Agronomy Research **13**(2), 577–584, 2015

Determination of the optimal injection time for adaptation SI engine on E85 fuel using self-designed auxiliary control unit

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Abstract. Article deals with problems of the operation of spark ignition combustion engine on high-percentage of blend bioethanol. The aim of the experiment was to find the optimal value of injection time of the engine injection valves with respect to the adaptive ability of the original engine control unit (ECU) when using a special auxiliary control unit (ACU) was adjusted injection time. Special dynamic driving cycle has been designed to assess the effects of prolonged injection time on the adaptive abilities of the ECU that stemmed from a real recording vehicle's rides with the same engine as was used in conducted experiments. The results proved that by changing the extension of the period of injection occurs a gradual adaptation of the original ECU, but this adaptation is gradual and underway predominantly in modes functional closed-loop control, thus in modes of low to medium of loads. Results of the experiment provide determination of the efficient frontier of the percentage extension injection time with regard to adaptive abilities of original ECU.

Key words: E85, bioethanol, emission, power, control unit.

INTRODUCTION

Nowadays issue of bio-fuels has been becoming more and more actual topic. The whole world is keep raising the usage of fossils fuels and growth of greenhouse gases (GHG) production. Estimation supposes that approximately 80% of primary energy comes from fossil fuels and almost 60% of this energy is used in transport section (Escobar et al., 2009). The various legislative measures are introduced in various parts of the world to support usage of the biofuels which have potential to reduce GHG production. The common targets of these measures are to reduce dependency on expendable fossils fuels with their growing and unstable prices.

The first measure of EU which led to using biofuels was European parliament and Council acceptance of directive 2003/30/EC about promotion of the use of biofuels or other renewable fuels for transport. According to the directive EU states should ensure that biofuels part will be 5.75% in the fuel market by the end of 2010 (EU Directive 2003/30/EC). This directive was replaced in 2009 by directive 2009/28/EC that demands to increase the renewable fuels part to 20% in 2020, 10% of this part is set up for transport section (EU Directive 2009/28/EC; Hromádko et al., 2009). Also the directive

2009/30/EC was accepted with directive 2009/28/EC. This new directive defines environmental specifications of engine fuel (acceptable part of added bio component to fuel) (EU Directive 2009/30/EC). Both directives clearly show that to meet desired goals in renewable sources is not possible by only required adding of low-percentage biofuels to the gasoline. It is necessary to add bio-fuels with high-percentage of bio component to meet desired goals.

One of the options to meet required goals is to use bio-ethanol as a high-percentage mixed biofuel in the E85 form (85% ethanol, 15% gasoline). In comparison with standard fuel the ethanol has lower energy density than gasoline (ethanol 23.5 MJ litre^{-1}, gasoline 34.8 MJ litre^{-1}). It causes higher consumption of fuel to keep the same operational values. Advantage of ethanol is its higher octane number (ethanol 104, gasoline 95) and also quicker combustion (Roberts, 2007; Park et al., 2010; Čedík et al, 2014a).

The disadvantages of ethanol are above mentioned lower energy density, often stated corrosion of gasoline pump and fuel line or diminished ability to start engine at lower temperatures (Rovai et al., 2005).

Researched ethanol influences on emissions production often present different results. Lower productions of carbon monoxide (CO) is very often mentioned, other emissions reach different results in comparison with used gasoline according to specific construction of combustion engine (Graham et al, 2008; Winther et al., 2012; Čedík et al, 2014b).

For the operation of internal combustion engines on a high-percentage alcohol fuel mixture is required certain engine modifications. The stoichiometric ratio for a specific mixture of alcohol and gasoline must be respected. In our case, for the fuel E85 mixing ratio 9:1 (air:fuel) must be observed. In comparison with gasoline (mixing ratio 14.7:1) it is necessary make richer mixture. According to the system of fuel management more modifications of engine are possible (Irimescu, 2012).

The aim is to increase the fuel dose, which can be done in the following ways: increase the system fuel pressure (Merola et al., 2010), using injectors with higher flow rate (Vancoillie et al., 2013) or extension injection time. Injection time can be changed by reprogramming the original ECU (Hsieh et al., 2002), or using additional control unit (ACU) (Irimescu, 2012).

Modern electronic fuel injection systems use the closed-loop control (it mean the ECU fuel injection strategy with feedback signal from the oxygen sensor placed in the exhaust pipe) for adaptation to different fuels by increasing fuel dose. This regulation has limits and is often necessary to use ACU to optimize the adaptive ability of ECU. These ACU extend the injection time thereby enrich the mixture. The question is, how much is necessary extend the injection time to adaptation ECU without errors (Hsieh et al., 2002).

In case of open-loop regulations, which occurs e.g. at cold starts or at higher engine loads, the mixture control is regulated by preprogrammed fuel maps for the initial fuel, ie gasoline. When E85 is used the air-fuel equivalence ratio (λ) moved toward lean mixtures (Irimescu, 2011).

The aim of this article was to analyse the operational parameters of the internal combustion engine and adaptability of the original ECU for various extension injection times. The special additional control unit (ACU) has been constructed for this purpose. ACU's task was to change the extension opening time of injection valves' according to programme. The majority of commercially offered additional units in Czech Republic provides only two adjustment possibilities of extension period e.g. for fuel E0-E50 or E50-E85. This paper's authors proposed design of ACU that can adjust the injection time extension gradually in steps of 5% (from 0% to 35%). The article presents a unique solution of ACU and points out the issues of ECU adaptive ability.

MATERIALS AND METHODS

The whole experiment was conducted on the test bed at the Department of Vehicles and Ground transport, CULS in Prague.

The measurement was carried out with a four-stroke inline three-cylinder engine Skoda Fabia 1.2 HTP (see Table 1 for detailed parameters) with multipoint injection system with close-loop control mode at part engine loads to keep the engine operating near stoichiometric air–fuel ratio (AFR) and open-loop control mode at full engine loads to produce maximum power.

Table 1. Technical parameters of tested engine

Engine code	AWY
Construction	3-cylinders, row, 6 valves
Volume	1198 cm^3
Compression ratio	10,3 : 1
Power	40 kW at 4,750 rpm
Torque	106 Nm at 3,000 rpm
ECU	Simos 3PD (multipoint injection)
Fuel	unleaded N95
emission standard	EU4

The tested engine was loaded with whirl dynamometer, the torque and engine speed were captured during measure. Whirl dynamometer V125 was used during experiment. Dynamometer reactions were captured with tensometric sensor with nominal load of 2 kN and with accuracy of 0.5% of the nominal load. Next values were also captured: ECU's instantaneous values, exhaust emissions and fuel consumption.

Special mobile five-component analyser VMK (technical specifications in Table 2) was used to measure emission. This analyser was constructed to measure emission under real operational conditions. The emissions of CO, CO_2, HC, NO_X and λ with a frequency of 1 Hz were continuously evaluated and stored.

The Flowmeter WF005 was used to measure fuel consumption. Technical specifications are shown in Table 3. System DataLab was used to record data from flowmeter. The development environment ControlWeb was used to create application for continuous data recording and visualising.

Diagnostic system VAG-COM was used for communication with ECU. This system was primary used to read values from control unit as engine speed, engine load and to check errors.

The engine was researched with the E85 fuel and with help of additional control unit (ACU) was gradually extended times of injection from 0, 5, 10, 15, 20, 25, 30 to 35%. The our-designed ACU was used to extend the time of injection. The ACU was connected between ECU and injectors. Inputs for this ACU were impulses from injectors emitted by ECU. These impulses were extended by ACU for a pre-set time in percentages.

Table 2. Technical parameters of the emission analyser

Measured component	Scope	Resolution	Accuracy
CO	0–10% vol.	0.001% vol.	0–0.67%: 0.02% 0.67–10%: 3% from measured value
CO_2	0–16% vol.	0.1% vol.	0–10%: 0.3% 10–16%: 3% from measured value
HC	0–20,000 ppm	1 ppm	10 ppm or 5% from measured value
NO_X	0–5,000 ppm	1 ppm	0–1,000 ppm: 25 ppm 1,000–4,000 ppm: 4% from measured value
O_2	0–22% vol.	0.1% vol.	0–3%: 0.1% 3–21%: 3% from measured value

Table 3. Technical parameters of the flowmeter WF005

Measuring principle	hall sonde
flow range	0.005–1.5 l min^{-1}
output	1,800 imp l^{-1}
viscosity	0–2,000 mPas
accuracy	+– 0.5%

Special dynamic drive cycle (Fig. 1) was designed to assess the impact of extended opening of the injectors. This cycle was designed in accordance to the real replay of the vehicle drive (also Skoda Fabia 1.2. HTP). Recorded values from real drive were used to set up throttle setting, engine speed and load on the testing engine for our measurement. Target was to operate the engine as much similar as in real traffic conditions.

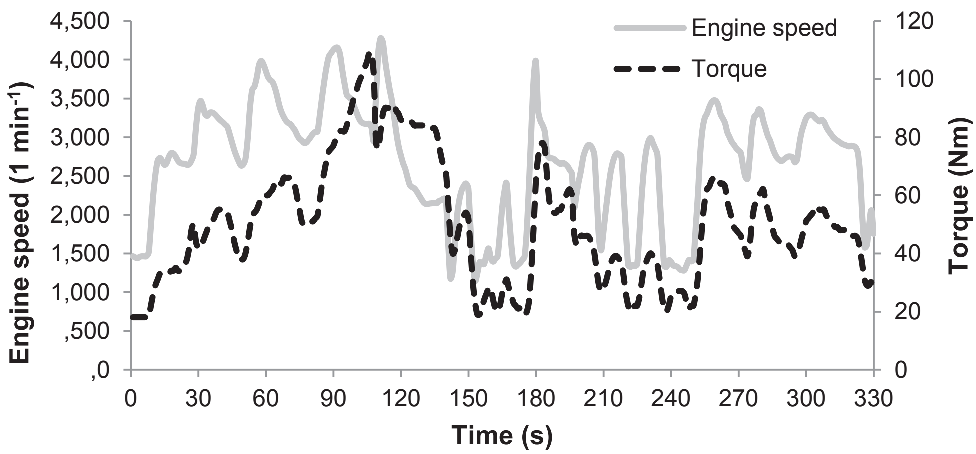

Figure 1. Test cycle.

RESULTS AND DISCUSSION

As can be seen in Table 4, there is a negligible impact on the engine's performance parameters. Fuel consumption is also essentially unchanged; the difference between the zero and maximum extension is average 4%. The emissions of CO increased when the injection time was extended. On the other hand emissions of CO_2 and NO_X were decreased. As seen the λ, the mixture was got richer when the time of extension increased. Results proved reaction of original ECU, where can be seen gradual decreasing of basic injection time with increasing extension. This is caused by mixture's correction based on the signal obtained from the exhaust oxygen senzor. Ignition advance shows no major impact on the extending time of the injection.

Table 4. Summary results of the operating parameters of the engine in driving cycle

Exten-sion (%)	CO (g)	CO_2 (g)	NO_X (g)	HC (g)	Avg. λ (1)	Avg. Torque (Nm)	Avg. Power (kW)	Avg. Injection time (ms)	Avg. Ignition advance (°)	Fuel consum ption (l)
0	1.6	1,204	34.34	0.2	1.057	50	15	8.79	29.62	0.642
5	10.1	1,250	19.39	0.24	1.034	50	16	7.9	30.38	0.653
10	10.1	1,247	17.98	0.2	1.021	51	16	7.28	29.75	0.658
15	36.97	1,225	1.3	0.35	1.026	51	16	6.8	29.85	0.66
20	25.27	1,216	1.04	0.2	1.032	51	15	6.24	29.81	0.652
25	25.57	1,210	1.76	0.15	1.032	50	15	5.83	29.49	0.651
30	46.68	1,202	0.5	0.36	1.021	50	15	5.46	29.51	0.662
35	59.67	1,184	0.17	0.46	1.017	50	15	5.28	29.62	0.668

Situation becomes less plausible when the on-going check of errors memory is observed. The original ECU logs errors when the extension is zero or higher than 25%. This error was called 'too lean or too rich mixture – regulation out of range'. The Table 5 shows the gradual adaptation of original ECU after repeating the driving cycle.

Table 5. Adaptation of the original ECU on 15% extension in driving cycle

Meas. num. (-)	CO (g)	CO_2 (g)	NO_X (g)	HC (g)	Avg. λ (1)	Avg. Torque (Nm)	Avg. Power (kW)	Avg. Injection time (ms)	Avg. Ignition advance (°)	Fuel consum ption (l)
1	57.1	1,210	2.34	0.413	1.021	50.7	15.66	6.83	29.96	0.678
2	47.5	1,216	0.31	0.406	1.024	51.1	15.58	6.83	29.89	0.669
3	34.8	1,223	0.56	0.349	1.026	51.9	15.58	6.81	29.91	0.656
4	26.1	1,237	0.72	0.317	1.028	52.1	15.64	6.80	29.58	0.649
5	19.1	1,239	2.56	0.257	1.031	51.8	15.56	6.73	29.92	0.647

Adaptation is reflected by gradual modification of the fuel mixture settings which reacts to the closed-loop control. As it can be seen on the Fig. 2, the CO emission is gradually decreased with a cycle's repetition. This corresponds with Fig. 3 that shows the gradual reduction of the average injection time.

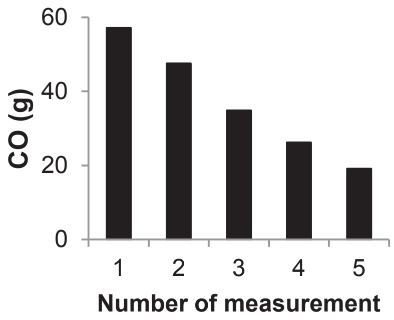

Figure 2. Process of CO emission on 15% prolong in repeat driving cycle.

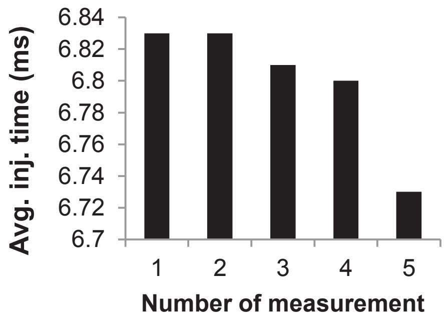

Figure 3. Process of avg. inj. time on 15% prolong in repeat driving cycle.

We can conclude, that ECU gradually adapts to a new fuel (by changing the basic injection time) after repeating the testing cycle. However the ECU cannot adapt according to the new fuel with injection extension less than 5% or more than 25%. When the extension time is set up lower than 5% then the ECU cannot adapt to the new fuel by increasing the dose of fuel enough to compensate too lean mixture. This situation was logged during testing cycle by ECU as too lean mixture error. This fact was also confirmed by the lowest CO emissions, the highest NO_X and the highest average λ during the driving cycle. This situation happens by combustion of lean mixture.

The similar situation happened when the extension of injection time was set on more than 25%. ECU was getting information from exhaust oxygen senzor that the mixture is too rich. However the ECU cannot sufficiently reduce base injection time which results in logging error 'too rich mixture' by ECU. These extreme states correspond with measured values of CO emission. As shown by above results, the optimal injection time is set by ECU according to signal from the exhaust oxygen senzor. ECU is able to regulate mixture in a specific range. This range is not sufficient for high-percentage ethanol mixture and it is necessary to adjust the injection time using ACU. This way causes the move of the ECU's adaptive range to ensure optimal injection time.

CONCLUSIONS

The tested engine has demonstrated the ability to operate on E85, however, ECU could not regulate the mixture without error. It has been shown, that without additional control unit ECU was not able to determine the optimal time of injection. Although ECU received from the exhaust oxygen senzor information about lean mixture, ECU has not been able to extend the time of injection, due to exceeding the adaptation range. By using the ACU can be moved ECU adaptation range.

These first carried out experiments have shown that there is mismatch between ACU and original ECU. Respectively: How much is extended time of injection by ACU, so much time is shortened on the basic injection time by ECU depending on the signal from exhaust oxygen sensor. Everything is depended on the adaptive abilities of the ECU. It was proved that original ECU has its own limits of adaptation abilities and in case those limits are exceeded, another adaptation does not take place and the error of wrong mixture of the fuel is logged in the error memory (too lean or too rich mixture errors).

Experiments determined the optimal interval of injection time extension from the measured values. This interval can be set up as extreme values, which was not recognized as bad mixture errors. In this case we can define the extreme values as 5% extension as minimal value (original ECU can adapt to this value). The maximal value can be set as 20%. Control unit is able to adapt even to this state of tested fuel.

The emission results show that increasing extension time of injection causes higher CO production, while NO_X emissions are lower. CO_2 emissions and fuel consumption do not show any significant changes. As shown in above emission results, the optimal extension value is 20% when the original ECU is able to adjust the optimal injection time.

ACKNOWLEDGEMENTS. This work has been realized with the contribution of Czech University of Life Sciences in Prague Internal Grant Agency, project 2014:31150/1312/3116 'Evaluation of the environmental benefits of bioethanol blending into motor fuels'.

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