

THE ASSESSMENT OF THE POLLUTANT EMISSION FROM THE SELF IGNITION ENGINE IN ITS DIFFERENT OPERATING STATES

Zdzisław Chłopek

Motor Transport Institute, Warsaw, Poland
e-mail: zdzislaw.chlopek@its.waw.pl

Abstract: Paper presents the results of pollutant emission tests from the self ignition engine in various states of its operation. Engine operating states were obtained on the engine test stand. The investigations were conducted in static and dynamic tests, both standard used in the type approval procedures as special ones, simulating specific engine operating conditions. The specific brake emission of carbon monoxide as well as those of hydrocarbons, nitrogen oxides and particulate matter, averaged during the tests, have been determined. The influence of the engine operating states on the pollutant emission of impurities has been evaluated. Very high sensitivity was established of the pollutant specific brake emission on the operating states of the engine, both static ones and dynamic.

Key words: self ignition engine, pollutant emission, static test, dynamic test

1. Introduction

Exhaust emission from internal combustion engines is highly dependent on the engine operating states: both static and due to the presence of dynamic states [1, 4, 5, 10–13, 25]. This dependence is various for different pollutants. The variety of the combustion engines' possible operating states, determined by the variety of operating conditions, makes that ecological characteristics of the same internal combustion engines, but with different applications, may differ considerably. This is a major difficulty in selecting control algorithms for the operating processes in the internal combustion engines due to their application. Such problems occur mainly with heavy diesel engines, which – depending on the version – can be used to drive among the others: motor vehicles, construction machinery, stationary devices and sailing vessels.

The study analyzed impact of the combustion engine operating states on the emission of pollutants. The tests were carried out on the Cummins 6C8.3 engine, used to drive, among the others: trucks, buses, power generators, and various construction machineries, such as bulldozers, loaders, graders and excavators. Both standard type approval tests [4, 27] were used in the studies as well as special tests, designated by the author and the test team [2, 15, 16, 20, 21].

2. Operating states and conditions of a combustion engine

The engine operation is described by the operating states and conditions. The concept of the physical quantity process is understood as a function of this quantity in time or relative to the monotone quantity in time [4, 5], for example, crank shaft rotation angle or distance travelled by the car while maintaining the condition of non-negativity speed.

The quantities describing the engine operation, regarded as a function of time, are the processes of the combustion engine operation.

Engine operating state is described as a set of values characterizing this operation during normal operation of the engine, and thus includes values that characterize [5]:

- energy properties according to the possibility of carrying out work, such as effective power, engine torque, engine speed, the cylinder pressure, mean indicative pressure, brake mean effective pressure, etc.,
- processes occurring in the engine subject to control, such as: controlling the engine by the operator, fuel metering, ignition timing and injection timing, boost pressure, temperature of the air filling the cylinders, engine thermal state, exhausts circulation coefficient, burning mixture content, sometimes compression ratio, etc.,

- economic characteristics according to fuel consumption, such as: thermal efficiency, mechanical efficiency, general efficiency, the flow rate of fuel consumed by the engine specific fuel consumption, etc.,
- properties characterizing the processes associated with the engine operation, such as: ecological properties according to the pollutant emission (concentrations of the exhausts components, pollutants emission intensity, specific brake emission of pollutants, and in the automotive applications – specific distance emission of pollutants) and the noise emission, such as: noise intensity and its level, or acoustic noise pressure or the engine's acoustic power output and its level.

Engine operating conditions are determined by [5]:

- environmental conditions influencing the operational resistances to the vehicle or machine, and weather conditions,
- engine control by an operator,
- resistance torque, dependent on the nature of the work performed by a vehicle or a machine.

If the engine operating conditions are defined by the set of physical quantities – **W**.

$$\mathbf{W} = \{W_1, W_2, \dots, W_{iW}\} \quad (1)$$

Engine operating state is described a set of physical quantities – **S**.

$$\mathbf{S} = \{S_1, S_2, \dots, S_{iS}\} \quad (2)$$

The engine work is characterized by a set – **P** which is the sum of the sets of working conditions and the operating status of the engine.

$$\mathbf{P} = \mathbf{W} \cup \mathbf{S} = \{P_1, P_2, \dots, P_{iP}\} \quad (3)$$

where: $iP \leq iW + iS$

Formally, the engine work is static, if all the values that describe the work of the engine, are independent of time t , i.e.

$$\frac{\partial P_i(t)}{\partial t} = 0 \quad (4)$$

for $i = 1, \dots, iP$.

If for any quantity, describing the operation of the engine, this condition is not fulfilled, the engine work is of dynamic character.

This criterion of qualifying the engine operation to the static or dynamic category has purely theoretical significance, for it may only apply to the analytical description cases of the $P_i(t)$

functions. If the $P_i(t)$ functions are presented in the empirical form of signals, which is always the case in practice, then meeting the conditions (4) is dependent on the frequency properties of the signals analyzed.

The studies of the combustion engines distinguish processes of the engine operating states and processes of the engine operating conditions. Classification into the static and dynamic processes refers in this case to the processes of the states and conditions of the engine operation. Formally, therefore, there are, for example, dynamic processes of the engine operating states. The usually a brief phrase is used: "dynamic states" rather than strict – "dynamic processes of the states".

To describe the operating conditions of combustion engines in the research testing, introduced is the concept of relative values of: engine speed and torque, which relate to the quantities of the external speed characteristics of the engine.

Relative engine speed is [2, 4]

$$n_w = \frac{n - n_{bj}}{n_N - n_{bj}} \quad (5)$$

where: n – engine speed,

n_{bj} – idling engine speed,

n_N – nominal engine speed.

Relative engine torque for the engine speed n is applied to the engine torque on the external characteristics for the same engine speed [2, 4]:

$$M_{ew} = \frac{M_e(n)}{M_{ez}(n)} \quad (6)$$

where: $M_e(n)$ – engine torque for the engine speed – n , $M_{ez}(n)$ – engine torque on the external characteristics for the engine speed – n .

Under static conditions there is a functional dependence of the engine speed, the engine torque and the engine controlled by the operator – it is in fact the general characteristics of the engine.

$$M_{nw-s} = f_{nw-s}(n_w, s) \quad (7)$$

$$n_w = f_{Mew-s}(M_{ew}, s) \quad (8)$$

$$s = f_{mw-Mew}(n_w, M_{ew}) \quad (9)$$

Properties of internal combustion engines tested in static conditions depend on those states. In the dynamic conditions, the equations (7–9) are of

the operator character [4, 5]. Therefore, the combustion engine in the dynamic states has no inherent properties, independent of the states, in which the engine is, not only because of the dependency on the states at any moment, but also because of the dependency of the engine characteristics on the courses of its states.

3. Tests for studying engine operating states

The awareness of the dependency of the pollutant emission from the internal combustion engines on the states of their operation caused a desire to create research tests, corresponding, in accordance with the accepted criteria, to the engines' operating conditions in their actual use. That way a numerous tests, both static and dynamic, were created, typically used in the type approval procedures [4, 14, 18, 19, 27], as well as tests based on the homologation tests [7, 12, 13, 22]. In addition, attempts were made to create special tests, corresponding to concrete conditions of the engines use [4, 9, 20, 21]. In the vast subject literature there are works on the criteria of the similarity of the combustion engines tests conditions and the conditions of their actual use [1, 4, 6–9, 12, 13, 20, 21, 26]. Sought are also methods to simulate combustion engines dynamic operating states by their static states [4, 6, 12, 13]. Many studies presented the combustion engines emissions results from various tests [4, 6, 12, 13, 17–19, 22, 24].

In this paper the studies of the specific emission of pollutants from self ignition engine were carried out in both the type approval and the special tests.

These are the following:

static tests:

- ECE R 49.02 – so called thirteen phase test, in accordance with 49.02 UN–ECE Regulation for testing automotive engines [4, 26],
- ESC (European Stationary Cycle or European Steady Cycle) – the test consistent with the No. 49.03 UN–ECE Regulations for testing automotive engines [27],
- NRSC (Non–road Stationary Cycle or Non–road Steady Cycle) – the test the same as the C1 test according to ISO 8178–4 for testing diesel engines of the construction machines [26],

- BBST (Bulldozer–Blade Static Test) – the test developed as part of the work [2, 20, 21], intended to test the bulldozer's engine operating with the blade,
- BRST (Bulldozer–Ripper Static Test) – the test developed as part of the work [2, 20, 21], intended to test the bulldozer's engine operating with the ripper,

dynamic tests:

- ETC (European Transient Cycle) – the test in accordance with the No. 49.03 UN–ECE Regulation to test automotive engines [26],
- HDDTT (Heavy Duty Diesel Transient Test) – the test for heavy diesel engines in accordance with the FTP Regulation (Federal Test Procedure) of the United States of America [4, 26],
- NRTC (Non–road Transient Cycle) – the test for the diesel engines of the construction machines [26],
- BBDT (Bulldozer–Blade Dynamic Test) – the test developed as part of the work [2], envisaged for testing the bulldozer's engine operating with the blade,
- BRDT (Bulldozer–Ripper Dynamic Test) – the test developed as part of the work [2], envisaged for testing the bulldozer's engine operating with the ripper.

To draw up the special BBST, BRST, BBDT and BRDT tests were used the results of empirical tests, conducted on the training ground using TD–15M tracked bulldozer, produced by Huta Stalowa Wola SA, powered by Cummins 6C8.3 engine [2]. Static tests were developed in accordance with the criterion of similarity of the two–dimensional probability density of the engine control processes and its relative engine speed in the actual conditions of its operation [2, 4, 20, 21]. Dynamic tests have been developed based on the faithful simulations in the time domain [2, 4].

Figures 1–4 show schematics of the special tests. As the combustion engine's operating states were used in the tests: the relative engine speed and engine control.

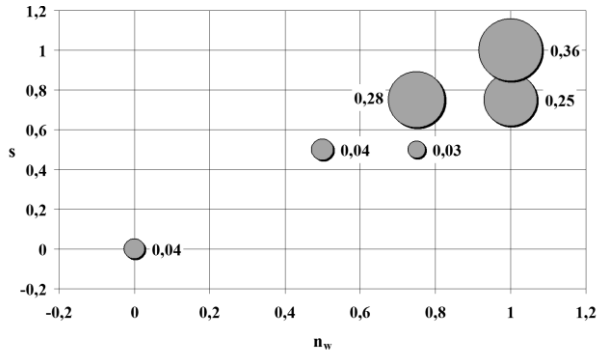


Fig. 1. The BBST test simulating static states of internal combustion engine operation of the bulldozer with the blade (circles' areas are proportional to the shares of the various points in the test), the graph has plotted shares of individual test points

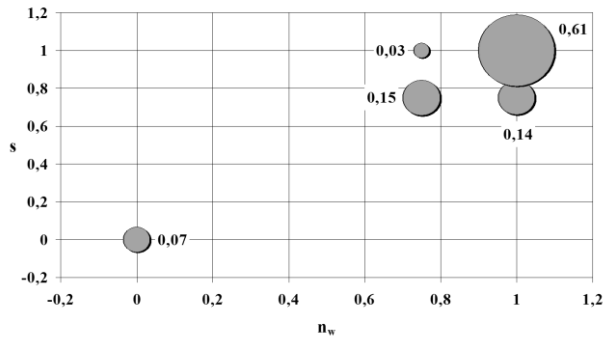


Fig. 2. The BRST test simulating static states of internal combustion engine operation of the bulldozer with the ripper (circles' areas are proportional to the shares of the various points in the test), the graph has plotted shares of individual test points

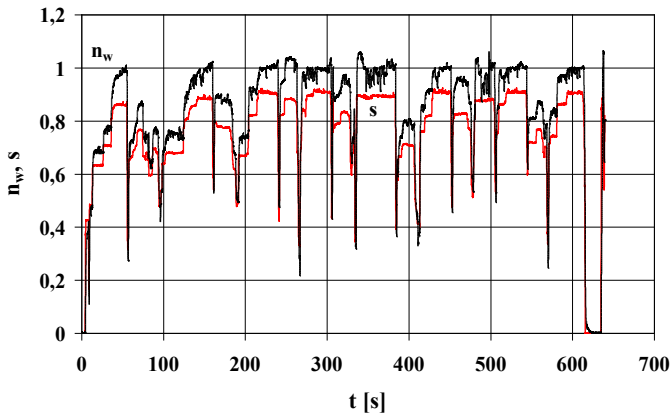


Fig. 3. The BBBDT dynamic test to examine internal combustion engine in operation of the bulldozer with the blade – courses of the relative engine speed and the engine control by an operator

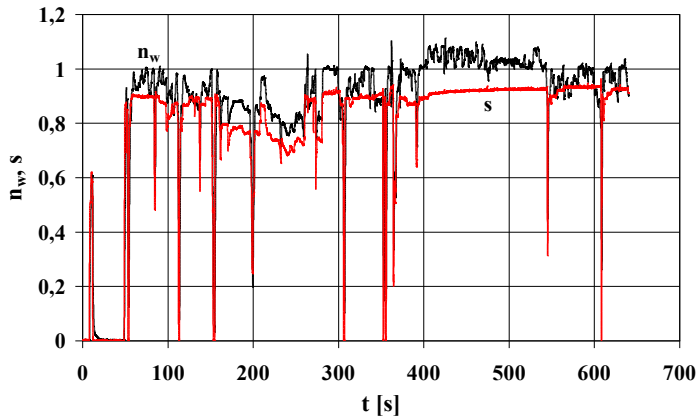


Fig. 4. The BBRT dynamic test to examine internal combustion engine in operation of the bulldozer with the ripper – courses of the relative engine speed and engine control by an operator

4. Evaluation of the specific brake emission of pollutants in various states of the engine operation

The object of empirical research was Cummins 6C8.3 engine. It is six cylinder self ignition engine with the swept volume of $8,3 \text{ dm}^3$ and nominal effective power of 153 kW at 1950 min^{-1} . Idle speed is 750 min^{-1} .

The studies of the combustion engine were carried out on the test stand equipped with:

- electric brake AFA-E 460/4,4–9 EU manufactured by AVL,
- engine speed digital meter and torque meter T10F manufactured by HBM,
- gas analyzers manufactured by CEB II manufactured by AVL,
- system for the measurement of particulate emissions: a Smart Sammler SPC 472 partial flow dilution tunnel by AVL firm and a MT5 mass meter manufactured by Mettler Toledo,
- system for measuring fuel consumption – type 735 with the device to stabilize the temperature of the fuel, produced by AVL firm,
- system for measuring air flow intensity of a Sensyflow P type.

The test equipment used complied with the requirements of the 97/68/EC Directive.

The table shows results of the specific brake emission of pollutants:

- carbon monoxide – CO,

- hydrocarbons – HC,
 - nitrogen oxides – NO_x , reduced to nitric oxide – NO,
 - particulate matter – PM
- for the Cummins 6C8.3 engine in research trials.

Table 1. The results of the pollutant specific brake emission in the tests of Cummins 6C8.3 engine

| Test | CO | HC | NO_x | PM |
|-------------|------------|------|---------------|------|
| | [g/(kW·h)] | | | |
| ECE R 49.02 | 0,98 | 0,86 | 9,80 | 0,17 |
| ESC | 0,92 | 0,74 | 9,60 | 0,13 |
| NRSC | 0,33 | 0,62 | 8,00 | 0,17 |
| ETC | 1,54 | 0,58 | 9,52 | 0,43 |
| HDDTT | 1,61 | 0,60 | 10,08 | 0,52 |
| NRTC | 1,54 | 1,84 | 11,54 | 0,27 |
| BBST | 0,90 | 0,82 | 9,49 | 0,24 |
| BBDT | 1,28 | 1,61 | 11,82 | 0,63 |
| BRST | 0,90 | 0,79 | 8,54 | 0,17 |
| BRDT | 1,32 | 1,54 | 10,93 | 0,69 |

Figures 5–8 show a comparison of the pollutant specific brake emission in the research tests. There are visible very significant differences in the specific brake emission of pollutants in the individual tests – the smallest variation of quantities occurs in the case of the specific brake emission of nitrogen oxides.

Figures 9–12 show the average value for the specific brake emission of pollutants: in all tests, the static tests, the dynamic tests, the automotive tests and non–road tests.

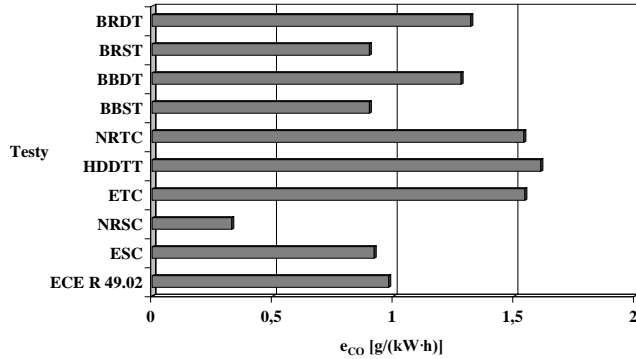


Fig. 5. The specific brake emission of carbon monoxide in the tests

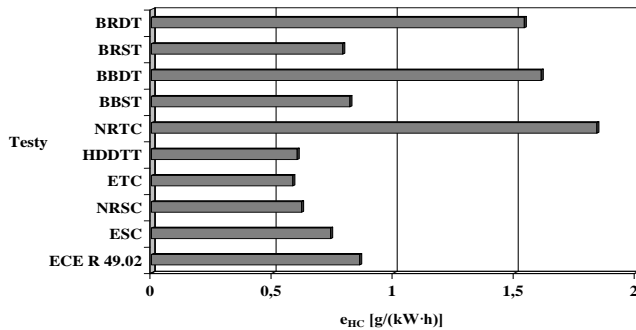


Fig. 6. The specific brake emission of hydrocarbons in the tests

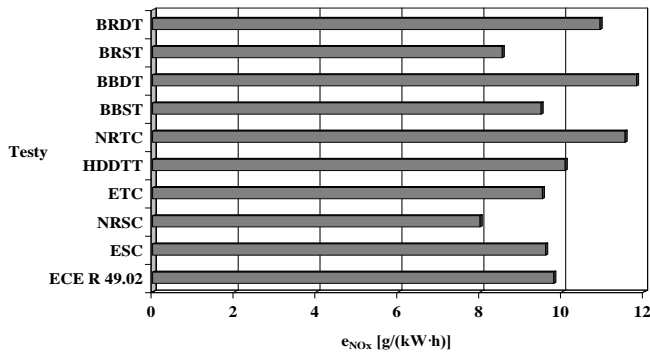


Fig. 7. The specific brake emission of nitrogen oxides in the tests

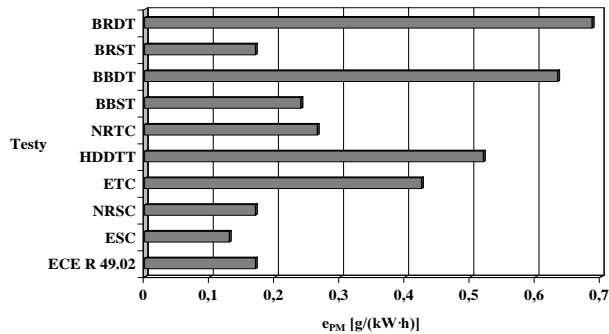


Fig. 8. The specific brake emission of particulate matter in the tests

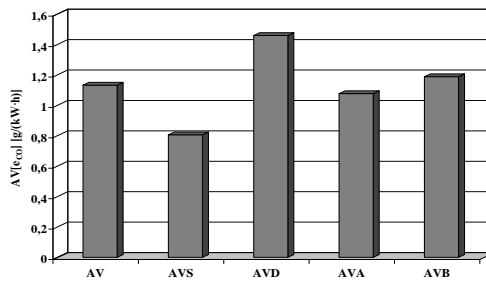


Fig. 9. The average value of the specific brake emission of carbon monoxide in: all tests – AV, the static tests – AVS, the dynamic tests – AVD, the automotive tests – AVA and the non-road tests – AVB

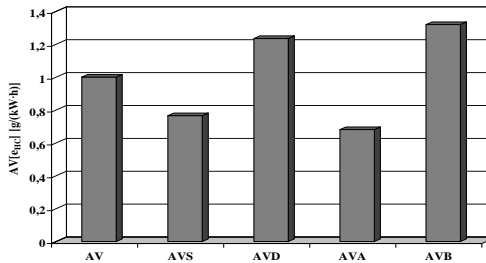


Fig. 10. The average value of the specific brake emission of hydrocarbons in: all tests – AV, the static tests – AVS, the dynamic tests – AVD, the automotive tests – AVA and the non-road tests – AVB

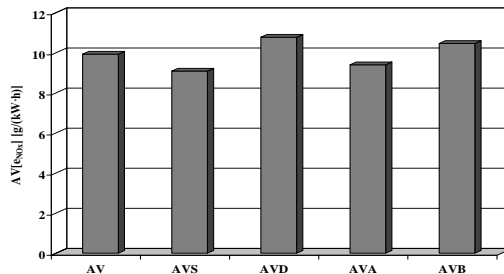


Fig. 11. The average value of the specific brake emission of nitrogen oxides in: all tests – AV, the static tests – AVS, the dynamic tests – AVD, the automotive tests – AVA and the non-road tests – AVB

There is a clear trend that the larger values of the pollutant specific brake emission occur for the dynamic tests in respect to the value of the static tests and for the values in the non-road tests relative to the value in the automotive tests.

In order to evaluate the scattering of the pollutant specific brake emission in various types of engine states, the variation coefficient of pollutant specific brake emission was tested: in all tests,

the static tests, the dynamic tests, the automotive tests and non-road tests – Figure 13.

The greatest dispersion of the specific brake emission of pollutants takes place for the particulates. Larger dispersion of specific brake emission of pollutants are usually for the dynamic tests agents, but there is no perceived regularity in comparing the results for the automotive and non-road tests.

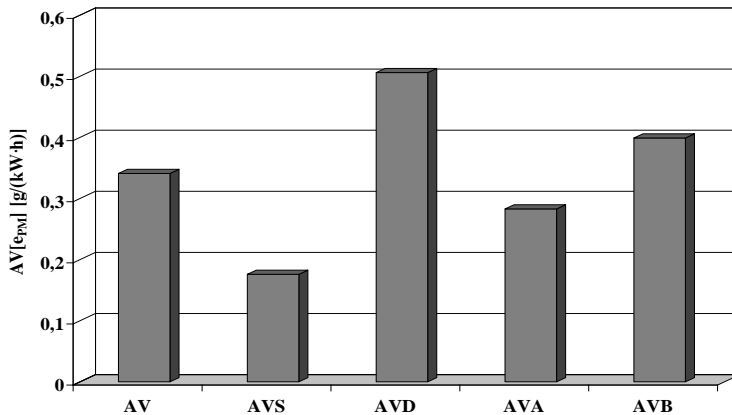


Fig. 12. The average value of the specific brake emission of particulate matter in: all tests – AV, the static tests – AVS, the dynamic tests – AVD, the automotive tests – AVA and the non-road tests – AVB

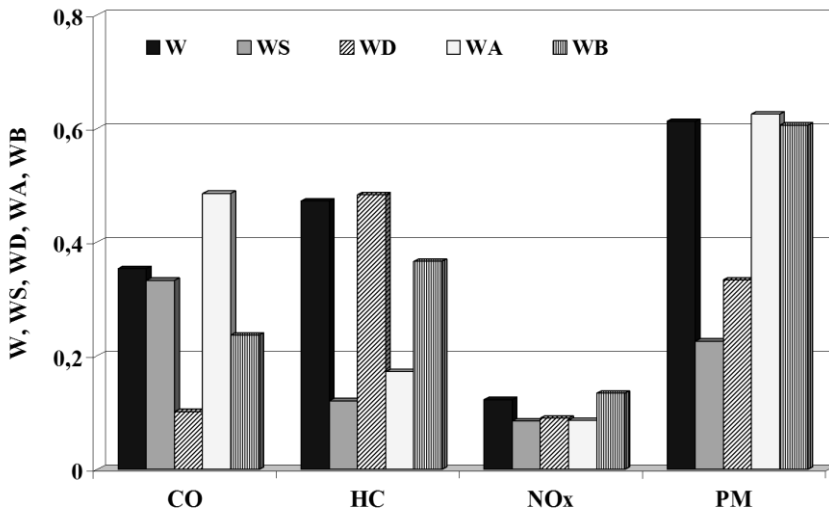


Fig. 13. Coefficient of variation of the pollutant specific brake emission of in: all tests– W, the static tests – WS, the dynamic tests – WD, the automotive tests – WA and the non-road tests – WB

5. Summary

The results of empirical studies of emission from the self ignition engine in significantly varying tests, both static and dynamic, confirm the high sensitivity of the emission from the engine to the operating states, not only static, but also in the occurrence of dynamic states. The first type of sensitivity of the pollutants emission, resulting from conducting this work, is consistent with the results of simulation tests presented in the papers [17–19]. Generally a trend is confirmed of the pollutant emission increasing in the dynamic tests. Studies carried out in this paper relate to characteristics of the engine, averaged over all the tests. Analysis of the elementary dynamic states enables to formulate more detailed conclusions [10, 11], but the extensiveness of the types of this analysis exceeds the available capacity of this paper.

References

- [1] Arregle J. et al.: Procedure for engine transient cycle emissions testing in real time. *Experimental Thermal And Fluid Science*, Volume 30, No 5, pp. 485–496, 2006.
- [2] Budny E., Chłopek Z., Chłosta M. et al.: Ocena skuteczności zasilania silnika spalinowego gazem ziemnym w celu ograniczenia emisji zanieczyszczeń w warunkach użytkowania silnika w maszynie do robót ziemnych – ciągniku gąsienicowym. (The assess of the effectiveness of the internal combustion engine su pp.ly natural gas to the reduce of the pollutant emission in the use of the internal combustion engine in the building machine). Projekt badawczy KBN nr 9 T12 D 013 23, 2006–2009. (In Polish).
- [3] Chłopek Z.: Analiza metod wyznaczania statycznych testów badawczych silników spalinowych. (The analysis of test methods for the determining the static tests of internal combustion engines). *Journal of KONES*, pp. 15–22, 1999. (In Polish).
- [4] Chłopek Z.: Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej silników spalinowych. (The modeling of the exhaust emission in conditions of the operation of traction internal combustion engines). *Prace Naukowe, Seria „Mechanika” z. 173, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 1999. (In Polish).*
- [5] Chłopek Z.: Some remarks on engine testing in dynamic states. *Silniki Spalinowe – Combustion Engines 4/2010(143)*, pp. 60–72.
- [6] Chłopek Z.: Stationary simulation tests of exhaust emission in dynamic tests for Diesel engines with various a pplications. *Silniki Spalinowe – Combustion Engines 2/2011(145)*, pp. 35–41.
- [7] Chłopek Z.: Statyczne testy badawcze silników spalinowych do symulacji testów dynamicznych. (Static tests of internal combustion engines to simulate dynamic test). *Journal of KONES*, pp. 20–30, Lublin 2000. (In Polish).
- [8] Chłopek Z.: Synteza statycznych testów badawczych silników spalinowych. (The synthesis of static tests of internal combustion engines). PAN Oddział w Krakowie, Teka Komisji Naukowo–Problemowej Motoryzacji, Zeszyt 18, pp. 21–26, Kraków 1999. (In Polish).
- [9] Chłopek Z.: Synteza testów do badań silników spalinowych autobusów miejskich. (The synthesis of tests to study the urban bus engines). Teka Komisji Naukowo–Problemowej Motoryzacji PAN, Kraków 2008. (In Polish).
- [10] Chłopek Z., Szczepański T.: Badanie właściwości użytkowych silników spalinowych w stanach dynamicznych. (Research of internal combustion engine useful qualities in dynamic states). *Zeszyty Naukowe Instytutu Pojazdów 1(92)/2013*.
- [11] Chłopek Z., Szczepański T.: Research concept of the combustion engines properties in dynamic states. *Combustion Engines 3/2013(154)*, pp. 168–174.
- [12] Cornetti G.M., Klein K., Fränkle G.J., Stein H.J.: US transient cycle versus ECE R49 mode cycle. *SAE Paper 880715*.
- [13] Fränkle G., Stein H.J.: Instationäre oder stationäre Abgasprüfverfahren für Nutzfahrzeug–Dieselmotoren, 1. Teil ATZ 1/1988, 2, Teil – ATZ 2/1988.

- [14] ISO 08178: „Reciprocating internal combustion engines – Exhaust emission measurement – Part 4: Test cycles for different engine applications”.
- [15] Marecka–Chłopek E., Budny E., Chłopek Z., Chłosta M.: Identification of combustion engine static states in real operation conditions of earthmoving machine. *Scientific Problems of Machines Operation and Maintenance* 4(156)2008, pp. 69–84.
- [16] Marecka–Chłopek E., Budny E., Chłopek Z., Chłosta M.: Wyniki badań stanów pracy silnika spalinowego w warunkach rzeczywistego użytkownika ciągnika gąsienicowego. (The research results of the work states of internal combustion engine in the conditions of the caterpillar tractor use). *Zeszyty Naukowe Instytutu Pojazdów Politechniki Warszawskiej* 2(69)/2008, pp. 101–110. (In Polish).
- [17] Marecka–Chłopek E., Chłopek Z.: Badania porównawcze emisji zanieczyszczeń z silników spalinowych o różnych zastosowaniach. (The comparative research of the pollutant emission from internal combustion engines of different uses). *Transport Samochodowy* 1/2009, pp. 71–84.
- [18] Marecka–Chłopek E., Chłopek Z.: Ocena emisji zanieczyszczeń z silników spalinowych o zastosowaniach innych niż samochodów. (The estimation of the pollutant emission from internal combustion engines to non–road machines). *Zeszyty Naukowe Instytutu Pojazdów Politechniki Warszawskiej* 2(69)/2008. (In Polish).
- [19] Marecka–Chłopek E., Chłopek Z.: Pollutants emission problems from the combustion engines of other applications than motor cars. *Eksploatacja i Niezawodność – Maintenance and Reliability* Nr 3 (35)/2007, pp. 81–85.
- [20] Marecka–Chłopek E., Chłopek Z.: Synteza testów do badań silników spalinowych maszyn roboczych. (The synthesis of tests for internal combustion engines to building machines). Rozdział w monografii „Uwarunkowania ekorozwoju rekreacji i turystyki” (Determinants of sustainable development of recreation and tourism), Wydawnictwo Naukowe Gabriel Borowski, Lublin 2008. (In Polish).
- [21] Marecka–Chłopek E., Chłopek Z.: Synteza testów statycznych do badania silników spalinowych o zastosowaniach innych niż samochodowe ze względu na emisję zanieczyszczeń i zużycie paliwa. (The synthesis of static tests to internal combustion engines for non–road applications due to the pollutant emission and the fuel consumption). *Przegląd Mechaniczny* 9/2007, pp. 35–40.
- [22] Merkiś J., Barski R.: O możliwościach zastąpienia 13–fazowego testu ECE R49 skróconym testem SET w badaniach toksyczności silnika ZS. (The possibilities of replacing the 13–phase ECE R49 test with the reduced SET test in toxicity studies of diesel engine). *Eko–Diesel* 1996. (In Polish).
- [23] Moser F.X., Haas E., Schlögl H.: Die Partikel–Hürde U.S. 1991: Vergleich der Testverfahren für Nutzfahrzeugmotoren – Bewältigung mittels innermotorischer Maßnahmen. 10. Internationales Wiener Symposium, VDI Fortschritt Berichte. Reihe 12, Nr. 122, VDI Verlag. Düsseldorf 1989.
- [24] SAE Recommended Practice: Test procedure for the measurement of gaseous exhaust emissions from small utility engines. SAE J1088, February 1993.
- [25] Steward D.: Transient cycle emissions testing. Southwest Research Institute. San Antonio 1998.
- [26] US Environmental Protection Agency: EPA nonregulatory nonroad Duty Cycles <http://epa.gov/nonroad-diesel/cycles/nrcycles.htm>.
- [27] Worldwide emission standards. Heavy duty & off–road vehicles. Delphi. Innovation for the real world, 2012/2013