

A Model Based Calibration Process for Robust Optimal Cam Position Selection Under all Engine Operating Conditions

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ABSTRACT

A traditional problem with calibration of optimal cam positions is that the calibration usually needs to compromise torque at normal operating conditions on good fuel (ie highest RON/MON) in order to avoid drivability issues via high COV of IMEP under more extreme (eg lowest RON, high ambient temperature) conditions.

A traditional approach to optimal calibration of VVT (Variable Valve Timing) positions uses one target fuel at one inlet air temperature. Often torque (BSFC) under normal conditions (eg emissions cycle) takes priority over the degradation in drivability under more extreme conditions, yielding non-robust cam calibration. Depending on the calibration approach, ignition angle may not be part of the design of experiment. With this traditional approach the effect of different fuels (RON/MON) and ambient conditions such as inlet air temperature are difficult to build into a robust cam calibration.

In this paper a calibration process is presented which takes into account the change in ignition angle efficiency (via decreasing RON and increasing inlet air temperature) and the corresponding optimal cam positions to allow best torque (BSFC) whilst satisfying COV limits to prevent drivability issues. The process outlined in this paper is a model based calibration process utilizing 1 and 2-stage statistical response models generated using MATLAB and the Model Based Calibration Toolbox.

INTRODUCTION

Torque and BSFC are usually the highest priority in terms of optimal calibration of cam phasing strategy for any given engine. COV of IMEP is often traded off against the loss in fuel consumption in the optimization process.

Also, the interaction between the optimal cam positions and spark timing, in terms of shifting of the knock limit, is not usually considered. Standard practice has been to conduct this optimization tradeoff of torque and COV of

IMEP from models generated from data collected at a standard intake air temperature of 25degC. Also, quite often the fuels used to collect this data are higher octane or even non-knocking fuel.

Often a gap in the calibration process of the cam phasing strategy exists because it is not possible to determine the knock limit for any given set of cam positions from the models. As a result, some additional testing needs to be conducted, usually in the form of spark tables, to determine the ignition angle in the knock limited region.

Even after the above process has been conducted no information exists as to how knock limited the engine will become under worst market fuel (low RON) and high intake air temperatures. Generally this is tested under high ambient conditions some time after the initial data collection, model building and optimization. If drivability issues exist under these conditions then the cam phaser calibration usually needs to change. This may put the entire calibration project into difficulty, as the remainder of the calibration strategy is usually a function of cam positions. For example, torque model or air path calibration areas may need to be revisited post this cam position calibration change.

It would be of great benefit to be able to link the cam positions and the knock limit under not only normal conditions but also under worst case conditions. If this was possible then the optimization of the cam calibration could be done by effectively a three way tradeoff. Torque, COV and the knock limit. Potentially this would allow optimal cam positions for all operating conditions.

THE ENGINE UNDER STUDY

In Table 1, the main characteristic of the engine used for the data collection for the study is shown.

Total piston displacement	2400cc
Bore and Stroke	80, 75mm

Valve number	16
Geometrical compression ratio	10.4
Intake and exhaust Cam phaser range	50 degs crank angle
Injection method	Port fuel injection

Table1: Test engine parameters

DESIGN OF EXPERIMENT

The design of experiment was broken into two separate tests. The first was a two stage, space filling design [2]. It had intake cam, exhaust cam and load as global inputs and ignition angle as the local variable. Non-knocking fuel was used to allow MBT to be found at each point.

The second set of tests used a one stage space filling design with intake cam, exhaust cam and load as the input variables. Intake air temperature (IAT) was used as a "stratification level" by running the same one stage experiment design at three IAT settings. Figure 1 shows the overall experiment and model based work flow.

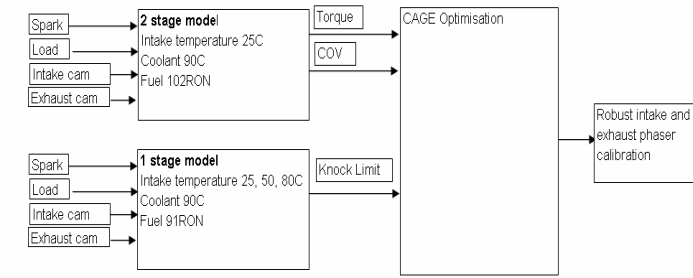


Figure 1: Design of experiment overview

TWO STAGE MODEL DESIGN OF EXPERIMENT

The purpose of the two stage model is to find optimal cam positions at MBT spark timing. This model will be generated from data collected on 102RON fuel. Hence this model has no consideration for the knock limit and how the knock limit changes with respect to other inputs such as intake cam, exhaust cam, IAT and load. The two stage model will provide the foundation for this model based approach. It will be the main model in terms of determining the torque and COV of IMEP.

The 2 stage model was designed using the Mathworks MBC design editor [1]. The test conditions for the 2 stage data collection were 25 degC inlet air temperature and 102 RON fuel. The design space was constrained to ensure best use of test points. The boundary constraints were setup to explore a relatively wide range of settings across the load range to capture the interaction of cam position, IAT and RON on Torque and COV. Load was measured in 'Air Per Cylinder' (mg). Intake and exhaust cam positions measured in deg cam with range of 0 to 25 deg cam for each.

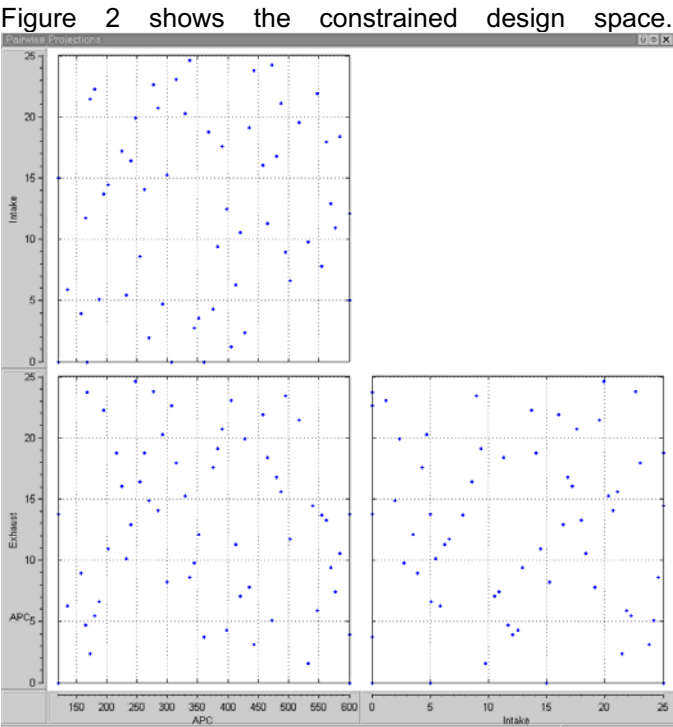


Figure2: Two stage model design space

A boundary was fitted to the above design space using the 'star shaped' option the MBC design editor [2]. This boundary is useful when using the models to identify only areas of interest and ensuring that the engine is still is a realistic engine operating window. The 'Radial Basis Function' width setting was kept at the default value of 2.4 [1]. Figure 3 shows the two stage boundary model. The red spheres around points indicate the points that have been selected as boundary points by the star shaped boundary process [2].

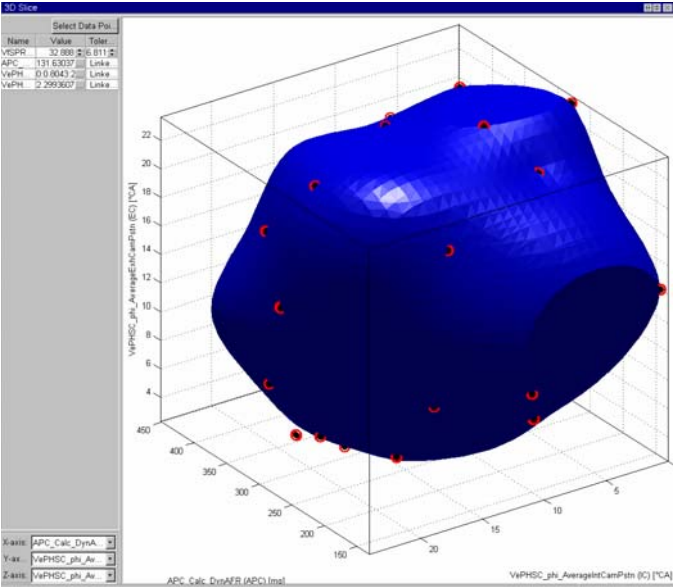


Figure3: Two stage boundary model

ONE STAGE MODEL DESIGN OF EXPERIMENT

The purpose of the one stage model was to define the interaction of the knock limit spark advance as a function of intake cam, exhaust cam, load and IAT.

Ideally the one stage points would have been exactly the same as the two stage points selected in the space filling design in figure 2. However, due to test facility issues this could not be achieved. The one stage design space is shown in figure 4.

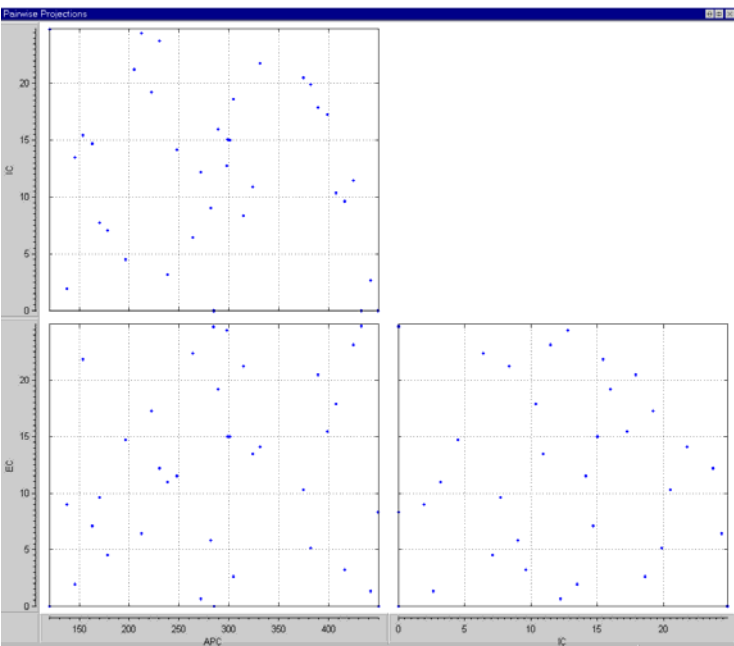


Figure 4: Design Space for the one stage model

Again the design space was filled using the space filling method inside the MBC design editor

The output of the one stage model can then be used as the spark input to the two stage model to allow cam positions to be re-optimized at high IAT and/or low RON fuel taking account of the change in the BLD point.

Again a boundary model was fitted using a ‘star-shaped’ boundary as per the two stage model.

DOE METRICS

A good metric for the DOE quality is ‘Predicted Error Variance’ (PEV). PEV values less than 1 will increase the measurement error and greater than 1 will reduce the error. [3] V-Optimal points were put into the corner points for improved predicted error variance (PEV) [2][3].

The PEV plots for both one and two stage models are shown in appendix 2 and 3 respectively.

DOE AND TEST METHODOLOGY

Spark Hook Process

The spark hook for the two stage model was done using the hook process as demonstrated in figure 5. This process was automated in the test bed for improved speed of data collection. The spark hook contains 9 points in total with 300 cycles of combustion data at each point.

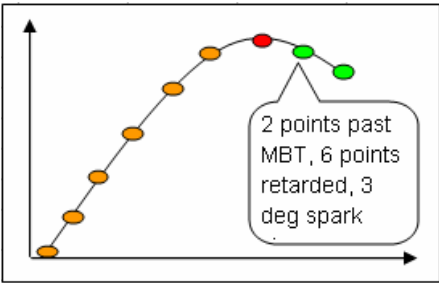


Figure 5: Spark hook process

MODEL VALIDATION

Before continuing with the analysis and using the models a validation check was done to ensure that the model accuracy was acceptable. The two stage model validation was 1.12Nm across the load range of the design space. This was an acceptable model validation result. Given that the maximum torque in the design space for this speed was in the order of 140Nm this indicated that the model could predict torque to within 1% at high load (120 to 140Nm). The Statistical treatments throughout the model building process are shown in table2. RMSE is the ‘Root Mean Squared Error’ (this is applicable for local and global models) and PRESS RMSE which is the ‘Predicted Sum of Squares Root Mean Squared Error’. Val RMSE is the ‘Validation RMSE’. [1]

102 RON PS32 Using Min PRESS RMSE as target for RBF:

Statistic:	Initial	1	2	3	Val RMSE
Local RMSE	0.187	0.187	0.187	0.187	1.12
2 Stg RMSE	0.52	0.649	0.507	0.319	
PRESS RMSE	1.337	1.08	N/A		

Table2: Statistical treatment table for two stage Torque model. Units in Nm.

- Treatments:
- Initial – default PS32 model with no treatments
 - 1. Trimmed some hooks. Outliers removed. Deleted hook 59.
 - 2. Build RBF’s (10, 0.5*No.Obs, 5) and picked best **PRESS RMSE**
 - 3. MLE.using Expectation maximisation algorithm

Original 102 RON PS32 Using Min PRESS RMSE as target for RBF:

Statistic:	Initial	1	2	Val RMSE
Local RMSE	0.088	0.088	0.088	
2 Stg RMSE	0.18315	0.2	0.13	
PRESS RMSE	0.31	0.23	N/A	

Table3: Statistical treatment table for two stage COV model. Units in %.

Treatments:

Initial – default PS32 model with no treatments

1. Trimmed some hooks. Outliers removed. Deleted hook 59.
2. Build RBF's (10, 0.5*No.Obs, 5) and picked best **PRESS RMSE**
3. MLE.using Quasi-Newton algorithm

Validation RMSE = 0.22 % COV

TEST POINT

The test point that was used for this analysis was 1600rpm and 400mg APC, (400mg APC is 52% relative load) [4]. This was chosen as it is a common driving condition in both real world and emissions cycle for this engine and platform combination.

OPTIMISATION IN CAGE

CAGE (Calibration Generation) is the Mathworks tool which interacts with the MBC (Model Based Calibration) toolbox to allow the interrogation of the models generated [2]. Several options exist in this tool. For the purposes of this paper the 'tradeoff' tool was used. This tool allows the visualization of the model outputs and clearly shows the interaction between variables. It is possible to achieve a similar outcome using the single objective optimization function in CAGE however for clarity the tradeoff tool was used. See Appendix 1 for more information. At optimization points 1 and 5, a single objective optimization was used to verify the tradeoff optimal positions.

MODEL EVALUATION PROCESS

The test point was evaluated using the one and two stage models generated from the DOE and data collection tasks. Under the test conditions a variety of cam positions and ignition angles were trialed. Table 4 shows the optimization philosophy using the tradeoff tool and single objective optimizations. The green squares show the evaluation flow using a set of cam positions optimized for 102RON at 25IAT. The red squares show the evaluation flow of cam positions optimized for 91RON and 80IAT. Conditions 1 and 5 are the points at which an optimization and evaluation take place.

IAT/RON	102	91	91	91
25	1			
25		2		
50			3	
80				4
80				5
50			6	
25		7		
25	8			

Table 4: Model evaluation flow

COV Target:

An upper COV constraint of 2.5% was used during the trade-off and optimisation processes.

OPTIMAL CAM POSITIONS AND EVALUATION

OPTIMAL CAMS AT CONDITION 1 (102RON, 25IAT)

Condition 1 is the traditional optimization condition. MBT spark is selected for each set of cam positions. Figure 6 shows the response of torque (upper row) and COV of IMEP (second row) with respect to intake cam (left column), exhaust cam (second column), IAT at constant 27 deg C and spark far (right column).

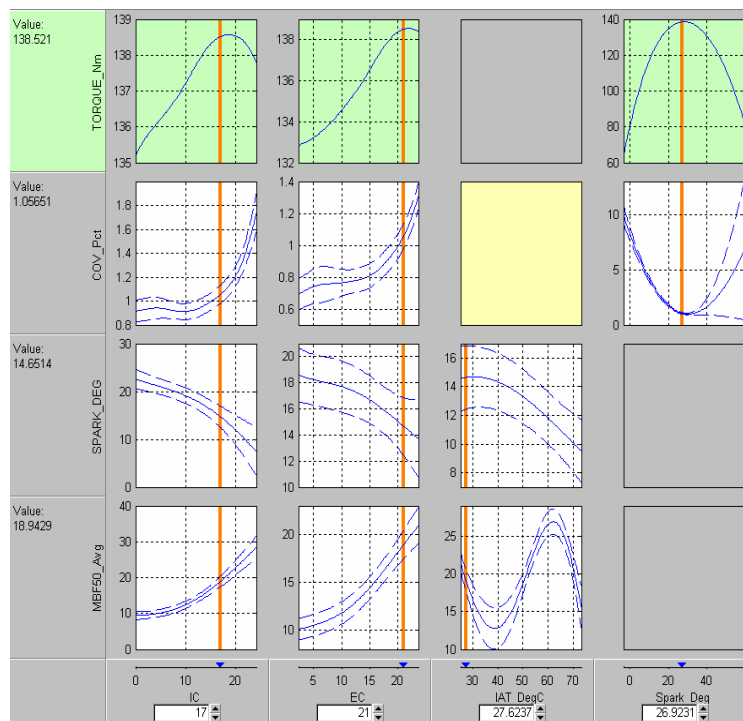


Figure 6: Optimal cam setting for condition1 (MBT spark of 27degCrk BTDC)

Single Objective Optimization for condition 1

A single objective optimization was also run in CAGE as confirmation of optimal setting. The objective was to maximize torque with constraints of model boundary and