Application of DoE Techniques to Engine Calibration

Justin Seabrook and David Clarke

Ricardo

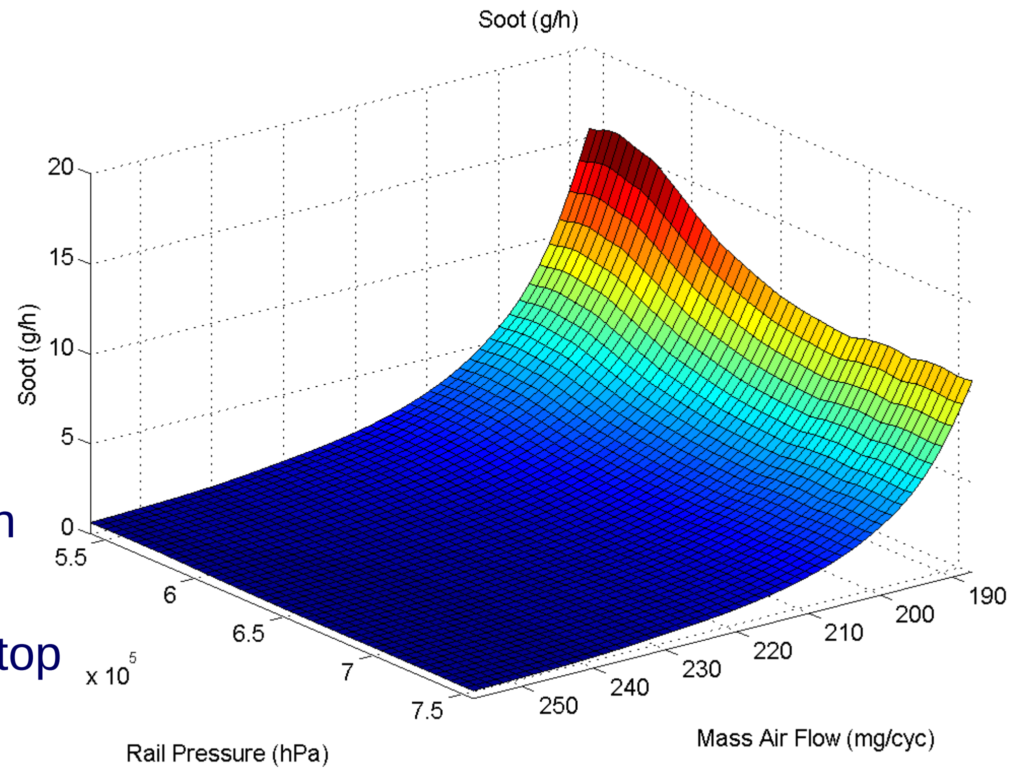
Automotive Testing Expo Europe

Stuttgart, May 2008

Contents

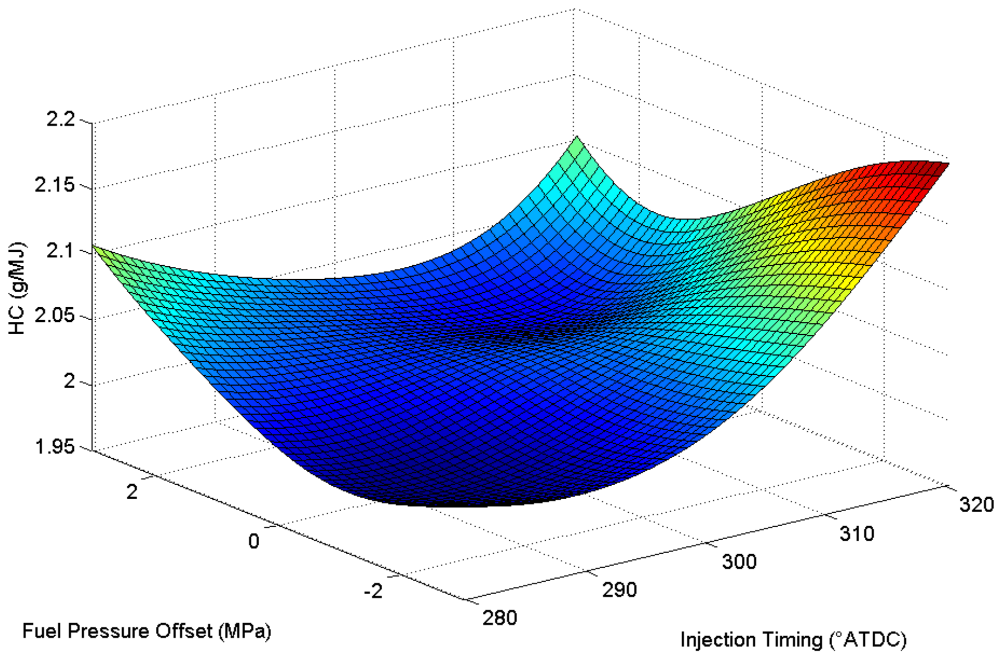
Introduction

- Trend in engine development is for
  - More variables
  - More interactions
  - More non-linear responses
  - More emphasis on robustness
- DoE delivers
  - Shorter development times
  - Better, more robust solutions
  - Delivers models as well as calibration
    - Useful if objectives change
    - "Test" and optimise engine at desktop
- DoE is now essential for many engine development and calibration tasks



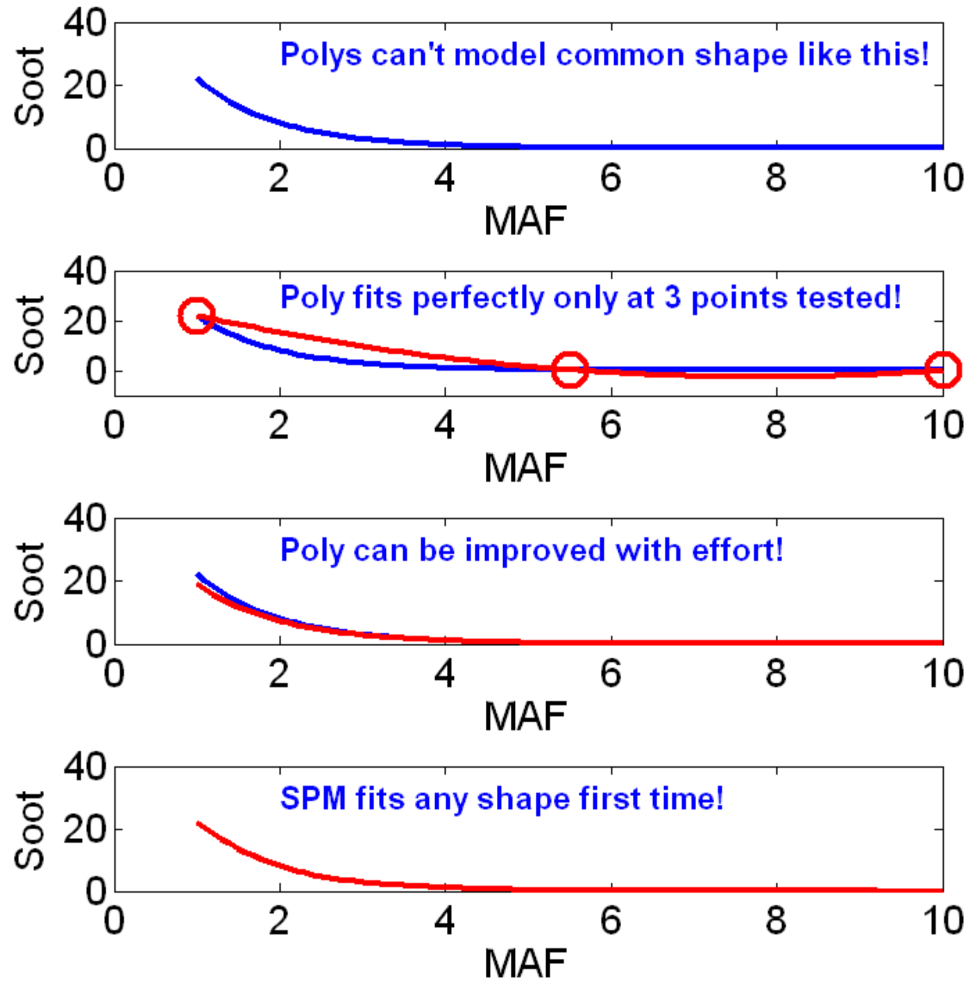
Introduction

- For calibration of VVT and G-DI systems
  - Classical DoE can be made to work adequately
  - Advanced modelling methods make life much easier!
- Classical DoE has many disadvantages
  - Inflexibility
    - Doesn't model exponential effects well
      - E.g. edge of misfire
  - Crude handling of interactions
  - Onerous range setting requirement
  - Requirement for orthogonality
- Stochastic Process Models (SPM) are best for engine calibration
  - Low number of test points
  - Very robust to noisy data



Introduction

- Most engineering DoE packages (CAMEO, DesignExpert, MODDE, etc) are based on polynomial models
- Polynomial models have some major disadvantages
  - Testing at 3 variable levels (settings) gives poor results for some engine characteristics
  - Range setting critical
    - Too wide ranges => poor model
  - Sensitive to noise on data and outliers
  - Not suitable for global models
    - Models with speed and load as inputs



Contents

SRH
Ricardo Horiba

Tools

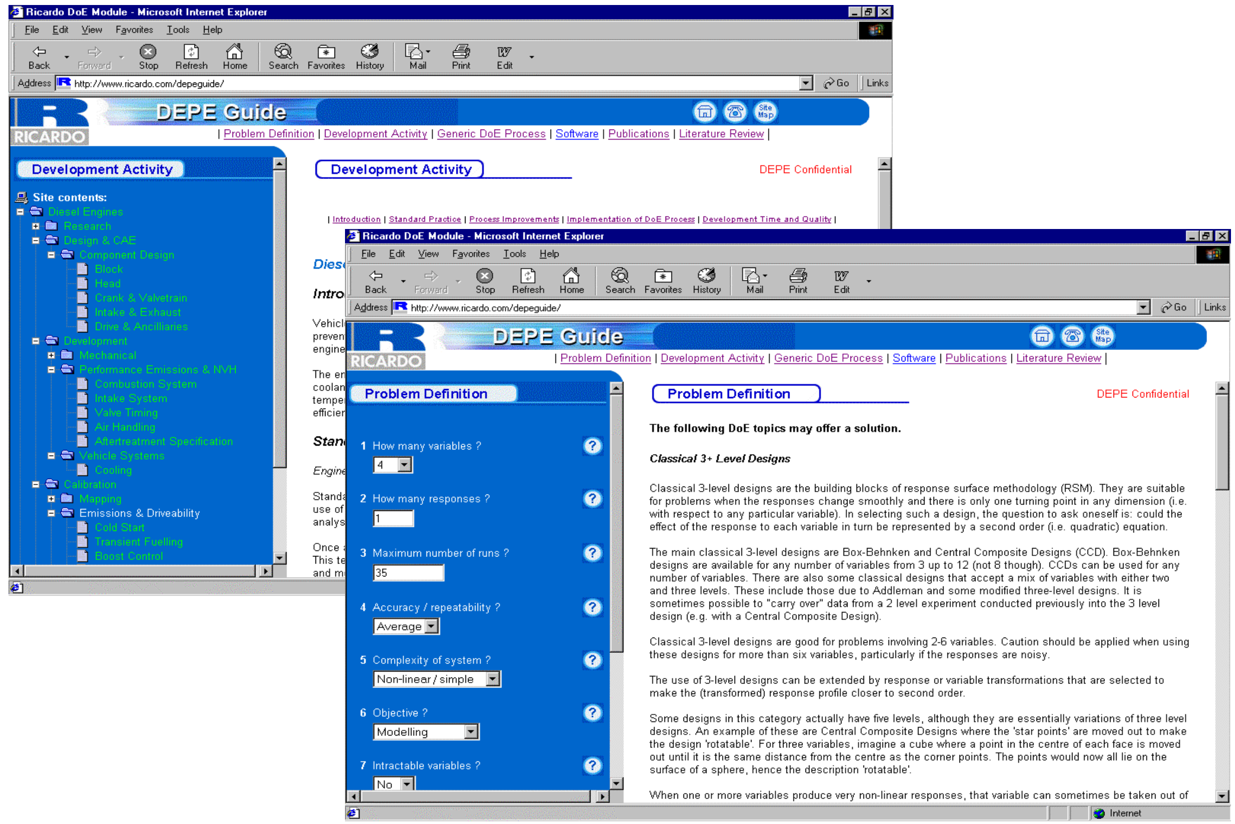
- A suite of tools based on the SPM technique was developed by Ricardo with the "DEPE Consortium", and has been in routine use at Ricardo for several years
- The core functions from DEPE and other Ricardo DoE tools are now being integrated with the STARS test automation platform
- These tools support the conventional DoE process
  - Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation
- Tools designed to minimise requirement for specialist DoE support
- Integration with STARS provides management of data between tools, and a common environment for test bed and office based DoE activities

Planning

Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation

- Planning
  - Set objectives
  - Select DoE method
  - Which variables to include
  - What resources are required

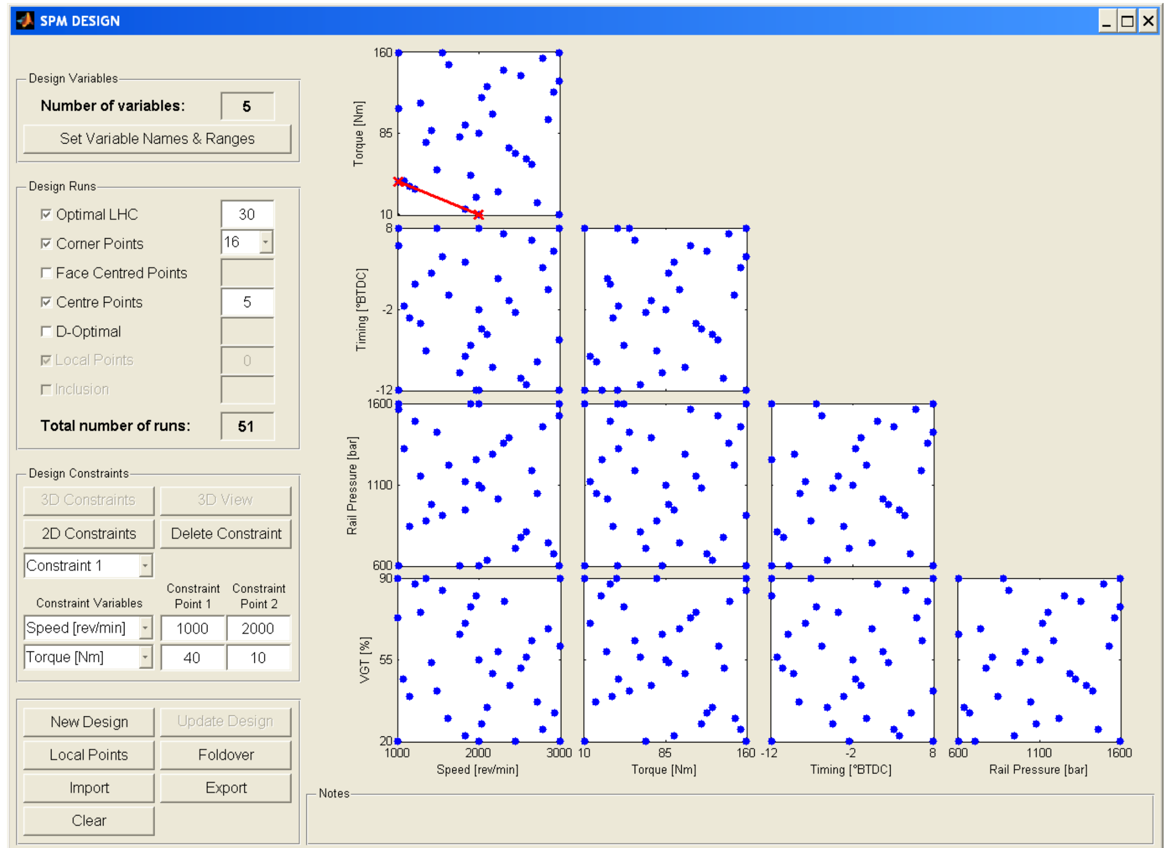
- Planning supported by on-line information system
  - "Virtual DoE Specialist"
  - Human specialist only involved if it's a novel application of DoE



Design

Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation

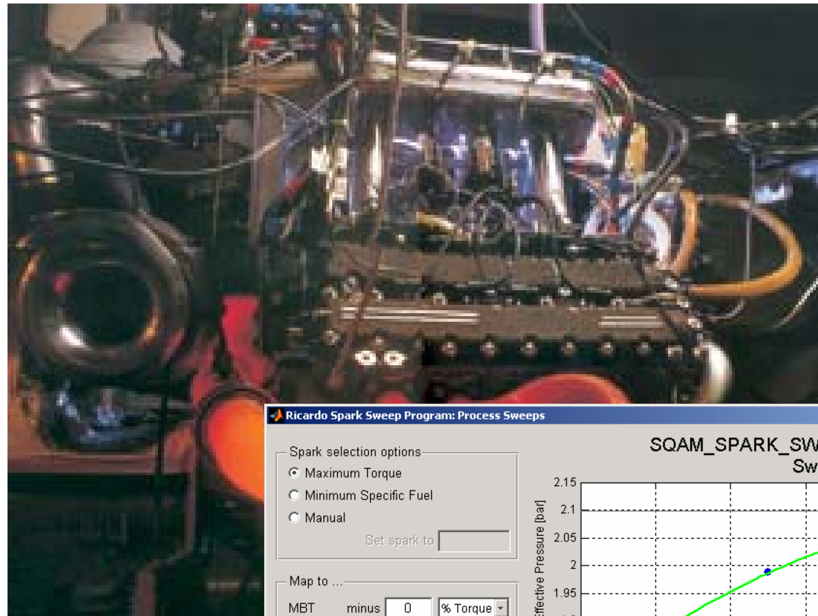
- Design tool is used to:
  - Generate space filling designs
  - Specify the make-up of the design
    - Optimal LHC
    - Corner Points
    - Centre Points
  - Apply constraints
- Range setting
  - Usually short preliminary test necessary
  - Sometimes a desktop exercise
- DoE specialist not usually required

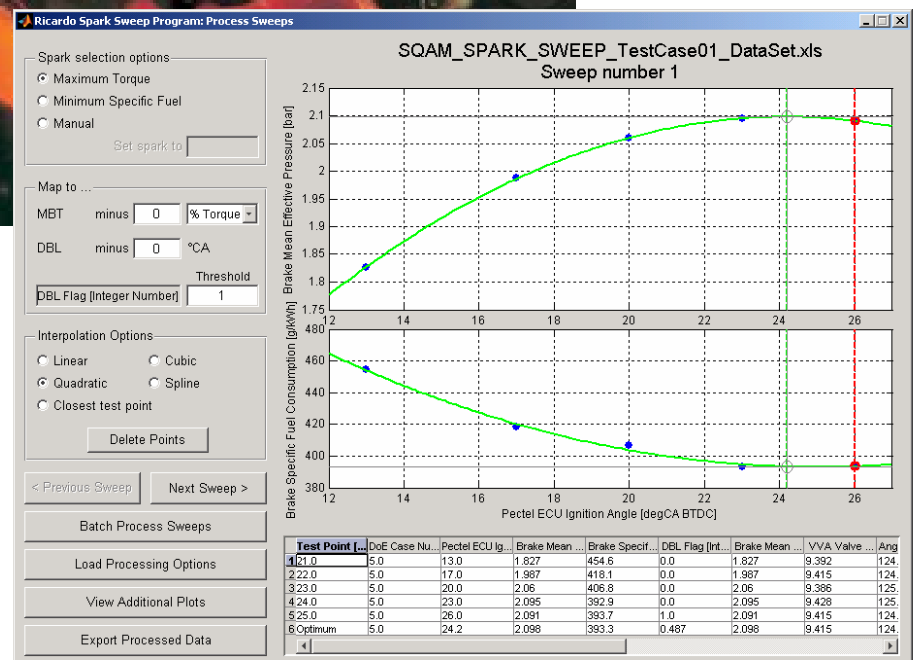


Testing

Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation

- Process is compatible with manual and automated testing
  - Automated testing is best for productivity and data quality
- Tools for processing data (e.g. spark sweeps) are included
- Formatting is handled automatically for data exchange between DoE tools and STARS
- DoE specialist not usually required

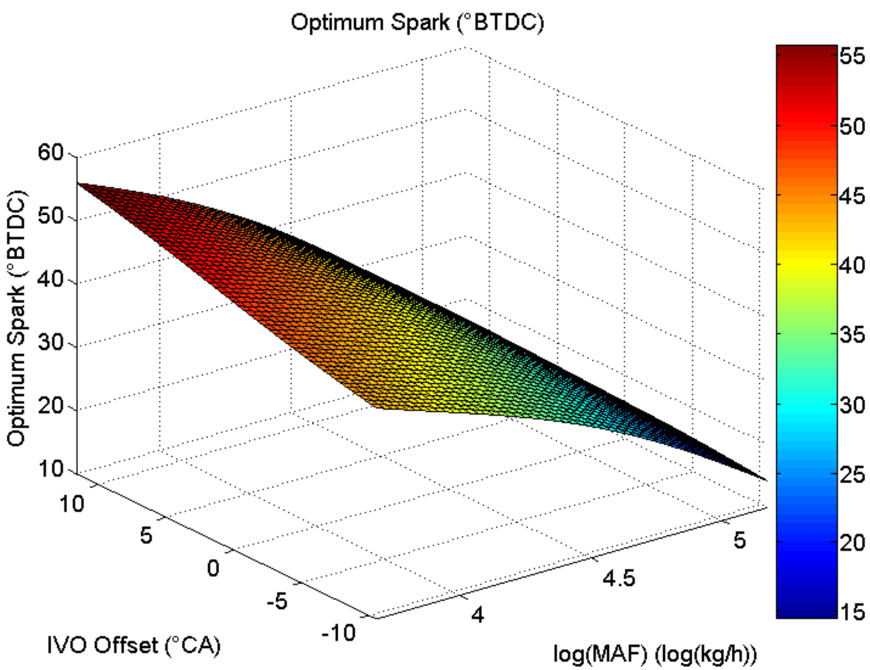


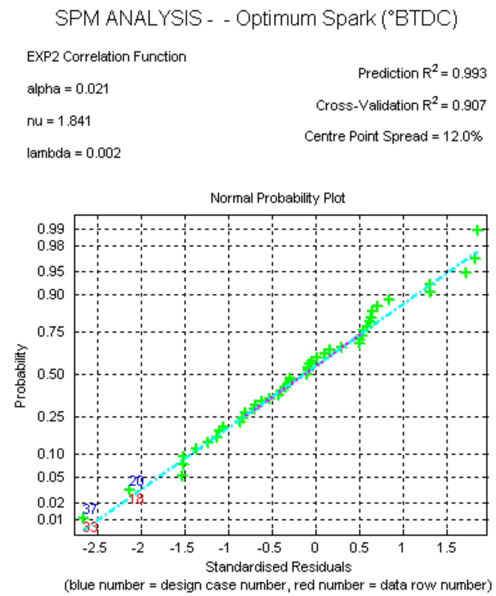


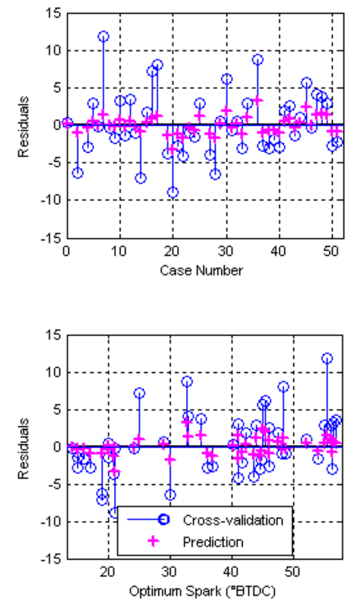
Modelling

Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation

- Tool for batch processing SPM models
  - Essential with automated testing in order to 'keep up' with testbed
- Modelling by calibration engineer
- DoE specialist has "Quality Assurance" role

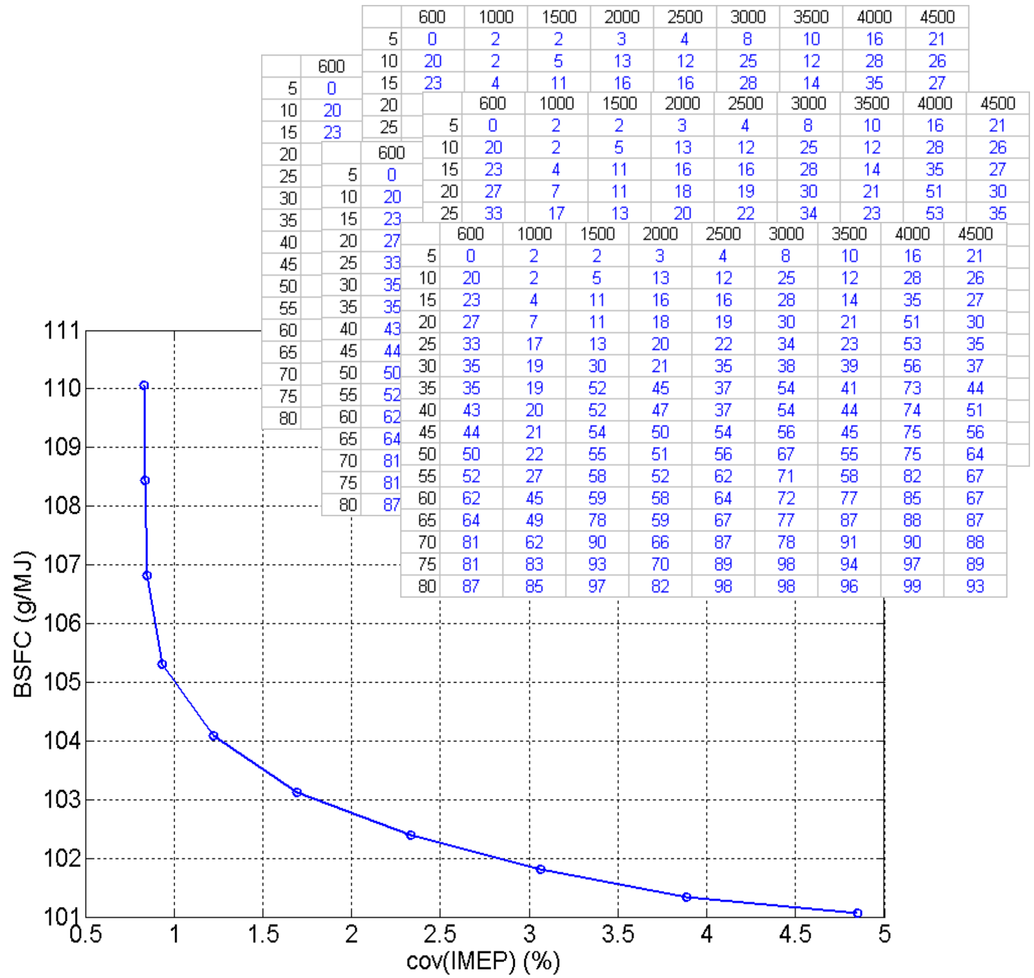






Planning ⇒ Design ⇒ Testing ⇒ Modelling ⇒ Optimisation

- Pareto Optimisation Tool
  - Multi-objective optimisation tool
- Generic constraint function
  - Keeps optimiser within “as tested” variable space
- Optimisation tool used by calibration engineer
  - DoE specialist not usually required
- Automated calibration generation



	600	1000	1500	2000	2500	3000	3500	4000	4500
5	0	2	2	3	4	8	10	16	21
10	20	2	5	13	12	25	12	28	26
15	23	4	11	16	16	28	14	35	27
20	27	7	11	18	19	30	21	51	30
25	33	17	13	20	22	34	23	53	35
30	35	19	30	21	35	38	39	56	37
35	35	19	52	45	37	54	41	73	44
40	43	20	52	47	37	54	44	74	51
45	44	21	54	50	54	56	45	75	56
50	50	22	55	51	56	67	55	75	64
55	52	27	58	52	62	71	58	82	67
60	62	45	59	58	64	72	77	85	67
65	64	49	78	59	67	77	87	88	87
70	81	62	90	66	87	78	91	90	88
75	81	83	93	70	89	98	94	97	89
80	87	85	97	82	98	98	96	99	93

Contents

Application - Dual VVT Gasoline Direct Injection Engine

- V6 gasoline engine
  - 3.5ℓ 24v with VVT and G-DI
- Large premium sector vehicle, series production application
- 4 major calibration variables
  - Continuously variable cam timing
    - IVT
    - EVT
  - Direct fuel injection (homogenous charge)
    - Injection timing
    - Fuel delivery pressure
- This presentation covers base steady state calibration for stoichiometric region only

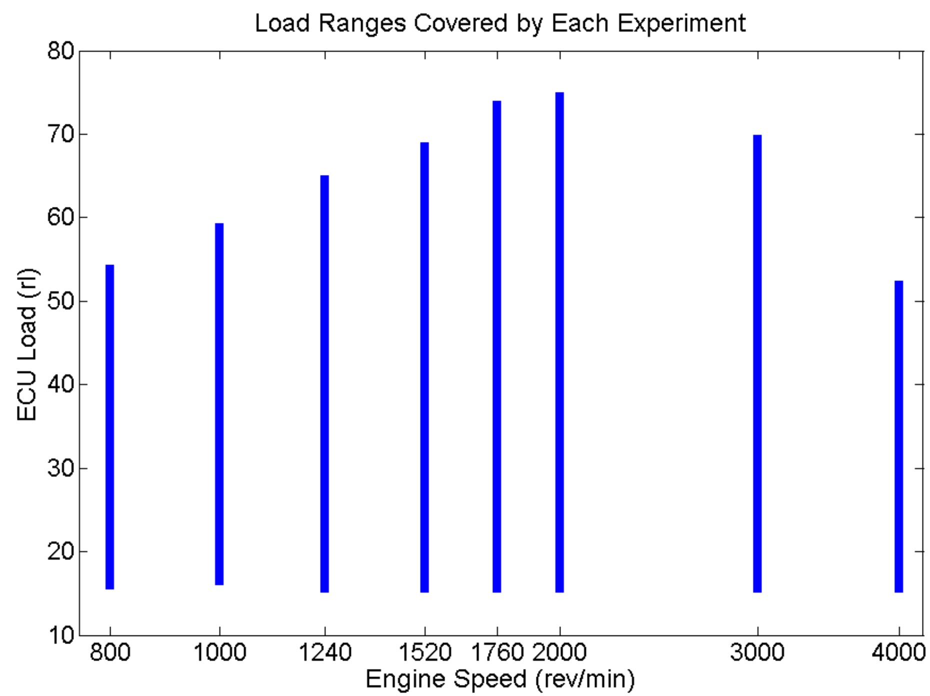
Planning and Design

- Planning
  - Design, Modelling & Optimisation at Ricardo
    - Stochastic process models
  - Testing at client facility
- Design
  - 8 experiments at fixed engine speeds
  - 52 test points per experiment
    - 416 spark sweeps in total
  - 5 variables for each experiment
    - Mass air flow
    - IVO
    - Overlap
    - Injection timing
    - Fuel delivery pressure
  - IVO, overlap and fuel pressure defined as offsets to nominal setting

Note:

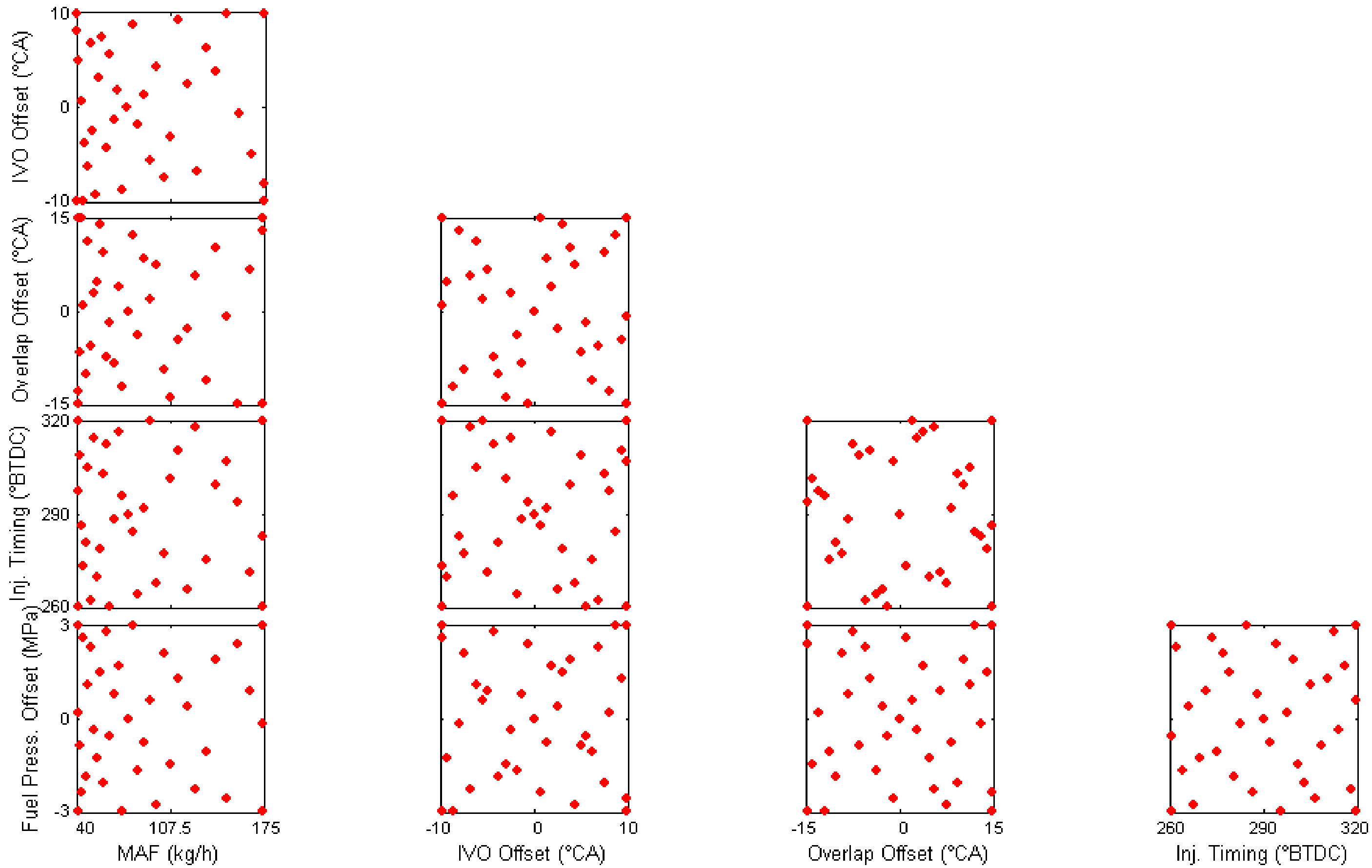
Spark timing not included as a variable

Optimum spark timing is modelled as a response



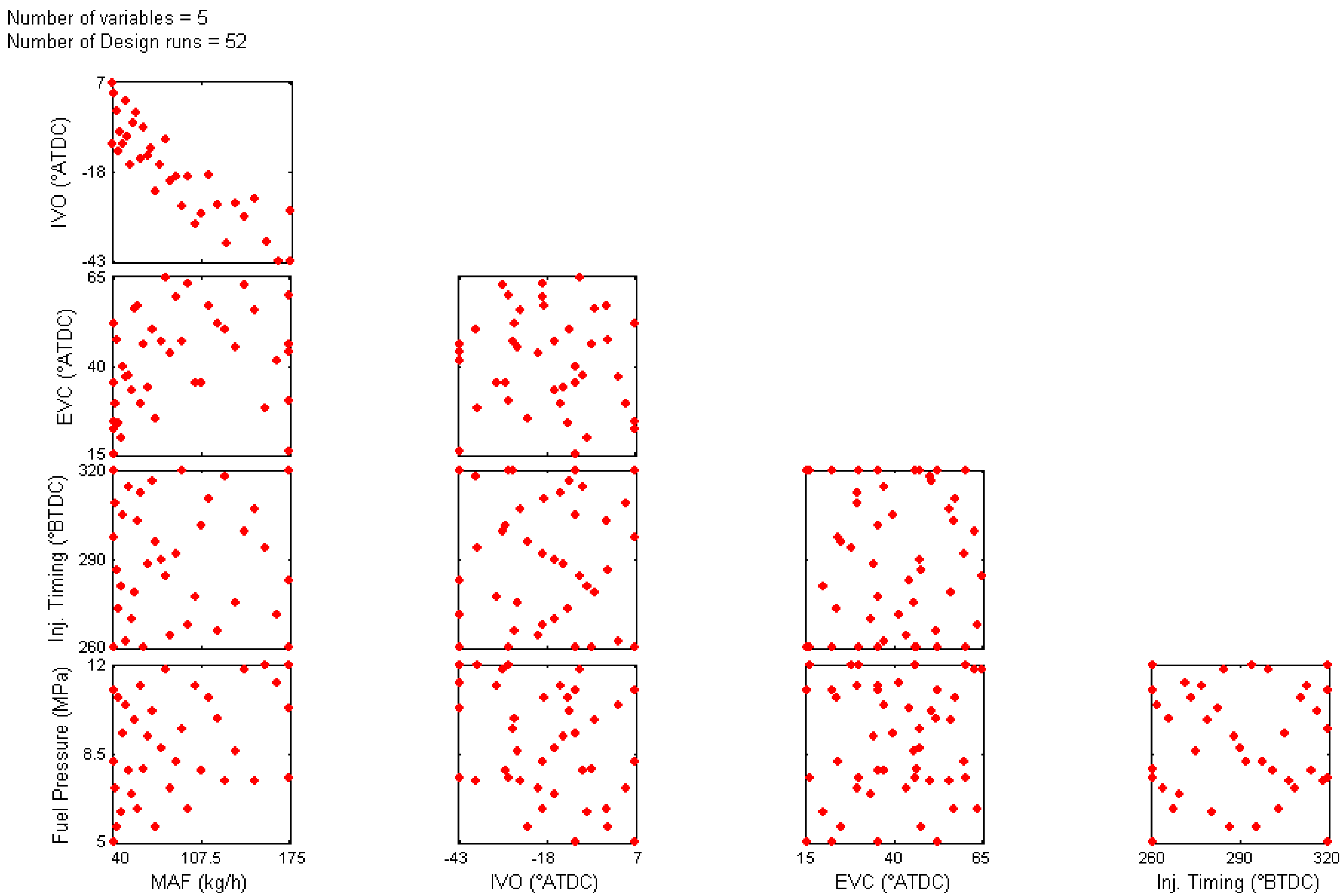
Test Matrix

Number of variables = 5
Number of Design runs = 52



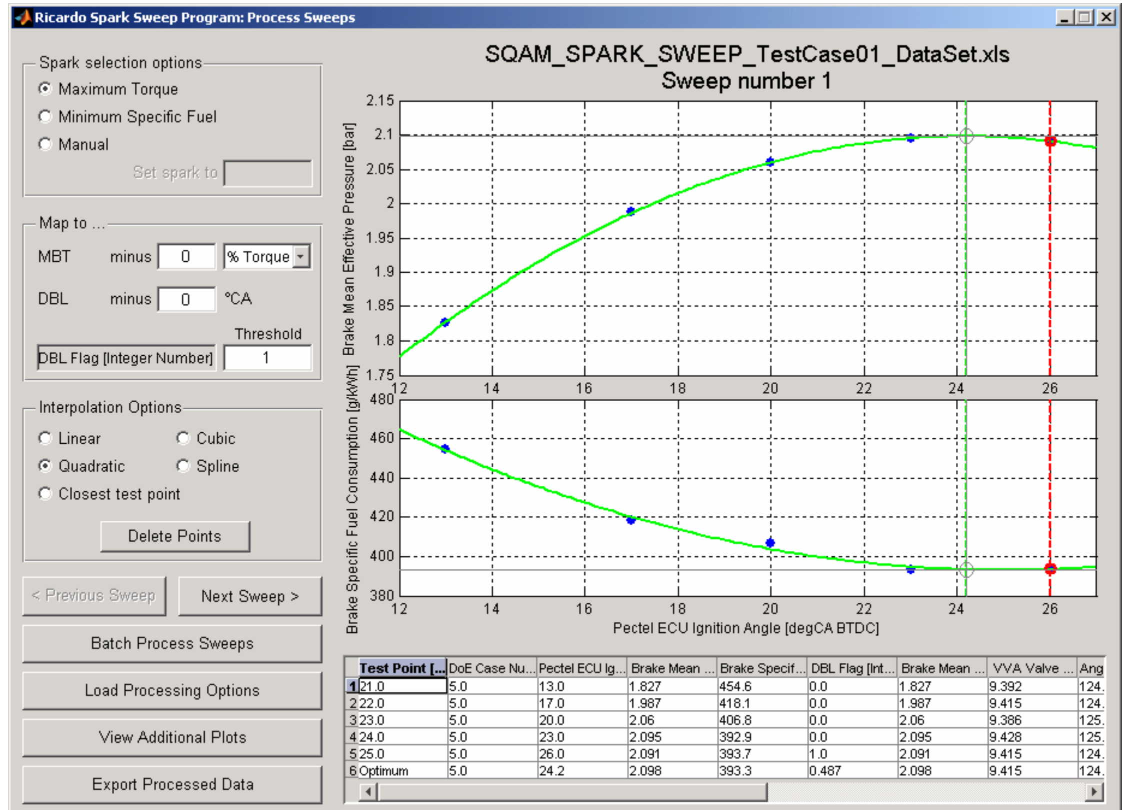
- Space filling design - note higher density of points at low MAF

Test Matrix

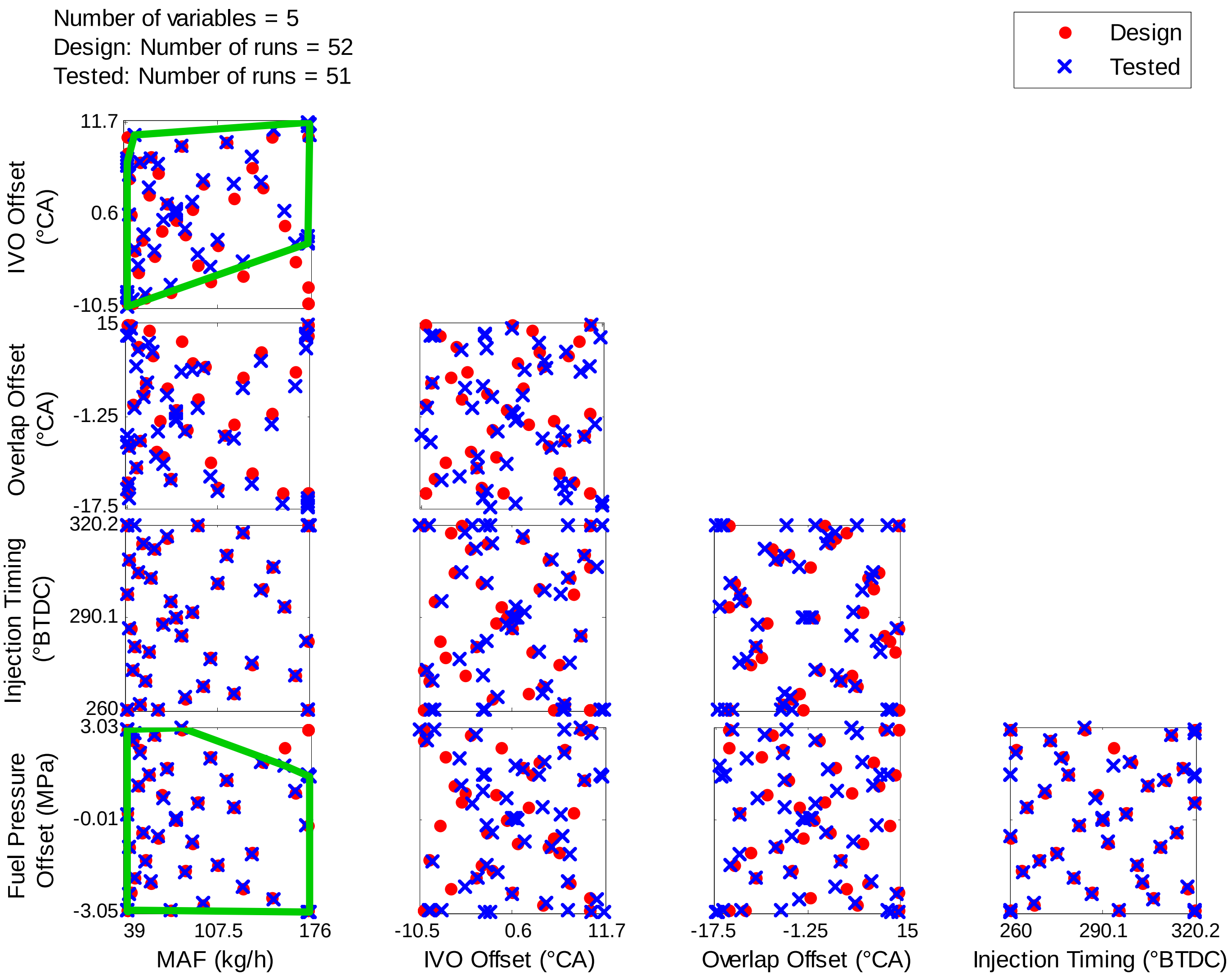


- Design space in "real units"

- Testing
  - Rapid testing
    - Fixed MAF spark sweeps
    - Exact set points not essential
  - IVO adjusted if test point unstable (e.g. at high overlap conditions)
    - This has no impact on modelling
  - Specialist Matlab tool for processing spark sweeps and formatting data ready for modelling can also be invoked from STARS

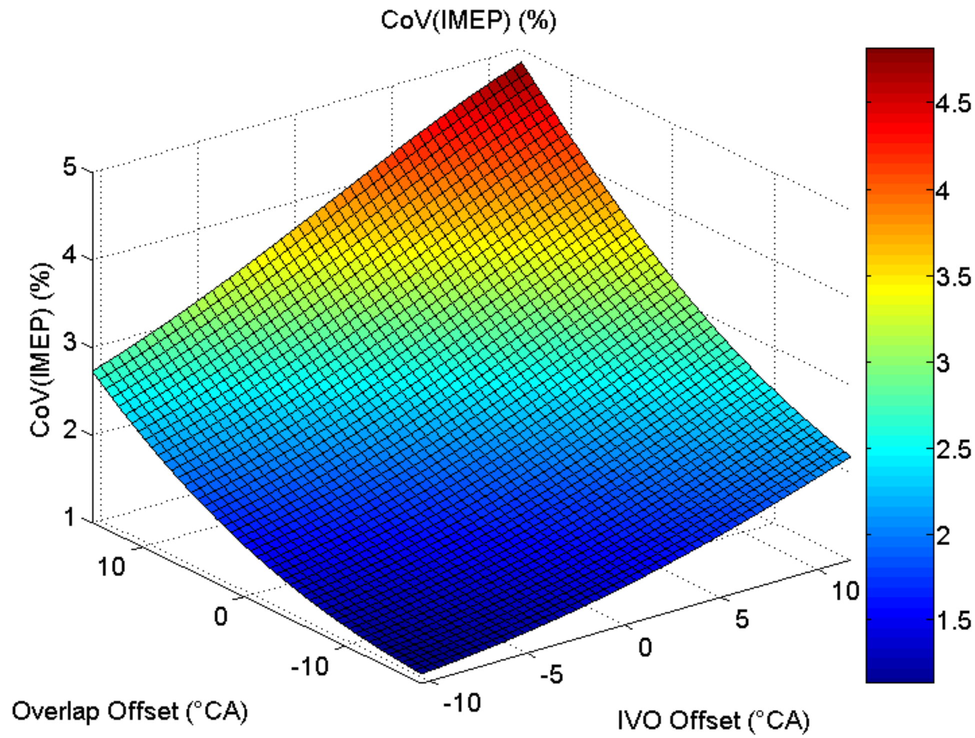


Modelling Preliminaries



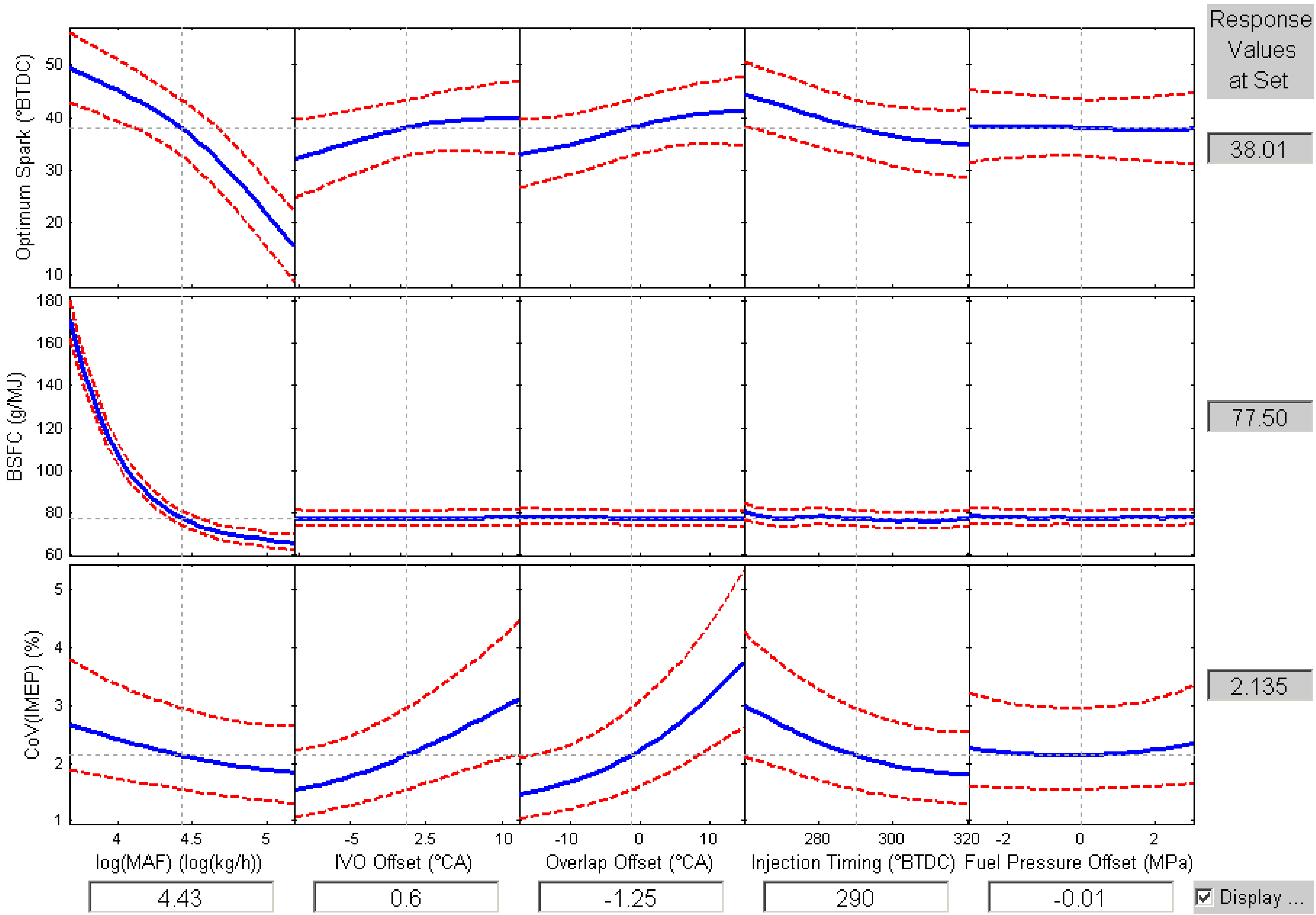
Modelling

- Modelling with SPMs
  - BSFC
  - BSNOx
  - BSHC
  - COV(IMEP)
  - Smoke
  - Optimum spark
  - Torque
  - Exhaust temperature
  - Manifold pressure



- Batch processing feature
  - Approximately one hour per set of responses

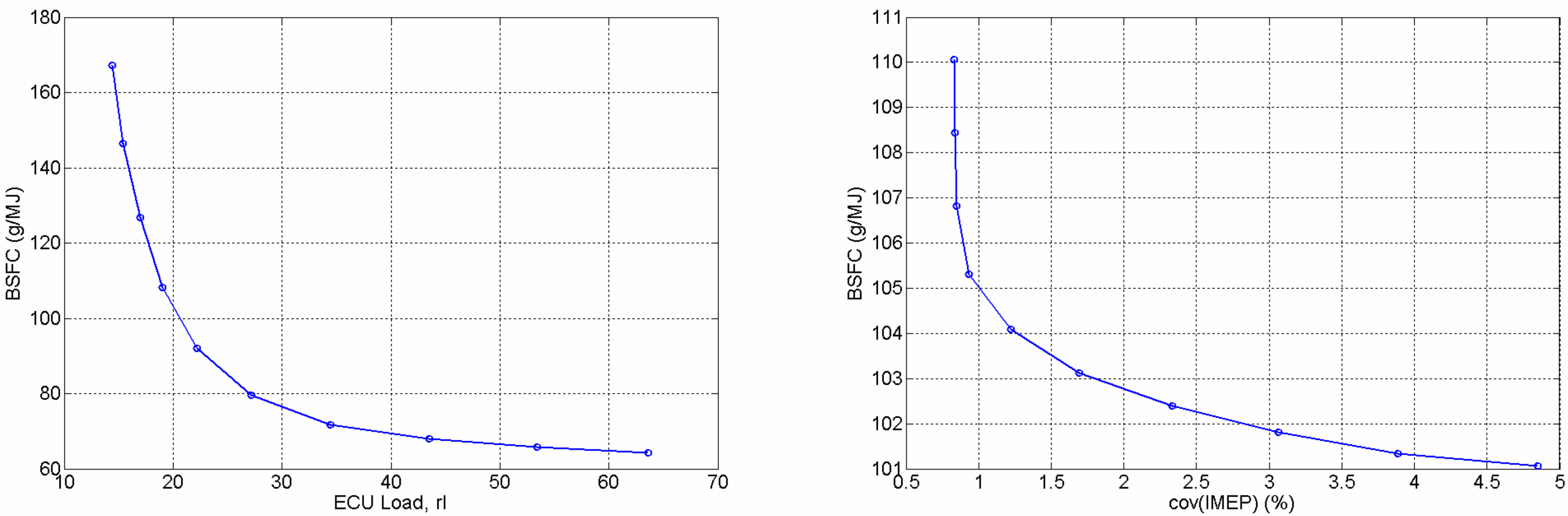
Modelling



- Example view of selected models at 2000 rev/min

Optimisation

- Optimisation
  - Matlab-based Pareto Optimisation Tool
    - At each ECU map site
      - Minimum BSFC with COV(IMEP) and smoke constraints



Contents

Ricardo Horiba

Conclusions

- The use of the SPM methods realises great benefit in terms of test time and calibration quality
- A successful application of these techniques to an engine with direct injection and variable valve timing has been presented
- Compared to polynomial methods
  - The variable range setting process is greatly simplified
  - Orthogonal or overly complicated experimental designs are not needed
  - The models are more resistant to unexpected non-linearity
  - The modelling process is less sensitive to test setting deviations
  - Testing considerably reduced
    - Number of test points reduced (by inclusion of MAF in DoE models)
      - 800 spark sweeps for polynomial
      - 400 spark sweeps for SPM
- DoE methods are well established with tools designed for both testbed and office based activities
- Good tools and techniques reduce requirement for specialist DoE expertise