Powertrain Calibration Optimisation

Optimisation

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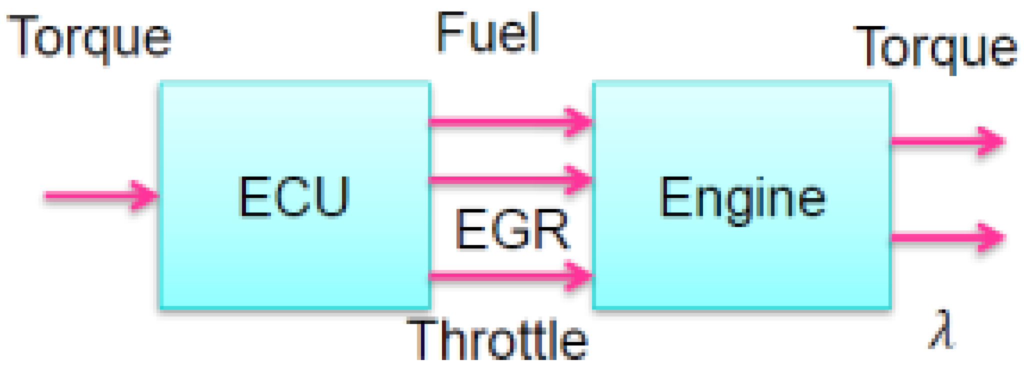
Aim

- Overview of the calibration objectives
- What is optimisation
  - Objective function
  - Algorithm – finding the minimum
  - Constraints
- Pareto curve and the NOx trade-off

Calibration Goal: Model Inversion

- Access the desired reference via
  - Inversion of the static non-linear model
  - Inversion of the dynamic model
  - Or control



Obtain the desired torque

Multi-objective Optimisation

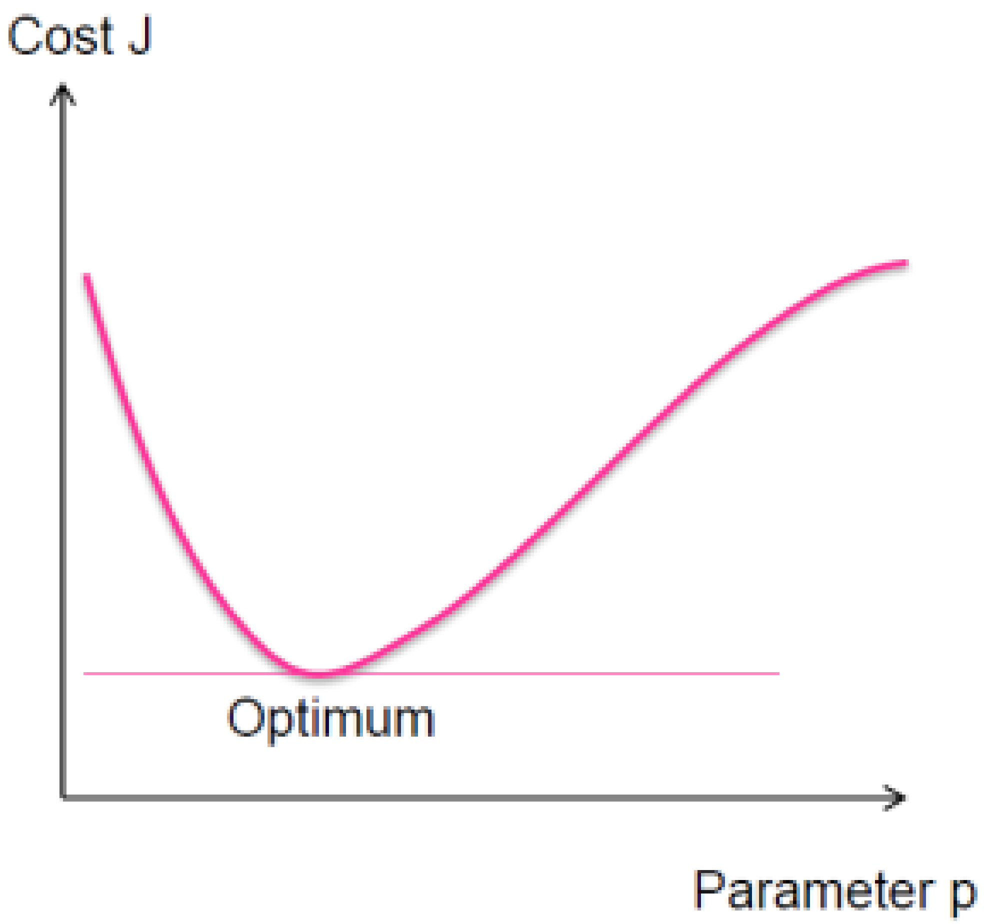
- Model all the relevant factor – responses
  - Fuel consumption
  - Emissions
  - Driveability

Create a weighted cost function:

$$J = \alpha J_{fuel} + \beta J_{emissions} + \ldots$$

Optimisation

- Use an algorithm to find the best compromise - the lowest total cost.
- Lots of dimensions to consider
- How to find this?



Limits

- Physical limits
  - Cylinder pressure
  - Fuel flow
  - Valve range
  - VGT range
- Legal limits
  - Emissions
  - Power
  - Noise

Limits

- Limits are difficult.
- Hard limits;
  - Constraints (equality or inequality)
- Soft limits
  - Cost penalty

→ Handling differs by algorithm and tool.

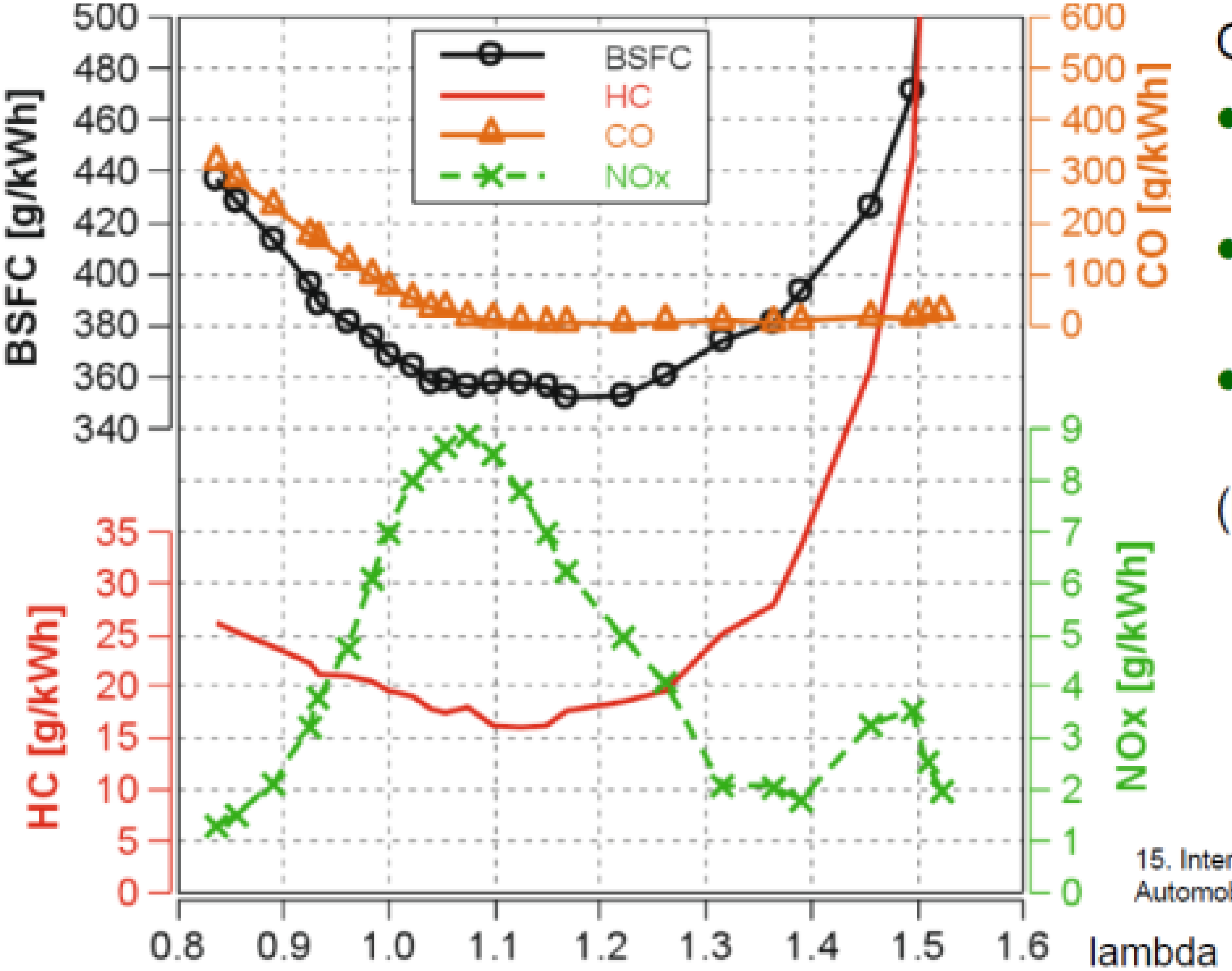
Optimisation with weighted Objectives

- Optimisation is the process of finding the best combination of controls (setpoints and gains) to meet a specified task.
- In an optimisation process a cost function is formulated and minimised.
- The cost function contains quantities to be minimised.
- The **weighting** is essential

$$\min_{p \in P} J(p) \text{ with } J = \sum_i \alpha_i f_i(p)$$

- f_1 may be a measure of fuel consumption
- f_2 may be a measure of NOx emissions etc
- p is the decision variable (a vector)

Engine Model



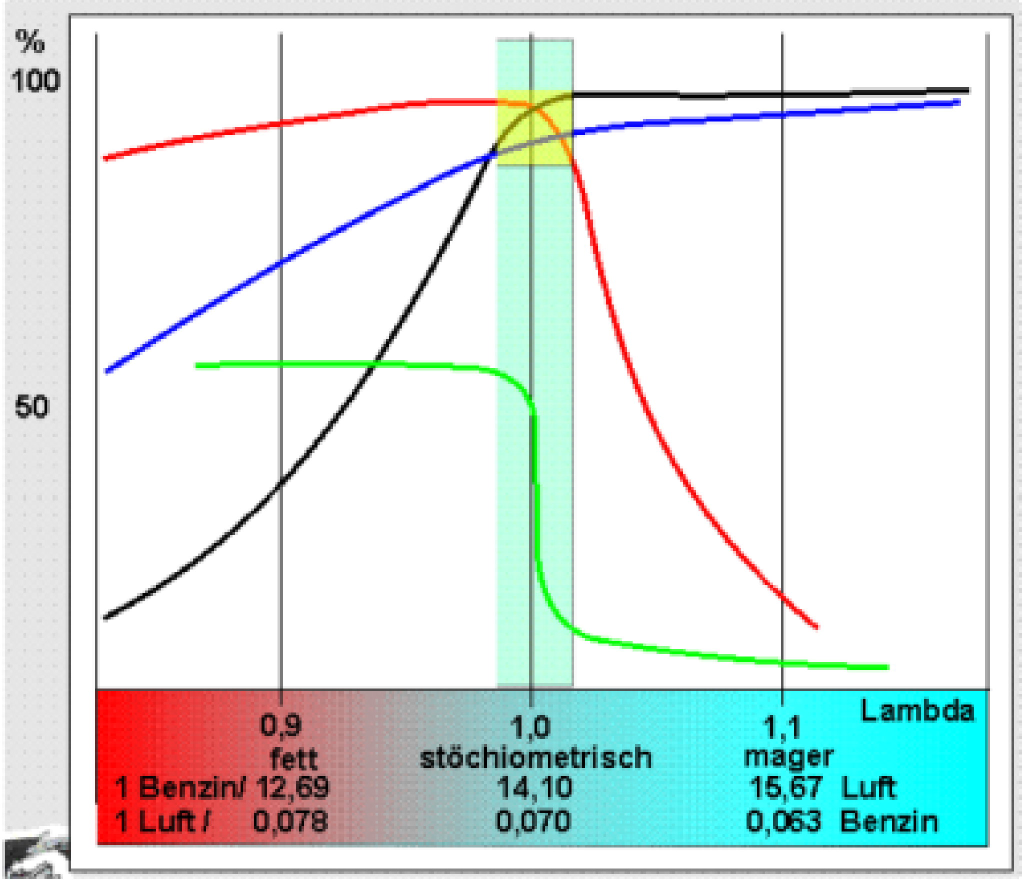
15. Internationales Stuttgarter Symposium: Automobil- und Motorentechnik, p252

Observations:

- BSFC is convex, min at 1.2
- CO is convex, min at 1.1
- NOx is bimodal, max at 1.1

(but mind the TWC)

Catalyst Performance

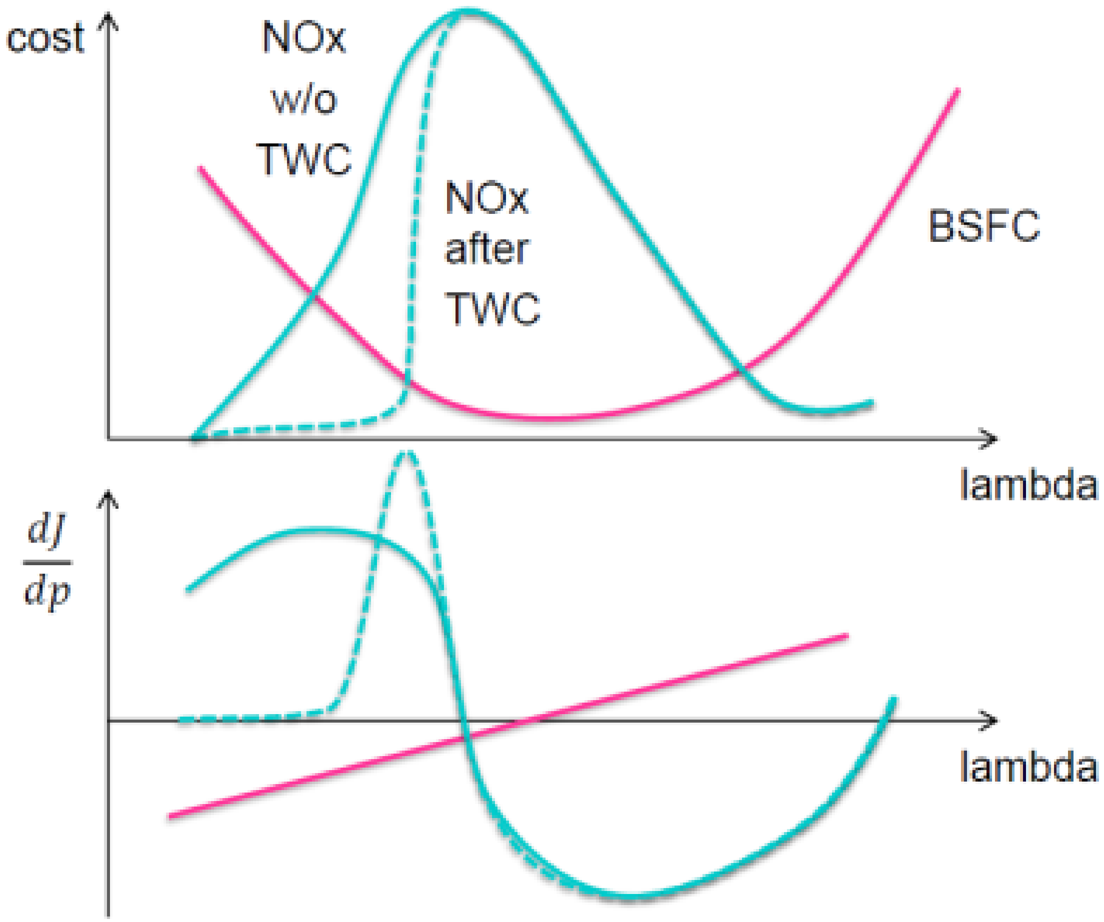


Observations:

- HC conversion from 1.0
- NOx conversion up to 1.0
- Very narrow operating window

http://www.powerboxer.de/auspuff/29-lambdasonde-und-kat

Finding the Optimum



Critical point:

$$\frac{dJ}{dp} = 0$$

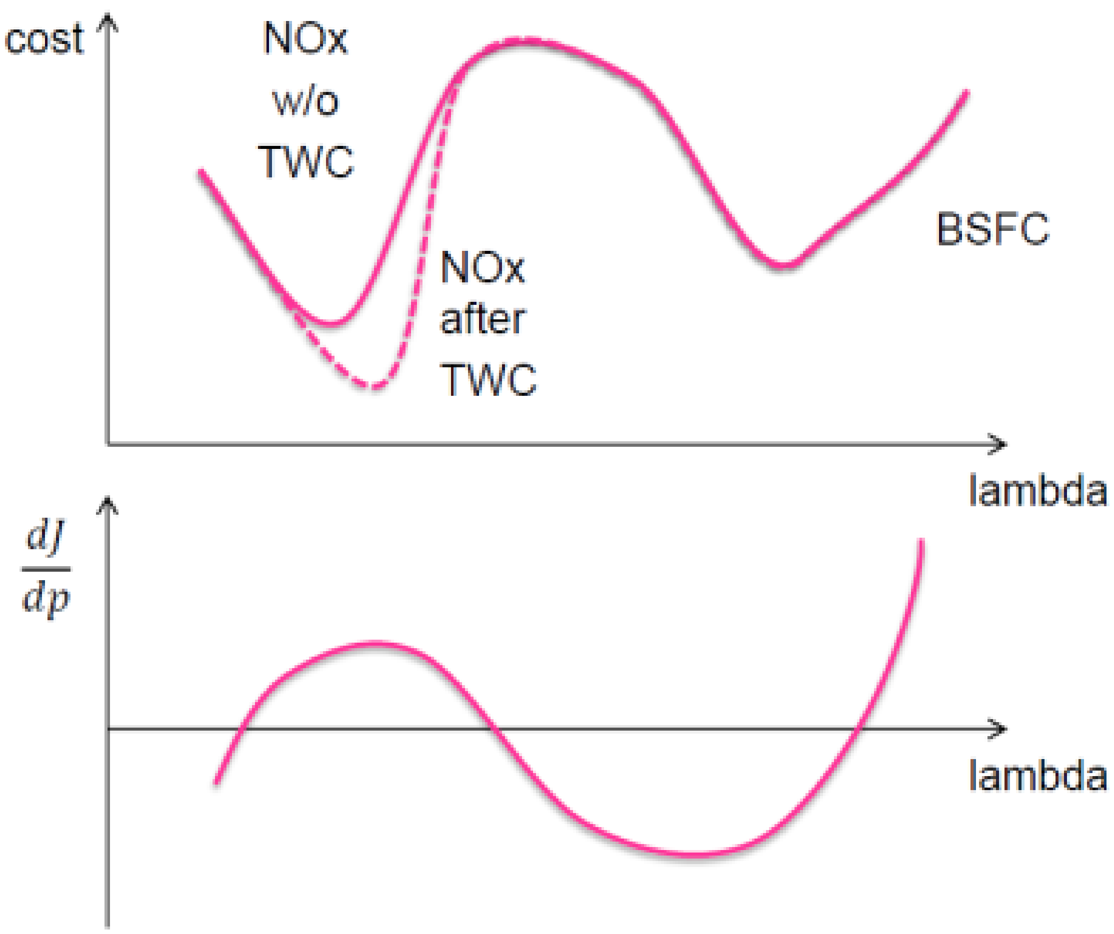
Or

$$\alpha_1 \frac{dJ_1}{dp} + \alpha_2 \frac{dJ_2}{dp} = 0$$

BSFC is:

- Convex
- → One optimum
- → Easy to solve

Finding the Optimum



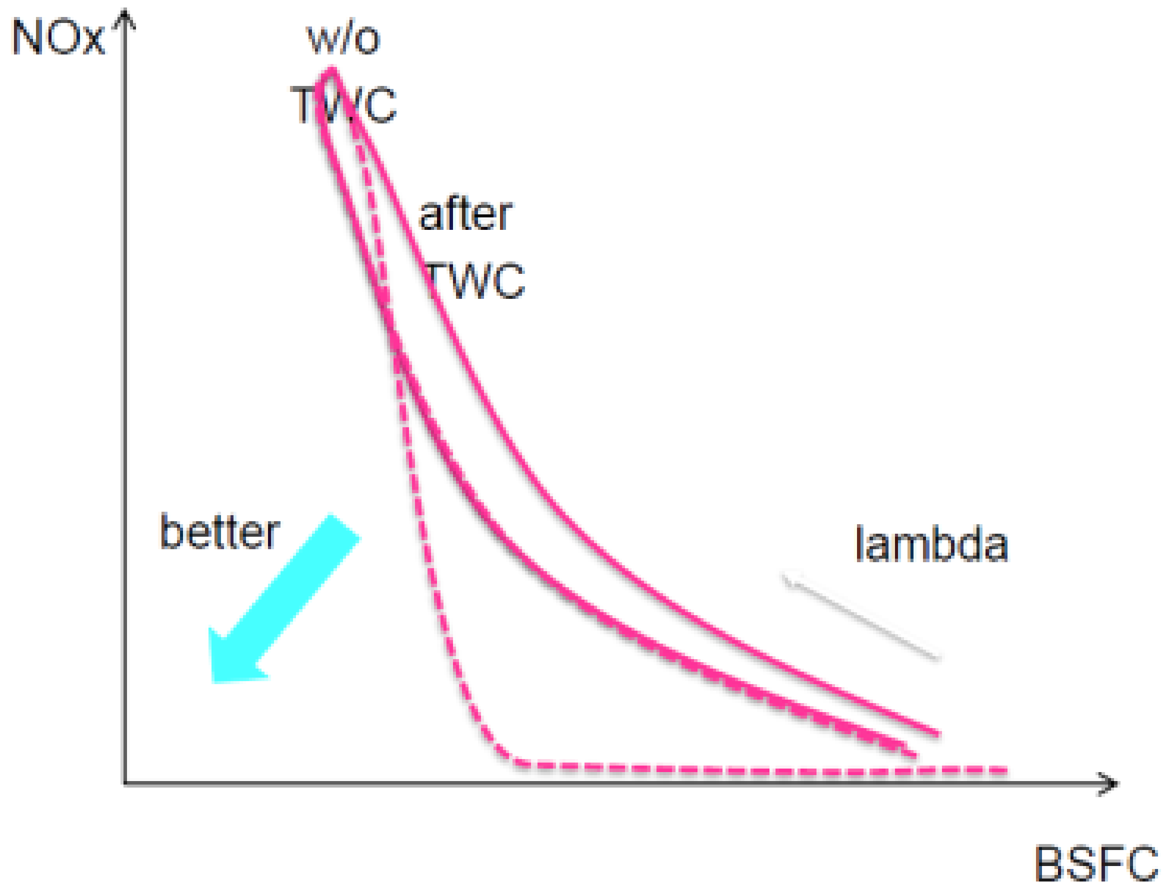
Total cost is:

- Bimodal
- Not convex
- Has a maximum

Derivative shows

- Sign reversal
- Three roots

Pareto Curve



Shows the trade-off

Slope corresponding to the ratio of weights defines the optimum

Disadvantage:

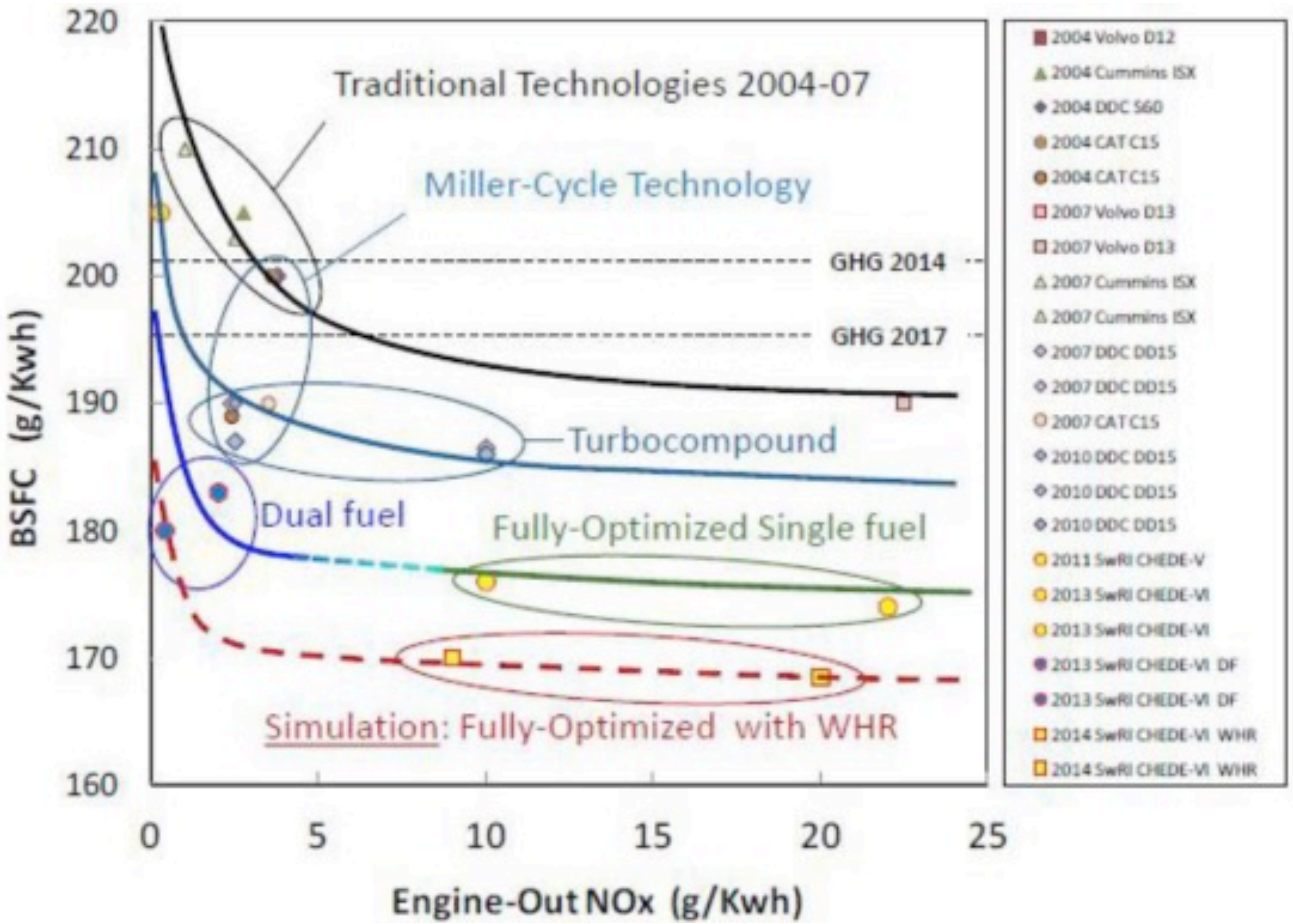
lambda is not visible

Conclusion:

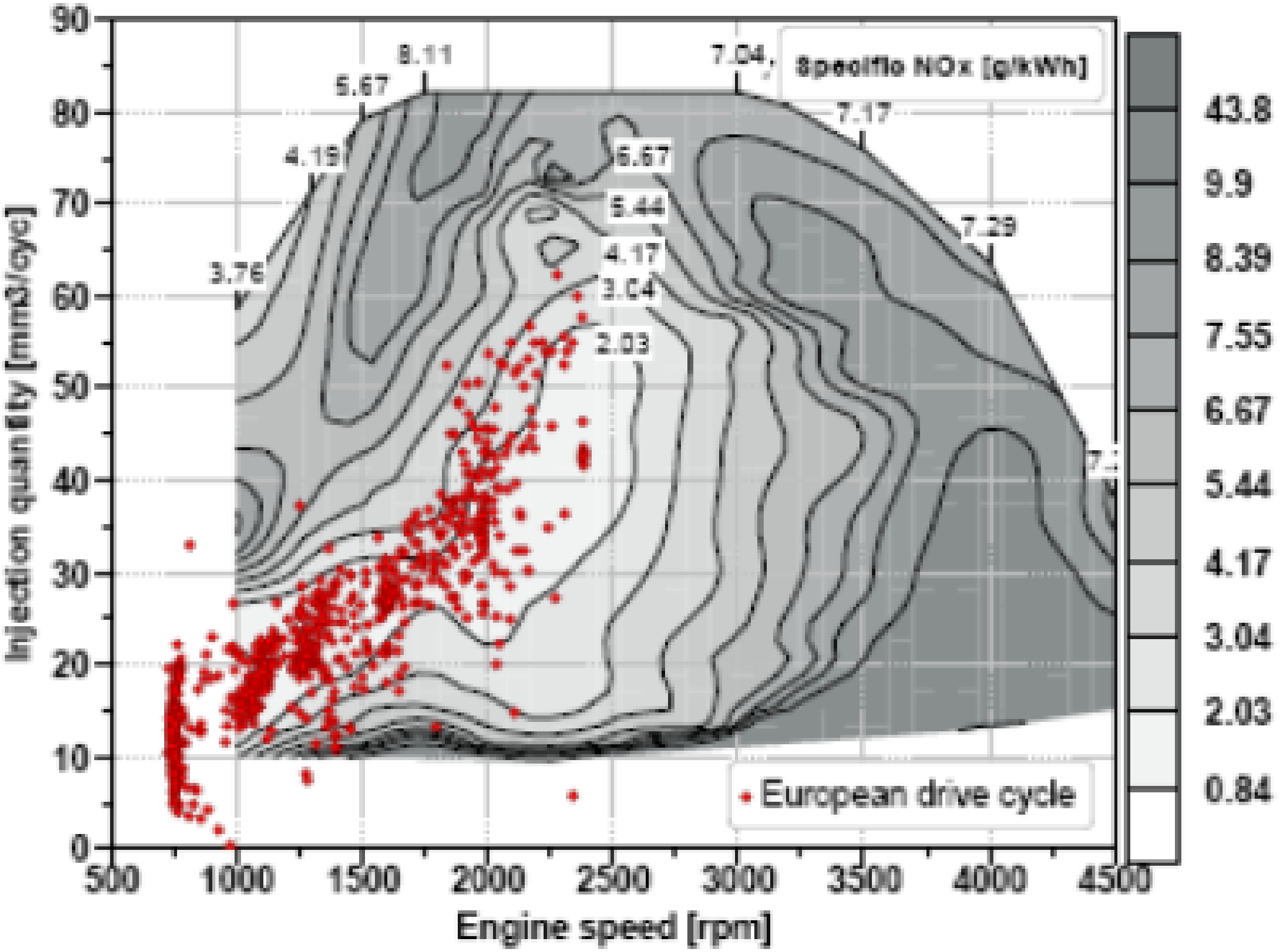
With TWC, lambda=0.99.

W/o TWC: lambda≈1.2

NOx Trade-off (CI)



Typical Calibration Results: NOx



Emissions are

- good on the NEDC
- bad elsewhere

Note the scale!

Case Study

- Dynamic Optimisation of Split Injection to minimise fuel consumption and PN simultaneously.
- Note: these are competing objectives and reduction of one will lead to an increase of another. Why?

Data Collection and Pre-Processing

Advanced Controls and Dynamic Optimisation Test Facility

Fully transient AVL Puma, dSPACE rapid protyping, ATI Vision and MATLAB test automation

Cutting edge equipment:

Sentronics Flowsonic Ultrasonic fuel flow meter

(Measurement rate: 2.2 kHz)

AVL Flowsonix Air Mass Flow meter

(Measurement rate: 100Hz)

Cambustion NDIR500 (CO, CO2)

(T90-10%: 8ms)

Cambustion HFR500 (HC)

(T90-10%: 0.9ms)

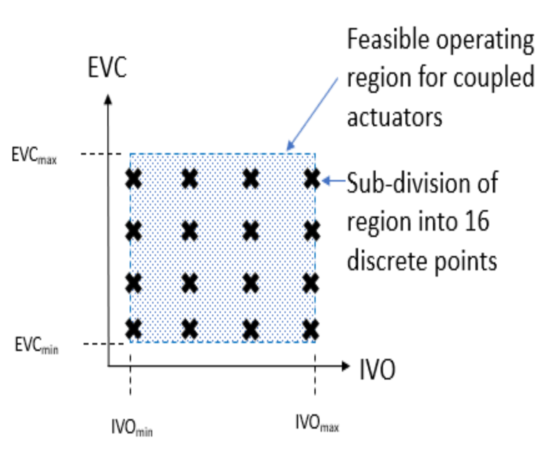
Cambustion DMS500 (PN)

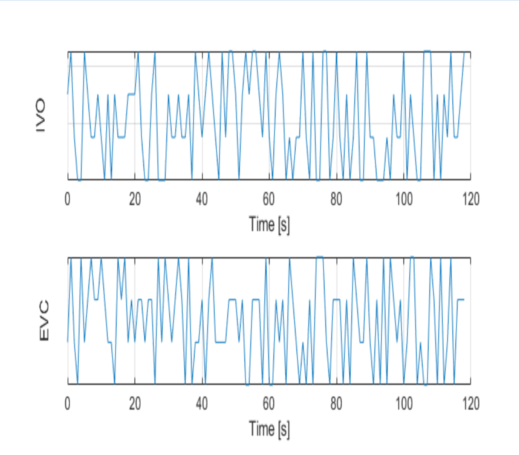
Excitation Signal Design (ESD)

Design approach to guarantee coverage of VCT system operating range at each point in a transient

Design of VCT (IVO, EVC) excitation signals:

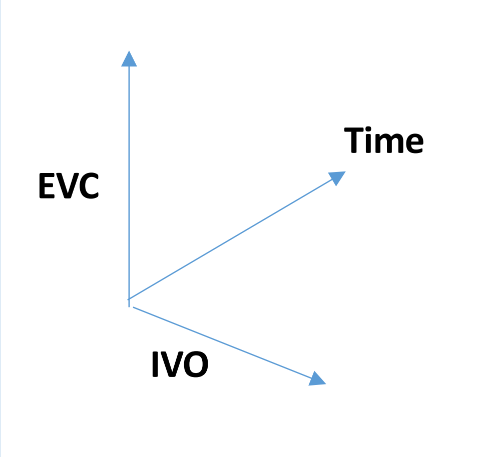
- Designed to cover the VVT system range of actuation.
- 16 discrete (IVO, EVC) points translated into time-based excitation signals:

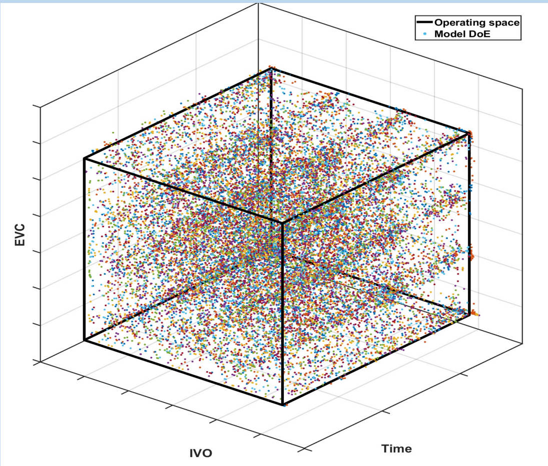




Design of VCT (IVO, EVC) excitation signals

- At each point in time the full VVT actuator space is explored.
- This is very important to ***minimise extrapolation*** of the NF model.

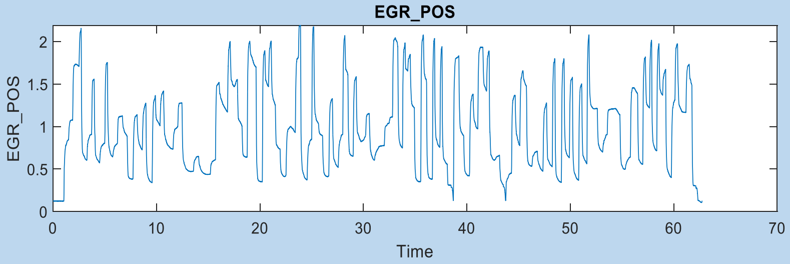




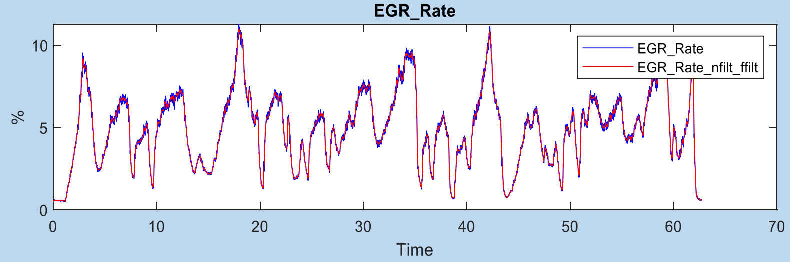
Data Collection and Pre-Processing

e.g. NF modelling of EGR system mass flow
EGR orifice delta pressure requires processing to removed engine fundamental frequency components…

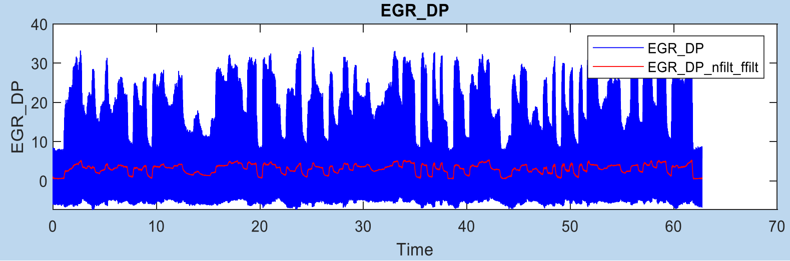
EGR valve excitation: amplitude modulated random binary sequence (AMRB)



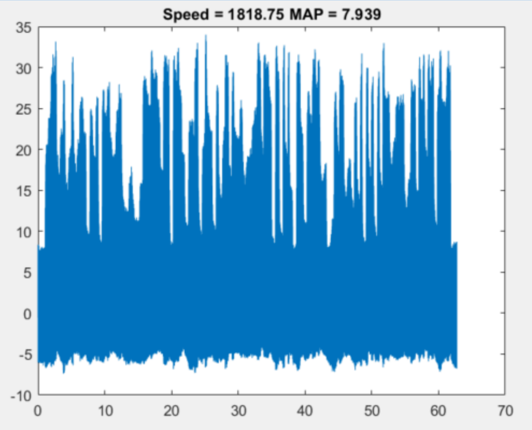
Cambustion NDIR500 fast CO_2 analyser measured EGR rate



EGR orifice raw and processed delta-pressure **(sampled at 1kHz)**

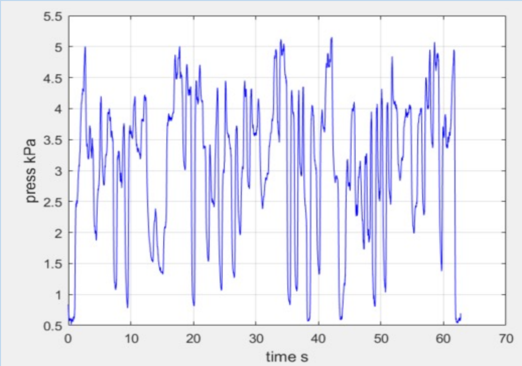


Pre processing of EGR orifice delta pressure:



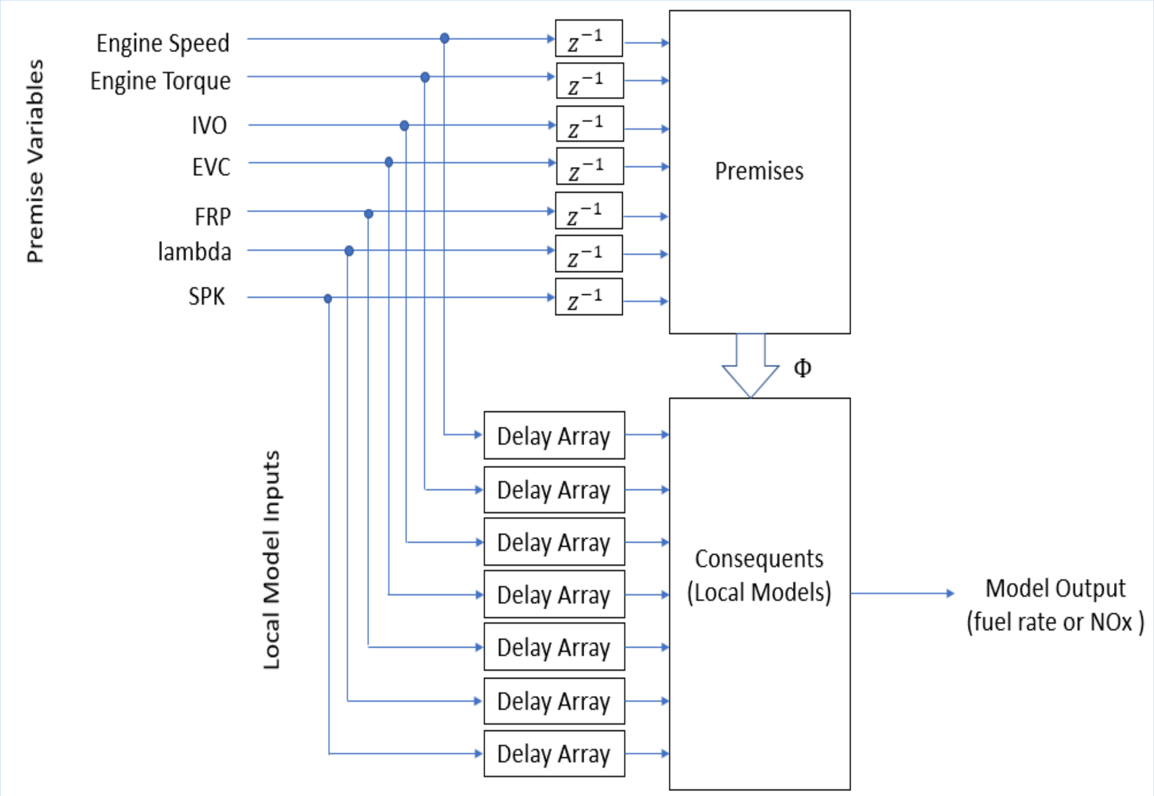
Filtering to remove engine fundamental frequencies to extract EGR orifice delta pressure signal for NF model training…

e.g. EGR orifice delta pressure with EGR valve AMPRB excitation:



Model Training

Model Structure Determination

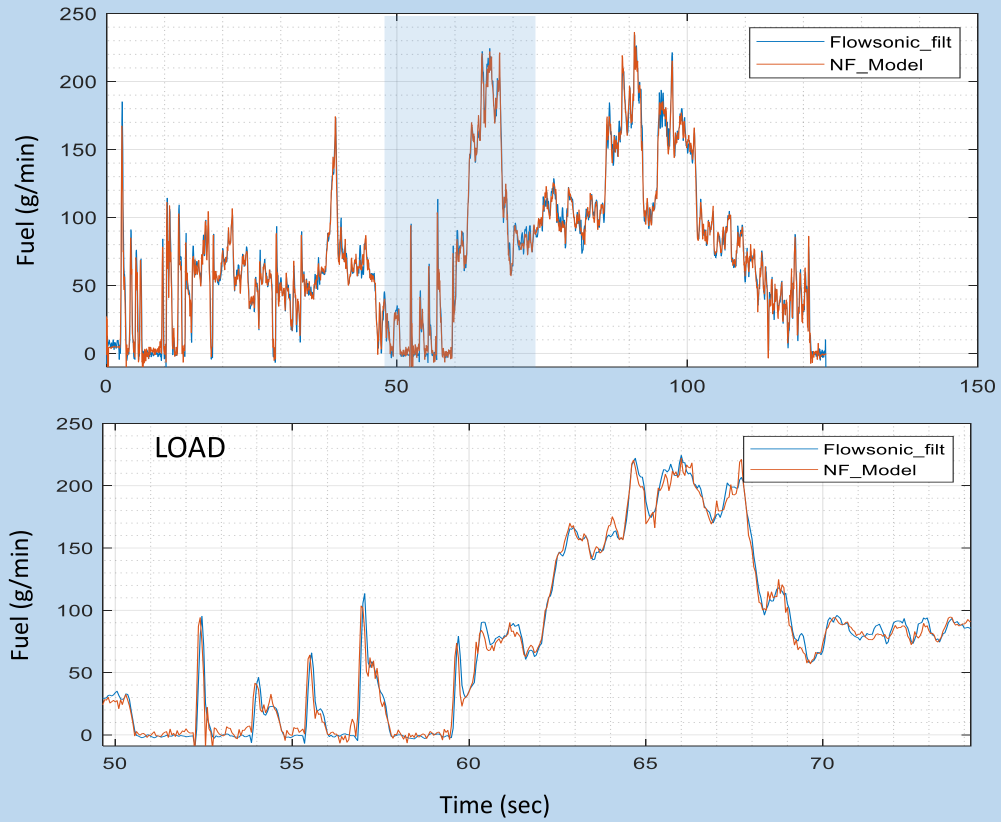


Model Training

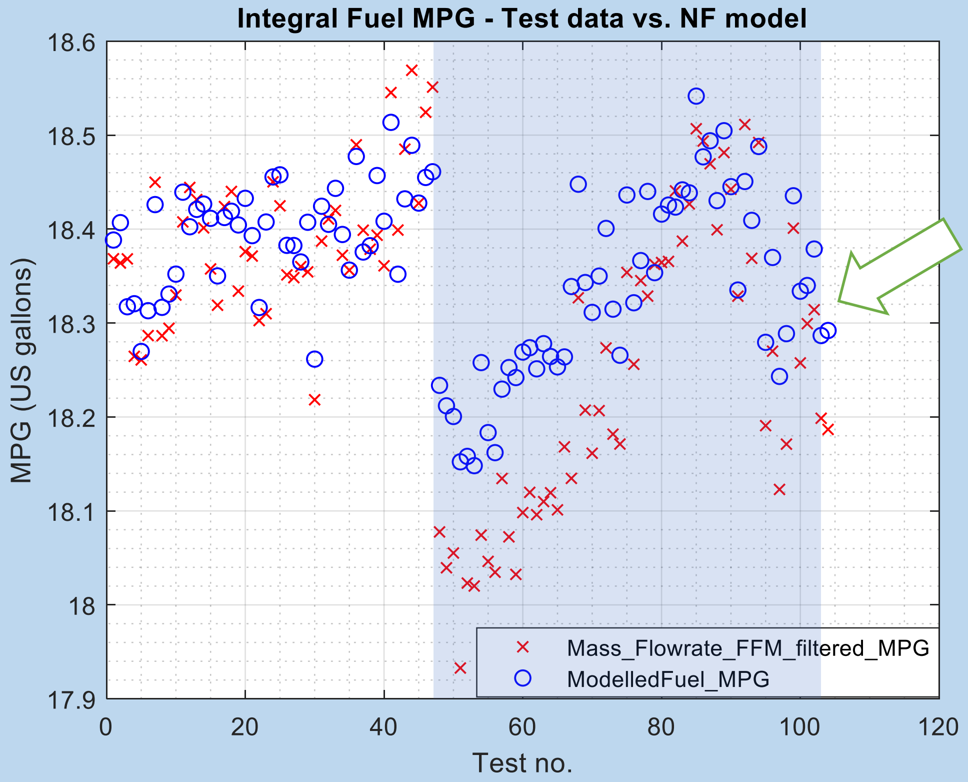
- Model input selection informed by prior screening study using DOE techniques.
- Developed own tools to identify model inputs from excitation data.
- Training feasible on a laptop: 1min – 2 hrs per model.

Model Validation

Neuro Fuzzy (NF) Fuel Model Performance (time based results)



NF Model Validation VCT Distance Sweep (integrated results)



Validation:
% error is **-1% to +0.5%.**

This is a measure of the model accuracy for a sweep of the key optimisation decision variable.

Application: Split Injection Optimisation

Objective Function:

$$\min \int_{1}^{T/t_s} f_{fuel}(k), \int_{1}^{T/t_s} f_{PN}(k)$$

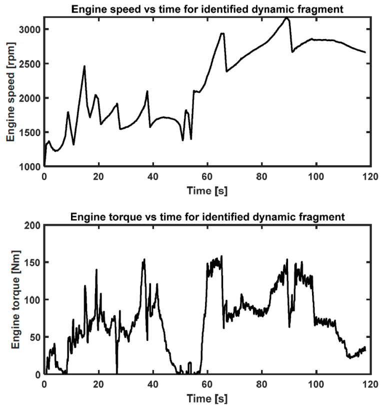
Decision Variables:

- **SOI** (start of injection)
- **FRP** (Fuel rail pressure)
- **Number of Injections** per cycle

Architecture

>300,000 different calibrations evaluated in 4 hours

Driving cycle



Speed

Torque

Engine Controller

- **SOI**
- **FRP**
- **Number of Injections**
- *+ spark & VCT*

Control signal

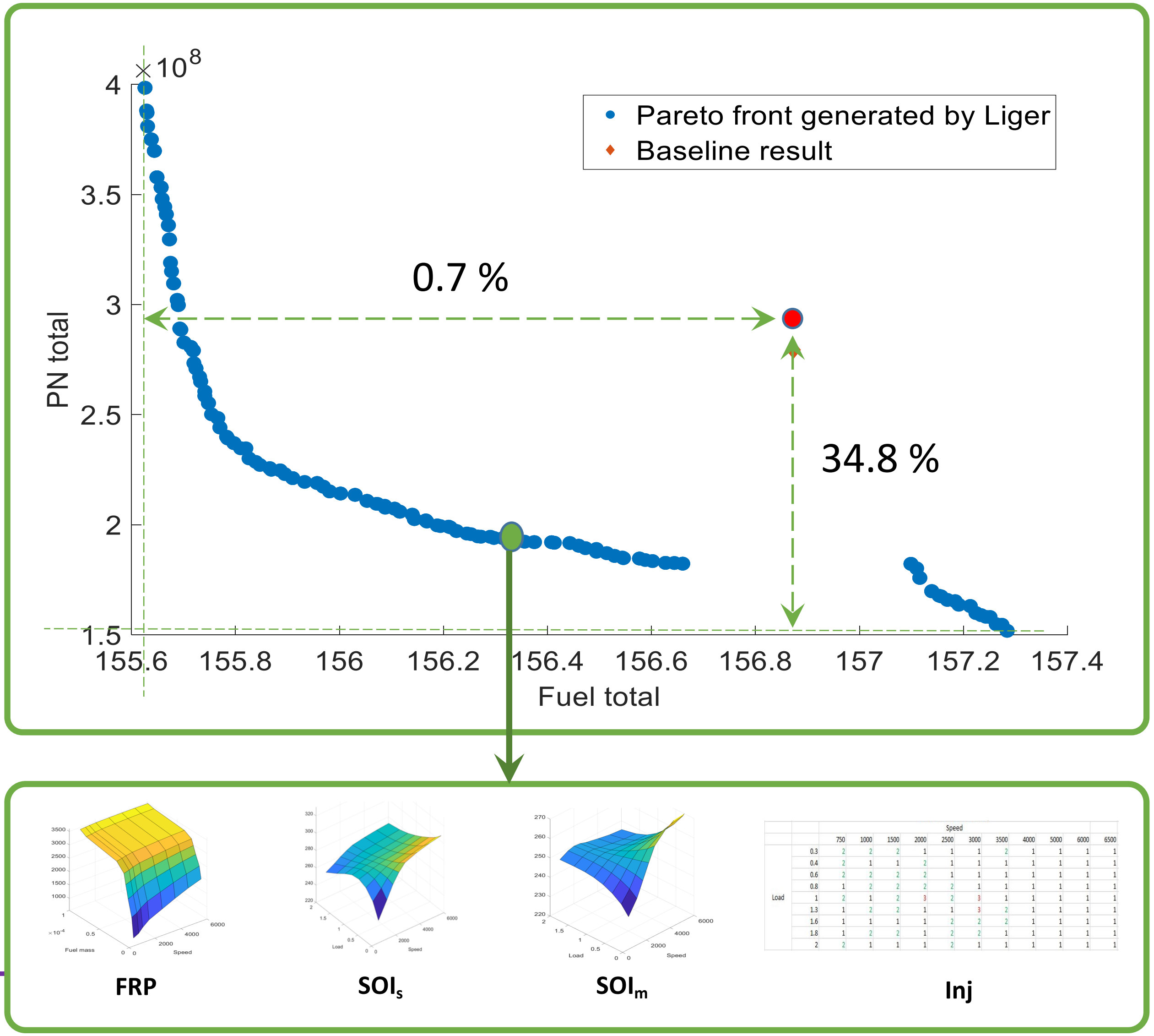
Engine Model (Neuro-Fuzzy models)

f_{fuel} → **Fuel consumption rate** [g/min]

f_{PN} → **Particulate Number** [N/cc]

Application: Split Injection Optimal Solutions

- Optimisation results show possible reduction of up to (baseline result);
  - 34.8 % cumulative PN
  - 0.7 % cumulative Fuel Consumption
- The above are not simultaneously achievable
- Models validated
- Calibration maps generated by optimisation
- Significantly less time taken



Conclusion

- Calibration is the structured selection of parameters
- Optimising a cost function vs finding a compromise
- For all environmental conditions / speed / load
- Software support is essential and available
- Parameters have to be considered together.