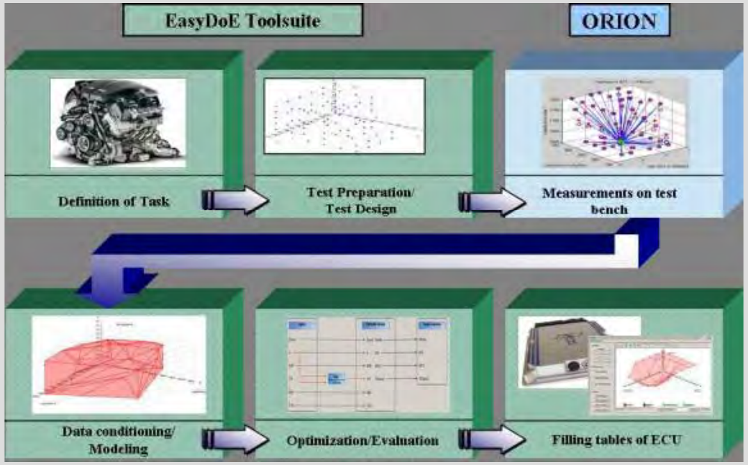

Model Based Engine Calibration

Using State of the Art Software Support

2010 Motorcycle & Engine Key Technology Seminar
Tanjin University
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Introduction

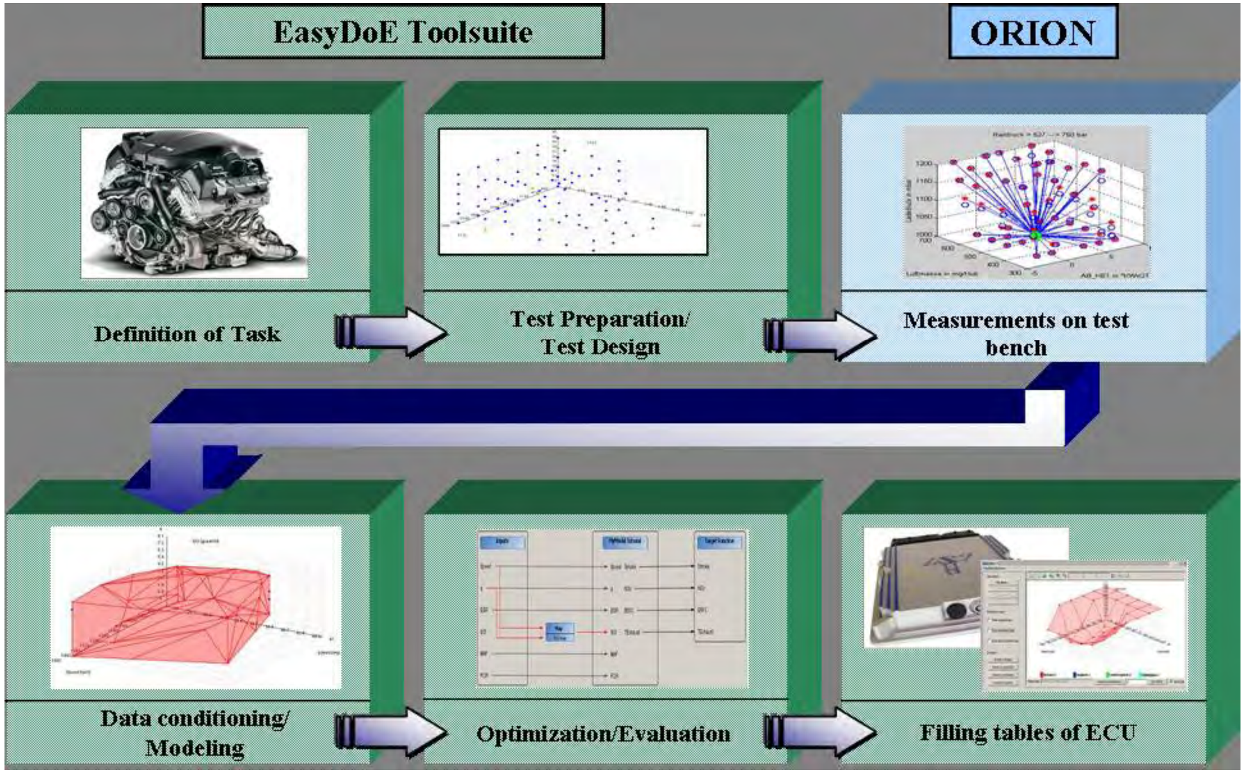
- Model based calibration
  - Use of models of the engine behavior for main calibration
  - Models are created using Design of Experiments (DoE) Methods
- DoE in engine development is more then just experiment design
  - It is a synonym for a structured methodology of calibration
- Split nature of the process
  - Statistical knowledge for analysis
  - Test cell automation for data gathering
- Typical end user understands engines / calibration
  - But is not a statistics expert
  - Does not specialize in test bed control systems

Objective

- Objective
  - Demonstrate how to use the software tools to execute a typical calibration task
  - Ease of use
- Calibration Goal
  - Optimize part of the speed/relative load map of a gasoline engine
- Definition of Factors
  - Define optimal settings for available parameters
    - Variable Valve Timing
    - Spark Advance
    - Lambda
- Optimization Objectives
  - Minimize brake specific fuel consumption (BSFC)
  - Minimize the BSFC and emissions
  - Maximize the torque

State of the Art Software Tools

- The use of state of the art software tools facilitates the process for the end user and organization
  - EasyDoE ToolSuite provides statistical methods
  - ORION provides procedures for automated testing



Definition of Factors and Responses

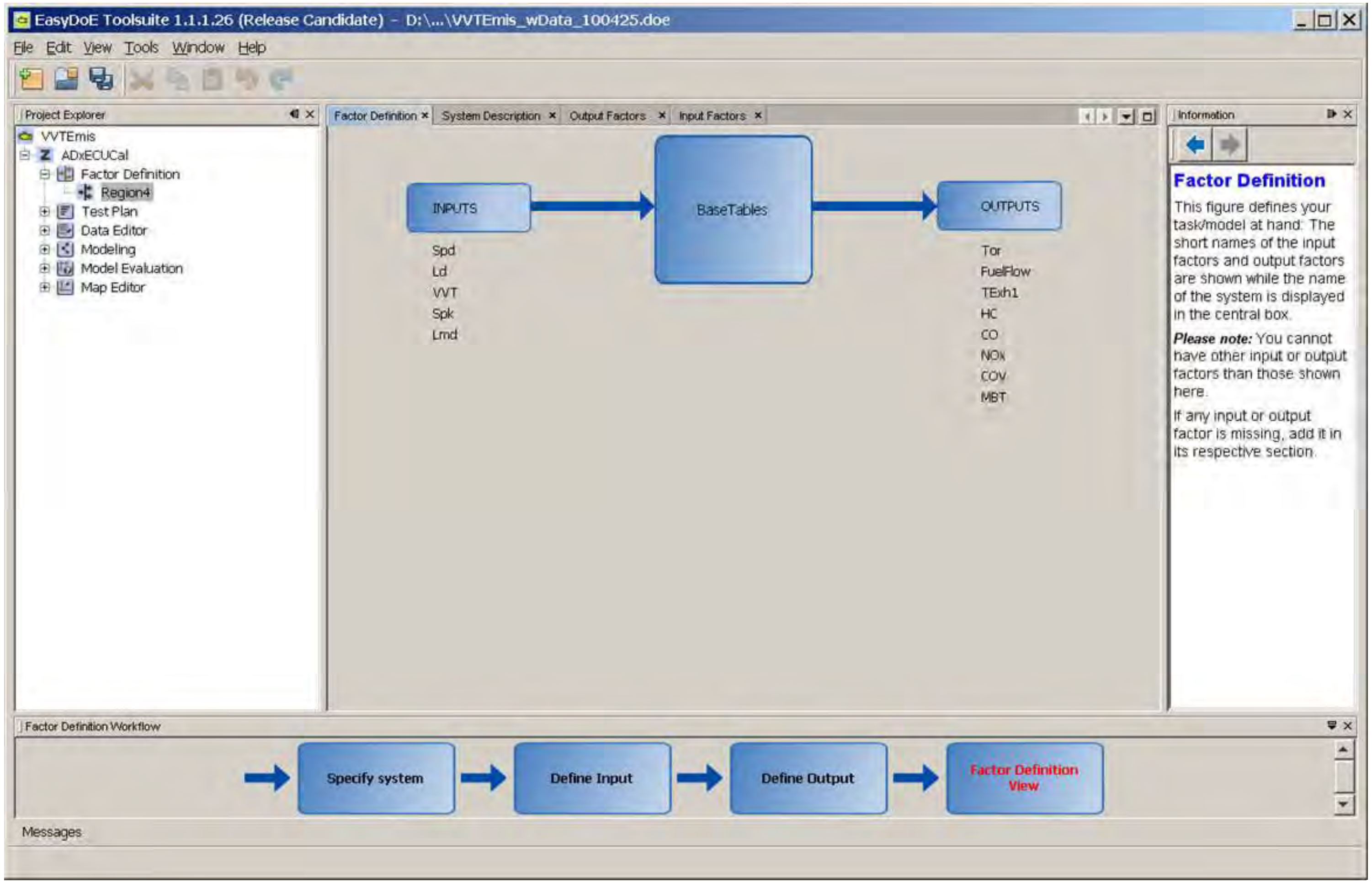
- The factors required are
  - Engine Speed
  - Relative Load
  - Variable Valve Timing
  - Spark Advance
  - Lambda
- The responses required are
  - Torque
  - Mass Fuel Flow
  - Exhaust Temperature
  - Maximum Brake Torque (MBT) Spark
  - Emissions HC/CO/NOx
  - Coefficient of Variation of Indicated Mean Effective Pressure (COV of IMEP)
  - BSFC (calculated)
- Optimization Constraints
  - Spark advance less than or equal to MBT Spark
- Monitor during data gathering
  - Knock Amplitude
  - Water, Oil Temperatures, etc.

$$R = f\left(Spd, Ld, VVT, Spk, Lmd\right)$$

$$MBT = f\left(Spd, Ld, VVT, Lmd\right)$$

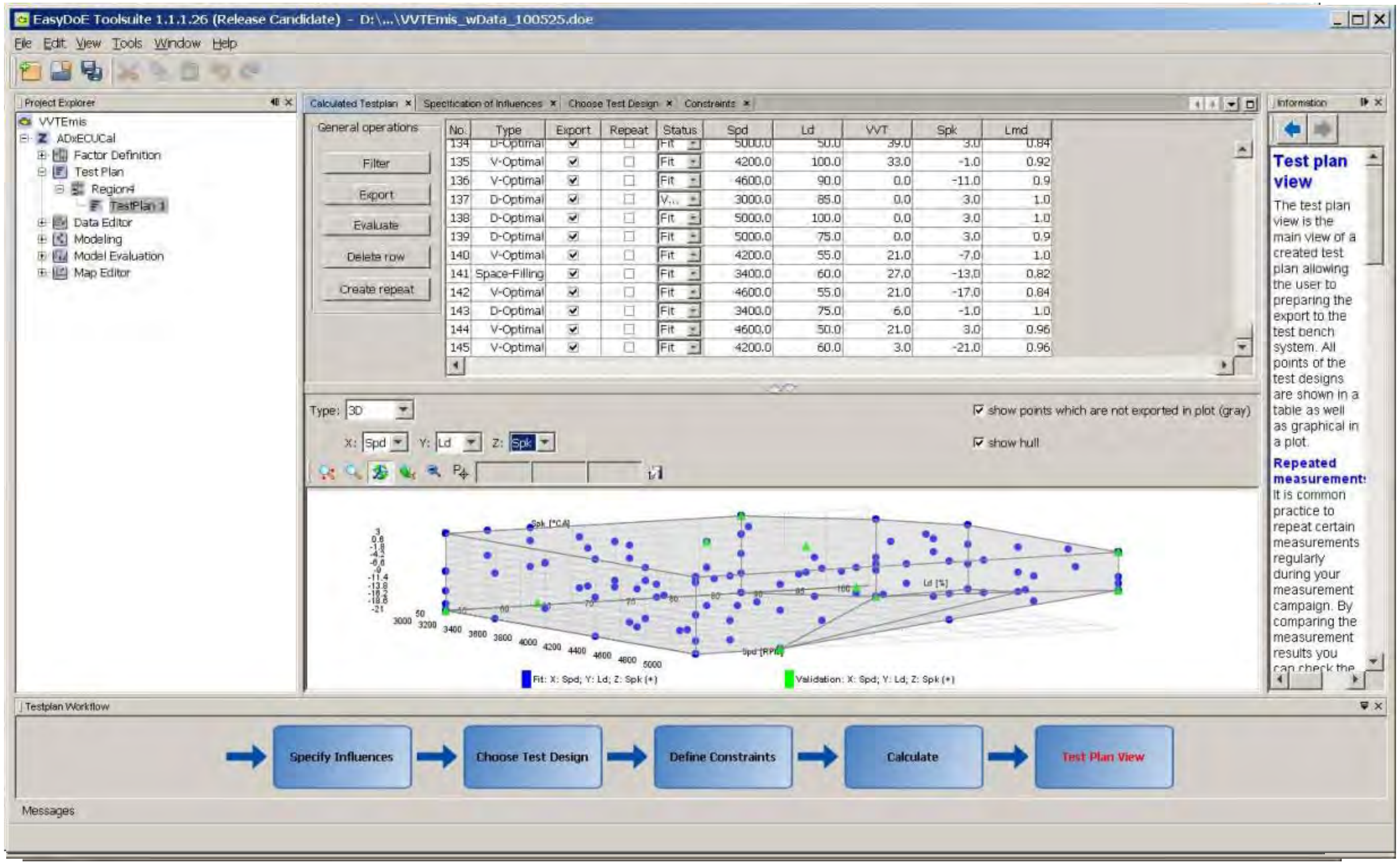
Set Up Project

- Factors and responses are entered into EasyDoE Toolsuite



EasyDoE Test Plan

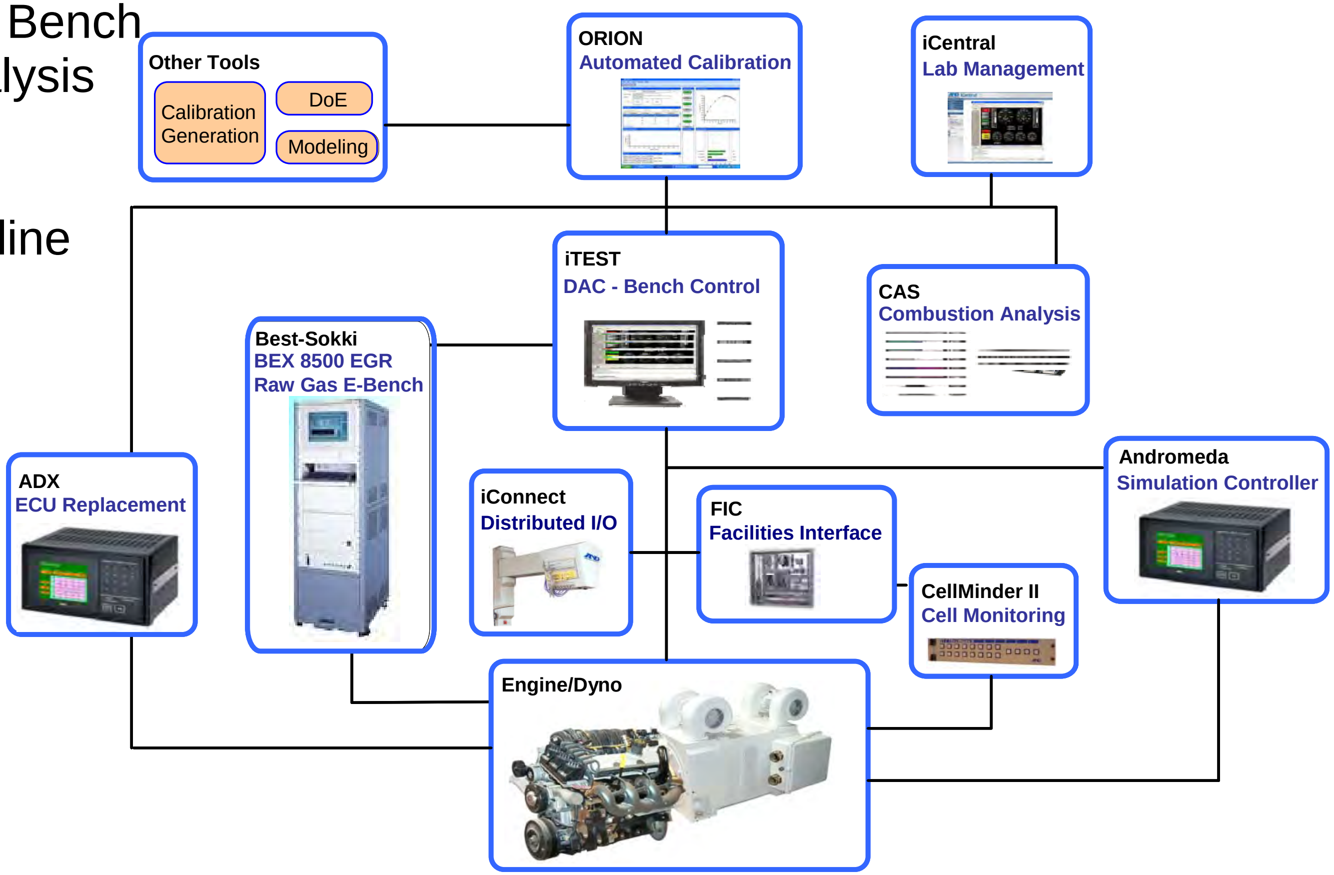
- The experiment design is entered, and 145 points are generated



A&D Technology's R&D Test Cell

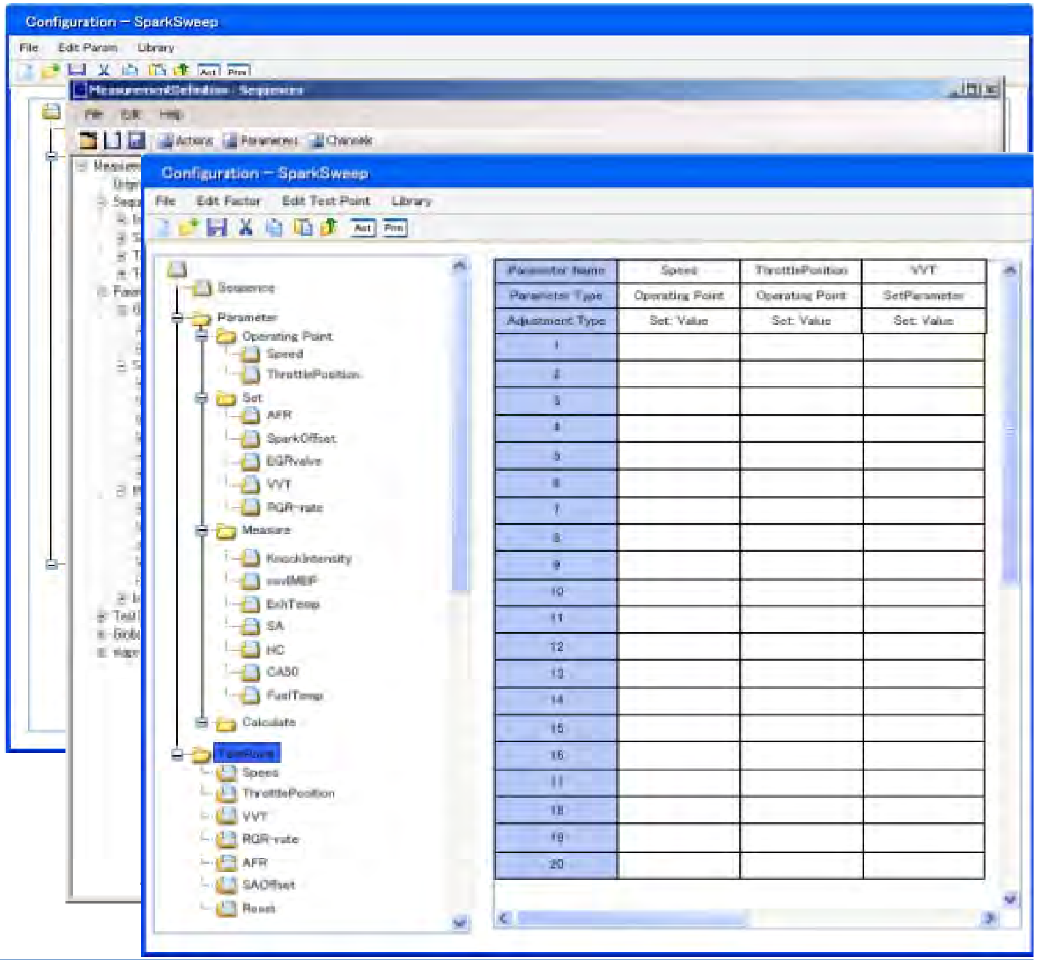
Test Cell Features:
- ORION Test Automation
- iTest Bench control
- ADX rapid prototype ECU
- Best Sokki Emissions Bench
- CAS Combustion Analysis

Engine Features:
- Production 4-cyl gasoline engine
- Variable Valve Timing



ORION Configuration

- ORION MDA is the key interface for the user creating the configuration
- Main configuration task is Compiling the following elements:
  - Parameters – both from the test cell and Calibration tool
  - Sequence – action to be executed in, flow-chart based
  - Test Plan – all values from the DoE that the sequence needs to execute imported from Easy DoE

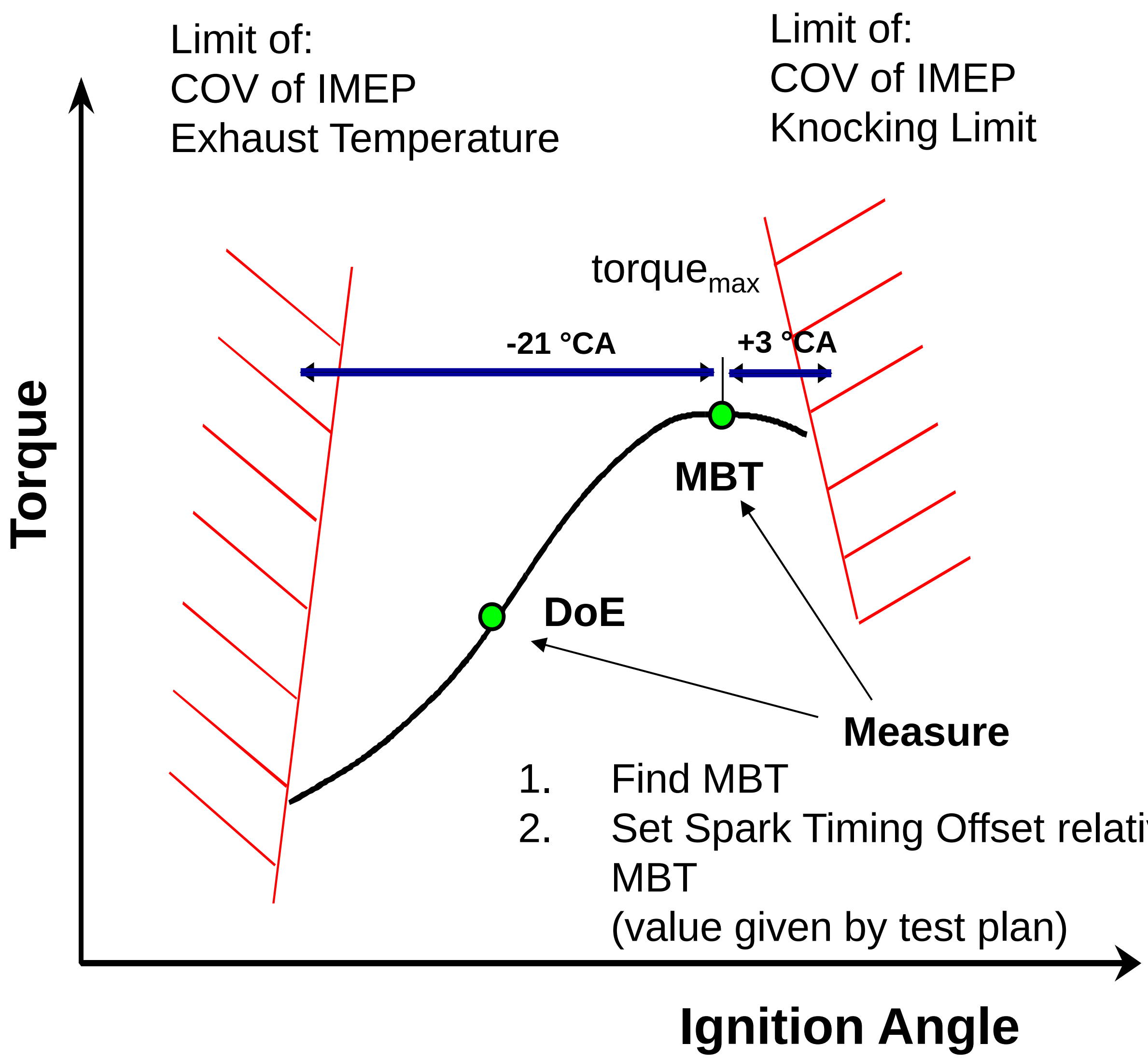


ORION Test Execution

- MA is the key interface for the operator in the test cell
  - Simple load the configuration file from MDA
  - Connect to test cell control and calibration tool
  - Execute sequence by pressing “start”
- Indicators and graphs keep the operator informed on progress and status
- Test cell system collects the data as directed by MA via ORION “Measure” action
- MA remembers state of test point – measured successfully
  - Easy to restart a test

Data Gathering Strategy

- Save existing cal values
- Set speed and load
- Set VVT
- Set Lambda
- Sweep spark for MBT
  - Measure
- Set offset spark value relative to MBT Spark
  - Measure
- Reset cal values



1. Find MBT
2. Set Spark Timing Offset relative to MBT
(value given by test plan)

Data Gathering Strategy

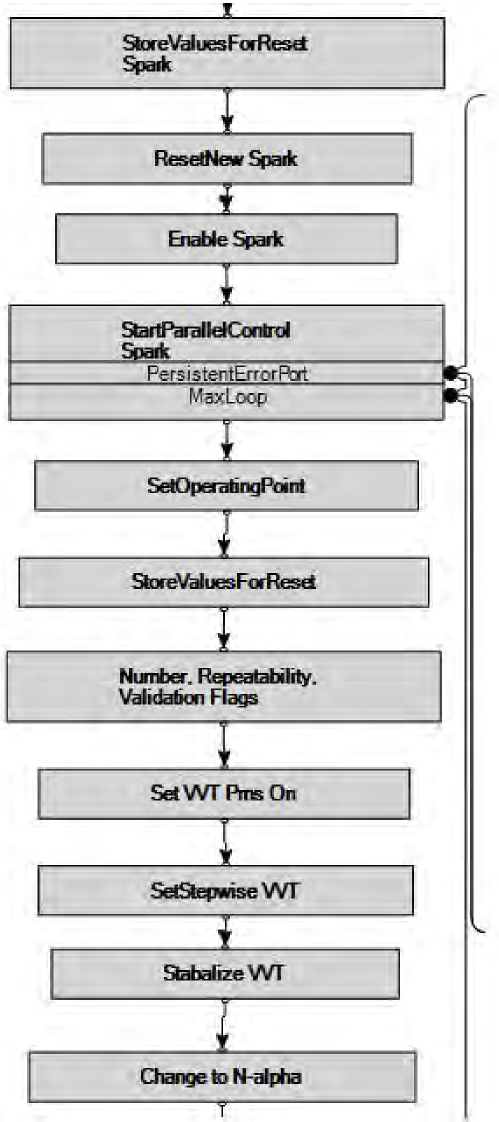
- Test cell run in speed / load mode

- Parallel control on spark advance during setting of speed / load and stepwise setting of VVT and Lambda
  - CA50
  - Monitored limits of temperature and knock

- Two data points taken for each Speed/Load/VVT/Lambda
  - On-line determination of MBT Spark using ORION optimization
  - Offset spark added to MBT

- Repeatability points are added
  - Center point of factor ranges
  - Used to check verify model quality

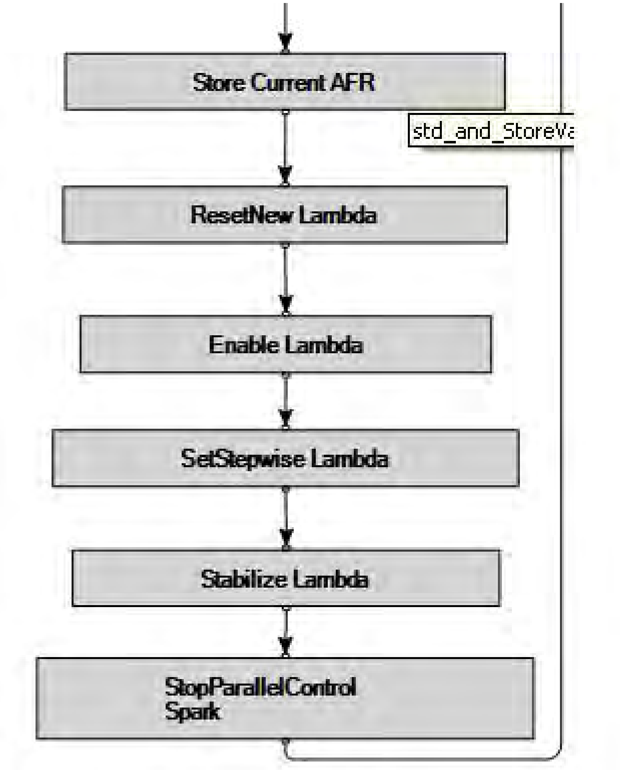
Data Gathering in the Test Cell with ORION



Part 1: Parallel Control of Spark CA50, Set stepwise VVT

- Store the initial values for the spark advance for reset at the end of the step.
- Start the parallel control for spark advance.
- Set the speed/load setpoint from the experiment design.
- Store the VVT value for reset.
- Store flags from the experiment design.
- Turn on VVT permission and set the VVT stepwise.
- Stabilize the temperature
- Change the dyno mode to speed / alpha to lock the air path.

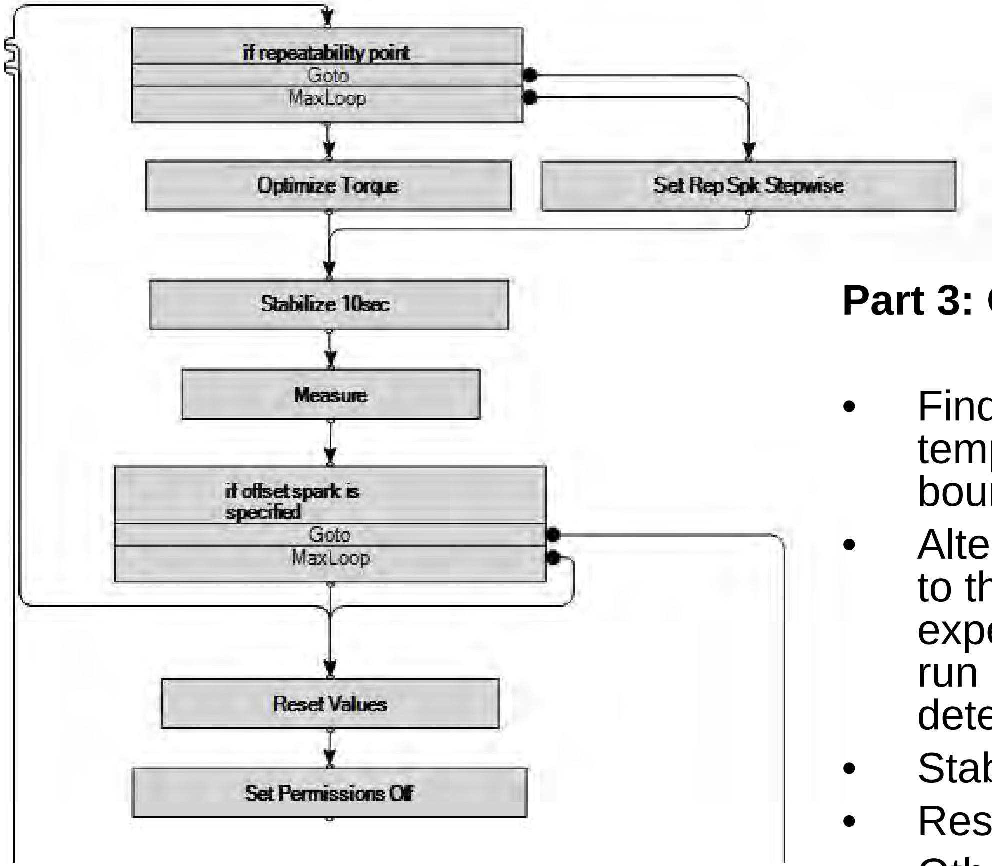
Data Gathering in the Test Cell with ORION



Part 2: Set Stepwise Lambda

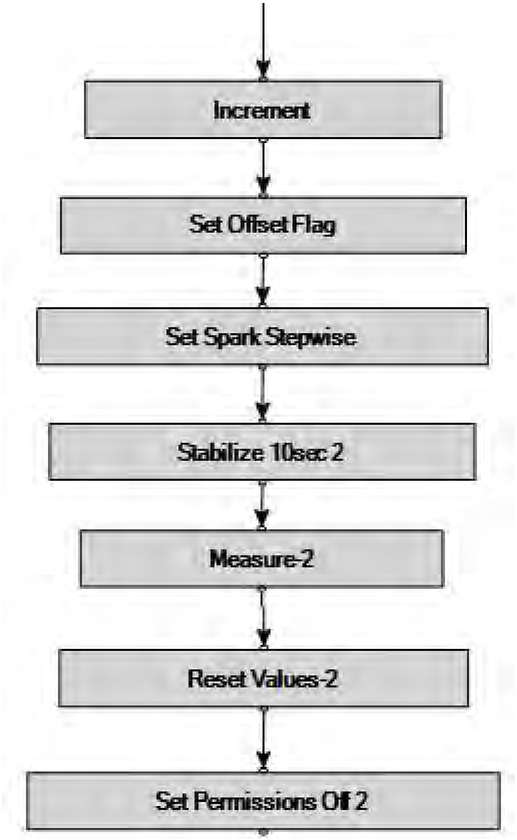
- Store the initial values for the Lambda for reset at the end of the step.
- Set the Lambda permission and set Lambda stepwise.
- Stop the parallel control for spark advance.

Data Gathering in the Test Cell with ORION



Part 3: Optimization

- Find optimal torque by sweeping spark. Exhaust temperature and knock are monitored to define boundaries.
- Alternatively, if this is a repeatability point, then set to the desired spark in the test plan. After every 10 experiment design points a repeatability point is run using the center point for each region to determine the variation of the response values.
- Stabilize for 10 seconds and then measure.
- Reset the values if this is a repeatability point.
- Otherwise continue to measure offset spark.

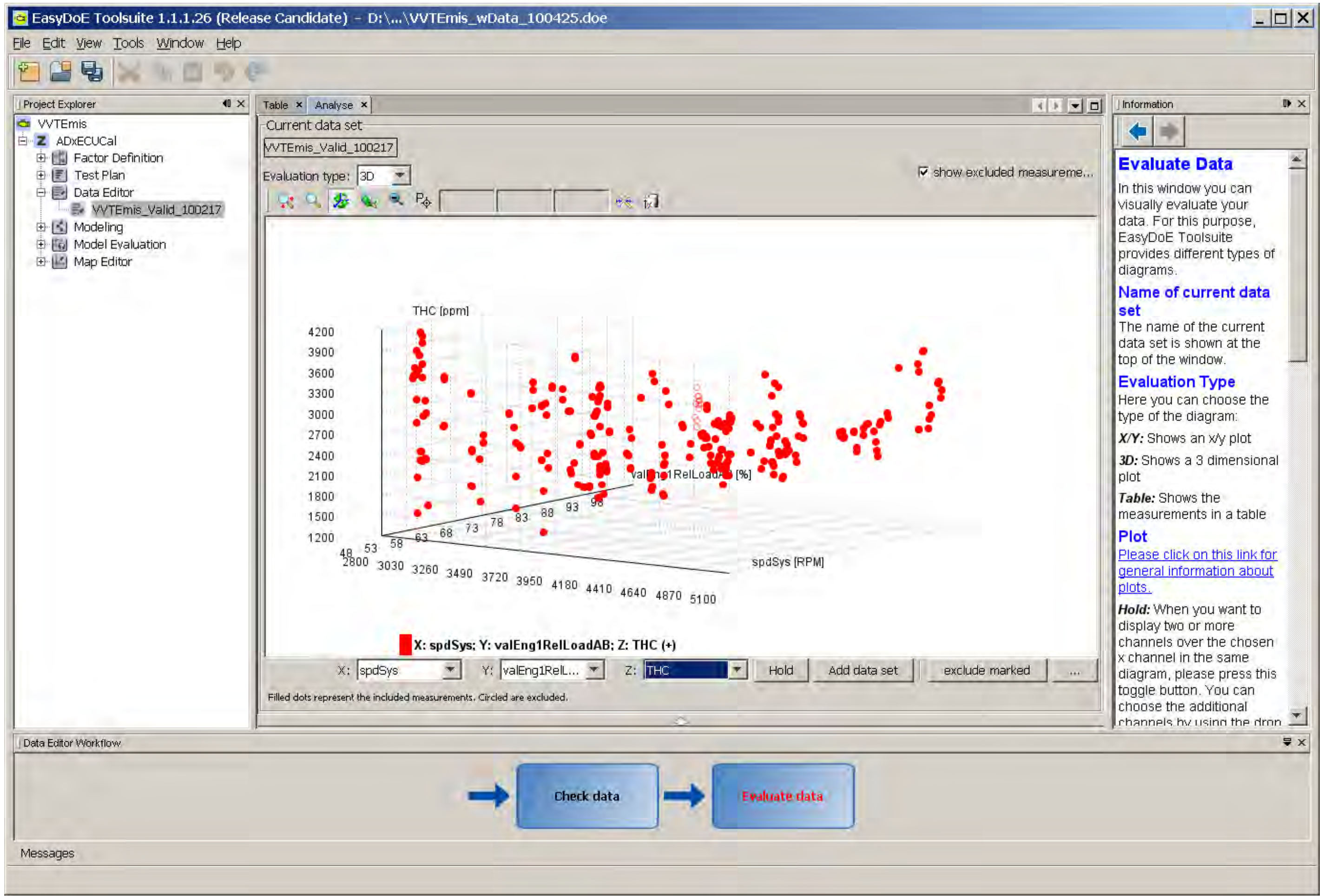


Part 4: Measure Offset Spark, Reset Starting Values

- Increment the spark advance by the offset spark value from the experiment design.
- Stabilize and measure.
- Reset the initial values and proceed to the next step.

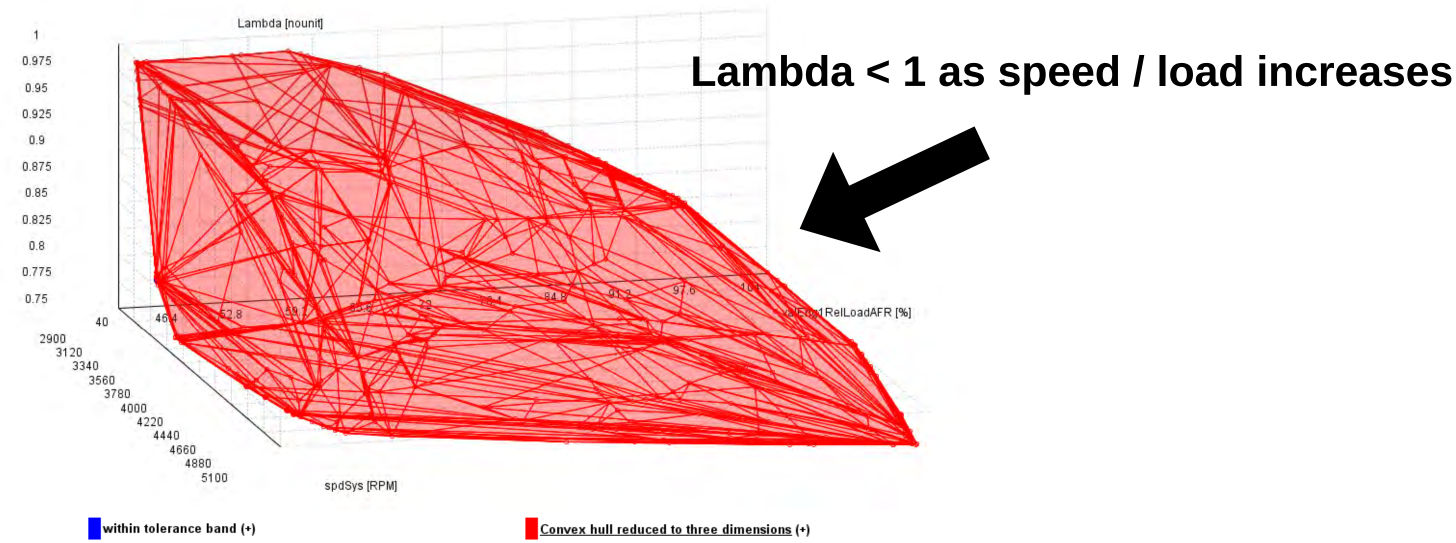
Data Review

- The data is imported into EasyDoE Toolsuite and reviewed via a user interface



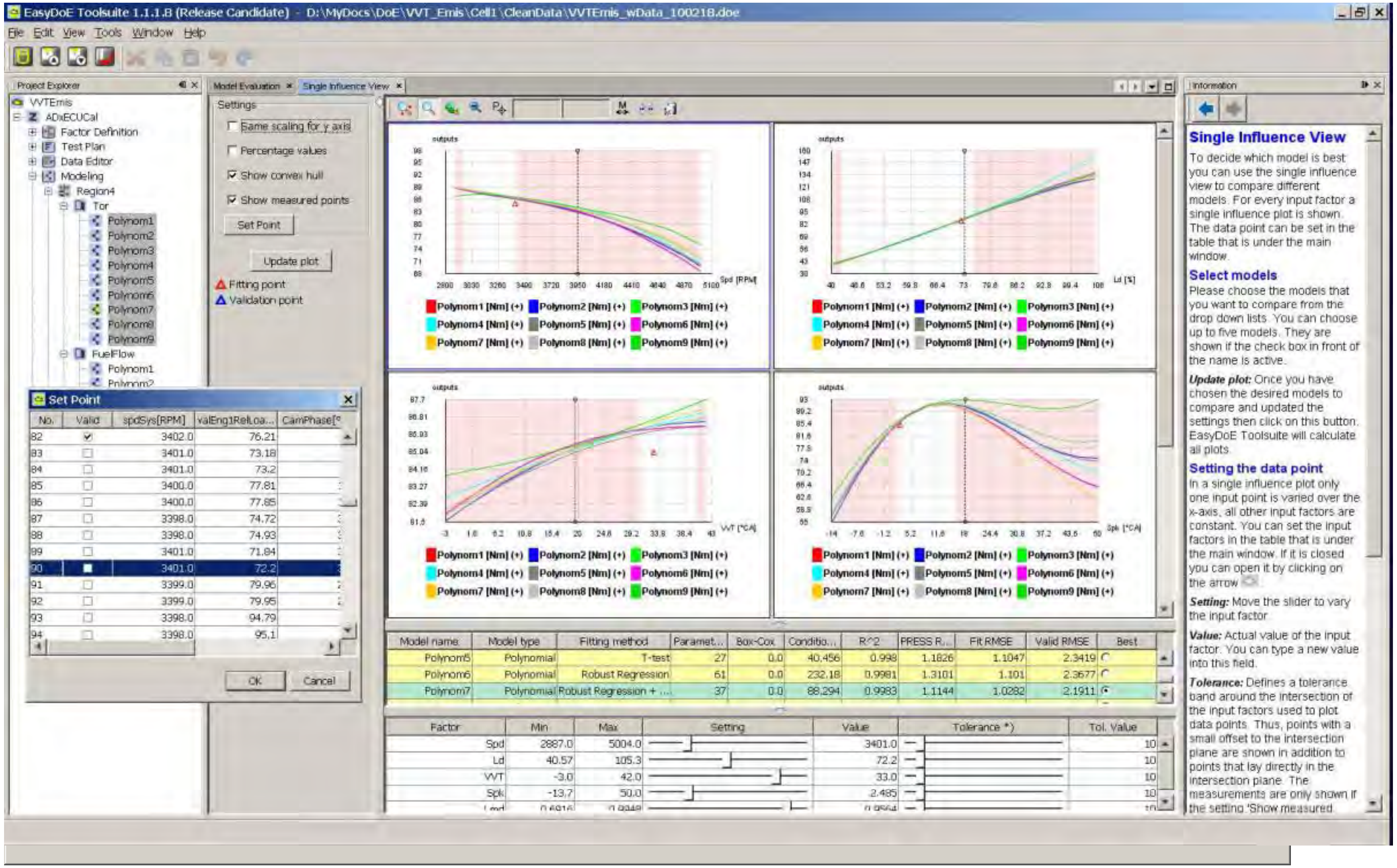
Data Review

- Temperature limits during data gathering set to 750°C
  - This was conservative; difficultly reaching lambda = 1
- Aftermarket Lambda sensor used for AFR feedback control
  - AFR calculated from bench was more reliable
  - Resulted in variation in the repeatability measurements for emissions



Modeling

- The data is associated with the factor definition and modeled
- A best model is selected for each response and stored as a result model



EasyDoE Fitting Methods

- Model fitting is done automatically in EasyDoE Toolsuite
- The following polynomial fitting methods are run for each model

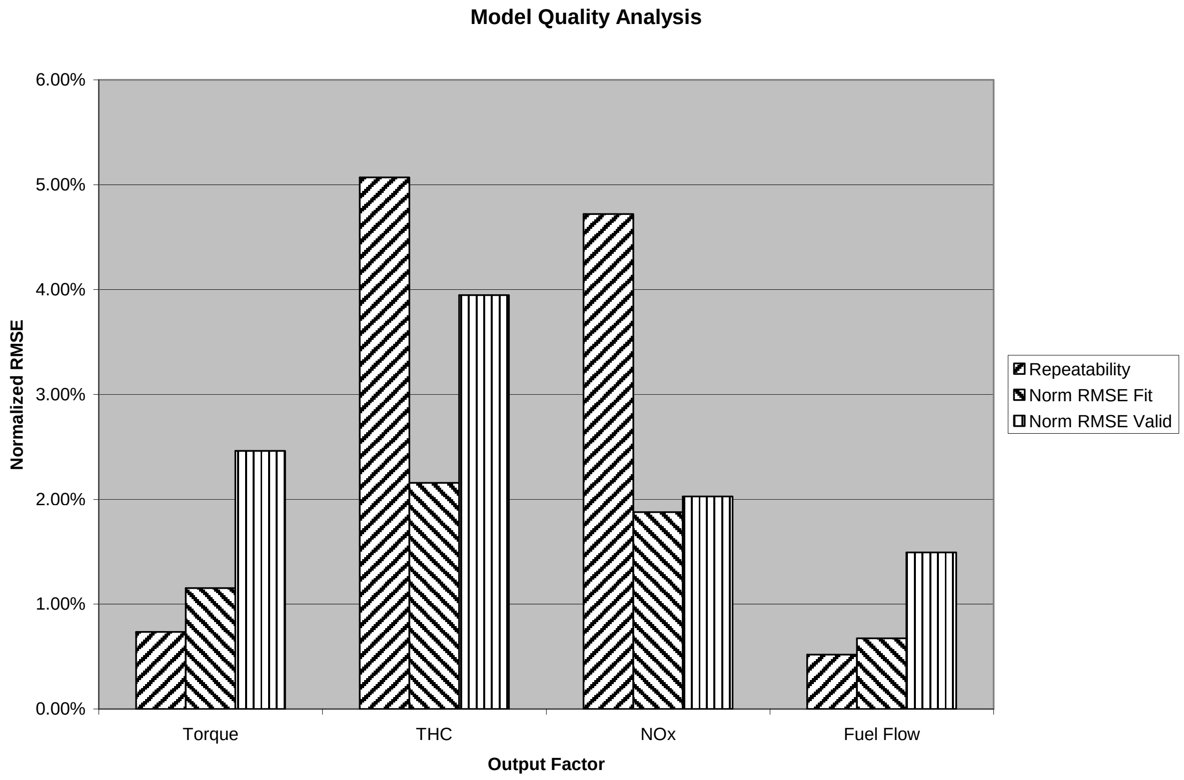
Polynomial Fitting Method	*Description*
1. **Standard Regression**	**Least Squares Estimation**
2. **Minimize PRESS**	**The PRESS value is used to select the model terms.**
3. **Stepwise Fit**	**Stepwise regression for term selection**
4. **OLS**	**Orthogonal Least Squares Estimation**
5. **T-test**	**Tests each coefficient to be zero with a specific probability (model structure). If the coefficient is likely to be zero it is taken out.**
6. **Robust Regression**	**Detects the bad data points and build models without these points.**
7. **Robust Regression + Minimize PRESS**	**Model is built without bad data points and trained with the 'best' terms selected by 'Minimize PRESS' algorithm.**
8. **Robust Regression + Stepwise Fit**	**Model is built without bad data points and trained with the 'best' terms selected by 'Stepwise Fit' algorithm.**
9. **Stagewise Regression**	**Incremental Forward Stagewise Algorithm i.e. incremental coefficient adaptation in direction of highest correlation to the current residuals.**

Model Quality Analysis

$$\text{Repeatability (\%)} = Average\left(\frac{\sigma}{mean}\right)$$

$*$ of the repeatability points

$$\text{Model Quality (\%)} = \frac{RMSE}{Range}$$



$$\text{Repeatability} < \text{Model Quality}_{\text{Fit}} < \text{Model Quality}_{\text{Valid \& Ver}} < 5\%`$$

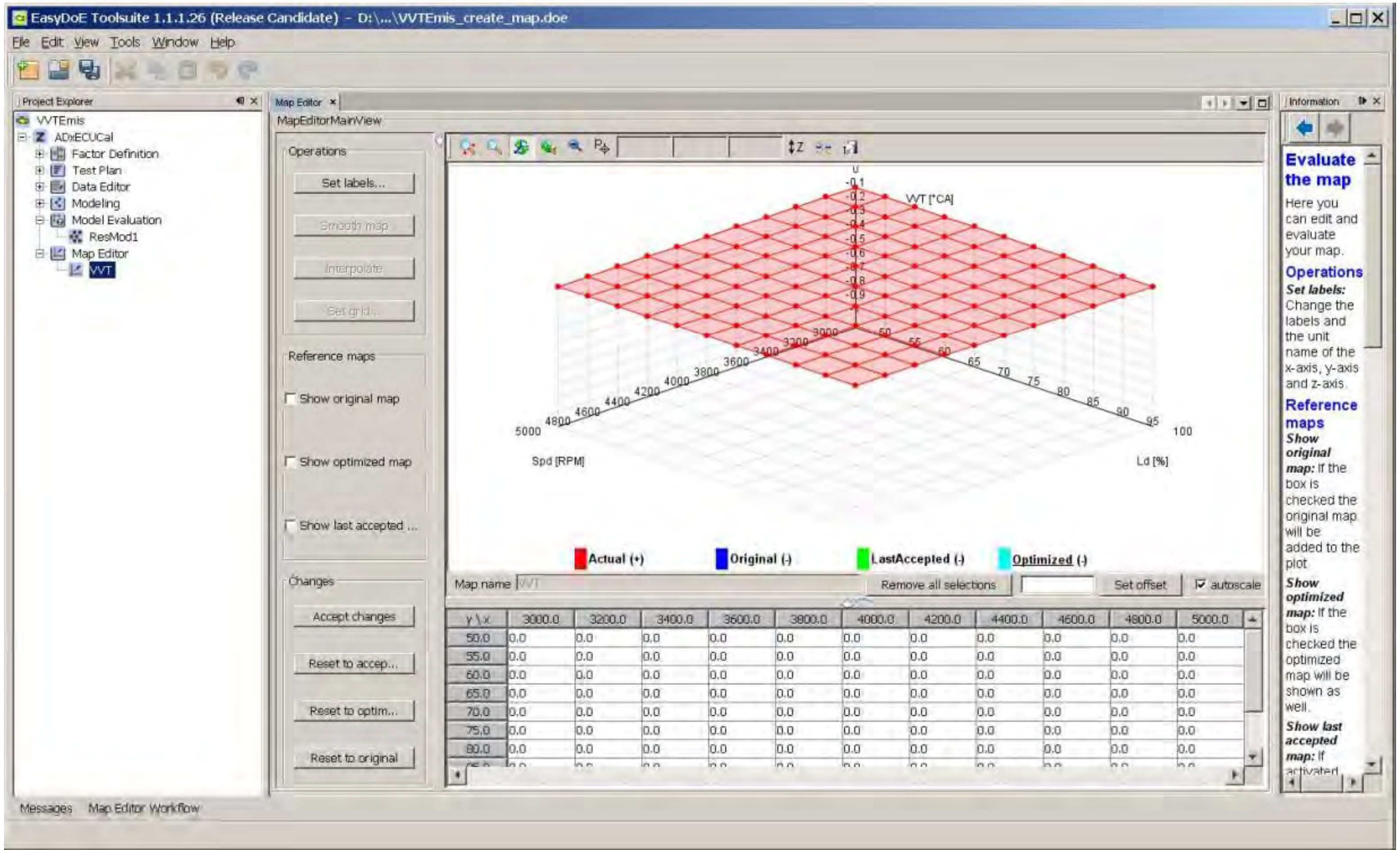
- Repeatability and Model Quality should correlate
- The variability of the AFR sensor resulted in higher repeatability values for emissions

Optimization Requirements

- In Model Evaluation a grid of speed / load points is defined:
  - Speed — 3000 to 5000 in 200 RPM increments
  - Relative Load — 50 to 100% in 10% increments
- A weighted sum gradient descent method is selected.
  - +1 — Maximize the response
  - - 1 — Minimize the response
  - 0 — No optimization on the response
- Three optimizations:
  - Minimize BSFC: — BSFC weight is set to -1
  - Minimize BSFC : — BSFC weight is set to -0.5.
    - Min HC/CO/NOx — HC/CO/NOx weights set to -0.05/-0.05/-0.4
  - Maximum torque: — Torque weight is set to +1
- A constraint is set to restrict the factor of
  - Spark advance < MBT spark

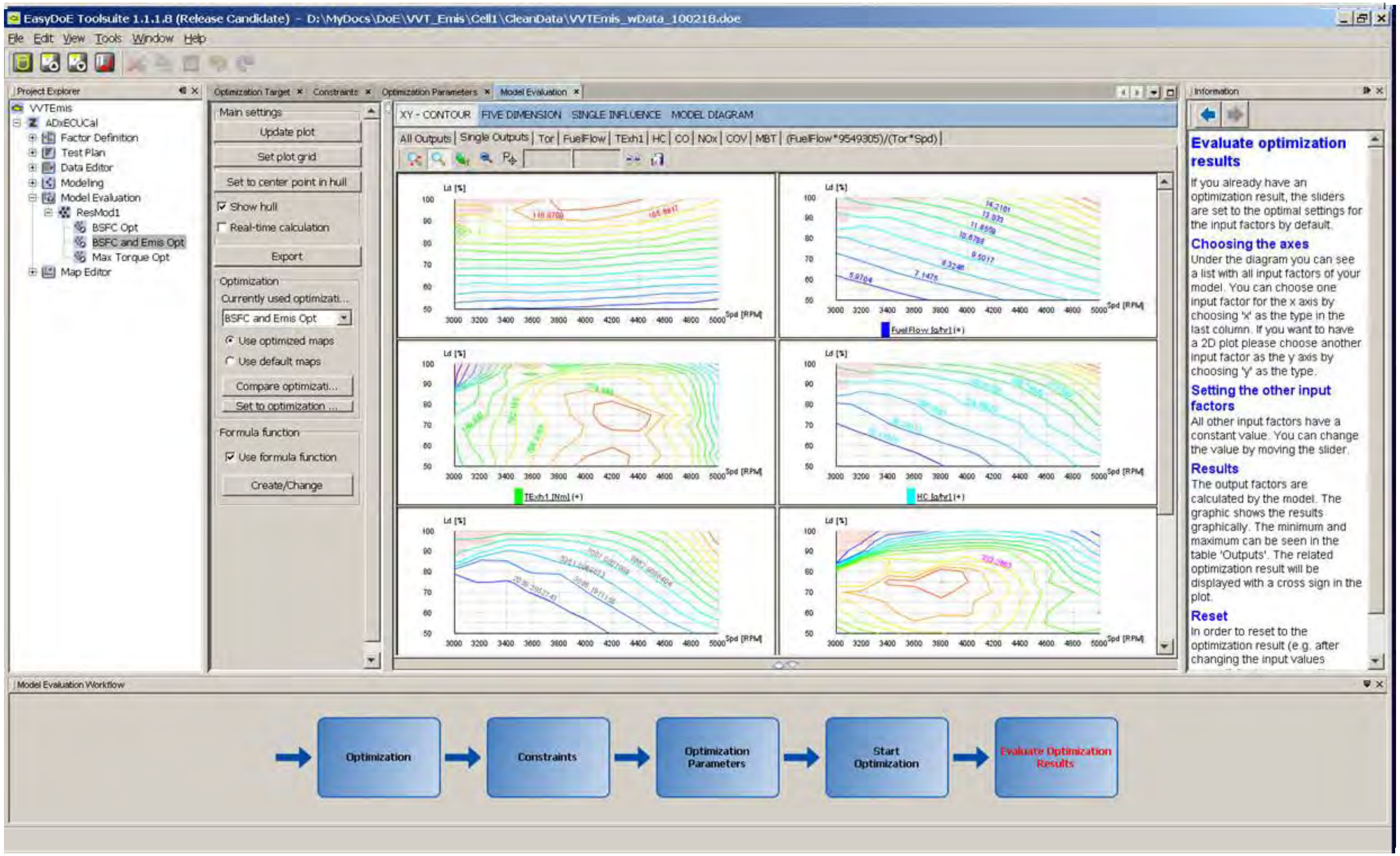
Model Evaluation – Map Creation

- Maps for each optimization are created in the map editor
  - VVT, Spark, Lambda



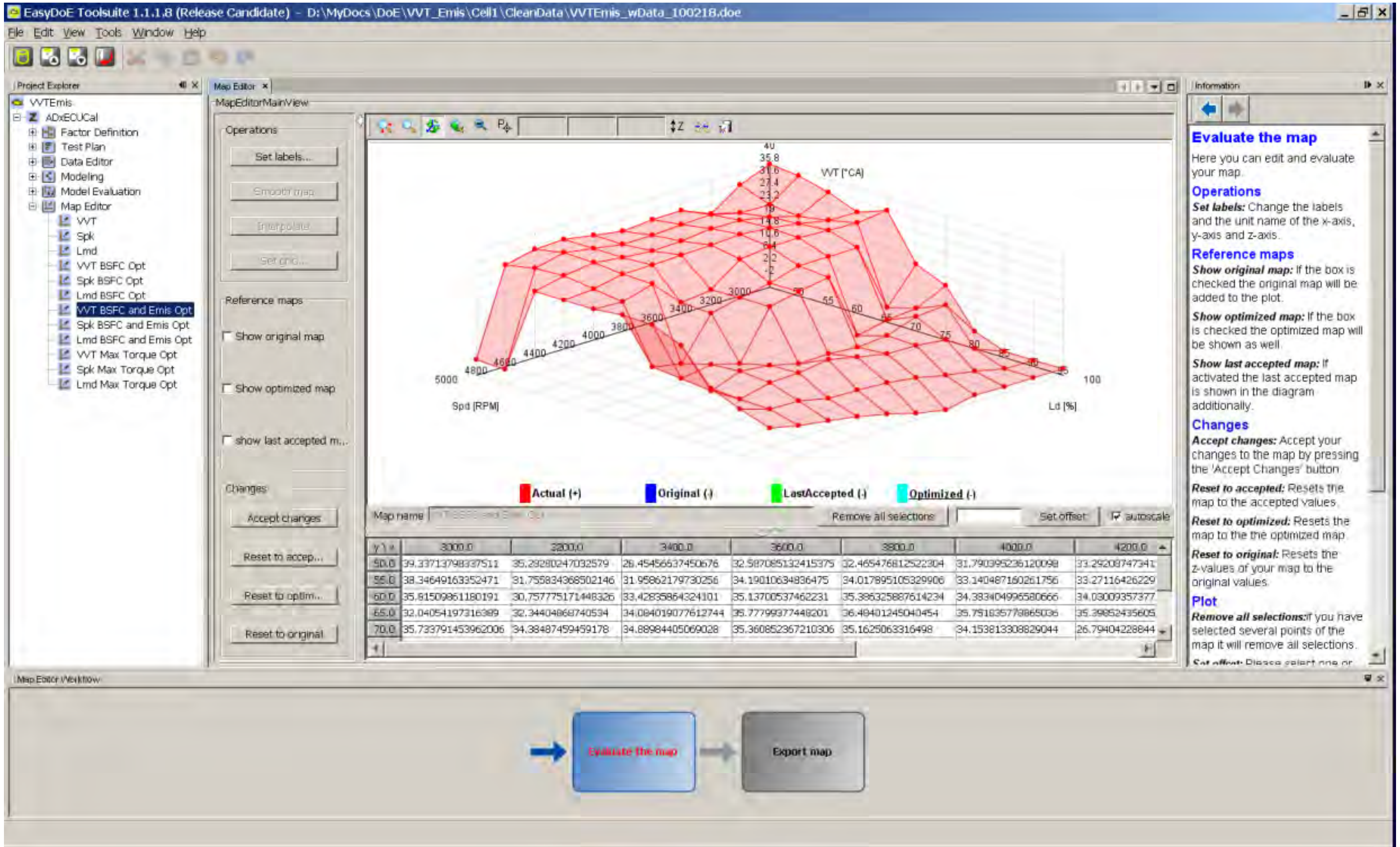
Model Evaluation - Optimization

- The optimization is performed in Model Evaluation



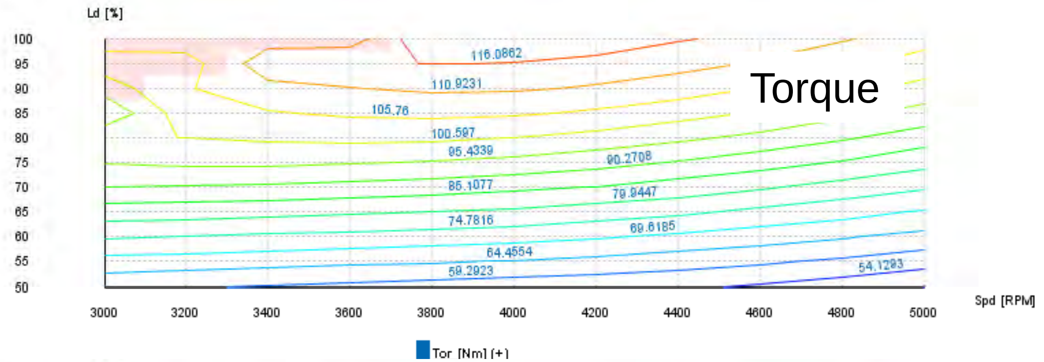
Model Evaluation – Map Editor

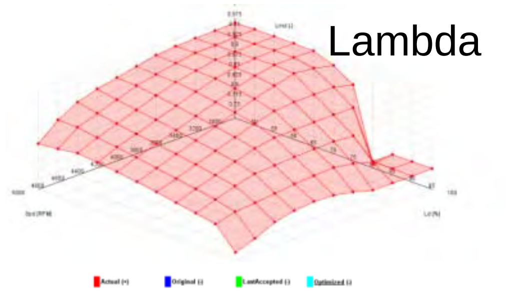
- After the optimization the maps can be edited graphically or in the table

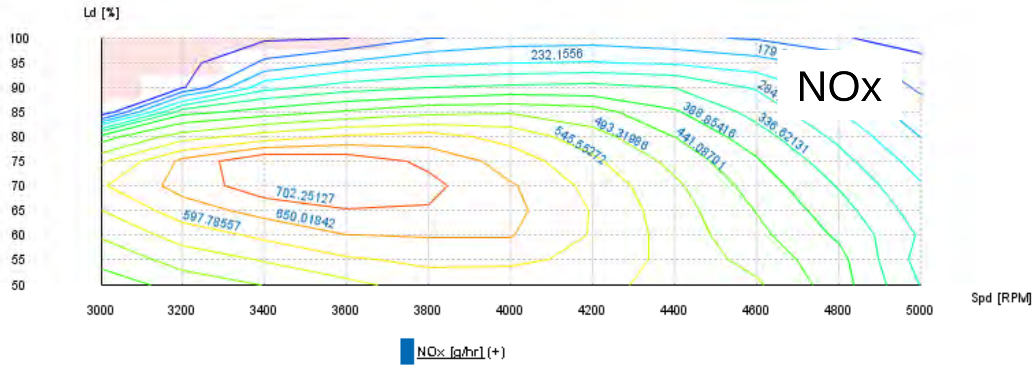


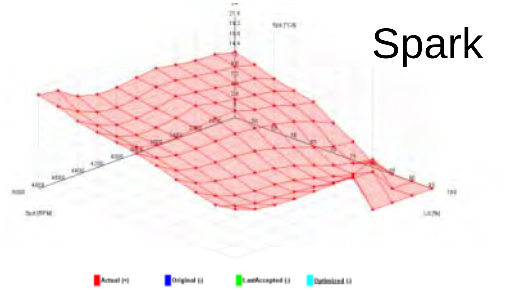
Model Evaluation

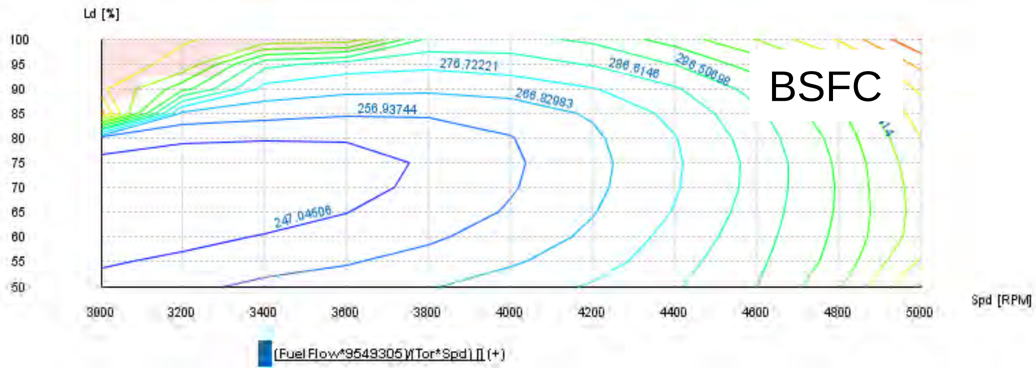
Objective BSFC

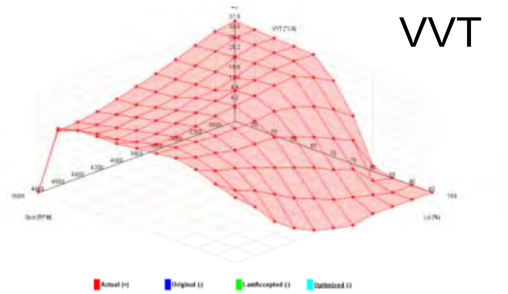






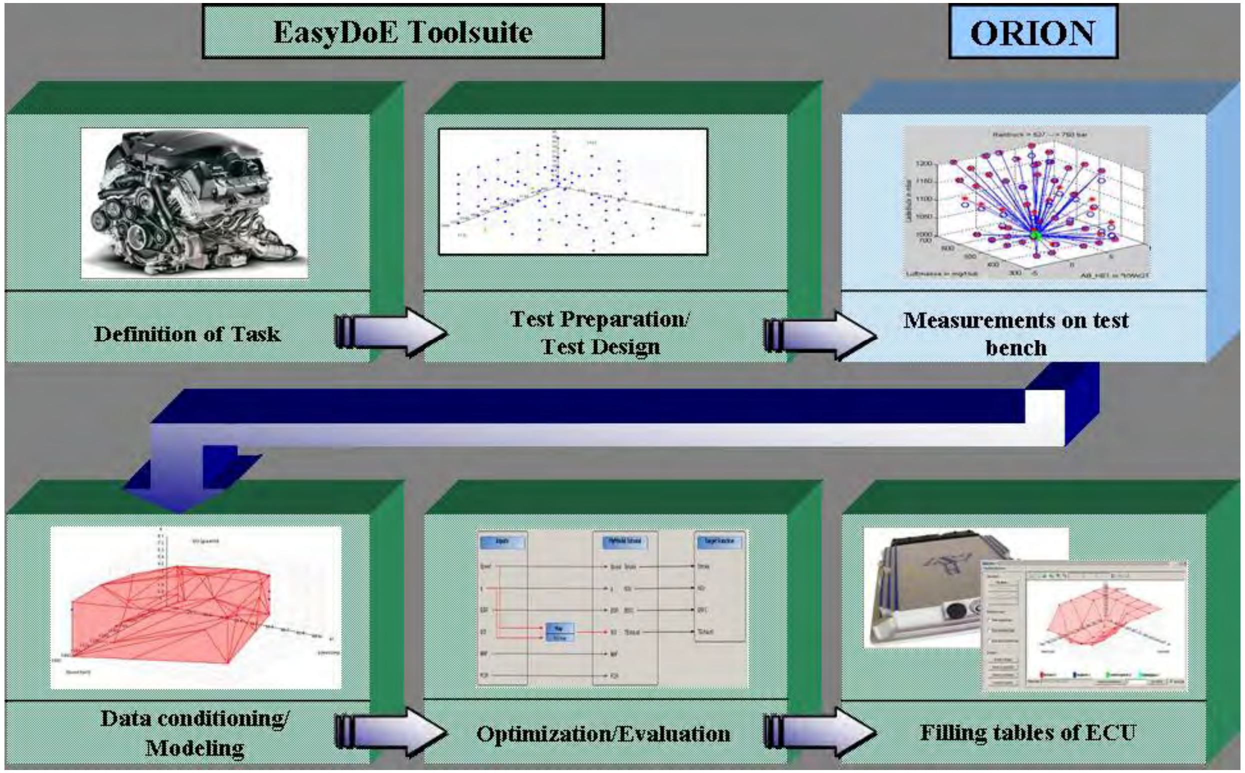






Conclusion

- **EasyDoE Toolsuite and ORION** provide effective methods for implementing DoE methods
  - Their GUIs make DoE easy to use
  - The results match the physical expectations



Thank you

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