MODELLING ANALYSIS OF MULTIPLE DIESEL INJECTION STRATEGIES WITH ONE-DIMENSIONAL SIMULATION COUPLED WITH ARTIFICIAL NEURAL NETWORKS

by

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In the modern Diesel injection systems the phasing of injection in the same cycle gives a high flexibility to engineers from the perspective of engines performance and emission optimization. Basically, the injection is separated in to three phases: the pilot, main, and post injection phases. The focus of this study is based on pilot injection strategy implementation, which can be used for emission control effectively. In this work, reference main and pilot + main injection strategy experiments were realized in a modern Diesel engine. The logged data groups were used to model the engine at 1-D thermodynamic simulation AVL BOOST. In the second stage of this work, the engine operating points which are not realized at test bench are made run at BOOST programme. The new model parameters of simulation are identified with artificial neural network technique. The results showed that the implementation of appropriate mass of pilot injection at the appropriate injection advance will reduce the NO_x emissions compared to reference main injection strategy. For reducing CO emissions the pilot injection mass should also be kept in the same range with higher injection pressure that can be achieved. Usage of 1-D simulation programme coupled with artificial neural network was found useful up to a certain extent especially for parametric analyses and optimization problems via with validation of calibration parameters at a huge experimental data.

Key words: *Diesel engine, combustion, 1-D modeling, neural networks, emissions*

Introduction

The share of Diesel engines, in the world market is permanently increasing year by year thanks to its efficiency and inherent fuel economy characteristics. The automotive industry is thus the key and the biggest sector for the Diesel engines market. The Diesel engine has been paid more attention because of the better performance, thermal efficiency, and low emission of CO_2. During the 80s, the well-known advantage of fuel economy made the direct injection (DI) Diesel engine increasingly attractive for passenger cars, especially in Europe [1]. The main pollutants that are emitted by the Diesel engine are NO_x, CO, HC, and particulate matter (PM) which is composed of soot. The stringent pollutant emission law limits of European Union for the manufacturers are getting narrower with every new coming euro emission stage and by the years. The new Euro 6 regulation foresees 55% reduction at NO_x emission (0.180 g/km to 0.080 g/km) without any change in PM emissions and 26% reduction at NO_x +

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HC emissions (from 0.230 g/km to 0.170 g/km) for compression ignition (CI) Diesel engines compared to Euro 5 emission limits [2]. In order to meet these increasing environmental concerns and more stringent emission regulations, current researches are carried out aiming the reduction of emissions simultaneously while maintaining reasonable fuel economy and engine power [3]. With the introducing of modern electronic common rail systems, the engine control architecture gives a high flexibility to engine manufacturers from the perspective of engines performance and emissions optimization which is needed for fulfilling the emission regulations [4]. Fundamentally, the pilot injection can be used for combustion noise and NO_x reduction and the post injection can be used for soot reduction. The main injection is generally assumed as the power injection of the cycle. In this context the optimization of pilot injection strategies is one of the key subjects that the researchers encounter during the development process. Implementing pilot injection increases the temperature of combustion chamber slightly. This decreases the ignition delay of main injection and decreases the peak temperatures created during the premixed combustion phase of main injection which diminishes NO_x formation [5-7]. Lots of valuable researches can be found in the literature.

Herfatmanesh *et al.* [8] studied the effect of multiple injection strategies (MIS) on engine performance, and emissions in a common rail direct injection (CRDI) single cylinder optical Diesel engine. The results showed that the NO_x and soot emissions were reduced when the first injection was retarded. Zhang *et al.* [9] studied MIS in a CRDI engine. They applied eight injection events in one cycle. They used the advantageous philosophy of MIS for creating more homogenous mixture coupled with the tuning ability of combustion development with high number of injections per each cycle. The results show that it was possible to reduce both soot and NO_x at the same time with using MIS, but for high load conditions, the MIS was proposed to be used coupled with exhaust gas re-circulation (EGR) and boost addition. An extended literature survey can be found in [10-12].

It can be easily seen from the literature that the start of injection (SOI) timings, the mass and pressure of injections, and their interactions are directly effecting the both performance and emission results. So developing an optimized strategy needs a reliable and fast method which will reduce the testing expenses during the development process of the engine. The researchers choose to use 1-D simulation codes instead of 3-D CFD codes for higher number of parametric optimization strategies works because of simulation time. The 1-D codes serves a great flexibility for testing the whole strategy coupled with complex driving cycles and its effects on engine performance and emissions up to a certain extent of approach. The well known of these codes are AVL BOOST [13], GT-Power [14], and Wave [15]. In this research AVL BOOST code, which is used by lots of researchers [16-18], was used as a solver coupled with MATLAB programme. When compared the 3-D codes the gas and air dynamics, combustion/flame speed, ignition delay, and spray development is characterized with the developed model parameters which should be identified for clearly during the model development process individually. The identification of these model parameters for each individual case needs an expertise, experience in this simulation process. In this research the artificial neural network (ANN) modeling, a widely accepted technology offering an alternative way to simulate complex and ill-defined problems and that has gained significant success of applicability on the internal combustion engines [19, 20], is used for model parameter identification process *via* using predefined huge number model parameters as training sets. This paper is dealing with the developing, validating and analyzing the parametric results of a method which developed with AVL BOOST code coupled with ANN methodology.

Methodology

The methodology that was covered in this research was consisted of six consecutive steps.

Step 1. The engine tests were carried out in this step. In first stage of engine experiments the reference single injection strategy was realized. In the second stage the pilot injection strategy was carried out. All engine performance parameters, temperatures, pressures, and relevant data was logged during this step.

Step 2. The test engine was modeled in 1-D thermodynamic modeling environment in AVL BOOST software. Then the model parameters are calibrated with the experiment results that are logged from the experiments.

Step 3. This calibrated model parameters were used to create a valid ANN model to accurately predicting the model parameters for untested operating points.

Step 4. The new engine operating parameters were fed to the developed ANN model at step 3 for identifying the new model parameters for untested points.

Step 5. These new model parameters were fed in to the 1-D thermodynamic model with new operating points and model was run.

Step 6. The parametric injection strategy analyze was carried out *via* 3-D maps with the new results of developed method. The methodology flow chart is given in fig. 1.

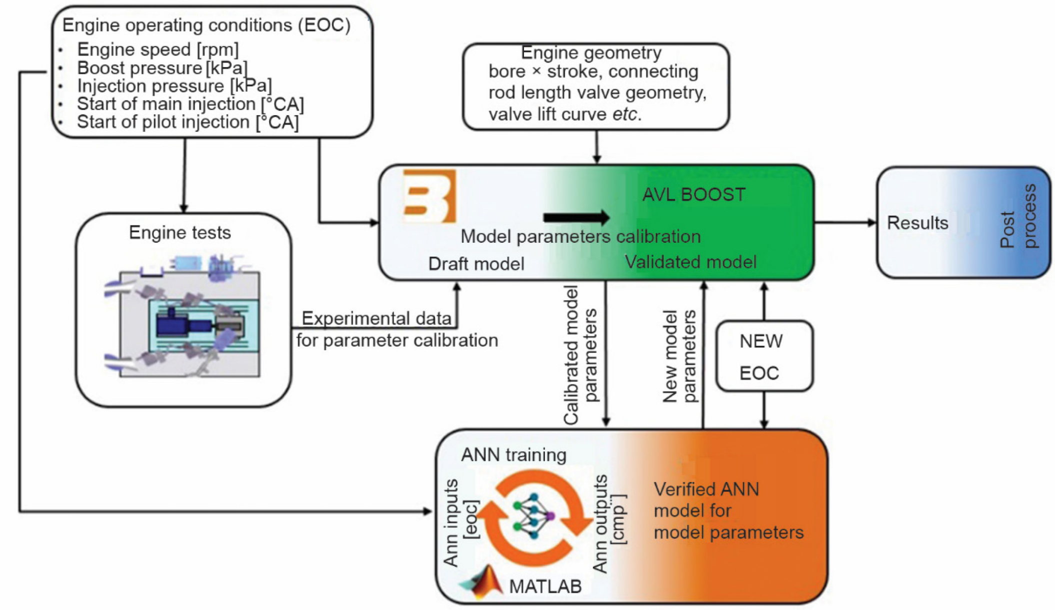

Figure 1. Methodology flowchart

Simulation

Complete engine model

For 1-D thermodynamic modeling of an internal combustion engine in BOOST simulation environment, the intake and exhaust system geometries, the volumes of all plenums, the properties of the boost system, the engine combustion chamber geometry, the valve timing diagrams, and also the injection system properties, injection rate profile, injection pressure for

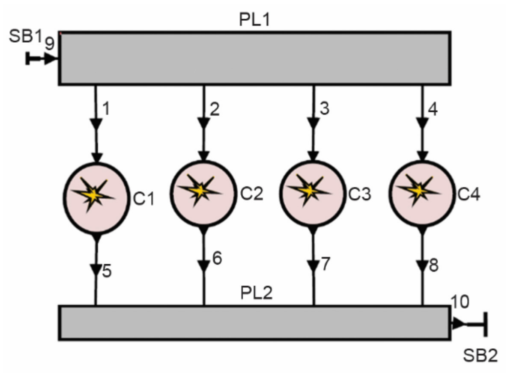

Figure 2. Complete engine model

the specified EOC, the combustion model and wall temperature, and heat transfer model should be provided for analyzing of heat release rate (HRR) and in cylinder pressure. The engine model layout is given in fig. 2.

Combustion model

For modeling combustion, the mixing controlled combustion (MCC) model [21-23] which makes the multiphase injection event modeling possible was used. The model also shortens the complex way of describing the partial processes in Diesel combustion in detail by using highly characteristic higher ranking regularities. The total HRR was taken in to consideration with:

$$\frac{\mathrm{d}Q_{\text{total}}}{\mathrm{d}\alpha} = \frac{\mathrm{d}Q_{\text{MCC}}}{\mathrm{d}\alpha} + \frac{\mathrm{d}Q_{\text{PMC}}}{\mathrm{d}\alpha} \tag{1}$$

Equations for modeling premixed combustion, mixing controlled combustion, droplet evaporation, heat transfer and emissions, are given in the paper according to reference [23].

Premixed combustion phase modeling

A vibe function is used to actually model at HRR at the premixed part of the MCC model:

$$\frac{\dfrac{\mathrm{d}Q_{\text{PMC}}}{Q_{\text{PMC}}}}{\mathrm{d}\alpha} = \frac{a}{\Delta\alpha_{\text{c}}}(m+1)y^{m}\mathrm{e}^{-ay^{(m+1)}} \tag{2}$$

where the total heat input, Q_{PMC}, during the premixed phase is modeled:

$$Q_{\text{PMC}} = m_{\text{fuel,id}}C_{\text{PMC}} \tag{3}$$

and the coefficient y, and premixed combustion duration, $\Delta\alpha_{\text{c}}$, is modeled:

$$y = \frac{\alpha - \alpha_{\text{id}}}{\Delta\alpha_{\text{c}}} \tag{4}$$

$$\Delta\alpha_{\text{c}} = \tau_{\text{id}}C_{\text{PMC-dur}} \tag{5}$$

and the ignition delay, τ_{id}, is calculated with Andree and Pachernegg [24] model:

$$\frac{\mathrm{d}I_{\text{id}}}{\mathrm{d}\alpha} = \frac{T_{\text{UB}} - T_{\text{ref}}}{f_{\text{id}}Q_{\text{ref}}} \tag{6}$$

as soon as the ignition delay integral, I_{id}, reaches a value of 1.0 (= at α_{id}) at the ignition delay, τ_{id}, is calculated from:

$$\tau_{\text{id}} = \alpha_{\text{id}} - \alpha_{\text{SOI}} \tag{7}$$

Mixture controlled combustion phase modeling

The mixing controlled part of the Diesel combustion was accepted as a function of the fuel available for combustion, f_1, and turbulent kinetic energy (KE) density, f_2:

$$\frac{\mathrm{d}Q_{\mathrm{MCC}}}{\mathrm{d}\alpha} = C_{\mathrm{comb}} f_1(m_{\mathrm{F}}, Q_{\mathrm{MCC}}) f_2(k, V) \tag{8}$$

$$f_1(m_{\mathrm{F}}, Q) = \left(m_{\mathrm{F}} - \frac{Q_{\mathrm{MCC}}}{\mathrm{LHV}} \right) (w_{\mathrm{oxygen,available}})^{C_{\mathrm{EGR}}} \tag{9}$$

$$f_2(k, V) = C_{\mathrm{rate}} \frac{\sqrt{k}}{\sqrt[3]{V}} \tag{10}$$

The C_{comb} is calibration factor that modifies the available amount of fuel for combustion and the HRR at the specific crank angle (CA). In other words it identifies the speed of combustion [17]. It is the most effecting parameter on the shape of heat release rate of BOOST model in the mixed controlled combustion phase. So the precise calibration of this parameter with the use of experimental results plays big importance. For considering the total KE effect the injection jets KE (JKE) was taken in to consideration. The intake KE and squish KE are neglected because of their very small magnitudes compared to JKE. Then the turbulence rate, k, was identified with the given equations.

$$\frac{\mathrm{d}E_{\mathrm{kin}}}{\mathrm{d}t} = 0.5\ C_{\mathrm{turb}} \dot{m}_{\mathrm{F}} v_{\mathrm{F}}^2 - C_{\mathrm{diss}} E_{\mathrm{kin}}^{1.5} \tag{11}$$

$$k = \frac{E_{\mathrm{kin}}}{m_{\mathrm{F,I}}(1 + \lambda_{\mathrm{diff}}\ m_{\mathrm{stoich}})} \tag{12}$$

$$v_{\mathrm{F}} = \frac{m_{\mathrm{F}}}{\rho_{\mathrm{F}}(\mu A)} \tag{13}$$

Droplet heat up and evaporation modeling

The equilibrium temperature for the droplet evaporation is calculated according to Sitkei [25] in the simulation:

$$\lambda_{\mathrm{c}}(T_{\mathrm{c}} - T_{\mathrm{d}}) = \frac{30.93 \cdot 10^4 \dfrac{T_{\mathrm{d}}}{p_{\mathrm{c}}}}{\mathrm{e}^{\frac{4150.0}{T_{\mathrm{d}}}} [20.0 + 0.26(T_{\mathrm{d}} - 273.15) + 0.3(T_{\mathrm{c}} - 273.15)]} \tag{14}$$

and the evaporation velocity, v_{e}, and the droplet diameter are calculated from:

$$v_{\mathrm{e}} = 0.70353 \frac{T_{\mathrm{d}}}{p_{\mathrm{c}} \mathrm{e}^{\frac{4159.0}{T_{\mathrm{d}}}}} \tag{15}$$

$$d_{\mathrm{d}} = \sqrt{d_{\mathrm{d,0}}^2 - v_{\mathrm{e}} t} \tag{16}$$

Table 1. Test engine specifications

Capacity	1.8 L
Combustion	Direct injection
Number of cylinders	4
Aspiration	VGT turbo charged
Type	Common rail injection
Bore [mm]	82.5
Stroke [mm]	82
Displacement [cm³]	1753
Compression ratio	17/1
Rated speed	3750 rpm
Max. power [kW]	81 kW at 3750 rpm
Max. torque	250 Nm at 1750-2500 rpm

Table 2. Uncertainity analayses

Measured parameter	Accuracy
Engine torque	±0.14%
NO_x	±1 ppm
CO	±1 ppm
Soot	±0.01 mg/m³
Fuel flow rate	±0.12%
In-cylinder pressure	±0.3%
Calculated results	**Uncertainty**
Indicated power	±0.35%
Brake power	±0.55%
BSFC	±0.8%
IMEP	±0.35%

Experimental method

The experiments for validating the 1-D model were carried on 1.8 L DI common rail CI Diesel engine. The test engine specifications are given in tab. 1. EN590 standard convenient fuel was used as tests during the experiments. For loading the engine a 220 kW AVL APA 204/8 dynamometer was used. The injected fuel mass was also controlled using Siemens l200 electronic control unit (ECU). The ATI VISION software package [26] was used to control the implemented injection strategies *via* the engine ECU. The fuel mass flow was measured with AVL735 C. The fuel temperature was controlled within the range 28 °C with a sensitivity of ±1 °C using an AVL 735S. The mass air flow was measured using an ABB SensyFlow-P. The relative air fuel ratio and CO_2, CO, total HC, and NO_x emissions were measured using a Horiba MEXA 7100 DEGR. The soot was measured with an AVL 415S smoke meter. The tests were run using an AVL Puma Open 1.4 ISAC400 test automation system. The ambient air temperature, relative humidity and atmospheric pressure were held constant during the tests. The manifold pressure was held constant during the tests using a variable geometry turbo algorithm. No EGR is implemented during the experiments. Two stage experiment method was used during this research. These multiple injection strategy experiment results were afterwards used for validating the model. An error analyses was also carried on managing the uncertainty with using Kline and McClintock method [see 27] given in tab. 2.

Stage 1. At first stage, only single injection strategy was implemented. Initially, 81 different single injection strategies were tested. The total fuel mass quantity injected per stroke, f_{q_tot}, engine speed, n, manifold pressure, p_{man}, injection pressure, p_{fuel}, and start of main injection, s_{oim} were varied during the stage 1 (ST1) experiments. The ST1 test points are given in tab. 3. After completing the ST1 experiments, the appropriate soim was chosen for the second stage tests (ST2) with considering engine mechanical limits (*i. e.* turbocharger inlet temperature, and maximum in-cylinder temperature).

Stage 2. The pilot injection strategy was implemented combined with main injection. The 5%, 10%, and 15% mass of f_{q_tot} in ST1 was extracted and injected as pilot injection,

Table 3. Single injection test points

n [rpm]	f_{q_tot} [mgstk^{-1}]	p_{man} [bar]	p_{fuel} [bar]	s_{oim} [°CA(bTDC)]
2000	25	2	1200, 1300, 1400	15, 10, 5
	38	2.2	1300, 1400, 1500	
	43	2.3	1300, 1400, 1500	
2500	28	2	1200, 1300, 1400	15, 10, 5
	37	2.2	1300, 1400, 1500	
	45	2.3	1300, 1400, 1500	
3750	25	2	1200, 1300, 1400	15, 10, 5
	38	2.2	1300, 1400, 1500	
	40	2.3	1300, 1400, 1500	

f_{q_pil}, with three different start of pilot injection timing, s_{oip} in [°CA] basis and then the remaining fuel is injected as main injection. While the s_{oim}, f_{q_tot}, n, p_{man}, and p_{fuel}, were held constant the s_{oip} was changed during the ST2 tests. The s_{oim} was kept as 5 °CA before top dead centre (bTDC) for every operating point. The strategy list with pilot injection is given in tab. 4. The implementation of strategies are given in fig. 3.

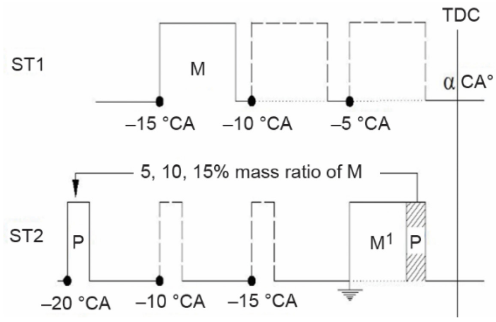

Figure 3. Injection test strategies

Table 4. Pilot injection test points

n [rpm]	f_{q_tot} [mgstk^{-1}]	p_{man} [bar]	f_{q_pil} [% f_{q_tot}]	p_{fuel} [bar]	s_{oip} [°CA]	s_{oim} [°CA]
2000	25	2	5	1200, 1300, 1400	20, 15, 10	5
	38	2,2	5, 10, 15	1300, 1400, 1500		
	43	2,3	5, 10, 15	1300, 1400, 1500		
2500	28	2	5, 10, 15	1200, 1300, 1400	20, 15, 10	5
	37	2,2	5, 10, 15	1300, 1400, 1500		
	45	2,3	5, 10, 15	1300, 1400, 1500		
3750	25	2	5, 10, 15	1200, 1300, 1400	20, 15, 10	5
	38	2,2	5, 10, 15	1300, 1400, 1500		
	40	2,3	5, 10, 15	1300, 1400, 1500		

– The first step of this stage is precise calibration of three critical combustion model parameters (CMP) given in tab. 5. These parameters are directly effecting the combustion physics of the model given in eqs. (1)-(16). The model parameters for the previously mentioned 314 test points (81 ST1 points from tab. 3 + 233 ST2 test points from tab. 4) are at first identified MATLAB Simulink-BOOST co-simulation *via* the IMEP$_{model}$/IMEP$_{test}$ for 720 °CA cycle, Emission-x_{model}/Emission-x_{test}, criteria should be fulfilled in ±10% error range. The calibrat-

Table 5. The ANN model regressions

Parameter	ST1	ST2
	Regression	Regression
C_{comb}	0.98466	0.98246
f_{id}	0.98745	0.96967
C_{PMC}	0.96765	0.97976

ed parameters of CMP are given in tab. 5. The 10 random chosen ST2 test points which are not used in this step, are saved for validation step. This ~5% number of pilot injection cases for validation are chosen considering to the design space of experiment representation which will give an idea about the accuracy of the model among the design space.

– As a second step these CMP are modeled with ANN method which can be called as a massively parallel-distributed processor, made up of inter-connected simple processing units, which has a natural propensity to store experiential information and to make it available for use [28]. The ANN methodology has different network types that researchers use for solving various problems. The multilayer perceptron (MLP) network is a feed-forward ANN that can map a set of input data to a set of appropriate outputs [29]. Also considering to the non-linear behavior of the problem, the MLP is one of the method that can be used in this stage [30]. He and Rutland [19], Uzun [31], Canakci [32], and the papers indicated in [20, 33, 34] used MLP for internal combustion engine related model predictions. The designed ANN whose inputs and outputs are given in fig. 4, was then trained in MATLAB neural network tool box [35]. The inputs are identified as the operating parameters of the engine that are changed during the experiments which effects its performance. The output parameters are identified as the three $V_{critical}$ CMP parameters that were identified with the method mentioned ar first, *i*, step. At the end of ANN training the modeling regressions of BOOST model parameters for ST1 and ST2 strategies ANN models are given in tab. 5. It can be seen that all of the model regressions are over 90% percent, which it can be interpreted as the prediction of model and physical parameters for untested points which will be fed in to the BOOST model are in acceptable range.

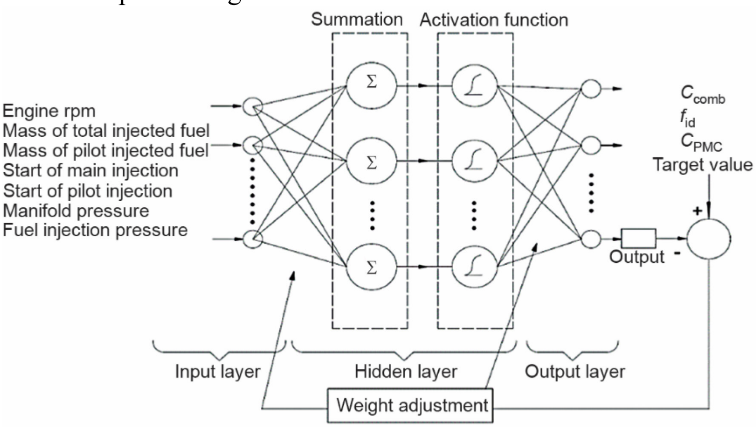

Figure 4. The ANN structure

Results

Results validation

The method is validated in terms of performance and emissions for ten test points. As shown in tab. 6, the prediction accuracy of developed method (BOOST+ANN) is acceptable for NO_x and CO emissions, IMEP and BSFC performance values.

The in-cylinder pressure data are given in fig. 5 (for the operating conditions of validation point No. 1 from tab. 6) as it is seen from figure, the pressure data derived with developed method shows a good correlation with the pressure change of measured data. The NO_x

emissions are modeled with Pattas and Hafner [36] based on Zeldovich mechanism and the CO emissions are modeled with Onorati [37] approach. For the soot emissions the simulation methodology results are not acceptable which they found at the out of the range of 10% range. The high error variation that was obtained for soot results are can be explained with the complex nature of soot formation and the difficulty of its modeling. The Schubiger [38] soot model parameter calibration that was used for soot prediction in BOOST software should be re-made for this test engine with a new approach (inputs, *etc.*) which was of this studies scope. In this context it is obvious that the developed model can be used as a fast responding model for NO_x, CO, IMEP, BSFC, and in cylinder pressure data prediction and analyses without any reservation.

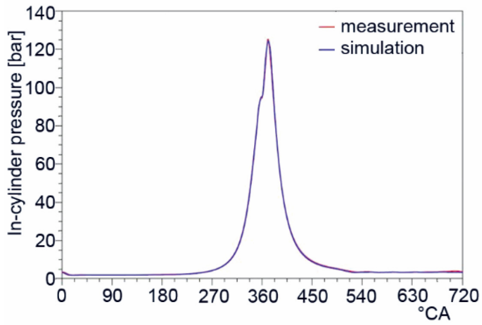

Figure 5. In-cylinder pressure comparison measurement and AVL BOOST simulation
(for color image see journal web site)

Table 6. Random test points chosen for validation

No.	n [rpm]	f_{q_tot} [mgstk^{-1}]	s_{oim} [°CA]	s_{oip} [°CA]	p_{man} [bar]	f_{q_pil} [mgstk^{-1}]	p_{fuel} [bar]	NO_x [ratio]	CO [ratio]	Soot [ratio]	IMEP [ratio]	BSFC [ratio]
1	2000	25	5	15	2	1.596	1300	1.06	1.08	1.27	1.07	1.00
2	2000	25	5	15	2	2.496	1300	1.01	1.06	1.46	1.09	0.99
3	2000	25	5	15	2	3.748	1300	0.97	1.18	1.53	0.98	1.05
4	2000	38	5	20	2.2	1.896	1400	1.04	1.12	0.61	0.98	1.11
5	2000	38	5	25	2.2	5.696	1300	1.14	1.02	1.26	1.06	1.01
6	2500	28	5	15	2	1.598	1300	1.06	1.05	0.82	1.03	1.05
7	2500	28	5	15	2	4.196	1200	1.04	1.04	1.33	1.03	1.08
8	2500	37	5	20	2.2	3.696	1300	1.09	1.02	1.75	1.01	1.03
9	2500	37	5	20	2.2	5.548	1400	1.10	1.04	1.07	1.02	1.07
10	2500	45	5	15	2.3	2.248	1500	1.09	1.04	0.70	1.02	1.05

SOI values are given in terms of bTDC

Pilot injection strategy results with developed method

After validating the developed method on the design space of experiments, the pilot injection strategies for different mass ratios and injection pressures at different SOI are run on the developed method for realizing a parametric research work. The new untested operating points are given in tab. 7. The type of simulations at the specified operating points are chosen to compare and analyses three different strategy results. *Type A*: Start of pilot injection *vs* mass of pilot injection, *Type B*: Start of pilot injection *vs* injection pressure, *Type C*: Mass of pilot injection *vs* injection pressure. The start of main injection is fixed at 5 °CA bTDC for all simulations and the total injected fuel during the stroke is kept as constant: 25 mg/stk.

The results and analyses for the new operating points for NO_x and CO are given in figs. 6-9.

Table 7. New simulation points

Simulation type	n [rpm]	f_{q_tot} [mgstk^{-1}]	p_{man} [bar]	f_{q_pil} [mgstk^{-1}]	p_{fuel} [bar]	s_{oip} [°CA (bTDC)]	s_{oim} [°CA (bTDC)]	No. of simulation
A	2000	25	2	1.20-5^{i}	1200	10-20^{ii}	5	1600
B	2000	25	2	1.25	1100-1500^{iii}	10-20^{ii}	5	1600
C	2000	25	2	1.25-5^{i}	1100-1500^{iii}	15	5	1600

^{i} Pilot injection mass is increased with +0.1 mg increments.
^{ii} Start of pilot injection timing is increased with +0.25 °CA increments.
^{iii} The injection pressure is changed with 10 bar increments.

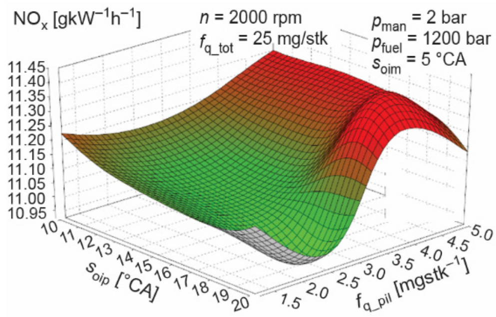

Figure 6. The NO_x emissions s_{oip}-f_{q_pil}

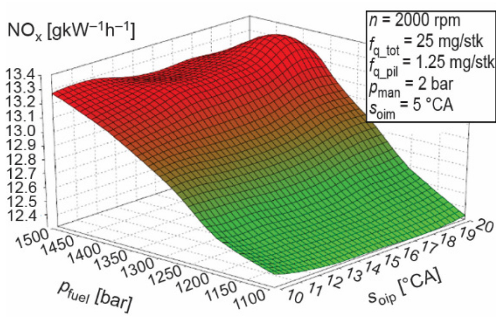

Figure 7. The NO_x emissions s_{oip}-p_{fuel}

The NO_x emission results

As seen in fig. 6. for the same f_{q_pil} up to 3 mg/stk, the NO_x emissions are decreased when the s_{oip} is advanced and also contrary to this behavior the NO_x emissions are increased if the f_{q_pil} is increased a value higher than 3 mg/stk when the s_{oip} is advanced. From the perspective of s_{oip}, for the same s_{oip} between 10-15 °CA, the NO_x emissions are increased with the increase of f_{q_pil} and for the CA between 15-20 °CA for the same s_{oip} the NO_x emissions are decreased slightly up to 3 mg/stk and increased for the values higher than 3 mg/stk. As it can be seen from fig. 6, it is possible to decrease the in cylinder NO_x emissions with the implementation of correct f_{q_pil} and s_{oip}. The change of NO_x emission with the increase p_{fuel} is given in fig. 7. As it is seen from fig. 7, for the same p_{fuel} when the injection is advanced, the smaller f_{q_pil} resulted as smaller NO_x values which can be explained with the decrease of injection delay and hence the decrease of premixed combustion HRR peak [39]. Also for the higher values of f_{q_pil} are resulted as increased NO_x values which can be explained as NO_x production of pilot injection itself which dominates the early combustion characteristics [40]. As it is seen from the figure, the NO_x emissions are increased independent of s_{oip} with the increase of p_{fuel}. This results can be explained with the improvement of combustion characteristics because of better atomization with the increase of p_{fuel} and hence the increase of in-cylinder combustion temperature which triggers NO_x formation [41].

The CO emission results

As it is seen from fig. 8 the CO emissions are increased independent of s_{oip} with the increases of f_{q_pil} up to 4.25 mg/stk. The CO emissions are decreased slightly with the increase of pilot injection from the values higher than 4.25 mg/stk. The CO emissions increasing tendency when the f_{q_pil} share is increased in f_{q_tot} share can be explained with the local zone enrichment in fuel spray with the increase of f_{q_pil} [41] which triggers engine out CO. Also the slight decrease in the CO emissions for the values higher than 4.25 mg/stk can be explained with the increase of CO oxidation with the increase pilot injection mass which dominates the CO formation mechanism.

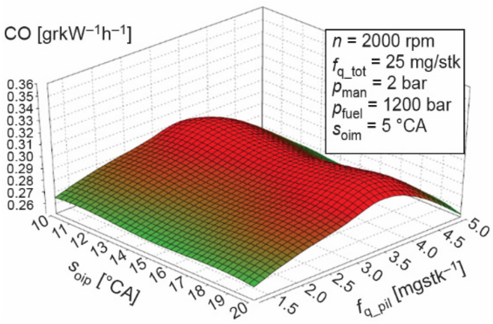

Figure 8. The CO emissions s_{oip}-f_{q_pil}

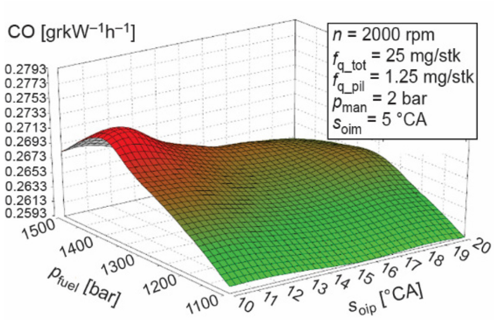

Figure 9. The CO emissions s_{oip}-p_{fuel}

The change of CO emissions with the increase p_{fuel} is given in fig. 7. As it is seen in the figure, the CO emissions are decreased independent of s_{oip} with the increase of p_{fuel}. These results can be explained with the improvement of combustion characteristics and hence the increase of in cylinder combustion temperature which decreases engine out CO emissions.

Conclusions

A 1-D simulation model, coupled with ANN are used for predicting engine performance values. The developed model parameters are validated with experimental results and the critical model parameters are modeled with ANN modeling. Then the model was run for untested points and the results were analyzed. The results revealed the following.

- The methodology developed can be used for engine performance and emission values prediction in the validated range except soot emissions.
- For soot model prediction the emission model parameters modeling in ANN environment should be developed with the new inputs.
- Analyzing the NO_x and CO results: appropriate mass of pilot injection at the appropriate start of pilot injection can be used effectively to decrease NO_x emissions which it was found 1-2 mg/stk for the test engine. Also for reducing CO emissions the pilot injection mass should be kept in the same range with higher injection pressure that can be achieved.
- It is obvious that the method can be used for reducing test costs during the engine developing processes but the method should be validated in a wide band of EOC with including after treatment systems.

Nomenclature

a	– vibe parameter (= 6.9)
C_{comb}	– combustion constant, [–]
C_{diss}	– dissipation constant, [1s^{-1}]
C_{EGR}	– the EGR influence constant, [–]
C_{PMC}	– premixed combustion parameter, [–]
$C_{PMC\text{-}dur}$	– premixed combustion duration parameter, [–]
C_{rate}	– mixing rate, [–]
C_{turb}	– turbulent energy production constant, [–]
d_d	– actual droplet diameter, [m]
$d_{d,0}$	– initial droplet diameter, [m]
E_{kin}	– kinetic spray jet energy, [J]
f_{id}	– ignition delay calibration factor, [–]
I_{id}	– ignition delay integral, [–]
k	– local density of turbulent kinetic energy [m^{2}s^{-2}]

m – shape parameter (= 2.0)
m_F – vaporized fuel mass (actual), [kg]
$m_{F,I}$ – injected fuel mass (actual), [kg]
$m_{fuel,id}$ – total amount of fuel injected during ignition delay phase, [kg]
m_{stoich} – stoichiometric mass of fresh charge [kgkg^{-1}]
p_c – pressure in the cylinder, [Pa]
P_{evo} – in-cylinder pressure at exhaust valve opening, [Pa]
Q – energy, [kJ]
Q_{MCC} – heat release for the mixture controlled combustion, [kJ]
Q_{PMC} – heat release for the premixed combustion, [kJ]
Q_{ref} – reference activation energy, [kJ]
Q_{total} – total heat release rate, [kJ]
T_c – temperature in the cylinder, [K]
T_d – equilibrium temperature of isothermic droplet evaporation, [K]
T_{ref} – reference temperature (= 505), [K]
T_{UB} – unburned zone temperature, [K]
V – cylinder volume, [m^3]
v_e – evaporation velocity, [m^{2}s^{-1}]
v_F – fuel injection velocity, [ms^{-1}]
$w_{oxygen,available}$ – mass fraction of available oxygen (aspirated and in EGR) at SOI, [–]

Greek symbols

α – crank angle, [°CA]
$\Delta\alpha_c$ – premixed combustion duration, [°CA]
α_{id} – ignition delay timing, [°CA]
α_{SOI} – start of injection timing, [°CA]
λ_c – thermal conductivity of the cylinder, [Wm^{-1}s^{-1}]
λ_{diff} – air excess ratio for diffusion burning, [–]
μA – effective nozzle hole area, [m^2]
ρ_F – fuel density [kgm^{-3}]
τ_{id} – ignition delay [second]

Abbreviations

BSFC – brake specific fuel consumption, [–]
IMEP – indicated mean effective pressure
LHV – lower heating value, [kJkg^{-1}]
MCC – mixing controlled combustion
SOI – state of injection

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