EFFECT OF IGNITION TIMING ON EMISSIONS OF SPARK IGNITION ENGINE USING E85 FUEL

Maris Gailis, Vilnis Pirs
Latvia University of Agriculture
maris.gailis@llu.lv; vilnis.pirs@llu.lv

Abstract
This experimental study assesses the influence of ignition timing on emissions from a production four cylinder port injection spark ignition engine. The aim of this research was to evaluate the necessity of ignition timing correction when the regular gasoline vehicle is being adapted for the use of E85 fuel. Tests were conducted in the Alternative Fuels Research Laboratory of Latvia University of Agriculture in December 2013. The engine was fuelled with the ethanol-gasoline blend E85 or the commercial gasoline A95. The engine was tested within a vehicle in a chassis dynamometer in steady state conditions, which resemble driving at 50 km h^{-1} and 90 km h^{-1}. The original engine control unit was replaced with a programmable one. Engine-out and tailpipe exhaust gas samples were taken and analysed with a FTIR-type analyser AVL SESAM. Carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), acetaldehyde and unburned ethanol emission volumetric share is presented. CO, HC and acetaldehyde emissions were not affected by variation of the ignition timing within the tested range. NOx and ethanol emissions were reduced with the ignition timing retard. The emissions of CO, HC and NOx were reduced, when the engine was fuelled with the E85 fuel, comparing with the gasoline use. Ignition timing, optimized for the gasoline, was found suitable for the E85 fuel from the emission analyses point.
Key words: ethanol, ignition timing advance, emissions.

Introduction

The biofuels are increasingly used as the energy source in the light passenger vehicles. The biofuels are considered as renewable energy source and contribute to the reduction of the greenhouse gas emissions (Costagliola et al., 2013). The ethanol has been known as a suitable fuel for the spark ignition engines since the 19th century. Currently all commercially available gasoline in Latvia is blended with the ethanol in 0.05 $m^3 \cdot m^{-3}$ volume ratio. One of the benefits of ethanol use as a fuel is the reduction of depletion of non-renewable energy resources. By adding ethanol, oxygen is blended into the fuel which favours the combustion of the gasoline, reducing toxicity of the emissions. The use of pure ethanol as the fuel is problematic due to the engine cold start difficulties below 13 °C. Gasoline on ratio 0.15 $m^3 \cdot m^{-3}$ is added to anhydrous ethanol to facilitate cold starting and act as a denaturing agent. Resulted fuel is designated E85 and is available in the service stations in many parts of the world, including Latvia. Due to the physiochemical differences of gasoline and ethanol, the use of E85 requires vehicle adaptation. Specially designed production vehicles (Flexible Fuel Vehicles or FFV) can use gasoline, E85 or mixture of both in any ratio. It is possible to convert regular gasoline vehicle for use of E85 fuel. Normally such converting is limited to increase of the fuel supply. Ignition parameters are usually left unchanged.

Engine tailpipe emissions of the vehicle, converted to use of E85, must be as low as possible and certainly within legal limits. Depending on the vehicle production date, different standards apply for acceptable level of certain, so-called ‘regulated’ emission gas components. Currently those emission gas components are nitrogen oxides (NOx), carbon monoxide (CO), total hydrocarbons (HC), non-methane hydrocarbons (NMHC) and particulate matter (PM). Ignition timing is known to be one of the factors that affect engine emissions (Heywood, 1998).

Combustion of the air-fuel mixture in the combustion chamber must occur in a certain moment of engine operating phase, to push piston downwards and efficiently convert chemical energy into mechanical energy. Due to the delay of ignition and duration of the combustion, ignition spark must be supplied with certain advance, depending on the engine design and operating conditions. Peak cylinder pressure and therefore temperature of combustion and exhaust gases are affected by spark timing. Timing, which provides maximal peak cylinder pressure, also provides maximal brake torque (MBT) (Heywood, 1988). Depending on the engine design, conditions of MBT may not provide optimally balanced emissions. Usually in production engines ignition timing is retarded from MBT. Retarded timing lowers burning temperature and increases temperature of exhaust gases. Lower burning temperature can decrease NOx emissions. Increased exhaust gas temperature can reduce hydrocarbon emissions (Heywood, 1988).

K. Silaipillayarputhur and S.A. Idem (2011) found that combustion duration increases with the engine speed. As combustion duration increases, engine output power decreases, because the cycle diagram further deviates from ideal Otto cycle. If the combustion duration increases, ignition advance must be also increased to maximize engine output power. Delay of ignition and combustion flame speed is different for ethanol and gasoline. Laminar flame speed of regular gasoline is 33 m s^{-1} and 39 m s^{-1} for ethanol (Hara and Tanoue, 2006; Turner et al., 2011). Therefore, using ignition advance parameters, which are optimal for gasoline operation, will lead to non-optimal operation on fuel with high ethanol content, such as E85.

C. Sayin (2012) evaluated the impact of varying spark timing on the performance and emissions of a gasoline engine. He found a decrease of brake thermal efficiency and increase of brake specific fuel consumption, emissions of CO and hydrocarbons (HC), when gasoline with higher research octane number (RON) than the requirement of an engine was used at a nominal spark timing. The increase of ignition advance for gasoline with higher RON boosted engine power and decreased emissions of CO and HC, and decreased fuel consumption.

T. Topgül et al. (2006) studied the effects of gasoline and gasoline-ethanol blends on a single cylinder spark ignition engine performance and emissions. Experiments were conducted at a constant speed in wide open throttle mode. They concluded that using E60 fuel, ignition timing had to be retarded by 4 degrees, comparing to the use of pure gasoline E0, to achieve maximal brake torque. The increase of ethanol content in the fuel led to a decrease of exhaust gas temperature. CO emissions were reduced with an increase of ethanol content. They found increase of HC emissions with increase of ethanol content. Slight decrease of HC emissions was found when the ignition timing was retarded.

N. Türköz et al. (2014) conducted experiments on 4 cylinder carburettor SI engine using E85 fuel. They investigated the effect of ignition timing advance on the engine performance and emissions. They reported best engine performance and emissions when ignition timing was advanced by 4 degrees, comparing to use of pure gasoline. NOx emissions were increased with increase of ignition advance, CO and CO2 emissions were mainly unaffected and HC emissions increased with ignition retarding.

From the literature review, the impact of the spark timing on emissions of SI engine running on E85 fuel is not clearly studied. Some researchers are conducting experiments with carburettor engines, in wide open throttle mode. Wide open throttle operating conditions are rarely used in real life. Results of optimal ignition timing for high ethanol content fuel, comparing with gasoline are contradictory. The authors of this study investigated the effect of ignition timing advance on modern SI engine emissions in conditions, which resemble regular driving. The aim of this research is to evaluate the necessity of ignition timing fine tuning for E85 when the regular gasoline engine is being adapted for use with E85. Only the effect on emissions is investigated.

Materials and Methods

Tests were performed using two different fuels, purchased at the commercial fuel stations. Main properties of the test fuels were obtained from the certificates, provided by the fuel suppliers. Gasoline (A95) of EN228 standard had research octane number (RON) 95.4; motor octane number (MON) 85.9 and ethanol content 0.048 m^3 m^{-3}. E85 had RON and MON above 101; ethanol content 0.781 m^3 m^{-3}.

Conventional port injection SI engine was used. The specifications of the engine and the vehicle are listed in Table 1. The original engine control module (ECU) was replaced by a programmable ECU VEMS V3 to maintain the engine operating parameters within the required limits. The original narrowband oxygen sensor was replaced by a wideband sensor Bosch LSU 4.2. The original catalytic converter was retained.

Table 1

Main specifications of test automobile

Parameter	Value
Model	Renault Twingo
Identification number	VF1C068AE28944909
Date of production	30.04.2003
Engine	Type D7F 702, 4-cylinder 8-valve
Displacement volume, cm^3	1149
Piston bore / stroke, mm	69.0/ 76.8
Volumetric compression ratio	9.65
Gearbox	Type JB1 517, 5-gear manual
Gear ratios	Final drive 3.866; 4th gear 0.966; 5th gear 0.820

The engine was tested within the automobile. Load conditions were simulated in the laboratory on the edgy current roll type chassis dynamometer Mustang MD1750. The exhaust gas temperature (EGT) was measured in engine exhaust manifold. Engine exhaust emission gas samples were taken before the catalytic converter and from the tailpipe. Composition of exhaust gas was analysed with the Fourier transform infrared spectrometer (FTIR) AVL SESAM. A beam of wide spectrum infrared light is passed through the cooled and dried sample gas. The amount of energy absorbed at each significant wavelength is analysed. Signatures of absorbed wavelength and relation of absorbed energy to the volume of the specific gas component was recorded during factory calibration of the equipment. Composition and concentration of the sample gas is determined using matrix calculation methods, comparing sample and calibration data. Measurement system allows for simultaneous measurement of 31 gas components with sampling rate 1 Hz. Results of the testing were expressed as a concentration timeline in volume unit share, parts per million (ppm). Volume shares of total HC and NOx were calculated by AVL SESAM system software. The results are not directly comparable to the results, obtained using other methods.

Wheel speed, power and torque were recorded using chassis dynamometer control software. The engine speed, exhaust gas temperature and air-fuel ratio were registered with ECU monitoring software VEMSTune.

Dynamometer was set at a constant speed mode, throttle opening was fixed to reach the required pressure in the inlet manifold. Variation of wheel power and torque between different test conditions was statistically insignificant and beyond the precision of chassis dynamometer measurement system.

Before testing, the ignition timing advance was mapped for maximal break torque (MBT) at stoichiometric air-fuel ratio for both fuels, E85 and gasoline. Detonation limits were not reached at chosen test conditions. Series of road tests were performed to find engine load conditions for two typical driving modes: at 50 $km \cdot h^{-1}$ and 90 $km \cdot h^{-1}$ steady driving on a flat road. All tests were performed at stoichiometric air-fuel ratio. Three test points of ignition timing advance, expressed in crank degrees before top dead centre (CA BTDC), at both driving modes were used:

- Timing set by vehicle producer for gasoline (nominal timing);
- Timing for maximal brake torque for E85 (MBT E85);
- Timing for maximal brake torque for gasoline (MBT A95).

Testing was conducted in steady state conditions, listed in Table 2.

Table 2

Test conditions

Parameter	Settings 1	Settings 2
Wheel speed, $km \times h^{-1}$	50	90
Engine speed, min^{-1}	1859	2834
Gear	4th	5th
Wheel brake torque, N×m	23.50	39.60
Wheel brake power, kW	4.57	11.74
Ignition timing advance, nominal setting, degrees CA BTDC	31.5	31.0
Ignition timing advance, MBT E85, degrees CA BTDC	34.0	33.0
Ignition timing advance, MBT gasoline, degrees CA BTDC	36.0	37.0

The vehicle was driven on the chassis dynamometer in selected conditions for 340 seconds before the actual measuring started. Each test lasted 40 seconds and was repeated 5 times. Arithmetic mean of 5 valid test results was used as a result. Confidence intervals were calculated for 95% confidence level.

Results and Discussion

Temperature of the exhaust gases depends on an average temperature in the combustion chamber and timing of combustion in the engine cycle. Decrease of EGT is attributed to higher ignition timing advance (Fig. 1). Higher ignition advance increases maximal pressure and peak temperature in combustion chamber (Heywood, 1988). This effect does not directly reflect on EGT. As with higher timing advance combustion starts earlier in the engine cycle, larger part of oxidation reaction chain takes place inside the cylinder, which causes decrease of EGT. Ethanol has higher heat of evaporation comparing to gasoline (Turner et al., 2011). It can be attributed to the decrease of EGT when engine was tested with E85 fuel.

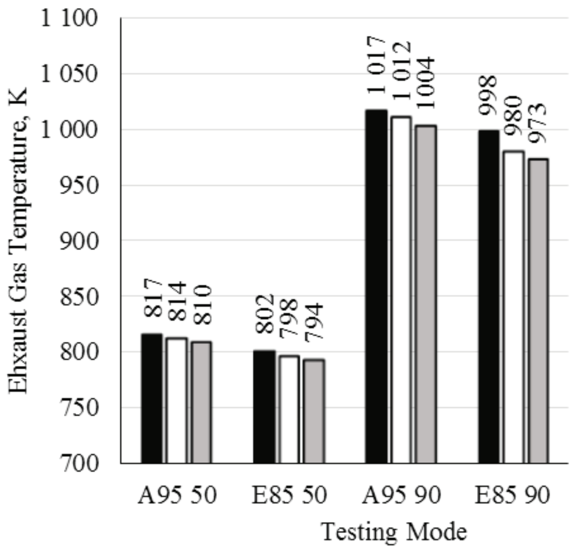

Figure 1. Temperature of engine-out exhaust gases: ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

Hydrocarbon emissions consist of unburned fuel in gaseous state. HC emissions are largely caused by partial or complete misfire. Emissions of HC are known to increase in light load, low engine speed conditions (Sayin, 2012). Chain of oxidation reactions of hydrocarbons continues during exhaust stroke and outside of the cylinder. Therefore variations of HC emissions are related to variations of EGT (Heywood, 1988). HC emissions were insignificantly affected by changing of ignition timing at selected test conditions for both fuels (Fig. 2; Fig. 7).

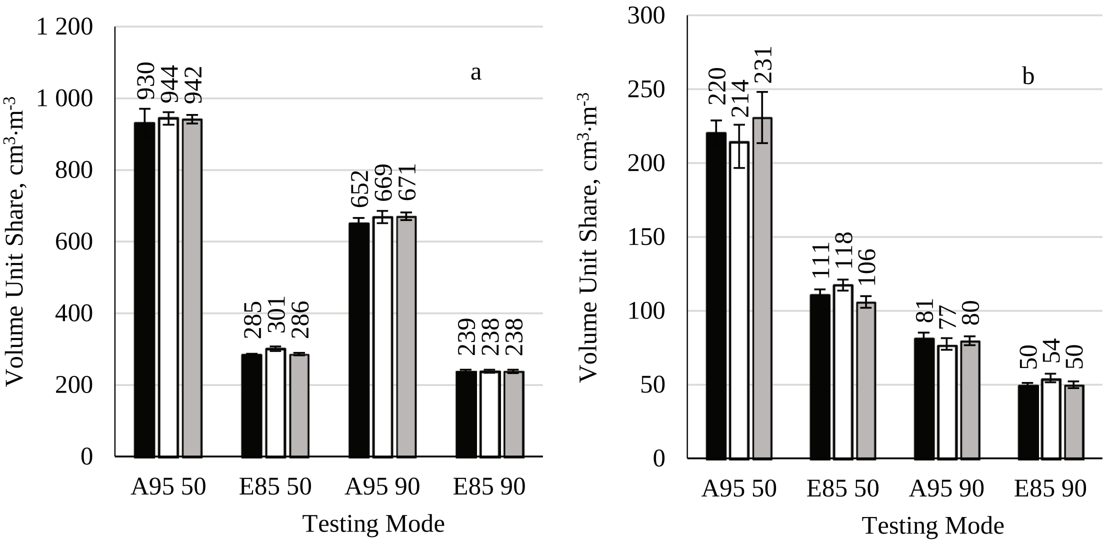

Figure 2. HC volume share:
a - engine-out, b - tailpipe; ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

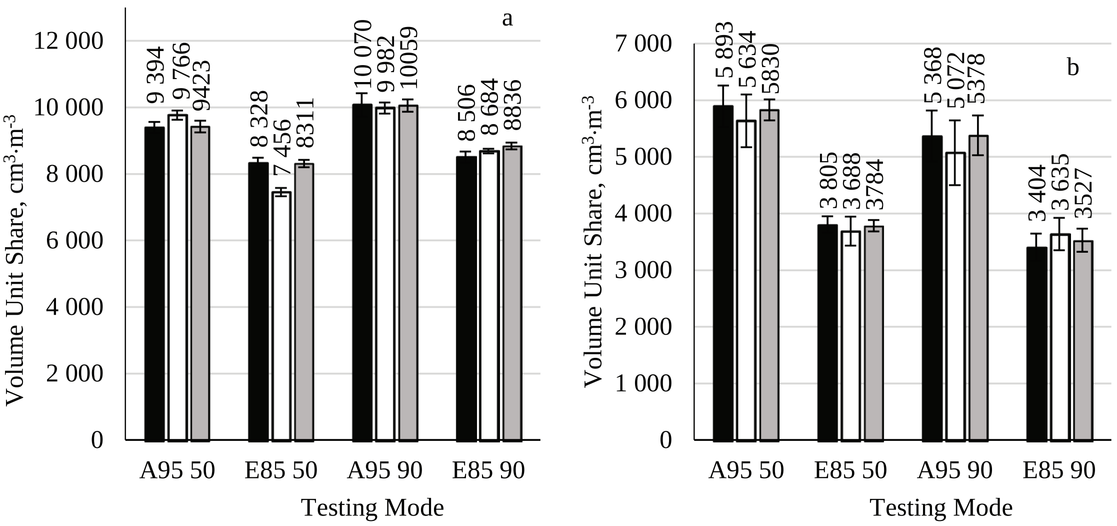

Figure 3. CO volume share:
a - engine-out, b - tailpipe; ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

Apparently misfire rate did not change within the tested ignition timing range. Slight increase of exhaust gas temperature with ignition timing retard did not have effect on the reduction of HC emissions. HC engine-out emissions were reduced by 63-69% by volume, using E85 instead of gasoline (Fig. 7). Higher EGT, engine speed and load in 90 km h^{-1} test mode were attributed to the reduction of HC emissions.

CO formation is one of the steps of burning of hydrocarbons. Oxidation of CO to CO_2 requires relatively high temperature above 973 K. When the temperature in the combustion chamber falls as a result of advancement of expansion stroke, some amount of CO is not oxidised and forms part of exhaust gases (Heywood, 1988). The amount of CO emissions were insignificantly affected by variation of ignition timing within the tested range (Fig. 3; Fig. 7). The amount of CO engine-out emissions were reduced by 11-16%, comparing E85 use with gasoline.

The principal source of NO and NO_2 (which are summed as NOx) is the oxidation of nitrogen during the peak temperature phase at the beginning of the expansion stroke. Emissions of NOx are not a direct product of fuel combustion but rather a side effect. Ignition timing has a significant influence on the combustion temperature.

If the timing is retarded, ignition places combustion in a later point of engine cycle, when the piston has

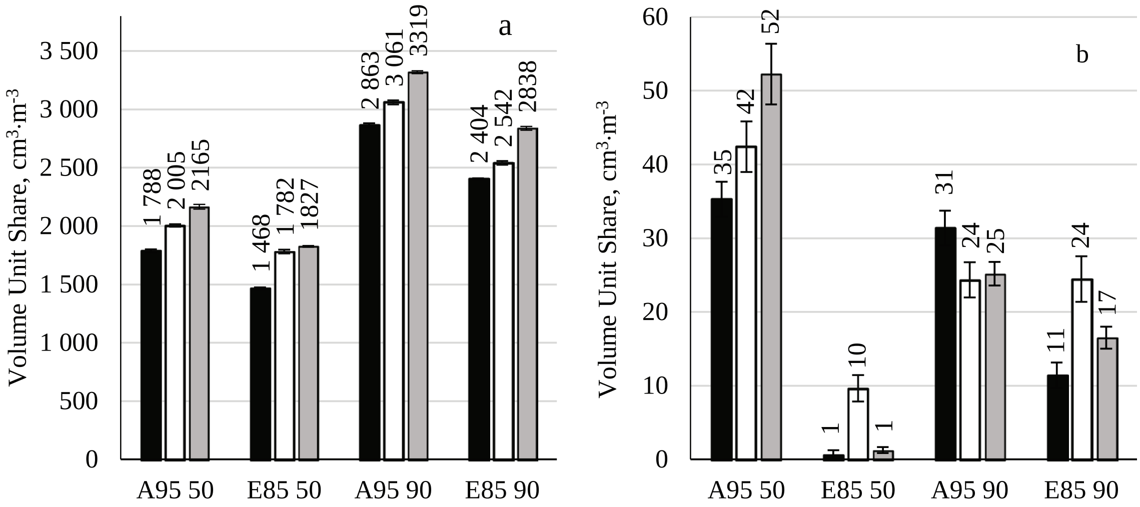

Figure 4. NOx volume share
a - engine-out, b - tailpipe; ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

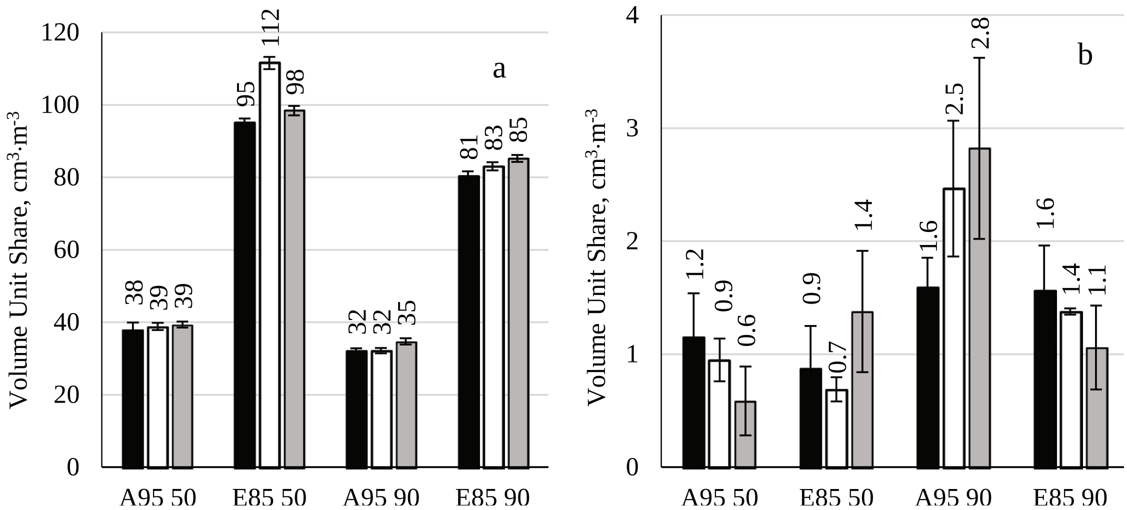

Figure 5. Acetaldehyde volume share:
a - engine-out, b - tailpipe; ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

already started downward movement. Peak pressure and temperature is therefore reduced (Heywood, 1988).Test results showed a significant dependence of NO_x emissions on the spark timing (Fig. 4; Fig. 7). Retarding of ignition from MBT point decreased NOx emissions in all test conditions. Reduced NOx emission level was observed when E85 was used instead of gasoline. This can be explained by lower peak temperature in the combustion chamber. The original ignition timing, tuned for lower emissions using gasoline, was also effective when E85 was used. The reduction of NOx emissions using E85 instead of gasoline, at original spark timing (31 and 31.5 degrees CA BTDC accordingly) was noted: 16-18% for engine-out and 64-98% for tailpipe emissions.

Aldehydes in the engine combustion chamber are formed by cleavages of C-C or C-H bonds of hydrocarbons at high temperatures and partial oxidation of ethanol (Wagner and Wyszynski, 1996). The amount of acetaldehyde is known to raise with increase of ethanol content in fuel (Kumar et al., 2011). Test results demonstrated agreement with that in engine-out emissions (Fig. 5).

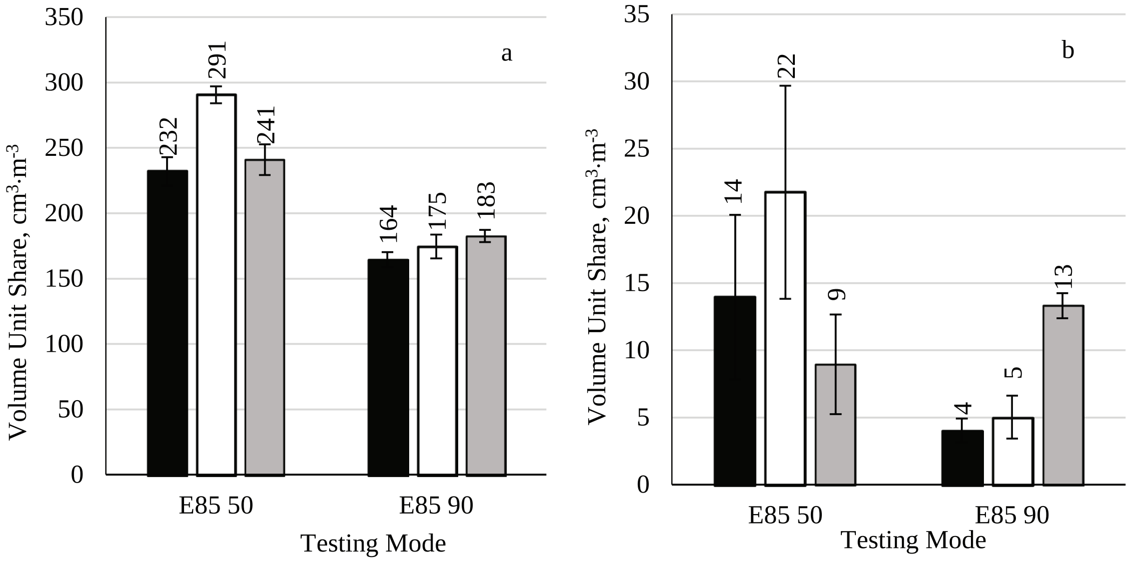

Figure 6. Unburned ethanol volume share:
a - engine-out, b - tailpipe; ignition timing: ■ 31.5…31, □ 34…33, ■ 36…37.

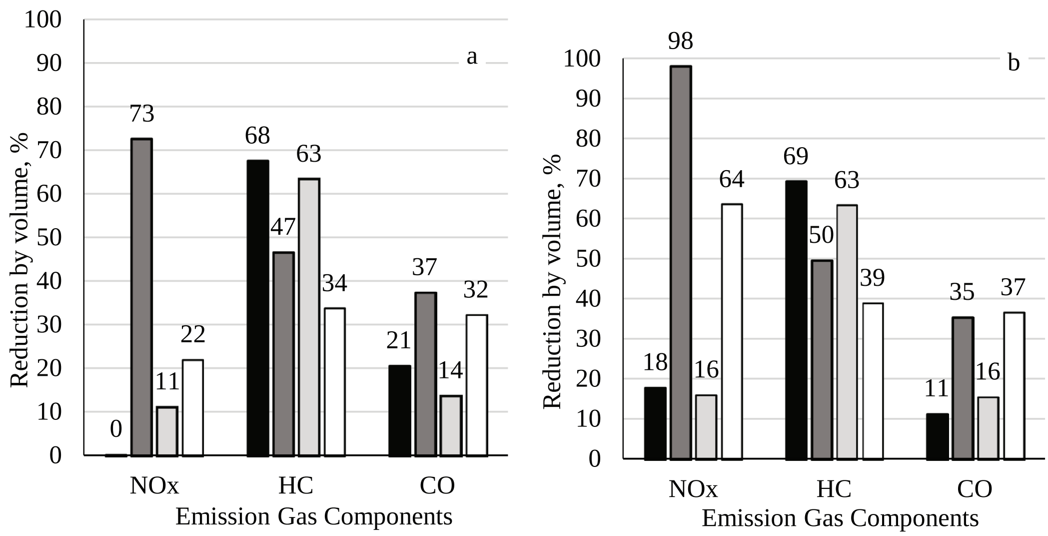

Figure 7. Comparison of reduction of regulated emissions using E85 with different ignition timing:
a - timing for MBT for E85 and nominal timing for gasoline, b - nominal timing for E85 and gasoline;
test conditions: ■ 50 km × h^{-1} engine-out, ■ 50 km × h^{-1} tailpipe,
■ 90 km × h^{-1} engine-out, □ 90 km × h^{-1} tailpipe.

Analysis of tailpipe emissions showed high efficiency of oxidising catalytic converter in the removal of acetaldehyde emissions. Emission levels at tailpipe did correlate directly with engine-out emissions of acetaldehyde. From the results it was concluded, that the ignition timing has no statistically significant effect on emissions of acetaldehyde.

Emissions of unburned ethanol were tested only with E85 fuel. Retarded ignition timing attributed to the reduction of ethanol engine-out and tailpipe emissions in 90 km h^{-1} test mode (Fig. 6). It can be explained with a higher average temperature in the combustion chamber and exhaust gases due to higher speed and load. When the exhaust gas temperature is high enough for oxidation of ethanol, the variation of temperature, caused by ignition timing, takes effect. Retarding of the ignition timing moves the start of ignition later in engine cycle, exhaust gas temperature is higher, and the amount of unburned ethanol is reduced in emissions.

Ignition timing for maximal brake torque using E85 in engine operating conditions, where detonations do not occur, have to be retarded, comparing to similar gasoline setup. Regulated emissions using E85 were found to be reduced, comparing to gasoline use in the tested steady state conditions. When adapting regular gasoline vehicle for the use of E85, the ignition timing for steady state operation can be left unchanged, at least from the emission analysis point. The impact of the ignition timing on the output parameters of cold start and dynamic driving using E85 is a subject for future work.

Conclusions

1. Volumetric share of the unburned hydrocarbons, carbon monoxide and acetaldehyde emissions was insignificantly affected by the variation of the ignition timing within the tested range.
2. The exhaust gas temperate increased with ignition timing retard and was higher when the gasoline was used, comparing to E85 use.
3. Nitrogen oxide emissions were reduced by 5-18% for engine-out and 25-42% for tailpipe emissions using E85 fuel at nominal spark timing comparing to maximal brake torque timing.
4. Unburned ethanol engine-out emissions were reduced by 6.3% in 90 km h^{-1} test mode at nominal spark timing comparing to maximal brake torque timing.
5. The emissions of the unburned hydrocarbons, carbon monoxide and nitrogen oxides were reduced in steady state test conditions using E85 fuel, comparing to the gasoline use.
6. The amount of acetaldehyde was increased up to 63% in the engine-out emissions using E85 fuel, when compared with the gasoline use.
7. Ignition timing, adjusted by the test vehicle’s manufacturer for gasoline use, was found suitable for E85 from the emission analyses point.

References

1. Costagliola M.A., De Simio L., Iannaccone S., Prati M.V. (2013) Combustion efficiency and engine out emissions of a S.I. engine fueled with alcohol/gasoline blends. *Applied Energy*, 111, pp. 1162 – 1171.
2. Hara T., Tanoue K. (2006) Laminar flame speed of ethanol, n-heptane, iso-octane air mixtures. Available at: http://www.fisita.com/education/congress/sc06papers/f2006sc40.pdf, 10 February 2014.
3. Heywood J.B. (1988) *Internal Combustion Engine Fundamentals*. McGrawHill, New York, 930 p.
4. Kumar S., Nayek M., Kumar A., Tandon A., Mondal P. (2011) Aldehyde, ketone and methane emissions from motor vehicle exhaust. *American Chemical Science Journal*, 27, pp. 1 – 27.
5. Sayin C. (2012) The impact of varying spark timing at different octane numbers on the performance and emission characteristics in a gasoline engine. *Fuel*, 97, pp. 856 – 861.
6. Silaipillayarputhur K., Idem S.A. (2011) Spark advance effects in spark ignition engines. *Journal of Applied Global Researche*, 10, pp. 59 – 77.
7. Topgül T., Yücesu H.S., Çinar C., Koca A. (2006) The effects of ethanol–unleaded gasoline blends and ignition timing on engine performance and exhaust emissions. *Energy*, 31, pp. 2534 – 2542.
8. Turner D., Xu H., Cracknell R.F., Natarajan V., Chen X. (2011) Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. *Fuel*, 90, pp. 1999 – 2006.
9. Türköz N., Erkuş B., İhsan Karamangil M., Sürmen A., Arslanoğlu N. (2014) Experimental investigation of the effect of E85 on engine performance and emissions under various ignition timings. *Fuel*, 115, pp. 826 – 832.
10. Wagner T., Wyszynski M. (1996) Aldehydes and ketones in engine exhaust emissions – a review. *Journal of Automobile Engineering,* 210, pp. 109 – 122.