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Embedded Torque Estimator for Diesel Engine Control Application

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ABSTRACT

To improve vehicle driveability in diesel powertrain applications, it is desirable to coordinate engine and transmission control functions. Transmission control algorithms in diesel powertrains can use torque information from the engine controller under a wide variety of powertrain operating conditions to improve shift quality. Unfortunately, direct engine torque measurement using powertrain sensors in production hardware is considered expensive. The aim of the work in this paper was to evaluate the feasibility of using an embedded torque estimation algorithm as an alternative to new sensor hardware in an off-road diesel application. The feasibility of estimating torque in a conventional engine control unit (ECU) was proven by developing and evaluating an engine torque estimator on an MPC555 processor using model-based design approaches.

PROBLEM DEFINITION

Two types of embedded torque estimators were designed, developed, and assessed for production implementation feasibility by measuring RAM, ROM, and throughput requirements on a Phytek PCM-995 evaluation board. The 20MHZ MPC555-based Phytek board was chosen for benchmarking estimator resources because of its relevance to conventional floating-point ECU technology currently being used by automakers in production. Two types of torque estimators were tested on the evaluation board to assess the tradeoff between model accuracy and ECU resource requirements. A proprietary diesel engine model, made in Ricardo WAVE software, was used to generate the data necessary to construct a statistical model of torque suitable for embedding in a conventional floating-point ECU. Figure 1 defines the input and output requirements of the torque estimator. The estimator was required to calculate brake torque for a 6 input degree-of-freedom common-rail diesel engine equipped with cooled EGR, a variable geometry turbocharger, and fuel rail pressure control. The engine and its estimator were intended to be operated over a narrow engine speed range from 1600 to 2200 RPM in an off-road diesel application, with torque output varying between 100 and 1600 NM.

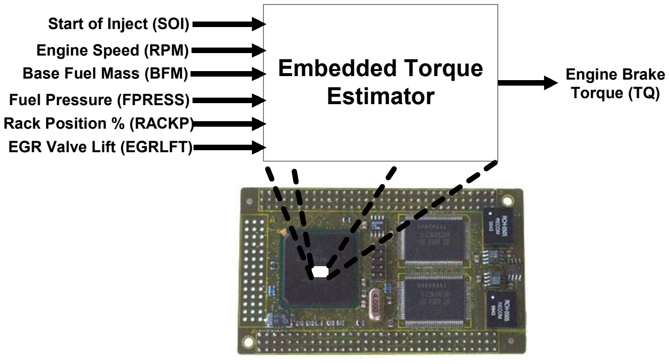


Figure 1: I/O Requirements of 6 DOF Embedded Torque Estimator

RESULTS SUMMARY

Table 1 summarizes the ECU resource requirements and model accuracy tradeoffs for two model types that were tested on the Phytek evaluation board.

Model Type	RAM (Byte)	ROM (Byte)	Time (μsec)	Max Error (NM)	Mean Error (NM)
Linear Cubic	92	2560	308	39.5	12.5
Quadratic Radial Basis Function	1952	6872	4400	4.9	1.5

Table 1: Estimator Resource and Accuracy Results Summary

INTERPRETATION OF RESULTS

In order to judge the results obtained in Table 1, it was necessary to develop criterion to use as a basis for rejecting or accepting a torque estimator design.

Feasibility Criterion

Table 2 shows the feasibility threshold assumptions used to judge the results in Table 1.

Maximum RAM (bytes)	Maximum ROM (bytes)	Maximum Time (μsec)
500	2500	500

Table 2: Torque Estimator Feasibility Threshold Assumptions

It was assumed that the torque estimator calculations could not exceed 1ms in duration to be deemed feasible for production application. For a 6-cylinder diesel application running at a top speed of 3000 RPM, fast control outputs such as the fuel injection logic would have to be serviced at a period no larger than 6.7ms . The maximum 500 μsec duration assumption for torque estimation was based on the assumption that torque estimate calculations must be significantly faster than the fastest control output calculations in the application. Practical RAM memory limits for a given process were assumed to be 2.5% of the maximum available RAM, to allow for RAM needed by other processes in the ECU. Since a typical production MPC555 ECU has a RAM capacity of about 20K bytes, it was assumed that 500 bytes of RAM was the upper resource limit for the torque estimator. ROM resource requirements were assumed to be 10% of total available ROM. For an ECU application with 256K bytes of ROM, it was assumed that 2.5K bytes of ROM was the upper resource limit for the torque estimator.

Design Selection

Assessment of torque estimator design feasibility for the linear cubic[1] and quadratic radial basis function (RBF)[2] shown in Table 1 were summarized according to the criterion in Table 2.

Linear Cubic Torque Estimator

- Meets requirements - **suitable**
- At upper ROM limit
- Torque error must be judged relative to application

Quadratic Radial Basis Function Estimator

- Fails to meet any of the requirements - **not suitable**
- In accuracy terms, suitable for many applications

Although the quadratic RBF torque estimator was rejected as infeasible, the following future developments could make it become feasible:

- The use of an ECU with DSP technology
- Increased ECU RAM and ROM capacity
- Increased ECU processor speed
- Implementing the estimator as a low priority task

TORQUE ESTIMATOR DESIGN

The linear cubic and quadratic RBF estimator designs were developed using a model-based design process.

ESTIMATOR DESIGN PROCESS OVERVIEW

Figure 2 shows the design steps taken for the two torque estimator designs. The process in Figure 2 was designed to methodically and efficiently take data from a high fidelity diesel engine model that is based on engine physics, produce a statistical model of the data, and automatically generate efficient code for model deployment on the Phytek MPC555 evaluation board.

Design of Experiments

The first step in the torque estimator design process shown in the upper left of Figure 2 was to design an experimental test plan to efficiently gather data from the WAVE diesel engine model. The first part of the design was to define the ranges of the torque estimator input variables shown in Figure 1. Table 3 summarizes the ranges of the inputs to the torque estimator.

Input Name	Units	Minimum Value	Maximum Value
SOI	Deg ATDC	-9	3
RPM	Rev/min	1600	2200
BFM	Mg/inject	20	200
FPRESS	MPa	90	160
RACKP	%	0.2	0.9
EGRLFT	mm	0.5	5

Table 3: Input Ranges of Torque Estimator

Due to the large number of input degrees of freedom required to accurately predict engine torque, it was essential to use Design of Experiments (DOE) methodology to minimize the number of test points

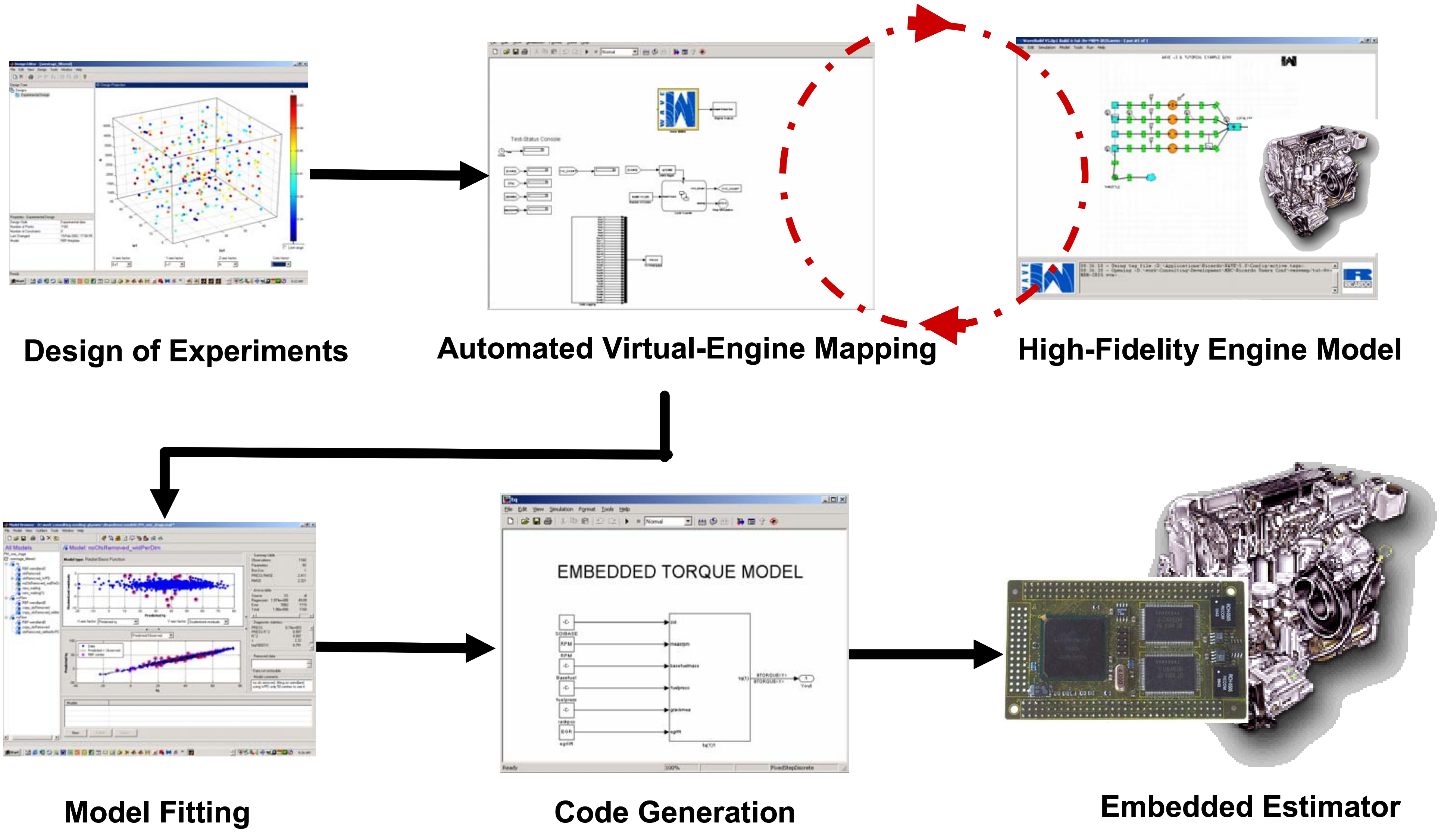


Figure 2: Model-Based Design Process Used for Torque Estimator

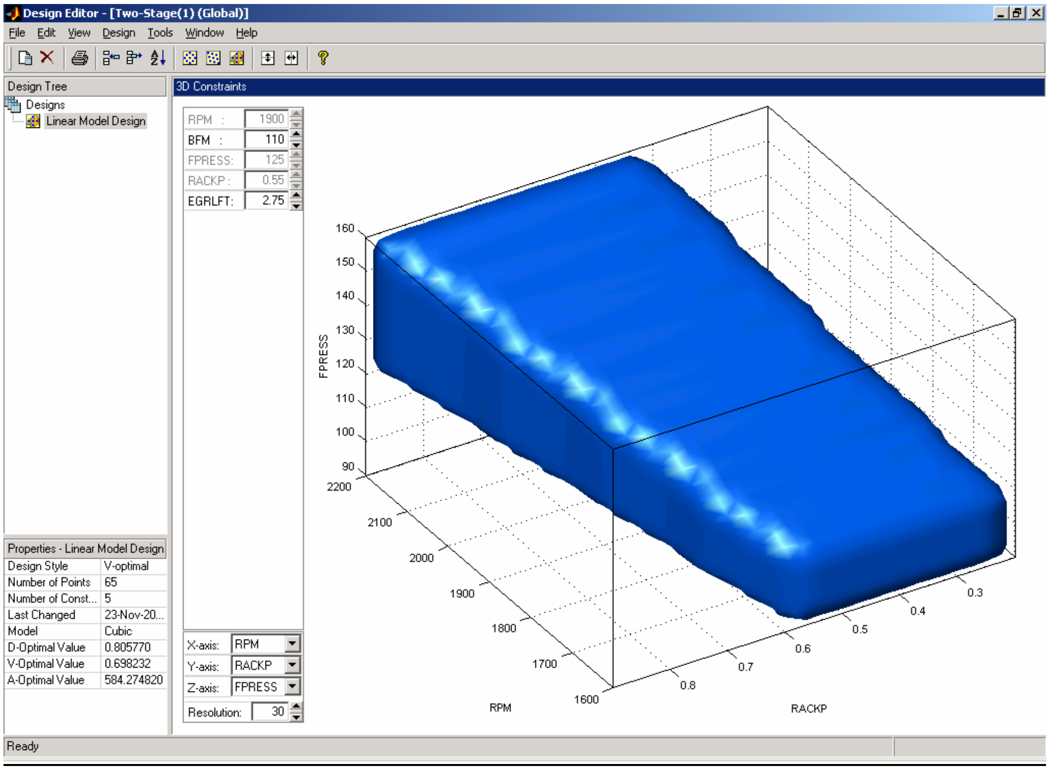
required to fit an accurate statistical model. The MathWorks Model-Based Calibration Toolbox was used to generate an efficient experiment design, given the input ranges shown in Table 3, input constraint boundaries shown in Figure 3, and the assumption that the torque response of the engine could be accurately represented by a linear cubic model form. The assumption of a linear cubic form allowed the use of a V-optimal experimental design. The names of the axis variables in Figure 3 were defined previously in Table 3 and Figure 1. Figure 4 shows a graphical representation of the 65-point V-optimal experimental design[3] generated by the Model-Based Calibration Toolbox, in pair-wise projection format. A two-stage approach to the testing was selected, with a local sweep of Start Of Inject (SOI) timing at each of 65 global DOE test points, resulting in a total of 455 test points. The names of the axis variables in Figure 4 were defined previously in Table 3 and Figure 1.

Automated Engine-Mapping Method

Data were gathered from a physically-based, high fidelity, proprietary model of a diesel engine implemented in Ricardo WAVE software. The WAVE model was used as a surrogate for a real engine, in order to avoid the expense of testing a real engine for the torque estimator feasibility study, and in light of the reasonable accuracy of a well-developed WAVE model in predicting engine torque. As shown in the middle/top block of Figure 2, MathWorks Simulink® and Stateflow® software were used to automatically map the WAVE engine model according to the optimal DOE design points via the WAVE S-function link block. The virtual engine mapping process took 72 hours to map the 455 test points on a 4-processor Linux PC.

Data Modeling

After the engine torque data were gathered from the automated virtual engine mapping process, the modeling step shown in the lower left of Figure 2 was executed. Two types of statistical models were fitted to the engine torque response using the Model-Based Calibration Toolbox. In Figures 5 and 6, the torque estimator residual errors are shown as a function of measured torque for the linear cubic and quadratic RBF models respectively. The units for the residual values on the Y axes in Figures 5 and 6 are NM. It was clear from the graphs that the use of an RBF model type greatly reduces model error, but the residual errors of the linear cubic model were within approximately 10% for the 100 to 1600NM operating range of the engine, and were considered to be reasonable for a driveability enhancement or engine diagnostic use.



RPM : 1900
BFM : 110
FPRESS: 125
RACKP : 0.55
EGRLFT: 2.75

X-axis: RPM
Y-axis: RACKP
Z-axis: FPRESS
Resolution: 30

Properties - Linear Model Design	
Design Style	V-optimal
Number of Points	65
Number of Const...	5
Last Changed	23-Nov-20...
Model	Cubic
D-Optimal Value	0.805770
V-Optimal Value	0.698232
A-Optimal Value	584.274820

Figure 3: 3D Visualization of Constraint Boundaries for VGT Position, Fuel Pressure, and Fuel Mass Inputs

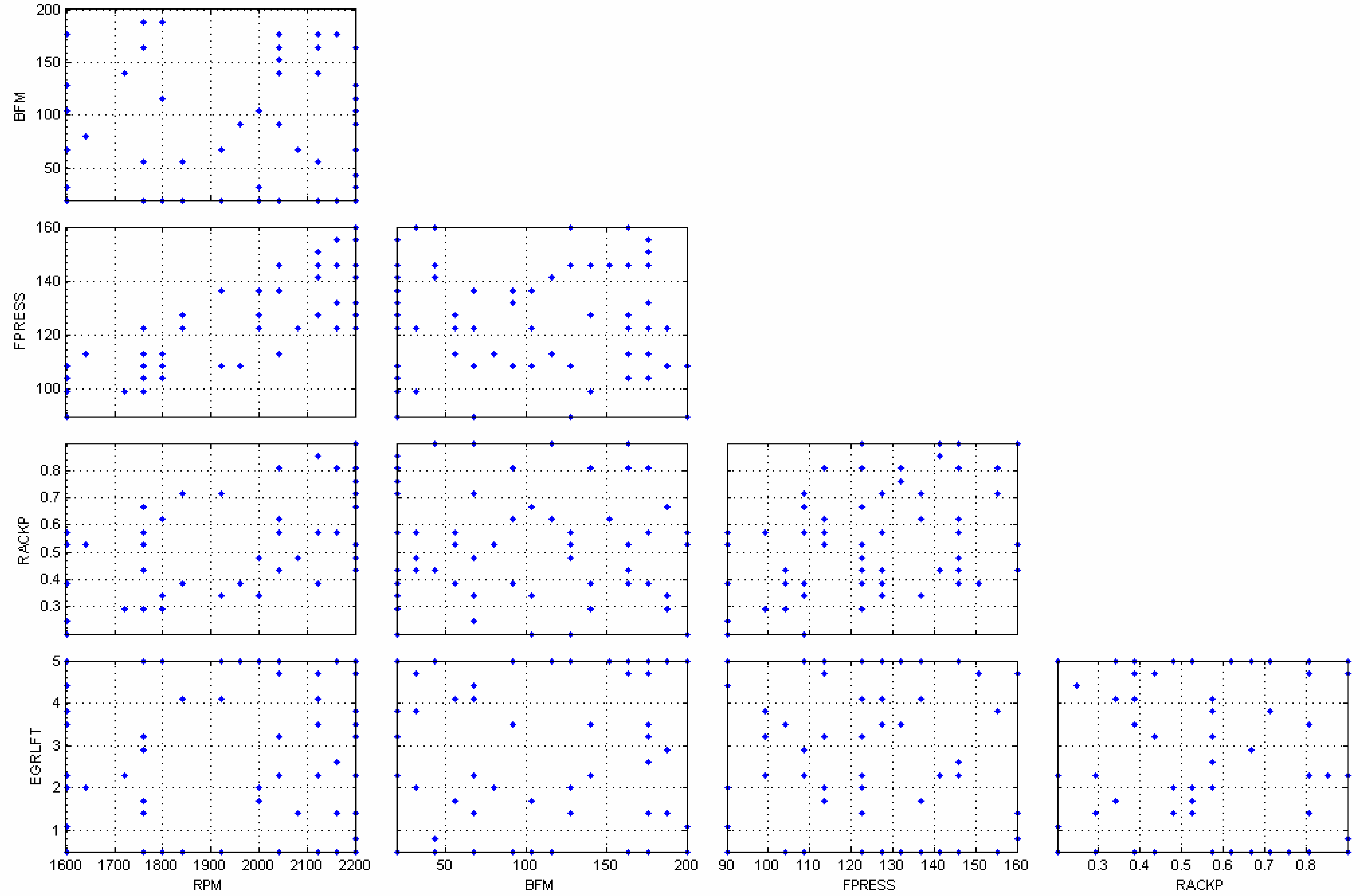
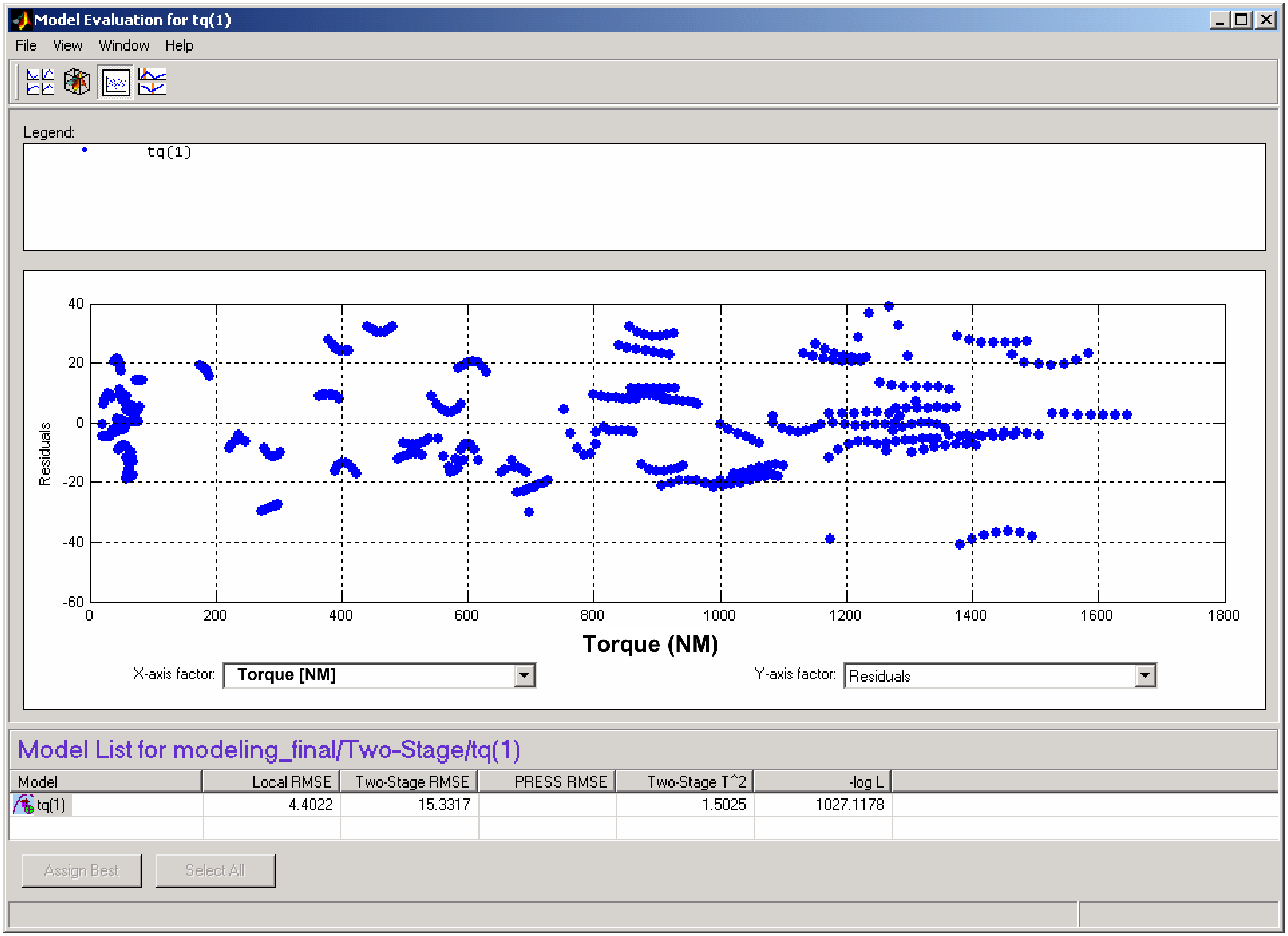


Figure 4: Pairwise Projection Visualization of Experimental Design



X-axis factor: Torque [NM]

Y-axis factor: Residuals

Model List for modeling_final/Two-Stage/tq(1)

Model	Local RMSE	Two-Stage RMSE	PRESS RMSE	Two-Stage T^2	-log L
tq(1)	4.4022	15.3317		1.5025	1027.1178

Figure 5: Torque Residual Errors vs. Measured Torque – Linear Cubic

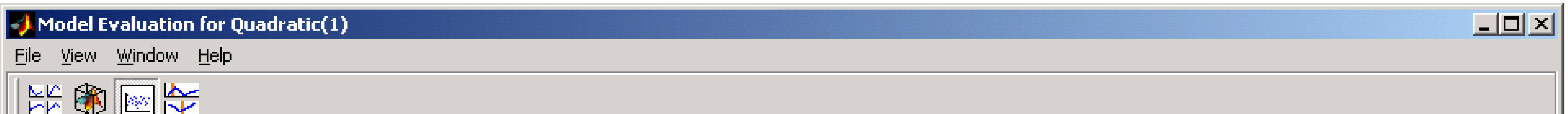
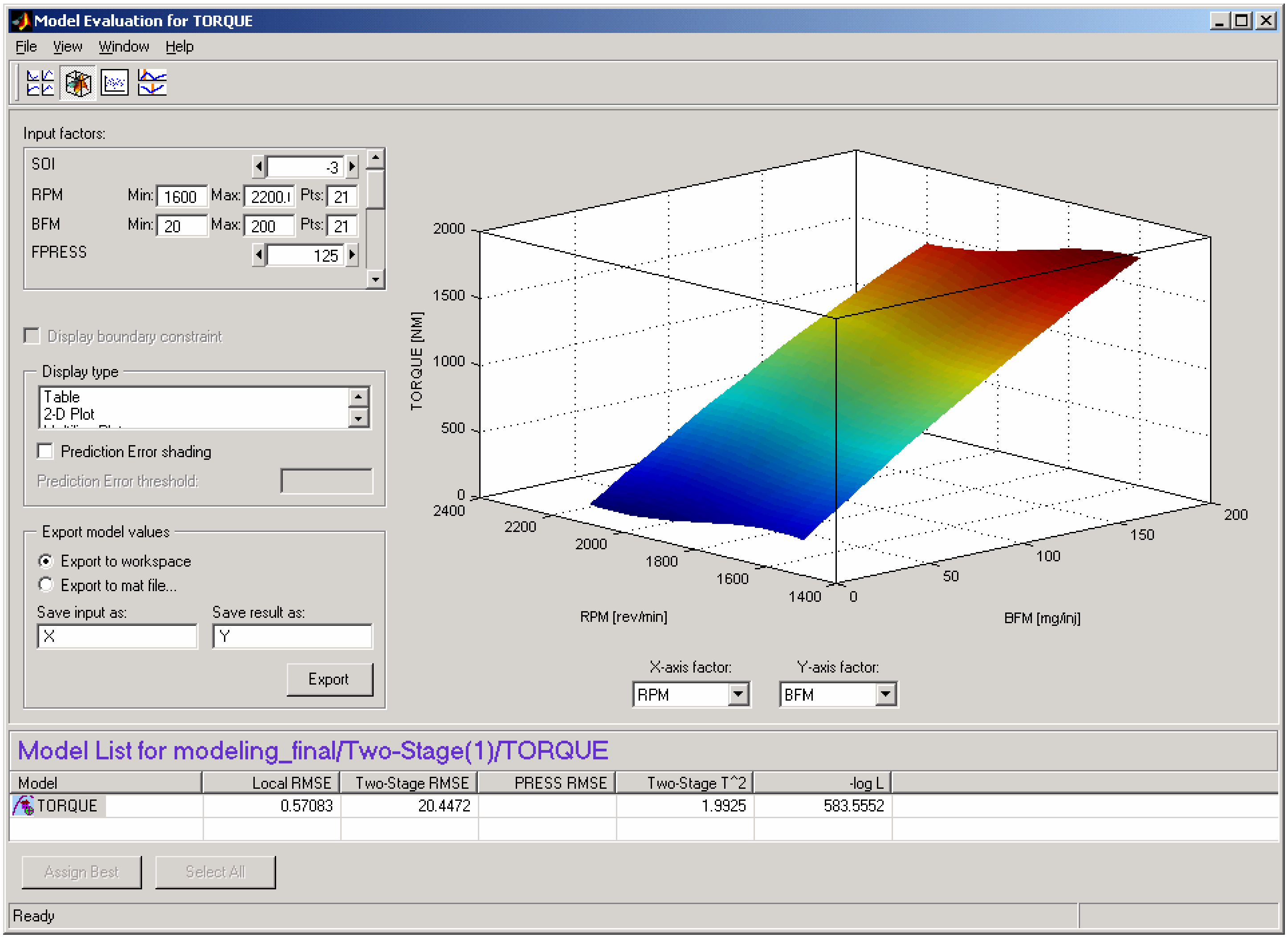


Figure 6: Torque Residual Errors vs. Measured Torque – Quadratic RBF

A qualitative review of the models was made to insure that the modeling process had delivered models that made sense from a physical standpoint. The Model-Based Calibration Toolbox was used to visualize the torque response by interactively changing the viewing angle and axes in several different graphical review tools available in the software. For example, in Figure 7, the statistically modeled linear cubic torque response of the engine is shown as a function of base fuel mass and engine speed, with other input settings fixed in the upper left of the Model-Based Calibration Toolbox GUI. The names of the axis variables in Figure 7 were defined previously in Table 3 and Figure 1.



Input factors:

SOI -3

RPM Min: 1600 Max: 2200.I Pts: 21

BFM Min: 20 Max: 200 Pts: 21

FPRESS 125

☐ Display boundary constraint

Display type

Table

2-D Plot

☐ Prediction Error shading

Prediction Error threshold:

Export model values

● Export to workspace

○ Export to mat file...

Save input as: X

Save result as: Y

Export

X-axis factor: RPM

Y-axis factor: BFM

Model List for modeling_final/Two-Stage(1)/TORQUE

Model	Local RMSE	Two-Stage RMSE	PRESS RMSE	Two-Stage T^2	-log L
TORQUE	0.57083	20.4472		1.9925	583.5552

Assign Best

Select All

Ready

Figure 7: Visualization of Linear Cubic Torque Model

Model Deployment

For the lower middle design process step in Figure 2, the automatic model export capability of Model-Based Calibration Toolbox was used to generate a Simulink block model of the linear cubic and quadratic RBF designs to facilitate automatic code generation. To implement the model, the MathWorks Real-Time Workshop Embedded Coder and OSEKWORKS target software were used in conjunction with WindRiver Tornado 3.0 software to generate and download efficient embedded code to the Phytek evaluation board. The final evaluation step was to use WindRiver SingleStep debugger software to determine the throughput of each model, and the code profiling capability of Real-Time Workshop Embedded Coder to determine RAM and ROM resource requirements.

CONCLUSION

Two embedded diesel engine torque estimator designs have been developed and evaluated on a MPC555 processor to prove the feasibility of estimating torque in a conventional engine control unit (ECU) for an off-road diesel application. The first linear cubic estimator design was determined to be feasible for production application with conventional ECU technology, making it a viable alternative to the introduction of new torque sensor hardware in production vehicles. The second, more accurate quadratic radial basis function estimator design was determined to be infeasible for production application at the present time, primarily due to high processor throughput requirements.

ACKNOWLEDGMENTS

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REFERENCES

1. The MathWorks, Inc., "Model-Based Calibration Toolbox: Model Browser User's Guide", 2003
2. ibid.
3. Montgomery, Douglas C., "Design and Analysis of Experiments", 5th ed., John Wiley and Sons, Inc. 1997

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