# IMPACT OF HYDROGEN INJECTION ON PERFORMANCE AND EMISSIONS OF TRACTOR DIESEL ENGINE OPERATING ON HVO

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**Abstract.** The use of alternative fuels is becoming increasingly relevant to meet environmental regulations. One of the most promising fuels is considered to be hydrotreated vegetable oil (HVO), which is available on the market and, according to previous studies, shows significant emission reductions. In recent years, the use of hydrogen in emission reduction from engines has also become increasingly relevant. In this regard, a study was conducted to understand the simultaneous use of these fuels, to check whether the ecological contribution could be even more significant, as well as to identify the impact on engine operation. Experimental tests were realized on a tractor Claas Ares 557ATX at 3 power take-off (PTO) shaft rotation frequencies (300, 450 and 600 $min^{-1}$) using diesel and hydrotreated vegetable oil (HVO) at different hydrogen injection volumes: 5 $l{\cdot}min^{-1}$, 30 $l{\cdot}min^{-1}$ and 50 $l{\cdot}min^{-1}$. A MAHA LPS ZW-500 power stand was used to load the tractor PTO shaft, determine power and torque, and maintain the PTO shaft speed. Fuel consumption was measured by laboratory scales, while emissions were determined using the AVL SESAM FTIR exhaust gas analytical system. As a result of the studies, no significant reduction in fuel consumption was observed, but an increase in torque and power on the PTO shaft was observed. With the addition of 5 $l{\cdot}min^{-1}$, a decrease in carbon dioxide ($CO_2$) emissions was observed. At the lowest H2 concentrations and PTO shaft speeds, a decrease in carbon monoxide (CO) was observed both when using HVO and conventional diesel fuel. Increasing the H2 concentration or PTO shaft rotation frequency resulted in an increase in CO emissions. At the same time, a decrease in hydrocarbon (HC) emissions was observed in all load modes when adding hydrogen gas.

**Keywords:** tractor, hydrotreated vegetable oil (HVO), hydrogen, power, emissions.

## Introduction

Nowadays, society is paying significant attention to improving the ecological situation in the field of transportation. In an attempt to improve the emission composition of existing internal combustion engines without affecting their efficiency, researchers have tested a wide variety of fuel types and combinations. Some of the fuels, such as biodiesel for diesel engines and ethanol for spark ignition engines, have been used in various blends for a long time in many countries around the world. Although the use of biodiesel in small blends makes a significant contribution to improving the ecological situation, it still retains significant limitations in terms of both physicochemical properties [1] and ecological improvements compared to another fuel produced from the same feedstock– hydrotreated vegetable oil (HVO).

HVO is known as an efficient drop-in fuel that can be used with other types of liquid fuels by blending, as also in dual-fuel mode in case of usage of gaseous fuels, like hydrogen. Different studies [2] show that the conversion of diesel engines for operation on diesel-hydrogen products is technically feasible and gives positive results in case of emissions and engine performance [3]. However, it must be taken into account that hydrogen cannot be used as a sole fuel in diesel engines without glow plug due to a high autoignition temperature, but it could be used with alternative liquid fuels in dual-fuel mode [4].

Different studies confirm that the use of the second fuel could more rapidly increase reduction of NOx emissions and improve engine performance. Such perspective could be realized by hydrogen showing positive impact on air quality as such products as hydrocarbons and carbon monoxide are not formed [5]. Besides of that hydrogen has many advantages, like high diffusion rate and flame speed, providing a more homogeneous air/fuel mixture and faster combustion process [6]. However, there are limited studies on the use of hydrogen with HVO, but some of these studies are briefly summarized below mostly dedicated to the use in dual-fuel mode.

Mukhtar [7] has tested single-cylinder diesel engine equipped with a common rail fuel injection system and a supercharger introducing hydrogen by a gas injector and injecting diesel fuel and HVO as pilot fuels. He found that smoke was lower using HVO as the pilot fuel in comparison to diesel, and also

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that HVO can be operated over a wider load range and at a wider hydrogen excess air ratio than in case of diesel fuel.

Pinto [8] also has chosen diesel and HVO as a pilot fuel in combination with compressed natural gas (CNG) and hydrogen testing on a commercial six-cylinder 150 kW diesel engine. While he found that CNG and hydrogen had no significant effect on the results of two pilot fuels, HVO showed a reduction in emissions of $CO_2$ by 6.3% and NOx by 4.3% and increase in the brake thermal efficiency by 6.5% and combustion efficiency by 0.1% in comparison to diesel fuel.

Szwaja [9] has tested Audi/VW TDI compression-ignition diesel engine with HVO and rapeseed methyl ester (RME) with injection of hydrogen into the intake manifold. Researchers concluded that hydrogen addition increases the maximum combustion pressure in the cylinder, as also significantly accelerates the combustion process in the premixed combustion phase.

De Morais [10] has tested and concluded that the use of hydrogen of up to 20% on energy basis is safe, and no modifications to engine settings are required.

Although the scope of research specifically with HVO is quite extensive, in combination with other types of fuel it is mainly used as a pilot fuel in dual-fuel mode. In this case, the novelty of this study is connected with assessment of the effects of hydrogen injection at different volumes fuelling tractor engines with HVO under different loads.

## Materials and methods

For this experiment, a Claas Ares 557ATX tractor was used. Parameters of this tractor are given in Table 1 [11]. The tractor was equipped with a Maha ZW500 power take-off dynamometer via the tractor PTO. The dynamometer has electronic strain gauge technology with measurable torque limit of 6600 Nm and maximum rotation speed of PTO of 2500 $min^{-1}$ [12]. The torque and power measurements from the dynamometer were repeated 3 times, with the average value used for further analysis. Fuel consumption was measured by measuring the weight of fuel consumed during the experiment for 30 seconds, resulting in a calculated amount of fuel consumed in $kg \cdot h^{-1}$. Fuel consumption measurements were repeated 3 times, with the average value used for further analysis. Fuel density was also measured, thus fuel consumption in $l \cdot h^{-1}$ can be calculated.

Table 1

**Claas Ares 557ATX tractor parameters**

| Parameter | Value |
|---|---|
| Engine model | John Deere DPS 4045 |
| Engine displacement, $cm^3$ | 4535 |
| Fuel delivery method | Mechanical high pressure fuel pump |
| Compression ratio | 17.2:1 |
| Number of cylinders | 4 |
| Engine type | Turbocharged, intercooled, in-line |
| Engine power, kW ($min^{-1}$) | 73.6 (2100 $min^{-1}$) |
| Engine torque, Nm ($min^{-1}$) | 419 (1400 $min^{-1}$) |
| Rear power take-off type | Independent |
| Power take-off clutch type | Wet disc |
| Power take-off rotation speed, $min^{-1}$ | 540/1000 |

Diesel fuel and hydrogenated vegetable oil (HVO) were used for this research. Both fuels used were purchased in the Circle K filling station, diesel fuel is compliant with the EN590 winter standard, meaning this fuel contains no biodiesel additives. The HVO fuel used was purchased at the same time, and it complies with the EN15940 standard for paraffinic diesel fuels. The hydrogen used in the experiments was supplied by Linde Gas Latvia, and is of 99.99% purity. The gas is filled in standard 50 litre high pressure tanks, at 200 bar pressure. Hydrogen density is 0.09 $g \cdot l^{-1}$. The gas was supplied to the tractor intake manifold via a hose connected through the air filter. For regulating the gas flow, a custom-made hydrogen flow regulator was used. It consists of a manual rotameter that is used for control and adjusting the gas flow, followed by a digital electronic flow meter, that is specifically calibrated to be used with hydrogen, that displays the flow rate and overall consumption (in $m^3$) of gas. This flow regulator is displayed in Fig. 1.

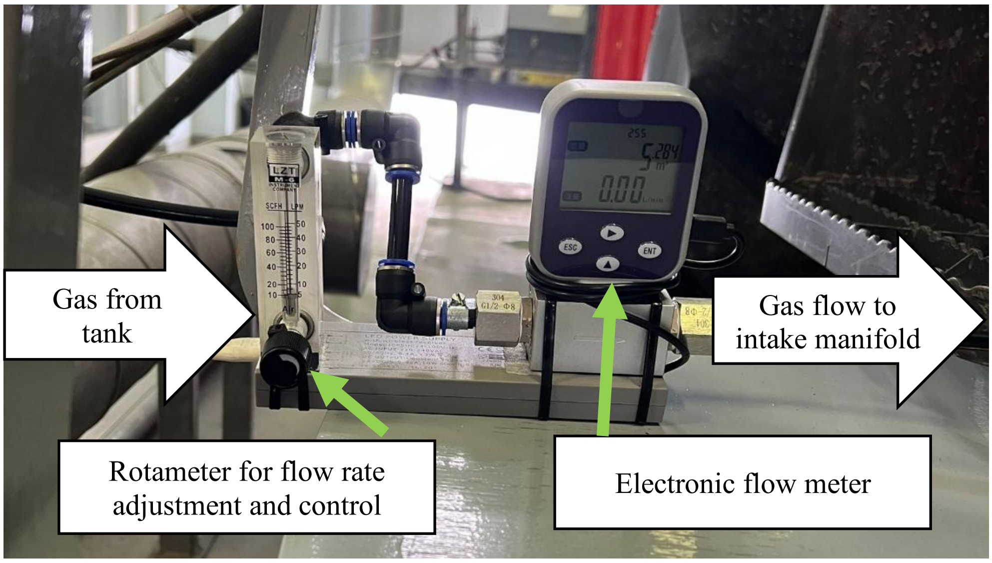

Fig. 1. **Hydrogen flow regulator**

For tractors, the engine speed (RPM) is proportional to the power take-off speed. For this experiment, PTO shaft rotation speeds of 300 $min^{-1}$, 450 $min^{-1}$ and 600 $min^{-1}$ were used to represent different load and engine speed conditions of the tractor. At 300 $min^{-1}$, the engine RPM and load is low, while at 600 $min^{-1}$, the engine is being operated at maximum load and RPM conditions. 450 $min^{-1}$ represents a middle position between both stages. As a result, a wide range of tractor engine speed conditions is being observed.

The flow rate of hydrogen gas was chosen 5 $l \cdot min^{-1}$, 30 $l \cdot min^{-1}$ and 50 $l \cdot min^{-1}$. The values were fixed during all repetitions of the experiments. 5 $l \cdot min^{-1}$ is a common flow rate of hydrogen gas generated via on-board hydrogen generators that use electricity from the tractor electrical charging system. It has been calculated that such flow rate corresponds to less than 1% of the energy consumed by the tractor engine. Because of this, the maximum flow rate was increased 10 times, resulting in the selected maximum of 50 $l \cdot min^{-1}$. The flow rate of 30 $l \cdot min^{-1}$ was chosen as an intermediate amount for hydrogen injection.

Emissions were measured using the AVL SESAM FTIR spectrometer that is capable of measuring more than 20 gases simultaneously. Most of the gases are measured directly, however, there are some exhaust gas components that are calculated by the exhaust gas measurement system during the data acquisition process. For this experiment, all of the emissions were measured, and more detailed analysis for regulated emissions (CO, $CO_2$, HC and $NO_x$) were conducted. The AVL SESAM FTIR spectrometer is capable of measuring exhaust gas components with a frequency of 1 Hz. The exhaust gas emission test was recorded for 30 seconds, meaning 30 data points were obtained during the experiment, with the average value being used for further analysis.

For all measured values, the average value is displayed in the graphs. For accuracy of the measurements, a statistical analysis was conducted, with the assumption that 95% of the results should be within 2 standard deviations ($\pm 2\sigma$) of the average value. Since the engine speed was observed from the tractor instrument cluster, 5% error is displayed.

## Results and discussion

The tests were conducted under the same conditions, resulting in precise measurements and results. The tests were performed at first with diesel fuel, then with the addition of hydrogen gas, followed by tests with HVO fuel and lastly with HVO fuel and added hydrogen additive. Performance factors such as power, torque and engine speed were recorded, with the PTO shaft speed being fixed. Fuel consumption was also measured. The regulated emissions were also recorded during these tests. The results in the engine power, torque, fuel consumption and engine speed are displayed in Fig. 2.

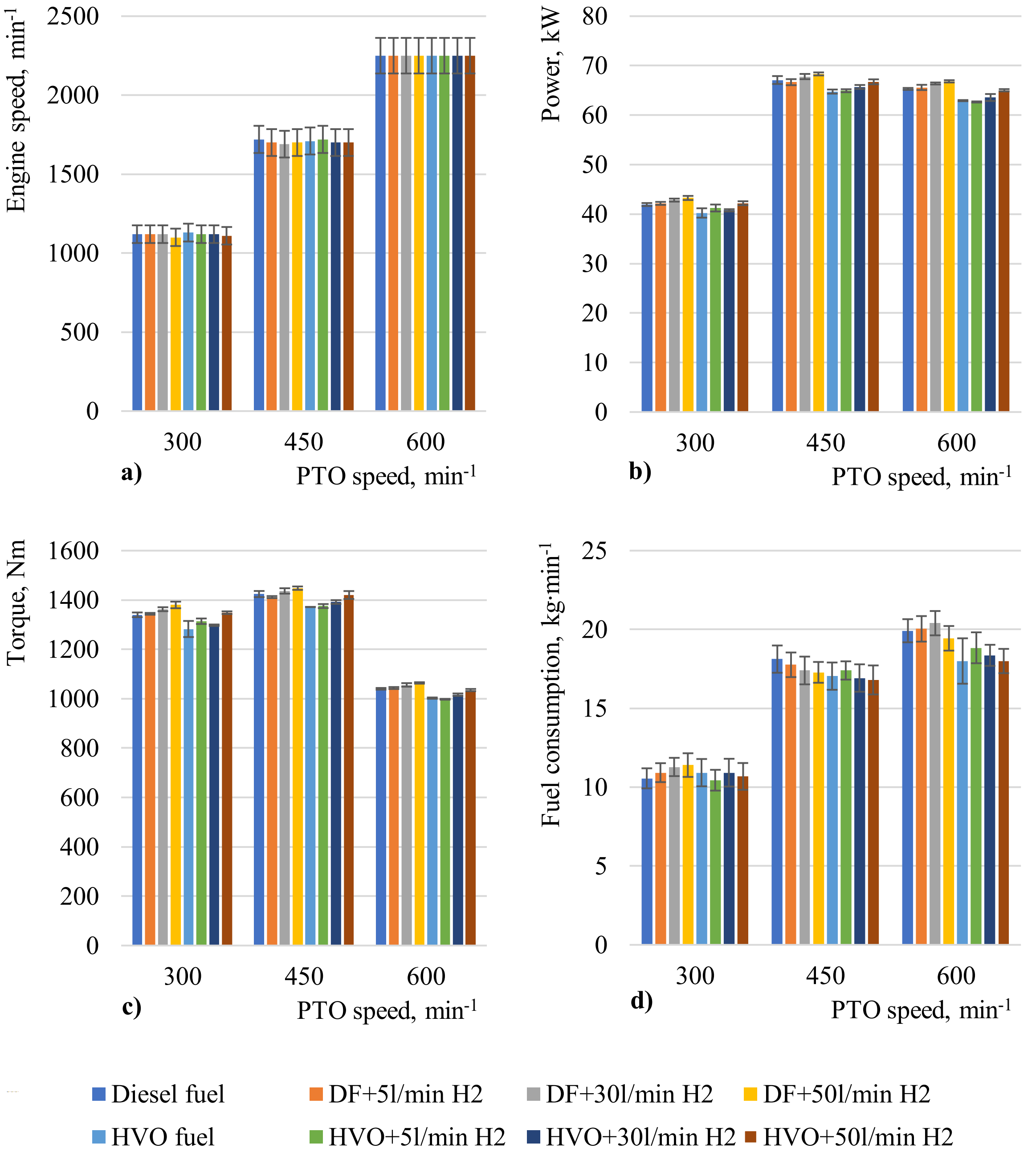

Fig. 2. **Tractor engine speed, torque, power and fuel consumption**

As it can be seen in the graphs in Fig. 2a, the engine speed during these tests was unchanged. This is due to the fact that the PTO shaft rotation speed is proportional to the engine speed, and since the PTO shaft speed was kept constant, the engine speed is also constant. When observing the output power in Fig. 2b, a slight increase in power (up to 3.2%) can be observed with the addition of hydrogen. Using HVO fuel, however, results in up to 4.82% reduction in overall output power when comparing to traditional diesel fuel. The trend can also be observed with the addition of hydrogen, where at the identical conditions, the power produced with HVO fuel and hydrogen is lower than that of diesel fuel and hydrogen. Similar trend may also be observed with the output torque, visible in Fig. 2c, where the addition of hydrogen results in up to 2.9% increase in the torque. The use of HVO fuel also reduces the output torque by up to 4.4%, when compared to diesel fuel with the same amount of hydrogen additive. The addition of hydrogen also impacts the tractor fuel consumption, as can be seen in Fig. 2d. It can be observed that the addition of hydrogen results in an increase in fuel consumption when using diesel fuel at 300 $min^{-1}$ of PTO speed. In these conditions, up to 7.9% or 0.84 $kg{\cdot}h^{-1}$ increase can be observed. When using HVO and hydrogen at the same PTO speed, fuel consumption fluctuates within

0.48 kg·h$^{-1}$. With the PTO speed of 450 min$^{-1}$, a decrease in fuel consumption can be observed when using diesel fuel and hydrogen additive, as well as HVO and hydrogen additive. In these conditions, up to 4.7% decrease can be observed with the addition of 50 l·min$^{-1}$ of hydrogen to diesel fuel. At PTO rotation speed of 600 min$^{-1}$, an increase, followed by a decrease in fuel consumption can be observed while using both diesel fuel and HVO fuel with the addition of hydrogen. At first, up to 2.5% increase can be observed, followed by up to 4.8% decrease. Overall, the use of HVO both with and without hydrogen additive has resulted in a decrease in fuel consumption. This can be explained with the fact that HVO has a higher heating value than diesel fuel, meaning that less fuel is required to achieve the same output results.

When comparing emission results, in Fig. 3a, it can be observed that hydrogen additive helps in reducing $CO_2$ emissions in 300 min$^{-1}$ PTO rotation speed. Although a slight increase in $CO_2$ emissions can be observed with 5 l·min$^{-1}$ of hydrogen added to both diesel fuel and HVO, in other test conditions, a reduction of up to 4% (for diesel fuel) and 9% (for HVO) can be observed. In other test conditions, $CO_2$ emissions remain relatively unchanged – the change in $CO_2$ emission value is within the error bar limits. When using HVO fuel, an overall decrease in $CO_2$ emissions of up to 5% can be observed. Similarly, when observing carbon monoxide emissions in Fig. 2b, it can be observed that the addition of hydrogen has relatively no impact on CO emissions at PTO speeds of 450 and 600 min$^{-1}$. At these conditions, the change in CO emissions is within the 2 standard deviations. At PTO speed of 300 min$^{-1}$, the addition of 5 l·min$^{-1}$ of hydrogen to both HVO fuel and diesel fuel results in a decrease in CO emissions of up to 25% in the case of HVO fuel. Increasing the hydrogen flow rate results in an increase in CO emissions of up to 77% when compared to fuels without added hydrogen. When observing the hydrocarbon results obtained and shown in Fig. 2c, the addition of hydrogen results in a decrease in HC emissions in all PTO rotation speeds, resulting in up to 99% reduction in HC emissions. When observing HC results with using HVO fuel, an overall decrease in HC emissions can be observed, however, the best results can be observed with the addition of 30 l·min$^{-1}$ of hydrogen, where a reduction in HC emissions of up to 70% can be observed. Adding 50 l·min$^{-1}$ of hydrogen results in a small increase over the results obtained with 30 l·min$^{-1}$ of hydrogen, but the results are still lower than using diesel fuel or HVO fuel only. Overall, it can be observed that the addition of HVO results in higher HC emissions than when using regular diesel fuel. When observing NOx emissions in Fig. 2d, adding hydrogen has resulted in an increase in NOx emissions in 450 and 600 min$^{-1}$ PTO speeds with both HVO fuel and diesel fuel, with an exception of using HVO and 30 l·min$^{-1}$ of hydrogen, where a slight decrease of 1% can be observed. With other concentrations of gas, up to 9.2% increase can be observed. At PTO rotation speed of 300 min$^{-1}$, using hydrogen in combination with diesel fuel results in an increase of up to 5.3% in NOx emissions with the flow rate of up to 30 l·min$^{-1}$ of hydrogen, whereas adding 50 l·min$^{-1}$ of hydrogen to diesel fuel results in NOx emissions falling below those of diesel fuel only by 1.2%. When adding hydrogen to HVO, adding 5 l·min$^{-1}$ of gas results in NOx concentration reduction of 3.2%. Adding more hydrogen results in NOx emission increase to the level of HVO fuel only, but adding 50 l·min$^{-1}$ of hydrogen results in 6% decrease in NOx emissions when compared to HVO fuel only.

For this engine, the main possible factor of no significant impact on emissions other than HC is due to the method of fuel injection. In this John Deere DPS 4045 engine, fuel is injected via a mechanical high pressure fuel pump. With this type of fuel injection, the injection quantity is fixed depending on the engine RPM. In this case, with the selected PTO rotation speeds, engine speeds observed were unchanged, meaning the injected fuel quantity was also unchanged. Due to the fact that the added hydrogen is an extra fuel, the increase in the engine power and torque can be explained. Similarly, since the density of HVO fuel is lower than that of diesel fuel (0.784 kg·l$^{-1}$ for HVO and 0.839 kg·l$^{-1}$ for diesel fuel, measured during the experiment), the overall amount by mass of HVO fuel injected is lower than that of diesel fuel, as the fuel pump injects fuel by volume. This could be a potential cause of several parameters being lower when using HVO fuel in place of diesel fuel.

When observing emissions, the relatively unchanged amount of diesel fuel injected can be the cause of stable $CO_2$ emission quantities, as $CO_2$ emissions are dependent on the carbon contents in fuel. Since hydrogen is supplied to the intake manifold, the addition of hydrogen can result in a decrease in intake air, that could explain the increase of CO emissions due to a lack of oxygen at low engine speed, accompanying low PTO rotation speeds.

Since the addition of hydrogen increases the temperature and maximum pressure in the combustion chamber [13], the NOx emissions have a tendency to increase. This is observed also in the research [13].

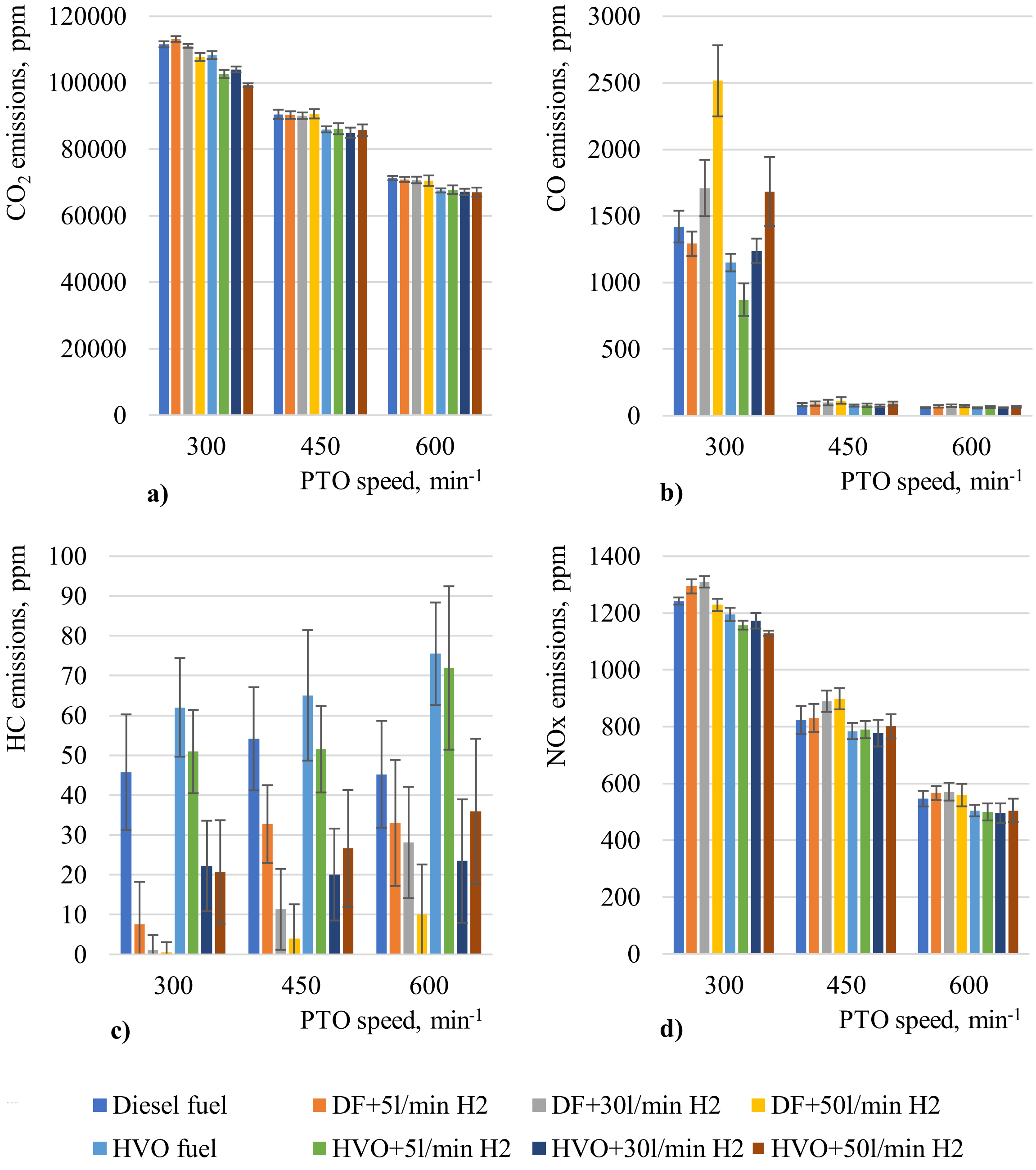

Fig. 3. **Tractor exhaust gas emissions**

Overall, it was observed that the emissions tend to decrease with the increase of the tractor PTO speed from 300 to 450 and 600 min$^{-1}$, both with diesel fuel and HVO. A possible cause of this could be the increase in the engine speed, and, subsequentially, exhaust gas temperature, that aids the catalytic converter in reaching its optimal temperature and providing a more efficient reduction in exhaust gas emissions.

The main factor to be analysed is the noticeable decrease in HC emissions. Since hydrocarbon emissions are an indicator of unfinished combustion and non-complete oxidation of fuel, it can be said that the addition of hydrogen even in small quantities of only 5 l·min$^{-1}$ can massively improve the combustion process, with increased concentration of 50 l·min$^{-1}$ having better effect on HC emissions in combination with diesel fuel, and 30 l·min$^{-1}$ having better overall effects in combination with HVO fuel.

It should be noted that the concentration of hydrogen in relation to diesel fuel per mass is relatively small. The maximum concentration of hydrogen can be achieved in the test conditions with the lowest fuel consumption and largest hydrogen flow rate – with PTO rotation speed of 300 $min^{-1}$ with the addition of 50 $l \cdot min^{-1}$ of hydrogen. In this case, the amount of hydrogen injected is 4.5 $g \cdot min^{-1}$, or 0.27 $kg \cdot h^{-1}$. When comparing this quantity to diesel fuel consumption that at its smallest is 10.56 $kg \cdot h^{-1}$, the energy amount provided by hydrogen is approximately 2.5% per mass or 7% on energy basis (since the heating value of hydrogen is approximately 2.8 times larger than that of diesel fuel, if lower heating value of H2, approximately 120 $MJ \cdot kg^{-1}$, is compared to lower heating value of diesel fuel at 42.9 $MJ \cdot kg^{-1}$).

## Conclusions

1. The addition of hydrogen to the tractor engine intake manifold can cause up to 99% reduction in hydrocarbon emissions and resulting in a more complete combustion of supplied fuel.
2. The addition of hydrogen does not have significant impact on the engine rotation speed, and can increase the tractor output power and torque on the PTO shaft.
3. The addition of hydrogen to an internal combustion diesel engine results in an increase of $NO_x$ emissions of up to 9.2% when using diesel fuel, however, adding hydrogen to HVO fuel, the $NO_x$ emissions have a tendency to remain stable or decrease in some cases.
4. When using HVO fuel in place of diesel fuel, it can be observed that $CO_2$, CO and $NO_x$ emissions are reduced, but so is the PTO output power and torque. The fuel consumption is also reduced.
5. The hydrogen concentration used during the experiments does not exceed 2.5% on mass basis or 7% on energy basis, meaning that the used concentration of hydrogen additive does not negatively affect the engine operating life.

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## Author contributions

Conceptualization, K.A., R.S. and G.K.; methodology, K.A., R.S. and G.K.; validation, K.A., R.S. and A.B; formal analysis, K.A., R.S. and A.B.; investigation, K.A., R.S., G.K. and A.B.; data curation, K.A., R.S. an G.K.; writing – original draft preparation, K.A., R.S., G.K. and A.B.; writing – review and editing, K.A. and R.S.; visualization, K.A., R.S. and G.K.; funding acquisition, K.A. All authors have read and agreed to the published version of the manuscript.

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