

Development and Application of a Virtual NO_x Sensor for Robust Heavy Duty Diesel Engine Emission Control

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ABSTRACT

To meet future emission targets, it becomes increasingly important to optimize the synergy between engine and aftertreatment system. By using an integrated control approach minimal fluid (fuel and DEF) consumption is targeted within the constraints of emission legislation during real-world operation. In such concept, the on-line availability of engine-out NO_x emission is crucial. Here, the use of a Virtual NO_x sensor can be of great added-value. Virtual sensing enables more direct and robust emission control allowing, for example, engine-out NO_x determination during conditions in which the hardware sensor is not available, such as cold start conditions. Furthermore, with use of the virtual sensor, the engine control strategy can be directly based on NO_x emission data, resulting in reduced response time and improved transient emission control. This paper presents the development and on-line implementation of a Virtual NO_x sensor, using in-cylinder pressure as main input. The development steps from off-line modelling, calibration and validation towards real-time on-line implementation and validation will be presented in great detail. The Virtual NO_x sensor is validated on a state-of-the-art EURO-VI Heavy Duty Diesel Engine. Steady-state validation results show that the performance of the Virtual NO_x sensor is similar to the physical NO_x sensor. Transient load ramp tests and frequency response function evaluation both show improved transient response from the Virtual NO_x sensor. Furthermore, the Virtual NO_x sensor is successfully applied as substitute for the physical NO_x sensor as input to the air path controller over a transient cycle. These validation results demonstrate the application of the Virtual NO_x sensor for engine control and show the potential for improved transient emission control.

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INTRODUCTION

Increasingly stringent emissions and OBD regulations are main drivers for the use of engine-out NO_x information as input to diesel engine and aftertreatment control systems. This has resulted in the application of physical NO_x sensors, positioned upstream of the NO_x aftertreatment components, to provide this information.

Virtual sensors are essentially mathematical models that estimate the target quantity, e.g. engine-out NO_x, by using input quantities, which are (already) available from the engine control unit (ECU). The interest in development of virtual engine-out NO_x sensors has grown. Here, the costs of the physical sensor and the need for improved (faster) response times used in engine controls and extended temperature operating range, such as cold start conditions, are the main motivators. Virtual sensors can target physical sensor replacement, but can also be used in parallel to the physical sensor in light of sensor diagnostics and redundancy resulting in increased robustness.

The core of a Virtual NO_x sensor is a mathematical model for in-cylinder NO_x formation. Kihás and Uchanski [1] present an overview of NO_x formation models targeting near-term or mid-term implementation on production intent automotive ECUs. Depending

on the level of detail, they categorize the NO_x formation models into physics-based, grey-box or black-box models. Physics-based NO_x formation models determine in-cylinder temperatures and species concentrations by crank angle resolved calculations using two or more "zones" or "packages". A measured in-cylinder pressure trace is typically used as main model input [3],[2],[3]. On-line use of these NO_x formation models as Virtual NO_x sensor therefore requires the presence of a physical in-cylinder pressure sensor, installed in one or more engine cylinders. A zero cylinder pressure sensor based concept is presented by Elbert et al. [4]. In their NO_x formation model, in-cylinder pressure data is used off-line to parameterize different Vibe laws representing on-line fuel burning rates. The physics based models allow fast off-line simulation, but are marginally applicable for on-ECU use due to the relatively high level of detail. Due to the physics-based approach, the models have good predictive capabilities. The Grey-box models are physics-inspired models that apply simplifying assumptions to reduce ECU resource loading. In this case, NO_x formation is typically not computed in a crank angle resolved fashion. The highest computational efficiency is obtained by the black-box models. These models heavily rely on measurement data implemented e.g. as look-up tables, artificial neural networks or polynomial expressions. Model calibration effort is high and predictive capability is limited.



Following the categorization used by Kihás and Uchanski, [3], the NO_x formation model used in this paper as base for the Virtual NO_x sensor is of the physics-based model type. In contrast to many literature references, as also cited by [3], this paper presents an actual implementation of the physics-based NO_x formation model as part of the Virtual NO_x sensor on a real-time platform. This allows to evaluate the potential of the Virtual NO_x sensor for optimizing engine performance and increasing system robustness.

The present work presents novelty towards real-time NO_x emissions estimation and control. As shown in the previous publications, results have been provided for real-time NO_x estimators using black box approaches [5]. Although progress has been done in implementing physical models on a real-time system [2], only few results have been accomplished in connection with running engines and real-time NO_x emission predictions [6]. Within this research the Virtual NO_x sensor is tested over the larger engine operating range. Finally, the usability of the virtual NO_x sensor for control purposes on a real heavy-duty diesel engine is proven by replacing the physical NO_x sensor by the virtual NO_x sensor in the engine's closed-loop air-path controller.

VIRTUAL NO_x SENSOR CONCEPT

Figure 1 provides an overview of the Virtual NO_x sensor concept. The Virtual NO_x sensor computes the in-cylinder NO_x formation during one combustion event for an individual cylinder using the measured in-cylinder pressure as main input. Currently, total engine-out NO_x is computed by assuming that all engine cylinders are equal to the cylinder from which the in-cylinder pressure measurement is taken. Though, cylinder-to-cylinder deviations can be significant, it is not trivial to online estimate the EGR distribution among the cylinders.

As shown in Figure 1 the main inputs to the Virtual NO_x sensor are the measured in-cylinder pressure from a single cylinder, the crank angle pulse and the ECU signals required to compute the in-cylinder conditions at Intake Valve Closing (IVC) and the fuel mass injection rate.

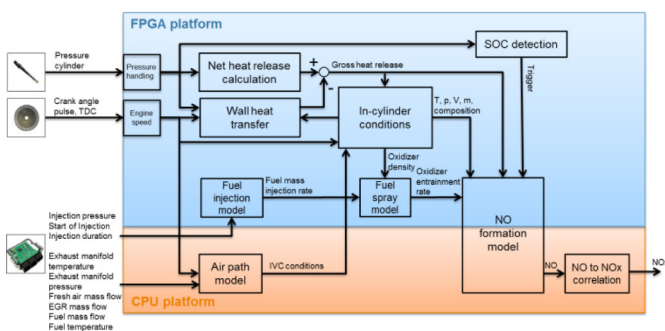


Figure 1. Overview of Virtual NO_x sensor concept implementation on real-time platform combining FPGA and CPU

The NO formation model is based on a physics-based model developed by Seykens [8]. Key features of this model are:

- NO formation in sequentially formed combustion product, so called “packages”;

- Combustion package formation rate derived from gross heat release rate profile obtained from measured in-cylinder pressure information and wall heat transfer model;
- Combustion product package composition and initial temperature computed from tabulated chemical equilibrium solver [9];
- Fuel injection process and spray model driven combustion product package oxidizer entrainment rate;
- Thermal NO formation by the extended Zeldovich mechanism [10];
- NO formation computed from local equivalence ratio and local temperature of the package [7].

The NO formation model computes NO formation from Start Of Combustion (SOC), as provided by the SOC detection algorithm, up to the crank angle after End Of Injection where the heat release first reaches a minimum threshold value.

The physics-based NO formation model outputs the computed in-cylinder NO. Total NO_x is determined by using an empirical correlation for the NO₂ fraction of NO_x based on measurement data.

The Virtual NO_x sensor performs complex mathematical operations at every crank angle degree during the aforementioned crank-angle window. Performing such operations within the time frame of the duration of a crank angle degree is a great challenge at high engine speeds. A second challenge is that the crank angle signal varies greatly in frequency during the operation of the engine. Therefore, the processing of every crank angle information takes place at different frequencies which is a hurdle for devices with fixed sampling times. The selected design is specially made to surpass these challenges while achieving the desired estimation accuracy and real-time condition.

As an example, at an engine speed of 2500 rpm, the crank shaft encoder signal presents a maximum frequency of 15 kHz. According to the Nyquist-Shannon sampling theorem, the continuous analogue signals need to be sampled at a minimum of 30 kHz to avoid aliasing of the signals. This processing frequency has not been achieved experimentally with the CPU present on the Speedgoat[®] target device while performing the mathematical computations required for NO_x estimation.

The Virtual NO_x sensor is implemented on a Speedgoat[®] real-time target machine containing an Intel[®] i7 3.5 GHz CPU and Xilinx Spartan 6 Field Programmable Gate Array (FPGA) chip. The CPU component of the Speedgoat[®] board is best suited for sequential and complex computations at a lower frequency than the FPGA, while the FPGA is suited for parallel and simpler computations than the CPU at a higher frequency. Cylinder pressure handling, i.e. pressure pegging and filtering, gross heat release, fuel mass injection rate, the oxidizer entrainment rate as derived from the fuel spray model and in-cylinder conditions calculations, are implemented on the FPGA platform. A data buffer is part of the NO model implementation at the FPGA side to transfer the data for the actual NO formation model at the CPU side. This buffer deals with the engine speed dependent time/crank angle based execution times for FPGA and CPU tasks, allowing decoupling with the FPGA sampling time. The CPU platform covers

the input and output signal interfacing for ECU signals, calculations for determining the in-cylinder conditions at IVC and the NO_x formation model.

The task assignment to either the FPGA or CPU is driven by the available floor space and processor computational load. The crank angle based input handling is performed by the FPGA to enable the real-time net heat release calculations also executed at the FPGA. Furthermore, wall heat transfer computation and SOC detection tasks are also assigned to the FPGA in order to have real-time (crank angle based) determination of in-cylinder conditions. All calculations are event-based, triggered by the crank angle pulse (CAP). Moreover, tasks are idling at the FPGA, when waiting for other task to be completed that are also required for the subsequent tasks to be executed.

The Virtual NO_x sensor subsystem most significantly contributing to the CPU load is the NO formation model, due to the formation and evolution of NO emission formation packages per crank angle. The tasks and total execution time of the Virtual NO_x sensor is depicted in Figure 2 and Table 1, respectively. The total execution time consists of three phases:

1. Period from IVC till SOI + 5°CA;
2. NO formation model for 100°CA;
3. NO formation model in case CPU is slower than CAP.

The additional 5°CA in phase 1 is included to make sure, there is data in the NO buffer to be processed.

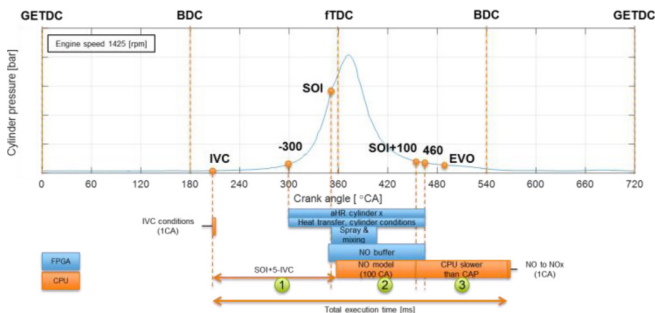


Figure 2. Schematic overview of Virtual NO_x sensor execution time

For the complete engine speed range, the Virtual NO_x sensor is able to predict NO_x emission prior to the next cycle (720°CA), because worst-case execution time equals 480°CA. The worst-case execution duration time of 82 ms occurs at engine idling, but in those conditions the CPU is waiting for data triggered by the CAP, because the CPU is faster than the CAP. Prediction of NO_x emissions cylinder by cylinder is only possible for engine speeds up to 800 rpm with current implementation. Further model reduction or optimization of CPU load and floor space is required to meet cylinder by cylinder NO_x predictions.

Table 1. Worst-case execution time

Worst-case execution time	Time [ms]	Time [CA]
Maximum engine speed, 2150 [rpm]	38	480
Idling engine speed, 525 [rpm]	82	257

VIRTUAL NO_x SENSOR DEVELOPMENT PROCESS

A systematic and stepwise approach has been defined for the Virtual NO_x sensor development, as shown in Figure 3. The Virtual NO_x sensor is designed off-line and converted to an on-line implementation in several steps allowing performance assessment at key development steps.

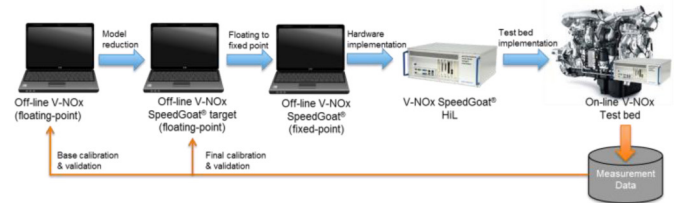


Figure 3. Virtual NO_x sensor development process

Development started with the off-line implementation of the main model components, as indicated in Figure 1, in Matlab/Simulink®. This off-line implementation targets highest accuracy on in-cylinder NO_x prediction. On-line implementation however, requires several adaptations to allow embedding on the real-time platform:

- Simplified pressure handling;
- Increase of computation step size from 0.1 to 1.0 crank angle;
- Simplified net heat release rate and motoring pressure calculation using fixed polytropic coefficient;
- Floating to fixed point conversions for FPGA related code;
- Tabulations for exponentials, power and trigonometric FPGA related functions.

Apart from these adjustments, the off-line implementation is retained on-line. This results in a reduced model implementation in Matlab/Simulink®. The next step is to convert this Matlab/Simulink® floating point implementation into a fixed point implementation compatible with the targeted real-time platform. This version of the Virtual NO_x sensor still runs off-line. In the subsequent step, the model is compiled into target platform code and downloaded onto the target platform. Finally, the Virtual NO_x sensor is integrated into the engine test bed setup. The complete process is listed:

1. Identification of tuning parameters of NO model of the virtual NO_x sensor with measurement data (offline);
2. Validation of NO_x estimation on simulation environment (offline);
3. Model reduction and architecture re-structuration for the real-time target platform (design on PC);
4. Conversion of the numeric format of the virtual NO_x sensor from floating point to fixed point for FPGA compatibility (design on PC);
5. Compilation and deployment of virtual NO_x sensor into the target device (Speedgoat®);
6. Validation of the integrated virtual NO_x sensor on engine test bed setup (On-line Speedgoat®).