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Multi-Objective Optimization of Transient Air-Fuel Ratio Limitation of a Diesel Engine Using DoE Based Pareto-Optimal Approach

Cetin Gurel, Elif Ozmen, Metin Yilmaz, Didem Aydin, and Kerem Koprubasi
Ford Motor Company

ABSTRACT

Emissions and fuel economy optimization of internal combustion engines is becoming more challenging as the stringency of worldwide emission regulations are constantly increasing. Aggressive transient characteristics of new emission test cycles result in transient operation where the majority of soot is produced for turbocharged diesel engines. Therefore soot optimization has become a central component of the engine calibration development process. Steady state approach for air-fuel ratio limitation calibration development is insufficient to capture the dynamic behavior of soot formation and torque build-up during transient engine operation. This paper presents a novel methodology which uses transient maneuvers to optimize the air-fuel ratio limitation calibration, focusing on the trade-off between vehicle performance and engine-out soot emissions. The proposed methodology features a procedure for determining candidate limitation curves with smoothness criteria considerations. Following the design of test plans, DoE testing is performed on the engine test bed using transient maneuvers which are representative of typical customer behavior. Transient data obtained from DoE tests are then projected into cumulative performance metrics. After modeling, multi-objective optimization is applied for the reconstruction of air-fuel ratio limitation maps considering Pareto optimality between soot emissions and engine performance. The methodology is applied to a diesel engine with Euro VI emission norms and experimental results are presented including the evaluation of performance and drivability metrics on a test vehicle. Potential areas of future work to improve data collection, modeling and optimization processes are also discussed.

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INTRODUCTION

Stringent pollutant emission regulations have been the driving force behind the evolution of hardware and software of internal combustion engines. Especially NOx and particulate matter emissions and particulate number play a very important role in the advancement of diesel engine aftertreatment technologies. New emission legislations include test cycles with highly dynamic characteristics. Therefore the transient nature of test cycles has shifted the focus of diesel engine development process to transient operation where the majority of soot is produced [1]. Software strategies to regulate air-fuel ratio are widely used during transient maneuvers and these strategies are proven to be effective for the reduction of transient soot emissions [2]. Common calibration methodology to optimize air-fuel ratio limitation involves iterative testing and development processes with subjective evaluation metrics [3]. In this paper, a calibration methodology for air-fuel ratio limitation is proposed featuring transient testing, statistical modeling and multi-objective optimization phases.

Following chapter gives a motivation and background information on the paper subject. In the second chapter, proposed calibration methodology is explained. The details of each step of the calibration methodology are discussed in each subsection such as curve generation, modeling and optimization. In the third chapter, results obtained by using the proposed methodology are given along with the test setup and engine information. Conclusions and potential future work are presented in the final chapter.

Motivation & Background

Exhaust emissions are a focal point for the development of internal combustion engine technology. Most attributes of a modern diesel engine, such as fuel economy and performance, are directly affected by emission constraints. NOx, HC, CO and particulate matter (PM) pollutant emissions are regulated in diesel engines since the initial application of the Euro I standard in Europe. Particulate number (PN) are later added to the regulated pollutants from Euro VI onward for heavy duty vehicles and Euro 5b for light duty and passenger car vehicles in Europe. With the application of each tier of emission regulations, cycle tailpipe emission limits for these pollutants are dramatically reduced. In addition to the reduction of emission limits, new test cycles are implemented with more transient characteristics that are similar to real world driving conditions.

For heavy duty vehicles in Europe, European Transient Cycle (ETC), which is introduced with Euro III emission regulations became the first emission test cycle featuring realistic driving characteristics. Later World Harmonized Transient Cycle (WHTC) replaced the ETC test with the introduction of Euro VI regulations. For light duty commercial vehicles and passenger cars in Europe, Worldwide Light-duty Test Cycle (WLTC) is expected to replace New European Driving Cycle (NEDC) test with the introduction of Euro 6.2 regulations. WLTC test features very aggressive transient maneuvers in contrast to mostly steady state NEDC test and covers a much wider engine operating range, including full load operating points. In addition to these transient emission tests, on-road emission tests are also implemented for heavy duty (Euro VI onward), light duty and passenger car (Euro 6b onward) vehicles. In-service conformity and Real Drive Emissions (RDE) tests consist of on-road emission testing using Portable Emission Measurement System (PEMS) and they feature highly dynamic characteristics due to the nature of real world driving conditions. These transient tests add another dimension to the existing complexity of calibration development processes, further increasing the emphasis of transient operation from the emissions and fuel economy perspectives.

The use of exhaust gas recirculation (EGR) in turbocharged diesel engines is one of the most effective and widely-used methods to reduce NO_x emissions in order to meet the strict regulations. NO_x formation is reduced due to reduced combustion temperatures and oxygen ratios in EGR applications. However, particulate matter and soot formation is increased by this same mechanism causing a trade-off between PM and NO_x emissions [4]. In a common real world driving profile, the engine mostly operates in transient conditions where the air-fuel ratio is much lower than steady-state conditions due to turbo lag, contributing more to soot and PM emissions, also leading to increased Diesel Particulate Filter (DPF) regeneration frequency and fuel consumption [1, 3]. Euro VI c heavy duty On-Board Diagnostics (OBD) emission regulations mandate the usage of soot sensors when engine-out soot emissions are above a certain limit. Therefore, the reduction of engine-out soot emissions enables the deletion of expensive soot sensors, providing cost and robustness benefit.

One of the most effective soot reduction methods in transient conditions is to achieve leaner engine operation. One method to achieve leaner operation is to reduce EGR ratio, which is undesirable due to the high NO_x penalty involved [5]. Another method is to reduce fuel injection quantity during transients, which can be achieved by filtering or limiting the fuel quantity demand. The effect of limiting the fuel quantity is significant in terms of tailpipe emissions, considering the most common vehicle maneuvers in a real driving cycle [2]. Among soot reduction methods, limiting the fuel injection quantity depending on the airflow mass or limiting the air-to-fuel ratio (AFR) is quite effective from cumulative drive cycle based perspective [3].

Model-based optimization of soot emissions is a promising approach for the reduction of engine-out emissions. Design of Experiments (DoE) followed by steady-state modeling and optimization is typically used. Model based calibration development methodology results in optimally selected calibration maps which are automatically generated using specialized software. Development processes that utilize Gaussian process modeling technique combined with optimization algorithms are widely used for stationary fuel economy optimization with emission constraints [6]. Promising results are also obtained by applying model-based calibration methods on cycle-based fuel economy optimization featuring transient engine operation [7]. However, modeling of soot emissions has always been a challenging topic for diesel engine development [8, 9]. Steady-state modeling approach requires a large set of measurements on the engine dynamometer and the inherent complexities of soot measurement techniques poses further difficulties [10, 11].

A significant amount of research has been conducted for steady-state modeling of soot formation using the DoE methodology [12]. The selection of relevant inputs and use of proper measurement techniques make it possible to achieve satisfactory modeling performance for the calibration optimization process. However, steady-state models prove to be insufficient as the transient behavior of new regulation test cycles becomes more dominant.

In recent years, alternative approaches using dynamic modeling techniques have emerged for engine-out soot characterization. Deng et al. [13] proposes using a combination of neural networks and physical models for PM characterization which provide acceptable model quality in both steady-state and transient operations. Although dynamic PM models can provide a good alternative to the steady-state modeling approach, there are several issues concerning the overall calibration optimization process. DoE testing for dynamical models is complicated since the selection and appropriate excitation of input channels play a crucial role. Model tuning and optimization steps are also relatively time-consuming compared to steady-state models.

Recent literature in calibration methodology for air-fuel ratio limitation relies on conducting transient torque step tests and measuring soot emissions with the opacimeter device [14] and includes multiple iterations between dynamometer and vehicle tests. Model-based calibration development techniques are becoming increasingly popular for eliminating trial-and-error procedures [15]. The data-driven black-box modeling approach has proven to be effective for calibration development purposes as it is proven to be a versatile technique for modeling most of the diesel engine responses [16]. The Gaussian process modeling approach is particularly known to provide good modeling accuracy and robustness [17]. Another important consideration for the calibration of air-fuel ratio limitation is the smoothness of resulting calibration maps as engine speed and airflow mass vary. The calibrated map points should not change abruptly to avoid undesirable transitions between different speed and mass airflow operating points during vehicle operation. This condition restricts the calibration of maps into a constrained space which must be taken into consideration during the modeling and optimization process. Smoothness constraints are often applied during calibration optimization [15]. Application of smoothness after the optimization step typically results in the generation of sub-optimal calibration maps. Many commercial modeling and optimization tools provide map smoothness criteria for optimization purposes [6]. However, applying smoothness criteria only during the optimization phase is not sufficient. In order to obtain high soot data quality during transient DoE testing, the input selection procedure should also take smoothness into consideration. This results in more favorable engine operating conditions during DoE testing since the test maneuvers are implemented using smooth air-fuel limitation map candidates.

CALIBRATION METHODOLOGY

Process Overview

The calibration process for air-fuel ratio limitation starts with candidate curve generation for the DoE test. Candidate limitation curves of lambda values (for selected engine speeds) are generated using the space-filling method with smoothness constraints. Lambda is defined as the air-fuel ratio divided by the stoichiometric air-fuel ratio. A commercial software package is used in this step [18]. A DoE test consisting of multiple torque-step maneuvers is conducted on the engine dynamometer by applying candidate limitation curves for each selected engine speed. Test maneuvers are chosen as torque steps. Starting point of the torque steps are zero-load and critical cruise power operating points. The ending points are full load and high load operating points. Engine speed is controlled constantly at the target operating point value by the dynamometer during the torque-step maneuvers. All torque-step maneuvers are run by applying the candidate limitation curves at every engine speed operating points selected. The numerical integrals of engine-out soot emissions and engine brake torque are calculated for all DoE test maneuvers. Limitation curves that result in torque reduction at stationary operating conditions as well as those that cause torque oscillations are filtered-out to avoid modeling inaccuracies.

After the post-processing of DoE data, the modeling process is applied to predict the integral of engine-out soot emissions and torque. Inputs of the model are engine speed and lambda values for each Mass Air Flow (MAF) operating point. For example, if the AFR limitation map includes 16 axis points for an engine speed, model inputs would be consist of the corresponding engine speed value and MAF values that belong to each 16 axis points, making 17 inputs in total. Multi-objective optimization of the air-fuel-limitation map in terms of engine-out soot and torque delivery is then conducted using the generated model. To minimize the iterations between vehicle and dyno testing stages, multiple candidate limitation maps are generated by multi-objective optimization. These maps are generated for different engine-out soot emission levels and the vehicle performance evaluation process is carried out. Among the candidate calibration parameter sets that meet vehicle performance metrics, the one with the minimum soot emissions can be selected as the final calibration. Details of the calibration process are explained in the following sections. A flowchart of the calibration process is shown in Figure 1.

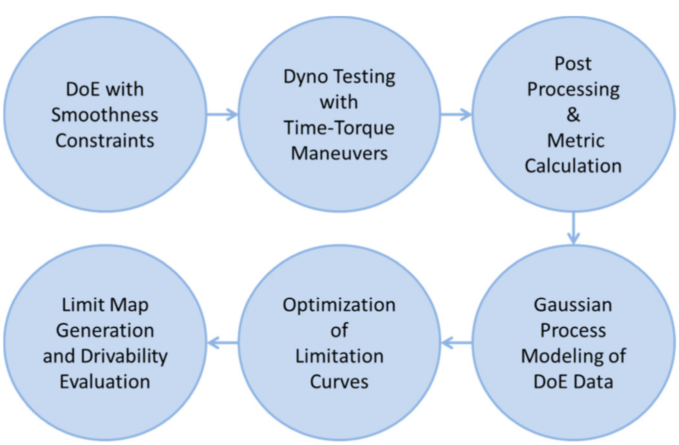

Figure 1. General process flowchart.

Curve Generation and Smoothness

Soot mass flow and engine torque are affected by a number of combustion parameters in addition to air and injection quantity (such as injection timing, rail pressure) which continuously vary during a transient maneuver. Thus, the optimal AFR limitation should be determined differently for each airflow value in the maneuver depending on the specific fuel-air calibration set points for that point. Therefore, in order to see as many scenarios as possible, tested limitation curves must be covering the potential airflow ratio limitation range for each air mass value. The maximum of potential air fuel ratio limitations are limited by the steady state operation AFR. Minimum value for the AFR limitation curves can be chosen by taking combustion stability into consideration, any AFR which is too low for stable combustion should be avoided.

DoE method is employed for the generation of candidate limitation curves for each fixed engine speed operating point. As shown in Figure 2, each MAF operating point is an input parameter of the DoE design. This allows the resulting DoE space to give candidate limitation curves for each engine speed. An overview of the curve generation process is shown in Figure 3. After generating the limitation curves within a minimum and maximum lambda range for each value of MAF, smoothness of the resulting curves are found and applied as a selection constraint for feasible candidates.

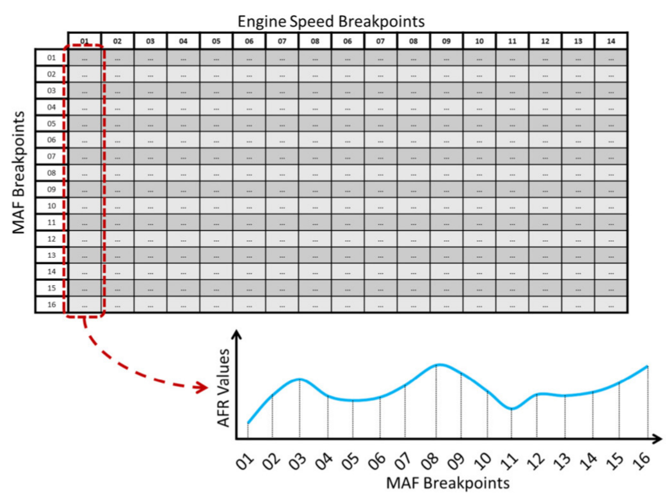

Figure 2. Transformation of AFR limitation calibration map to candidate limitation curves at fixed engine speed levels.

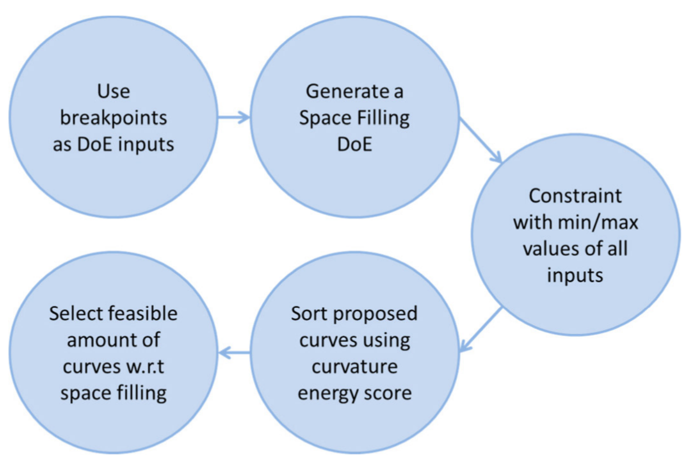

Figure 3. Overview of Design of Experiments process.

For a 2-D curve given parametrically in Cartesian coordinates as, $y(t) = (x(t),y(t))$, curvature is calculated as

$$\kappa = x' * y'' - y' * x''/\left(x'^2 + y'^2\right)^{3/2} \tag{1}$$

where first and second derivatives with respect to t are shown as prime and double-prime respectively. For a general case of a 2-D curve given explicitly as $y = f(x)$ the signed curvature can be simplified as [19];

$$\kappa = |\, y''| / \left(1 + y'^2\right)^{3/2} \tag{2}$$

Using this curvature formulation, each candidate limitation curve is assigned a curvature energy score. This energy score Γ, given in (3), is the integral of squared values of curvature for each breakpoint of the candidate limitation curve:

$$\Gamma = \sum_{i=1}^{n} \mathrm{K}(\mathrm{i})^2 \quad , \quad \mathrm{n} = \text{number of breakpoints} \tag{3}$$

The candidate curves with minimum curvature energy score have better smoothness properties compared to the ones with higher curvature energy score. In Figure 4, two candidate curves with different curvature energy scores are shown. A reduced set of smooth candidate curves is selected from the original large DoE space. This selection is done without compromising space-filling criteria for input coverage.

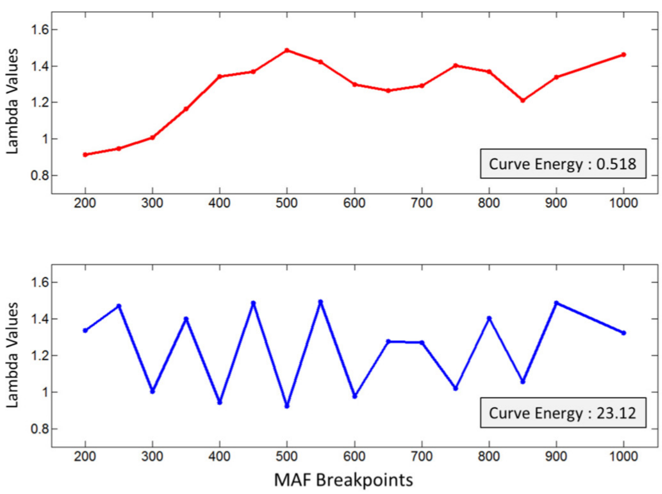

Figure 4. Comparison of two different curves using Curve Energy Score calculation.

Selection of Test Maneuvers

In order to reduce testing time and compare candidate curves more effectively, several torque steps are applied at fixed engine speeds. Torque steps are determined according to the characteristics of real-world driving maneuvers and the significance of these maneuvers for performance evaluations. The EGR rate of these maneuvers is also an important parameter since soot emissions are affected by EGR rate to a large extent. EGR ratio set point of the engine is not changed during the test maneuvers. The only intervention to the engine operation is changing the transient torque limitation according to AFR values. Applied torque steps are shown in Table 1.

Determination of Evaluation Metrics

The main focus of the calibration process is to deliver a Pareto-optimal between vehicle performance and transient engine-out soot emissions. Thus, the cumulative soot mass over the duration of the test maneuvers M_{cum} is used as a metric for soot emissions. Vehicle performance metrics cannot be accurately predicted in the dynamometer environment. However, since the primary factor that affects vehicle performance is engine torque, a dynamometer test metric can be defined to correlate engine torque response to vehicle acceleration performance. Therefore, the integral of engine brake torque during test maneuvers τ_{cum} are selected as a performance metric as shown in Equations (4) and (5). Both metrics are normalized to eliminate potential issues due to order of magnitude differences. Area under the torque response curve of the engine brake torque correlates better with vehicle acceleration performance during tip-in compared to time-to-torque metric. The total work created by the engine may vary significantly depending on the shape of the torque delivery curve as well as time-to-torque.

$$\tau_{cum} = \int_{t_{step}}^{t_{step}+3} \tau \, dt \tag{4}$$

$$M_{cum} = \int_{t_{step}}^{t_{step}+3} M_s \, dt \tag{5}$$

where τ is engine brake torque and Ms is instantaneous soot mass flow. t_{step}, corresponds to the step times of transient maneuvers.

Table 1. Torque Step Maneuvers

Operating Point	1st Load Step	2nd Load Step	3rd Load Step	4th Load Step
Speed Axis 01	%0 load to %100 load	%23 load to %100 load	%46 load to %100 load	%0 load to %70 load
Speed Axis 02	%0 load to %100 load	%18 load to %100 load	%36 load to %100 load	%0 load to %70 load
Speed Axis 03	%0 load to %100 load	%13 load to %100 load	%29 load to %100 load	%0 load to %70 load
Speed Axis 04	%0 load to %100 load	%8 load to %100 load	%18 load to %100 load	%0 load to %70 load
Speed Axis 05	%0 load to %100 load	%6 load to %100 load	%15 load to %100 load	%0 load to %70 load
Speed Axis 06	%0 load to %100 load	%6 load to %100 load	%13 load to %100 load	%0 load to %70 load
Speed Axis 07	%0 load to %100 load	%6 load to %100 load	%12 load to %100 load	%0 load to %70 load

The time period for the torque integral may vary depending on engine size, turbocharger performance and dynamometer inertia. The integral period must be selected equal to the highest time-to-torque value among the DoE test maneuvers and should be kept as a constant value for the post-processing of all DoE points to eliminate any differences due to the metric calculation between test runs. For this study 3 seconds are selected as integral time period since it is the highest time-to-torque value observed the DoE test. Therefore, the torque signal should be integrated for all test runs after the load step is initiated for the duration of selected integral period as shown in Figure 5. In addition to the torque integral magnitude, smooth torque delivery is also important since torque oscillations and non-smooth torque delivery often causes drivability issues. Therefore, any air-fuel ratio limitation curve that fails to meet the torque smoothness requirements should be eliminated from the DoE data.

All DoE maneuvers are examined to meet the smoothness criteria. The approach is based on extracting the torque signal between 5% and 95% of max torque and fitting a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) to this data segment. This is done to achieve a continuously differentiable function for the relevant segment of the torque signal. Then, the first derivative of this function between step time and rise time instances gives the rate of change of torque during the rise period. Any sign change in the derivative signal can be used as an indicator for detecting non-smooth torque build-up curves. An example curve for the evaluation of non-smooth torque response is given in Figure 6 along with its derivative signal. These maneuvers are excluded during the modeling phase to enhance model quality.

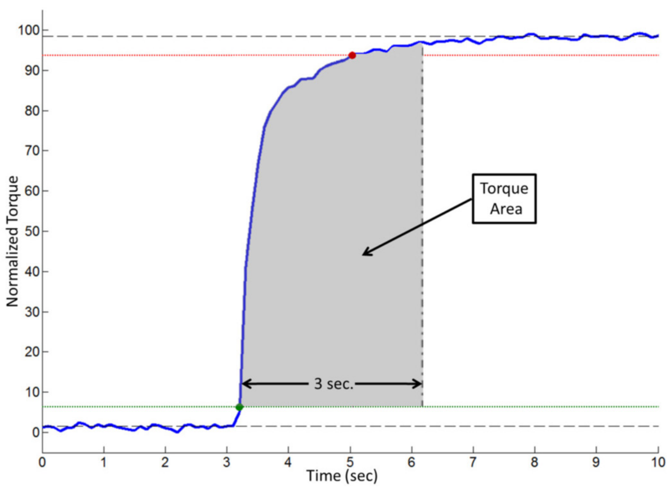

Figure 5. Example for torque trace integral interval.

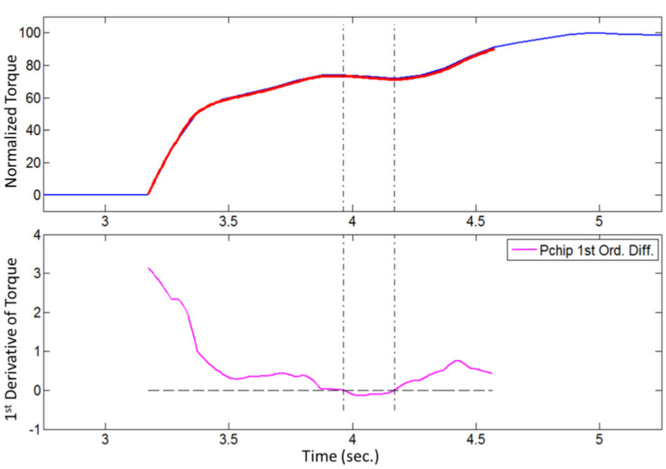

Figure 6. Example curve for evaluation of unsmooth torque response.

Post Processing & Modeling

When the tests are completed, each recording that corresponds to the DoE step runs are post-processed for modeling purposes. Recorder files are analyzed with respect to the evaluation metrics explained in the previous section. For each step of the DoE run, the integral of torque and soot are converted into a weighted cumulative result for each of the four torque maneuvers at constant engine speeds. This allows the four maneuvers to be combined into a single cumulative metric in terms of torque response and soot formation. The weight of each maneuver is taken as 1, i.e. every maneuver is assumed to be of equal importance. Next, measurements with non-smooth torque responses are eliminated. Also, torque responses where smoke limitation is in effect during steady-state have been excluded from the training data. Gaussian Process Modeling is a stochastic process which uses the squared exponential covariance function as a kernel for model training [17]. In this work, a commercial tool which employs this technique has been used for modeling [6]. Inputs of the model are engine speed and MAF values written in the corresponding axes of the AFR limitation calibration maps. An overview of the model inputs and outputs are given in Figure 7. Also, a comparison of measurements and model predictions is given in Figures 8 and 9. As shown, model quality is considered to be sufficient for optimization purposes.

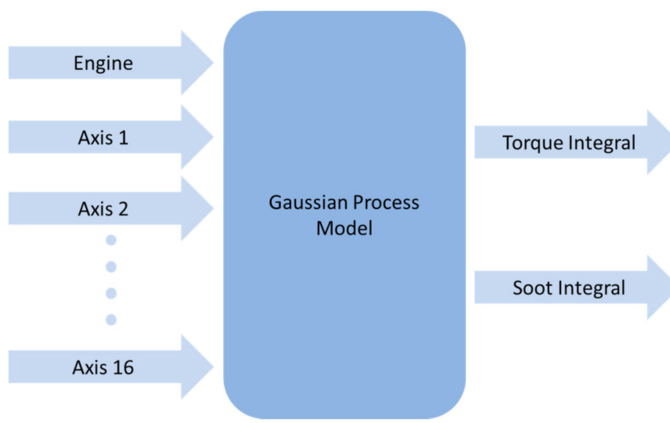

Figure 7. Overview of the model inputs and outputs.

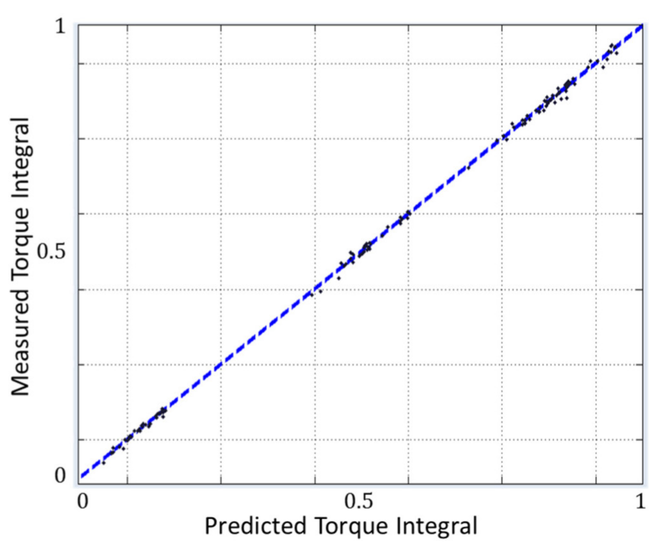

Figure 8. Prediction results of Torque Integral: $R^2 = 0.99$

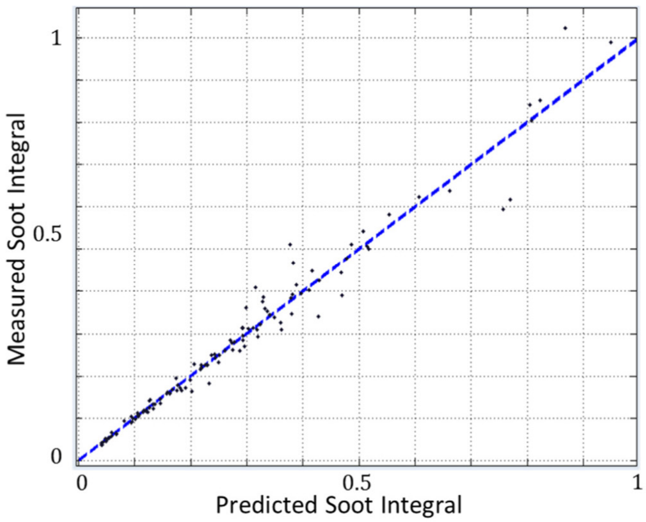

Figure 9. Prediction results of Soot Integral: $R^2 = 0.97$

Final Map Determination and Optimization

Multi-objective optimization in terms of soot emissions and cumulative torque delivery is performed after the models are constructed. In this paper, a multi-start global search algorithm is used for multi-objective optimization.

Objectives of the optimization process are normalized cumulative soot emissions and normalized integral of engine brake torque delivery. The curvature energy metric explained in previous sections is used as an optimization constraint to avoid non-smooth air-fuel ratio limitation curves. Multi-objective optimization is used to generate trade-off curves of solutions for each engine speed; each solution on the Pareto curve representing a lambda curve for a fixed engine speed. The feasible operating regions can be determined from the trade-off curves for all engine speeds using the optimization results. Gaussian Process model prediction of a trade-off curve example from the optimization results is shown in Figure 10.

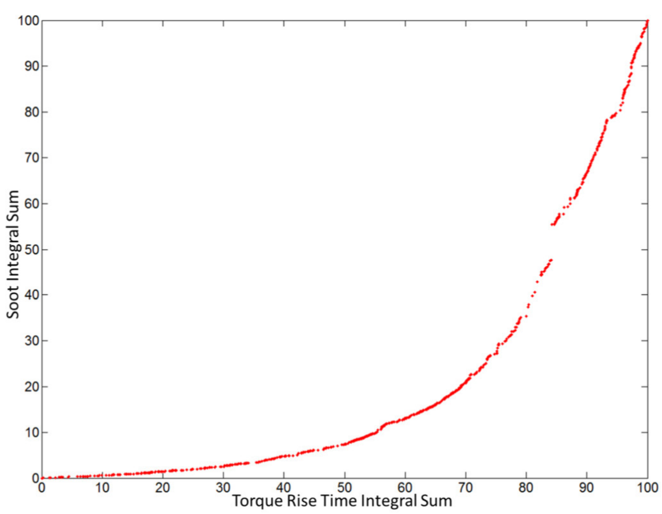

Figure 10. Example plot for optimization results trade-off from the model.

After the optimization of limitation curves for each engine speed is completed, the air-fuel ratio limitation maps are constructed using the resulting curves. Multiple candidate limitation maps can be constructed for various soot levels also considering the smoothness of maps in the engine speed axis direction. These candidate calibration sets are then evaluated in terms of vehicle performance; and among evaluated the maps, the one that provides the minimum soot emissions is selected as the final calibration.

RESULTS

Test Setup & Engine Information

The engine used in this study is a turbocharged direct injection diesel engine with 1.5L displacement by Ford Motor Company. The engine is installed on a transient capable dynamometer test bench fully instrumented with pressure and temperature sensors, in-cylinder pressure sensors and emission measurement devices. At the engine exhaust port, a soot sensor with transient measurement capability is used to measure soot emissions.

The CAN Interface is used to facilitate fast data transfer between the test bed and the engine control unit (ECU). ECU signals are shared with the dynamometer control software via the TCP-IP connection.

Test Automation & Measurement Devices

The test schedule comprises sequence of maneuvers grouped according to engine speed. Before each maneuver, a recorder is activated and measurement signals from the dynamometer instrumentation are acquired via the CAN Network. The recorder is stopped 20 seconds after the maneuver is completed. The torque steps at discrete speed levels are repeated for each candidate curve. After all of the torque maneuvers are completed for a single engine speed, zero point check is performed using the micro soot sensor. The sensor requires periodic zero check operation. The measurement value of the zero point check is used for baseline correction to account for the signal drift. This drift is often caused by the accumulation of soot on the measuring window.

The micro soot sensor is used for continuous measurement of soot concentration. Its measurement principle is based on the photoacoustic method. Exhaust gas is directed through a measuring chamber where it is exposed to modulated laser light. The periodical warming and cooling and the resulting expansion and contraction of the carrier gas produce periodic pressure pulsations, which are then detected by a microphone as acoustic waves. The output rises proportionally to the concentration of soot in the measurement volume [7].

Dynamometer Test Results

Cumulative torque and soot data from the dynamometer DoE test results for various engine speeds are shown in Figures 11, 12 and 13. Red markers (square) represent the test points for which AFR limitation prevents target load from being achieved at steady state operating conditions. The trade-off between soot and torque integrals can be easily seen from the test data. The Pareto curve becomes very steep at high torque integral sum values, which emphasizes that a certain feasible operating region in terms of engine-out soot emissions and vehicle performance exists. Steep behavior approaching near high soot region can be explained as the amount of increased fueling is converted to torque with reduced efficiency due to air shortage, and therefore, radically increasing soot emissions while delivering negligible torque increase. On the other hand, behavior approaching near low torque integral region shows that soot benefit rate is greatly reduced compared to torque build-up deterioration while operating at increased air-fuel ratio. Therefore, the feasible calibration for the air-fuel ratio limitation map resides in the region where the slope of the trade-off curve is relatively modest.

Comparison of optimization results from Gaussian Process model and DoE data are shown for an engine speed operating point in Figure 14, where red markers (square) represent the test points for which AFR limitation prevents target load from being achieved at steady state operating conditions. Multi-objective optimization gives Pareto optimal results inside the DoE testing range as output map smoothness is also improved using smoothness constraints. Similar trend is observed for the other engine speed operating points.

Vehicle Evaluation

Since the air fuel ratio is also a contributing factor to vehicle performance and drive comfort, both objective evaluation and subjective evaluation by a trained driver is required to validate the optimization results that are obtained from dynamometer tests and computer simulations.

After the evaluation of optimization results, candidate calibration data sets are generated to be used in the vehicle application. Using the test results, three different calibration sets are generated. One of the calibration data sets targets favorable transient vehicle performance, whereas the second set targets soot emissions reduction. The last calibration data set is optimized to provide an intermediate solution in terms of performance and soot emissions.

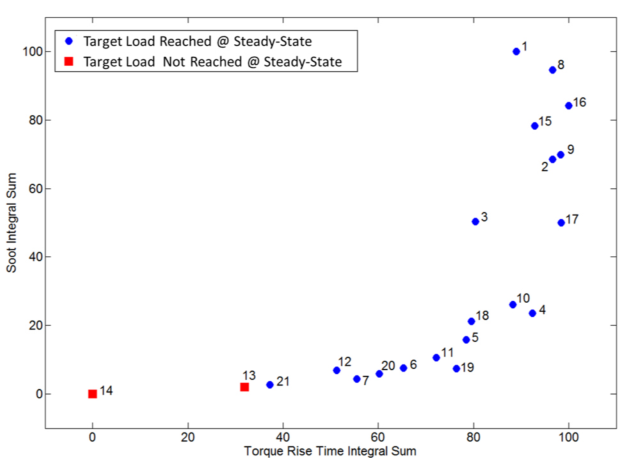

Figure 11. Cumulative Soot and Torque from DoE Data (2000 rpm).

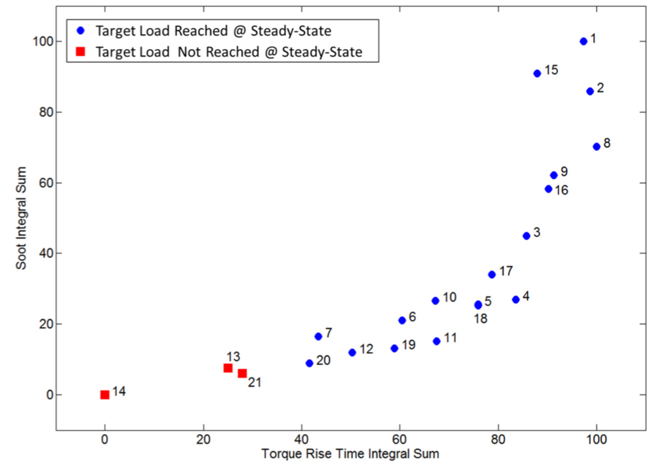

Figure 12. Cumulative Soot and Torque from DoE Data (2500 rpm).

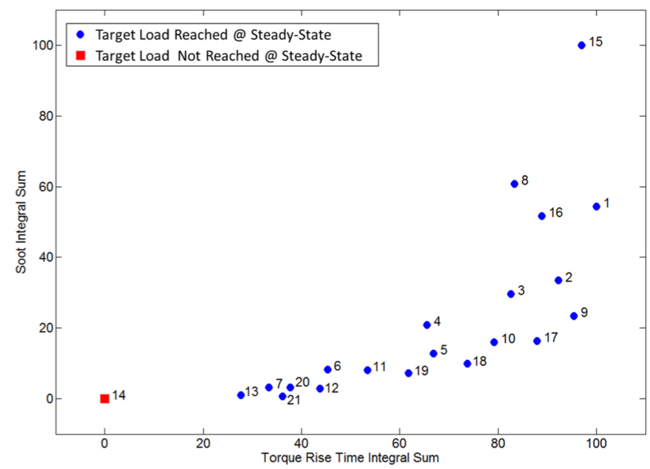

Figure 13. Cumulative Soot and Torque from DoE Data (3000 rpm).

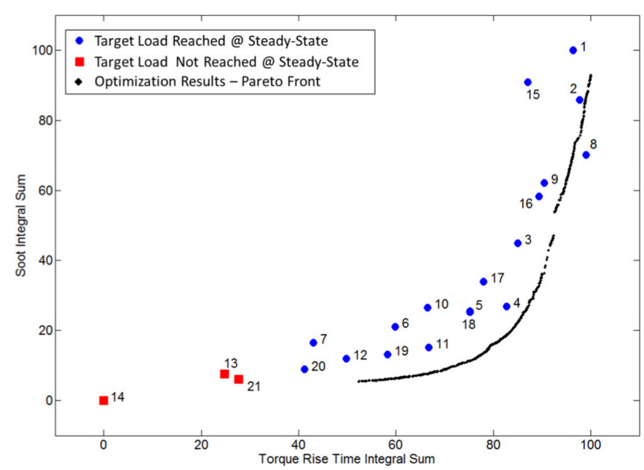

Figure 14. Optimization results from the model vs. DoE Data (2500 rpm)

A set of performance evaluation maneuvers is selected and executed in the vehicle. Selected driving maneuvers are common indicators of vehicle performance and they also reflect the characteristics of dynamometer test maneuvers. These maneuvers consist of accelerations from idle and medium engine speeds at seven different acceleration pedal positions and also full-load acceleration from stand-still. The vehicle speed profiles from vehicle tests are evaluated and the results are shown in Figure 15.

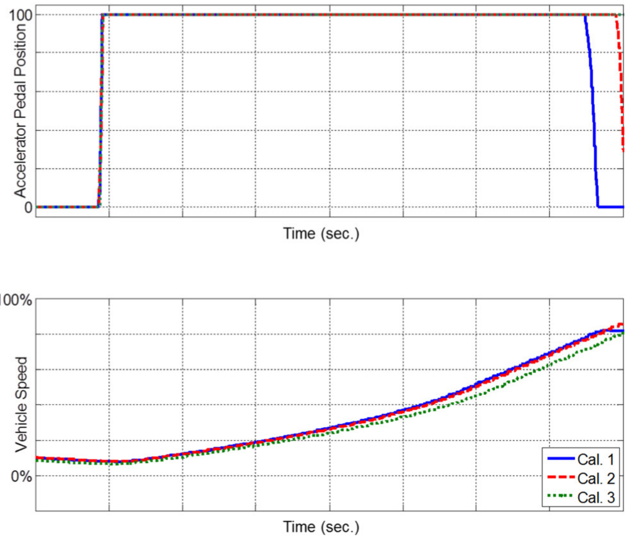

Figure 15. Drivability Assessment (Cal. 1: High Soot; Cal. 2: Medium Soot; Cal. 3: Low Soot)

Subjective evaluation by trained driver reported only minor differences between the calibration data set which targets performance and the intermediate calibration. The calibration set which targeted soot emissions reduction by further limiting fuel injection quantity is classified as under-responsive and insufficient in terms of vehicle performance.

CONCLUSIONS & FUTURE WORK

A novel methodology for air-fuel ratio limitation map calibration is proposed. Test design, hardware setup, modeling and optimization stages of the calibration methodology are explained in detail; dynamometer and vehicle test results are also presented. Testing time required to develop the AFR limitation calibration is reduced by nearly 50% using the proposed methodology compared to methodologies that involve steady state measurement of engine operation. In addition, the proposed methodology also eliminates the possible iterations between vehicle evaluation testing and dynamometer testing since the DoE data obtained by dynamometer measurements can be re-used for possible iterations required during calibration development.

A torque-step DoE test is used to simulate the transient engine operating conditions. Considering the influence of MAF sensor dynamics and non-linear soot emission behavior at low air-fuel ratio operation, modeling of cumulative torque and cumulative soot emissions is applied. Trade-off characteristics between the engine-out soot emissions and performance from test data suggests a feasible calibration region for the air-fuel ratio limitation map. Multiobjective global optimization of the calibration map is conducted with the objective of minimizing engine-out soot emissions while considering vehicle performance requirements as a constraint. Multiple optimized limitation maps are generated to be evaluated in terms of vehicle performance. This approach minimizes the iterations between vehicle and dynamometer testing stages; therefore, reducing the testing time and development costs of the overall calibration process.

Potential future work for the calibration process may include the application of dynamic modeling techniques to enable time-based soot prediction and offline estimation of vehicle performance. By modeling vehicle performance and soot emissions in the simulation environment, the air-fuel ratio limitation map may be optimized by applying direct constraints on vehicle performance, thus eliminating the need to generate multiple calibrations. Dynamic DoE testing provides the opportunity to improve soot modeling and allows the prediction of real-world vehicle driving cycles (such as RDE) and the optimization of calibration according to real world driving behavior.

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CONTACT INFORMATION

Gurel
Powertrain Calibration & Controls Department Ford Otosan – Product Development Akpinar Mah. Hasan Basri Cad. No:2 34885 Sancaktepe / Istanbul / Turkey
cgurel@ford.com

Ozmen
Powertrain Calibration & Controls Department Ford Otosan – Product Development Akpinar Mah. Hasan Basri Cad. No:2 34885 Sancaktepe / Istanbul / Turkey
eozmen@ford.com

Yilmaz
Powertrain Calibration & Controls Department Ford Otosan – Product Development Akpinar Mah. Hasan Basri Cad. No:2 34885 Sancaktepe / Istanbul / Turkey
myilma43@ford.com

Aydin
Powertrain Calibration & Controls Department Ford Otosan – Product Development Akpinar Mah. Hasan Basri Cad. No:2 34885 Sancaktepe / Istanbul / Turkey
daydin3@ford.com

Koprubasi
Powertrain Calibration & Controls Department Ford Otosan – Product Development Akpinar Mah. Hasan Basri Cad. No:2 34885 Sancaktepe / Istanbul / Turkey
kkopruba@ford.com

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ABBREVIATIONS

PM - particulate matter

PN - particulate number

ETC - European Transient Cycle

WHTC - World Harmonized Transient Cycle

WLTC - Worldwide Light-duty Test Cycle

NEDC - New European Driving Cycle

RDE - Real Drive Emissions

PEMS - Portable Emission Measurement System

EGR - exhaust gas recirculation

OBD - on-board diagnostics

AFR - air-to-fuel ratio

DoE - design of experiments

MAF - mass air flow

PCHIP - Piecewise Cubic Hermite Interpolating Polynomial

ECU - engine control unit