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Determination of specific fuel consumption of IC engine in transient conditions

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Summary. This paper presents the results of motor vehicle traction research obtained with the use of satellite navigation techniques as an alternative test method of determination the external characteristics of the engine. The characteristics take into consideration the weather and the vertical profile of the route with simultaneous determination of specific fuel consumption based on measurement of the fuel injector opening time.

Key words: combustion engine, specific fuel consumption, transient conditions.

INTRODUCTION

The paper presents the results of measuring the light fuel injector flow characteristics and the results of calculating the specific fuel consumption of spark ignited engine obtained with the use of above mentioned characteristics at the time of vehicle acceleration:

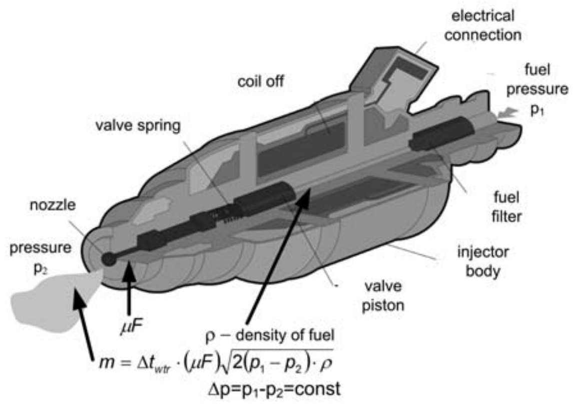

Fig. 1. Fuel flow diagram (description in text) [authors' own, http://commons.wikimedia.org, 2011]

The fuel dose flowing through the injector (fig. 1) can be controlled by variation of the effective area of the minimal section μF, the difference between the fuel pressure p_1 and the injector ambient pressure p_2 or by injector opening time Δt_{wtr}. The mass m flowing uniformly out of the nozzle at the Δt_{wtr} time can be determined by the following equation (1):

$$m = \Delta t_{wtr} \cdot (\mu F)\sqrt{2(p_1 - p_2)\cdot \rho}\,. \qquad (1)$$

The fuel dose can be easily controlled as the injector opening time depends on the value of electrical signal. The total amount of fuel delivered to the cylinder is determined by both the duration of single pulse and the number of injections in time. The basic injector characteristics is the dependence between the fuel dose and the injector opening time at constant rotational speed or constant injection frequency.

PURPOSE AND METHODS

Assuming the condition of constant pressure difference p_1 and p_2 and constant fuel temperature (fig. 1), the jet of fuel from the injector is dependent on the diameter and geometry of nozzle as well as the shape and lift of nozzle needle. In order to simplify the measuring results interpretation method, the inertia of injector's moving elements has been neglected in the calculations and it has been assumed that the nozzle needle lift course is inversely proportional to the current curve in the injector coil. The instantaneous fuel consumption of engine operating in transient conditions on the vehicle test house or during the traction research can be determined at known injector characteristics by measuring – recording the opening time and recording or controlling the fuel pressure and temperature independently from the selected injector opening time control system (controlling by the single pulse, controlling with the current bound or multi-pulse controlling). The engine rotational speed can be recorded with the use of rotational speed sensors installed in the combustion engine control system or it can be determined on the basis of vehicle velocity during acceleration on specific gear measured with the use of e.g. satellite navigation techniques. The research verifying the usefulness of measuring method of the instantaneous fuel consumption in transient conditions were carried out with the use of combustion engine with sequential multipoint injection controlled by single rectangular signal. It is a spark ignited engine of cubic capacity equal 1199 cm^3 and power of 55 kW at 5600 rpm. The maximal torque of above mentioned engine is 110 Nm at 4000 rpm. Using the measurement of injector opening time to determine the specific fuel consumption entails the necessity of determination the characteristics of injector installed in the given combustion engine [10, 11]. Such characteristics are difficult to obtain and therefore the measurement of fuel flow capacity (constant fuel pressure and temperature) in relation with opening time of injector controlled by single pulse at constant opening frequency [20] was carried out. The variation window of injector opening time was determined on the basis of measurements during vehicle acceleration at the conditions of real vehicle exploitation.

The volumetric method was used in order to determine the injector characteristics given by (2):

$$d_w \left[\frac{mm^3}{ms}\right] = f(\Delta t_{wtr}[ms]), \tag{2}$$

where :

d_w - injector fuel flow, mm^3/ms,

Δt_{wtr} - injector opening time, ms.

In the above mentioned method the microprocessor counts the number of pulses in the specific time at the injector opening time controlled by the microprocessor and recorded by the multichannel A/D converter. In the method of determination the injector characteristics, the specific dose of fuel from the injector can be described by the following equation (3):

$$d_w = \frac{V_p}{i_c \cdot \Delta t_{wtr}} \quad \left[\frac{mm^3}{ms}\right], \tag{3}$$

where:

V_p - the volume of injected fuel, *mm^3*;

i_c - the number of cycles/injections, *cycle*;

Δt_{wtr} - duration of the single cycle, *ms.*

The error of the injector characteristic determination was set as the average square error described by the following equation (4):

$$\Delta d_w = \sqrt{\left(\frac{\delta d_w}{\delta V_p}\right)^2 \cdot \left(\Delta V_p\right)^2 + \left(\frac{\delta d_w}{\delta i_c}\right)^2 \cdot \left(\Delta i_c\right)^2 + \left(\frac{\delta d_w}{\delta \Delta t_{wtr}}\right)^2 \cdot \left(\Delta\left(\Delta t_{wtr}\right)\right)^2}. \tag{4}$$

For the injection time between 11 and 18 ms (corresponding with values at the vehicle acceleration at the throttle fully opened, fuel pressure before the injector equal p_1=0.38 MPa and temperature approximately 42°C), the real flow characteristics at constant injection frequency is not linear and the non-linearity error [21] is at the level of 5% in the range of short opening times as well as for the maximal opening time.

DETERMINATION OF THE ENGINE'S EXTERNAL CHARACTERISTIC IN UNSTEADY CONDITIONS

The application of method using telecommunication techniques [4, 13, 16] to automotive vehicle traction research is fully justified [7], but it requires the knowledge concerning the characteristics of injector in which the vehicle's engine is equipped as well as the correlation between the injector opening times recording units and the software recording the basic physical quantities of vehicle movement in transient conditions obtained with the use of satellite navigation (UTC time, dislocation components P-X, P-Y, P-Z and velocity components V-X, V-Y i V-Z in WGS-84 system) [6, 12, 18]. In order to verify the above mentioned method the research concerning vehicle acceleration [1] with simultaneous recording of its movement parameters using the satellite navigation were carried out. The measuring system was equipped with the set dedicated to registering the injectors opening times, fuel pressure and temperature and the inlet system pressure. The fuel system was equipped with the PLU -116H [3] flow meter with pulse output of resolution equal 6.15 mm^3 per one generated electrical pulse. The flow meter measured the total fuel consumption. The schematic diagram of the measuring system is depicted in figure 2. The analysis of technical data [3, 17] of the applied flow meter reveals that the determination of the fuel consumption is performed with the accuracy of approximately 5 to 7% (at the average injector opening time during tests at the level of 15 to 20 ms).

The following quantities were registered during research:

- Vehicle location components P-X, P-Y i P-Z in WGS-84 system;
- Vehicle velocity components V-X, V-Y i V-Z in WGS-84 system;
- UTC time;
- Wind speed and direction;
- Ambient pressure and temperature;
- Injector opening times (fig. 3) with frequency of 40 kHz;
- Instantaneous fuel consumption (recording of pulses generated by the PLU 116H flow meter with the frequency of 40 kHz);
- Fuel pressure in the fuel rail using the Kistler piezoresistive probe with the frequency of 40 kHz;

Inlet system pressure using the Motorola MPX 5500DP absolute pressure piezoresistive probe with the frequency of 40 kHz;

Fuel temperature in the fuel rail and in the PLU 166 H flow meter (NiCr-NiAl thermocouple).

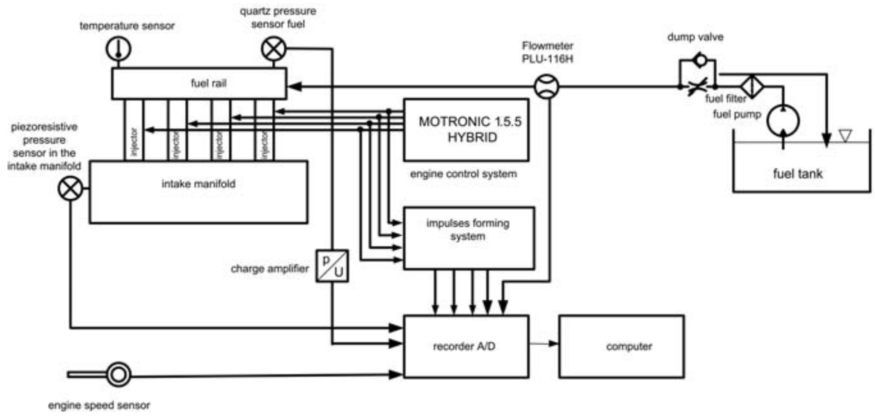

Fig. 2. The schematic diagram of the fuel consumption recording system during the acceleration of vehicle with 1.2 16V Z12XE engine

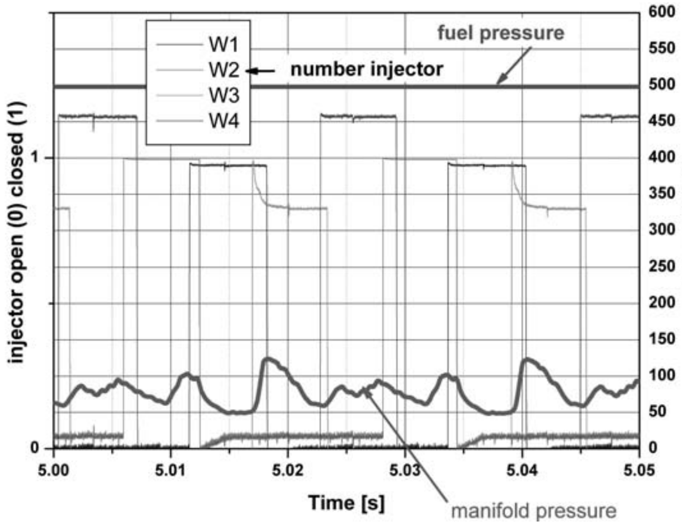

Fig. 3. Injector opening times (W1 ... W4), in relation to changes of pressure in the intake manifold and fuel pressure during acceleration of a vehicle with 1.2 16V Z12XE engine

The exemplary curves depicting injector state (low state – „0"- is the opened injector), variation of fuel pressure in the fuel rail and intake manifold pressure – the pressure sensor located in the vicinity of the injector no. 1 (W1) are depicted in figure 3.

The external characteristics of power and torque as well as specific fuel consumption were obtained from the measurements and analysis of vehicle acceleration on the third gear using the satellite navigation technique. The calculations were carried out taking into consideration the vertical rout profile – the average change in the altitude (5 m) on a test track (596 m) results in the average inclination of 0.84% (the allowable value 0.5% [14, 15]). The calculation results were corrected using the DIN 70020-5 [2] standard to the normal conditions: ambient pressure 1013.25 hPa, ambient temperature 293K. The results depicted in table 1 do not differ significantly from the catalogue data [8].

The analysis of obtained results of injector opening times [5] and the attempt to estimate the specific (taking into consideration the conditions, in which the individual injectors were calibrated – injection to the environment $p_2=b_0$) and hourly fuel consumption revealed rather large differences between the results obtained by measuring

Table 1. The measured maximal values of torque and effective power

Measured values according to [DIN70200-5, 1987]		Catalogue values [http://carfolio.com, 2012]	
Maximal power	Maximal torque	Maximal power	Maximal torque
56.7±1.47(kW) 56.7(kW)± 2.59%	107.1±4.57(Nm) 107.1(Nm)± 4.26%	55.9	110
Difference in relation to catalogue data		1.4%	2.6%

the instantaneous fuel consumption using PLU 116H flow meter. The correlation factor *B* has been introduced. The factor takes into account both the fact that the injection occurs into the intake manifold, in which the pressure is different than the ambient pressure (the recorded value is marked as p_2 in fig. 1), and the recorded fuel pressure in the fuel rail. The correlation factor was prepared in the form of spatial map $B=f(WT, n)$ – WT – injection time, n – engine rotational speed. The approximating function was the smoothing of least squares weight by distance [21]. The correlation factor was set by equation 5 as relative error of injector outflow in relation to injection to the intake manifold of pressure p_2 assuming the constant product (μF) and fuel density reduced to normal conditions:

$$B\,[\%] = \left[\frac{\sqrt{p_1} - \sqrt{(p_1 - p_2)}}{\sqrt{(p_1 - p_2)}} \right] \cdot 100, \qquad (5)$$

where:
p_1 - absolute pressure of fuel in the fuel rail,
p_2 - absolute pressure in the intake manifold.

The exemplary spatial map of error of estimating the amount of injected fuel in relation to injector opening time and rotational speed taking into consideration the pressure difference $\Delta p=p_1-p_2$ for injector no. 1 is depicted in fig. 4. The range of injector opening times during the vehicle acceleration on a selected gear at the throttle fully opened is marked in fig. 4. The values of correlation factors for each injector were calculated taking into account the phase shift resulting from the four stroke engine cycle.

The maximal relative error of measurement using the selected method was set assuming the normal distribution of instantaneous fuel consumption results for 16 measuring series based on the PLU 116H flow meter results as well as based on the injector opening time

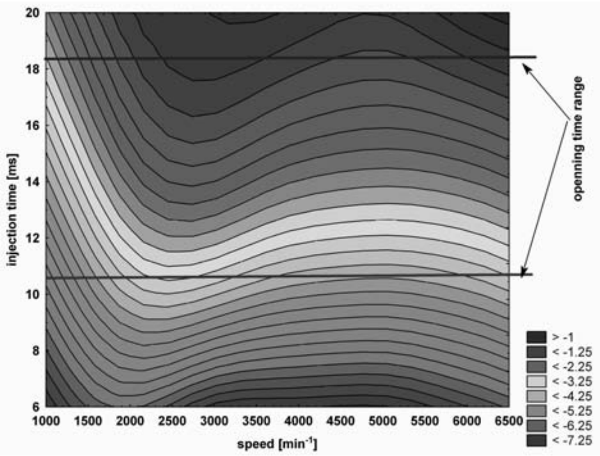

Fig. 4. Percentage relative error of injector 1 outflow in relation with the opening time (WT1) and the engine rotational speed taking into account the inlet manifold pressure and fuel pressure before the injector

(taking into account pressure before and after the injector and fuel temperature) at the confidence level of 0,95. In case of PLU 116H flow meter the relative error for steady measures was taken into consideration. According to the calibration certificate [17] the above mentioned error does not exceed 1% and the relative error resulting from the measuring device resolution is 6.15ml per pulse [3, 17] which in accordance to the measured values gives the average relative error at the level of approximately 6.04±0.14% and the maximal error of measures using the flow meter is at the level of 7%. The instantaneous and average values (approximately 7.2%) are illustrated in fig. 5. In case of PLU 116H flow meter the relatively high time constant of approximately 500 ms [3] must be taken into consideration. It radically overestimates the results concerning the fuel consumption and makes questionable the applicability of this type of flow meter to

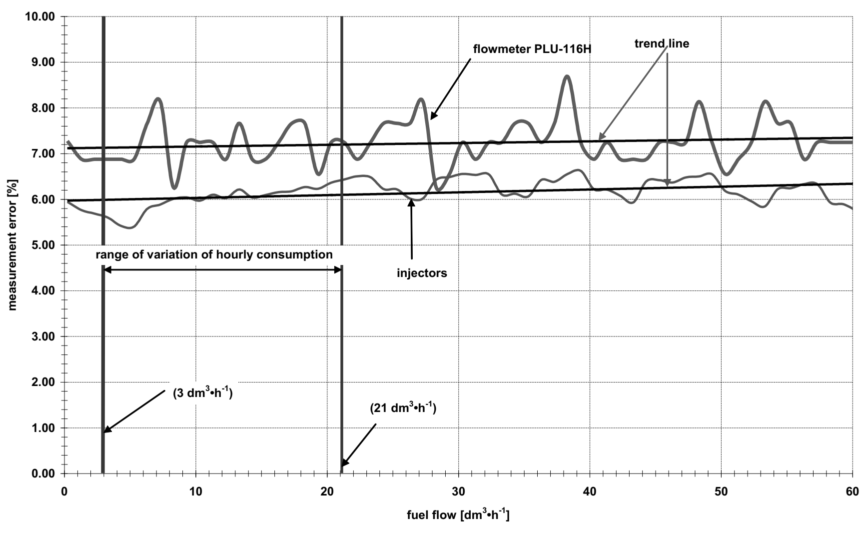

Fig. 5. Maximum errors of fuel consumption measurement using the PLU 116H flow meter and using the injector opening time as a function of fuel flow - the black lines depict the exponential ($y=a \cdot e^{b \cdot x}$) trend line, blue line is the range of changes in hourly fuel consumption during vehicle acceleration

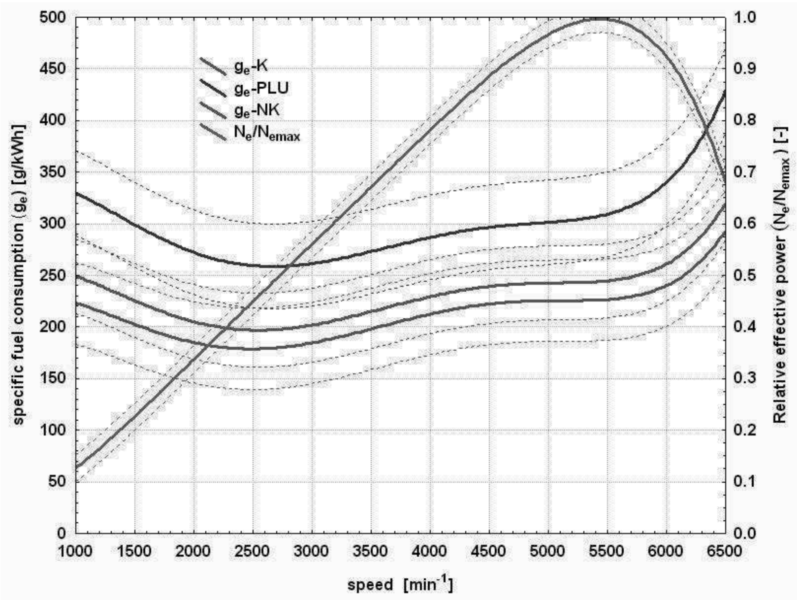

Fig. 6. External characteristic of specific fuel consumption and relative effective power with marked confidence intervals (95%) - (data for 16 measurement series) - the description in the text

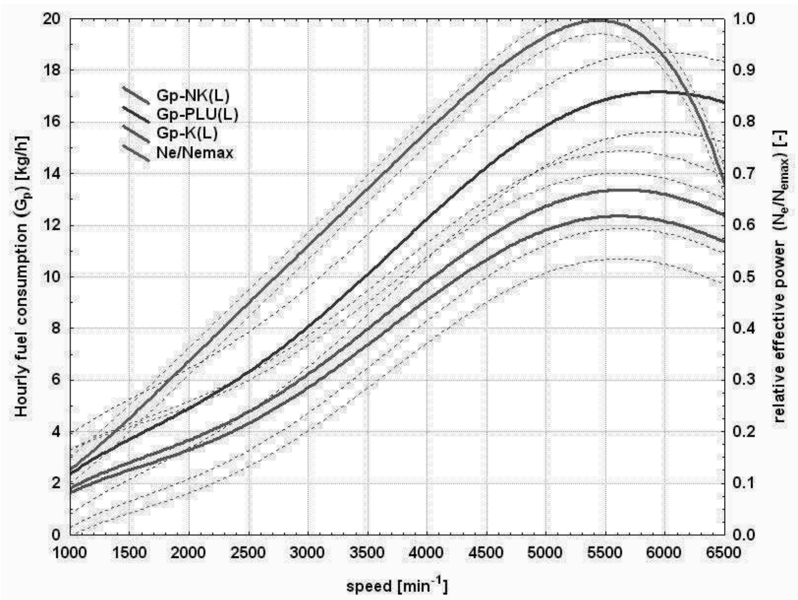

Fig. 7. External characteristics of hourly fuel consumption and relative effective power with marked confidence intervals (95%) - (data for 16 measurement series) - description in text

measurements concerning fuel consumption of combustion engine operating under fast changing unsteady states.

Setting the maximal relative error of instantaneous fuel consumption measurement based on injector opening time generates the relative error of instantaneous liquid fuel consumption (*mm*^{3}) equal 5.75±0.3%. The injector's average calibration error is at the level of 4.56% (in relation to fuel dose corresponding with single injector opening window in milliseconds). The instantaneous and mean values taking into account the above mentioned normal distribution give the method relative error (approximately 6.0%), which has been illustrated in fig. 5. Fig 6 and 7 depict the measurement results taking into consideration the above mentioned calculus of errors and after correcting the obtained results to normal conditions according to DIN70020-5 standard [2]. The results are shown in the form of external characteristics, specific fuel consumption and hourly fuel consumption (g_e-*K*, G_p-*K(L))* taking into consideration the pressure before and after the injector and fuel temperature, (g_e-*NK*, G_p-*NK(L)* without fuel pressure after the injector, (g_e-*PLU*, G_p-*PLU*) – measurement using the PLU 116H flow meter) and course of relative effective power (N_e/N_{emax}) determined using the satellite navigation system.

CONCLUSIONS

The application of the described method to traction research of car vehicles using the telecommunication techniques requires knowledge concerning the characteristics of injector in which the vehicle's engine is equipped as well as the correlation between the injector opening times recording units and the software recording the basic physical quantities of vehicle movement in transient conditions obtained with the use of satellite navigation (UTC time, dislocation components P-X, P-Y, P-Z and velocity components V-X, V-Y i V-Z in WGS-84 system) or other recorders of fast changing parameters of vehicle movement. The errors of estimating the instantaneous fuel consumption during the car vehicle unsteady movement based on measurement of injector opening times with simultaneous measurement of pressure before and after the injector are connected with error resulting mainly from nonlinearity of injector characteristic. The above mentioned errors do not exceed 6%. Using the flow meter of too high time constant (500ms) is not recommended because of the overstating its indications. The voltage decay on the coil at the time of initiating the injectors opening as a result of inertia of its moving elements leads to delay in injector opening. Moreover it is not compensated by delay in the injector closing caused by decreasing force in the needle spring during closing.

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WYZNACZANIE JEDNOSTKOWEGO ZUŻYCIA PALIWA SILNIKA SPALINOWEGO W WARUNKACH NIEUSTALONYCH

S t r e s z c z e n i e. W pracy przedstawiono wyniki badań trakcyjnych pojazdu samochodowego uzyskane z wykorzystaniem technik nawigacji satelitarnej, jako alternatywnej metody badawczej, mających na celu wyznaczenie charakterystyki zewnętrznej jego silnika z uwzględnieniem warunków atmosferycznych i profilu pionowego trasy z jednoczesnym wyznaczeniem jednostkowego zużycia paliwa w oparciu o pomiar czasu otwarcia wtryskiwacza paliwa.

S ł o w a k l u c z o w e: silnik spalinowy, jednostkowe zużycie paliwa, warunki nieustalone.