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Assessing the addition of hydrogen and oxygen into the engine's intake air on selected vehicle features

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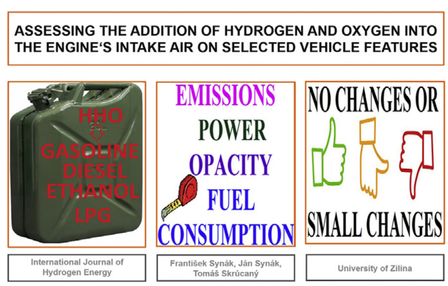
HIGHLIGHTS

- HHO addition slightly reduced the engine power and torque.
- Taking electric energy for the HHO generator to be driven reduced the power on the wheels.
- The fuel consumption at the idling speed with HHO decreased by 10%.
- Taking electric energy for the HHO generator to be driven increased the fuel consumption by 20%.
- HHO in the amount of 2 $dm^3\ min^{-1}$ is considered very low for a common vehicle.

GRAPHICAL ABSTRACT



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ABSTRACT

Road transport has a significant effect on air pollution. Therefore, the article focuses on the impact of addition of “oxyhydrogen”, known as HHO, on selected vehicle features. These features, on which this study is focused, include the engine power and torque, composition of the exhaust gases and fuel consumption. There was also an impact of HHO on the value of pre-ignition as well as engine cleaning observed. HHO has been obtained from the generator designed and constructed for the purposes of this article. The measurements were performed under conditions of taking electric energy needed for HHO operation from the vehicle used in the measurements and also from the other source. The measurements were performed with vehicles of different kilometres driven, different technical conditions and different fuels and they were conducted under laboratory conditions to ensure a higher accuracy of the results. The results have shown a low impact of HHO addition of 2 $dm^3\ min^{-1}$ on concentration of particular components of the exhaust gases. With HHO added, it was measured a mild decrease in the engine power and torque. Taking electric

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energy needed for HHO operation from the vehicle used in the measurement has evinced more considerably than addition of HHO into the engine.

Introduction

Each liter of gasoline consumed in the combustion engine leads to the production of at least 2.5 kg of carbon dioxide – CO_2, and each liter of diesel oil consumed leads to the production of 2.8 kg of CO_2 [1]. Besides the greenhouse gas, CO_2, road transport is also a producer of other emissions that have a global warming potential, or can even adversely affect human health [2–5]. These emissions include, for instance, carbon monoxide – CO, hydrocarbons – HC, nitrogen oxides – NO_x, particulate matter – PM, volatile organic compounds, photochemical smog and many others CO [6–10]. CO is produced from the partial oxidation of carbon, especially when there are unfavorable conditions of combustion in the internal combustion engine, i.e. engine's poor technical condition, driving while the engine does not have a working temperature or when there is not enough oxygen, etc. [11]. Higher concentration of CO in the air of a large urban city in which many vehicles are driving while their engine does not have a working temperature is also described in the publication [12]. In fact, CO binds to haemoglobin more effectively than oxygen, resulting in headache, coma, heart diseases or even death [13]. HC concentration in the exhaust gases is also increased at the engine's poor technical condition, ignition's leaving out or at other conditions lowering the combustion quality. HC can be carcinogenic [14,15].

NO_x gases are produced at high pressures, high temperatures and at the presence of a lean mixture in the combustion engines [16]. Nitrous oxide – N_2O as a main representative of NO_x depletes the ozone layer and is toxic to humans [17]. Another NO_x representative is nitrogen oxide (NO) that contributes to the production of photochemical smog and acid rains [18]. Nitrogen dioxide – NO_2 is irritating to humans and is conducive to ground-level ozone formation [19]. There is also a correlation found between NO_2 concentration in the urban air and the spread of COVID-19 [20].

Particulates (PM) are produced mainly at local oxygen deficiency. Oxygen consumes more reactive hydrogen, resulting in free carbon molecules. These are bound to HC and then clustered together into larger particles [21]. Human reaction to PM can result in asthma attacks, respiratory or cardiovascular diseases, shortened average life expectancy, cancer, etc. [22,23].

Volatile organic compounds are produced by vaporization from the vehicle fuel tank at the engine cold start and by vaporization from the engine crankcase as a result of incomplete combustion [24]. They play a part in the production of photochemical smog [25]. Photochemical smog results from the reactions between HC, volatile organic compounds and NO_x under solar radiation [26]. It has irritant effects and can cause respiratory problems and even death [27].

Reducing the adverse effect of various components of the exhaust gases on the environment and human health is conditioned by reducing the concentration in the exhaust gases, ideally up to zero. In order to reduce it, there are a number of studies made focusing on devices which regulate the exhaust gases composition as well as on the control management of the combustion process in the internal combustion engines. As also mentioned in the introduction of this publication, the amount of CO_2 produced is in direct relation with the amount of fuel consumed. Thus, the studies performed for the purpose of reducing CO_2 production are often focused on reducing the fuel consumption or on replacing conventional fossil fuels like gasoline and diesel with other low carbon fuels [28–30]. The publication [28] shows that CO_2 production was reduced by 20% when added 20% by volume of biodiesel with reduced viscosity. CO_2 emissions were also reduced by using low carbon biofuel with the exhaust after-treatment system as seen in the publication [31]. The publications [32,33] are focusing on the engine using the argon power cycle with zero CO_2 emissions.The engine on argon power cycle uses hydrogen or methane as fuel, oxygen as oxidant, and argon as the working fluid. Hydrogen fuelled engines use a mixture of argon and oxygen as the charge, with direct-hydrogen injection. In theory, the exhaust gases consist of argon and steam (the steam is water as vapor droplets at the boiling temperature), which can be separated using a high-efficiency condenser. The argon can then be recycled as recycled working gas, as also seen in the publication [32]. The possibility of having stable hydrogen combustion in the argon atmosphere with satisfactory results has been also studied in the publications [34–37].

The publication [38] mentions the reductions of CO concentration in the exhaust gases through the combustion of gasoline and hydrogen mixture ($G + H_2$). In this case, the reduction of CO measured was by 34%. In the publication [39], the possibility of reducing CO concentration was determined by intake air oxygen enrichment in relation to CI engine. In this way, CO was reduced by 65.4%. Reduction of HC emissions in the exhaust gases was tested by increasing oxygen in the intake air from 21% to 25% in the publication [40]. However, together with HC reduction it led to a high increase in NO_x. Humidifying the intake air caused a reduction of NO_x as well as reduction of engine thermal efficiency. At a full engine load, NO_x reduction by humidifying the intake air was ineffective. In the publication [41], addition of water into diesel with dosing of carbon nanoparticles brought a reduction of HC at a low engine load, however at higher load, it had contrary effect, so HC increased. The publication [42] pays attention to the reduction of HC concentration as well. This reduction is achieved by intake air oxygen enrichment. In this way, it also led to a significant reduction of smoke opacity. However, as follows from this publication, the impact of this way of reduction of HC concentration on the formation and distribution of typical intermediates such as OH*formaldehyde and CO during the combustion process are still unclear to the authors, which needs to be further studied to provide a better understanding on the mechanism of spray flame development at oxygen-enrichment conditions.

The most common method used for reducing the concentration of NO_x in the exhaust gases is the technology of exhaust gas recirculation, known as EGR, for both CI and SI engines, which can be concluded from the publications [43–45]. Transmission of the exhaust gases into the engine combustion space leads to the reduction of oxygen concentration resulting in deterioration in NO_x production [46]. However, a lower amount of oxygen can potentially cause an increase in smoke opacity [47]. The relation between the engine smoke opacity and the amount of exhaust gases recirculated as well as NO_x concentration that is seen as "compromise" is also described in the publication [48]. Higher volume of the recirculated exhaust gas can lead to an increase in HC concentration as well [49]. In the publication [50], a substantial reduction of HC concentration by using EGR technology and by biobutanol-gasoline combustion was achieved by hydrogen addition. A common alternative to EGR technology is a selective catalytic reduction technology, known as SCR [51]. However, here again, under certain operational conditions, it can lead to an increased engine's smoke opacity, as mentioned in the publication [52] as well. Following from the findings of the publication [53], HC production and the value of smoke opacity highly depend on the flame temperature. In this case, the flames were diluted with Ar, N_2, and CO_2 to control the flame temperature. The publication [54] focused on the effect of two-stage injection on emissions under high EGR rate on a diesel engine by fueling blends of diesel/gasoline, diesel/n-butanol, diesel/gasoline/n-butanol and pure diesel. Based on the results, the authors conclude that the smoke opacity increases first and then declines with the retard of post injection timing. Compared to diesel, the smoke emissions of blended fuels are more sensitive to the variation of post injection strategy. The authors of the publication [55] have also paid attention to the reduction of smoke opacity. Concerning such a reduction to zero value, the most favourable results would be achieved by using pure gasoline or *n*-heptane.

The current trend in the amount of emissions produced by road transport is unfavorable [56]. Therefore, the European Union is committed to achieve carbon neutrality by 2050 [57]. Road transport is responsible for more than a third of CO_2 emissions, and city road transport is a prevailing source of air pollution [58]. Vehicles with combustion engines combusting fossil fuels are still the most dominating inroad transport [59]. Immediate switch to electric powered vehicles is not possible [60,61]. Due to these facts, there are also attempts to use fuels with lower or zero amount of carbon [62,63]. The carbon-free fuel can be represented by hydrogen as well [64].

The most common usage of hydrogen as a fuel is seen in its form of so-called Brown's gas – HHO [65,66]. HHO is also known as "oxyhydrogen" and consists of hydrogen and oxygen in the ratio 2:1. Burning of HHO results in water vapor [67]. It is not used as itself, but as a fuel additive into the gasoline, diesel oil or LPG, in order to ensure faster mixture combustion, higher engine efficiency, lower emissions, and to reduce the fuel consumption [68–70]. HHO is also added into the engines using compressed natural gas, known as CNG, as seen in the publications [71,72]. Besides being used with conventional fuels, HHO is used with several biofuels as well [73–75]. In the publication [76], using a combination of biodiesel with HHO is described as one of the most viable type of fuel for increasing the engine power. The study in the publication [77] shows that using this fuel combination resulted in a reduction of CO concentration, vibrations and sound levels, but on the other hand, CO_2 and NO_x concentrations increased. Reduction of CO by using biodiesel in the form of pure hydrogen is also seen in the publication [78]. Concerning the engine with small volume, HHO and biodiesel combination caused an increase in the engine thermal efficiency by 9.4% and reduction of brake specific fuel consumption (BSFC) by 8.19%, as mentioned in the publication [79]. However, significant effects were probably caused by a relatively high amount of HHO (2.81 dm^{-3} min^{-1}) into the engine with volume of 0.315 dm^{-3}. HHO is also involved in a combustion of shale gas, as follows from the publications [80,81], and the authors of both publications conclude that the combustion stability of HHO can be obtained by electrolysis of water as well [82]. The HHO generator might be placed directly in the engine section, and the electric energy needed for electrolysis is taken from a vehicle in which the HHO generator is mounted. The generator can be of two types, dry cell and wet cell and the principle of their function is described in the publications [81,83–85]. The comparison of these types is also given in the publication [86] in which the authors state that there is, under the same entry conditions, a higher amount of HHO produced in relation to the dry cell HHO generator. This is also mentioned in the publication [87]. The amount of HHO produced and the amount of energy (usually electric) delivered into the generator depend, besides being dry or wet cell, on several settings and factors, such as electrodes' material, mutual distance of electrodes and the overall mechanical design of generator, as also given in the publication [88]. As the authors in the publication [89] say, the important factor affecting the efficiency of the HHO generator is the electrolyte parameter. The basic parameters of electrolyte are KOH and NaOH concentrations [90]. As follows from the publications [91,92], electrolyte with KOH is stable and can be used at low temperatures, however, electrolyte with NaOH is considered as higher effective. According to the HHO generator dealers, when using these generators, it is possible to reduce the harmful emissions produced by the combustion engines considerably. Specifically, there is a reduction of CO by 46% and HC by up to 84% [93]. Besides this, also the fuel consumption shall be reduced up to 60% according to the HHO generator producers [94]. They proclaim a strong increase in a vehicle's performance and cleaning effects on the engine and its intake and exhaust manifold [95–97].

There are several publications paying attention to the use of the HHO generators, and to the effect of HHO added into the combustion engines, including the publications [98–100].

Concerning the compression ignition engines, such effects of HHO are reflected in the publications [101–104]. These publications indicate that the measured impacts of HHO on emissions, fuel consumption and the engine power are substantially lower than declared by the manufacturers. The authors inform that when using HHO, there is an increase in the concentration of nitrogen oxides – NO_x [103].

Several publications also focus on the effects of HHO in the spark-ignition engines – SI, for example the publications [105,106].

The results are captured in the summarizing papers as well, for example in the publications [107–109]. Same as in relation to CI engine vehicles, in this case, the authors inform about a substantially lower impact of HHO on vehicle features than declared by the HHO generator manufacturers. A higher effect of HHO has been measured after adjusting the injection timing and other parameters via the added electronic control unit [109].

Considerable increase in the engine power or torque, or a reduction by half in fuel consumption, as specified by the manufacturers of the HHO generators, cannot be concluded either on the basis of the results given in the summarizing publications [110,111]. However, it can be assumed the reduction of fuel consumption by approximately 20%–25% [110].

This article pays attention to the impacts of HHO addition into the combustion engine on selected vehicle characteristics. HHO was taken from the HHO generator which was designed and constructed for the measurement purposes given in this article. The measurements consisted of the course of the engine power and torque, composition of the exhaust gases, and the value of pre-ignition. In order to secure the utmost measurement accuracy, the fuel consumption was not measured directly, but there was measured the length of fuel injection at the constant pressure. Therefore, it was possible to monitor precisely each change in the amount of fuel transported into the engine's cylinders, which represents an equivalent to fuel consumption.

The measurements were performed by two CI engine vehicles and three SI engine vehicles. They differed in number of kilometres driven, from 1000 km up to 320,000 km, in their controlling level of engine parameters, in the overall technical condition, and in fuels: gasoline, diesel oil, LPG and ethanol E85.

The measurements were conducted under laboratory conditions. In order to secure the results as accurate and objective as possible, the measurements were repeated with the vehicles individually.

Novelty of this publication lies in the choice of vehicles intended for the measurements, measurement comprehensiveness as well as way of measuring the fuel consumption. Many publications focused on the impact of HHO addition are based on the measurement with only one vehicle. These are for example [112–115]. However, HHO added in relation to only one vehicle can have diametral effects as for the other vehicle. In this article, the measurements were performed with five vehicles together with different parameters, as mentioned above. Wider selection of vehicles enables more objective assessment of the impact of HHO addition on selected vehicle parameters, since HHO effects can be affected by the engine control unit, level of engine management, fuel, number of kilometres driven, vehicle technical condition, EGR and by many other parameters [116]. The vehicles were chosen in order to ensure the highest possible objectivity. The measurements with five different vehicles diversely fuelled were also performed in the publication [117], however, only at the engine idling speed and only measuring the composition of the exhaust gases. On the other hand, in this publication, the measurements were performed with several vehicles at higher engine speed as well, or at greater engine load. By increasing the engine speed and load, it leads, inter alia, to the change in the amount of fuel injected and air intake that can affect the ratio between fuel, air and HHO. In comparison with the publication [118], the advantage of this publication is the number of parameters which are measured simultaneously. These include the composition of the exhaust gases, fuel consumption, engine power, etc. The benefit of this measurement comprehensiveness lies in more objective assessment of HHO effects, for example in the situation in which although the concentration of exhaust gases is reduced, there can theoretically be a decrease in the engine power or an increase in fuel consumption. Or, the engine power may increase, however, it can lead to an increase in the concentration of harmful components of the exhaust gases as well. This is not determined by these measurements, likewise in the publication [119].

There is also an innovation brought by the method of determining the fuel consumption owing to HHO addition via oscilloscope. In relation to some vehicles, as for LPG vehicles, it is very difficult to use a volume flow meter to determine the fuel consumption. The fuel, in some cases, returns from the injectors back to the fuel tank, and needs either two flow meters, or repeated return of fuel in front of the flow meter by using the T hose coupling. Concerning the second one, it is necessary to provide cooling since, mainly in relation to CI engine vehicles, it leads to intense heat of fuel, which can result in the damage of engine components. In relation to vehicles with “Pumpe – Düse” System (UIS - Unit Injector System), or Common Rail, it leads to fuel foaming due to high pressures in the fuel system and, thus, it highly affects the measurement accuracy. Therefore, measurement methodology via oscilloscope brings a very simple and very accurate method of measuring the fuel consumption without any assembly. This method can be also used when there is an OBD port needed for the vehicle to communicate with the dynamometer's computer, exhaust gas analyser, or when there is no OBD. The signal of an oscilloscope can also be, in relation to the CI engine vehicle without the OBD port, obtained by a needle lift sensor by which the vehicles with even the simplest electronic engine control are equipped with. Objectivity and assessment of the measured results are also supported by the authors' experience with the measuring devices and vehicles used in the measurements. Based on the experience, the authors are aware that the same vehicle can have a slightly different composition of the exhaust gases under approximately the same conditions. This conclusion made by the authors of this article is proven by their experience gained during several measurements within the studies of the same vehicles and devices used in this vehicle [120–122]. For example, change in the value of HC from 10 ppm to 8 ppm in relation to gasoline after HHO added, cannot be automatically considered as a decrease of HC concentration by 20% since such changes normally occur during measurement without any apparent cause. Such a decrease in HC concentration can also be caused by a slight change in temperature inside the catalytic converter, or at a lambda sensor, and by many other factors that may not be noticed by the measurer [123–125].

Methodology

Hydrogen production device

The device as a source of hydrogen has been designed on the electrolysis principle, see Fig. 1.

The tank 1 (Fig. 1) contains the electrolyte which is transported by the pump 2 into the electrolyzer 3. The electrical power is delivered into the electrolyzer via conductors 4. The rest of electrolyte together with hydrogen produced is being transported back into tank 1. It is further transported from tank 1 through the cooling container 5 into hose 6 which is connected to the vehicle's intake manifold.

The hydrogen generator is constructed according to the diagram in Fig. 1, see Fig. 2.

Position 1 in Fig. 2 represents the cooling container, position 2 represents the tank for electrolyte, position 3 is the ammeter, position 4 is the ventilator, position 5 is the electrolyzer, and position 6 represents the device supporting frame.

Electrodes in the electrolyzer are made of steel complying with the standard EN 17,040 W, and they are bipolar, see Fig. 3.

Bipolar connection (Fig. 3) means that there is only each sixth electrode connected. The unconnected electrodes act as bipolar and have both polarities at the same time, and thus the voltage is reduced. At a voltage of 14 V, there is only a voltage of about 2 V between the electrodes, and then water splitting is more efficient. The device works at an electric current of about 80 A. At a voltage of 14 V in a vehicle electric network, the device input power is of about 1220 W.

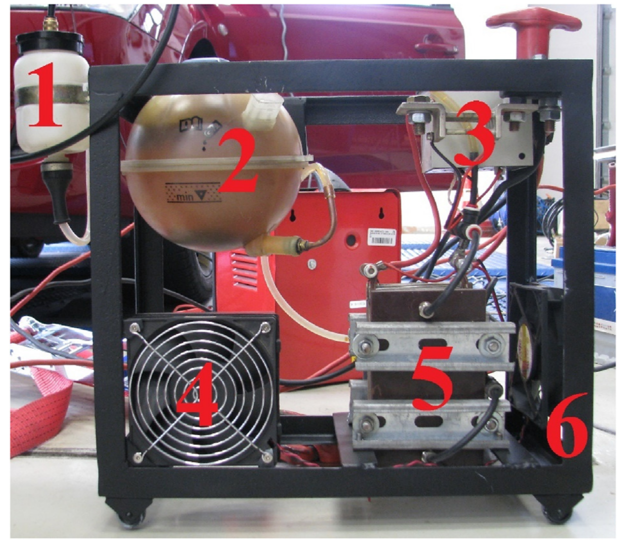

Fig. 2 – Hydrogen generator.

Potassium hydroxide (KOH) and sodium hydroxide (NaOH) in various concentrations were added into the tank with distilled water by the time when there was a maximum amount of the generated hydrogen from the hydrogen generator obtained. The maximum constant amount of hydrogen that the given device is able to produce, is 2 dm^{-3} min^{-1}, respectively 120 $dm^{-3}.hod^{-1}$. Increasing or reducing KOH or NaOH concentrations always led to the reduction of hydrogen production.

Measurement conditions

During measurements, electric energy needed for the hydrogen generator to be active was taken from two sources. The first one was an accumulator of the vehicle used for measuring. The second source represented a vehicle not used for measuring. The second vehicle was started for all the time in order to deliver electric current of about 80 A throughout the measurements without fluctuating.

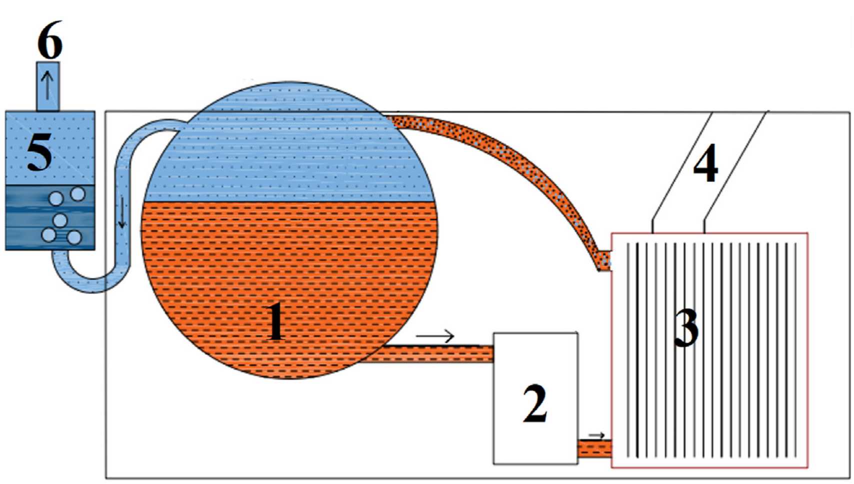

Fig. 1 – Hydrogen generator diagram.

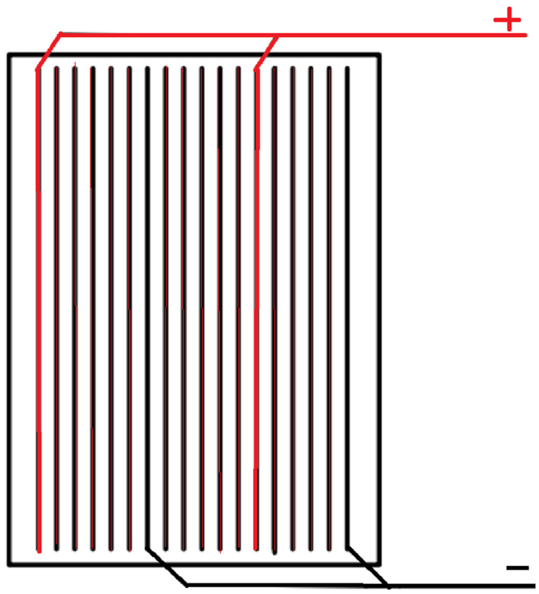

Fig. 3 – Bipolar electrode connection.

All the measurements were performed in the laboratory at ambient temperature from 17 °C to 22 °C.

Vehicles were warming to working temperature which was further kept by jet ventilators.

In order to have the engine, gearing and tyres warmed up, each vehicle drove approximately 10 km at all gears used while measuring at the MAHA MSR 1050 dynamometer.

Measurements of composition of the exhaust gases were repeated 5 times at the same conditions.

When the cooling ventilators started to be active during measurement of the fuel consumption or emission composition, the measurement was stopped in order to prevent the results from being affected by electric energy taken from the vehicle for the ventilator to be driven. Other devices taking energy from the engine for their working, for instance the air-conditioner, windscreen heating and so on, were switched off during measurements.

All the measurements were repeated until there were consequently 3x the same results measured in order to ensure the highest accuracy possible.

Table 1 – Vehicle sused formeasuring.

Name	Engine	Fuel	Date of production	Number of km driven
Škoda Felicia 1	1.9 D	Diesel	1997	190,000
Škoda Felicia 2	1.3 MPI	Gasoline/LPG	1998	240,000
Škoda Fabia 2	1.4 MPI	Gasoline/LPG	2004	320,000
Kia Sportage	1.6 CRDI	Diesel	2011	1000
Kia Ceed	1.6 CVVT	Gasoline/E85	2009	50,000

Vehicles used for measuring

The measurements were performed with 5 vehicles. Parameters of each vehicle are given in Table 1.

Škoda Felicia 2 is a vehicle fuelled by LPG Lovato Lov ECO 4 system with LPG vacuum proportioning in front of the throttle. The amount of LPG delivered is calculated by the LPG system control unit and controlled by an electronic control valve.

Škoda Fabia is a vehicle fuelled by Lovato Lov ECO 3 system with LPG vacuum proportioning in front of the throttle, however, the amount of LPG delivered into the engine is controlled only mechanically. The system does not contain either a control unit or an electronic control valve.

Measuring with Škoda Felicia 1

In relation to HHO added, there were following measurements performed with Škoda Felicia 1:

- the course of engine power and torque's curves
- composition of the gaseous emissions
- engine's smoke opacity
- possibility of cleaning the engine intake manifold by hydrogen

All the measurements were conducted with free and blanked-off delivery ducting of the EGR valve, and before and immediately after cleaning the intake manifold by hydrogen. Duct between the EGR valve and intake manifold was blanked off via metal blank.

The course of engine power and torque's curves was measured by MAHA MSR 1050 dynamometer, Fig. 4.

Position 1 in Fig. 4 represents the vehicle measured – KIA Sportage 2, position 2 is a dynamometer MAHA MSR 1050 and 3 represents the dynamometer's cylinders. The rear axle is not fixed on the cylinders because Kia Sportage has only the front axle, so there is no need for it. When the rear axle is away from the cylinders, the accuracy and safety during the measurements are increased.

Prior to measuring, there was a connection made between the engine control unit and dynamometer's computer through the OBD connector. Firstly, the wheels were driven,

Fig. 4 – MAHA MSR 1050 dynamometer.

then, the second highest gear was used and the acceleration pedal was fully applied. In this way, the value of power delivered onto the wheels, respectively onto the dynamometer's cylinders, was measured. After the maximum engine speed was reached, a driver applied the clutch pedal and left the second highest gear engaged. Speed of the driving axle's wheels gradually decreased. In this way, the power needed for mechanical losses to be overcome was measured between the engine's output and dynamometer's cylinders. The engine power was calculated by addition of power delivered onto the dynamometer's cylinders and power needed for mechanical losses to be overcome. While measuring, the vehicle was cooled by air from a jet ventilator in order to prevent it from overheating. The measurement deviation is ±2% from the power measured [126]. To resist the ambient factors such as ambient temperature or air humidity that affect the value of the engine power and torque measured, the dynamometer's computer adjusts the engine power values to ambient conditions specified in DIN 70,200 standard.

The engine's smoke opacity was determined by the MAHA MDO LON opacitemer via free-acceleration method [36,127]. The device has a measurement accuracy of ±1%.

The composition of the exhaust gases was specified while engine idle running. To measure this, MAHA MGT 5 analyzer was used. Measurement accuracy is 0.03 vol % CO, 0.05 vol % CO_2, 10 ppm vol. HC, 0.1 vol. O_2 and 32 ppm vol. NO_x.

The impact of hydrogen on the intake manifold's fouling was determined by adding hydrogen into the engine manifold for about 2 h. The engine was at idle speed and, approximately, each 15 min the speed was increased for a short period. Cleaning effect of hydrogen was checked visually – before and after cleaning by hydrogen, the intake manifold, in the area of the EGR valve is connected to, was dismounted and pictures were taken. The impact of cleaning by HHO was also determined by measuring the composition of emissions, the engine's smoke opacity and torque.

Measuring with Škoda Felicia 2 and Škoda Fabia

There were following measurements performed with Škoda Felicia 2:

- Composition of the gaseous emissions
- Time of gasoline injection

The measurements were done with both gasoline and LPG running.

The composition of gaseous emissions was measured by MAHA MGT 5 at the engine idling speed and at the engine increased speed, ranging from 2500 rpm up to 2700 rpm.

Diagnostic software VAG V·C.D.S. 11.11.01, which is connected to the engine control unit, could determine the length of injection. Concerning LPG vehicles, LPG is transported into the throttle, not through the gasoline injector. However, the engine control unit, which controls the engine designed for gasoline, is still calculating the length of injection needed via the gasoline injectors [128]. The data on the length of injections represent a relevant source of information in relation to LPG as well.

Measuring with Kia Sportage

In relation to hydrogen added, there were following measurements performed with Kia Sportage:

- course of the engine power and torque's curves
- composition of the gaseous emissions
- engine's smoke opacity
- length of fuel injection
- temperature of the exhaust gases
- amount of intake air

The course of the engine power and torque's curves, the engine's smoke opacity and composition of the exhaust gases were measured by the same method and with the same devices as for Škoda Felicia 1.

The engine's smoke opacity was determined by MAHA MDO LON opacitemer via free-acceleration method.

The length of fuel injection period, temperature of the exhaust gases and the amount of intake air were determined by Bosch KTS 590 diagnostics.

Measuring with Kia Ceed

There were following measurements performed with Kia Ceed:

- course of the engine power and torque's curves
- composition of the gaseous emissions
- length of fuel injection
- average fuel consumption
- pre-ignition

All the measurements were performed with gasoline and E85.

The course of the engine power and torque's curves was measured under the same conditions and with the same devices as for Škoda Felicia 1.

The composition of the gaseous emissions was measured by MAHA MGT 5 analyzer of the exhaust gases.

The length of fuel injection and pre-ignition were determined by NT PRO multi-channel oscilloscope. The connection diagram of the oscilloscope is given in Fig. 5.

Position 1 in Fig. 5 displays the ignition coil, position 2 represents the sparking plug, 3 is the injector, 4 is the engine control unit, 5 is the crankshaft speed sensor, 6 is the vehicle accumulator, 7 is the oscilloscope and position 8 displays the computer connected to oscilloscope.

Graphical output from the computer connected to NT PRO oscilloscope is shown in Fig. 6.

Red colour represents the output signal from the ignition coil, green colour represents the signal from the injector, and blue colour represents the signal from the crankshaft speed sensor.

The length of fuel injection period was subtracted from the period of duration of the change in voltage displayed in the green curve, see Fig. 6.

In order to determine the value of pre-ignition, it was first necessary to determine the duration of one engine revolution from Fig. 6. Then, it was needed to determine which projection

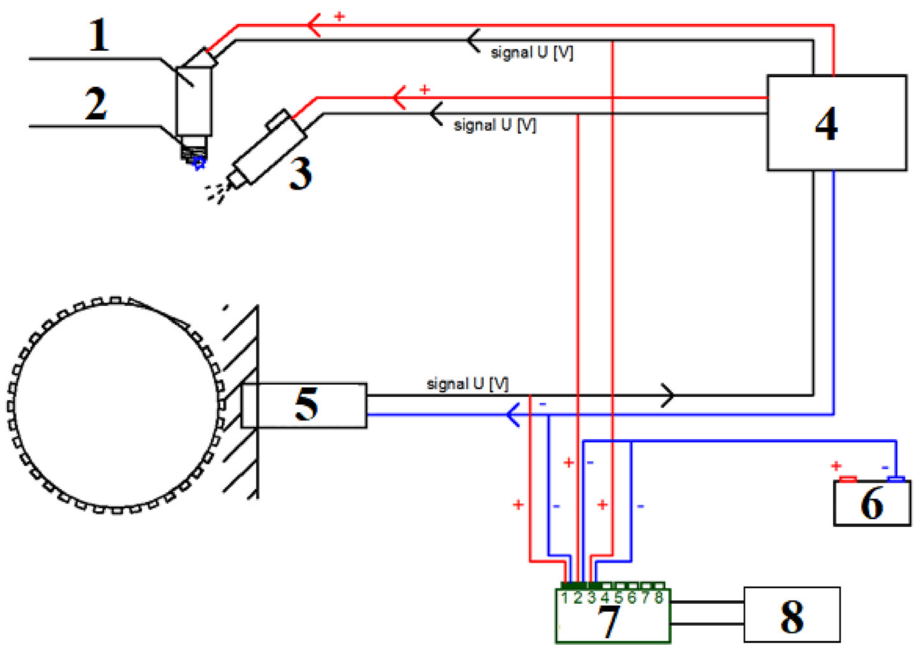

Fig. 5 – Connection diagram of NT PRO oscilloscope.

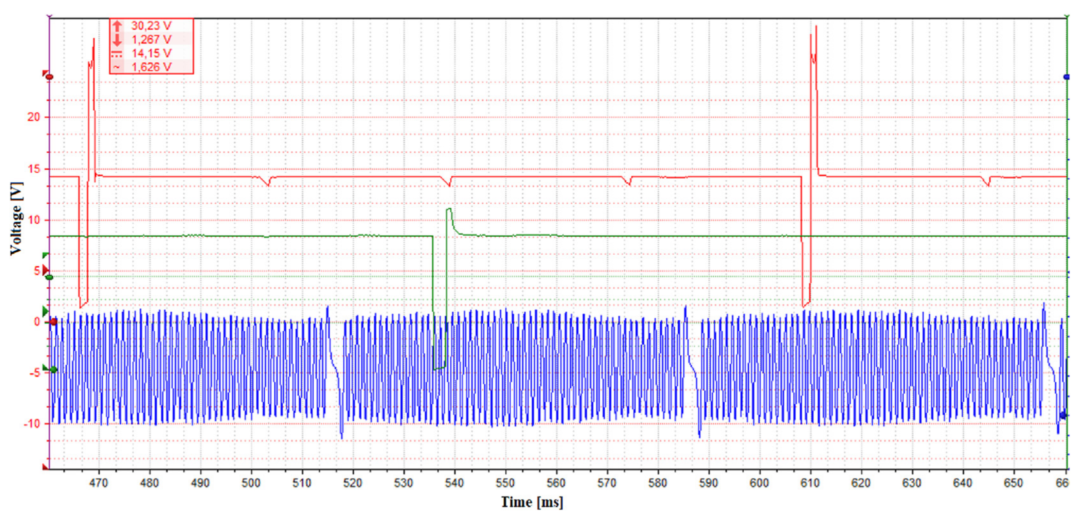

Fig. 6 – Graphical output from NT PRO oscilloscope.

represented by the blue curve in Fig. 6 corresponds to the top dead centre (TDC) of the first cylinder. The position of TDC was determined by spinning the driving axle's wheel at a gear engaged, and the position of the piston was monitored through the opening for the sparking plug in the cylinder head. After knowing the projection at which the piston of the first cylinder is in the top dead centre, time between the spark ignition moment and the moment of TDC was determined. The value of pre-ignition in degrees was calculated by direct proportion.

The length of injection, pre-ignition and composition of the gaseous emissions were measured while vehicle driving at the speeds of 50 km h^{-1}, 90 km h^{-1} a 130 km h^{-1} as well. Such speed is the maximum speed permitted within towns, outside towns and on highways in most European countries [38,129]. Measuring at the speed of 50 km h^{-1} was performed with the fourth gear engaged, and measuring at 90 km h^{-1} and 130 km h^{-1} was with the fifth gear engaged.

In order to ensure the same measurement conditions, the measurements at all speeds were conducted under laboratory conditions at the MAHA MSR 1050 cylinder test station. It was necessary to enter the driving resistances of each vehicle used while measuring into the cylinder test station's computer. The values of driving resistances were obtained from the coasting deceleration measurement of vehicle resistance according to the standard EN 30 0556. During this measurement, a vehicle starts running up to the speed about 120 km h^{-1}, and then the engine's wheel drive is discontinued. During vehicle coasting, the speed and time is recorded. The vehicle speed depending on time elapsed during vehicle driving with the engine broken off is seen in Fig. 7.

Data from Fig. 7 were entered into the cylinder test station's computer. Measuring the vehicle speed depending on time was subsequently repeated on the MAHA MSR 1050 cylinder power test station to determine the change in rolling resistance caused by dynamometer's cylinders. The vehicle mass was measured and entered into the computer as well. Thus, the driving resistances simulated by dynamometer had the same values as if the vehicle was driving by road.

To calculate the specific fuel consumption, the amount of fuel consumed was needed to be determined by the flow meter AIC 1203. The connection diagram of the flow meter is displayed in Fig. 8.

The flow meter's deviation is ±0.5% from the volume measured according to the manufacturer [39,130].

Results

Measurement results with Škoda Felicia 1

The course of the engine power and torque's curves measured with Škoda Felicia 1 is shown in Fig. 9. Solid lines display the course of the engine power (P) and dashed lines display the course of the engine torque (T). Black curves represent the data measured without HHO adding (without HHO), red curves represent the data measured with HHO adding and taking electric energy for the HHO generator to be driven from the other external vehicle (external el.). Green curves represent the data measured with HHO adding, and taking electric energy for the HHO generator to be driven from the measured vehicle (own el.).

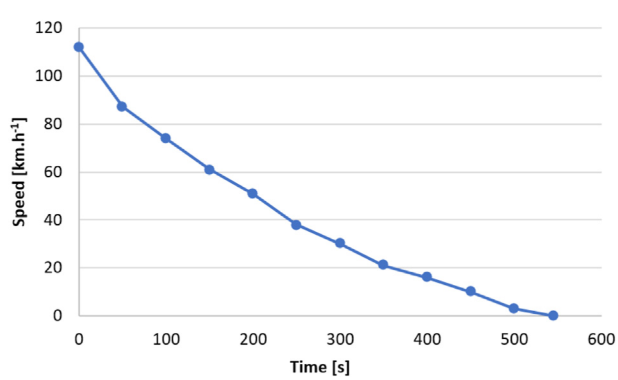

Fig. 7 – Driving speed during coasting deceleration measurement of vehicle resistance.

As seen from Fig. 9(red and black curves), addition of hydrogen into the engine intake manifold of Škoda Felicia 1 had not hardly any effect on the engine power and torque. Taking into consideration the measurement deviation of MAHA MSR 1050 dynamometer, the course of red and black curves can be considered constant. Greater effect was seen when taking electric energy needed for a hydrogen generator to be supplied from the measured vehicle (green curves). In this case, a higher resistance of alternator and decrease in the engine power and torque evinced. The same values were measured after cleaning the engine by HHO as well, Fig. 10.

The composition of the exhaust gases measured after cleaning the vehicle by hydrogen is given in Table 2. Table 2 shows the concentrations of selected components of the exhaust gases without HHO added, with HHO added and supplying HHO generator from the electrical system of the measured vehicle, and the results relating to supplying the hydrogen generator from the other vehicle. Table also includes the data measured with functional and then with non-functional EGR valve.

When adding HHO, the concentration of CO was changed only slightly as seen from the data in the second column of Table 2. Similar results were measured at concentrations of HC, CO_2 and O_2 as well. When taking electric energy from the measured vehicle, the value of λ coefficient significantly reduced. Concerning the concentration of NO_x, it increased when taking electric energy from the vehicle. On the other hand, the vehicle's smoke opacity decreased as seen from the data in the last column of Table 2.

Table 3 includes the data measured after cleaning the intake manifold and engine of Škoda Felicia 1.

Following from the comparison of Tables 2 and 3, CO concentration slightly reduced. Concentration of other compositions of the exhaust gases remained almost stable.

Fig. 11displays the intake manifold from the EGR valve before and after cleaning by hydrogen. Condition before cleaning is on the left, condition after cleaning is on the right.

Hydrogen cleaning did not affect the level of fouling the intake manifold as also seen in Fig. 11.

Measurement results with Škoda Felicia 2

The impact of HHO addition on concentration of particular components of the exhaust gases is evident from the data given in Table 4. Table shows the data measured while the

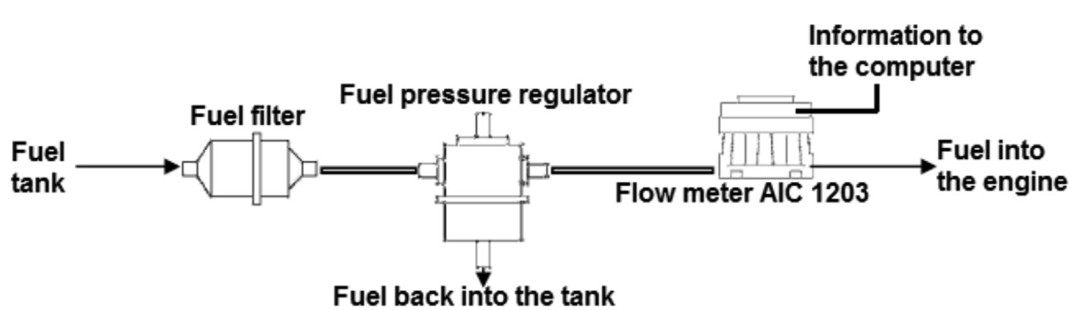

Fig. 8 – Connection of flow meter AIC 1203 into the vehicle fuel system during measurement.

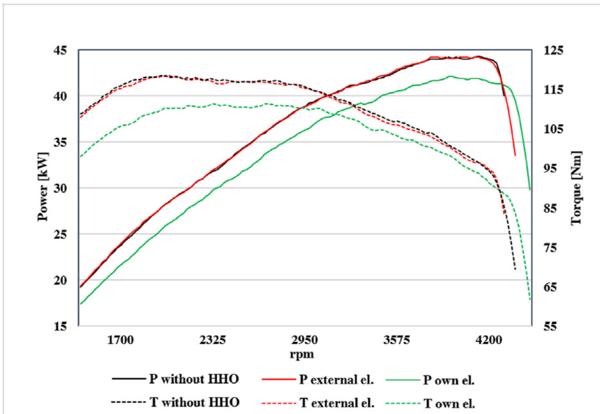

Fig. 9 – Measurement results of the course of the engine power and torque's curves with Škoda Felicia 1 before cleaning.

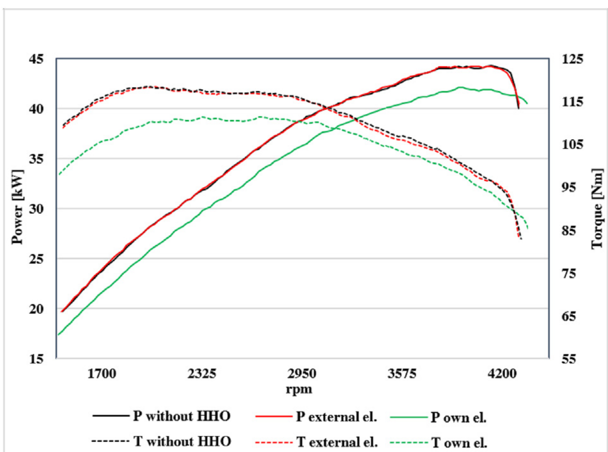

Fig. 10 – Measurement results of the course of the engine power and torque's curves with Škoda Felicia 1 after cleaning.

engine is running with gasoline as well as LPG. The values measured at idling speed are given in front of the slash, and the values measured at increased engine speed between 2500 rpm up to 2700 rpm are given behind the slash.

HHO addition had hardly any effect on CO concentration or on taking electric energy from the measured vehicle, and it can be concluded under the data from the first column of Table 4. The value of HC concentration slightly increased, especially when HHO added and when taking electric energy from the external vehicle at both gasoline and LPG running. The richness of mixture in relation to gasoline retained, whereas it was mildly enriched in relation to LPG, mainly when taking electric energy from the measured vehicle. Taking electric energy from the measured vehicle and HHO addition had hardly any effect on CO_2, O_2, and No_x concentrations in relation to gasoline engine driving. When adding HHO, CO_2 concentration increased while LPG driving, however, when taking electric energy from the measured vehicle, it reduced afterwards. Taking electric energy from the measured vehicle, O_2 and NO_x increased as well.

Table 5 shows the values of the length of fuel injection at the engine idling speed.

HHO addition significantly reduced the needed injection length by about 10% at both gasoline and LPG driving. However, when taking electric energy from the measured vehicle, it led to a considerable increase in injection length by more than 20% at both variations as seen from Table 5.

Measurement results with Škoda Fabia

Table 6 shows the results reflecting the impact of HHO addition on composition of the exhaust gases from Škoda Fabia.

HHO addition had only a low impact on CO concentration at both gasoline and LPG driving. Table 6 shows higher changes reached when taking electric energy from the measured vehicle. HC concentration was increased mainly due to taking electric energy from the measured vehicle fuelled by gasoline. In this case, concerning the vehicle fuelled by LPG, NO_x concentration mildly increased as well.

Table 7 shows the values of the length of fuel injection at the engine idling speed.

In all situations, HHO addition considerably shortened the injection length by about 10%. This follows from the data given in Table 7. It is also evident that addition of hydrogen when taking electric energy from the measured vehicle needed for the hydrogen generator to be driven caused a significant increase in the fuel injection length required by approximately 20% at both gasoline and LPG engine driving.

Measurement results with Kia Sportage

Fig. 12shows the course of the engine power and torque's curves measured without HHO added (black colour), with HHO added (red colour) and when taking electric energy from the measured vehicle (green colour).

Table 2 – Composition of the exhaust gases from Škoda Felicia 1 before cleaning the intake manifold.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]	Smoke opacity[m^{-1}]
Functional EGR							
Without HHO	0.01	1	2.556	5.8	12.76	9	1.20
HHO + exter. el.	0.02	3	2.599	5.7	12.86	22	1.25
HHO + own el.	0.01	1	2.451	5.8	11.95	26	1.10
Non-functional EGR							
Without HHO	0.01	0	2.784	5.8	12.97	26	1.17
HHO + exter. el.	0.02	2	2.786	5.9	13.02	39	1.20
HHO + own el.	0.01	0	2.557	5.7	12.84	45	1.04

Table 3 – Composition of the exhaust gases from Škoda Felicia 1 after cleaning the intake manifold.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]	Smoke opacity [m^{-1}]
Functional EGR							
Without HHO	0.00	1	2.559	5.7	12.79	8	1.19
HHO + exter. el.	0.01	4	2.521	5.8	12.76	21	1.26
HHO + own el.	0.01	2	2.399	5.6	11.82	29	1.09
Non-functional EGR							
Without HHO	0.01	0	2.723	5.8	12.89	29	1.16
HHO + exter. el.	0.01	5	2.678	5.8	12,94	46	1.19
HHO + own el.	0.00	1	2.512	5.8	12.48	49	1.04

Fig. 12 shows that HHO addition affected the course of the engine power and torque's curves not so much in relation to Kia Sportage. However, covering the whole speed spectrum, it caused a slight decrease in the engine power and torque. When taking electric energy from the measured vehicle, it led to a stronger fall of the curves of the engine power and torque.

Table 8 shows the results reflecting the impact of HHO addition on composition of the exhaust gases from Kia Sportage. The values were specified at the engine idling speed. In this case, λ coefficient is not given since during all the measurement time was its value outside the scope of MAHA MGT 5 measuring device, so the value was higher than 4.

Concerning Kia Sportage, HHO addition led to a mild increase in HC, CO_2 and mainly NO_x concentrations. Table 8 shows that hydrogen addition had hardly any effect on CO concentration and on the value of smoke opacity. Taking electric energy from the measured vehicle reflected in the increase in CO_2 concentration and in O_2 reduction.

Table 9 shows the data about the amount of fuel injected, intake air and temperature of the exhaust gases.

HHO addition had no impact on the amount of intake air and on the amount of fuel injected. Temperature of the exhaust gases was increased by 1 °C. When HHO adding and taking electric energy from the measured vehicle at the same time, it led to doubling of the amount of fuel injected and to a mild increase in the amount of intake air as follows from the data in Table 9.

Measurement results with Kia Ceed

Fig. 13 shows the impact of HHO addition and taking electric energy for the hydrogen generator to be operated on the course of the engine power and torque depending on the engine speed. The results relate to the measurement performed with gasoline.

Addition of HHO evinced in a mild decrease in the engine power and torque within all the spectrumof engine speed

Fig. 11 – Comparison of fouling the intake manifold before and after cleaning by hydrogen.

Table 4 – Composition of the exhaust gases from Škoda Felicia 2.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x[ppm]
Gasoline						
Without HHO	0.00/0.01	8/4	1.002/1.001	14.3/13.9	1.15/1.09	3/2
HHO + exter. el.	0.00/0.01	10/5	1.003/1.002	14.1/14.0	1.57/1.12	6/4
HHO + own el.	0.00/0.01	8/5	1.003/1.002	14.3/14.1	1.15/1.11	3/3
LPG						
Without HHO	0.00/0.00	51/21	1.102/1.103	12.6/12.4	1.91/1.84	15/14
HHO + exter. el.	0.00/0.00	69/24	1.065/1.121	14.3/12.8	1.35/1.89	6/9
HHO + own el.	0.00/0.01	64/22	1.077/1.098	11.9/12.2	3.07/2.05	42/17

Table 5 – Length of injection measured with Škoda Felicia 2.

Measurement conditions	Length of fuel injection [ms]
Gasoline	
Without HHO	1.90
HHO + exter. el.	1.70
HHO + own el.	2.40
LPG	
Without HHO	2.30
HHO + exter. el.	2.10
HHO + own el.	2.80

Table 7 – Length of injection measured with Škoda Fabia.

Situation	Length of fuel injection [ms]
Gasoline	
Without HHO	2.00
HHO + exter. el.	1.81
HHO + own el.	2.40
LPG	
Without HHO	2.20
HHO + exter. el.	1.95
HHO + own el.	2.70

(Fig. 13). Taking electric energy from the measured vehicle reflected more significantly (green curves).

Specific fuel consumption was measured during the measurement of course of the engine power and torque's curves as well. The results are given in Fig. 14.

The lowest specific fuel consumption was reached with gasoline. After HHO added, specific fuel consumption increased. It also increased when taking electric energy from the measured vehicle as follows from Fig. 14. Concerning the gasoline fuel, the average value of specific fuel consumption was 277.271 g kW^{-1} h^{-1}. HHO addition caused an increase in specific fuel consumption to 280.385 g kW^{-1} h^{-1} and when taking electric energy from the measured vehicle it increased to 283.912 g kW^{-1} h^{-1}.

Fig. 15shows the graph of measurement while the Kia Ceed vehicle was fuelled by E85.

Concerning E85, HHO addition did not change the engine power and torque. Taking electric energy from the measured vehicle and HHO's assistance at the same time, led to a decrease in the engine power and torque within the whole spectrum of the engine speed (Fig. 15).

Fig. 16 shows the course of specific fuel consumption's value during measurement of the engine power and torque.

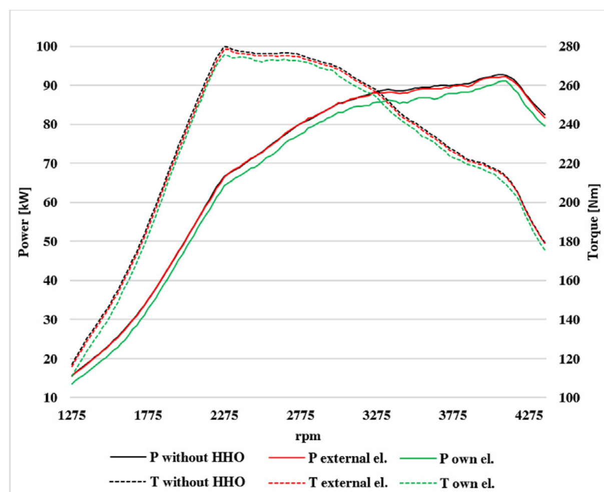

Fig. 12 – Measurement results of the course of the engine power and torque's curves with Kia Sportage.

After HHO added, it led to an increase in specific fuel consumption from 286.880 g.kw^{-1}.h^{-1} to 288.783 g.kw^{-1}.h^{-1} while measuring with E85. HHO addition caused an increase

Table 6 – Composition of the exhaust gases from Škoda Fabia.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Gasoline						
Without HHO	0.38/0.43	122/46	1.015/0.994	14.52/14.97	4.60/4.25	13/10
HHO + exter. el.	0.41/0.66	123/47	1.021/0.988	14.39/14.75	4.72/4.34	12/10
HHO + own el.	0.10/0.39	441/168	1.227/1.015	10.93/13.51	4.58/0.79	8/7
LPG						
Without HHO	0.00/0.39	441/168	1.227/1.015	10.93/13.51	4.58/0.79	9/7
HHO + exter. el.	0.00/0.51	444/189	1.545/0.987	10.78/13.44	4.86/0.24	10/9
HHO + own el.	0.00/0.48	439/175	1.215/1.224	12.85/11.45	4.62/0.67	10/8

Table 8 – Composition of the exhaust gases from Kia Sportage.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Without HHO	0.01	8	1.7	18.166	41	0.00
HHO + exter. el.	0.01	12	1.8	18.025	78	0.00
HHO + own el.	0.01	11	3.6	15.539	82	0.00

Table 9 – Selected values measured with Kia Sportage.

Situation	Amount of fuel per injection [mm^{-3}]	Amount of intake air [g/s]	Temperature of the exhaust gases [°C]
Without HHO	4	3.05	137
HHO + exter	4	3.05	138
HHO + own	8	3.06	137

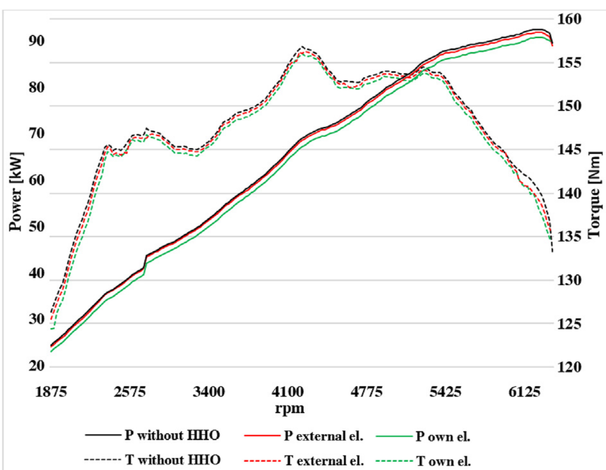

Fig. 13 – Measurement results of the course of the engine power and torque's curves with Kia Ceed gasoline vehicle.

in specific fuel consumption to 280.385 g kW^{-1} h^{-1} and when taking electric energy from the measured vehicle it increased to 290.938 g kW^{-1} h^{-1}.

Table 10 shows the composition of the gaseous emissions at both gasoline and E85 vehicle driving.

HHO addition and taking electric energy from the measured vehicle for the hydrogen generator to be driven had hardly any effect on the composition of emissions from Kia Ceed (Table 10). The biggest change was measured at HC concentration – 3rd column, Table 10.

Table 11 shows the concentrations of selected compositions of the exhaust gases measured while vehicle driving at the constant speed of 50 km h^{-1} on level ground.

HHO addition caused an increase predominantly in NO_x concentration in the exhaust gases at both vehicles fuelled by gasoline and E85. After taking electric energy from the measured vehicle, it led to a mild decrease in NO_x concentration, however, the concentration was still higher than without hydrogen added. Other compositions of emissions did not cause a significant change.

Table 12 shows the composition of emissions while vehicle driving at the speed of 90 km h^{-1}.

HHO addition and taking electric energy from the measured vehicle for the hydrogen generator to be driven had hardly any effect on composition of the exhaust gases as follows from the data given in Table 13.

Table 14 shows the results measured at the driving speed of 130 km h^{-1}.

HHO addition led to a mild increase in CO and HC concentrations at both gasoline and E 85 driving. When taking electric energy from the measured vehicle, CO concentration decreased, but not under its original level.

Table 14 shows the values of the length of fuel injection and pre-ignition at the engine idling speed.

HHO addition led to a decrease in period of injection by about 10% at both gasoline and E 85 driving. However, taking electric energy from the measured vehicle for the HHO generator to be operated led to an increase in the period of injection by about 20%. HHO addition also caused a decrease

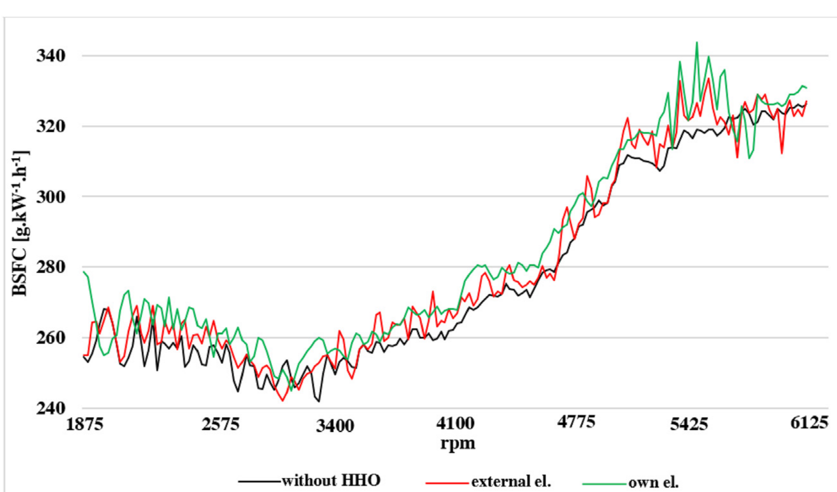

Fig. 14 – Specific fuel consumption of Kia Ceed gasoline vehicle.

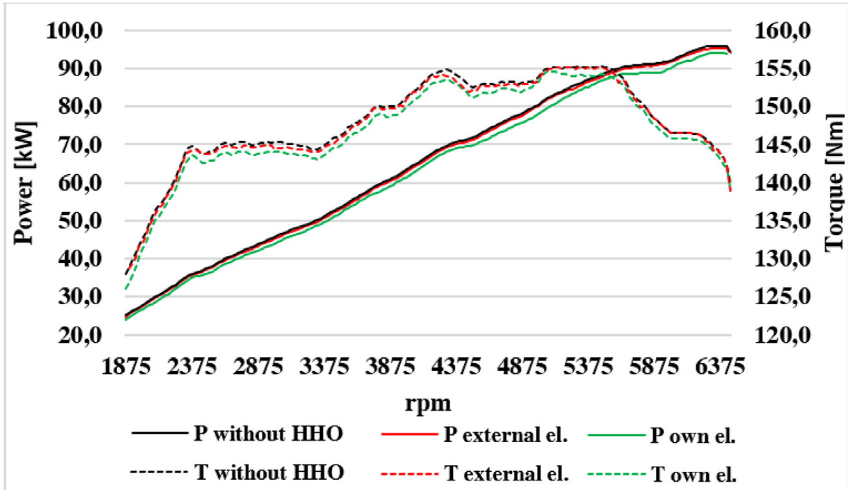

Fig. 15 – Measurement results of the course of the engine power and torque's curves with Kia Ceed vehicle fuelled by E85.

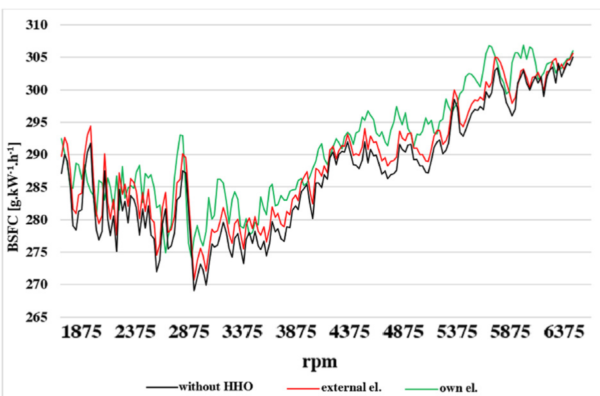

Fig. 16 – Specific fuel consumption of Kia Ceed vehicle fuelled by hydrogen.

in value of pre-ignition, and by taking electric energy from the measured vehicle this value decreased even more.

Table 15 shows the values of the length of injection and pre-ignition measured while vehicle driving.

HHO added slightly decreased the length of fuel injection while gasoline driving at the speed of 50. km.h^{-1}. At the speed of 90 km h^{-1}, the value of gasoline fuel injection's length remained unchanged. Hydrogen addition and taking electric energy from the measured vehicle in all cases caused an increase in the value of the length of fuel injection at both gasoline and E 85 driving.

Table 11 – Composition of the exhaust gases from Kia Ceed while driving at the speed of 50 km h^{-1}.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Gasoline						
Without HHO	0.09	6	1.002	14.92	0.09	0
HHO + exter. el.	0.10	7	1.001	14.95	0.09	9
HHO + own el.	0.07	6	1.000	14.96	0.08	4
E85						
Without HHO	0.00	6	1.002	14.89	0.05	3
HHO + exter. el.	0.01	7	1.003	14.91	0.06	4
HHO + own el.	0.00	5	1.002	14.94	0.06	3

The value of pre-ignition was decreased due to hydrogen added in all cases, and when taking electric energy from the measured vehicle, it led to even greater decrease in pre-ignition's value as follows from Table 15.

Discussion

HHO and the engine power and torque

HHO added into a vehicle with minimum involvement of the control unit in the engine management of Škoda Felicia evinced in a mild decrease in the engine power and torque within all spectrum of the engine speed (Figs. 9 and 10). The same situation happened after HHO added into a vehicle with

Table 10 – Composition of the exhaust gases from Kia Ceed.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Gasoline						
Without HHO	0.00/0.01	6/8	1.003/1.003	15.42/15.34	0.09/0.08	4/2
HHO + exter. el.	0.01/0.02	7/9	1.002/1.003	15.41/15.31	0.09/0.09	5/3
HHO + own el.	0.00/0.01	2/4	1.001/1.003	15.43/15.33	0.08/0.09	5/4
E85						
Without HHO	0.01/0.03	4/6	1.001/1.001	14.9/14.8	0.05/0.06	4/4
HHO + exter. el.	0.00/0.03	5/8	1.001/1.002	14.8/14.9	0.06/0.05	6/5
HHO + own el.	0.00/0.02	2/5	1.002/1.002	14.9/14.8	0.05/0.06	7/7

Table 12 – Composition of the exhaust gases from Kia Ceed while driving at the speed of 90 km h^{-1}.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Gasoline						
Without HHO	0.14	7	1.002	15.01	0.07	2
HHO + exter. el.	0.19	8	1.000	14.98	0.07	6
HHO + own el.	0.14	7	1.001	14.91	0.07	5
E85						
Without HHO	0.13	6	1.001	14.92	0.06	5
HHO + exter. el.	0.14	8	1.000	14.95	0.05	3
HHO + own el.	0.12	4	1.001	14.91	0.06	4

Table 13 – Composition of the exhaust gases from Kia Ceed while driving at the speed of 130 km h^{-1}.

Measurement conditions	CO [%]	HC [ppm]	λ [–]	CO_2 [%]	O_2 [%]	NO_x [ppm]
Gasoline						
Without HHO	0.21	8	1.001	15.01	0.05	6
HHO + exter. el.	0.26	10	1.001	14.99	0.04	5
HHO + own el.	0.22	10	1.000	14.99	0.04	6
E85						
Without HHO	0.22	9	1.001	15.02	0.5	5
HHO + exter. el.	0.29	10	1.001	15.01	0.5	6
HHO + own el.	0.25	11	1.000	15.01	0.4	6

Table 14 – The values of the length of fuel injection and pre-ignition from Kia Ceed at the engine idling speed.

Measurement conditions	Idling	
	Length of fuel injection	Pre-ignition
Gasoline		
Without HHO	2.50	13.6
HHO + exter. el.	2.25	13.1
HHO + own el.	3.04	12.8
E85		
Without HHO	3.09	13.7
HHO + exter. el.	2.73	13.2
HHO + own el.	3.58	12.7

CRDI technology – Kia Sportage (Fig. 12). In both cases, it led to a mild decrease in the engine power and torque. Similarly, in both cases, when taking electric energy from the measured vehicle, it led to a strong decrease in the engine power and torque. In relation to Škoda Felicia 1, it led to the highest decrease in the engine power by 2.2 kW, which is 5% decrease, and in the engine torque by 10 Nm, which is 8.6% decrease. In relation to Kia Sportage, the highest decrease in power measured was only by 2.3%, and decrease in the engine torque was by 1.1%. This was due to the fact that Kia Sportage reaches, in comparison with Škoda Felicia 1, significantly higher engine power and torque as well as the amount of electric energy taken for the HHO generator to be driven, and thus, the load of alternator was broadly the same in both cases. Similar results as for decrease in power after HHO added into CI engine and taking electric energy from the measured vehicle was also mentioned in publication [40,131] as seen in Fig. 17as well.

In relation to measurements from Ref. [131], fall of the course of the engine power and torque was slightly lower as seen in Figs. 9–11. This was probably due to the fact that only electric current of 20 A was taken from the vehicle at the same voltage of about 14.4 V. Thus, the power taken from the combustion engine, which is needed for the HHO generator to be driven, was lower. The publication [132] also includes a mild decrease in the engine power after HHO addition.

Increasing of power after HHO added, or not increasing of power when taking electric energy form the measured vehicle at the same time, would be expected when changing the fuel injection timing as follows from publication [133]. Fuel injection timing change in relation to Škoda Felicia 1 is relatively easy to apply by adjusting the position of the rotary injection pump. In relation to Kia Sportage, injection timing change would require substantially more demanding modification of the engine control unit software. However, an increase in the engine power and torque would not be probably noticeable during normal driving [120,134]. More considerable increase in the course of the engine power and torque would be assumed when using diesel with 25% of biocomponent by addition of hydrogen of approximately up to 7 dm^{-3} min^{-1} and without taking electric energy from the measured vehicle as seen in publication [135]. However, during normal vehicle operation such a goal is difficult to obtain since the HHO generator

Table 15 – The values of the length of fuel injection and pre-ignition while Kia Ceed vehicle driving.

Measurement conditions	50 km h^{-1}		90 km h^{-1}		130 km h^{-1}	
	Length of fuel injection	Pre-ignition	Length of fuel injection	Pre-ignition	Length of fuel injection	Pre-ignition
Gasoline						
Without HHO	2.65	35.7	4.21	35.0	5.66	22.8
HHO + exter. el.	2.61	34.3	4.21	33.5	5.83	22.2
HHO + own el.	3.81	33.8	4.83	33.1	6.24	21.9
E85						
Without HHO	3.31	35.8	4,87	34.9	7.63	22.6
HHO + exter. el.	3.38	34.2	4.89	33.6	7.82	22.1
HHO + own el.	4.25	33.8	5.24	33.1	8.16	21.8

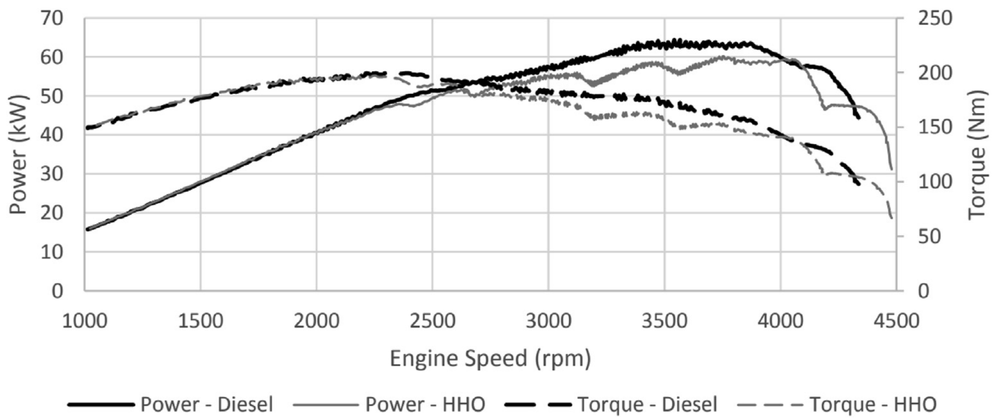

Fig. 17 – Impact of HHO addition and taking electric energy from the measured vehicle on the course of the engine power and torque's curves of CI engine [131].

would require a considerable supply of electric energy, or it would be necessary to have a large HHO container in a vehicle. In this case, increase in the engine power would be of maximum 5 kW as follows from Fig. 18 as well.

According to several sources, coming mainly from the HHO generator dealers, it is able to increase the engine power and torque significantly by activation of the HHO generator [136–139]. During measurements of the engine power and torque with Škoda Felicia 1, it led to a significant increase in both engine power and torque while being repeated. After fixing a vehicle on the cylinder dynamometer MAHA MSR 1050, its engine power and torque was measured for several times successively. As also stated in "Measurement methodology" in this article, the maximum engine speed is being gradually achieved when having the acceleration fully applied during the measurement. Without HHO, it led to an increase in the maximum engine power from 28.7 kW to 44.1 kW, and from 58 Nm to 118 Nm between the first and the ninth measurement gradually as also seen in Figs. 9 and 10. After the ninth measurement, it led to a stabilization of these values and further measurements did not observe any decrease or increase in the engine power and torque measured. The

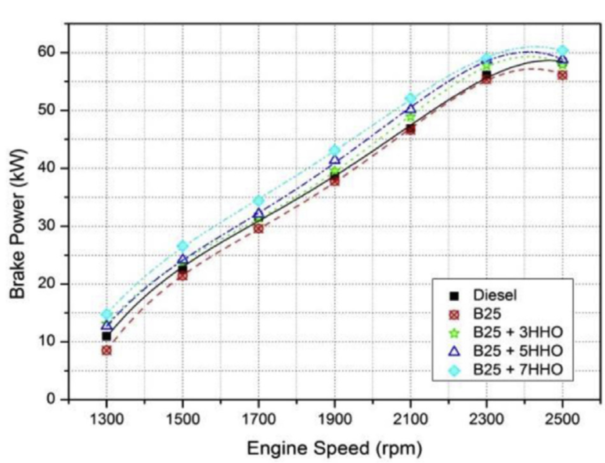

Fig. 18 – Impact of higher amount of HHO added into the biodiesel engine [135].

curves' courses remained the same. An increasing number of measurements also led to a decrease in the value of smoke opacity from 4.2 to the values given in Tables 2 and 3 The increase in the engine power and torque, and decrease in the value of smoke opacity were measured only with the diesel engine without HHO added. It was probably due to not reaching such high engine speed while driving with Škoda Felicia 1 at normal vehicle operation and the acceleration pedal was not fully applied as well. This type of driving resulted in a gradual depositing of impurities in the intake and exhaust engine manifolds [140,141]. Reaching the high engine speed led to a progressive unclogging resulting in a relatively high smoke opacity measured. While measuring with Kia Sportage, the maximum engine power increased from 87 kW to 92 kW, and from 261 Nm to 278 Nm. It was probably due to gradual adaptation of the engine control unit since the vehicle drove under 1000 km. Normally a process that can be supposed to employ includes the HHO generator installation into a diesel vehicle at which the first engine power and torque's measurement shall be made together with further second measuring with HHO added. This is also supported by the fact that the average price of one measurement at the cylinder dynamometer is about 50 € [142,143]. Therefore, repeated measuring until the values are stabilized would be highly overpriced. The increase in the engine power and torque, and decrease in the value of smoke opacity is often wrongly attributed to HHO addition.

HHO and composition of the exhaust gases

Concerning Škoda Felicia 1 and Kia Sportage, CO, HO and CO_2 concentrations are considered almost unchanged (Tables 2, 3 and 8). The publication [144] informs about the decrease in concentrations of the above-mentioned components of the exhaust gases even at a lower amount of HHO added. However, in the publication [144], the measurement was performed at the engine speed of 1500 rpm at its full load, that means at other conditions than set in this article. There is an exception seen in the increase of CO_2 value in Table 8 when taking electric energy from the Kia Sportage vehicle. This was probably due to the higher amount of fuel used as follows from Table 9.

HHO addition resulted in NO_x increase in the exhaust gases in relation to Škoda Felicia 1 as well as to Kia Sportage with the engine control unit (Tables 2, 3 and 8) Taking electric energy from the measured vehicle even caused an increase in NO_x production in all cases. NO_x is produced mainly when there is oxygen surplus, higher pressure and higher temperature in the engine combustion section [145,146]. Evidently, addition of HHO fulfilled all the above mentioned conditions. Such an increase in NO_x concentration and the same explanation is also given in publication [68]. Similar increase in NO_x was seen in research of clean diesel and in the measurements with biodiesel blend with kerosene additive [147–149] as well.

Thanks to HHO, the engine's smoke opacity of Škoda Felicia 1 increased from 1.20 m^{-1} to 1.25 m^{-1} at functional EGR, and from 1.17 m^{-1} to 1.20 m^{-1} at non-functional EGR (Tables 2 and 3). In relation to Kia Sportage, HHO addition did not cause any change in smoke opacity since its value had a zero value for each time (Table 8). HHO addition of an amount 0.75 dm^{-3} min^{-1} decreased the smoke opacity by up to 49% during measurements described in publication [150]. However, in this case, the engine load was up to 80% [150]. Engine load caused by the alternator also resulted in lower increase in smoke opacity (Tables 2 and 3). These are still increases, not decreases in the smoke opacity.

Long-term effects of HHO did not cause a reduction in the amount of components of the exhaust gases as follows from the data comparison of Tables 2 and 3. It also did not cause any visible reduction of fouling the intake manifold, which is proven by comparison given in Fig. 11. During the measurements from the publication [151], HHO cleaning brought the results given in Table 16.

Cleaning the engine by HHO produced visible results as follows from Table 16, from which the data given are copied from publication [151]. The reasons why HHO cleaning did not have any results in this article and, on the other hand, had significant results in publication [151], are several. The underlying reason is the amount of HHO added. Concerning the publication [151], while cleaning the engine, the amount of HHO added was 6 dm^{-3} min^{-1}. Concerning this article, while cleaning the engine, the amount of HHO added was three times lower - 2 dm^{-3} min^{-1}. It is due to the fact that the HHO generator is primarily intended for production of such an amount of HHO which is needed for continuous addition while driving, not for engine cleaning. The HHO generator is powered from the vehicle electric system, while the HHO generator used in the publication [69] is powered by 220 V. HHO generator operating on electric voltage equals to voltage in a vehicle (approximately 14 V) was chosen for safety reasons [152,153]. Another reason for different results also lies in the way of the measurement. In the publication [151], the measurements were conducted after 2 min during which the engine was switched off. In this article, after cleaning the engine by HHO, Škoda Felicia 1 then drove about 10 km with different engine loads. This method would aim to specify the results and to avoid impact of engine idling over a longer period, it means during 90 min. The results given in the compared publication might be different after driving several kilometres. Concerning the measurement methodology from publication [151], the results might have been affected by engine idling over a longer period [154,155].

Table 16 – HHO cleaning results [151].

Time [min]	CO [%]	Smoke [%]	Cleaning quality [%]
0	0.48	62.3	35
15	0.46	54.5	35
30	0.32	22.8	57
45	0.23	17.1	80
60	0.21	16.7	85

Effects of HHO on composition of the exhaust gases in relation to Škoda Felicia 2 and Škoda Fabia were very low. A similar observation can be also seen in relation to Kia Ceed fuelled by both E 85 and gasoline (Tables 10–13).

However, Škoda Fabia had a considerably higher concentration of all components of the exhaust gases based on the comparison of values measured with Škoda Felicia 2 (Table 4) and Škoda Fabia (Table 6). It is necessary to take into consideration that the analyzer of the exhaust gases MAHA MGT 5 displays the values of components in volume percentage from the overall volume of the exhaust gases [156]. However, concentrations of the components from Škoda Felicia 2 and Škoda Fábia are diametrically different. It can be also assumed that in relation to naturally aspirated vehicles with engine capacity of 1.3 dm^{-3} and of 1.4 dm^{-3} at the same engine speed, the amount of exhaust gases is the same [157]. Concerning Škoda Fabia, it can be presumed to have its worse technical condition [158]. It also did not lead to a reduction of concentration of the measured components even after 5 h HHO adding into the intake manifold.

Thus, in relation to all three vehicles with the spark-ignition engines, there was hardly any change in composition of the exhaust gases due to HHO added. At the same time, in relation to all three vehicles fuelled by gasoline, LPG and E 85, it can be seen a mild increase in HC (Tables 4, 6 and 10). Publication [117] shows the modest decrease in HC in relation to three vehicles with the spark-ignition engine. CO, according to measurements from Ref. [117], slightly increased in one case, remained the same in the other case, and once slightly decreased. HHO added in the amount of 2 dm^{-3} min^{-1} in this article, and of 1.3 dm^{-3} min^{-1} in the publication [117] did not clearly affect the composition of the exhaust gases. It was much more affected by the engine load due to taking electric energy from the measured vehicle. The publication [159] includes the results also measured with Škoda Felicia 2 with the same engine as used in this article. However, only 0.3 dm^{-3} min^{-1} of HHO was added into the engine. HHO addition and taking electric energy from the measured vehicle at the same time evinced in a decrease in CO, HC and NO_x as also given in Fig. 19. The first left picture a) displays the values measured at the engine speed of 1500 rpm, the middle picture b) displays the values at 2000 rpm, and the right picture c) shows the values at 2500 rpm. The bottom axis shows the power taken from the engine through braking, the brake power (BP) in kW.

Decrease in CO concentration was measured in publication [159] as well as in this article, not only with Škoda Felicia 2, but also with Škoda Fabia 2 and Kia Ceed all fuelled by gasoline, LPG and E85. However, in all cases, the decrease in CO concentration was measured after taking electric energy from the

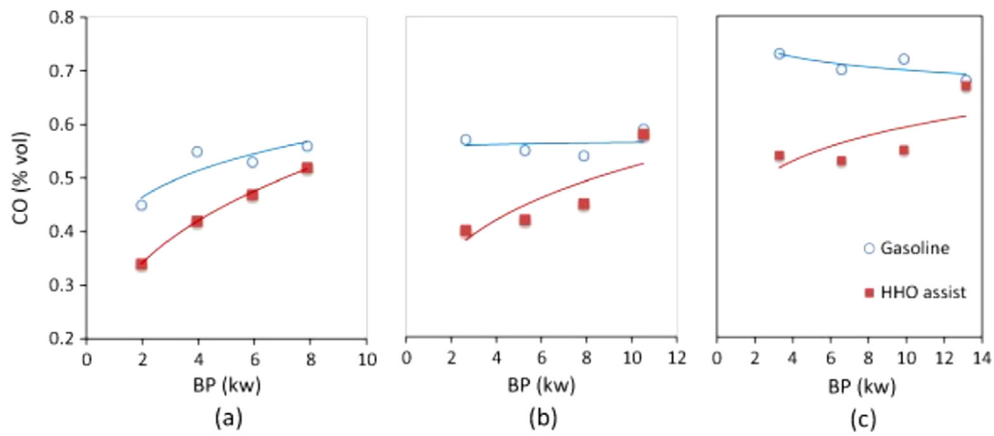

Fig. 19 – CO concentration of compared Škoda Felicia 2 [159].

measured vehicle, which led to an increase in the engine load by alternator. It cannot be clearly said that only HHO added itself would result in a decrease in CO concentration in the exhaust gases.

Fig. 20 shows the courses of HC concentration.

HHO addition and taking electric energy from the measured vehicle at the same time led to a mild decrease in HC concentration in the exhaust gases in relation to compared Škoda Felicia 2 (Fig. 20). Value of HC of compared Škoda Felicia 2 mentioned in the publication [159] is substantially higher than the value of HC of Škoda Felicia 2 from this article. The same applies to CO. As seen in Škoda Fabia, it can be presumed to have worse technical condition.

The results given in Figs. 19 and 20 can be compared to the results from Tables 11–13 since both measurements were performed under a certain engine load. It can be said that HHO addition caused an increase mainly of CO and HC at all driving speeds with both gasoline and E85 fuels. On the other hand, when taking electric energy from the measured vehicle, it led to a decrease, or to a retaining the same values as measured before HHO added. When comparing the data from Tables 11–13, and the data in Fig. 19 and 19, it can be concluded their sameness.

Significant reduction of CO by 53%, CO_2 by 38%, HC by almost 40%, and NO_x by 21% caused by HHO added itself is seen in publication [160], in which the research was made with a single-cylinder engine with low capacity of 0.07 dm^{-3}. Ratio of gasoline and HHO was 7:3. Similar results are also mentioned in publication [161], which described the measurement with the engine with a very low capacity of 0.197 dm^{-3} as well.

HHO and amount of fuel delivered into the engine

During the engine idling speed, the length of fuel injection was shortened by about 10% in relation to Škoda Felicia 2, Škoda Fabia and Kia Ceed after HHO added. This occurred independently from the fuel (Tables 5, 7 and 14). Higher decrease in fuel consumption, up to approximately by 20%, was reached with engines of substantially lower capacities [160–162]. The length of fuel injection after taking electric energy from the measured vehicles Škoda Felicia 2, Škoda Fabia and Kia Ceed extended by more than 20%. Thus, in relation to all three vehicles, HHO adding and taking electric energy from a vehicle during engine idling speed had the same effects. After HHO-being added into the Kia Sportage, the fuel injected remained at the same level, however, after taking electric energy, the amount of fuel injected increased by 100%. On the other hand, in relation to Kia Ceed, HHO adding did not shorten but extended the length of fuel injection (Table 15).

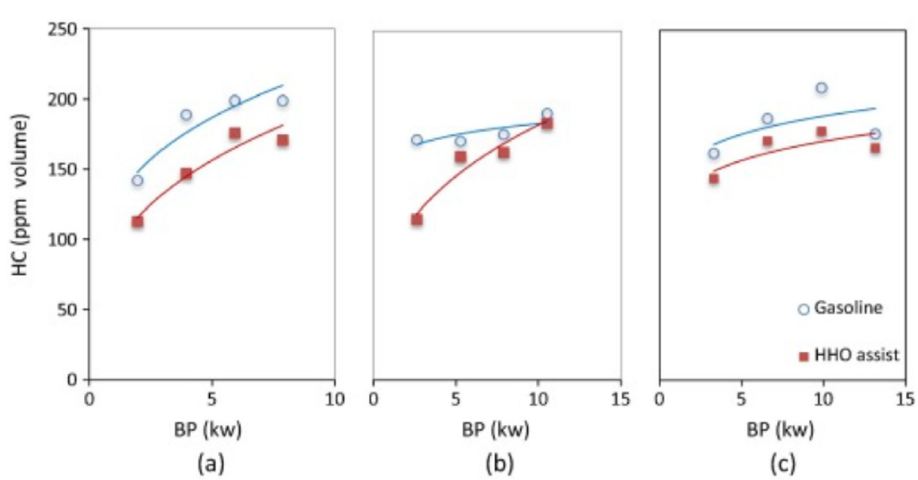

Fig. 20 – HC concentration of compared Škoda Felicia 2 [159].

Only in one case it led to shortening of injection length due to HHO addition. In all the other cases, besides one in which there was no change in injection length, HHO addition caused an extension in the length of fuel injection. Taking electric energy extended the injection period as well.

Conclusion

The purpose of this article was to determine the impact of HHO addition into the engine's intake manifold on selected vehicle parameters. On this point, several measurements have been made with five different vehicles.

HHO added into the engine's intake manifold brought a mild decrease in the engine power and torque in relation to all vehicles. Decrease in power was measured with vehicles fuelled by diesel, gasoline and E85. Taking electric energy from the measured vehicle, needed for the HHO generator to be operated, decreased the engine power and torque of all vehicles even more. HHO addition into the engine, under conditions given in this article, thus cannot be considered a way to increase the engine power. Difficulty of increasing the engine power and torque by HHO can be also caused by the fact that the HHO generator needs for its operation a relatively high supply of electric energy taken from a vehicle alternator. Such an increase in the engine power and torque would be probably able to be achieved at a substantially higher amount of HHO added, while HHO would be delivered from the container, not from the generator, using the electric engine from the vehicle. At the same time, it would be necessary to adjust the data in the engine control unit.

HHO addition had not a significant impact on composition of the exhaust gases. Concerning some components, like CO, HHO adding caused a mild decrease, however, in relation to NO_x, there was an increase measured. Smoke opacity slightly increased as well. Reducing the harmful components of the exhaust gases by HHO added cannot be achieved under the conditions defined in this article. Certain changes in composition of the exhaust gases, for instance seen in Table 6, can be seen as considerable. However, when assessing, it is necessary to take into consideration that some changes could be caused even without HHO with the same vehicle under the same conditions. As with the engine power and torque, in this case, it led to a greater change in composition of the exhaust gases caused by the engine load owing to the alternator after taking electric energy, not by HHO added. Increase in the engine load for affecting the composition of the exhaust gases, especially for decreasing of HC concentration and smoke opacity, is a commonly used, even illegal, method practiced during regular emissions inspection [76,123].

Cleaning effect of HHO has not been proven by the measurements in this article. Visual inspection did not bring any change after HHO addition for a few hours. Likewise, any significant change was not seen throughout the measurements focusing on composition of the exhaust gases.

The length of fuel injection, which is an equivalent to fuel consumption, decreased by an average of 10% after HHO added during the engine idling speed. Such a significant change in fuel consumption was measured with gasoline, E85 and LPG. Reduction of fuel consumption was measured by LPG system controlled as well as not controlled by the electronic control unit. However, after taking electric energy from the measured vehicle driven by the HHO generator, or when measuring while driving, HHO addition caused an increase in fuel consumption in all cases, respectively an increase in BSFC in Kia Ceed. Decreasing in fuel consumption via HHO shall not be considered as perspective in this case.

The engine control unit responded to the presence of HHO in the combustion space of the Kia Ceed engine by making the angle of pre-ignition smaller. This intervention of the engine control unit, although being evident in all measurement conditions with both gasoline and E85, have not affected the vehicle characteristics described above significantly. However, change in the value of pre-ignition together with change in the injection length may be a clear signal that the presence of HHO, respectively its effects, was recorded by the engine control unit, and affected the engine management. Conclusions of the producers and sellers of the commercial HHO generators that there is a significant improvement of vehicle parameters have not been proved by a comprehensive study. It may be recommended to the producers either to produce the HHO generators with a higher amount of HHO produced, or to produce the HHO generators with about 1 dm^{-3} min^{-1} of HHO for the engines with maximum volume up to 0.3 dm^{-3}. Based on the findings from this article, it may not be recommended to the fleet managers to mount the commercial HHO generators in their vehicles as well. Using the commercial HHO generators as a tool for reducing the air pollution by road vehicles, or for reducing the vehicle energy efficiency is inconceivable regarding the results from this article. It is also inconceivable to use the commercial HHO generator as a tool for increasing the engine power and torque, since all the experiments were performed with the HHO generator producing a higher amount of HHO than the commercial one. HHO in the amount of 2 dm^3 min^{-1} was insufficient in relation to the engines with cylinder capacity above 1 dm^3.

Despite the fact that the measurements from this article have not demonstrated unequivocally an improvement of selected vehicle parameters thanks to HHO adding, HHO plays an important role within the reduction of negative effects of road transport.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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