# PERFORMANCE MEASUREMENTS ON AN EXPERIMENTAL OTTO/DIESEL ENGINE OPERATING WITH DIFFERENT FUELS

by

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Original scientific paper
https://doi.org/10.2298/TSCI171117305D

*Multi-process working principle is one of the modern approaches to development of internal combustion engines. By combining the original features of the Otto and Diesel working processes, an improvement of the engine efficiency and ecological characteristics can be achieved. Examples for that are spark ignition engine with stratified charge as well as compression ignition engines with homogeneous charge. The experimental multi-process engine was developed as well as testing methodology, for the basic researches efficiency and ecological characteristics of the Otto/Diesel engine. This paper presents the results of the combination of Otto/Diesel working processes when the engine working with both conventional and bio-fuels. Results of initial tests of Otto/Diesel engine show a high potential to reduce particulate emissions. The investigation has shown certain disadvantages of the engine and the ways for theirs overcoming.*

Key words*: compression ratio, efficiency, emission, experimental engine, working process*

## Introduction

It is known that the way the engine working process realization has a dominant influence on the engine efficiency and emission. The main characteristics of the working process of internal combustion (IC) engines are listed in tab. 1. Classical concepts of Otto and Diesel engines are conditioned by the properties of the used fuel and they have generic advantages and disadvantages. Modern technologies of engine equipment have allowed synthesis of the good features of traditional working processes.

Thus, spark ignition of very lean inhomogeneous mixture, reduction of pump losses at low loads and increase of the compression ratio is enabled in gasoline direct injection (GDI) engine with stratified charge, thanks to the internal formation of mixture. In this way, engine efficiency at low and moderate loads is much-improved [1]. At medium and high-loads, working process is conducted according Otto process. However, Diesel attributes of the working process have brought their shortcomings: the sensitivity of the process of forming the mixture to flow in the combustion chamber (misfiring) and particulate emission [2, 3].

Homogenous charge compression (HCCI) ignition working process may be achieved both in the Otto and Diesel engine concept. Very lean homogeneous mixture is ignited by compression on overall volume of combustion chamber and simultaneously combusts with

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**Table 1. The main characteristics of working processes of modern engines**

| Working process | Working process characteristics | | | | | |
|---|---|---|---|---|---|---|
| | Mixture forming | Mixture Homogeneity | Global air/ Fuel ratio | Load regulation by | Mixture ignition by | Flame propagation |
| Otto | Out of cylinder | Homogeneous | Stoich./rich | Throttling | Spark | Frontal |
| Diesel | In cylinder | Inhomogeneous | Lean | Fuel quantity | Compression | Diffusion |
| GDI | In cylinder | Inhomogeneous<br>Homogeneous | Lean<br>Stoich./rich | Fuel quantity<br>Throttling | Spark | Diffusion<br>Frontal |
| HCCI | In/out of cylinder<br>In cylinder | Homogeneous<br>Inhomogeneous | Lean | Fuel quantity | Compression | Simultaneous<br>Diffusion |

controlled speed. High efficiency, ultra-low $NO_x$ emissions and negligible particulate emissions are well known advantages [1]. Despite numerous opportunities for the control of the working process, it is very difficult and complicated to maintain its stability in the overall working area [4, 5].

In this paper, the multi-process motor principle is realized by selecting either otto or Diesel process depending on the speed and load of the engine. Therefore, were used two fuel substantially different characteristics (gasoline or LPG or CNG or bioethanol for otto process and diesel fuel or biodiesel fuel for diesel process). Application of bi-fuel systems today does not represent a major technological problem and they already exist in practice (gasoline/LPG, gasoline/CNG). We believe that the use of an Otto/Diesel engine is justified in road vehicles. The development of Diesel engine equipment has made it possible to reduce significantly the dimensions of its cylinders so that the Diesel engine (diesel process) can also be used in smaller passenger cars.

The main objectives of this paper are:

– realization of the experimental multi-process engine and its equipment,
– identification of the main characteristics of the working process of the experimental engine when it operating in otto and diesel processes,
– to defining the testing methodology for the evaluation of the efficiency and ecological characteristics of the Otto/Diesel engine, and
– to checking the potential of the Otto/Diesel engine for the improving the engine efficiency and ecological characteristics.

## Experimental investigations

In order to research the multi-process working principle, an experimental engine and a measurement installation for determination of the effective, indicator and emission parameters were built in our laboratory. Testing methodology is based on the use of the European Stationary Cycle (ESC) test (Directive 1999/96/EC). The test results of the combination of otto/diesel working processes in the same cylinder are presented in this paper.

### *Realisation of the Otto/Diesel engine*

The experimental engine is realised based on a multi-purpose model DMB-3DA 450 module 328, tab. 2. Multi-process features are obtained with the following actions:

– reconstruction of the cylinder head and the piston,
– building the intake manifold with the throttle and the injector,
– equipping the engine with crank shaft position encoder, sensors and actuators,
– building the laboratory micro-controller system for engine control, and
– building the ignition system of a multi-charge ignition type.

**Table 2. Basic and experimental engine specifications**

| | Basic DMB-3DA450 | Experimental engine | |
|---|---|---|---|
| Description | Four stroke, single cylinder, air-cooled, natural aspirated, | | |
| Swept volume | 454 cm$^3$ | | |
| Rated speed | 3000 rpm | | |
| Valve timing | Intake valve opened: 16 °CA bTDC Exhaust valve opened: 40 °CA bBDC<br>Intake valve closed: 40 °CA aBDC Exhaust valve closed: 16 °CA aTDC<br>Valve overlap 32 °CA | | |
| Working process | Diesel D.I. | Diesel D.I. | Otto |
| Rated power | 6.6 kW | – | – |
| Compress. ratio | 17.5 | 12.5 | |
| Fuel system characteristic | Mono-block fuel pump, fixed timing 18.5 °CA bTDC, Mech. closed cup injector, All-regime mech. governor | Mono-block fuel pump, fixed timing, mech. closed cup injector, all-regime mech. governor, ON/OFF actuator | Intake port injection, BOSCH components laboratory control system |
| Ignition system | – | Multi spark, spark-plug cleaning mode, laboratory control system | Multi spark, ignition mode, laboratory control system |

To achieve the otto working process, the engine is equipped with both the ignition system and the fuel injection system (to intake manifold). The appearance of the combustion chamber is shown in fig. 1. By increasing the diameter of the piston chamber, compression ratio of 12.5 is achieved. This is a compromise value, high for otto working process and almost limiting for running of the diesel working process in this engine [5]. Layout of the experimental engine is shown in fig. 2.

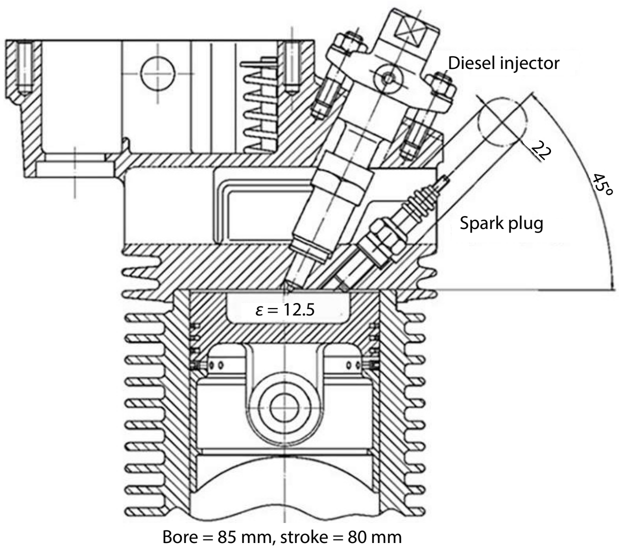


**Figure 1. Experimental engine's cross-section**

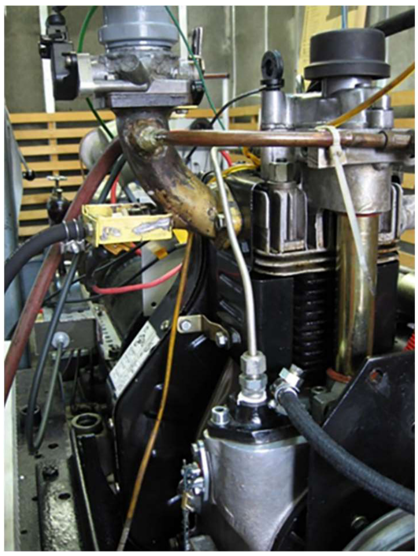

**Figure 2. Experimental engine on testing bench**

Engine management is performed by a micro-controller system, fig. 3, with the following option;

– selection either otto or diesel working process,
– setting the injection and ignition parameters in otto process (either manually or automatically),
– setting the injection parameters in diesel process (either manually or automatically),
– monitoring of measured and specified outgoing parameters, and
– determination of injector characteristics (a special subroutine).

The parameters of a spark advance angle and injection advance angle can be set in increments of 1°CA, whereas the injection time in otto and diesel process may be set with precision 0.01 ms. In this case, a factory fuel injection system is used in diesel process, so there was only the possibility of automated turn-off of the high-pressure pump during transition to otto process.

The ignition system is of multi spark type, operating at a frequency of 10.5 kHz. In addition to the basic function of ignition in the otto process, it has the ability to diagnose the absence of ignition. By continuous sparking during engine operation in diesel process, the effect of self-cleaning of spark plugs is achieved [6].

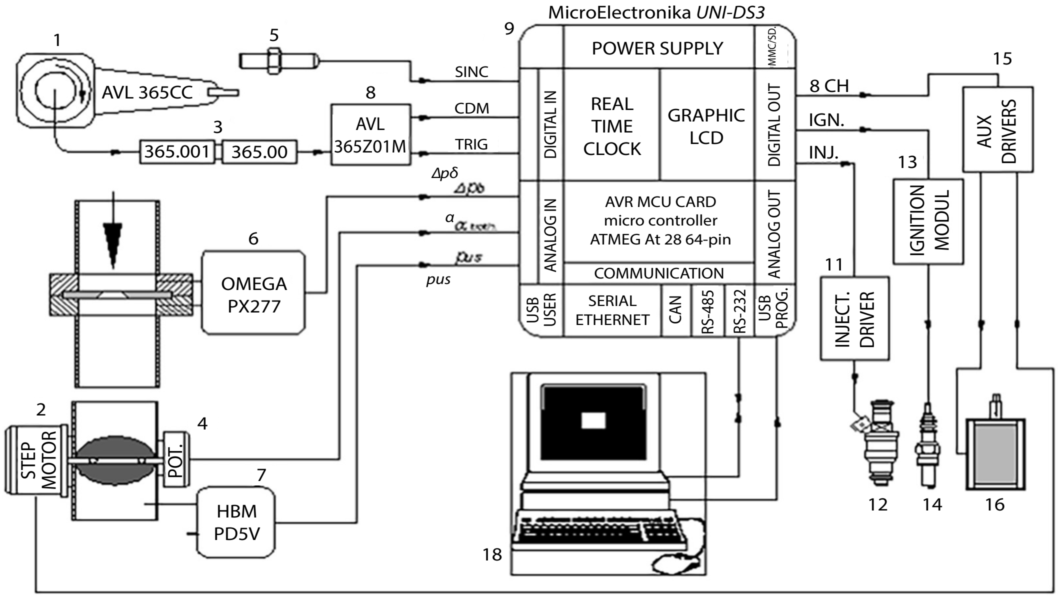


**Figure 3. Block structure of laboratory engine control system;** *1– encoder °CA/TDC 2, – throttle actuator, 3 – optical transmitter, 4 – throttle pos. sensor, 5 – valve status sensor, 6 – diff. pressure gauge,7 – pressure gauge, 8 – pulse multiplicator, 9 – controller board, 10 – PC, 11 – injector driver, 12 – injector, 13 – multi-spark ign. module, 14 – spark plug NGK C7HSA, 15 – 8-ch. digital driver, 16 – fuel pump ON/OFF actuator*

## *Characteristics of the used fuels*

Tests were conducted with commercial and bio-fuels produced by *VICTORIA OIL* Sid. Bio-fuels are especially interesting considering the selected compression ratio of the experimental engine. Bio-ethanol is more resistant to detonation combustion than commercial gasoline, whereas bio-diesel (soybean methyl ester) has better self-ignition properties compared to commercial diesel fuel. In tab. 3, some of the important characteristics of the used fuels are listed. Cetane numbers (CN) of diesel fuel are determined by own engine method, previously published in [7].

**Table 3. Some of the relevant fuels characteristics**

| | Fuel trademark | Gasoline BMB 95 | Bio-ethanol | Diesel ECO-3 | Bio-diesel | |
|---|---|---|---|---|---|---|
| | Standard | EN228:2005 | – | EN590:2005 | EN14214 | |
| Characteristic | Dimensions | | | | | Test method |
| Density at 15 °C | [kgm$^{-3}$ ] | 770 | 798 | 835 | 884 | IP 190/64 |
| Viscosity at 40 °C | [mm$^2$s$^{-1}$] | – | – | 2.20 | 3,86 | Vogel-Ossag |
| Flashpoint | [°C] | – | 12.7 | 76.3 | 177 | EN ISO 13736<br>EN ISO 22719 |
| Higher heating value | [kJkg$^{-1}$] | 47100 | 29200 | 45770 | 38920 | SRPS B.H8.318 |
| Lower heating value | [kJkg$^{-1}$] | 43950 | 26250 | 42850 | 36220 | SRPS B.H8.318 |
| Cetane number | CN | – | – | 52.0 | 55.5 | MFK method [7] |
| Research octane No. | RON | 95 | 110-115 | – | – | Literature data [8], [9] |
| Elementary composition: | | | | | | |
| Carbon | [%] m/m | 86.0 | 52.2 | 87.0 | 77.0 | |
| Hydrogen | | 14.0 | 13.1 | 13.0 | 12.0 | |
| Oxygen | | 0.0 | 34.7 | 0.0 | 11.0 | |
| Stoichiometric A/F ratio | $kg_{air}/kg_{fuel}$ | 14.7 | 9.0 | 14.7 | 13.8 | |
| Molecular weight | [kg kmol$^{-1}$] | 100-105 | 46.07 | ≈200 | ≈292 | |

## *Testing procedure*

The testing was conducted with application of ESC 13-mode homologation test for heavy-duty vehicles emission, fig. 4 [3]. Definition of the working regimes is done based on factory declaration of the base engine. At idle speed, there has been an insignificant load of approximately 160 W (minimal brake friction resistance). This circumstance has been taken into account in calculation of emission and effective efficiency.

The drive with a bio-ethanol in the otto process was enabled significant increase the engine power. Regimes denoted by A, B, and C are obtained at the detonation limit. Oscilloscopic monitoring of the pressure signal were used for discovered a detonation.

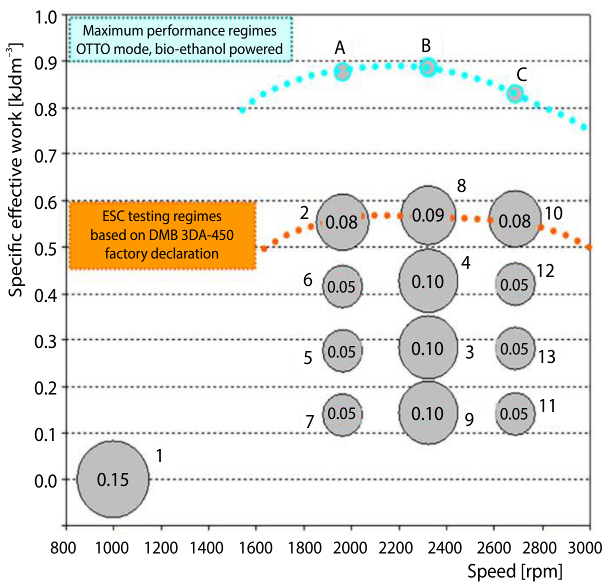


**Figure 4. The ESC based testing regimes definition and weighting factors**

Whenever it was possible, the following criteria were respected at setting the working regimes in otto process:

– stoichiometric mixture composition, and
– ignition advance angle such that the centre of the combustion is between 8 °CA and 12 °CA after TDC.

Raw exhaust emission has been measured by AVL DICOM 4000 Analyser. The gas sampling line has not been heated, so the measured HC emission in diesel process is lower than in reality. The test emission indicators are determined by using the prescribed procedure, except for the particle emission, which was calculated using the Motor Industry Research Association correlation based on the measured Bosch smoke number (*BSN*), eq. (1). This method is applicable because of the technological level of the base engine.

$$PM_{\text{conc}} = 982 \cdot BSN \cdot 10^{(BSN \cdot 0.1272 - 1.66)}, \ [\text{mgm}^{-3}]$$
$$PM_{\text{mas}} = \frac{1}{1.293 \cdot 10^{-3}} PM_{\text{conc}} \cdot G_{\text{ig}}, \ [\text{gh}^{-1}] \tag{1}$$

where $PM_{\text{conc}}$ is volumetric concentration *PM*, $PM_{\text{mas}}$ – the mass concentration *PM*, *BSN* – the Bosch smoke number, and $G_{ig}$ – the wet exhaust gases flow.

In order to compare engine emission characteristics by overall working area, emissions are measured during each mode of the ESC test cycle and averaged over the cycle using a set of weighting factors. The final emission results are expressed in [$\text{gkW}^{-1}\text{h}^{-1}$].

Indicated parameters were measured by AVL Indimer 619 system on the sample of 50 consecutive cycles. Their average values were used in later calculations and diagrams. Statistical parameters of the sample (standard deviation *etc.*) were used to determine regime's stationarity during the measurements.

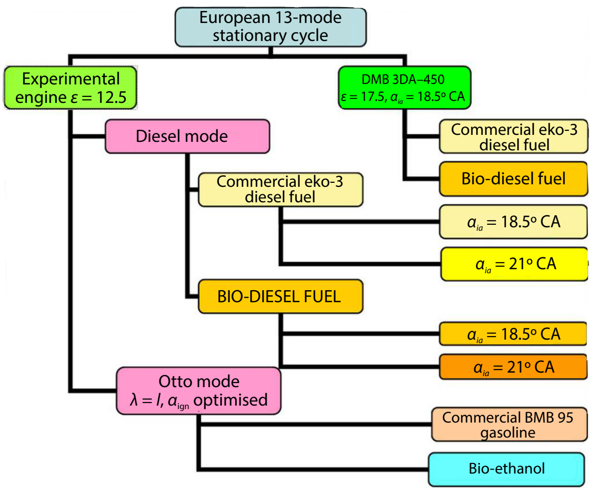


**Figure 5. Testing schedule**

Indicated, $\eta_{\text{i}}$, and effective, $\eta_{\text{e}}$, efficiency are measured and calculated during each mode the ESC test cycle and averaged over the cycle using the same set of weighting factors and methodology as in calculations of emissions. Friction losses were estimated by calculation of a mechanical efficiency $\eta_{\text{m}}$.

The testing schedule shown in fig. 5 was organized in such a way to realize the effects of the type of fuel, compression ratio and regulating parameters on operating in both process. Tests were conducted in separate sessions.

## Discussion of the results and observations

Design simplicity and technological anachronism of the base engine has not enabled the on-line optimization of fuel injection parameters in diesel process. By piston reconstruction, besides the lowering of compression ratio, there was also a change in the shape of the combustion chamber. The central nipple has been removed and the extrusion area has been reduced.

Consequently, there were the following problems in operation of the experimental engine in diesel processes:
– cold start was successful only when ambient temperatures exceed 22 °C, so the cranking was performed in otto process,
– at idle speed regime and at low loads (regimes 7, 9, 11, and 13), intensive white smoke and decrease in efficiency were observed, and
– at maximal loads (regimes 2, 8, and 10), diesel knock were observed during operation with classic fuel.

Reconstruction of the combustion chamber from the aspect of running of Otto working process has also certain disadvantages:
– the spark plug is placed at the edge of the chamber, so there was a long path for propagation of flame, and
– spark plugs electrodes were in the cavity with poor ventilation and it worsens the ignition conditions.

These circumstances have led to extended and less efficient combustion at lower loads in otto process.

Large valve overlap (32° CA) has caused the penetration of mixture into the exhaust system in otto process. In addition, in conditions of enriched mixture combustion, a small quantity of oxygen was detected in the exhaust emission. Therefore, it was not possible to apply the mixture composition control in closed loop. Another consequence was the increased HC emission in otto process, especially at idle speed regime.

An interesting observation was made by analysing the experimental engine pumping losses. Table 4 shows the correlation between engine pumping losses and engine loads for both operating process. Diesel process has a significant advantage relative to otto process up to 50% of the load, but already at over 50% of the load, diesel process loses an advantage in this regard. Regarding to the speed of the engine, the lower values of pumping losses were registered at 1962 rpm, and higher values at 2687 rpm.

**Table 4. Pumping losses of the experimental engine**

| | Pumping losses [%] $W_i$ | |
|---|---|---|
| Load (ESC test cycle) | Diesel process | Otto process |
| 0% (idle) | 7 | 86 |
| 25% | 14/21 | 22/25 |
| 50% | 10/15 | ≈ 14 |
| 75% | 8/11 | 9/11 |
| 100% | 6/11 | 7/9 |
| Max. performance | – | 6/9 |

There was a high sensitivity of the experimental engine to the regulation of injection advance angle.

Test results are grouped according to the type of the fuel used.

Table 5 presents the achieved results of average emission and efficiency of the base and experimental engine during working with commercial fuels: Diesel ECO-3 or gasoline BMB-95.

**Table 5. Results of the base and experimental engine when they use commercial fuels**

| | Parameters of ESC- test | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average emissions [g kW$^{-1}$ h$^{-1}$] | | | | Average efficiency | | |
| Configuration of the test | CO | HC | $NO_x$ | PM | $\eta_i$ | $\eta_m$ | $\eta_e$ |
| Base engine, diesel ECO-3 fuel | 17.106 | 0.187 | 8.428 | 1.726 | 0.388 | 0.606 | 0.235 |
| Exp. engine, diesel-process, diesel ECO-3 | 21.429 | 0.424 | 8.733 | 0.202 | 0.350 | 0.620 | 0.217 |
| Exp. engine, otto-process, gasoline BMB-95 | 48.659 | 0.765 | 20.920 | – | 0.341 | 0.648 | 0.221 |

The reduced value of the compression ratio in the experimental engine has led, among other things, to deterioration of efficiency. In otto process, the indicated average efficiency was reduced significantly, because the engine was running at the edge of detonation with rich mixture and with retarded ignition at high loads. At the same time, mechanical losses, caused by low pressure in the cylinder were reduced, so that the effective average efficiency was at the diesel process level.

In diesel process, emissions of gaseous pollutants were increased, whereas the PM emissions have been significantly reduced. Substantial mixture enrichment ($\lambda \approx 0.92$) in otto process has led to significant increase of gaseous pollutants at high loads, tab. 5.

After the analysis of efficiency, emission and parameters of the working processes at each mode of the ESC test cycle, combinations of otto and diesel process were made based on two criteria. Figure 6 shows the combination of working process of the experimental engine according to maximum efficiency criterion. Figure 7 shows the combination of operating process of the experimental engine according to minimum PM emissions criterion.

Table 6 presents the results of these optimizations. It is obvious that the optimization according to efficiency criterion had not given any significant results, whereas the optimization according to PM emission has led to its drastic reduction.

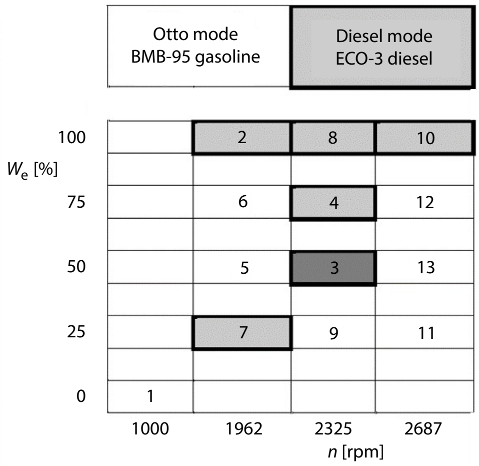


**Figure 6. The combination of operating ESC modes of the experimental engine according to maximum efficiency criterion (commercial fuels) – $\alpha_{ia}$ = 18.5 °CA, except the mode 3 where $\alpha_{ia}$ = 21 °CA**

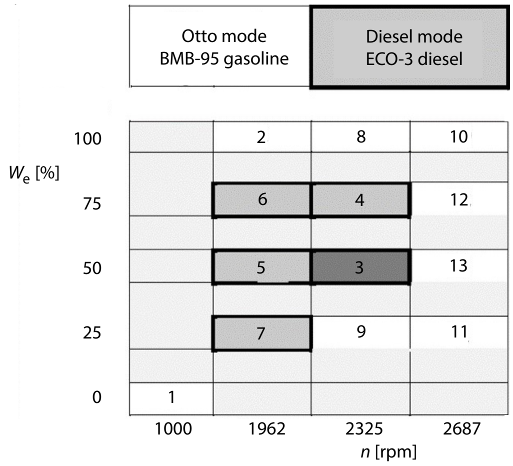


**Figure 7. The combination of operating ESC modes of the experimental engine according to minimum PM emissions criterion (commercial fuels) – $\alpha_{ia}$ = 18.5 °CA, except the mode 3 where $\alpha_{ia}$ = 21 °CA**

**Table 6. Results of the experimental engine optimization when it use commercial fuels**

| | Parameters of ESC test | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average emissions [$gkW^{-1}h^{-1}$] | | | | Average efficiency | | |
| Configuration of the test | CO | HC | $NO_x$ | PM | $\eta_i$ | $\eta_m$ | $\eta_e$ |
| Exp. engine otto/diesel process optimum efficiency | 16.165 | 0.502 | 14.621 | 0.194 | 0.356 | 0.632 | 0.225 |
| Exp. engine otto/diesel process for minimum PM emissions | 39.998 | 0.570 | 14.245 | 0.034 | 0.353 | 0.629 | 0.222 |

In tab. 7, the obtained results of emission and efficiency of the base and experimental engines are presented for engine operation with bio-fuels. Reduced value of the compression ratio at experimental engine has led, among other things, to somewhat smaller deterioration of efficiency than with using the commercial fuel.

**Table 7. Results of the base and experimental engine when they use bio-fuels**

| | Parameters of ESC test | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average emissions [g kW$^{-1}$ h$^{-1}$] | | | | Average efficiency | | |
| Configuration of the test | CO | HC | $NO_x$ | PM | $\eta_i$ | $\eta_m$ | $\eta_e$ |
| Base engine, bio-diesel fuel | 14.821 | 0.298 | 10.752 | 0.980 | 0.398 | 0.612 | 0.238 |
| Exp. eng., diesel process, bio-diesel fuel | 23.880 | 0.347 | 8.654 | 0.054 | 0.343 | 0.653 | 0.224 |
| Exp. eng., otto process, bio-ethanol fuel | 47.794 | 0.600 | 8.762 | – | 0.352 | 0.653 | 0.230 |

In diesel process of experimental engine operating with bio-fuels, CO and HC emissions have increased, whereas the $NO_x$ emission is reduced by about 20% and PM emission by more than 90%. Jagadish, D., *et al.*, [10] have noticed that NO values are lowered with ethanol and smoke opacity is significantly reduced with ethanol-ester-diesel blends.

The richer mixture in otto process have led to significant increase of CO and HC emissions, whereas $NO_x$ emission was reduced at high loads, tab. 7.

After the analysis of efficiency, emission and working process parameters at each mode of the ESC test cycle, combinations of otto and diesel process were made according to two criteria whereas working with bio-fuels. Figure 8 shows the combination of operating process of the experimental engine according to maximum efficiency criterion. Figure 9 shows the combination of operating process of the experimental engine according to minimum PM emissions criterion.

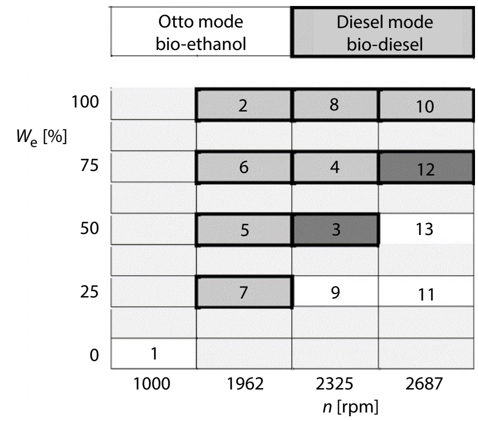


**Figure 8. The combination of operating ESC modes of the experimental engine according to maximum efficiency criterion (bio-fuels) – $\alpha_{ia}$ = 18.5 °CA, except modes 3 and 12 where is $\alpha_{ia}$ =21 °CA**

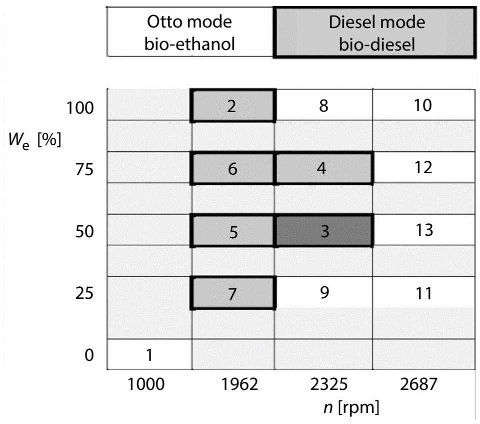


**Figure 9. The combination of operating ESC modes of the experimental engine according to minimum PM emissions criterion (bio-fuels) – $\alpha_{ia}$ = 18.5 °CA, except the mode 3 where is $\alpha_{ia}$ = 21 °CA**

Table 8 shows the results of these optimizations. Optimization according to efficiency has given similar results as in working with commercial fuels, whereas optimization according to PM emission has led to its drastic reduction.

**Table 8. Results of the experimental engine optimization when it uses bio-fuels**

| | Parameters of ESC test | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average emissions [g kW$^{-1}$ h$^{-1}$] | | | | Average efficiency | | |
| Configuration of the test | CO | HC | $NO_x$ | PM | $\eta_i$ | $\eta_m$ | $\eta_e$ |
| Exp. engine otto / diesel process optimum efficiency | 12.131 | 0.310 | 9.968 | 0.047 | 0.353 | 0.640 | 0.226 |
| Exp. engine otto / diesel process for minimum PM emissions | 33.933 | 0.435 | 8.983 | 0.006 | 0.343 | 0.641 | 0.220 |

## Conclusions

Modern trends in engine development go in the direction of synthesis of good features of different working processes in the IC engine cylinder.

Experimental engine was made according to old technology and it was compromisingly reconstructed in order to obtain multi-processing features. The main drawback is the inability electronically control the parameters of the injection in diesel process.

To enable compare engine efficiency and ecology parameters by overall engine working area the testing methodology was designed. In this methodology, engine efficiency and emissions are measured during each mode of the ESC test cycle and averaged over the cycle using a set of weighting factors. As well as to enable a comparative analysis of the engine efficiency and ecological parameters in each individual modes of the ESC test.

Application of bio-fuels at experimental Otto / Diesel engine provides greater possibilities to optimize and increasing the engine power. Decreasing of the exhaust emissions, especially PM emissions and increasing of the engine efficiency, compared to using classical fuels, were achieved.

Unsatisfactory results obtained in optimization of economy of experimental Otto / Diesel engine were the consequence of uneconomical operation at low loads in diesel process. The reason for this is the incomplete combustion brought about by poor mixture preparation.

Application of measures to increase the temperature of the charge in the moment of fuel injection as with EGR and pre-injections may considerably improve the efficiency and ecological parameters of the Otto / Diesel engine dealt with in the present study.

## Nomenclature

CO – emission carbon monoxide, [g kW$^{-1}$h$^{-1}$]
HC – emission unburned hydrocarbons, [g kW$^{-1}$h$^{-1}$]
$NO_x$ – emission nitrogen oxides, [g kW$^{-1}$h$^{-1}$]
PM – emission particulate matter, [g kW$^{-1}$h$^{-1}$]
$W$ – specific work, [kJ dm$^{-3}$], or [%]

*Greek symbols*

$\alpha_{ia}$ – injection advance angle (timing), [° CA]
$\alpha_{ign}$ – ignition advance angle, [° CA]
$\varepsilon$ – compression ratio, [–]
$\eta$ – efficiency, [–]
$\lambda$ – air excess ratio, [–]

*Abbreviations*

aBDC – after bottom dead centre
aTDC – after top dead centre
bBDC – before bottom dead centre
bTDC – before top dead centre
CN – cetane number
CA – crank angle, [°]
DI – direct injection,
ESC – European Stationary Cycle
GDI – gasoline direct injection
HCCI – homogeneous charge compression ignition
TDC – top dead centre

*Subscripts*

e – effective
i – indicated
m – mechanical

## Acknowledgment

The paper is a result of the research within the project TR 35041 financed by the Ministry of Science and Technological Development of the Republic of Serbia.

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Paper submitted: November 17, 2017
Paper revised: December 16, 2017
Paper accepted: December 16, 2017