

# Model Based Engine Calibration

Using State of the Art Software Support

2010 Motorcycle & Engine Key Technology Seminar  
Tanjin University  
June 2.-3.

Tony Gullitti, IAV Automotive Engineering, Inc  
Don Nutter, A&D Technology, Inc  
Dr. Jürgen Bredenbeck, A&D Europe GmbH



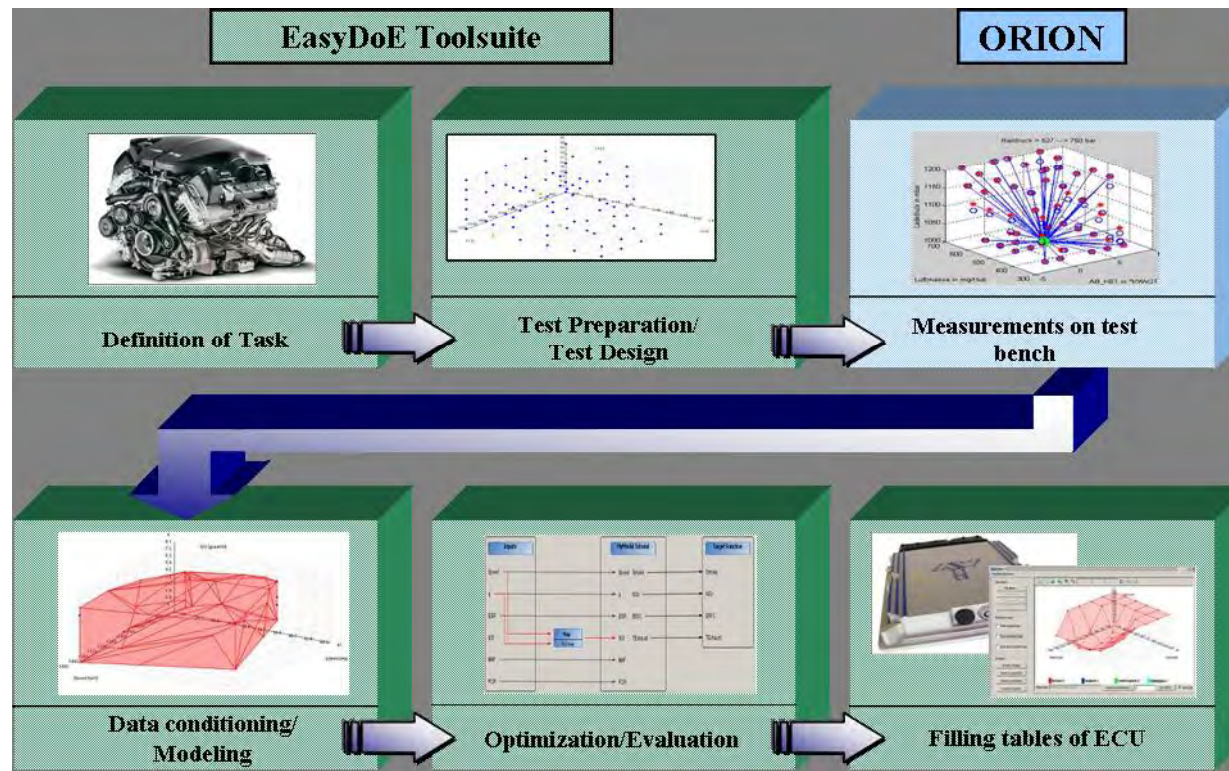
- Model based calibration
    - Use of models of the engine behavior for main calibration
    - Models are created using Design of Experiments (DoE) Methods
  - DoE in engine development is more than just experiment design
    - It is a synonym for a structured methodology of calibration
  - Split nature 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
    - 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
- Optimization Constraints
  - Spark advance less than or equal to MBT Spark
- Monitor during data gathering
  - Knock Amplitude
  - Water, Oil Temperatures, etc.

- 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)

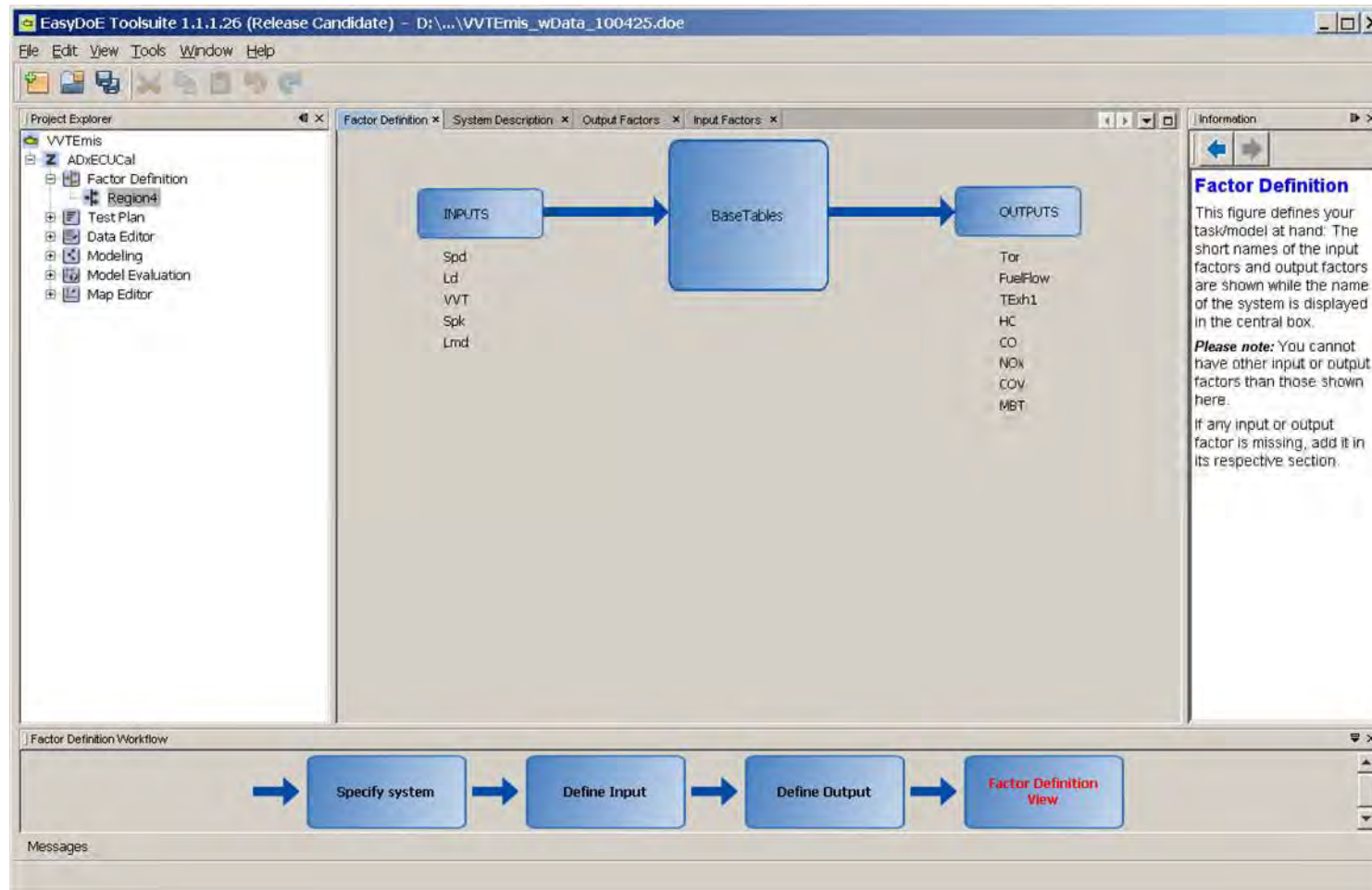
$$R = f(\text{Spd}, \text{Ld}, \text{VVT}, \text{Spk}, \text{Lmd})$$

$$\text{MBT} = f(\text{Spd}, \text{Ld}, \text{VVT}, \text{Lmd})$$

# Set Up Project



- Factors and responses are entered into EasyDoE Toolsuite



# EasyDoE Test Plan



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

The screenshot displays the EasyDoE software interface. The main window shows a table of 145 generated test points. The table columns include No., Type, Export, Repeat, Status, Spd, Ld, VVT, Spk, and Lmd. The points are categorized as D-Optimal, V-Optimal, and Space-Filling. Below the table, a 3D plot visualizes the points in a coordinate system with axes Spd, Ld, and Spk. The plot includes a legend for 'Fit' and 'Validation' points. On the right side, there is an 'Information' panel with a 'Test plan view' section explaining the view and a 'Repeated measurement' section. At the bottom, a 'Testplan Workflow' diagram shows the sequence: Specify Influences → Choose Test Design → Define Constraints → Calculate → Test Plan View.

No.	Type	Export	Repeat	Status	Spd	Ld	VVT	Spk	Lmd
134	D-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	5000.0	50.0	39.0	-3.0	0.84
135	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4200.0	100.0	33.0	-1.0	0.92
136	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4600.0	90.0	0.0	-11.0	0.9
137	D-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	V...	3000.0	85.0	0.0	-3.0	1.0
138	D-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	5000.0	100.0	0.0	-3.0	1.0
139	D-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	5000.0	75.0	0.0	-3.0	0.9
140	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4200.0	55.0	21.0	-7.0	1.0
141	Space-Filling	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	3400.0	60.0	27.0	-13.0	0.82
142	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4600.0	55.0	21.0	-17.0	0.84
143	D-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	3400.0	75.0	6.0	-1.0	1.0
144	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4600.0	50.0	21.0	-3.0	0.96
145	V-Optimal	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Fit	4200.0	60.0	3.0	-21.0	0.96

# A&D Technology's R&D Test Cell

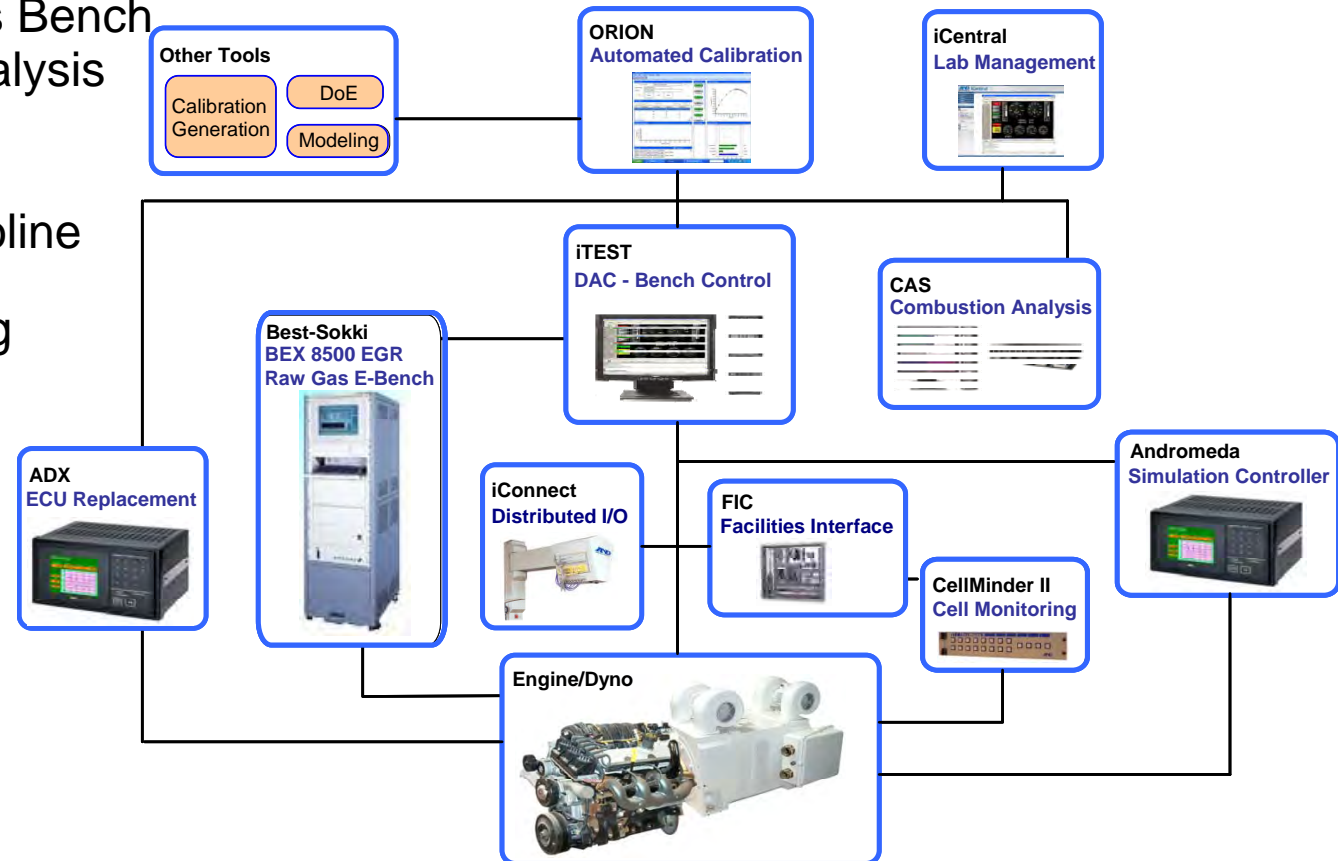


## Test Cell Features:

- 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

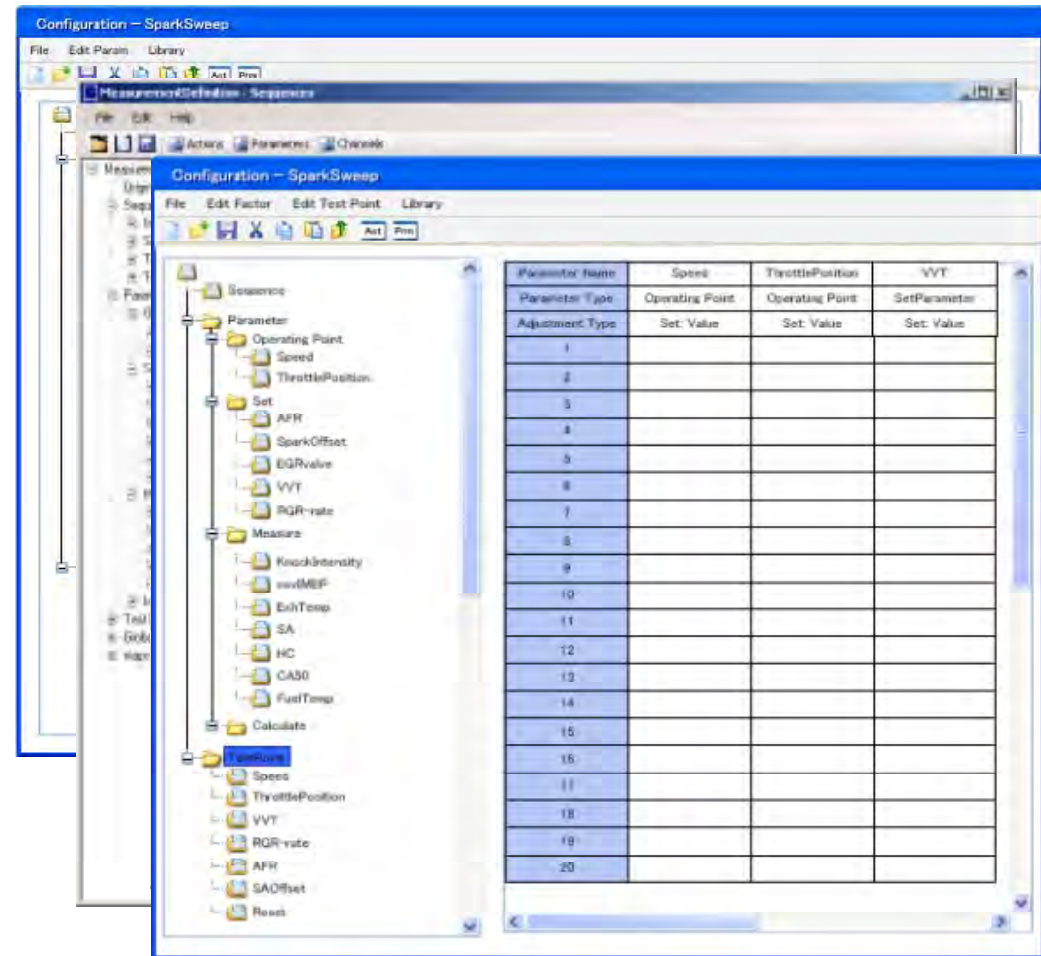




# ORION Configuration



- 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



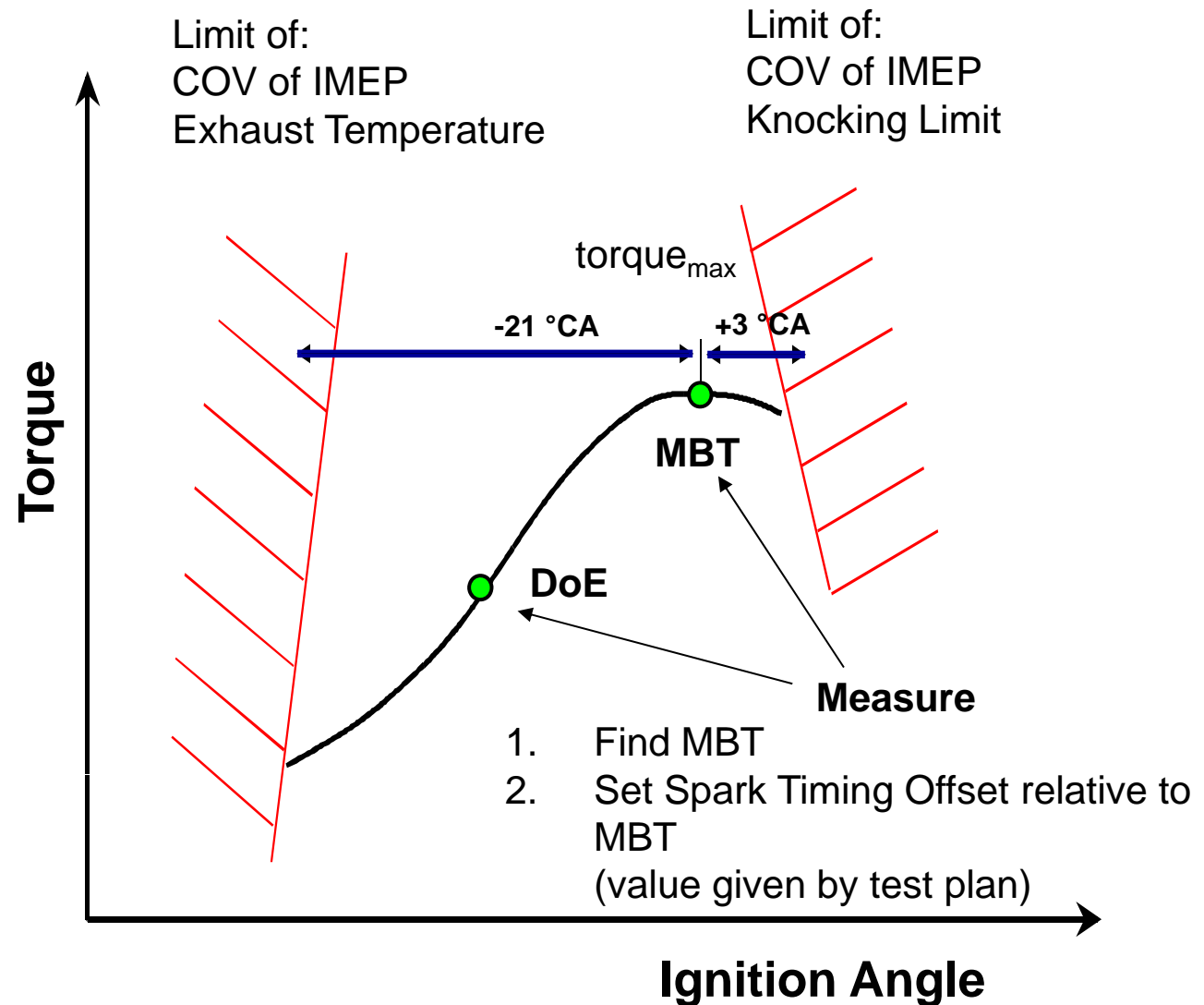
- MA is the key interface for the operator in the test cell
  - Simple load the configuration file from MDA
  - Connect to test cell control and calibration tool
  - Execute sequence by pressing “start”
- Indicators and graphs keep the operator informed on progress and status
- Test cell system collects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



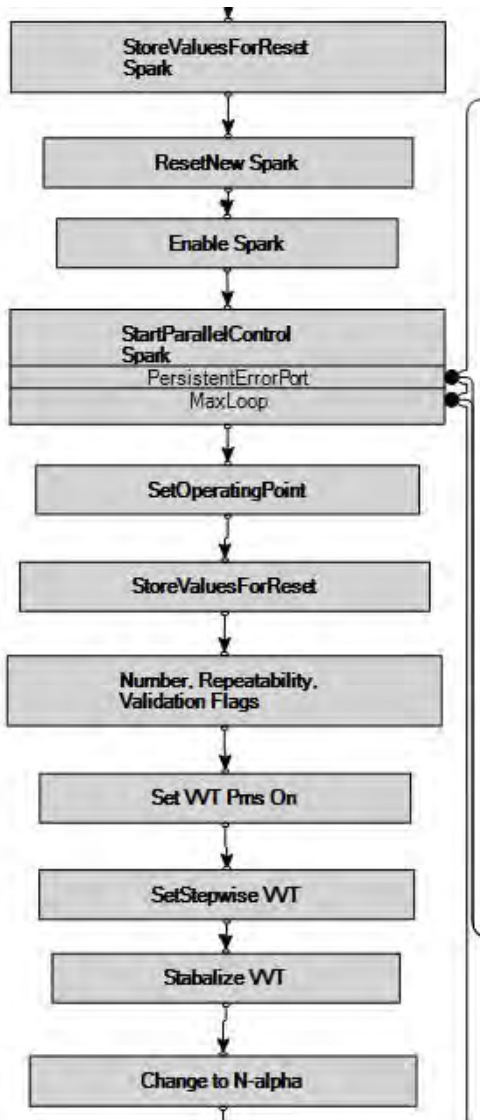
# Data Gathering Strategy



- 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

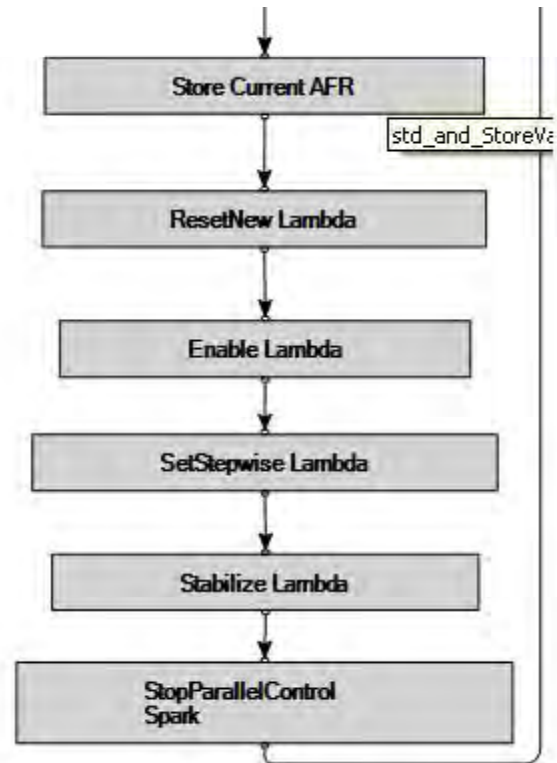


- Test cell run in speed / load mode
  - Parallel control on spark advance during setting of speed / load and stepwise setting of VVT and Lambda
    - CA50
    - Monitored limits of temperature and knock
  - Two data points taken for each Speed/Load/VVT/Lambda
    - On-line determination of MBT Spark using ORION optimization
    - Offset spark added to MBT
  - Repeatability points are added
    - Center point of factor ranges
    - Used to check verify model quality
-



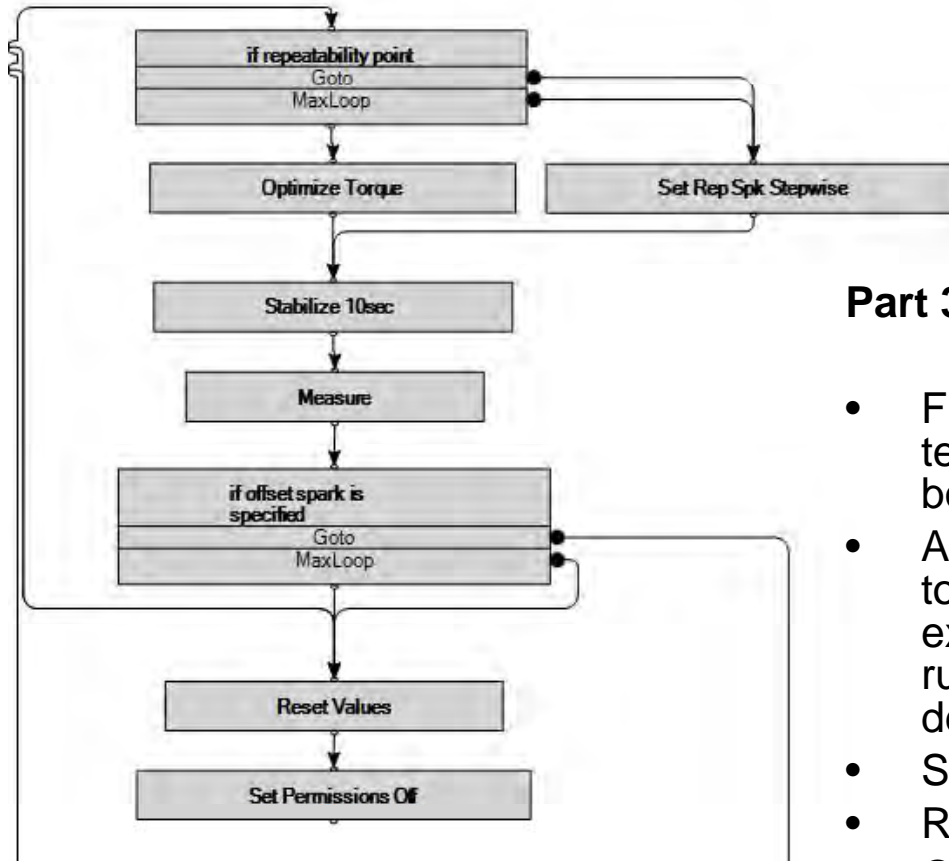
## Part 1: Parallel Control of Spark CA50, Set stepwise VVT

- 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.



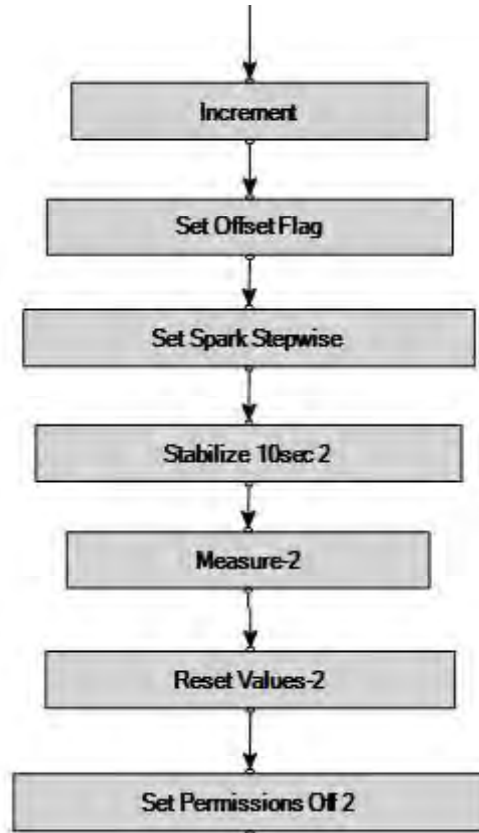
## Part 2: Set Stepwise Lambda

- 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.



## 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

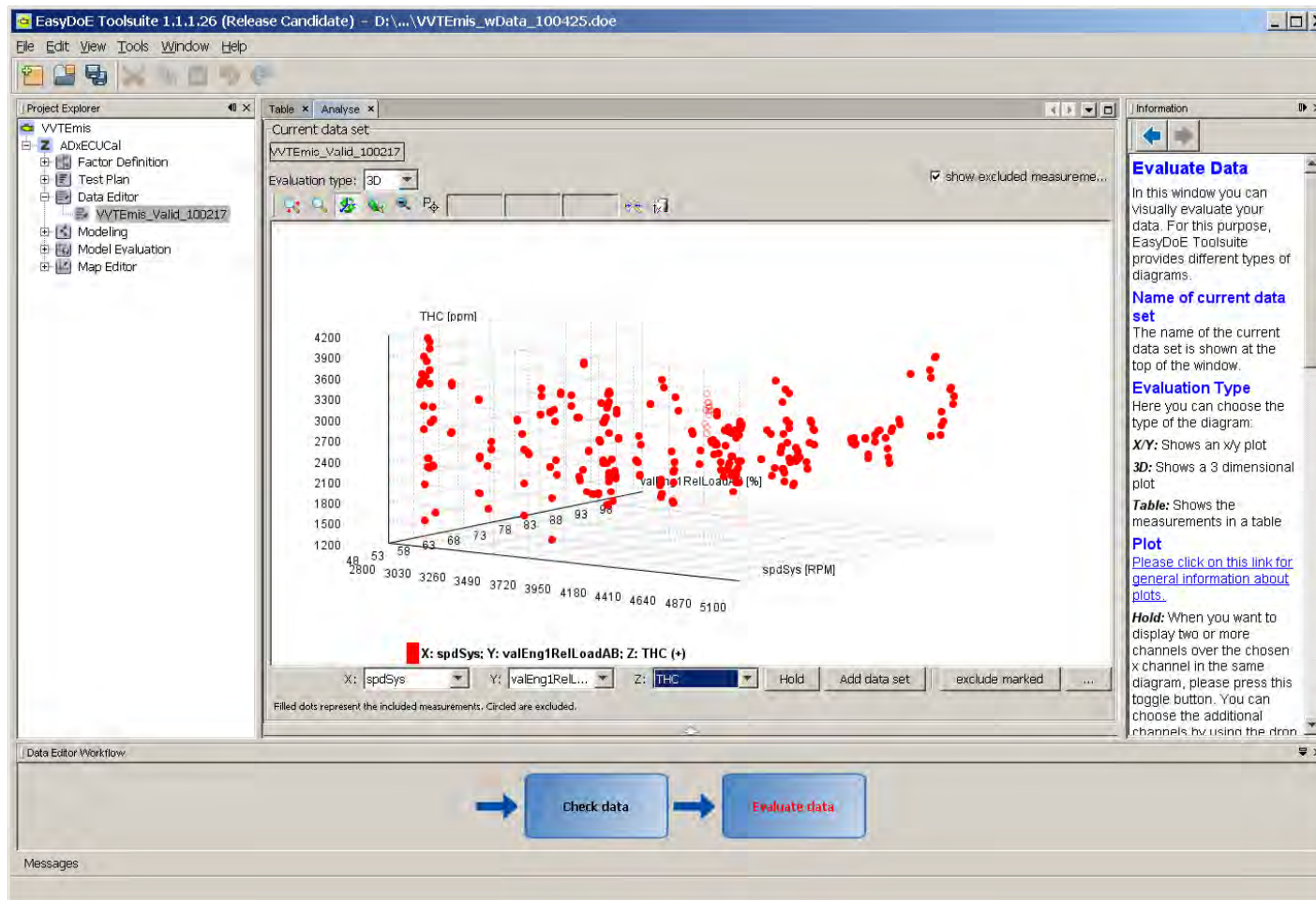
- Increment the spark advance by the offset spark value from the experiment design.
- Stabilize and measure.
- Reset the initial values and proceed to the next step.



# Data Review



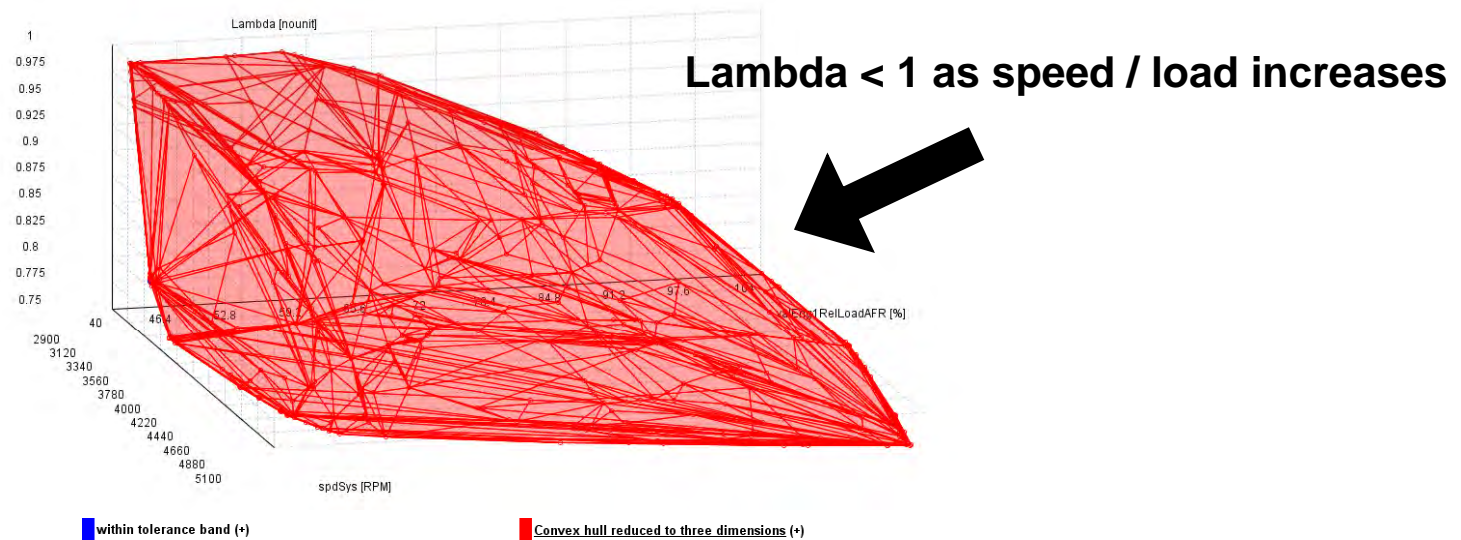
- The data is imported into EasyDoE Toolsuite and reviewed via a user interface



# 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

The screenshot displays the EasyDoE Toolsuite 1.1.1.B software interface. The main window is titled "Single Influence View" and shows four plots of output versus input factor. The plots are arranged in a 2x2 grid. The top-left plot shows output vs. Spd [RPM], the top-right plot shows output vs. Ld [mm], the bottom-left plot shows output vs. VVT [°CA], and the bottom-right plot shows output vs. Spk [°CA]. Each plot contains multiple colored lines representing different polynomial models (Polynom1 to Polynom9). A vertical dashed line indicates the current input factor setting. Below the plots is a table of model statistics and a table of factor settings.

**Model Statistics Table:**

Model name	Model type	Fitting method	Paramet...	Box-Cox	Conditio...	R <sup>2</sup>	PRESS R...	FIT RMSE	Valid RMSE	Best
Polynom5	Polynomial	T-test	27	0.0	40.456	0.998	1.1626	1.1047	2.3419	C
Polynom6	Polynomial	Robust Regression	61	0.0	232.18	0.9981	1.3101	1.101	2.2677	C
Polynom7	Polynomial	Robust Regression + ...	37	0.0	88.294	0.9983	1.1144	1.0282	2.1911	C

**Factor Settings Table:**

Factor	Min	Max	Setting	Value	Tolerance (*)	Tol. Value
Spd	2887.0	5004.0		3401.0		10
Ld	40.57	105.3		72.2		10
VVT	-3.0	42.0		33.0		10
Spk	-13.7	50.0		2.485		10

**Single Influence View Information:**

**Single Influence View**  
To decide which model is best you can use the single influence view to compare different models. For every input factor a single influence plot is shown. The data point can be set in the table that is under the main window.

**Select models**  
Please choose the models that you want to compare from the drop down lists. You can choose up to five models. They are shown if the check box in front of the name is active.

**Update plot:** Once you have chosen the desired models to compare and updated the settings then click on this button. EasyDoE Toolsuite will calculate all plots.

**Setting the data point**  
In a single influence plot only one input point is varied over the x-axis, all other input factors are constant. You can set the input factors in the table that is under the main window. If it is closed you can open it by clicking on the arrow.

**Setting:** Move the slider to vary the input factor

**Value:** Actual value of the input factor. You can type a new value into this field.

**Tolerance:** Defines a tolerance band around the intersection of the input factors used to plot data points. Thus, points with a small offset to the intersection plane are shown in addition to points that lay directly in the intersection plane. The measurements are only shown if the setting 'Show measured' is active.

# EasyDoE Fitting Methods



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

<i>Polynomial Fitting Method</i>	<i>Description</i>
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

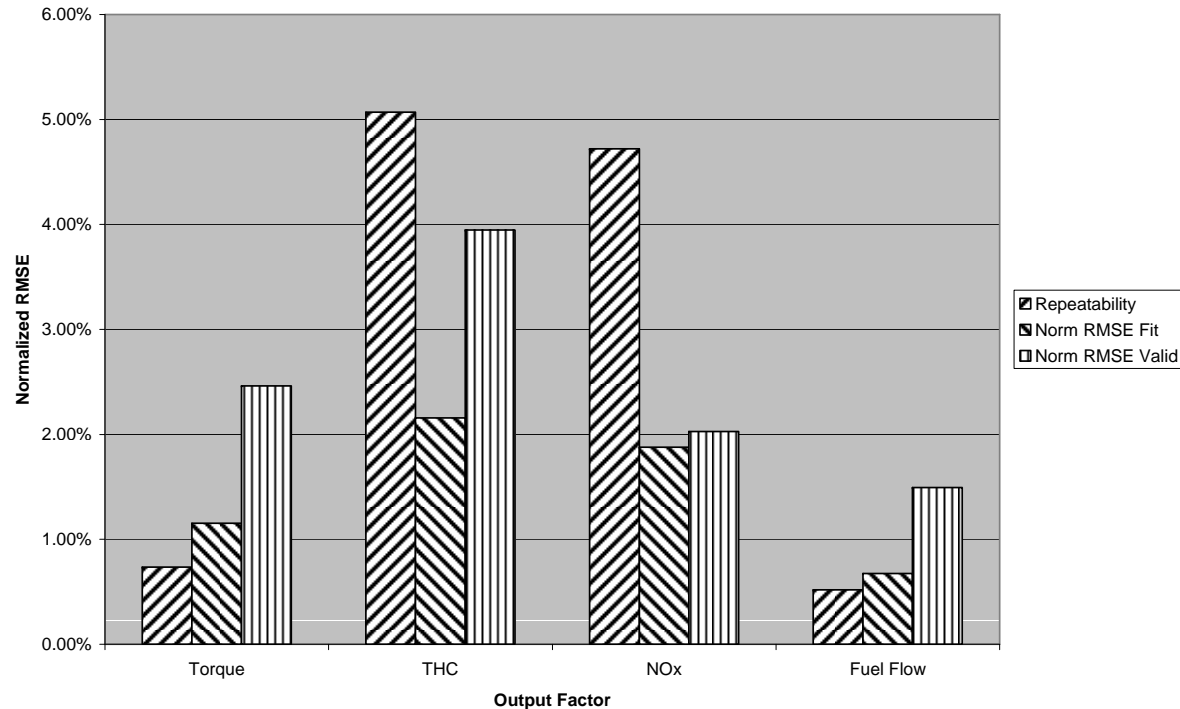


Model Quality Analysis

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

\* of the repeatability points

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



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

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

# Optimization Requirements

---

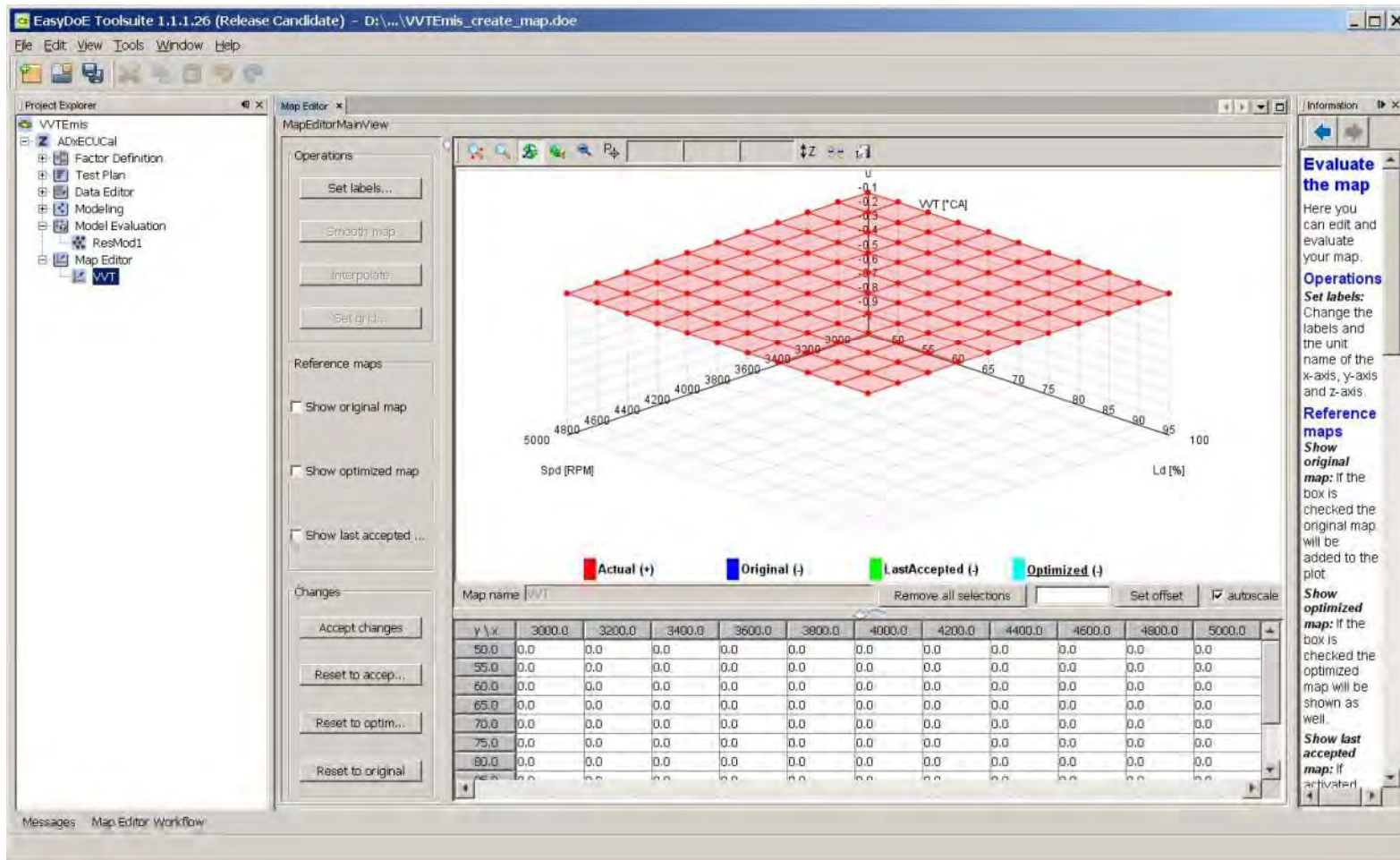


- In Model Evaluation a grid of speed / load points is defined:
    - Speed 3000 to 5000 in 200 RPM increments
    - Relative Load 50 to 100% in 10% increments
  - A weighted sum gradient descent method is selected.
    - +1 Maximize the response
    - - 1 Minimize the response
    - 0 No optimization 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

EasyDoE Toolsuite 1.1.1.8 (Release Candidate) - D:\MyDocs\DoE\WVT\_Emis\Cell1\CleanData\WVTEmis\_wData\_100218.doe

File Edit View Tools Window Help

Project Explorer: VVTEmis, ADxEOUCal, Factor Definition, Test Plan, Data Editor, Modeling, Model Evaluation, ResMod1, BSFC Opt, BSFC and Emis Opt, Max Torque Opt, Map Editor

Optimization Target: Update plot, Set plot grid, Set to center point in hull, Show hull, Real-time calculation, Export

Optimization: Currently used optimization: BSFC and Emis Opt, Use optimized maps, Use default maps, Compare optimization..., Set to optimization...

Formula function: Use formula function, Create/Change

Model Evaluation: XY - CONTOUR, FIVE DIMENSION, SINGLE INFLUENCE, MODEL DIAGRAM

All Outputs | Single Outputs | Tor | FuelFlow | TEsh1 | HC | CO | NOx | COV | MBT | (FuelFlow\*9549305)/(Tor\*Spd)

Information: Evaluate optimization results, Choosing the axes, Setting the other input factors, Results, Reset

Model Evaluation Workflow: Optimization -> Constraints -> Optimization Parameters -> Start Optimization -> Evaluate Optimization Results



# Model Evaluation – Map Editor



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

EasyDoE Toolsuite 1.1.1.8 (Release Candidate) - D:\MyDocs\DoE\VWT\_Emis\Cel1\CleanData\VWTEmis\_wData\_100218.doe

Project Explorer: VWTEmis, ADVESUCal, Factor Definition, Test Plan, Data Editor, Modeling, Model Evaluation, Map Editor, VWT, Spk, Lmd, VWT BSFC Opt, Spk BSFC Opt, Lmd BSFC Opt, VWT BSFC and Emis Opt, Spk BSFC and Emis Opt, Lmd BSFC and Emis Opt, VWT Max Torque Opt, Spk Max Torque Opt, Lmd Max Torque Opt

Operations: Set labels..., Smooth map, Interpolate, Set grid...

Reference maps: Show original map, Show optimized map, show last accepted m...

Changes: Accept changes, Reset to accept..., Reset to optimi..., Reset to original

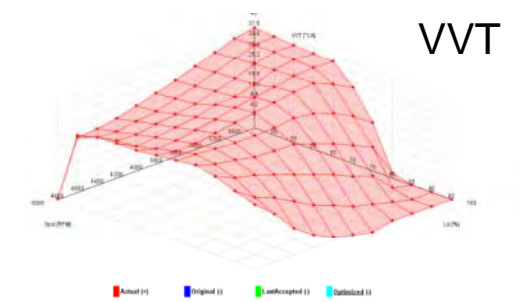
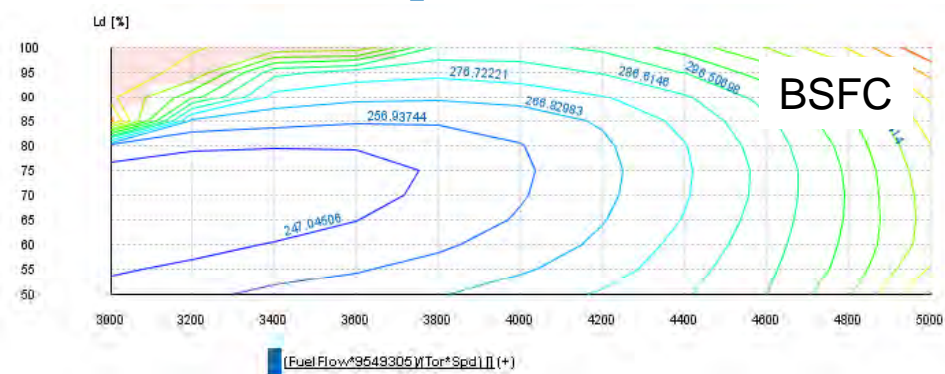
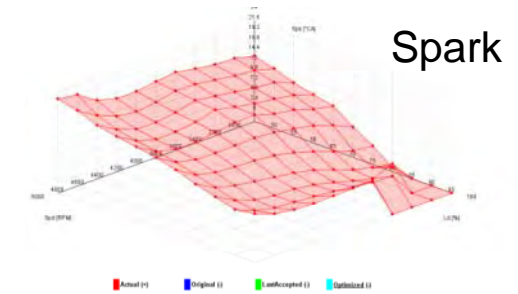
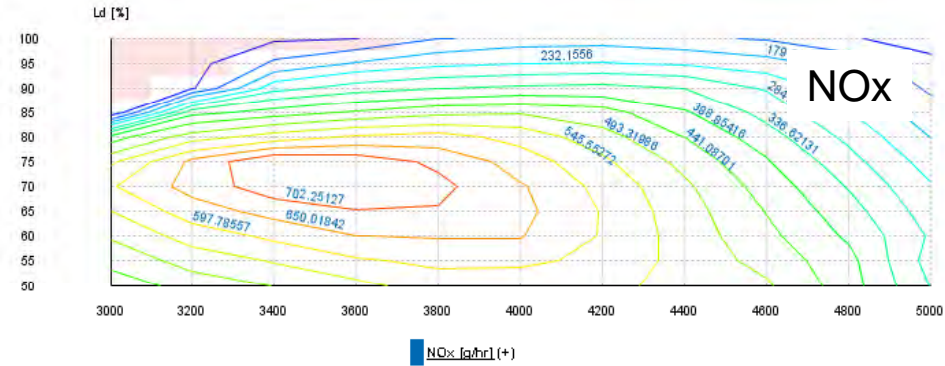
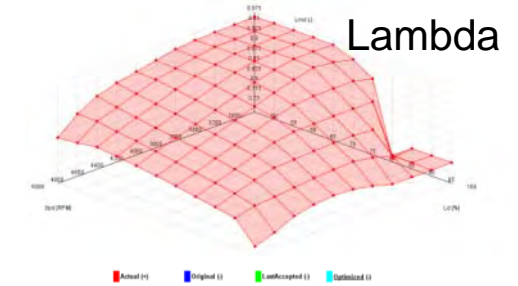
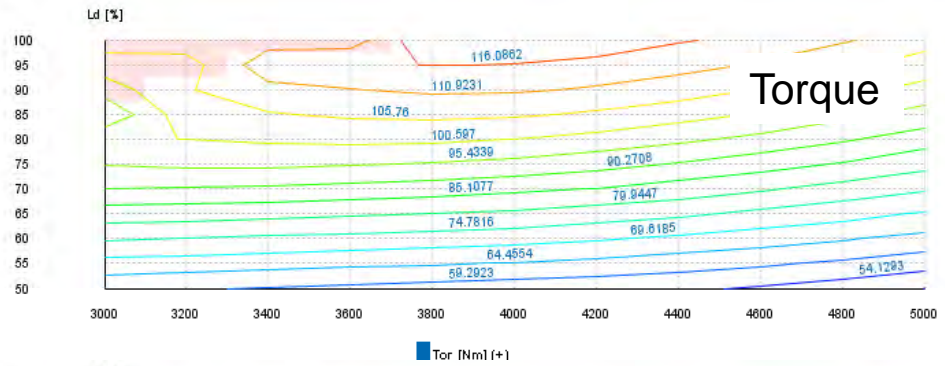
Information: Evaluate the map, Here you can edit and evaluate your map. Operations: Set labels: Change the labels and the unit name of the x-axis, y-axis and z-axis. Reference maps: Show original map: If the box is checked the original map will be added to the plot. Show optimized map: If the box is checked the optimized map will be shown as well. Show last accepted map: If activated the last accepted map is shown in the diagram additionally. Changes: Accept changes: Accept your changes to the map by pressing the 'Accept Changes' button. Reset to accepted: Resets the map to the accepted values. Reset to optimized: Resets the map to the the optimized map. Reset to original: Resets the z-values of your map to the original values. Plot: Remove all selections: If you have selected several points of the map it will remove all selections. Set offset: Please select one of...

y \ x	3000.0	3200.0	3400.0	3600.0	3800.0	4000.0	4200.0
50.0	39.33713798337511	35.2929047032579	26.45456537450676	32.507085132415375	32.465476812522304	31.790395235120098	33.25203747341
55.0	38.34649163352471	31.755834368502146	31.95862179730256	34.19010634836475	34.017895105329906	33.140487160261756	33.27116426229
60.0	35.61509861180191	30.757775171448326	33.428358643241011	35.13700537462231	35.386325887614234	34.383404996580666	34.03009357377
65.0	32.04054197216909	30.344048669740534	34.064019077612744	36.7799977448201	36.49401245040454	36.781636779665036	35.39852435605
70.0	35.733791453962006	34.38487459459178	34.88984405069028	35.360852367210306	35.1625063316498	34.153813308829044	26.79404228844

Map Editor Workflow: Evaluate the map → Export map

# Model Evaluation

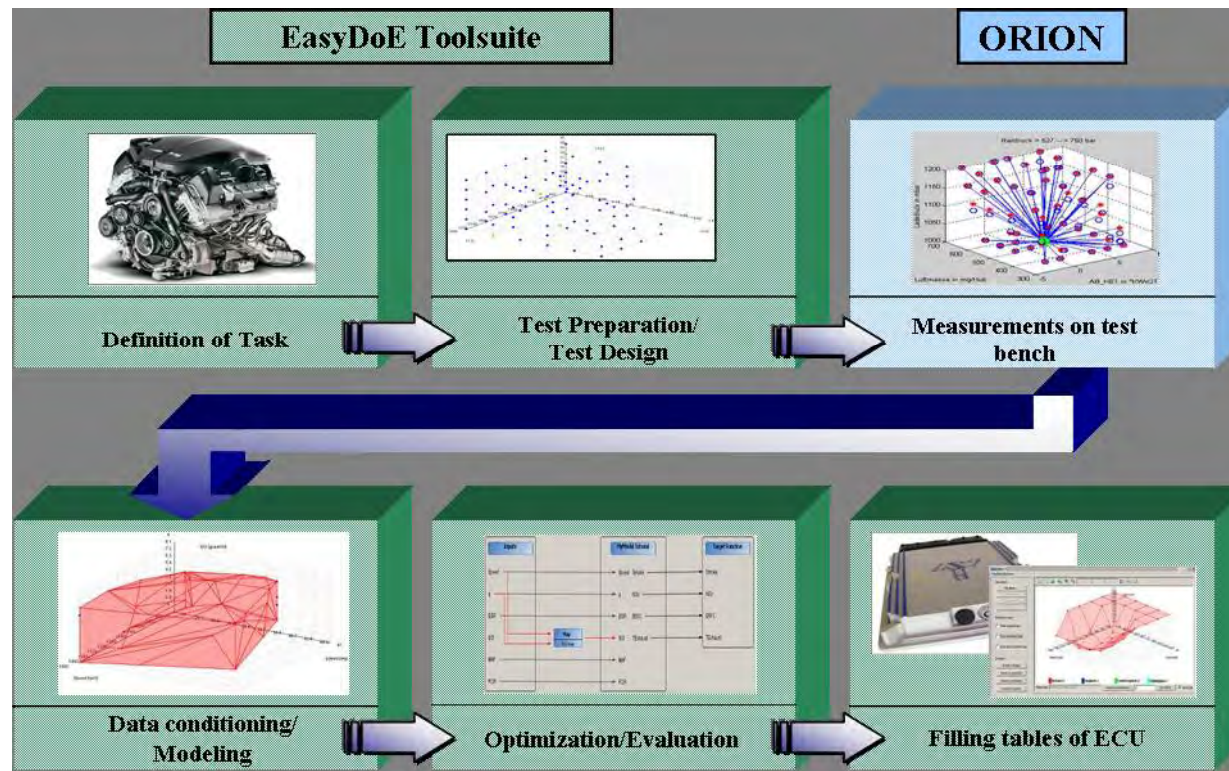
## Objective BSFC



# 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

**Tony Gullitti**

IAV Automotive Engineering, Inc  
15620 Technology Drive  
Northville, MI 48168  
Phone: +1(734) 233-3352  
anthony.gullitti@iav-usa.com

**Don Nutter**

A&D Technology, Inc  
4622 Runway Blvd  
Ann Arbor, MI 48108  
Phone: +1(734) 822-9564  
dnutter@aanddtech.com

**Dr. Jürgen Bredenbeck**

A&D Europe GmbH  
Im leuschnerpark 4  
64347 Griesheim  
Germany  
Phone: +49(6155) 60 52 50  
bredenbeck@aanddeurope.com