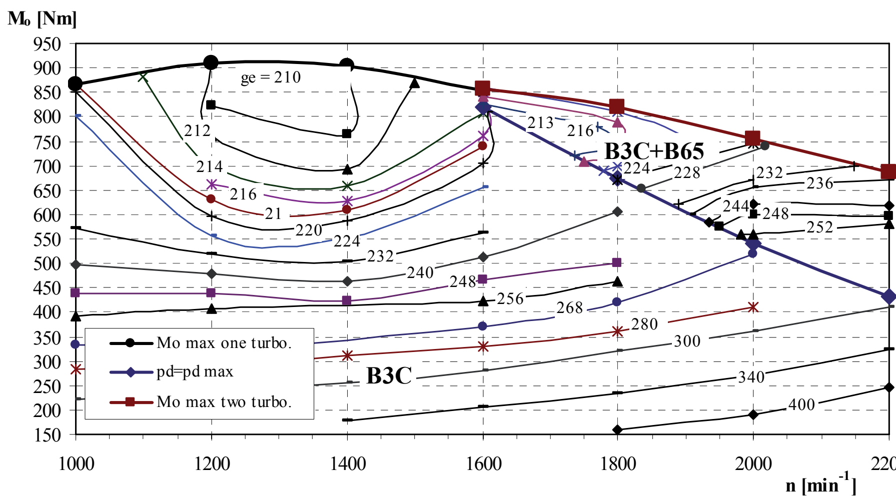

Fig. 4. Universal characteristics of the SW-680 engine with sequential turbo-charging for the set of B3C turbo-chargers with A_T=17 cm² and B65 with A_T=5.65 cm². The visible line of the limit pressure p_d=$p_{d\,max}$, above which engaging of the second turbo-charger takes place

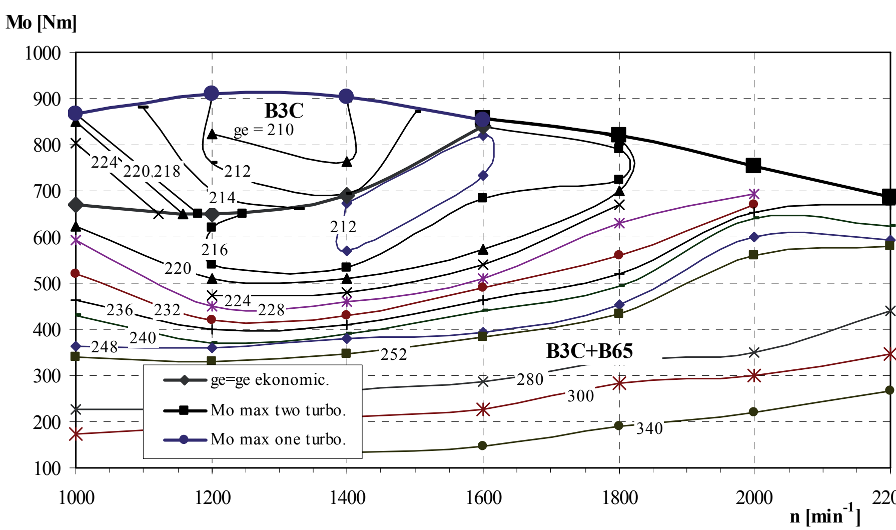

Fig. 5. Universal characteristics of the SW-680 engine with sequential turbo-charging for the set of B3C turbo-chargers with A_T=17 cm² and B65 with A_T=5.65 cm². The visible boundary line g_e=$g_{e\,ekon.}$, above which – due to economy of the engine operation – engaging of the second turbo-charger takes place

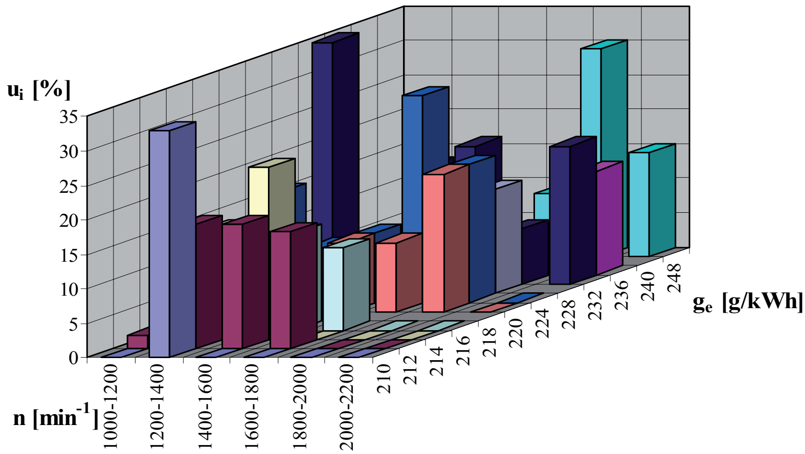

Fig. 6. Chart of participations u_j of fields with established specific fuel consumption g_e in bar chart arrangement prepared on the basis of the universal characteristics presented in Fig. 4.

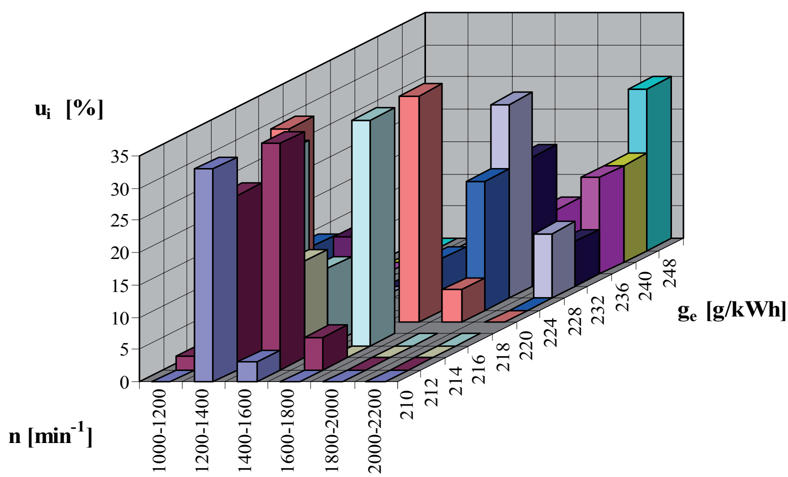

Fig. 7. Bar chart of participations u_j of fields with established specific fuel consumption g_e prepared on the basis of the universal characteristics presented in Fig. 5.

The optimisation criterion is constituted by the Q function defining the equivalent fuel consumption in the adopted driving cycle, with adopted weight factors u_j.

$$Q(d_1,d_2,d_3,d_4,d_5) = \sum(g_{e,j} \cdot u_j) \tag{4}$$

The constraints imposed on the parameters under optimisation relate to meeting the mentioned requirements as to the soot emission expressed by means of the function dependence C, in which the percentage participations u_j of particular fields of the characteristic (TD) are the weights of the smoke opacity of the exhaust gases c:

$$C(d_1,d_2,d_3,d_4,d_5) = \sum(c_j \cdot u_j) \qquad (5)$$

The values of the specific fuel consumption g_e and the soot emission c for various conditions of the engine operation and sets of turbo-chargers were determined on the basis of the universal characteristics obtained through measurements during tests in the engine test house.

Also constraints concerning ensuring constant and reliable operation of the engine-turbo-charging unit set were taken into consideration. During the executed preliminary tests, the suitability of each of the turbo-chargers was defined, from which the turbo-chargers of the B3A and B65 series of types with the catalogue numbers of rotors of 259K, 279K was rejected as well as 50 due to their inadequate flow characteristics [9]. This showed the purposefulness of use of the following turbo-chargers as the decision variables: d_1 – 309K turbo-charger and d_2 – 60 turbo-charger. It was also found that with use of the B3C turbo-charger with the intersection of the inlet box of the turbine A_T = 14 cm^2, too high supercharging pressure was obtained in the conditions of full engine load. As the result, the d_3 variable was limited to the turbine with the inlet box with the intersection of A_T = 17 cm^2. This reduced the quantity of turbo-chargers to one set that, with taking the permitted quantity of the turbine variants into consideration, gave two sets of the device meeting the constraints.

A typical optimisation problem with constraints was rearranged to the problem without constraints as to use of the penalty function with building of a new objective function Q_1.

In order to simplify the procedure, decomposition of the problem was carried out that allowed for the elimination of discrete variables from the objective function, defined by the sets of the turbo-charging device meeting the constraints. Each set was treated as a parameter, i.e. a separate variant that requires a separate consideration. Therefore, a series of optimisation problems were solved for the adopted sets of turbo-chargers and established characteristics of the operation of the system controlling the operation of turbo-chargers. The A_T values were sought for the turbines of the 2nd sequence that minimise Q_1:

$$Q(d_4) = \sum(g_{e,j} \cdot u_j) \qquad (6)$$

RESULTS OF CALCULATIONS

The solutions of the optimisation problems (finding of A_T for the turbine of the turbo-charger of the 2nd sequence as well as characteristic of the system controlling the operation of turbo-chargers) are presented in Table 1.

Table 1. The obtained values of the objective function Q_1 for the sought values A_T of the turbines of the 2nd sequence as well as the established characteristics of operation of the controlling system

		Q_1[g/kW h]	
		Controlling according to the economy limit	Controlling according to the strength limit
AT [cm2]	3.31	240.5	244.9
	5.65	239.7	244.5

The lowest value of the criterion function Q_1 calculated on the basis of the adopted model of the engine operation was obtained for the intersection of the inlet box of the turbine of the 2nd stage A_T = 5,65 cm^2 and such characteristics of the system controlling the operation of turbo-chargers, according to which engaging of two turbo-chargers takes place already at low engine speeds and loads. Moreover, in this case it is not necessary to take into consideration the limit of the permissible supercharging pressure as above the engine speed of n=1600 min^{-1} there are in operation two turbo-chargers that do not reach this limit, whereas the differences in the Q_1 values for the analysed A_T values and characteristics of the operation of the system controlling the turbo-chargers are 2,2%. This gives approximately 8 litres of savings at driving fuel consumption with ten-hour working day [4].

The results of the research presented here allow for the statement that in both the construction and the controlling of the engine there are still hidden reserves as to the economy of its operation as well as reduction of pollution to the natural environment with toxic components of exhaust gases. However, the condition for the execution of this problem, in particular solved with optimisation methods is to link the index of assessment of the analysed solution to the conditions of the engine operation (TD) that should finally decide on the selection of solution.

REFERENCES

Urbaniec K. 1979: Optymalizacja w projektowaniu aparatury procesowej. WNT. Warszawa.

Auiler J.E., Zbrozek J.D., Plumberg P.N.: Optimization of automotive engine calibration for better fuel economy methods and applications. SAE Technical Paper Series 850205.

Cassidy J.F.: A computerized on-line approach to calculating optimum engine calibrations. SAE Technical Paper Series 770078.

Mysłowski J. 2004: Zastępcze jednostkowe zużycie paliwa. Eksploatacja silników spalinowych. Katedra Eksploatacji Pojazdów Samochodowych Politechniki Szczecińskiej. Zeszyt 11, Szczecin, p. 63-69.

Cichy M. 1986: Nowe teoretyczne ujęcie charakterystyki gęstości czasowej. Silniki Spalinowe nr 2-3, p. 31-34.

Danilecki K. 1995: Kształtowanie charakterystyki zewnętrznej silnika trakcyjnego przy zastosowaniu systemu doładowania zakresowego., Journal of Kones Interal Combustion Engines Vol. 2, No 1, Warsaw – Poznan, p. 111-119.

Danilecki. K. 1998: Analiza możliwości obniżenia zużycia paliwa silnika SW 680 z doładowaniem zakresowym. Zagadnienia Eksploatacji Maszyn. Zeszyt 3 (115). Wydawnictwo Naukowe PWN, Warszawa, p. 461-471.

Danilecki K. 1998: Wpływ doładowania zakresowego na wybrane aspekty pracy silnika. Teka Komisji Naukowo-Problemowej Motoryzacji. Konstrukcja, badania, eksploatacja, technologia pojazdów samochodowych i silników spalinowych. Polska Akademia Nauk Oddział w Krakowie, Zeszyt 15. Kraków, p. 267-274.

Mysłowski J., Danilecki K. 1996: Wpływ kompletacji turbosprężarek na parametry pracy silnika SW-680 z układem doładowania zakresowego. Teka Komisji Naukowo-Problemowej Motoryzacji. Konstrukcja, badania, eksploatacja, technologia pojazdów samochodowych i silników spalinowych. Polska Akademia Nauk Oddział w Krakowie, Zeszyt 8, Kraków, p. 127-138.

Danilecki K. 2004: Определение характеристики регулирования давления на впуске автомобильного дизеля с системой секвенционного турбонаддува. Problems of Applied Mechanics International Scientific Journal Nr 4(17)/2004. Georgian Committee of the International Federation for the Promotion of Mechanism and Machine Science, Tbilisi, p. 51-56.

Bluhm K., Ganz M., Voght R. 1988: Erfahrungen mit der Registeraufladung in einer Reiselimousine. Aufladetechnische Konferenz, Zurich.
Borila Y.G.: A sequential turbocharging method for highly-rated truck diesel engines. SAE Technical Paper Series 860074.
Kowalczyk M., Kozak W., Jaskuła A., Wisłocki K. 1986: Warunki pracy silnika spalinowego jako podstawa doboru turbosprężarki, Silniki spalinowe 1, pp. 23-27.
Łęgowicz J. 2005: Doładowanie typu twin-turbo. Auto Moto Serwis. 3.
Galindo J., Lujan J., Climent H., Guardiola C.: Turbocharging System Design of a Sequentially Turbocharged Diesel Engine by Means of a Wave Action Model. SAE Technical Papers 2007-01-1564.
Luttermann C., Mahrle W.: BMW High Precision Fuel Injection in Conjunction with Twin-Turbo Technology: A Combination for Maximum Dynamic and High Fuel Efficiency. SAE Technical Papers 2007-01-1560.
Materiały firmy Scania.