

Contribution of High Accuracy Temperature Sensors Towards Fuel Economy and Robust Calibration

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ABSTRACT

Tighter emission limits are discussed and established around the world to improve quality of the air we breathe. In order to control global warming, authorities ask for lower CO₂ emissions from combustion engines. Lots of efforts are done to reduce engine out emissions and/or reduce remaining by suitable after treatment systems.

Watlow, among others, a manufacturer of high accurate, active temperature sensor ExactSense™, wanted to understand if temperature sensor accuracy can have an influence on fuel consumption (FC). For this purpose a numerical approach was chosen where several non-road driving cycles (NRTCs) were simulated with the data base of a typical Stage IV heavy duty diesel engine. The engine is equipped with an exhaust gas after treatment system consisting of a DOC, CDPF and an SCR. In this work scope, the investigations shall be restricted to the FC benefits obtained in the active and passive DPF regeneration. The numerical investigations were performed using DPF soot loading and oxidation models using a commercially available software program.

The passive regeneration by NO₂ oxidation (CRT effect) and the active regeneration by O₂ oxidation are modeled using the temperature sensors installed upstream and downstream DOC, along with other signals as inputs. The modeled soot load was used to trigger the activation and deactivation of the heat mode for active regeneration. The models used to calculate NO₂ formation over the DOC and the CDPF, as well as those used for NO₂ and O₂ oxidation in the CDPF are comparable to commonly used models in engine control units (ECUs).

Temperature sensor tolerances show significant influences on active regeneration durations, resulting in noticeable fuel savings benefit for high accuracy temperature sensors in the NRTC. Depending on the regeneration intervals and therefore depending on the application this potential might be considerable. Further it has been shown that high accuracies in temperature measurement lead to a more robust model calibration.

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INTRODUCTION

Air quality improvement and global warming are major topics in our world today. USA and Europe took the lead and are launching US non-road Tier IV, Euro non-road Stage IV and on-road Euro VI emission limits. Other countries are following suit to tighten the limits for the emission of harmful substances. Lower CO₂ emission and fuel consumption limits are imposed by regulatory agencies to avoid further global warming and energy dependency. To achieve these stringent regulations controls and diagnostics of powertrain, vehicle or equipment systems require better and more frequent control of the components and their performance, in certification tests and real world driving cycles. Unfortunately all this measures do increase not only the initial cost of the vehicles but also the operational costs. Those are clear drawbacks in a very competitive market sector and small advantages in one or the other of the topics above can influence the customer decision which vehicle to buy. Therefore engineers are working to find system solution approaches to come to the best compromise of all requests and challenges.

One component which is already in use today, but its real potential is barely used is the temperature sensor.

Watlow, among others, a manufacturer of high accurate, active temperature sensor ExactSense™ (ES), evaluated the impact of the temperature sensor accuracy on the fuel consumption of single aftertreatment system (DPF and SCR) during various test cycles. In addition the effects on sub-components have been studied (oil dilution effect, DOC lifetime and diagnosis).

For this purpose a numerical approach was chosen where several non-road transient cycles (NRTC) were simulated with the data base of a typical Stage IV heavy duty diesel engine. The engine was equipped with an exhaust gas after treatment system consisting of a Diesel oxidation catalyst (DOC), catalyzed Diesel particulate filter (CDPF) and a selective catalytic reduction catalyst (SCR)

The details and results of this investigation will be presented on the following pages.

SIMULATION TOOL & INVESTIGATION METHODS

Simulation Tool

The simulations were executed by FEV with FEV's in-house developed 1D-simulation tool PROcal-EAS. This tool provides combined simulation of combustion engine and the applied aftertreatment system (EATS) for any transient operation cycle of the engine (Figure 1). The engine model is based on extensive empirical engine mapping of the engine operating conditions. With given engine and load conditions, the engine out exhaust emissions and temperature profile can be modeled. This vector information is fed to the EATS model. For each EATS component DOC, CDPF and SCR a common

library provides a suitable sub-model incl. dosing controls for urea dosing and DPF regeneration operation. The parameterization of these sub-models was done by state of art catalyst properties.

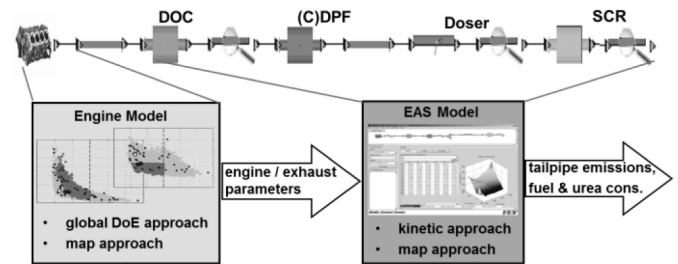


Figure 1. Simulation Tool FEV PROcal-EAS

As result of the integrated simulation the tailpipe emissions, temperature profiles, engine fuel consumption as well as urea consumption is obtained. For investigations regarding impacts by DPF the soot load of the filter was evaluated.

Engine and EATS Layout

As virtual engine a state of the art medium range heavy duty engine capable of achieving non-road Tier 4 final and on-road EU VI regulations was used (Table 1).

Table 1. Specification of the "virtual" engine

Engine displacement	ca. 7000 ccm
Engine power	ca. 200 kW
Max. injection pressure	2000 bar
EATS	DOC, CDPF, Va-SCR
Target applications	On- and off-road heavy duty
Target legislation	US Tier 4F / EU Stage IV & Euro VI

Besides the most fuel economic operation mode (normal mode) the engines features a SCR heat mode, required for achieving the demanded SCR efficiencies. It also features a DPF regeneration mode for removing the trapped particulates off the filter by active regeneration. As shown in Figure 2, the EATS consists of a DOC enabling high NO₂ production for passive regeneration, a common low backpressure cordierite DPF and a vanadium based SCR including a suitable urea dosing control unit.

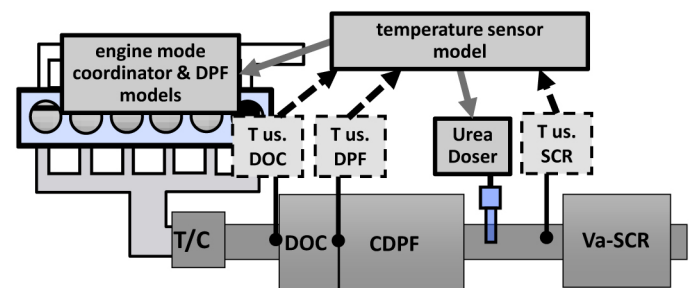


Figure 2. Engine and EATS layout w/ sensor locations

In the focus of the presented investigations are the three temperature sensors in the exhaust system: A) upstream of the DOC, B) downstream from the DOC and upstream of the DPF and C) upstream of the SCR. For each sensor the simulated temperature is fed to the temperature sensor model that provides a modified temperature signal according to the different sensor characteristics to the engine control - such as mode coordinator, urea dosing unit and DPF models.

Investigated Operating Cycles

In total four different transient operating cycles have been considered for the temperature sensor investigations. In the following figures the frequency of operation is indicated within the relative engine operating map by bubble size and color. The operating cycle is the well-known off-road certification cycle NRTC covering almost the entire engine operating range (Figure 3). This cycle is merged from different applications and consequently represents a “synthetic” average of those only.

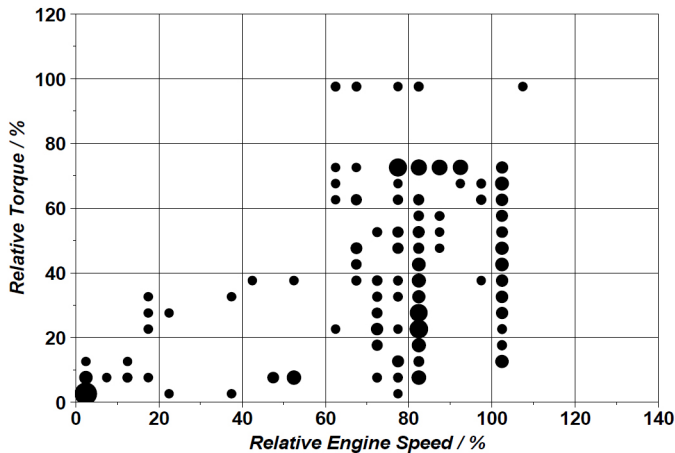


Figure 3. Frequency distribution of NRTC

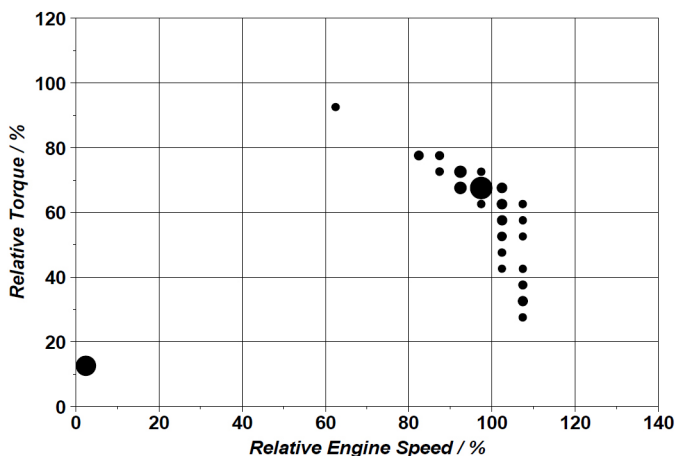


Figure 4. Frequency distribution of Customer Cycle 1

In order to have more significant results of real world operation three more customer cycles were added to the simulation matrix. The customer cycle 1 is operating in a very small area

of the engine map mostly at high speed and medium load typical for high performance construction machinery as shown in Figure 4.

The operating points of customer Cycle 2 are widely distributed over the entire map. The typical characteristics of this cycle are high frequencies in areas of the low-end torque and rated power combined with significant share of idling. This is common operating cycle for material handling machinery. The operating area of this cycle is depicted in Figure 5.

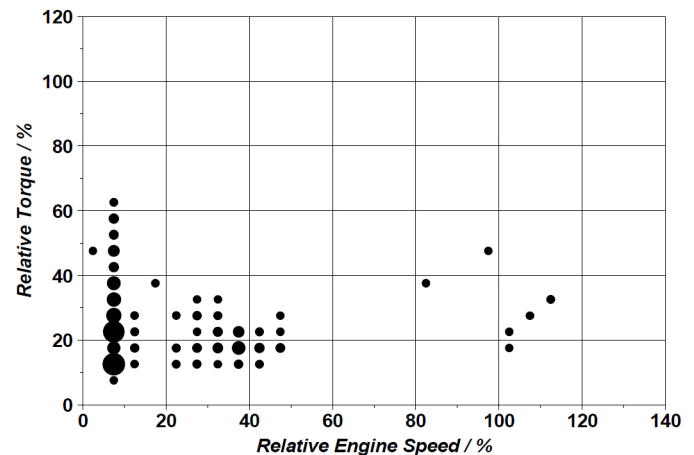


Figure 5. Frequency distribution of Customer Cycle 2

The customer Cycle 3 is strongly focused on 4 steady state engine speeds as displayed in Figure 6. This implies that the transient changes are mostly done through changes in engine load. This characteristic is quite common for agricultural machinery.

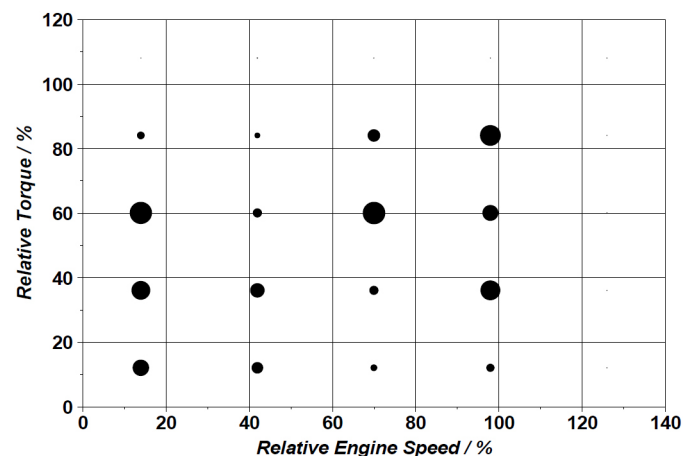


Figure 6. Frequency distribution of Customer Cycle 3

Of strong interest for the investigations are the temperature traces of the individual operation cycles at the aftertreatment components. For the SCR investigations NRTC, customer cycle 1 and 2 were selected. The temperatures of the SCR for these conditions are shown in Figure 7. For the DPF related simulations the NRTC as well as customer cycle 1 and 3 were taken into account. The profiles of the DPF temperatures are displayed in Figure 8.

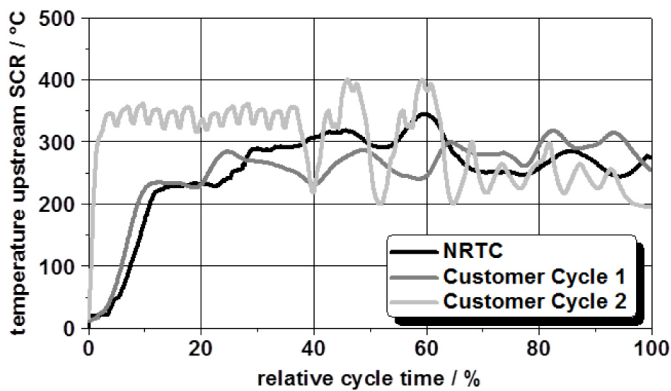


Figure 7. Temperature distribution at SCR

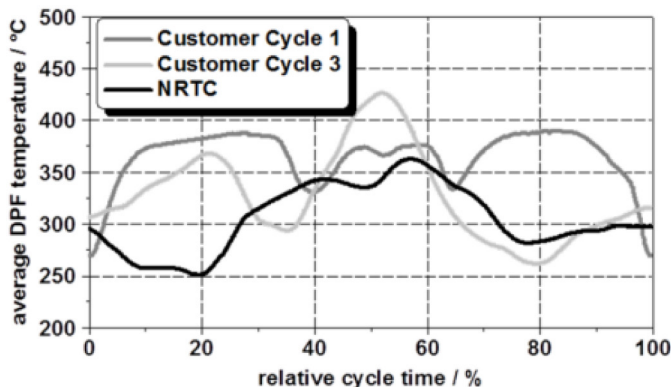


Figure 8. Temperature distribution at DPF

In the following sections the detailed methodology of how the accuracy impacts of these sensors were investigated in the different cycles is explained.

SCR Investigation Method

The temperature sensor upstream of the SCR is used for two types of control that contribute to the fuel consumption (FC).

Typically the SCR heat mode activation and deactivation are governed by monitoring the SCR temperature. Most EU Stage IV / US Tier 4 final applications are calibrated with this kind of heat mode. This heating is done to increase the EATS temperature during the cold phases of a cycle [1]. This is required for achieving the demanded conversion rates of the catalysts especially the SCR. The higher exhaust temperature and low engine out NO_x level of the SCR heat mode cause significant FC increase. A more accurate switching of the engine operating modes based on better temperature information therefore implies a direct impact on FC.

The threshold for activation and deactivation of the SCR heat mode were set to commonly used values of 280°C upstream SCR and a hysteresis of 20°C. The hysteresis in the switch is required to avoid high frequent changes of the engine modes. Moreover the impact of the hysteresis width - changed from 20°C to 40° - was part of the simulation work scope.

The release of the urea dosing is coupled to the current exhaust temperature condition. The injection of urea is inhibited at low temperatures to avoid deposits of crystallized urea in the exhaust pipes. If the temperature acquisition is more accurate the dosing release is earlier and therefore more SCR conversion could be obtained. With higher conversion efficiencies of the SCR typically the level of engine-out NO_x can be increased and simultaneously the fuel consumption decreased. As a result there might be an indirect impact on fuel consumption by the urea dosing release. The release threshold was also set to the usually calibrated value of 180°C.

All cycles are simulated as cold starts with the initial temperature of the exhaust gas aftertreatment system of 25°C. In this case the cycles start without urea dosing and with the SCR heating mode which is switched off as soon as the threshold for heat mode deactivation is reached and reactivated when the temperature upstream SCR drops below the lower threshold of the hysteresis. Obviously, the influence of the accuracy of the thermocouple is higher the more often those thresholds are reached.

DPF Investigation Method

For investigations regarding the DPF operation the potential of reducing fuel consumption was examined by the impacts of the temperature sensor upstream of the DOC and upstream of the DPF. Both temperature sensors are used for the soot loading model of the DPF. The engine ECU computes the DPF soot-loading as well as oxidation of soot by NO_2 (passive regeneration) and O_2 (active regeneration) [2]. Two major processes are influenced by the sensor accuracy: soot-loading and DPF regeneration. Both - upstream DOC & DPF - sensors are used to calculate the brick surface temperature of the DOC. This temperature is strongly governing the formation of NO_2 . The temperature upstream of the DPF is used for simulation its surface temperature which is essential for modeling the soot combustion process. Consequently these two sensors have an impact on the computed soot loading when the temperature level is high enough to perform passive regeneration. The desirable temperature range at DOC/DPF is about 250-350°C. In this temperature window, the DPF achieved what is called a balance point temperature, where the soot emission and NO_2 oxidation of soot are balancing so the DPF loading stays at a constant level. If this level is below the trigger limit of 70% of maximum DPF soot load the regeneration is triggered by an operation time based value of typically 50 to 100h (Figure 9)

During the active regeneration phase of the DPF the soot loading decrease is processed by an oxidation model and the regeneration mode is stopped when the DPF empty threshold is reached. Due to the fact that regeneration mode has very high fuel consumption - e.g. during NRTC about 50% higher than in normal mode - the time spent in this mode should be kept as low as possible.