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MONITORING OF BASIC PARAMETERS FOR SELECTIVE CATALYTIC REDUCTION SYSTEM USED IN AN AGRICULTURAL TRACTOR

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Abstract

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Presented paper describes monitoring of basic parameters for selective catalytic reduction (SCR) system used in an agricultural tractor. SCR systems are used to reduce emissions of nitrogen oxides (NO_x) produced by combustion of fuel. The usage of SCR catalytic converters entails certain disadvantages in the use of reducing agent and the necessity of suitable operating conditions to achieve optimum efficiency of the catalytic converter. This paper aims to predict consumption of AdBlue depending on the temperature of SCR catalytic converter, which reflects the engine load and monitoring the effectiveness of SCR catalytic converter when operating a tractor engine with a maximum dose of fuel. To fulfill those aims, the measurements have been performed on the Case Puma 185 CVX agricultural tractor. As the measurement results indicate, the lowest NO_x emissions correspond to high consumption of AdBlue. Other studies imply that the catalytic converter operates at optimal operating temperature and with the highest efficiency of NO_x emission reduction. The effectiveness of NO_x emission reduction is thus affected not only by quantity of injected reagent but also by catalytic converter thermal load. Further measurement results indicate that the lowest amount of emissions of NO_x (and the highest efficiency rate) is achieved by catalytic converter in a range in which the engine operates with the highest engine efficiency.

Keywords: SCR Catalytic Converter, AdBlue, NOx Emissions

INTRODUCTION

The conversion of fuel chemical energy into mechanical work is a complex process with multiple aspects and products. Many of them are harmful not only to the environment but also to human health. For these reasons not only the European Union but also other countries of the world introduce standards "forcing" the manufacturers of internal combustion engines to develop new technologies and devices complying to strict emission limits. There are numerous aspects affecting harmful exhaust gas emissions. They include thermal, shape, and vortical properties of combustion chamber. Method and quality of fuel injection is crucial as well. However, despite the usage of modern concepts of internal combustion engines, it is not possible to achieve relevant emission standards without additional flue gas processing. The basic methods of flue gas processing include SCR catalytic converters (*Vlk, 2006*). A SCR (Selective Catalytic Reduction) catalytic converter is a device designed to reduce the concentration of nitrogen oxides (NO_X) in exhaust gases.

Nitrogen oxides are formed by oxidation of nitrogen delivered to the combustion chamber in the intake air together with oxygen intended for the fuel oxidation or oxygen contained in the fuel (especially in bio-produced fuel types). Nitrogen oxides include nitric oxide (NO), nitrous oxide (N_2O), and nitrogen dioxide (NO_2). They are formed at high temperatures and pressures in the combustion chamber and their amount is therefore dependent on the mixture richness and the oxygen concentration. Nitrogen oxide emissions reach maximum when the diesel engine operates with the highest efficiency and the concentrations of HC and CO emissions are very low (*Šmerda and Čupera, 2011*).

One of the ways to reduce the combustion temperature and pressure is delayed fuel injection. However, this approach results in increased production of HC and solid particle emissions. In order to operate the engine with the highest possible engine efficiency, an additional flue gas processing is required to reduce quantity of NO_x emissions released into the atmosphere. By using ammonia NH_3 reacting with nitrogen oxides, the oxides convert into nitrogen N_2 and water vapor H_2O within the SCR catalytic converter. In this process, ammonia acts a reduction agent. Due to its high toxicity it is supplied to the exhaust piping as mixture of urea and water. Commercial designation of this mixture is "AdBlue". The AdBlue contains 32.5% of urea – $CO(NH_2)_2$. The rest is demineralized water which is evaporated after injection into the exhaust piping and acts in further chemical reactions (*Bauer et al., 2013*). AdBlue injection and evaporation are essential in terms of resulting efficiency of the entire SCR system (*Grout et al., 2013*). Ammonia enters the exhaust piping after thermolysis of urea and subsequent hydrolysis of resulting products. Chemical reactions of nitrogen oxides with ammonia follow the following formulas:

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O \qquad (1)$$

$$NO + NO_2 + 2\,NH_3 \rightarrow 2\,N_2 + 3\,H_2O \qquad (2)$$

$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2 + 12\,H_2O. \qquad (3)$$

AdBlue dosage is performed according to the engine rpm and quantity of injected fuel. In addition to these parameters, an adjustment is made according to the content of NO_x (catalytic converter intake/outlet port values), exhaust gases temperature, etc. Injected quantity of AdBlue ranges between 0.1 and 10% relative to current fuel consumption (*Bauer et al., 2013*).

This paper describes attempts to predict consumption of AdBlue depending on the engine load. Also, attention was paid to monitoring the effectiveness of SCR catalytic converter in tractor engine modes with maximum fuel supply.

MATERIALS AND METHODS

Experimental measurements were performed with the Case Puma 185 CVX agricultural tractor. For technical specifications of tested tractor and engine, see Tab. I. All measurements have been performed in laboratory conditions at the Department of Technology and Automobile Transport at the Mendel University in Brno (see Fig. 1).

Fig. 2 shows individual components of the SCR system used on the Case Puma 185 CVX Tractor.

I: *Technical Parameters of Tested Tractor*

Tractor Parameter	Value
Tractor manufacturer	Case IH
Model	Puma 185 CVX
Year of manufacture	2012
Moto hours	8
Engine	
Type	diesel
Number of cylinders	6
Engine displacement	6724 cm3
Rated power (dle ECE R120)	136 kW
Rated power with boost (dle ECE R120)	162 kW
Maximum torque	862 N.m
Maximum torque with boost	1019 N.m
Fuel injection system	Common Rail

In the experiment, the following measuring equipment was used:

Electrical (eddy-current) dynamometer was used for engine load and torque measurement. The dynamometer was connected to the tractor via the rear output shaft (see Fig. 1). The parameters of the dynamometer include: maximum braking torque (1,592 Nm), maximum rpm (3,000 min^{-1}), and maximum braking power (500 kW).

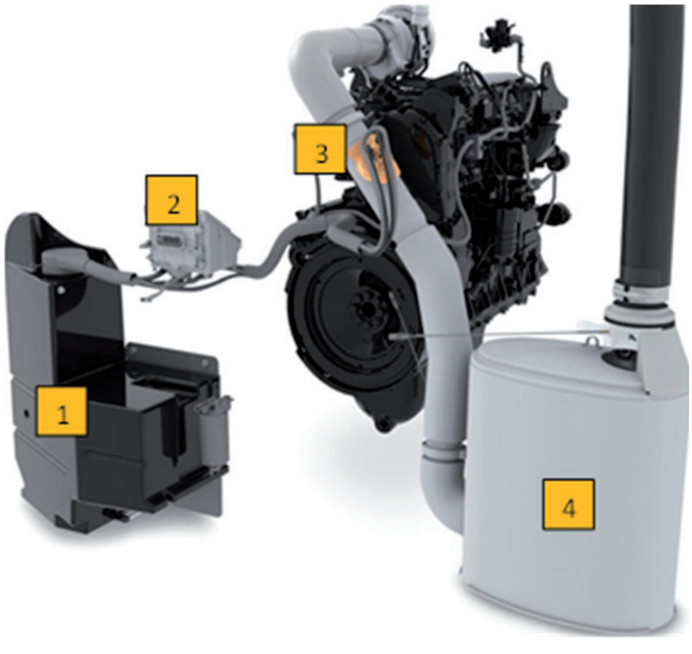
An analyzer Bosch type ESA 3.250 was used to measure concentration of NO_x emissions at catalytic converter output side. Data from the analyzer was uploaded via the Ethernet network to the test room control computer.

Data from the CAN-Bus network was used for several parameters such as hourly fuel consumption, consumption of AdBlue reducing agent, AdBlue temperature, SCR catalytic converter, and fuel temperature. Proprietary software written for the purpose of measurement in LabVIEW programming environment by the National Instrument Company was used for processing and subsequent data upload to the test room control computer. The software interface is shown in Fig. 3.

All measurements were made according to the OECD methodology and in compliance with the allowed deviations as listed in the ČSN ISO 789-1 standard.

Recording sessions were performed in steady engine running modes with maximum fuel delivery in range from 950 to 2,100 rpm. The values were recorded incrementally in stages (step 100 rpm). At every stage the engine has been loaded using the eddy-current dynamometer. After common stabilization of the measured values (usually 30 seconds) the average value was calculated. All the values have been recorded with sampling frequency of 18 Hz. The entire measurement was done automatically using the high-end test site equipment.

1: *The Case Puma 185 CVX tractor in Vehicle Laboratories of the Department of Technology and Automobile Transport, Mendel University in Brno*



2: *Components of the SCR system (CASE IH); 1 – Heated AdBlue tank, 2 – System control unit with pump, 3 – AdBlue injection nozzle, 4 – SCR catalytic converter with intake/outlet port NOx sensors*

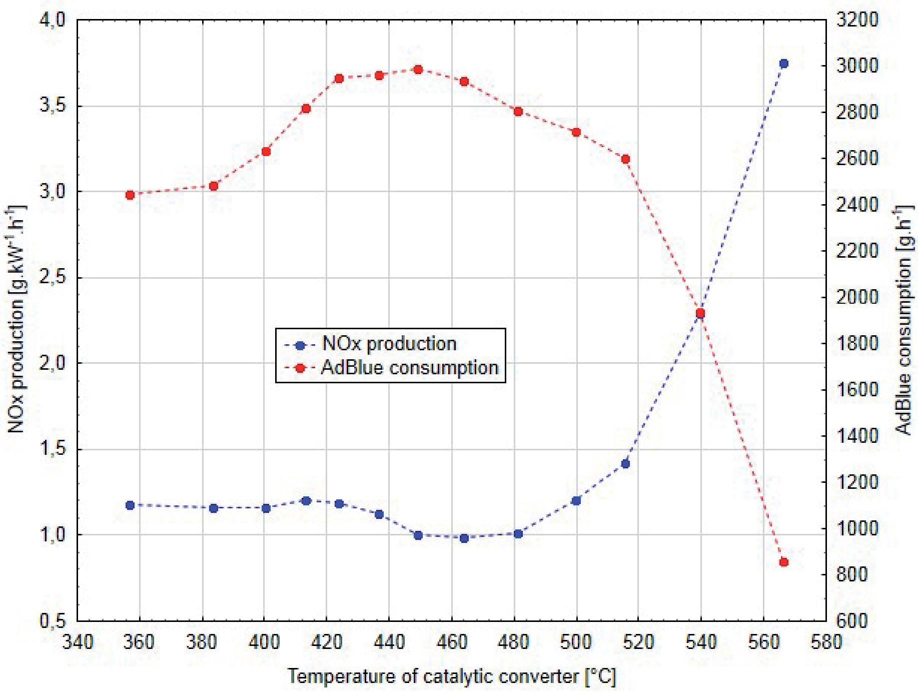
RESULTS AND DISCUSSION

Acquired data served for graphical dependencies and detailed analysis of results. The basic goal was to find relationships between engine load, AdBlue consumption, and SCR catalytic converter efficiency.

Fig. 4 shows dependence of NO_x emissions emitted into the atmosphere, AdBlue consumption, and SCR catalytic converter temperature.

As already mentioned in the introduction section, NO_x emissions are largely dependent on the combustion temperature and pressure. This presumption was confirmed by the measured values. As seen in Fig. 4, from a certain temperature of catalytic converter, the NO_x concentration rises. SCR catalytic converter temperature has a high correlation with the exhaust gases temperature and/or combustion temperature that represents the

3: *Software interface for easy viewing of measured values from the CAN-Bus network*

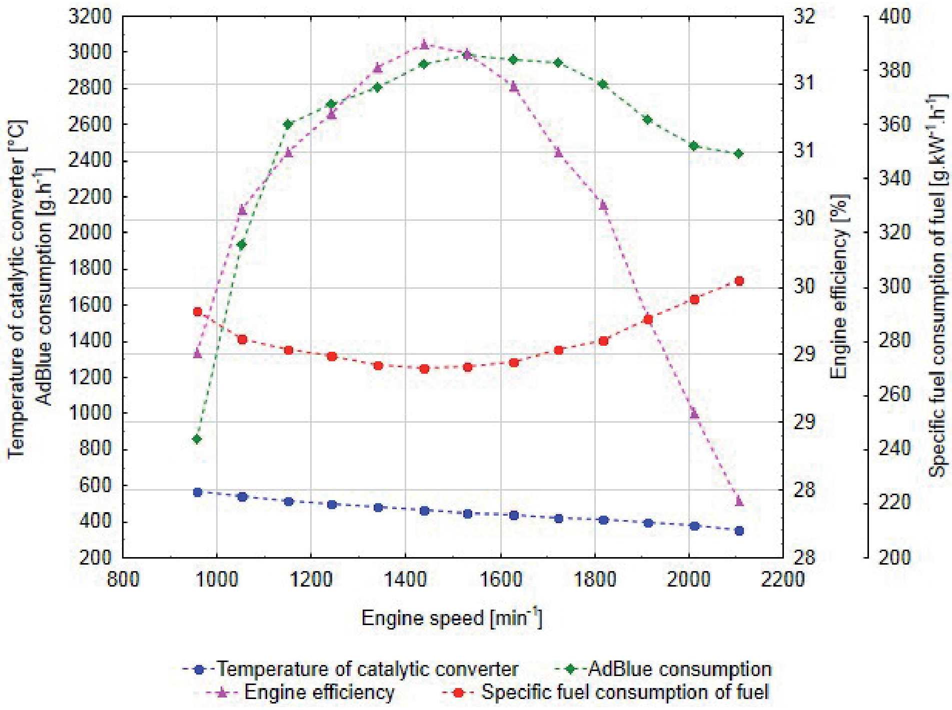


4: *Dependence of NO_x Emissions, AdBlue Consumption, and SCR Catalytic Converter Temperature*

engine load. Graphical relationships clearly indicate that from the catalyst temperature of approximately 480 °C, injected AdBlue dose was lower. The decrease of injected AdBlue dose resulted in high NO_x emissions.

The catalytic converter operating temperature ranges up to approximately 450 °C. If its temperature exceeds the specified limit, the conversion efficiency weakens (*Brož & Trnka, 2009*). Parallel reactions featuring imperfect reactions of ammonia NH_3 with nitrogen oxides NOx take place in the catalytic converter under high temperature conditions. The high dose of urea would therefore cause the release of free ammonia into the atmosphere and also the formation of dangerous compounds that might clog active surfaces of catalytic converter and reduce its operation (*Javed et al., 2007; Radivojevic, 1998*). For this reason, the AdBlue dose is intentionally reduced with increasing temperature.

SCR catalytic converter effectiveness under variable operating temperatures was addressed in several studies, for example (*Kobayashi & Miyoshi, 2007*). Their measurement results are comparable to results achieved in this experiment. The results



5: *Dependence of selected parameters and engine rpm*

of their study indicate that the highest conversion efficiency is reached in the catalytic converter temperature ranging from 450 °C to 500 °C. Our results imply that the temperature range features also the highest decrease in NO_x emissions.

Differences in the quantity of injected AdBlue dose are mainly caused by different engine loads, by different combustion temperature, and pressures as well. Thus, injected dose is optimally adapted to the amount of produced emissions detected by NO_x sensors. These sensors were present on the examined tractor type. Their purpose was to keep the parameters within an optimal range. The sensors were mounted at SCR catalytic converter intake/outlet ports and provided useful feedback. As further measurement results indicate, the highest consumption of AdBlue and thus the highest decrease of NO_x emissions were reached when engine operated with high engine efficiency (see Fig. 5).

As indicated by results of this study, at rpm of 1,400 min^{-1}, the engine has the highest engine efficiency. This represents the most efficient conversion of fuel chemical energy into mechanical work. This mode is also characterized by high torque, combustion temperature, and area with the lowest specific fuel consumption level (see Fig. 5). Obviously, it the area in which the tractor engine will be operated most frequently.

Fig. 5 also shows that the highest temperature of SCR catalytic converter and therefore high NO_x emissions happen at maximum load of tractor engine at low engine rpm. However, this mode will not be commonly used due to very low engine power.

CONCLUSION

Negative impact of exhaust gases on the environment and on human health requires implementation of emission limits for all internal combustion engines. For agricultural and forestry tractors, these limits are listed in *Directive 2000/25/EC* with Amendment *2005/13/EC* (measures against the emission of gaseous and particulate pollutants by engines intended to power agricultural or forestry tractors). Emission limits are established for determined range of engine power and validity period and are given in specific units ($g \cdot kW^{-1} \cdot h^{-1}$). With increasing legislative pressure to reduce emissions, engine manufacturers are constantly forced to develop new technologies and devices to reach relevant emission limits. In addition to particulate filters, EGR valves, three-port, hopper, and oxidation catalytic converters, so called SCR catalytic converters have been used as well. Results of various studies indicate that SCR systems help very effectively to reach compliance with relevant regulations for NO_x emissions. These systems are widely used in trucks and tractors. With respect to strict emission standards for passenger cars, the usage of these systems can be anticipated in these vehicles As well.

Measurements and studies confirm that optimal function of SCR catalytic converters is achieved only in certain engine operation modes. At high loads and very low rpm, the efficiency of SCR system will significantly decrease. From this perspective, it is necessary to take into consideration the manufacturer's instructions how to operate the engine in economic and ecological terms.

SUMMARY

This article aims to predict consumption of AdBlue depending on the temperature of SCR catalytic converter, which reflects the engine load. The effectiveness of SCR catalytic converter was monitored in periods when the tractor engine ran with a maximum dose of fuel. Complex measurements were performed with the Case Puma 185 CVX tractor in vehicle laboratories at Department of Technology and Automobile Transport, Mendel University in Brno. Engine loading was performed using electrical (eddy-current) dynamometer connected to tractor engine via the rear output shaft. Bosch ESA 3.250 analyzer was used for measuring the concentration of NO_x emissions at the catalytic converter outlet. Data from the CAN-Bus network included hourly fuel consumption, AdBlue consumption, AdBlue temperature, SCR catalytic converter, and fuel temperature. All measurements were made according to the OECD methodology with the maximum fuel dose. The basic parameters evaluated included AdBlue consumption, AdBlue temperature, NO_x emissions, and SCR catalytic converter temperature. Graphical plot of parameter dependencies and in-depth analysis of data were carried out. Attention was paid especially to relationships between engine load, AdBlue consumption, and SCR catalytic converter efficiency. Nitrogen oxide emissions depend on the combustion temperature and pressure. This assumption was confirmed by measured values. With increasing temperature of SCR catalytic converter, NO_x rise. SCR catalytic converter temperature showed high correlation with exhaust gas temperature, thus reflecting the engine load. The results revealed that when the catalyst temperature reached approximately 480 °C, injected dose of reducing agent was lower. Smaller AdBlue dose resulted in increase of NO_x emissions. The catalytic converter operating temperature ranges up to approximately 450 °C. If the temperature exceeds the specified limit, the conversion efficiency weakens. As proved by other studies, the most efficient conversion occurs when the catalytic converter temperature ranges from 450 °C to 500 °C. This fact was confirmed by our results as well.

Differences in the quantity of injected AdBlue dose are mainly caused by different engine loads, different combustion temperature, and variable pressure. As further measurement results indicate, the highest consumption of AdBlue and thus the highest decrease of NO_x emissions were reached when engine operated with high engine efficiency.

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