Diesel Engine Emission Model Transient Cycle Validation

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Abstract: A control intended data driven B-spline model for NO_x and soot emitted was developed and validated for the 5-cylinder, 2.4-litre Volvo passenger car diesel engine in earlier work. This work extends on the same methodology with some improvements on the model structure for more intuitive calibration and is also developed for the new generation 4-cylinder, 2-litre Volvo passenger car diesel engine. The earlier model was validated using steady state engine measurements and proposed that the model would hold good for transient engine operation. The hypothesis formulated is that a transient engine emission model can be envisioned as a sequence of multi-step steady state engine operation points with minor deviations from the nominal engine operating conditions. The theory is supported by the literature that provides more insight into the transient operation. This idea is carried out in the current work using engine test cell measurements validated for a NEDC as well as a normal road drive cycle that depicts a more transient driving behaviour in comparison to the standard emission driving cycles. Nearly 4600 engine operating points with steady state measurement including nominal and deviant conditions have been used in the development of the model. The ability of the data driven approach to mimic the engine emission generation characteristics during the engine transient operation is analysed and its superior performance in comparison to the Nominal model and the Regression model is demonstrated.

Keywords: Diesel Engines, Engine modelling, Splines, Automotive Emissions, Transient Analysis

1. INTRODUCTION

Harmful effects of Nitrogen Oxides and Particulate Matter emitted from automobile sources are well established in several studies. The ill effects of both short term and long term exposure to diesel exhaust in all intensities could induce respiratory complications and lifetime cancer risk among other hazards. The environmental effects of diesel exhaust such as acid rain, smog and the much debated climate change impose several concerns for the future of human well-being forcing actions by the respective regional transport bodies such as the European Union, US Environment Protection Agency etc., in establishing diesel exhaust emission norms and enforcing stricter norms with the passage of time and advancement of technology. See US EPA. (2002).

1.1 Emission Norms

The path taken by exhaust emission regulatory agencies for the passenger car segment (light duty diesel engine applications) until the recent past (eg. from Euro 1 to Euro 6b) have been more of a reduction in the limits of permitted NO_x and Diesel soot for a specific driving cycle. The representative cycle has not changed significantly to adapt to technological changes over decades. The steps in emission norm updates have led to the introduction of emission reducing technologies such as Diesel Oxidation Catalyst, Cooled EGR, Diesel Particulate Filter and Lean NO_x Trap. Statistical evidence from on road emission tests have recorded dramatic increase in exhaust emissions widening the gap between perceived realities and expected emission reduction and thus non-attainment of emission goals envisioned. This has led to the framing of upcoming emission norms which will include on road emission monitoring and thus be based on real driving conditions with enhanced coverage of engine operating conditions. See CARS (2020).

In order to comply with real drive emission limits, significant improvements in Engine and After-treatment design have to be undertaken to bring emission compliance in areas that were once considered out of bounds. The impacts on the diesel engine calibration are on both the coverage area of Speed - Load of the engine as well as the operating conditions such as handling transient behaviour, ambient conditions, and driver- disturbances. The changes imparted would lead to enhanced challenges on the control of the transient characteristics of the engine.

1.2 Modelling perspective: Cost-Accuracy trade-off

Emission formation in engines is a complex non-linear process that is dependant on a wide range of operating conditions. The established formation mechanisms used in simulations today, already involving complex calculations using powerful computers might be able to model the diesel emissions after considerable effort. However this is still a simplified model considering only a few combustion parameters and needs to be adapted to the specific engine being dealt with. These methods based on first principles are extremely slow in comparison to real time applications and are intended for research phases. A more hybrid methodology using simplifications of the first principles and calibrated using real measurement data is used in conceptual phases. Considering the computational power and the response time requirement in the Engine Management System (EMS), it is not possible to implement first principles based models in production systems and thus makes the case for data driven model implementation. Moreover, estimation of emissions in absolute values have been easier with data driven models in comparison. From a user point of view, data driven methods offer far better tuning and calibration opportunities.

1.3 NO_x and Soot modelling

NO_x and soot predictability is a highly effective tool for a well-integrated supervisory control of the engine and after treatment system. The emission models in the EMS needs to be fast and accurate to trigger after-treatment control measures. The accuracy of the emission models will be vital for the further development of closed loop emission controls. The simplification processes that the model undergoes to be able to be faster involve significant deterioration in accuracy of the emission estimation. Therefore it is a combined goal of increasing the accuracy with minimal increase in model complexity. This is being attained with the help of advanced mathematical methods that have shown promising results. The use of Gaussian methods, Neural networks, Regression models, Bayesian techniques and Splines have been experimented by the researchers in this field. While most have documented performance on Steady state engine operating conditions, few have ventured into their transient response. Even as these transient behaviour are examined they are mostly limited to the standard emission test cycles. See Berger et al. (2011) Brahma et al (2009) Grahn M et al (2012a).

2. EMISSION FORMATION IN TRANSIENT ENGINE OPERATION

A transient engine operation occurs due to change in requested engine speed or load. Engine speed dynamics result in altered time per diesel cycle leading to disturbances in the combustion chamber and the air entrapment until the attainment of an assumed steady state. Dynamics in engine load alters the air-fuel ratio that affect the power and heat release resulting in thermal fluctuations compared to steady state operation. See Constantine and Evangelos (2009), Heywood (1988) for more theory.

2.1 Soot and NO_x formation

Soot formation during transient engine conditions deviates from steady state operation because the boosting system dynamics are not as fast as the fuelling rate changes. The resultant soot emitted in the diesel exhaust is influenced by the obtained air - fuel mixture. NO_x formation is strongly dependant on in cylinder temperature which in turn depends on Oxygen concentration and combustion duration. During an engine transient, change of load leads to increased fuelling and smoke control measures such as EGR starvation then may lead to a NO_x spike.

In order to estimate the emission components during the engine transient operation, these causes should be suitably captured by the underlying model.

3. B-SPLINE MODEL FOR NOx AND SOOT MODELLING

3.1 Background

The work carried out with respect to NO_x and soot modelling using first order B-Splines utilising their linear equivalence has been established and documented in the early works in Grahn M et al (2012b). A globally optimised, smoothened, regressive parameter based, B-Spline function applied to perform model calibration using data fitting method was established and verified in static engine operating conditions for a 5 cylinder Volvo diesel engine. The model is summarised as

$$log\left(\frac{\hat{\alpha}}{x_1 \cdot x_2}\right) = f_0(x_1, x_2) + \sum_{i=1}^{3} z_i \cdot f_i(x_1, x_2) \qquad (1)$$

where $\hat{\alpha}$ denotes the predicted Engine out soot or NO_x, x_1 and x_2 are the input signals Engine Speed and Fuel Injected quantity respectively, z_i are other emission affecting input signals to the model, $f_0(x_1, x_2)$ and $f_i(x_1, x_2)$ are model parameters represented by two dimensional linear interpolation maps.

This paper focuses on simulating such a model developed for a real world driving condition applied to the new Volvo Diesel engine, specifications of which are listed below

Table 1. Engine Specification

Cylinder pitch(mm)	91
Bore(mm)	82
Stroke(mm)	93.2
No. of cylinders	4
Swept Volume (l)	1.969
Compression ratio	15.8

3.2 Desired model properties

The development phase of a diesel engine normally undergoes years of calibration updates for efficient engine control. It is the motive of this work to capture the effect of such changes without requiring to acquire new data from the engine repeatedly with each calibration. Thus given no hardware changes on the engine, the model would be representative of the engine irrespective of the calibration change since the dynamics of the emission formation are captured by operating the engine with the permissible degrees of freedom.

The models should be comprehensible to the calibration engineer and be intuitive as to how the factors in the calibration affect the predicted quantities. The objective is a model of the diesel engine soot and NO_x emissions that can be implemented in the engine management system. This serves the control and management of diesel active and passive particulate filter regeneration as regards the diesel soot. The $\mathrm{NO_x}$ emissions estimate serves to replace or assist the $\mathrm{NO_x}$ sensors that serve as the primary input for the diesel $\mathrm{NO_x}$ After-treatment control such as the Lean $\mathrm{NO_x}$ trap, Selective Catalytic Reduction etc.,

3.3 Scope of the model

The scope of the work carried out here is limited to analysing the behaviour of the estimation in transient conditions. Ambient operating condition limitations, engine cold start, sensor delays, special after-treatment modes or any drastic events are not in the scope of this work. Assumptions here include that considerable effort has been applied in bringing down or stabilising the effect of the transient emissions during all anticipated engine operating conditions keeping the engine emission compliant as well as drivable. Turbo lag, gear up shifting, fuel injection rate changes and all variables that influence emission formation due to the transient effect of the actuators and combustion are calibrated before modelling the emission formation.

4. MODEL STRUCTURE AND DESIGN OF EXPERIMENT

4.1 Choosing the control signals

The model fundamentals and methodology has been maintained as in the original work Grahn M et al (2012a). The changes done in establishing the new model in comparison are the input signals chosen which impact the emission formation. The input signals for the model chosen after considering the emission formation process and the available measured or estimated variables in the EMS are Fuel Rail pressure, Global Equivalence ratio, Oxygen concentration at intake manifold and Fuel injection timing. All the variables are carefully chosen such that they are accurate by comparing them against additional measurement equipment. Since all the variables are available for the online estimation of emissions, the model can be implemented in the engine management system.

The global equivalence ratio gives a better estimate of the mean combustion quality of the engine during the transient engine operating condition since this is provided by a fast lambda sensor. The oxygen concentration at the intake manifold should be able to put in summary the quality of intake fresh air - EGR mixing, response of the turbocharger and the pumping dynamics affecting the fresh air charge during the engine operation. The fuel injection timing is necessary to characterise the engine combustion.

4.2 Mathematical expression

The model structure developed in the early works modified for better calibration intuition and using control signals chosen is mathematically expressed as

$$log\left(\frac{\hat{\alpha}}{x_1 \cdot x_2}\right) = f_0(x_1, x_2) + \sum_{i=1}^{4}(z_i - z_{0i}(x_1, x_2)) \cdot f_i(x_1, x_2) \tag{2}$$

where z_{0i} is the nominal value of the emission affecting input and z_i is the actual value of the emission affecting input. The notations and the corresponding description is summarised in the following table

Table 2. Input and Output signals for Emission modelling

Notation	**Description**	**Unit**
$\hat{\alpha}$	$\mathrm{NO_x}$ or Soot	mg/s
x_1	Engine speed	rpm
x_2	Fuel injected mass	mg
z_{0i}	Nominal operating condition value for emission affecting inputs (1 to 4)	
z_i	Deviation correction for emission affecting inputs w.r.t nominal operating condition	
z_1	Fuel injection timing	CAD
z_2	Intake oxygen fraction	%
z_3	Global equivalence ratio	-
z_4	Fuel rail pressure	Pa

4.3 Experiment and Measurement

The models have been developed using the measurement data from the new generation Drive-E Volvo Engine Architecture Family, 4-cylinder 2-Litre, Euro 6b compliant diesel engine with two stage turbocharger, an Exhaust gas recirculation system and i-ART injectors with a common rail system described in Crabb D et al (2013) and summarised in Table 1. The measurements have been done in an emission test cell that is equipped with the state of the art instantaneous emission measurement equipment for diesel soot, $\mathrm{NO_x}$, fuel mass balances. The exhaust after-treatment system is unspecified since the current work is aimed at estimating engine out emissions.

A Part load map with as much grid points as possible was done to capture all the nominal driving condition for steady state engine behaviour. In doing so, more than 950 operating points with engine speeds ranging from 850 *rpm* to 4500 *rpm* and fuel injection mass spanning from 0 to 60 *mg* have been measured and recorded. In order to include the deviations from the nominal engine operation behaviour which is highly expected to occur during transient operating conditions, a design of experiments with a target to explore the degrees of freedom in the emission influencing input signals that have been decided is carried out. This subjects the engine to some of the unknown operating conditions that the engine could possibly incur while in transient operation.

The objective is to capture data of the characteristics mainly of system with known variations in the input signals and their ability to portray the emission components. The experiment was designed in such a manner that variation of the individually identified components characterising the emission formation are represented. Thus it is seen to it that the spread in fuel rail pressure, intake oxygen fraction, global equivalence ratio and the fuel injection timing are deviating from the nominal engine operating conditions. In all nearly 4600 operating points were run using state of the art automated engine rig systems. The significance of the spread will be realised in the section covering the transient analysis.

5. MODELS

5.1 B-Spline Model

The model structure defined is calibrated against measured data received from the steady state nominal and the experimentation engine operating points. Smoothening of the Maps is carried out such that the RMSE of the predicted emissions is minimised. The calibration is done for a total of 15 axis points for the engine speed and the Fuel injected quantity. The results of the model calibration for both the emission components i.e. NO_x and Soot are carried out and the nominal map of NO_x thus obtained is shown in the following figure.

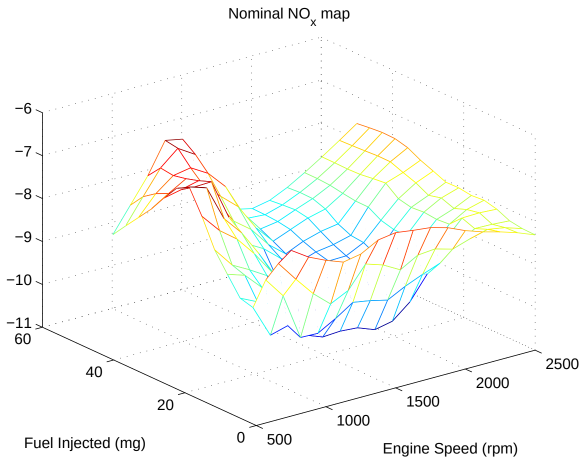

Fig. 1. Typical map of NO_x generated for nominal engine operating conditions constituting $f_0(x_1, x_2)$ in equation (2) i.e. without any compensatory factors for deviations.

The compensation maps that constitute the remaining part of the equation (2) are carried out and as an example the rail pressure compensation for NO_x modelling is shown in Figure 2. Note that the map provides a compensation factor for the deviation in rail pressure from its nominal value or target value. Similarly the compensation maps for the other input signals are determined. The nominal values of the input signals are calculated using the part load mapping of the engine which is used in determining the nominal emission model map.

5.2 Global regression

In the global regression model, all the signals used for predicting the emission model in the B-Spline model are included namely Engine Speed, Fuel Injected Mass, Fuel Rail pressure, Fuel Injection timing, Oxygen concentration in the intake manifold and the Global Equivalence ratio. A full quadratic regression with linear, interaction and quadratic terms is used resulting in 28 regression terms similar to the model used in Brahma et al (2009).

5.3 Nominal Model

The nominal model is derived by neglecting the emission affecting input signals that were used to derive the main model using the B-Splines. Thus this is the result of simplification of (2) using only the $f_0(x_1, x_2)$ term expressed mathematically as

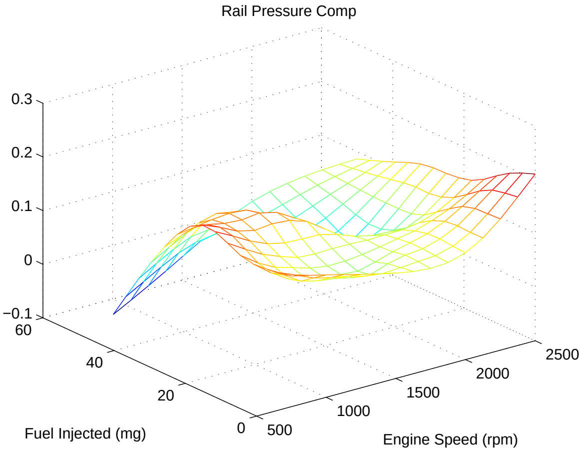

Fig. 2. Compensation map for Engine NO_x due to deviation in Rail pressure from the nominal pressure corresponding to the term $f_4(x_1, x_2)$ in equation (2).

$$log\left(\frac{\hat{\alpha}}{x_1 \cdot x_2}\right) = f_0(x_1, x_2) \qquad (3)$$

Thereby the model is primarily defined only by the Engine Speed-Load operating point irrespective of the other signals. The data thus used includes only the engine nominal operating points. The model is very similar to the Figure 1 since they represent the same mathematical expression.

5.4 Steady state performance comparison and analysis

The steady state operating points used in the creation of the models are used in the validation of the steady state performance of the models thus developed. The Table 3 shows the comparison of the correlation and the root mean square error of the NO_x mass flow and soot mass flow.

Table 3. Comparison of Steady state model results - Including all engine operating points for validation

		B-spline Model	Nominal Model	Global regression
NO_x mass flow	RMSE (mg/s)	0.9768	5.4722	2.136
	Corr (ratio)	0.9936	0.7982	0.969
Soot	RMSE (mg/s)	0.2542	0.9137	0.3602
	Corr (ratio)	0.9678	0.3603	0.9326

A second comparison is carried out with only nominal engine operating points as validation data. The results are in Table 4. This provides an explicit way of comparing the B-Spline model for just the nominal operating conditions. It can be seen that the B-Spline model outperforms the Regression and the Nominal model in both cases. Nominal operating points are not perfectly nominal and

Table 4. Comparison of Steady state model results - Including only nominal engine operating points for validation

		B-spline Model	Nominal Model	Global regression
NO_x mass flow	RMSE (mg/s)	0.2819	0.5796	1.1541
	Corr (ratio)	0.9995	0.9979	0.992
Soot	RMSE (mg/s)	0.0684	0.0930	0.206
	Corr (ratio)	0.9901	0.9814	0.9188

small deviations will be prevalent. The B-Spline model is able to capture even the small deviations and allocate corresponding correction factors. Thus the B-Spline model is able to outperform the nominal model even when only nominal operation points are evaluated.

6. DYNAMIC CYCLE ANALYSIS

6.1 Experimentation and Data collection

The objective of the model, if used in the engine management system, is to predict the soot and NO_x in the real driving conditions. For this a real driving cycle was logged from a passenger car. This drive was replicated on the engine dynamometer and the engine was operated in the same Engine Speed - Load condition as the car on road. The air system dynamics and the responses were compared so that the deviation was acceptable. The test cycle on the engine dynamometer was repeated several times so that the statistical average performance is more reliable. The input signals required for the models and the corresponding emission measurement were recorded. In running such a test, the engine had a combination of steady states and real transients as would be expected for a real driving condition, thus capturing the effect of the transient engine. The transient cycle used for this work is shown in the following figure.

The models have also been evaluated for multiple NEDC cycles performed on the same engine setup. However the goal of the work is not to be limited to the NEDC operational area and thus the choice of a real driving cycle makes a better use case and hence both are included for a comparison.

6.2 Methodology and Analysis

The recordings from numerous cycles run on the dynamometer were aligned back to back. The logged input signals for the model were filtered to fit the scope of the current work. In doing so, the special engine modes were neglected. The input signals extracted after filtering were used by the model to generate the emission estimate for the entire loop of all the cycles in a cumulative manner. The cumulative emissions measured was compared against the cumulative model estimates. The error in estimation is the cumulative error across all the cycles together.

Measurement of soot and NO_x is challenging due to the presence of varying transport delay involved depending on factors such as the exhaust mass flow and the temperature. However, the model developed estimates the instantaneous emission components and thus is expected to be faster than the measurement equipment. Also the filtering effect present in the measurement device during engine transients would not be present for the direct model output. The cumulative emissions considered here offer a better comparison of the model against measurement. The cumulative sum trajectory of the predicted emission constituents should lie in the same path and react to the indicated measurement thereby also ending up close to the real average emission of the cycle.

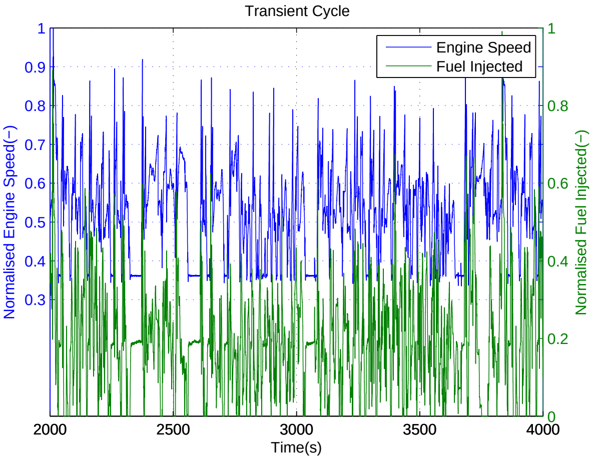

Fig. 3. One representative period of the on road test cycle used for model evaluation: Normalised Engine Speed - Fuel Injected.

6.3 Results

The model is simulated and compared to the measurement for the transient cycles and the results are summarised in Table 5. As was mentioned in the section on Experiment and measurement, the inclusion of measurements of the deviations of the emission influencing parameters under transient engine operation from the nominal conditions play a significant role in increasing the accuracy of the emission model in transients. The impact of this usage is clearly seen in the evaluation summary. It can be seen that while the nominal model is better in the steady state evaluation, the transient results are far worse than the comparative B-Spline model. The Global regression model fails to have a better estimate than the others and clearly is not suitable to handle transient estimations.

Table 5. Summary of results from transient simulation

Emission comp.	Drive Cycle	Cumulative Error over the cycle %		
		B-spline Model	Global regression	Nominal Model
NOx	Road drive	8.7	57.5	39.8
	NEDC	8.6	32.9	29.1
Soot	Road drive	22.6	34.3	18.5
	NEDC	14.1	33.5	34

The cumulative error for the road driven test cycle of the engine NO_x and Soot predicted is shown in the Figure 4 and Figure 5. Clearly the B-Spline emission model follows the dynamics of the measured emissions. The accuracy of the model in the transient cycle is highly influenced by its accuracy in the steady state operating condition.

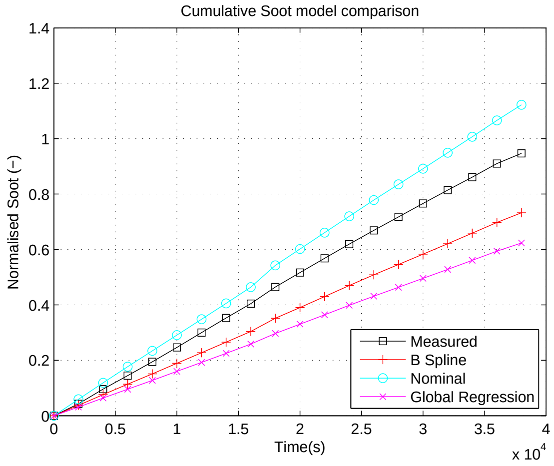

Fig. 4. Cumulative Soot model comparison for the on road test cycle.

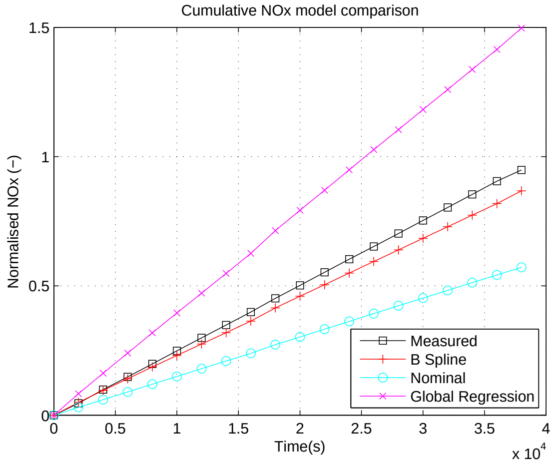

Fig. 5. Cumulative NO_x model comparison for the on road test cycle.

6.4 *Close up analysis*

A smaller time section of the on road drive cycle with the instantaneous and the cumulative soot emission is shown in Figure 6 and Figure 7 respectively. Soot is chosen to be analysed here since it is the lesser accurate estimation by the model and hence will display the negative characteristics. It can be seen that there is a good correlation at some instances and there are a few bad areas. Also noticed is that the cumulative soot emission follows the same trajectory as per the hypothesis. The lag between the estimate and measurement is noticeable since this effect has not been corrected. Also the measurement is smoother due to the filtering.

6.5 *Areas of improvement*

Consider the same time period of the emission predicted as in Figure 6. When the used input signals in the model are beyond the deviation data used in the creation of the model, the estimate is expected to be poor. This is shown in Figure 8 which helps in understanding the underlying reason. The deviation is calculated as the ratio between the current input signal deviation $(z_i - z_{oi})$ and the maximum

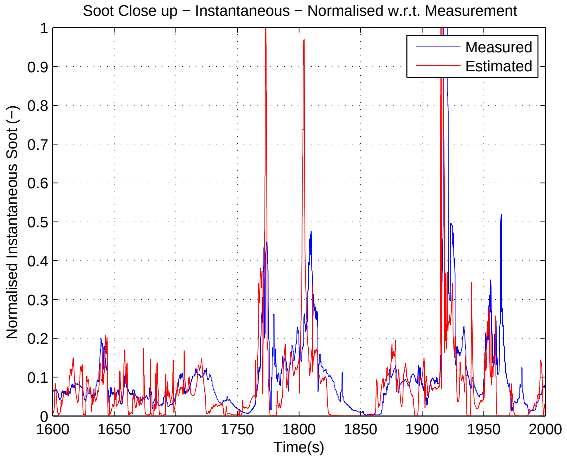

Fig. 6. Close up analysis of one time period (1600 to 2000s) of soot emissions seen here with instantaneous values.

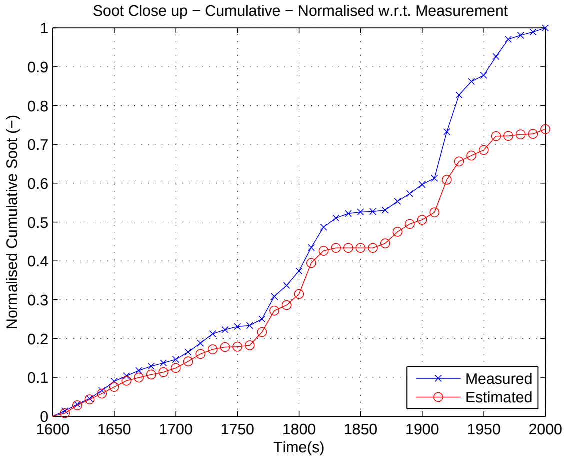

Fig. 7. Cumulative soot emissions for the same period (1600 to 2000s) for which the instantaneous emissions have been shown in Fig 6.

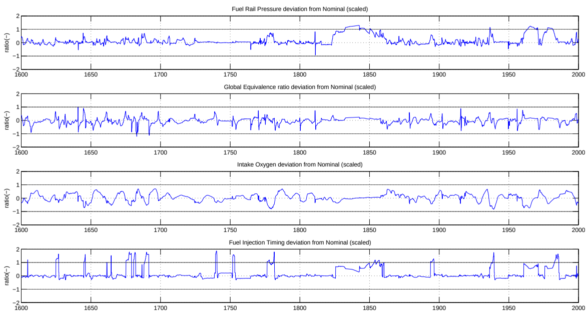

Fig. 8. Deviation of contributing factors: Fuel Rail Pressure, Oxygen fraction in inlet manifold, Equivalence ratio and Main injection timing, used in emission modelling. The time period is the same period as being analysed(1600 to 2000s). The deviation on the Y axis is calculated as the ratio between the difference from the nominal value to the maximum measured deviation in the measurement campaign.

input signal deviation max(abs($z_i - z_{oi}$)) that was observed while performing the deviation steady state measurements. It is noticed that the Fuel rail pressure and Fuel Injection timing breach the deviation considered while modelling. Although this may not be the physical reason behind the inaccuracy in the model prediction, it is the reason that the model points out for the specific incident. The actual reason could be other non considered signal deviations or that the measurement equipment is inaccurate.

A wider collection of the contributing factors deviating from the nominal engine operating point in the model creation will increase the accuracy in the transient driving conditions. Looking at the absolute results, considerable improvement in determining the soot modelling emissions is necessary since the steady state emission estimate need to be accurate in order to increase the transient emission modelling accuracy. There also may be reason to investigate the actual soot measured data.

7. SUMMARY

7.1 Discussion

It is noticed that under the transient driving conditions as indicated by the verification test, the developed model is able to replicate similarly accurate results as in the steady state conditions. The engine out NO_x modelled in this manner is seen to be acceptably accurate for the purpose of implementation in the engine management systems and hence a definite candidate for a simplified solution in terms of calibration, engine tests, cost, performance and a reliable control. It is seen that the soot emissions verified with the transient data are equally deviant as in the steady state operating verification points. It is clearly evident and logical to state that the transient behaviour can be only as good as the behaviour in the steady state verification points. Adding to the argument is the similarity in the response translation of the global regression models and the nominal model when their comparison of steady state and dynamic results are performed.

7.2 Conclusion

Measuring transient engine emissions and related data with advanced measurement devices is a challenge in the production environment. Therefore it is sensible to develop a model that is based on reliable measurements which in that case is done at steady state engine conditions. The developed model is suitable for implementation in the engine management system as it holds good for dynamic driving conditions expected to occur in the real driving case. This is a valuable precursor to predictive emissions and for framing of engine and after treatment control optimisation for a real on road drive condition which is one of the objectives of the future work to be carried out.

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