Model-Based Calibration Toolbox

Calibrate complex powertrain systems

Model-Based Calibration Toolbox™ provides design tools for optimally calibrating complex powertrain systems using statistical modeling and numeric optimization. You can define test plans, develop statistical models, and generate calibrations and lookup tables for complex high-degree-of-freedom engines that would require exhaustive testing using traditional methods. By using the toolbox with MATLAB® and Simulink®, you can develop a process for systematically identifying the optimal balance of engine performance, emissions, and fuel economy, and reuse statistical models for control design, hardware-in-the-loop testing, or powertrain simulation.

Key Features

▪ Interactive workflow tools for designing experiments, fitting statistical models to engine data, and producing optimal calibrations
▪ Classical, space-filling, and optimal designs, based on Design-of-Experiments methodology, for creating optimized test plans
▪ Techniques for developing high-fidelity nonlinear statistical models from test data
▪ Linear regression and radial basis function modeling techniques for creating accurate fits to data
▪ Built-in and user-definable libraries of empirical model forms
▪ Boundary modeling to keep optimization results within the engine operating envelope
▪ Optimization and tradeoff tools for solving calibration problems at individual operating points or over drive cycles
▪ Generation of lookup tables from models, optimization results, or test data
▪ Calibration import and export links to ETAS INCA and ATI Vision

Designing and Managing Tests

Model-Based Calibration Toolbox enables you to design a test plan based on Design of Experiments, a methodology that saves test time by letting you perform only those tests that are needed to determine the shape of your engine response.

The toolbox offers a full range of proven experimental designs, including:

▪ Classical: Box-Behnken, Central-Composite, and Full Factorial
▪ Space-filling: Latin Hypercube and Lattice
▪ Optimal: V, D, and A optimality criteria
You can use the experimental design to define the test points to be run in an engine dynamometer. You then bring the test data into Model-Based Calibration Toolbox to develop engine models.

Using the Design Editor in the toolbox, you can generate, augment, and visually compare designs without needing to know the detailed mathematics of Design of Experiments.

Defining a space-filling design in the Design Editor (left) and investigating the properties of the design using the Design Evaluation Tool (right).

Model-Based Calibration Toolbox integrates experimental design with three widely used test strategies:

- One-stage
- Two-stage
- Point-by-point

One-Stage Test Strategies

One-stage test strategies introduce a single source of variation, between tests, and are used for performing variable screening and design-space mapping. The Design of Experiments methodology is typically used to generate test plans that vary all variables simultaneously in this type of approach.

In Model-Based Calibration Toolbox, you can use the one-stage test strategy to identify and model the relationships among the variables in complex systems with multiple variables. For example, you can test an engine at different operating points and control actuator settings defined by a space-filling design for engine speed, load, and air-fuel ratio to develop a performance characterization of the engine using a response surface model.
Two-Stage Test Strategies

Two-stage test strategies introduce two sources of variation: local and global. They are used for tasks that involve sweeping a single control variable while holding other variables constant, as in collecting engine data by sweeping spark at a given engine speed, load, variable valvetrain settings, and air-fuel ratio. In this example the local variation occurs within the test when the spark angle is changed, and the global variation occurs between tests when the engine speed, load, variable valvetrain settings, and air-fuel ratio are changed.

Model-Based Calibration Toolbox lets you estimate local and global variations separately by fitting local and global models in two stages. You can use two-stage modeling to map the complex relationships among all the variables that control the behavior of the engine.

Collecting engine data for each test by sweeping spark while keeping speed, load, variable valvetrain settings, and air-fuel ratio constant.
Conducting a series of tests, each at a different value of speed, load, variable valvetrain settings, and air-fuel ratio. A model is then fitted to each test (local fitting).

Using the local models to calculate global models of the engine’s behavior as speed, load, variable valvetrain settings, and air-fuel ratio vary (global fitting).
Performing global fitting for several aspects of engine behavior. (Images courtesy of Ford Motor Company.)

Point-by-Point Test Strategies

Point-by-point test strategies enable you to develop statistical models at each operating point of an engine with the necessary accuracy to produce optimal engine calibrations when two-stage test strategies can no longer model engine performance responses accurately enough. Using a point-by-point test strategy in Model-Based Calibration Toolbox, you can accurately model and calibrate modern multiple-injection diesel engines and gasoline direct-injection engines.

Modeling the Engine Envelope

Acquiring data and modeling the engine must account for the operating regions of the system that can be physically tested. Model-Based Calibration Toolbox lets you add constraints to your experimental designs and create boundary models that describe the feasible region for testing and simulation. Supported boundary model types include:

- Convex hull – minimal convex set containing the data points
- Star-shaped – interpolation of all data points on boundary
- Range – data range for each input
- Ellipsoid – minimum volume ellipsoid containing all data points

Two-stage and point-by-point models provide additional boundary models for these types of test plans.
Using the Boundary Editor to define and visualize the feasible testing region and associated test conditions.
Data Analysis and Response Modeling
Model-Based Calibration Toolbox uses MATLAB functions for data analysis and visualization, statistics, and optimization to fit the models and generate a graphical representation of an engine’s behavior. The toolbox provides the Model Browser to help you ensure that test points taken in the laboratory match the original experimental design. Using the Model Browser, you can interactively fit different model types to the collected data.

Preprocessing Data
The toolbox provides the Design Editor for analyzing engine data and transforming it into a form that is suitable for modeling. With the Design Editor you can perform a variety of preprocessing operations, including filtering to remove unwanted data, adding test notes to document findings, transforming or scaling raw data, grouping test data, and matching test data to experimental designs.
Using the Data Editor to select a subset of tests and view the data in different formats: a 2D plot, a 3D plot, and a table.

Selecting and Fitting Models
Model-Based Calibration Toolbox provides a library of empirical model types for modeling engine behavior such as torque, fuel consumption, and emissions. Models include polynomials, splines, radial basis functions, growth models, user-defined MATLAB files, and Simulink models.
Using the Model Browser to fit and evaluate different model types for a gasoline engine.

Generating Optimal Calibrations

The Calibration Generation (CAGE) tool in the Model-Based Calibration Toolbox is a graphical user interface that lets you calibrate lookup tables for your engine control unit (ECU). With the CAGE tool, you can fill and optimize lookup tables in ECU software using Model Browser models. You can:

- Generate optimal calibrations directly from empirical engine models
- Compare calibrations with test data
- Export calibrations to ETAS INCA and ATI Vision

Optimizing Engine Performance

The CAGE tool lets you generate optimal calibrations for lookup tables that control engine functions, such as spark ignition, fuel injection, and inlet and exhaust valve timing. Calibration of these features typically involves tradeoffs between engine performance, economy, reliability, and emissions. You can:

- Make tradeoffs between competing design objectives
- Perform multiobjective optimizations
- Deal with multiple constraints
• Perform weighted optimizations based on typical drive cycles
• Use built-in or custom optimization routines
• Manipulate table values with custom functions

Producing Smooth Calibration Tables

Complex calibration problems can require different optimizations for different regions of a table. The table-filling wizard enables you to incrementally fill tables from the results of multiple optimizations with smooth interpolation through existing table values. The CAGE tool extrapolates the optimization results to pass smoothly through table masks and locked cells (fixed table values). Use these features when you want to use separate optimizations to fill different regions of a lookup table.

The CAGE tool also provides gradient constraints for controlling table smoothness in optimization-based and feature-based table filling.

Optimizing Engines with Different Operating Modes

Model-Based Calibration Toolbox enables you to produce optimal calibrations for engines with multiple operating modes. You can use the composite model type to combine a number of models that represent engine responses under different operating modes. Using the composite model in the CAGE tool produces optimal calibrations for engines with multiple operating modes, where the goal is to fill a single table for all modes or to fill a table for each mode.

Calibrating Estimator Features

ECU software often includes features for estimating states that are too difficult or costly to measure in production vehicles, such as torque and borderline spark. Using the CAGE tool, you can describe estimator features graphically with Simulink block diagrams, fill the lookup tables for these features, and then compare the estimators with empirical engine models made from measured engine data.
Performing Simulations in Simulink

You can export statistical models developed in Model-Based Calibration Toolbox to Simulink or use them for hardware-in-the-loop (HIL) testing.

Plant Modeling and Optimization

Use statistical models developed in the toolbox to capture real-world complex physical phenomena that are difficult to model using traditional mathematical and physical modeling. For example, you can export models for torque, fuel consumption, and emission (such as engine-out HC, CO, NOx, and CO2) to Simulink and perform powertrain-matching, fuel economy, performance, and emission simulations to improve powertrain component selections, drivability-related controls, and emission-related controls. Since the key physical components of your model have been derived from measured engine performance data, your models yield more accurate results than detailed physical models from theory that do not capture the complete physical phenomenon of the real-world system.

You can also reduce long-running or computationally intensive simulations by creating an accurate statistical surrogate model of an existing detailed high-fidelity engine model. For example, you can use the toolbox to generate accurate, fast-running models from complex Simulink models or subsystems over the design space of interest. The statistical surrogate can then replace the long-running subsystems in Simulink to speed up simulation time.

Hardware-in-the-Loop Testing

Model-Based Calibration Toolbox models exported to Simulink can be used in real-time simulations with hardware to provide fast, accurate plant model emulation to the ECU sensor and actuator harnesses. Since developing models in the toolbox takes advantage of a methodical process, you can reduce bottlenecks related to the current art of HIL plant model development, resulting in earlier validation of ECU algorithm designs.