

Real Time Implementation of DOC-DPF Models on a Production-Intent ECU for Controls and Diagnostics of a PM Emission Control System

Nishit Nagar, Xiaolai He, Vikram Iyengar, Nirav Acharya and Arkadiusz Kalinowski
Pi Shurlok, LLC

Adam Kotrba, Timothy Gardner and Argun Yetkin
Tenneco Inc.

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ABSTRACT

This paper describes the joint development by Tenneco and Pi Shurlok of a complete diesel engine aftertreatment system for controlling particulate matter emissions. The system consists of a DOC, DPF, sensors, controller and an exhaust fuel injection system to allow active DPF regeneration.

The mechanical components were designed for flow uniformity, low backpressure and component durability. The overall package is intended as a complete PM control system solution for OEMs, which does not require any significant additions to the OEM's engine control strategies and minimizes integration complexity. Thus, to make it easier to adapt to different engine platforms, ranging from small off-road vehicle engines to large locomotive engines, model-based control algorithms were developed in preference to map-based controls.

Pi's recently-developed general-purpose OpenECU electronic controller, based on the MPC-5534 processor core, was applied to run the advanced 1-D DOC and 0-D lumped DPF thermo-chemical models in real time to control the fuel injection system. The system was integrated with a Cummins 5.9 L engine in the engine dynamometer laboratory at Tenneco. The control algorithm and models were first calibrated offline using the experimental and baseline engine data using Hardware-In-the-Loop test environment. The control strategies were then tested in real time on the engine dynamometer. The models were able to predict DOC and DPF parameters such as temperatures, pressure

drop, soot load and emissions in real time with good accuracy. These "virtual sensor" measurements provide great scope for advanced diagnostic strategies to detect component or sensor failures. During active regeneration, the control strategy was able to control the DOC outlet temperature within a range of ± 50 °C from the set target and effectively regenerate the DPF under engine transients. The HC slip measured was less than 60 PPM during active regeneration.

These system performance results confirmed the feasibility of active DPF regeneration in the context of increasingly stringent regulations for emissions limits and increasingly complex diagnostic requirements.

INTRODUCTION

There is a substantial need to reduce Particulate Matter (PM) emissions for off-road diesel engine and locomotive engines to meet the upcoming regulations set by EPA. Apart from modification to engine design, a PM aftertreatment control system with Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) will be widely employed in all types of applications. In order to actively regenerate the filter, high temperature in the range of 600-650 °C is required. To achieve this temperature, fuel is sprayed before the DOC under certain controlled conditions. Two prominent strategies which are used to provide the required fuel are – 1) late in-cylinder post injection; 2) a separate fuel injector mounted to the exhaust pipe which injects upstream of the DOC. Although, having a late post injection in-cylinder reduces the system cost, it can lead to lubricant

oil contamination [1] and subsequently reduce the life of the engine. Having a separate fuel injector in the exhaust provides the capability to better control the regeneration and decouple the engine dependency. An ELIM-NOx injector, as shown in Fig. 1, was used for this work. The injector provides well atomized fuel into the exhaust stream and has internal fuel recirculation for cooling purposes. The orifice plate inside the injector can be easily changed, thus making it easier to tune the injector fuel delivery range for a particular engine application depending of exhaust flow rate.



Figure 1. Tenneco's ELIM-NOx injector with internal fuel recirculation circuit for cooling the injector

In order to meet the stringent emission regulations with minimal fuel penalty, it is necessary to design a PM aftertreatment system with a control system which can regenerate the filter at optimal intervals with low HC slip and fuel consumption. Apart from performance, it would be extremely beneficial to reduce the experimentation and calibration effort required to integrate a PM aftertreatment system to existing engine platform with minimal changes to engine control strategy. A model based control strategy which can predict the state of DOC and DPF in real time within acceptable accuracy bands can help address these issues. Since the models are based on first principles and use very few calibration maps, the re-calibration effort required when a different engine platform or the geometric properties of catalyst/filter is changed is very low. The models also provide virtual sensor output to predict HC slip, soot loading and substrate temperatures which can't be measured on the actual vehicle for a production application. This added information helps in better controlling and diagnosing the system.

A number of different approaches have been described in the literature for modeling both DOC and DPF [2], [3], [4] and [6] which have investigated DOC and DPF models for PC based simulation under different operating conditions. However, in order to use these

models on a production application, it is necessary to develop models which can be easily executed on a production intent ECU in the form of embedded software. Moreover, it would be beneficial to understand how these models perform in real time and how they can be used for controlling and diagnosing the aftertreatment system.

The paper first provides an overview of the control system with details of the hardware and control strategy that was applied. Then the DOC and DPF modeling approach is explained, as well as the necessary assumptions that have been made to reduce complexity for real-time application. The results of these embedded models running on M460 OpenECU in an engine dyno environment are then discussed. The performance of control strategy during filter regeneration is then discussed followed by how the model output can be used for diagnostics and the conclusions.

CONTROL SYSTEM ARCHITECTURE

Figure 2 provides the overview of the system architecture used for this work. An injector was placed directly before the DOC with a 30 inch mixing length and no mixer. The fuel to the injector was supplied through a separate fuel tank and fuel pump.

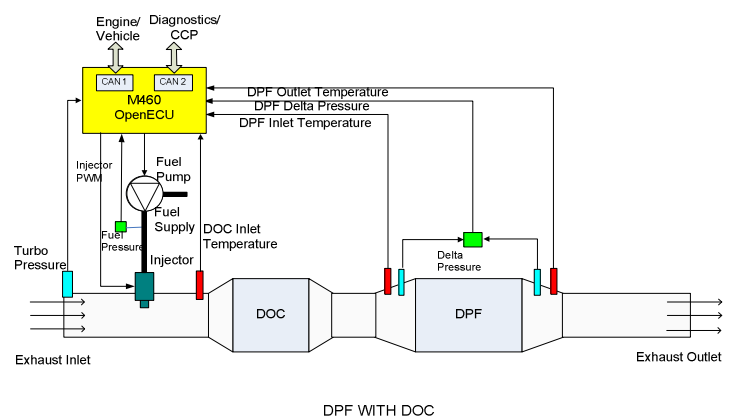


Figure 2: Setup for PM aftertreatment system

Resistive temperature devices (RTD) were used to measure exhaust gas temperature (EGT) before the DOC, after the DOC and after the DPF. Fuel line pressure sensor was used to maintain desired fuel pressure during injection. In this case, turbo out pressure sensor was used to measure absolute pressure for determining the exhaust flow density and subsequently exhaust space velocity which is used by the DOC and DPF models. When the injector was not used, the fuel pump would run at low PWM rate to circulate enough fuel to keep the injector cool.

The M460 OpenECU controls the fuel injection based on the sensor measurements and embedded models. M460 OpenECU receives the engine information such as engine speed, engine load, intake mass flow rate and engine fuel consumption over high speed CAN from the engine dyno DAQ as the specification of engine ECU

CAN messages were not available. The specification of M460 OpenECU is provided in Table 1.

Table 1: Specification of M460 ECU which is used here for diesel aftertreatment system

Processor	MPC 5534
Application Code Space	512KB
Internal SRAM	64KB
RTD Inputs	11
Thermocouple Inputs	2
Generic 0-5V inputs	19
Injector Drivers	4
Multipurpose PWM Drivers	11
Digital/Frequency Inputs	6
CAN Channels	2

M460 OpenECU is a rapid prototyping platform which has a powerful 32 bit floating point processor making it easier to run computationally intensive models in real time. The control strategy, including the DOC and DPF models, were developed in Simulink. The model was then autocoded using Real Time Workshop. The build process results in a memory image and A2L file. The module can be then flashed using a calibration tool like ETAS Inca or ATI Vision.

The high level control strategy architecture is shown in Figure 3 which is later discussed in more detail

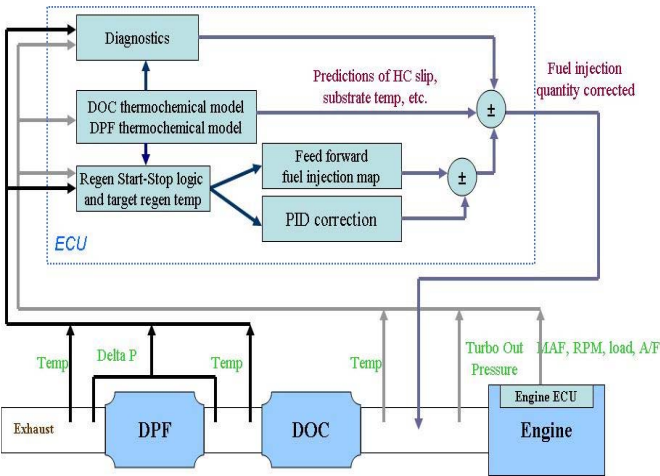


Figure 3: Overview of the control strategy used for regenerating the filter

Regeneration (regen) of the filter is initiated primarily based on delta pressure measurement and soot loading predicted by the DPF model. Once the regen is initiated the fuel injection is controlled using a feedforward and closed loop proportional integral (PI) control law. The values predicted by the DOC model like HC slip are used to adjust the fuel injection quantity in order to maintain desired DOC outlet temperature with minimal HC slip. The models also act as “virtual” sensors and provide values for the DOC outlet gas temperature, DPF outlet gas temperature, DPF delta pressure and substrate

temperatures, which are used to better diagnose the system and ensure safe regeneration.

DOC AND DPF MODELLING APPROACH

There are number of numerical models that have been described in literature which provide detailed mathematical equations governing the catalyst and wall flow filter. However, in most cases these models are used for simulation on a PC. The models used for this work have been designed for specifically running on a production intent embedded controller. This initial work is intended to capture catalyst and filter behavior so that the fidelity of the models are good enough to be used for controls and diagnostics, yet the memory and RAM requirements are small enough so that the models can be even executed on an ECU which has a 16-bit fixed point controller. This has been achieved during internal projects at Pi Shurlok.

DOC THERMOCHEMICAL MODEL

As mentioned earlier, the DOC model is a 1-D model which considers heat and mass transfer along the length of the catalyst. In order to simplify the model for embedded application following are the key assumption that have been made –

1. The temperature and concentration of gases varies only along the length of catalyst and there is no radial variation.
2. The flow is uniform across all channels
3. The fuel injected before the DOC breaks down into fine droplets and mixes uniformly before reaching the catalyst
4. All other reactions other than oxidation of HC are ignored.
5. Propene is used to represent the average molecular structure of diesel and it is assumed that the fuel that reacts gets completely oxidized as assumed in Eq. 1.

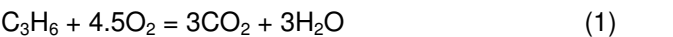


Figure 4 shows that the various phenomenon that are assumed to be taking place in the catalyst. As the exhaust gases move forward, HC and O₂ diffuse in the boundary layer. Here they react on the catalyst surface. The conductive and convective heat transfer equations are then used to determine the substrate and gas temperatures.

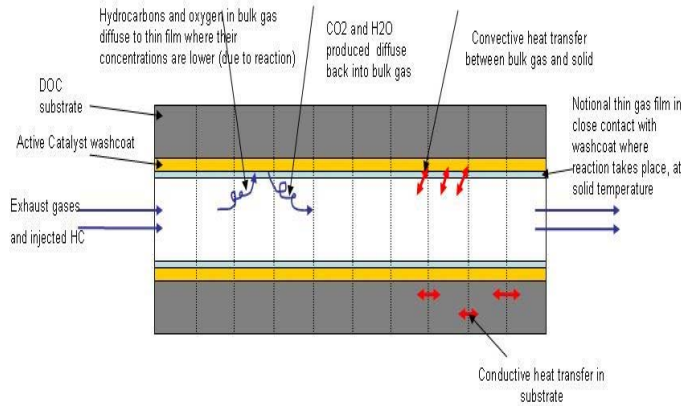


Figure 4: Phenomenon which are assumed to be occurring in a single channel of the DOC catalyst for modeling purposes

The mass balance for HC and O_2 in the catalyst is calculated based on the partial differential equation described in Eq. (2) and (3) respectively –

HC mass balance -

$$\begin{aligned} \varepsilon_g \frac{\partial C_{HC(g)}}{\partial t} &= -\varepsilon_g u \frac{\partial C_{HC(g)}}{\partial x} + k_{mHC} A_s (C_{HC(g)} - C_{HC(s)}) \\ (1 - \varepsilon_g) \frac{\partial C_{HC(s)}}{\partial t} &= k_{mHC} A_s (C_{HC(g)} - C_{HC(s)}) - R_{oxd} \end{aligned} \quad (2)$$

Oxygen mass balance-

$$\begin{aligned} \varepsilon_g \frac{\partial C_{O_2(g)}}{\partial t} &= -\varepsilon_g u \frac{\partial C_{O_2(g)}}{\partial x} + k_{mO_2} A_s (C_{O_2(g)} - C_{O_2(s)}) \\ (1 - \varepsilon_g) \frac{\partial C_{O_2(s)}}{\partial t} &= k_{mO_2} A_s (C_{O_2(g)} - C_{O_2(s)}) - \frac{2}{9} R_{oxd} \end{aligned} \quad (3)$$

Where, $C_{HC(g)}$ and $C_{HC(s)}$ is the concentration of HC in exhaust gas and solid (wash-coated substrate), $C_{O_2(g)}$ and $C_{O_2(s)}$ is the concentration of O_2 in the exhaust gas and on solid. The reaction rate R is computed as described in Eq. (4)

$$R_3 = k_{oxd} C_{HC(s)} C_{O_2(s)} \quad (4)$$

The reaction constant k_{oxd} is calculated using Arrhenius equation.

$$k_{oxd} = A e^{\frac{-E}{RT}} \quad (5)$$

The mass transfer coefficients k_{mHC} and k_{mO_2} are calculated using following equation –

$$k_m = \frac{Sh \cdot D_m}{d_h} \quad (6)$$

The heat balance for the catalyst is calculated based on the partial differential equation shown in eq. (7)

$$\begin{aligned} (1 - \varepsilon_g) \rho_s C_{Ps} \frac{\partial T_s}{\partial t} &= k_{cs} (1 - \varepsilon_g) \frac{\partial^2 T_s}{\partial x^2} + h_g A_{sg} (T_g - T_s) - h_s A_{ss} (T_s - T_{amb}) \\ \varepsilon_g \rho_g C_{Pg} \frac{\partial T_g}{\partial t} &= -h_g A_{sg} (T_g - T_s) - \varepsilon_g \rho_g C_{Pg} u \frac{\partial T_g}{\partial x} \end{aligned} \quad (7)$$

In order to convert the differential equation into algebraic equations which can be solved in an ECU, the DOC is divided into n small cells along the length of the catalyst. It is assumed that the concentration of HC, O_2 and the temperature remain constant inside each cell. As a small time step of 5 ms is being used to execute the model, steady state conditions can be assumed in each cell, thus –

$$\frac{\partial C_{HC(g)}}{\partial t} = \frac{\partial C_{O_2(g)}}{\partial t} = \frac{\partial C_{HC(s)}}{\partial t} = \frac{\partial C_{O_2(s)}}{\partial t} = \frac{\partial T_s}{\partial t} = \frac{\partial T_g}{\partial t} = 0 \quad (8)$$

A high level diagram providing an overview of the implementation is provided in Fig. 5.

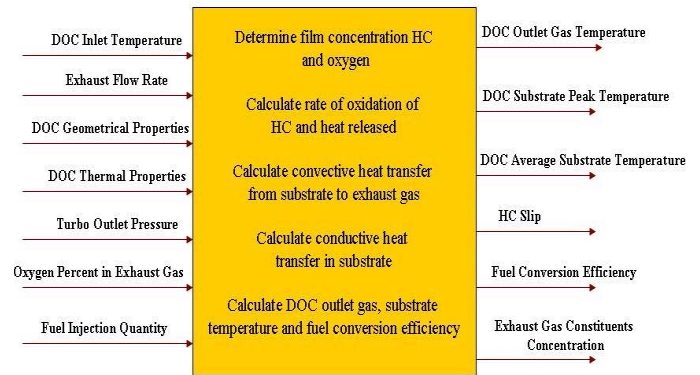


Figure 5: Overview of the steps being executed to solve the DOC model

A supervisory Stateflow logic determines which part of the model needs to be solved in a given time step and keep tracks of the state of each cell. For the first cell, the DOC inlet conditions are used for calculating concentrations and temperatures. Then for the subsequent cells, the input from previous cells is used to determine the cell state. The output from the final cell is then used for the controls and diagnostics.

DPF THERMOCHEMICAL MODEL

The DPF model used for this work is a 0-D lumped model. The model is based on following assumption –

1. There is no variation in soot loading along the length or radius of the filter.