

Automated Model Fit Method for Diesel Engine Control Development

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ABSTRACT

This paper presents an automated fit for a control-oriented physics-based diesel engine combustion model. This method is based on the combination of a dedicated measurement procedure and structured approach to fit the required combustion model parameters. Only a data set is required that is considered to be standard for engine testing. The potential of the automated fit tool is demonstrated for two different heavy-duty diesel engines. This demonstrates that the combustion model and model fit methodology is not engine specific. Comparison of model and experimental results shows accurate prediction of in-cylinder peak pressure, IMEP, CA10, and CA50 over a wide operating range. This makes the model suitable for closed-loop combustion control development. However, NO emission prediction has to be improved.

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INTRODUCTION

The ever-increasing emission legislation and fuel costs have resulted in the addition of many new technologies to the diesel engine system over past decades. Especially, the focus on system robustness for real-world variations (In-Use Compliance), like ambient conditions, production tolerances, wear adds great complexity to the diesel engine/ aftertreatment control system. This has resulted in a dramatically increased effort, both in time and costs, for engine and aftertreatment control development, calibration and validation. Here, accurate, fast-computing and predictive engine and aftertreatment simulation models are valuable tools for reducing this effort by replacing part of the physical testing by virtual development and testing.

In order to apply such engine and aftertreatment models to the control development and calibration process, it is of utmost importance that a sound and validated set of model parameters, dedicated to the engine/aftertreatment system at hand, is available. The effort in determining a validated set of model parameters should be relatively low and easily reproducible for different engine types and power ratings.

This study presents an automated fit method for a physics-based combustion model [14]. This model has been used in earlier work for the development of closed-loop combustion control strategies [13]. The potential of this method is demonstrated for two modern heavy-duty diesel engines.

This paper is organized as follows. First, the studied combustion model is introduced. Then, the method to fit the combustion model parameters is described in detail and applied to a heavy-duty Euro VI diesel engine. Parameter identification results are shown using the estimated model parameters on an independent set of data. Finally, the parameter estimation method is repeated on a different, Tier4, diesel engine as a check on the robustness of the proposed estimation method.

PHYSICS-BASED COMBUSTION MODEL

Mean value engine models are widely used for system analysis and control development. These models are based on first principle models for the intake and exhaust manifold, turbocharger and crankshaft in combination with semi-empirical models for valves, coolers, and turbocharger, see e.g. Wahlstrom and Eriksson [2].

Typically, detailed combustion models that predict in-cylinder heat release and emission formation are lacking. This limits the applicability for integrated engine and aftertreatment control development and calibration. For this purpose, a physics-based in-cylinder combustion model has been developed [3], [4]. In TNO's simulation tool DYNAMO, this combustion model is implemented in a dynamic mean-value engine model, as indicated in Figure 1.

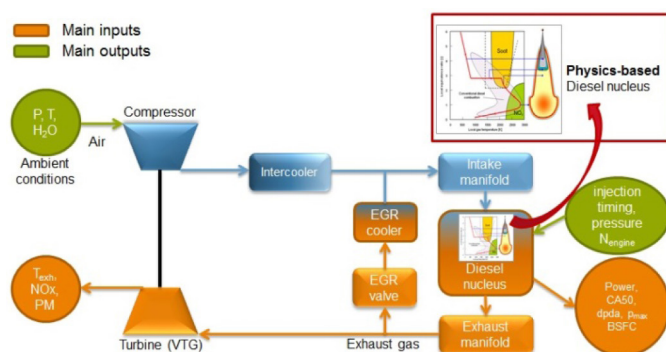


Figure 1. Overview of control oriented diesel engine model incorporating the developed physics based in-cylinder diesel combustion model.

Overview and Main Features

A complete overview of the combustion model with its main inputs, outputs and components can be seen in Figure 2. The inputs of the model are formed by the manifold conditions (pressure, temperature and composition (EGR)), the control settings of the fuel injection system (injection pressure, duration and timing of injection), the engine speed and the wall temperature of the combustion chamber.

The main outputs are the predicted emissions of NO and soot, the mean in-cylinder conditions of pressure, temperature and composition and combustion diagnostic parameters, like CA50.

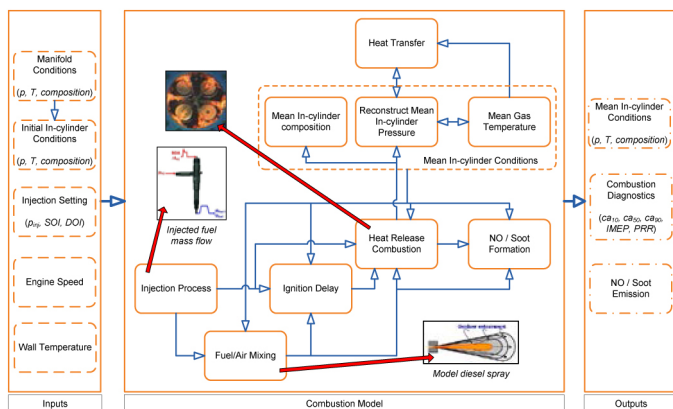


Figure 2. Overview of physics-based in-cylinder combustion model [14].

The implemented soot model is in an early development stage and is not considered in this study.

Main features of the in-cylinder combustion model are:

- Crank-angle based;
- Fuel injection rate model predicting injected mass flow rate and velocity;
- Zero-dimensional thermodynamic in-cylinder combustion model;
- Heat release rate model describing the premixed and mixing-controlled combustion phases;

- One-dimensional fuel-spray model quantifying the fuel-oxidizer mixing process;
- Heat transfer model based on Woschni [4] correlation;
- Quasi-dimensional NO formation model based on Zeldovich reaction kinetics [5].

For a detailed description of the model, the reader is referred to [3], [4]. The Appendix provides a brief overview of the main implemented model equations that will be discussed in the next sections on the model parameter identification process.

COMBUSTION MODEL FIT METHOD

Introduction - Parameter Estimation

In the combustion model, many model parameters (> 100) are applied, which puts a great challenge on the model parameter identification process. In general, the model parameters can be divided into three classes:

- 1). *Geometrical parameters*: These parameters like bore, stroke, etc., are in general specified by the engine manufacturer with high accuracy. These parameters are engine specific and fixed.
- 2). *Physical parameters*: parameters like density, molar mass, gas constant, are known from literature and are considered as given.
- 3). *Fuel and combustion specific model parameters*: these model parameters are dependent on the combustion system in combination with a specific fuel. They can have a physical or chemical character (like discharge coefficients or activation temperatures) or a non-physical background, i.e. tuning parameters. These parameters have to be identified by the model calibration tool on basis of performed measurements.

The combustion model fit tool makes use of different data fitting techniques. These techniques are based on minimizing the difference between the measured (or observed) and the predicted value from the model, see. The goal of the estimation process is to find the parameter vector $\hat{\beta}$, which gives a "best" $f(x, \hat{\beta})$ of the measured quantities y . Data fitting is the process of finding the estimate $\hat{\beta}$ that minimizes a specified error norm of the residuals $\|\epsilon\|$, with ϵ given by:

$$\epsilon = y - f(x, \hat{\beta}) \quad (1)$$

Probably, the best known error norm is the least squares error norm:

$$S_{LS}(\beta) = \|\epsilon\|_2^2 = \sum_{n=1}^N \epsilon_n^2 = \sum_{n=1}^N (y - f(x, \beta))^2 \quad (2)$$

A more elaborate form of the least squares norm is the weighted least squares error norm, where weights are added to the data points to increase their relative significance.

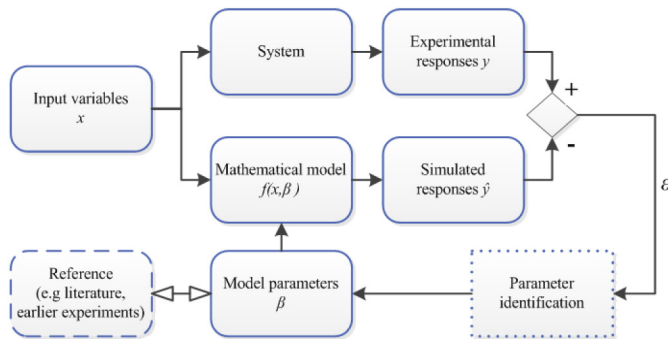


Figure 3. Representation of the parameter estimation problem [14].

For linear systems, analytical solutions can be derived for this optimization problem, so the solving procedure is computationally efficient. The nature of the diesel combustion model is however strongly non-linear in the model parameters. As a consequence, the parameter identification process for the different sub-models has to use iterative solving procedures. These iterative methods start with an initial guess of the parameter vector and generate a sequence of improved estimates until they terminate on the basis of a predefined convergence criteria. Three different iterative procedures are used in this study:

- 1). Nelder-Mead Simplex method
- 2). Sequential Quadratic Programming
- 3). Genetic Algorithm

Overview of Model Fit Process

The required vector β for the combustion model contains 20 combustion model parameters that have to be identified by the fit method. Simultaneous estimation of all the parameters is possible in theory. In practice, it is a computational burden without guaranteed success. Therefore, the parameter estimation process problem is divided into several smaller sub problems in which only a few model parameters are estimated at once.

Figure 4 gives an overview of the developed step by step process of the parameter identification method that finally results in a fully estimated parameter vector β . The different components of the combustion model can also be recognized in the different steps within this process. As shown in the figure, the identification process for the heat release and heat transfer model follows an iterative procedure in which the parameters from the fuel injection rate model (timing and shape) are updated for overall best result. This is required as a result of the relatively high uncertainty on the actual value of the start of injection (SOI).

The stepwise approach is used to isolate different parts of the complete combustion model as best as possible. A main prerequisite for this approach is that the measurement procedure can be specified, such that the effect of the model parameters at hand can be isolated from the overall process. This has also been the main focus during development of the measurement setup and measurement procedure.

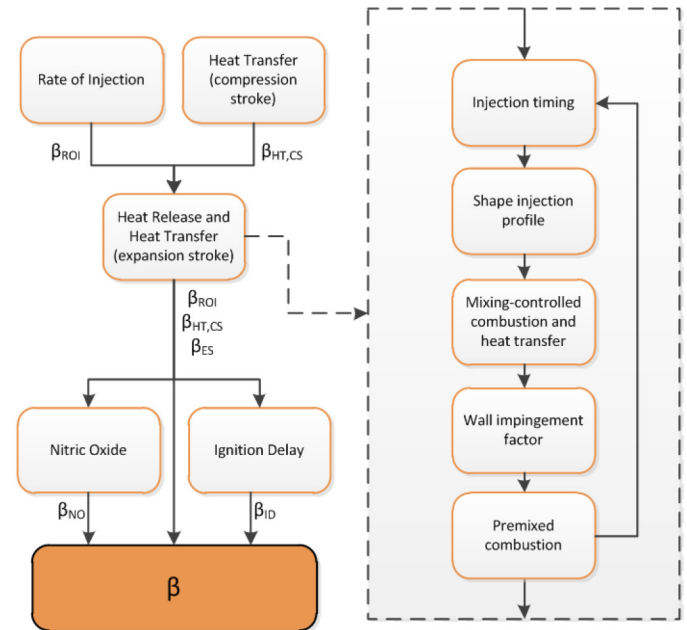


Figure 4. Schematic overview of the parameter estimator of the combustion model [14]. The indicated parameter vectors correspond to the table in the Appendix.

In the Appendix an overview of the complete parameter vector is provided.

Test Setup

Figure 5 presents an overview of the test setup used to generate the data required for the combustion model fit tool. First, the model fit method is applied to a Euro-VI heavy-duty diesel engine. Table 1 lists the main specifications of the used engine. The sensory system contains:

- Engine torque and speed;
- Pressures and temperatures over main engine components (air filter, compressor, charge air cooler, manifolds, turbine, EGR valve, EGR cooler.);
- Fresh air, EGR and fuel mass flow rate;
- Turbo speed;
- Ambient conditions (pressure, temperature, humidity);
- Coolant temperature;
- Engine-out NO and NO_x emission.

All signals listed above are logged with a sample frequency of 1Hz. For the combustion model fit, the following more dedicated measurement signals are used (all at 1 Hz resolution) :

- Crank angle
- In-cylinder pressure sensor cylinder #1 (crank encoder side)
- Fuel injection pressure at entrance of fuel injector cylinder #1
- Injector current on cylinder #1

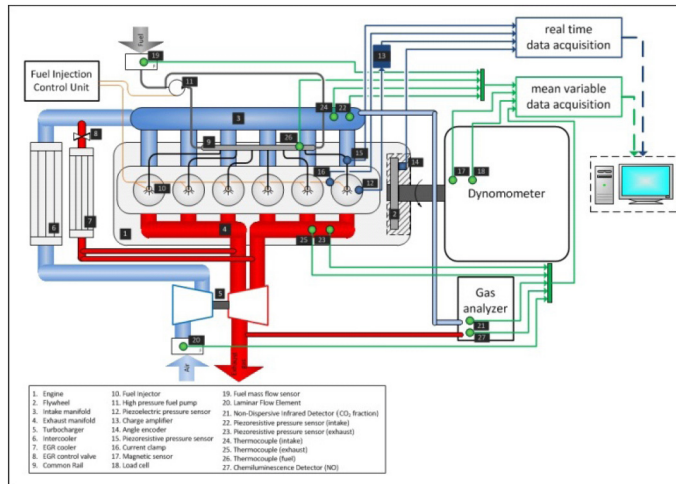


Figure 5. Overview of test setup used for engine model calibration.

Table 1. Overview of engine specifications - engine 1.

Engine type	6 cylinder, HD diesel engine
Displaced volume	12.9l
Compression ratio	17:1
Fueling system	Common rail type, 2000 bar
EGR system	High pressure cooled EGR
Turbocharger system	VTG

Table 4 presents a complete overview of the measurements used as input to the parameter estimation process. It will be discussed in more detail in following sections.

Measurement Data Pre-Processing

The combustion model calibration tool requires input variables, such as for example the start of combustion, that are not readily available from the measurements. Pre-processing of the raw measurement data is therefore required to derive all the input variables. Important input variables that require pre-processing of the measurement data are:

- In-cylinder pressure
- Injection timing and quantity : start of injection (SOI), end of injection (EOI), fuel mass
- Net heat release rate $dQ_n/d\phi$
- Start of Combustion (SOC)
- Initial in-cylinder conditions at Intake Valve Closing (IVC)

In-Cylinder Pressure Signal

The measured in-cylinder pressure signal is the only available measurement signal containing instantaneous information on the in-cylinder combustion process. It requires however significant processing in order to provide this information to the calibration tool. The data processing consists of four steps, namely:

- digital filtering: a weighted moving average filter as suggested by Harndorf [6] is used
- absolute pressure referencing: because the raw signal is a relative measurement, the pressure signal needs to be referenced to a known pressure at some point in the engine cycle. Based on the findings of Lee et al. [7], the Least-squares method with a variable polytropic coefficient is used in this study.
- crank angle referencing: correct phasing of the in-cylinder pressure and combustion chamber volume is essential for accurate combustion analysis. The crank angle encoder is calibrated by shifting the peak motoring pressure to the crank angle position of the geometric Top Dead Center (TDC) minus the thermodynamic loss angle (TLA). This TLA is obtained from the engine manufacturer.
- cycle averaging: due to cycle-to-cycle variations (resulting from variations in e.g. fuel timing, trapped air mass and composition) it is necessary to average the in-cylinder pressure over several consecutive cycles. In this study 100 consecutive cycles are used to average the pressure signal.

Fuel Injection Timing and Quantity

The injection timing (SOI and EOI) is determined from the measured current profile to the injector and the fuel injection pressure at the entrance of the fuel injector. Both signals are measured with a 0.1 °ca resolution. Figure 6 shows a typical response of the injector current and fuel injection pressure during an injection event. The current profile shows a clear indication of the actuation timing of the injection event. However, due to physical delays within the injector this timing does not correspond to the actual start and end of fuel injection into the engine's cylinder. For a more precise determination of the injection timing, the fuel injection pressure is used. The fuel injection pressure profile shows a rapid decrease in pressure as a result of the actual start of fuel injection which initiates pressure waves traveling through the fuel injection system. The rapid closing of the injector causes the so-called "water hammer effect" showing as a steep fuel pressure increase. The onset of the fast pressure decrease following the SOA is taken as the actual start of injection. The onset of the water hammer effect is taken as the actual end of injection, see Figure 6. A correction is applied to compensate for the transport delay between sensor location and actual injection nozzle hole. However, the inaccuracy on the injection timing is large, approximately 1 °ca. Improved accuracy can be expected when a needle-lift sensor is applied, but this is not considered a conventional sensor.

Found values for SOI and EOI define the total injection duration (DOI). The delays at opening (SOA - SOI) and closing (EOA - EOI) of the injector are tabulated as a function of injection pressure and duration.

Measuring the instantaneous fuel injection rate requires dedicated setups like used in [3]. On the engine only the total time-averaged mass flow rate to the engine for steady state conditions $\overline{\dot{m}_f}$ is available. The amount of fuel injected per cylinder is derived from this signal as:

$$m_{f, inj} = \frac{\overline{\dot{m}_f}}{n_{inj}} = \overline{\dot{m}_f} \cdot \left(\frac{1}{2} \frac{\overline{N_e}}{60} \cdot n_{cyl} \right)^{-1} \quad (3)$$

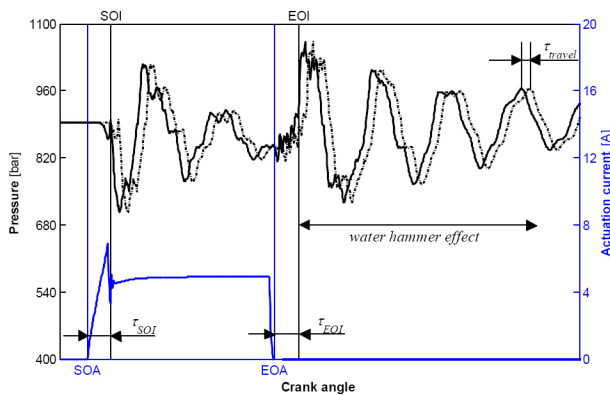


Figure 6. Measured pressure in the injector feed pipe (dashed) and corrected for transport delay (solid) together with the injector actuation current signal. Initial rail pressure is 900 bar.

Net Heat Release Rate

The net heat release rate is derived from the first law of thermodynamics using the measured in-cylinder pressure signal as input together with the in-cylinder volume as derived from geometrical cylinder and crank-slider properties:

$$\frac{dQ_n}{d\phi} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\phi} + \frac{1}{\gamma-1} V \frac{dp}{d\phi} \quad (4)$$

where γ is the ratio of specific heats derived from NASA polynomials [5] based on temperature and gas composition.

Start of Combustion - SOC

The start of combustion is required by the combustion model fit tool to identify the parameters of the ignition delay model. The ignition delay is defined as the period of time between the start of injection and the start of combustion (SOC). Following katrašnik [8], the start of combustion is determined from the gross heat release rate $dQ_g/d\phi$ as derived from the measured in-cylinder pressure signal:

$$\phi_{SOC} = \max \left(\frac{d^3 Q_g}{d\phi^3} \right) \quad (5)$$

Initial In-Cylinder Conditions

The initial in-cylinder conditions are determined from the 'pegged' in-cylinder pressure signal and the ideal equation of state. Composition is based on measured air and EGR flow rates together with their assumed compositions. Temperature follows from the measured in-take temperature which is corrected for heat transfer in the intake system and cylinder using the empirical correlation of Zapf [9]. The in-cylinder mass then follows from the ideal equation of state.

Parameter Estimation of Fuel Injection Rate

Optimization Problem - Definition of Error Norm

The fuel injection rate is modeled as a top hat profile with finite opening and closing rates quantified by a rise and fall time, respectively Δt_{rise} and Δt_{fall} , see also Figure 7. See the Appendix for a more complete model description. For the fuel injection rate model, two options are available to define the error norm:

- 1). Minimizing the error between the estimated and measured injected fuel mass given a known injection duration
- 2). Minimizing the error between the estimated and measured injection duration given a known injected fuel mass

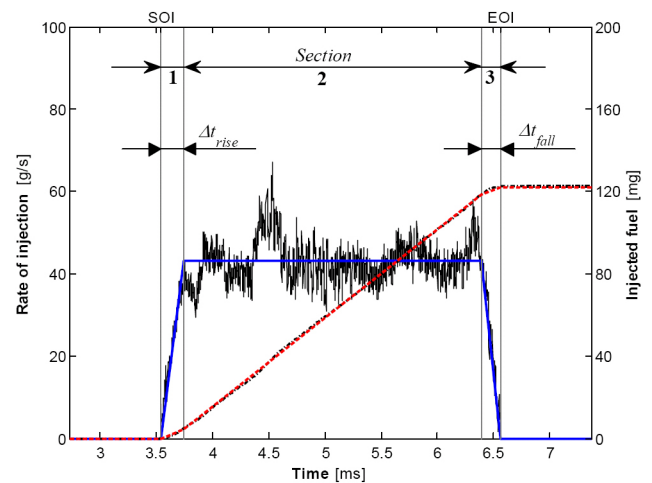


Figure 7. Measured rate of injection (solid black), reconstructed injection profile (solid blue), measured cumulative injected fuel mass (dashed black) and estimated cumulative injected fuel mass (dashed red) for a 2.5 ms (actuated) injection at an initial rail pressure of 750 bar. Experimental data originates from [3].

An assessment on the uncertainties in the dependent variables has shown that the duration of injection is by far the largest source of uncertainty in the correlation. This because the