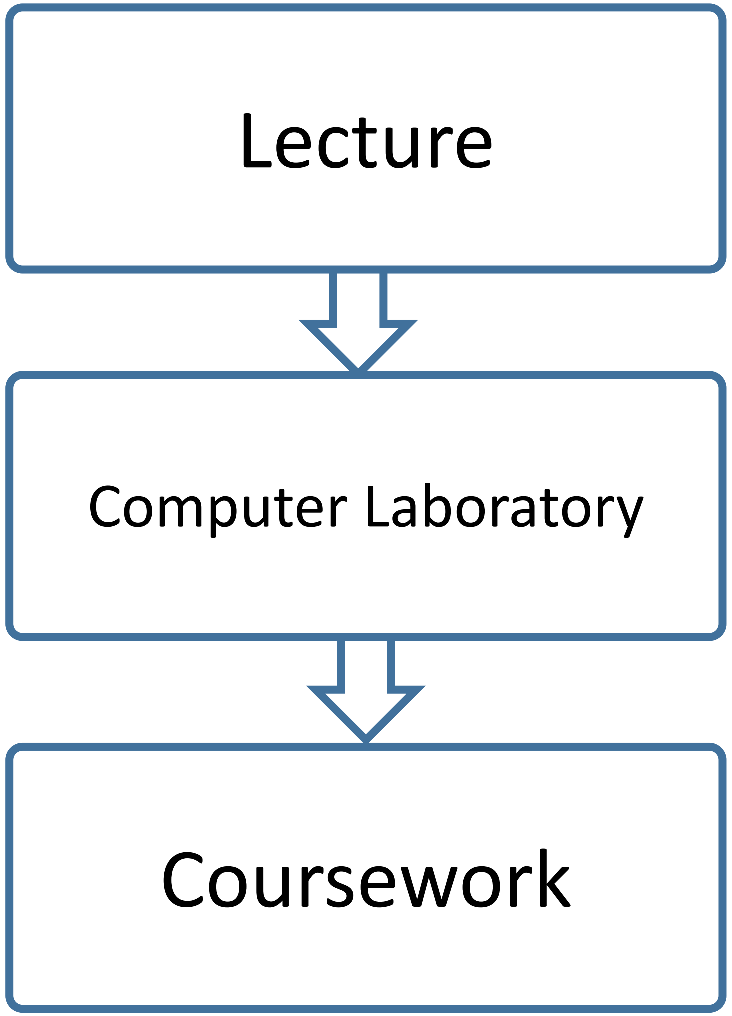
Powertrain Calibration Optimisation

Introduction to Calibration

Module Outline

- System characterisation
  - Statistics
  - Design of experiments
  - Model based calibration toolbox (MBC Toolbox)
- System identification
  - MBC Toolbox
- Optimisation
- Calibration generation



Timetable

Week	Lecture	Lab/Tutorial
1	Introduction to Calibration	
2	Statistics	MATLAB and Simulink ONRAMP
3	Optimisation	Optimisation Lab
4	Design of Experiments	Optimisation Lab
		Design of Experiments Lab
5	Design of Experiments	Design of Experiments Lab
6	Response Surface Modelling	Response Surface Modelling Lab
7	Introduction to Coursework	Coursework Questions and Answers
8	Calibration Exercise	Calibration Lab
9	Calibration Lab	Calibration Lab
10	Future Challenges	Coursework Questions and Answers
11	1:1 Support as required	
12	1:1 Support as required	

Assessment Structure

- Coursework 1 (5%)
  - MATLAB Onramp
- Coursework 2 (25%)
  - Experimental Design Assignment
- Coursework 3 (70%)
  - Calibration Activity Assignment

Aim

- Discuss engine control and gain an understanding of the complexity and issues
- Build on the idea of torque control
- Continue to define the calibration task
- List the phases of calibration and introduce the technologies used to implement the requirements

What is calibration?

A Control System

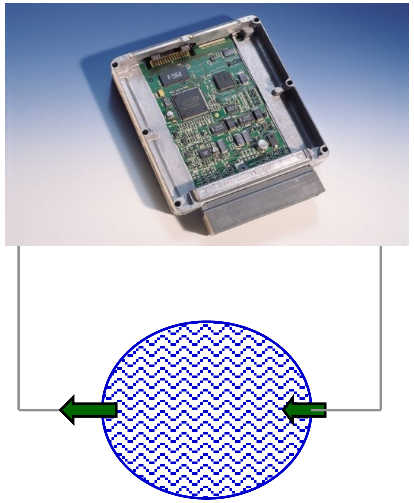
A control system always measures one or more quantities and makes a decision based on a calculation

Three essential components

- a sensor to measure a physical or chemical quantity
- a processor to calculate a control action
- an actuator to make a control action

Production engines typically have smallest sensor set possible

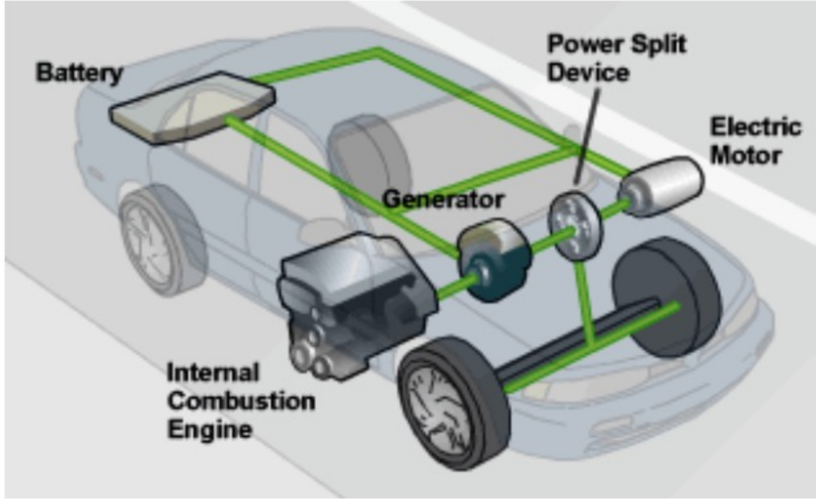
- Much of the information available to the control system is inferred
- Obtained through characterisation experiment



Texh
$TORQUE_i$ MBT
Tman
ECT
MAF
$TORQUE_b$ N_TURBO
AIRCHG MAP PBOOST

Effective control of hybrid requires some prior knowledge of the system

Power Avail
SOC
EGR
AFR
Spark
VVT
Shifts
Injection
Drive by wire

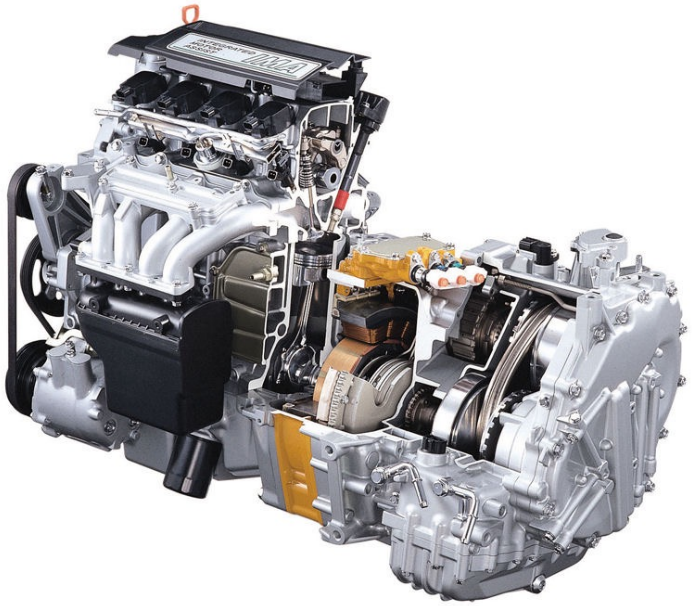


Torque
Emissions
Noise
Driveability
Power Use

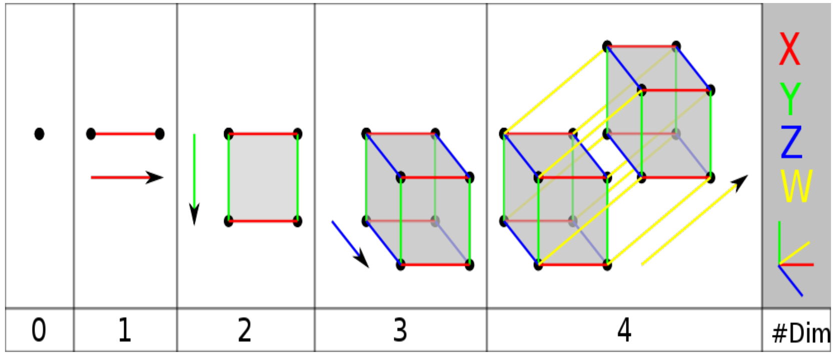
controller

Tables

High degree of freedom powertrains



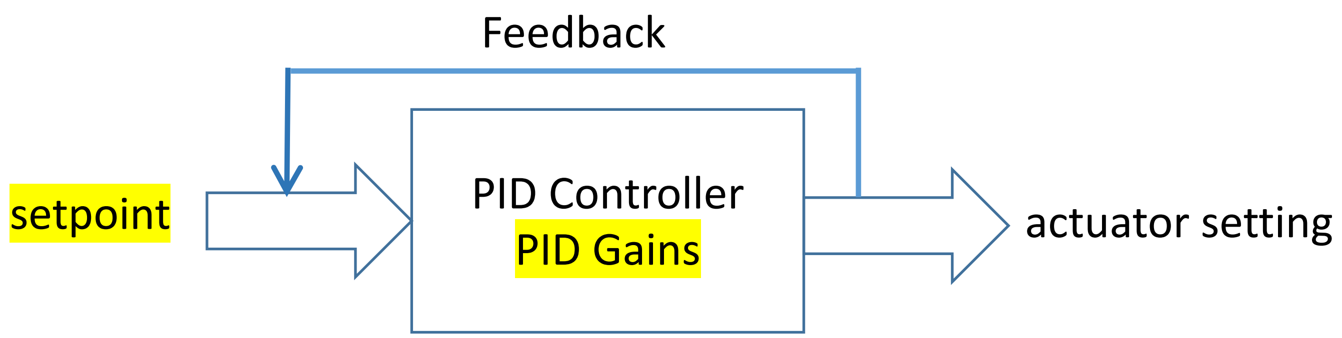
- Modern engines have
  - Fuel injection with multi-pulse capability
  - VVA
  - Variable geometry boost and EGR
  - Cylinder pressure feedback
  - Etc
- Modern electric machines
  - Simpler system
  - Interface between EM and Engine in the problem
    - Torque split
    - Torque estimation
- Dimensionality of control and calibration problem is increasing

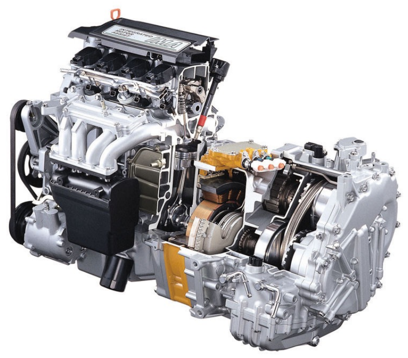


What is calibration?

Calibration is the process of selecting the parameters of an electronic control unit (ECU) to ensure that the system under control runs optimally.

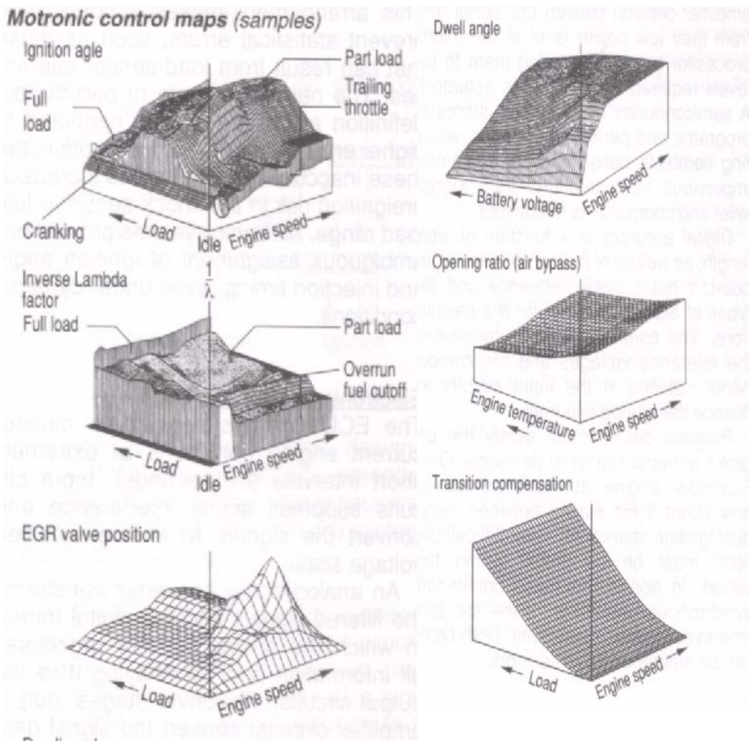
- □ Parameters are selected (up to 50,000!)
- □ Vehicle performance is set according to customer requirements and interests
- □ Legal limits are set by the country in which the vehicle is sold (in our case the EU)





A Modern Powertrain Management System (PMS)

- In a modern EMS, there are many controlled variables
- There are therefore many tables and as a consequence more interactions.
- Table structure begins to get particularly complex with hybridization for example.



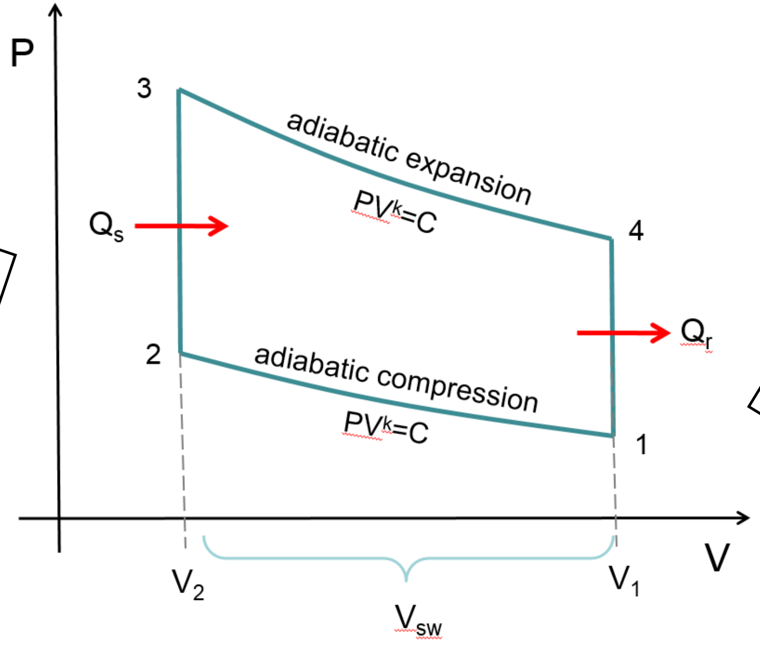
Diagrams from Bosch Automotive Handbook, 4th Edition, p479

Combustion is dead?

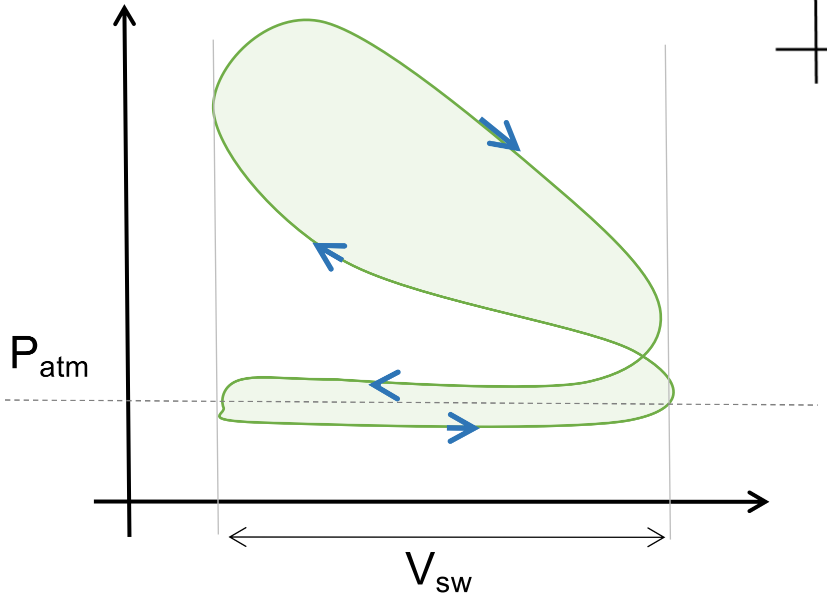
- Recent announcements about major OEMs getting involved with F1 (synthetic fuels)
- Hydrogen investment is increasing significantly
- Off-highway and many heavy duty applications cannot be electrified due to energy density
- Technologies are diversifying (becoming more specialised for each application)
- The future is much greater complexity which requires advanced engineering methods

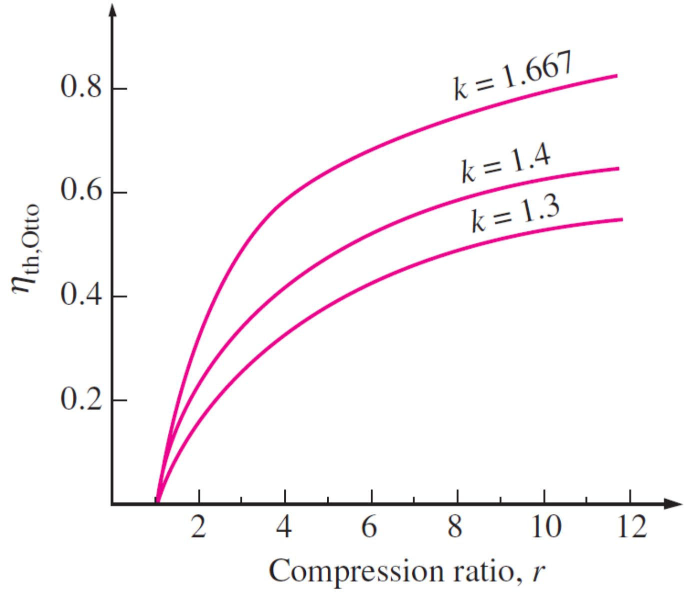
Some engine fundamentals

- Pumping losses
- Compression ratio
- Efficiency limit

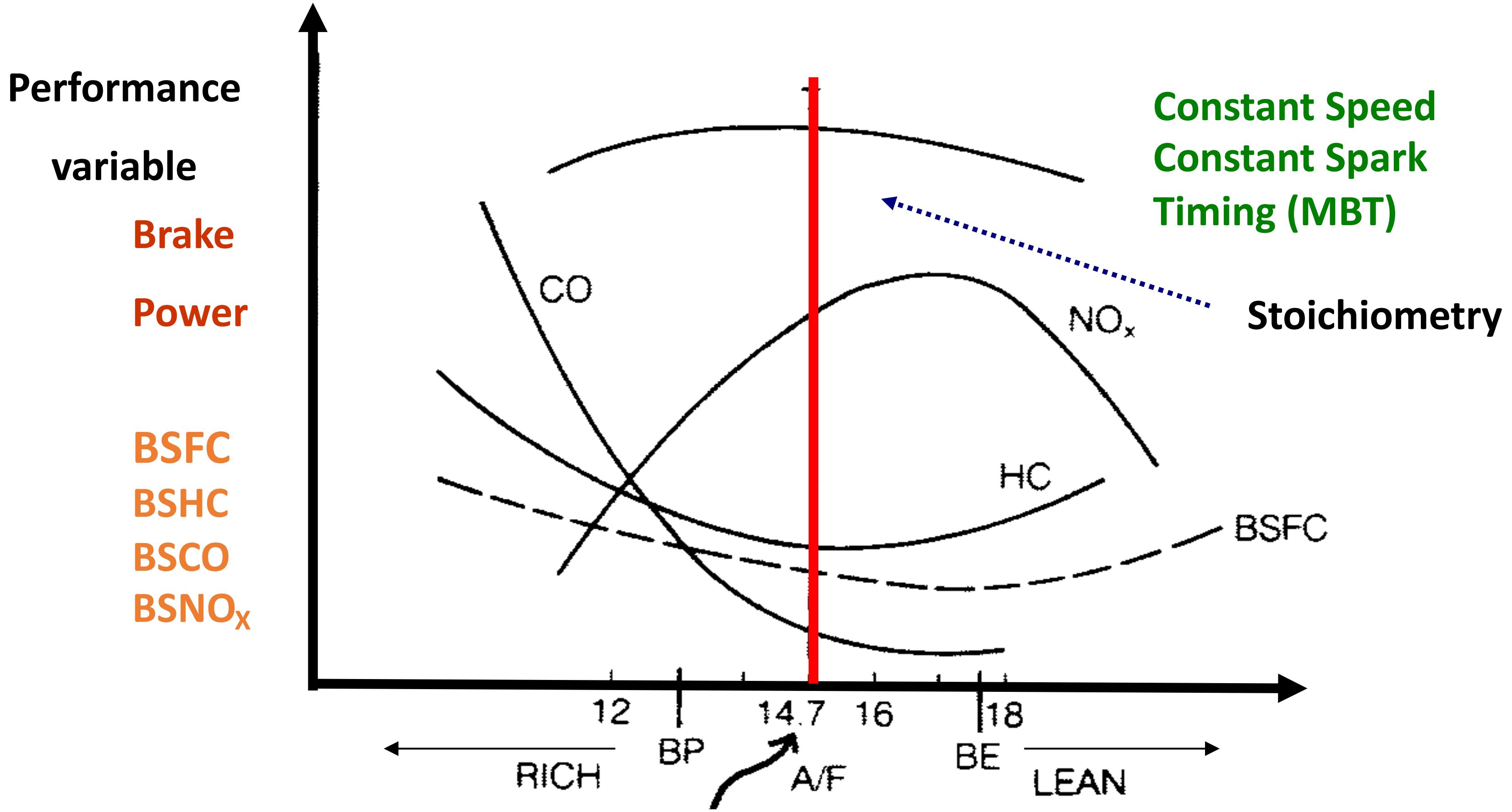


$$\eta = 1 - \frac{1}{r^{k-1}}$$



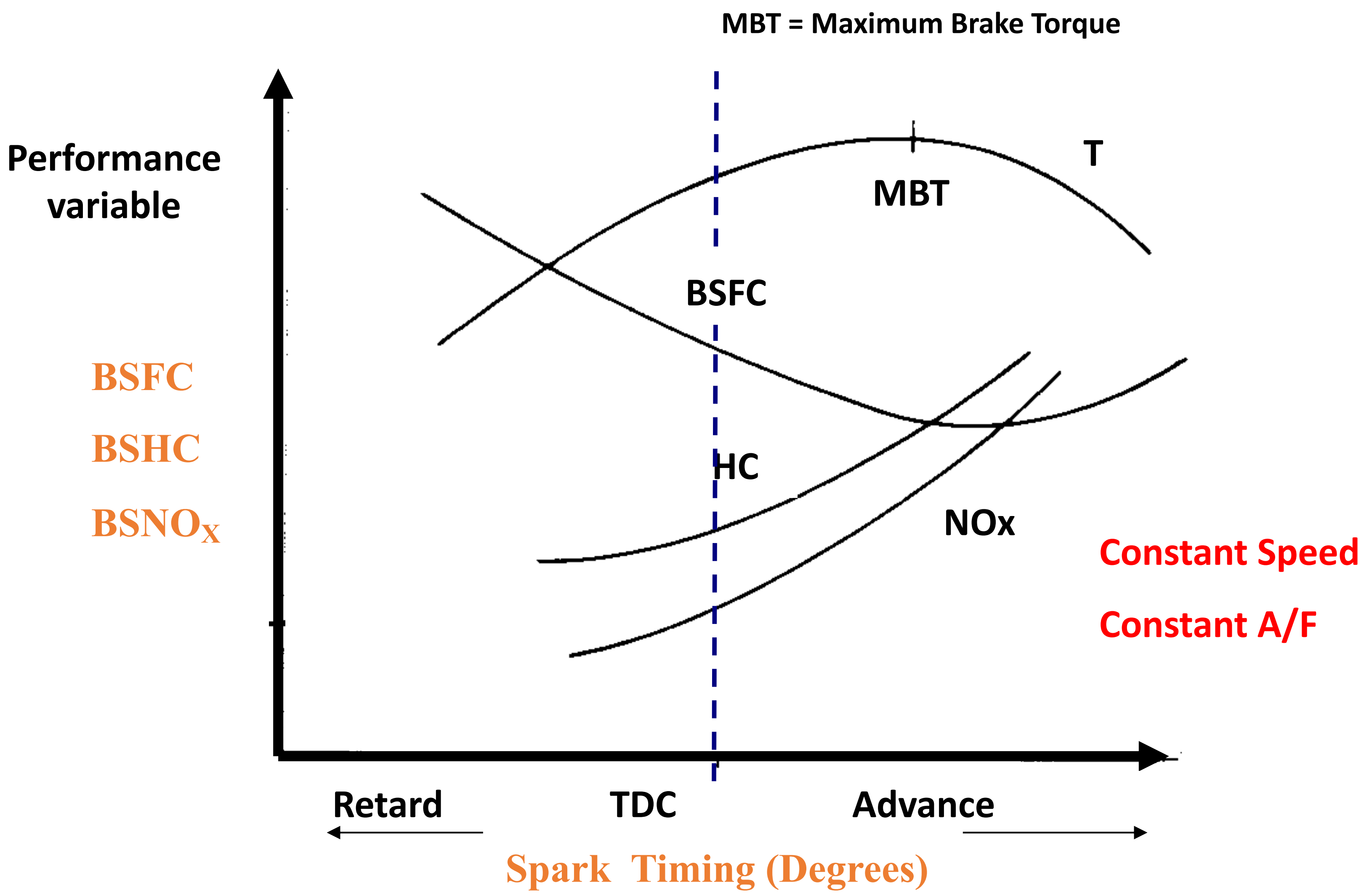


Typical Variation of Performance with a Variation in Air/Fuel



BSFC – Brake specific fuel consumption.

Typical Variation of Performance with spark timing



Motivation

- Three main drivers
  - Legislation (noxious emissions)
    - To allow sale i.e. system/component type approval
    - First 70/220/EEC October 1970, HC and CO
    - Present 715/2007/EC, Euro 5 and 6 (vehicles on sale from Sept 2015)
  - Fiscal (CO_2)
    - To reduce penalties (CO_2) e.g. 443/2009. Penalties on a sliding scale (up to €95/g/km) for each vehicle exceeding these targets.
    - Fleet average 130 g CO_2/km from 2012 (gradual introduction)
  - Customer
    - Product differentiation
    - Taxation

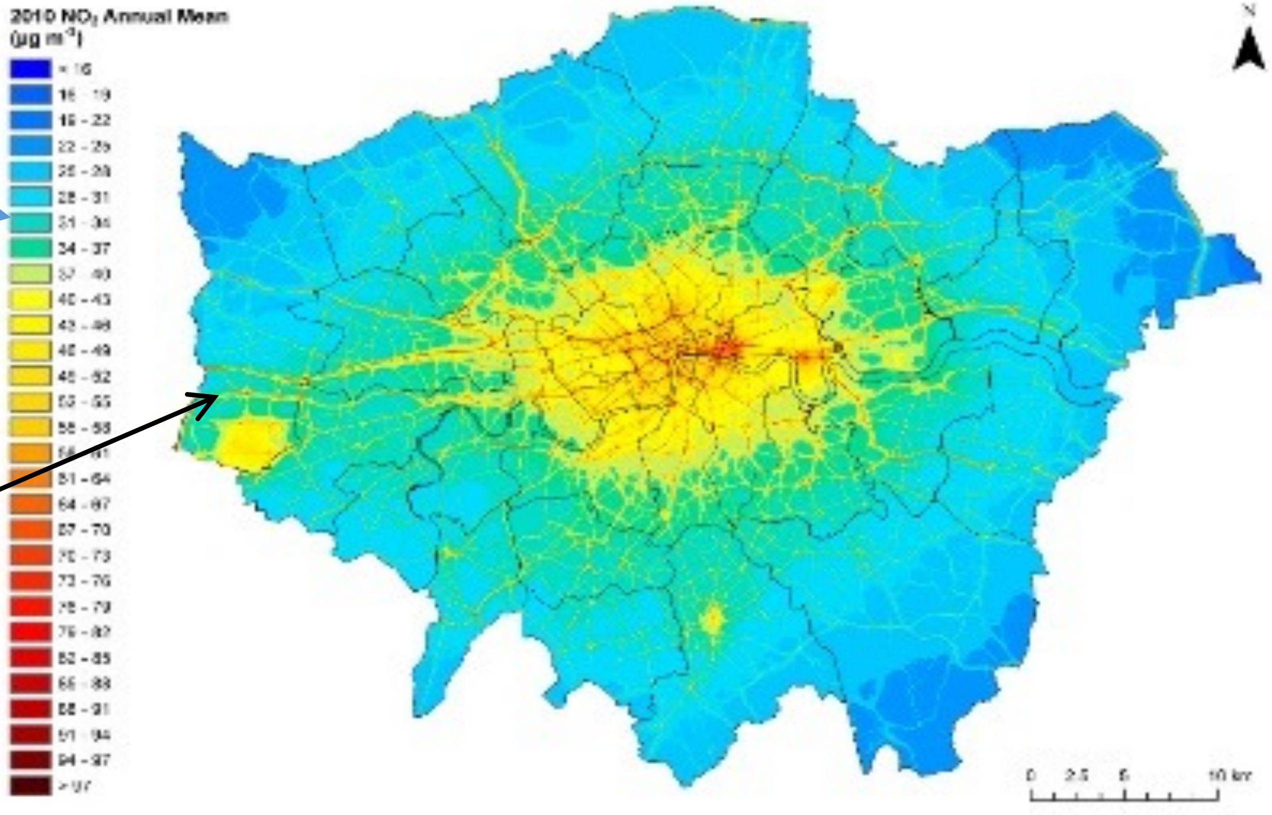
Legislation – EU (Noxious Emissions)

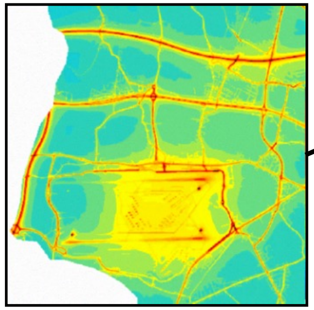
European Emissions Standards (g/km) (gasoline light duty)								
		CO	THC	NMHC	NOx	HC+NOx	PM	PN [#/km]
Euro 1†	Jul ‘92	2.72 (3.16)	-	-	-	0.97 (1.13)	-	-
Euro 2	Jan ‘96	2.2	-	-	-	0.5	-	-
Euro 3	Jan ‘00	2.3	0.20	-	0.15	-	-	-
Euro 4	Jan ‘05	1.0	0.10	-	0.08	-	-	-
Euro 5	Sep ‘09	1.0	0.10	0.068	0.060	-	0.005	-
Euro 6	Sep ‘14	1.0	0.10	0.068	0.060	-	0.005	6×10^{11}

The London NO_x Problem

Modelled NO_2 annual average concentrations (µg/m³)

1 year legal limit (40 µg/m³)





Similar story for PM10

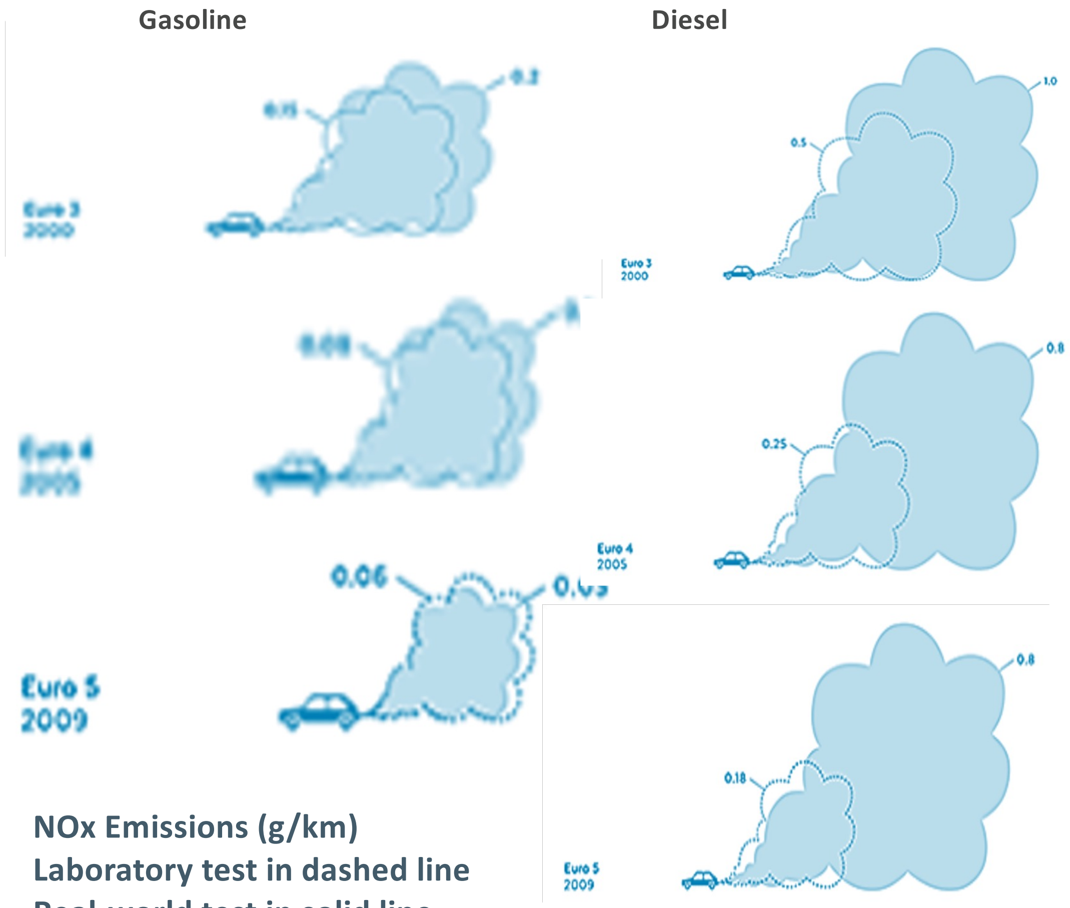
Data from Environmental Research Group, Kings College London (8 March 15)

0-200 µg/hr

Legal limit 40 µg/m^3, (1 year limit)

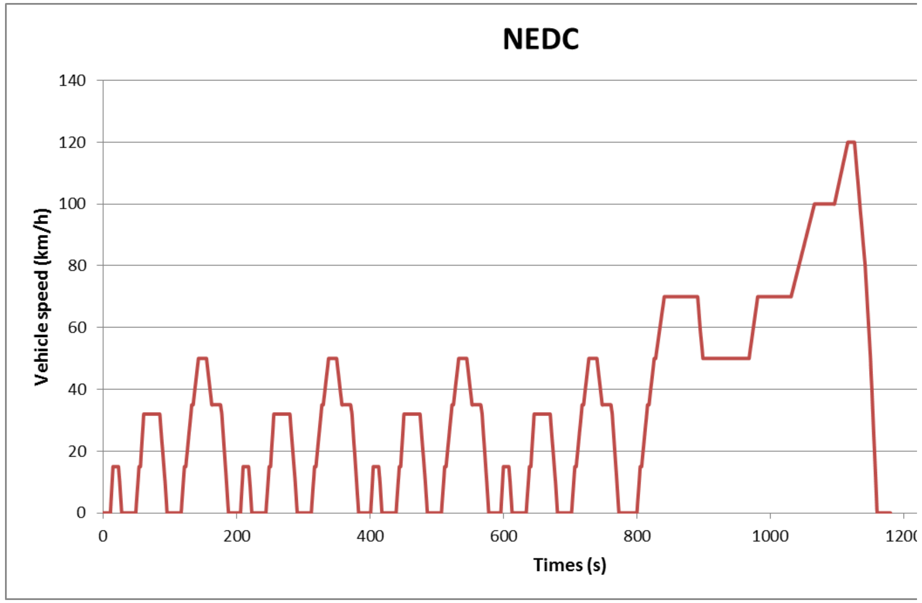
Laboratory versus Real World: Discrepancies in NOx emissions

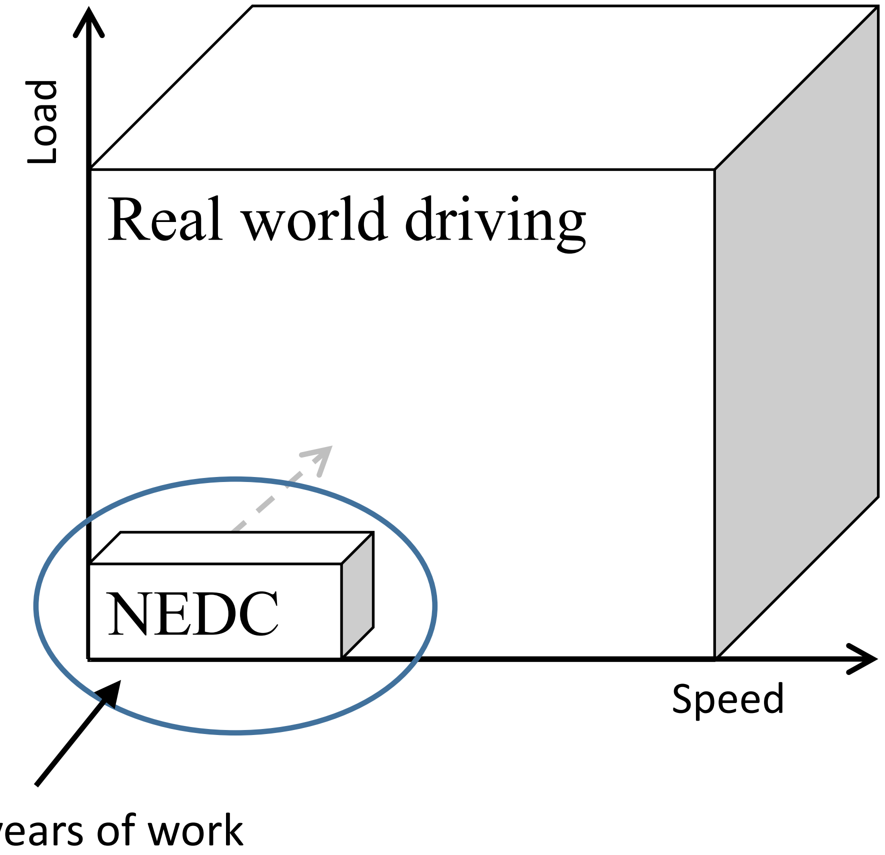
- For gasoline vehicles NOx emissions measured in the laboratory are similar to those measured on-road
- In a recent publication the European Commission's Joint Research Centre (JRC) summarises on-road test results for a number of vehicles and comes to the conclusion:
- **"The on-road NOx emissions of diesel cars, furthermore, appear to exceed substantially applicable emissions standards."**
- **"Still, all tested cars, including the Euro 6 diesel car, exceed their NOx emissions standards on the road by 260 ±130%". (Source: ICCT, European Vehicle Market Statistics, 2013)**



NOx Emissions (g/km)
Laboratory test in dashed line
Real-world test in solid line

Real Driving Emissions



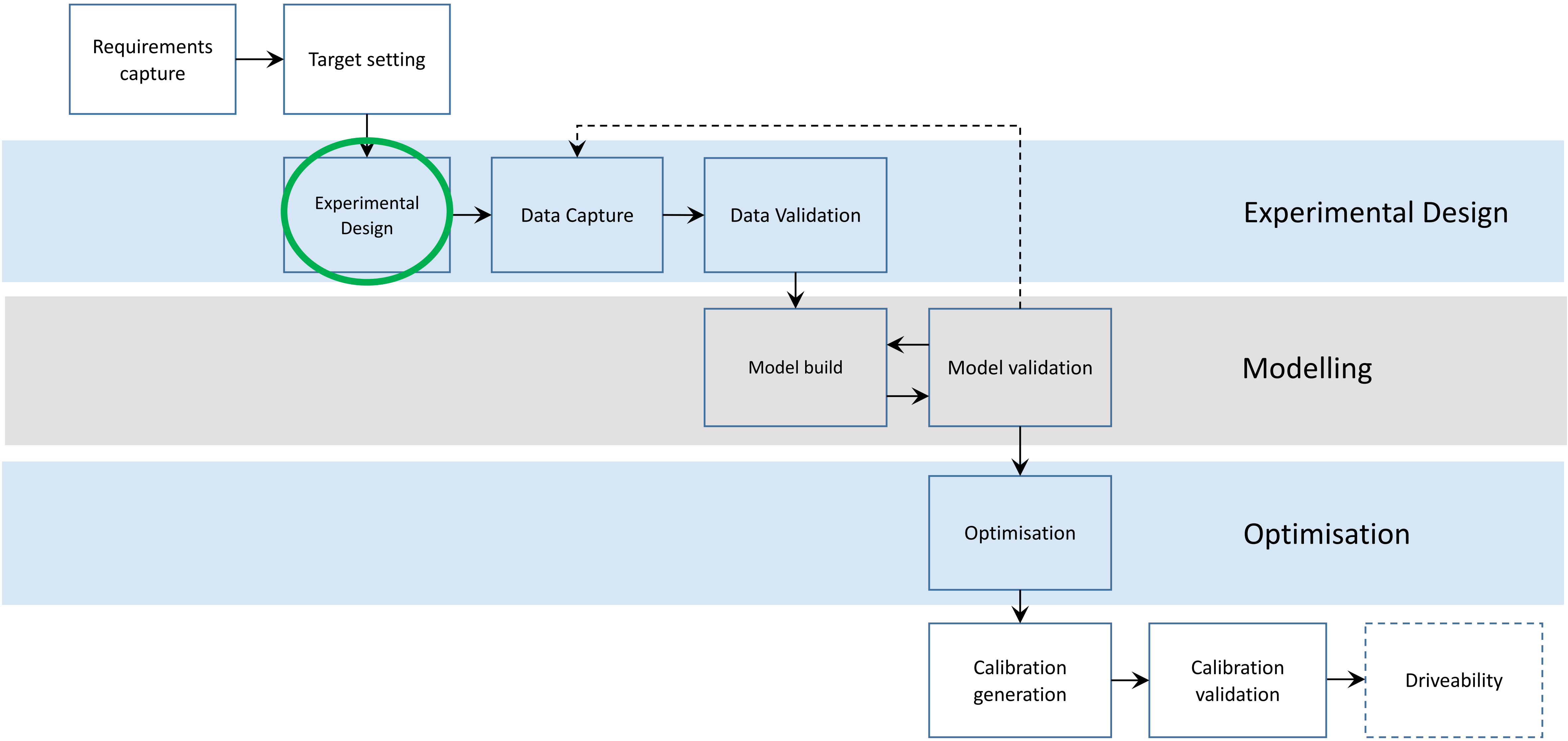


Four major steps in calibration

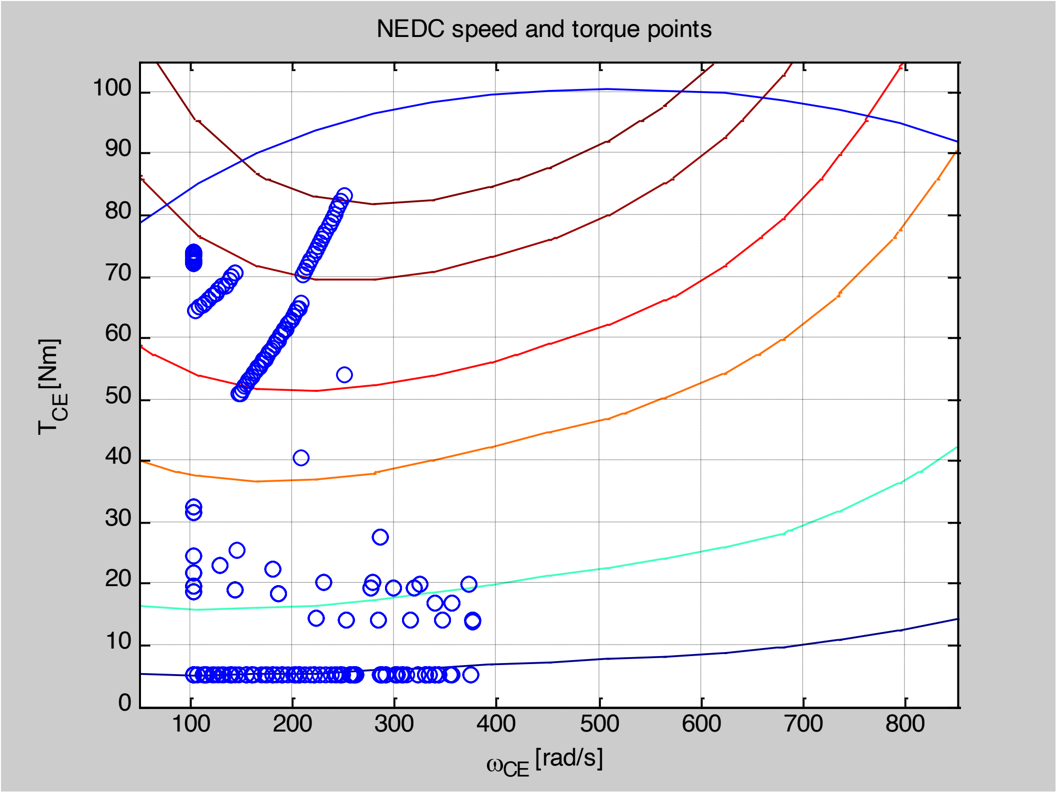
- Plan the experiments
  - With limited test bed time what is the best way to gather data? Identify modal points – plan experiments.
- Acquire the data
  - There is always a significant volume of data; automated methods are essential
- Fit models
  - Models will be quick to fit and accurate and represent engine behaviour
- Conduct optimisation
  - Using models, identify the combinations of controls that give *best* engine behaviour

Powertrain Calibration Optimisation

High Level Overview



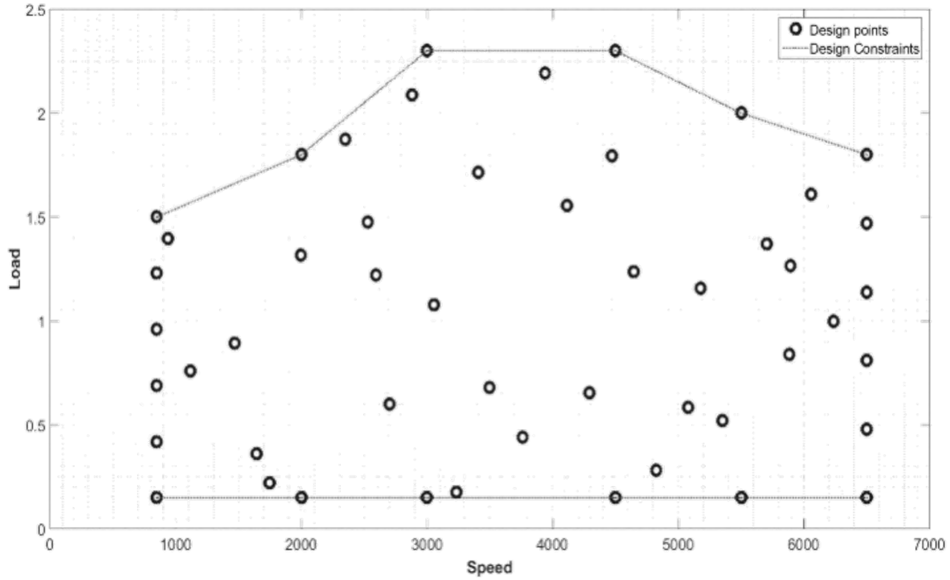
NEDC speed and torque points



Design of Experiments is used to plan engine testing

- Design of Experiments (DOE) provides one route efficient experimentation
- DOE is widely used in the process and medical industries

Torque experiment



3^k factorial experiments

k	Test Points
2	9
3	27
4	81
5	243
6	729
7	2187

Design of Experiments (DOE) - What do you do?

- Find the variables which influence the output (speed, load, ignition timing ..)
- Estimate the levels that are of interest (high, low ..)
- Two levels and n variables gives a 2^k design
  - 2^k is likely to be too many
  - select a fraction
- There are many ways to select a fraction
- Estimate *main effects* first - then *first order* interactions - and so on.

Quadratic surface model

$$\widehat{y_q} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2$$

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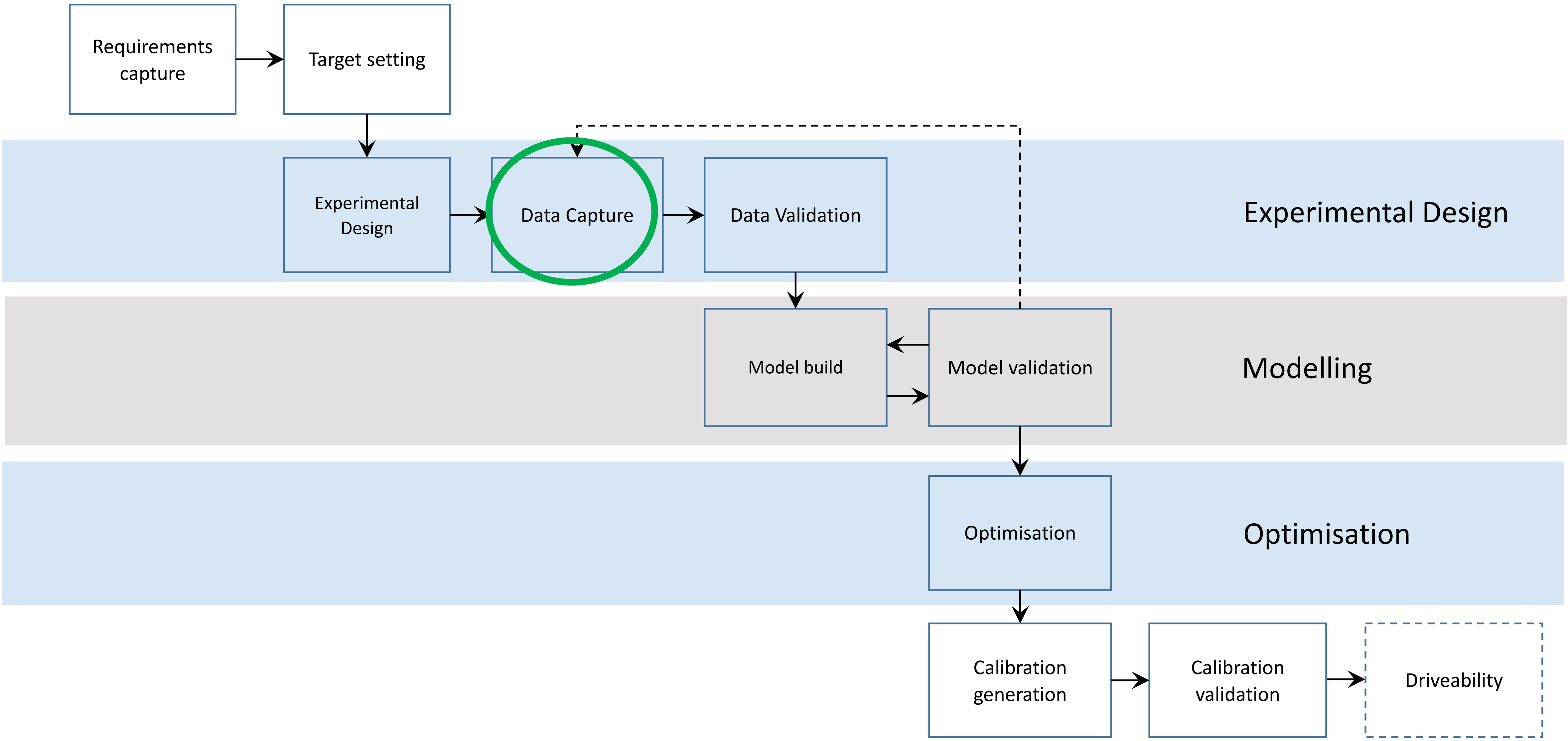


Different testing environments are used throughout the Calibration Development Process:

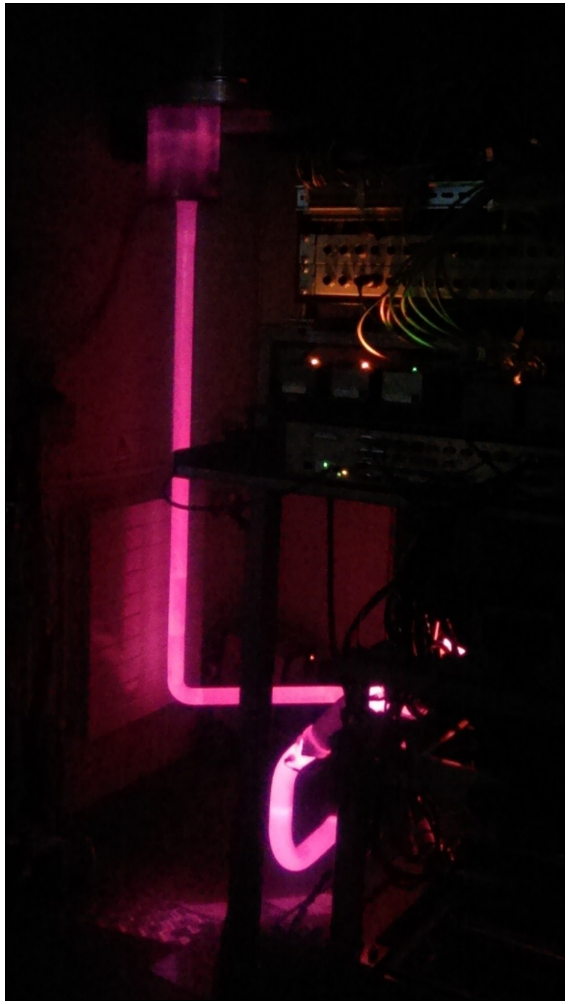
- ❑ Engine Testbed (Dyno)
- ❑ Chassis-rolls Dyno/ Powertrain Testbed (Vehicle)
- ❑ Public roads, Test Trips (Vehicle)
- ❑ Hardware-in-the-Loop, HiL (Simulation Environment)

❑ Engine Testbed

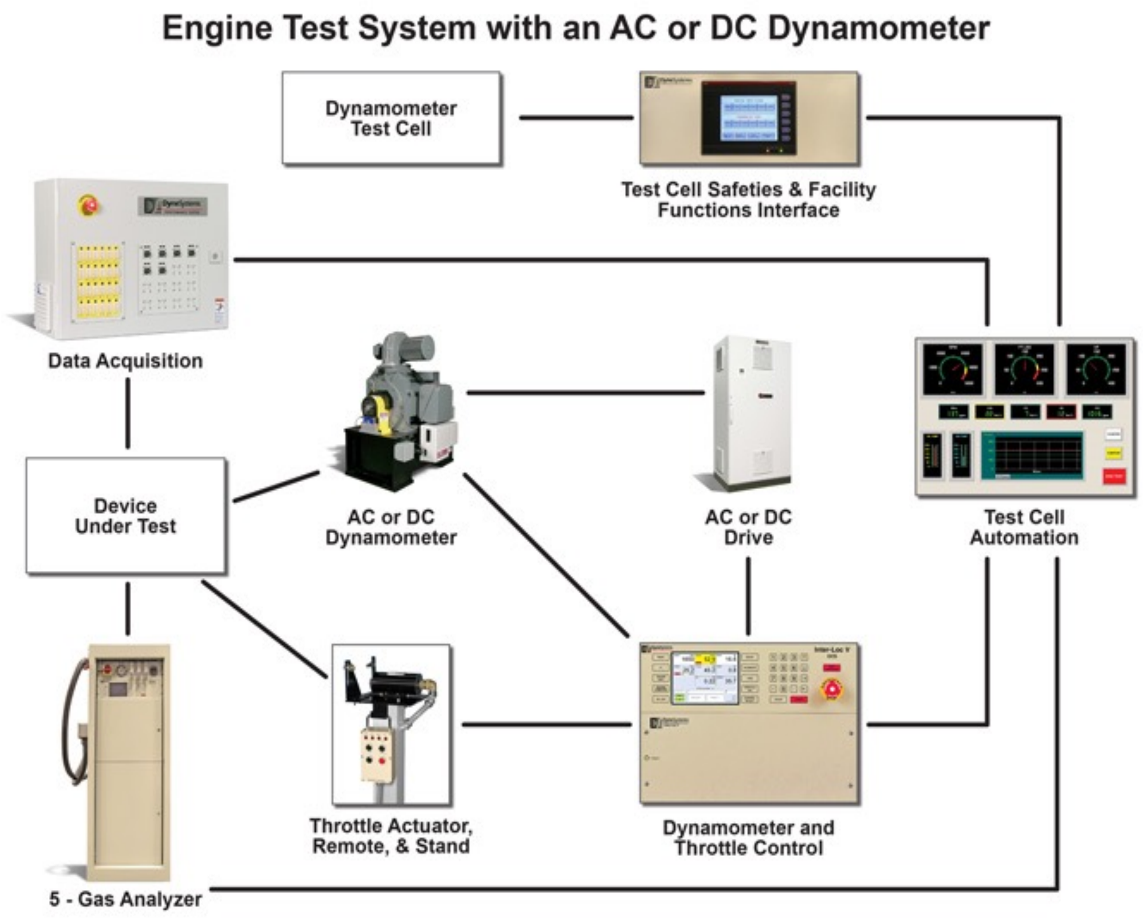
- ❑ Engine connected to a dynamometer
  Control of engine speed and load
- ❑ Control of coolant and oil temperatures
- ❑ Instrumentation of Engine and Exhaust
  Temperatures, pressures, …
- ❑ Emissions Measurement Systems
- ❑ Test Automation
- ❑ Controlled testing environment for repeatable and steady conditions calibration tasks

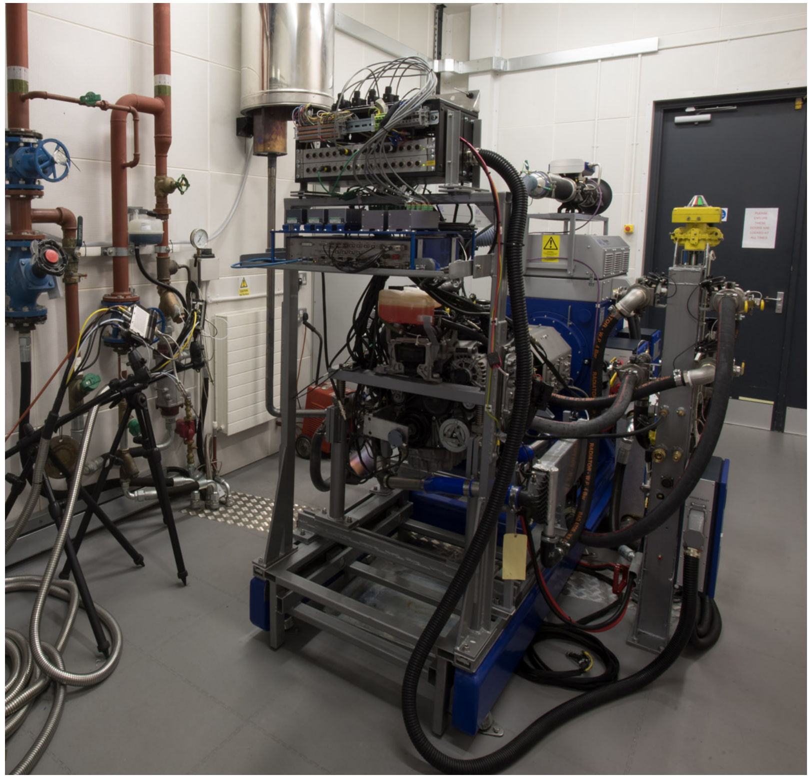
Acquiring the data

- The process starts with the estimation of the key speed load points. Depends on:
  - the drive cycle [for legal requirements]
  - road load and acceleration [to meet customer interests]
- The engine mapping is the process of acquiring the data at these speed and load points
- Experiment to acquire the data are performed at these speed-load points at steady state.



An Automation Scheme





❑ Chassis-rolls Dyno

- ❑ Testing of vehicle with complete powertrain on rolls with simulation of various driving resistances
- ❑ Simulation of various environmental conditions: cold/hot climate, altitude,…
- ❑ Vehicle and engine with additional instrumentation (temperature, pressure sensors,…)
- ❑ Emissions Measurement Systems
- ❑ Tests Automation
- ❑ Controlled testing environment for transient/dynamic conditions

❑ Road Testing/Test Trip

- ❑ Cold Climate
- ❑ Hot Climate
- ❑ Altitude
- ❑ Tests tracks for specific manoeuvres
  (high speed testing,...)
- ❑ Testing environment in real conditions

❑ Hardware-in-the-Loop HiL

- ❑ Engine simulation model connected to a physical ECU
- ❑ Vehicle simulation model can be integrated
- ❑ The HiL simulation controller supply the sensors inputs to the ECU and reads the actuator outputs to simulate the engine
- ❑ Depending on model accuracy a various range of calibration tasks can be realized on the HiL environment
- ❑ Extreme environmental boundary conditions can be simulated without risk of damaging engine or vehicle prototype

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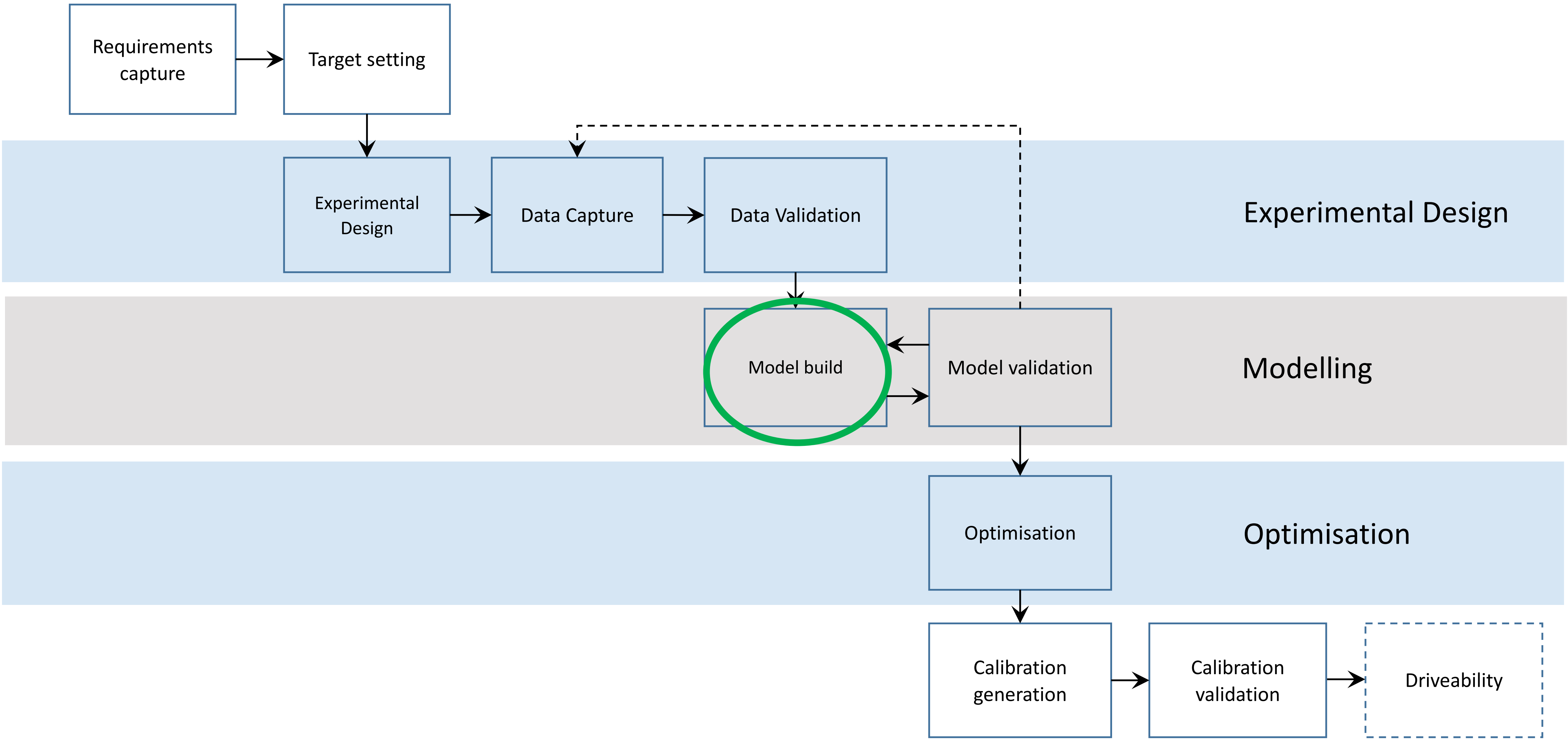
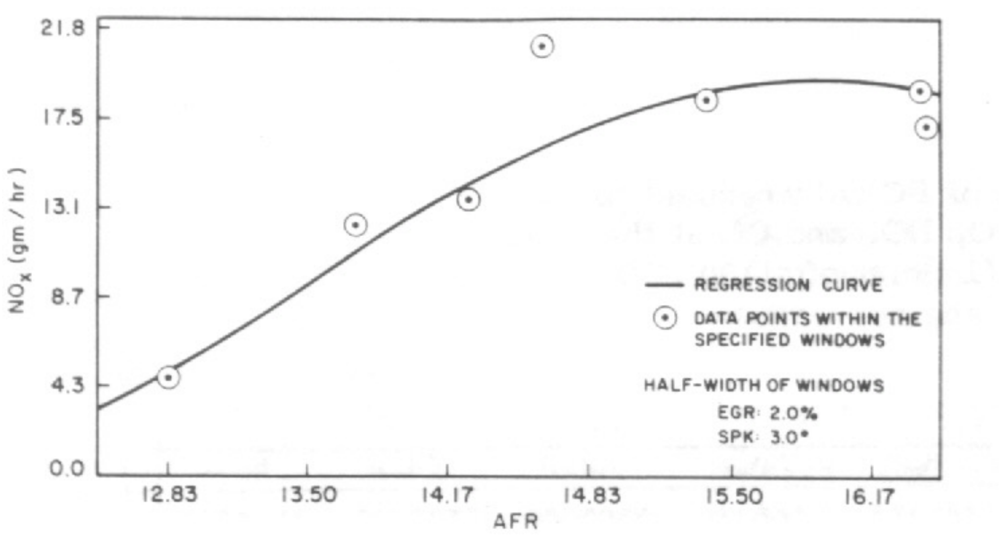
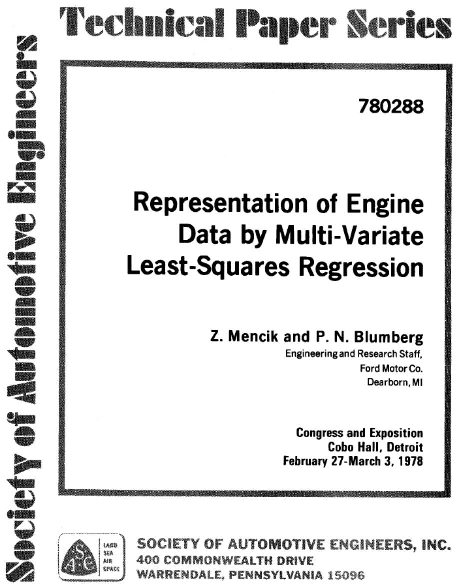


Creating models of the data

The data generated during the engine mapping process is reduced to a form that is easy to work with

- A model is fitted to the data
- Optimisation is conducted on the model





Radial Basis Functions

- Polynomial functions remain the most popular technique for the representation of models
- Radial basis functions are gaining in popularity
- They offer a broader range of representation
- A radial basis function is based on the sum of functions located at a number of centres

$$f_i = K\left(\frac{\|x_i - c_i\|}{\sigma}\right)$$

$$\hat{y}(\vec{x}) = \sum_{i=1}^{n} \beta_i f_i(\vec{x})$$

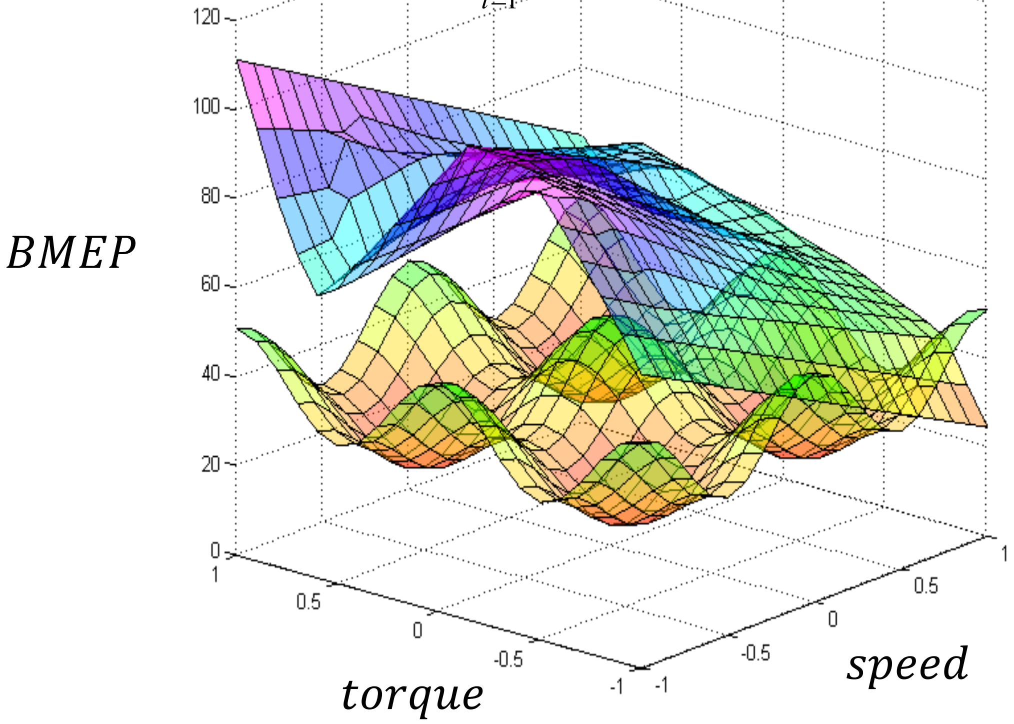
Types of models - Radial basis function

A BMEP response surface model using RBF with two inputs (torque and speed):
Parameters requiring training:

1. Weights w_i
2. Centers $c_{i,1}$ $c_{i,2}$
3. Widths σ_1^2 σ_2^2

In MBC, the training is done Automatically. It only needs training data and maximum no of centers
to use.

$$f_{BMEP}(x) = \sum_{i=1}^{9} w_i e^{-\frac{1}{2}\left(\frac{\left\|x_{torque} - c_{i,1}\right\|^2}{\sigma_1^2} + \frac{\left\|y_{speed} - c_{i,2}\right\|^2}{\sigma_2^2}\right)}$$



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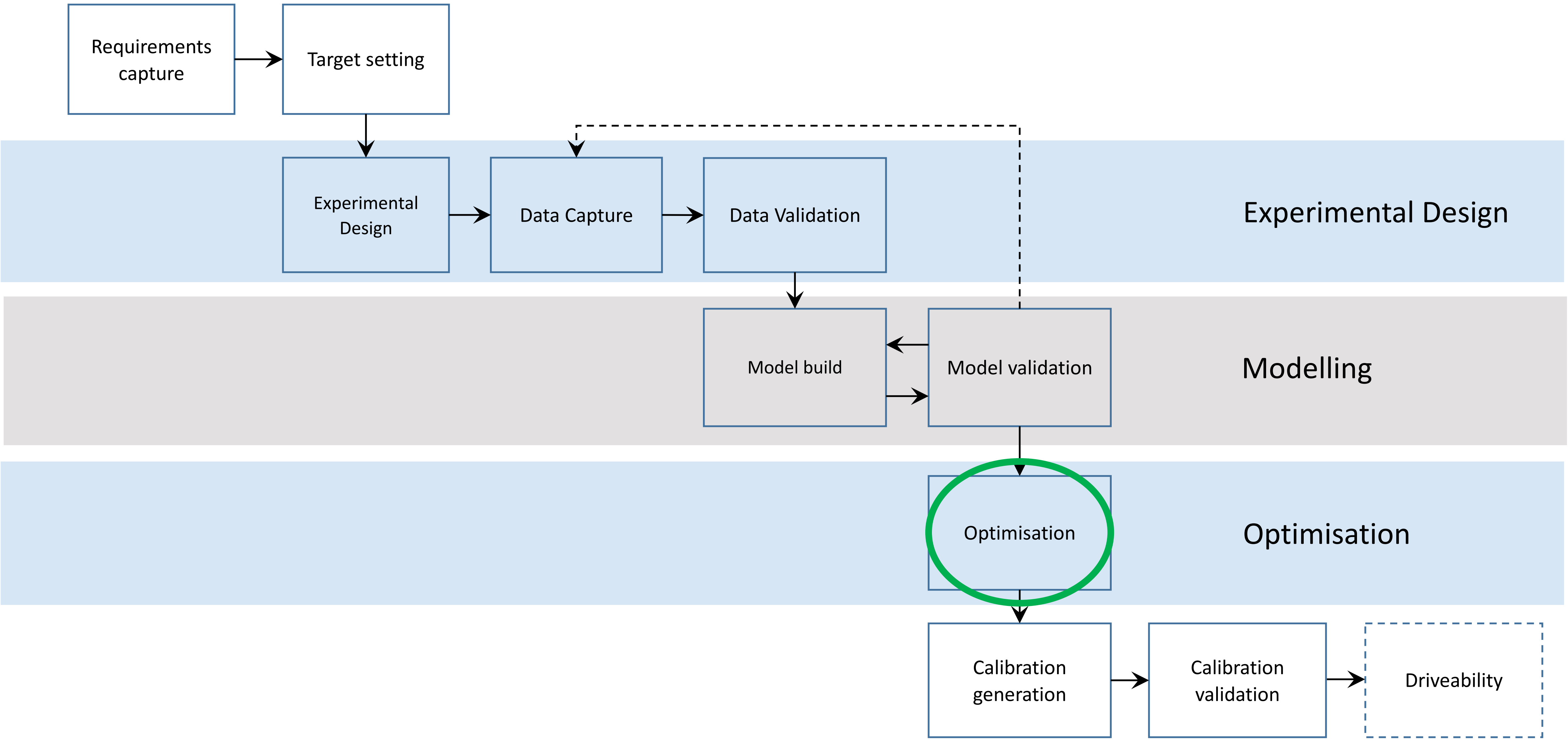


Optimisation

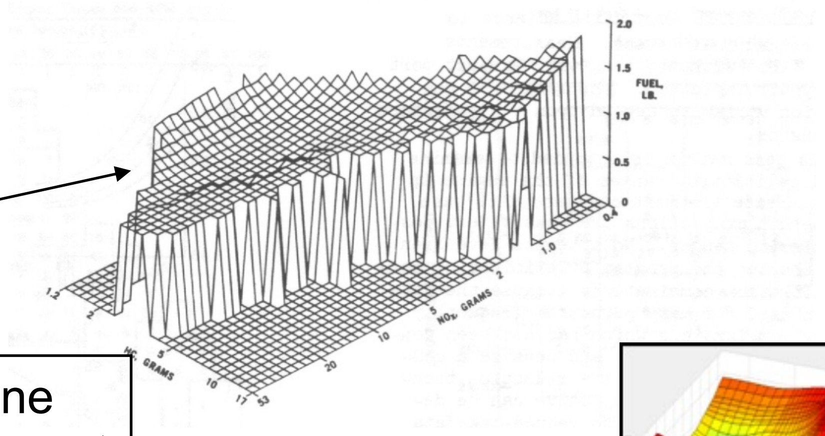
- Optimisation is the process of finding the best combination of controls to meet a specified task
- In an optimisation process a cost function is formulated and minimised
- The cost function contains quantities to be minimised
- This is a simple example of a cost function to be minimised that would result in low fuel consumption and torque delivery

$$J = \sum f + \left(\left. \frac{\partial T}{\partial t} \right|_{n,T,\ldots} \right)^{-1}$$

- f is a measure of fuel consumption
- $\left. \frac{\partial T}{\partial t} \right|_{n,T}$ is a measure of torque delivery at a given engine state

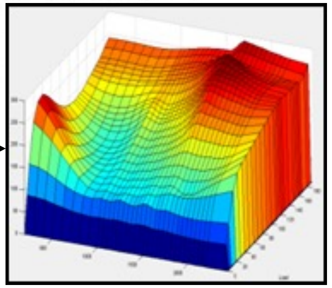
Optimising with engine data

- *"The selection of calibrations at each speed-load point such that the cycle weighted summation of fuel consumption is minimised while the cycle weighted emissions are held within constraints"*
- *[from SAE 77077]*



Each speed-load point is optimised for emissions and fuel consumption

Alternatively whole engine calibration is of great interest but still computationally challenging



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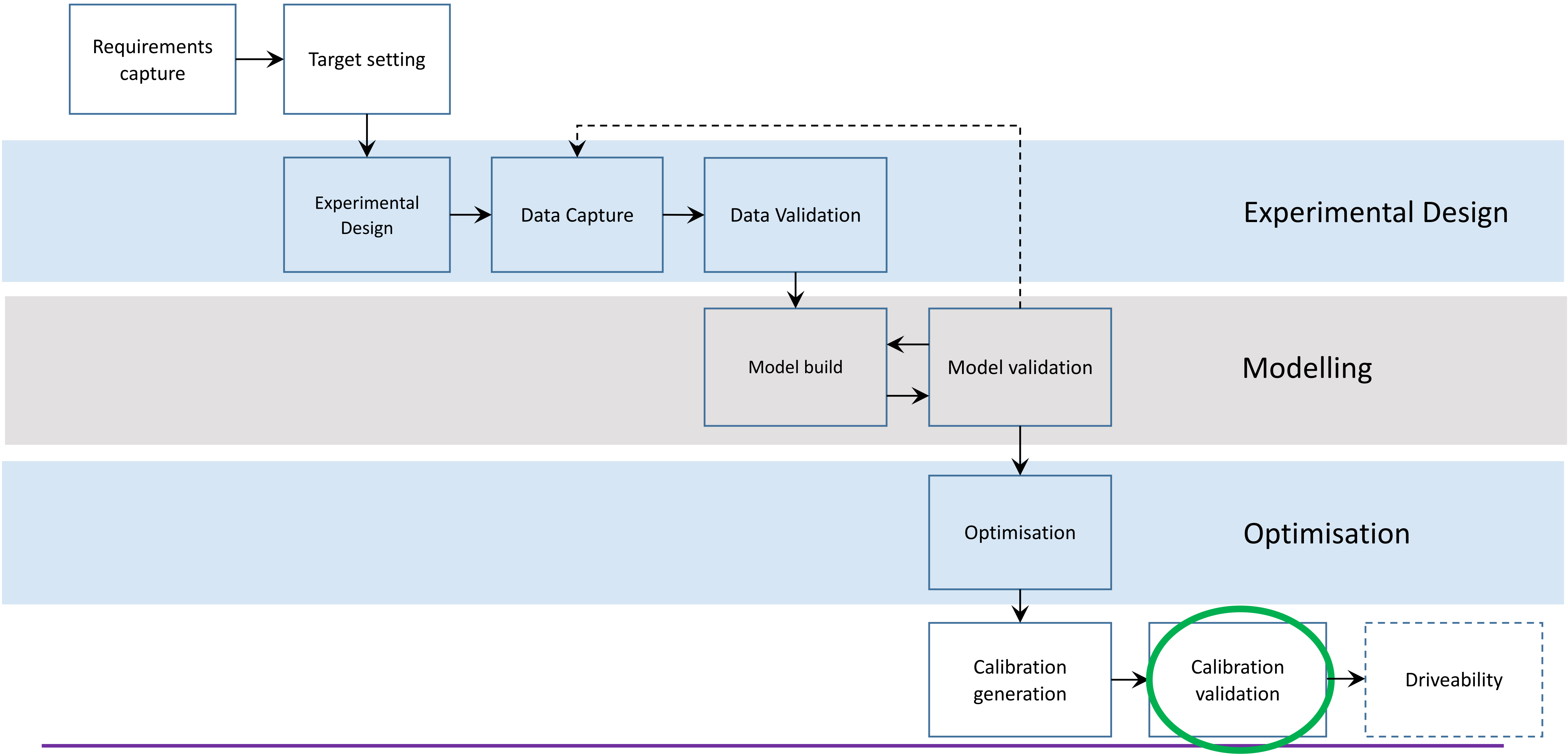
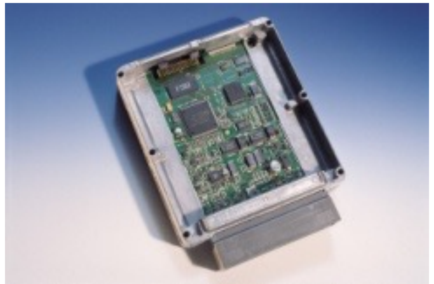
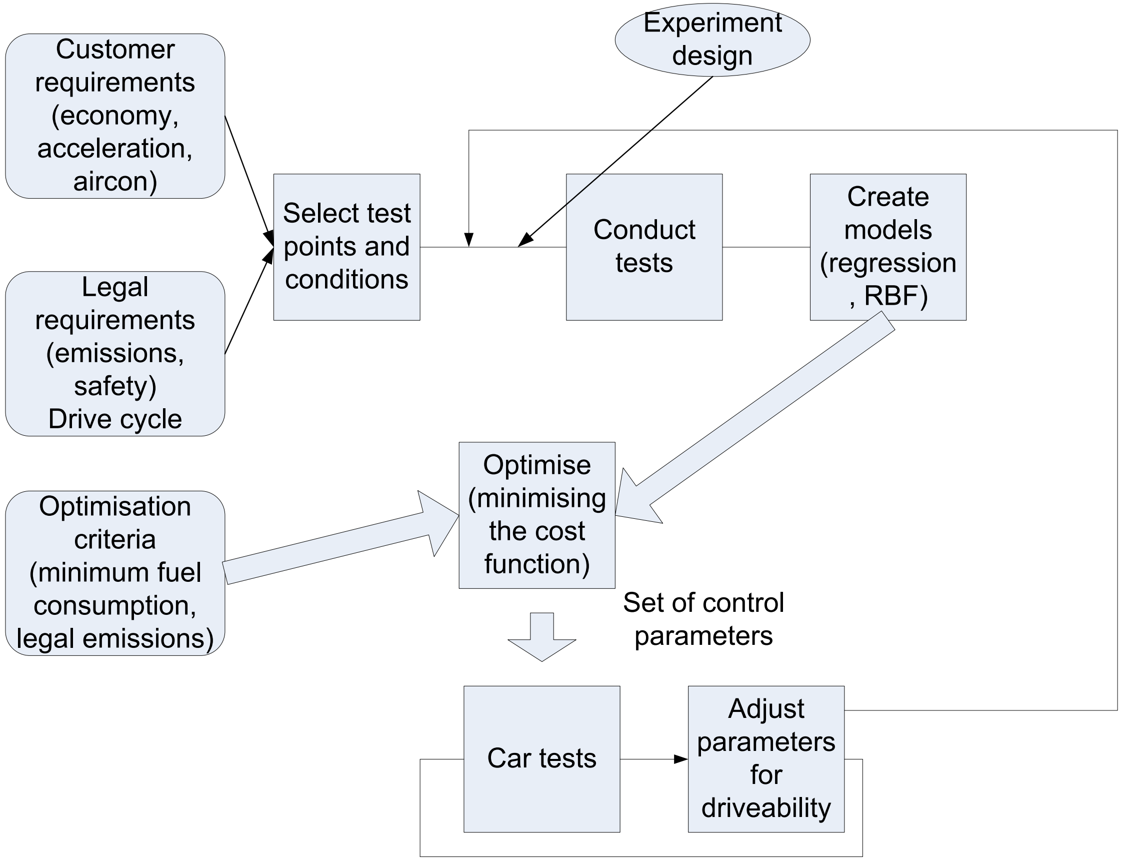


Driveability - delivering the customer appeal

- The job is not complete until the driveability is considered satisfactory
- The focus in this phase of work is transient effects
  - Avoidance of engine knock
  - “Good” delivery of torque
- Driveability is likely to lead to compromise
- Other vehicle level attributes that may require further iteration

Calibration process





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