Loughborough University

Engine Testing & Calibration

Byron Mason
Ed Winward

Summary

- Why do we need engine testing?
- Types of engine testing
- Test Infrastructure
- Measurement Techniques
- Data Collection and Data Processing
- Repeatability
- Calibration Software

Why do we need engine testing?

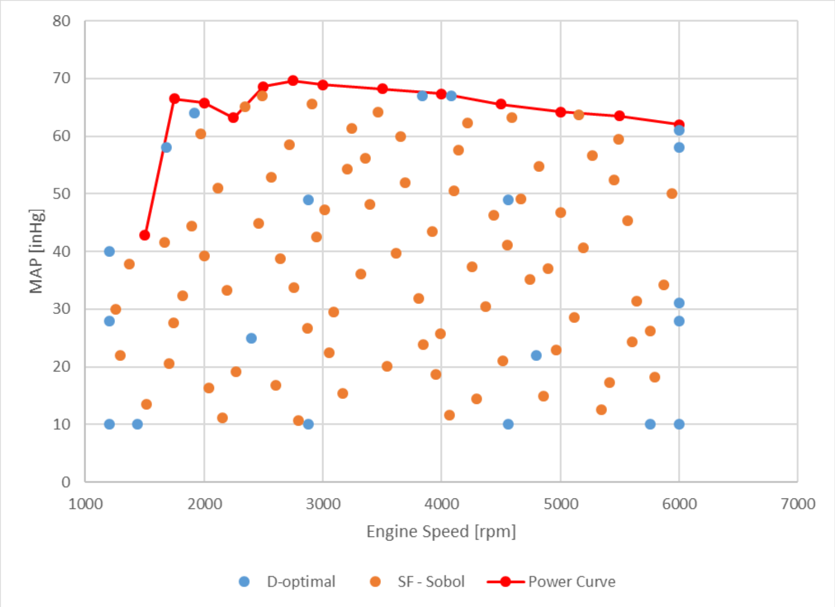
- We can't model all the complexities of an ICE engine sufficiently over all the operating range and over all operating conditions to be able to rely on modelling alone.
- We need to confirm durability and life cycle predictions.
- We sometimes need to collect data to build engine models *e.g. data driven models*.
- We need to **validate** the models we develop.
- Certification.

Types of Engine Testing

1). Steady-State Engine Testing:

- Sequence of engine speed and load (torque) points - sometimes may use Intake Manifold Air Pressure (MAP) rather than load.
- Engine is held at each point for a prescribed amount of time **to first stabilise the engine thermally (5-10 min)**.
- At the end of the stabilisation, a steady-state measurement is taken (typically a 1 minute measurement in which each recorded channel is averaged over the one minute).
- OEMs have different steady-state tests for different purposes e.g. daily checks, durability, mapping (calibration).
- **Examples** of steady-state test names used by OEMs 'array test', 'modal test', 'mini-map point test'.

Steady State: e.g. speed-MAP points for a Design of Experiments (DOE)

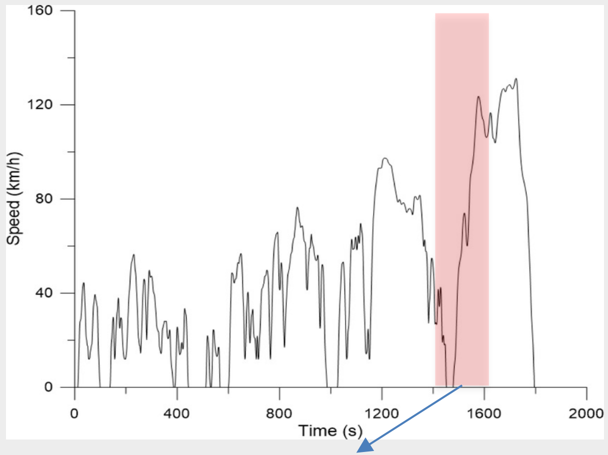


Types of Engine Testing

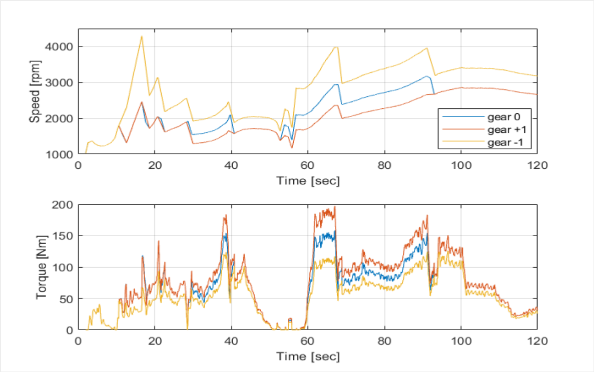
2). Transient Engine Testing:

- Usually a speed-load (torque) sequence vs time which the engine is tested over.
- Requires a transient capable dynamometer to precisely absorb large changes in engine load over short time periods (e.g. 100s ms) and also motor the engine in some cases.
- **Examples of official transient cycles**:
    - **NEDC** – New European Driving Cycle
    - **WLTP** - Worldwide Harmonised Light Vehicle Test Procedure
    - **NRTC** – Non Road Transient Cycle

WLTP: Vehicle speed vs. time



Engine Speed and Torque for this section (different gear profiles)



Engineer Roles in Industry & University

- **Test Engineer** – Design and specify the engine tests, analyse data, report findings.

- **Facilities Engineer** – Oversees the test cell facility and mange the infrastructure
  - Mechanical – Design and spec. prop shafts, mounting, valves, heat rejection etc.
  - Electrical – Engine loom interfacing, power supplies, hybrid systems etc.

- **Instrumentation Engineer** – Temps, Pres., Emissions, cylinder pressure etc.

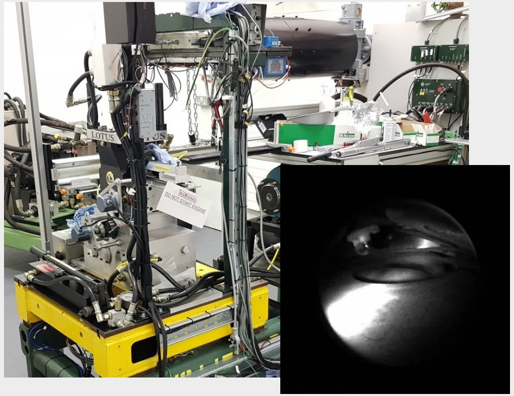
- **Research Engineer** – Multi-disciplinary, system requirement setting, component/test system design, system build, software development, system testing, result analysis etc.

Examples of Engine Test Cells

Example: 8 Test Cells at Loughborough University which are focussed on industry supporting research and teaching:

Single Cylinder Research Engines

- Lotus optical engine with fully variable valve train (fuel spray and combustion imaging).
- AVL diesel research engine (Low Temp. combustion, fuels).

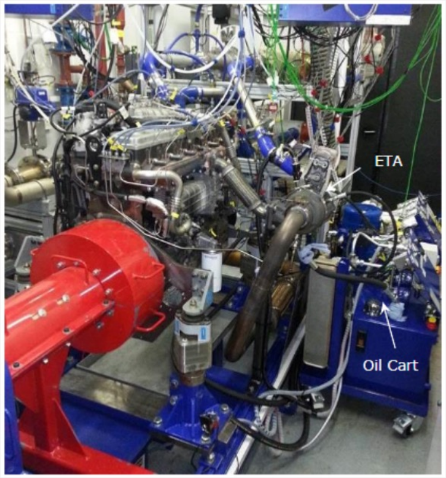


Light Duty SI Engines

- Ford 1.0L Eco Boost optical engine.
- Ford 1.0L Eco Boost advanced controls and optimisation engine.

Medium Duty Diesel Engines

- Cat C4.4 diesel optical engine.
- Cat C7.1 diesel engine equipped with electric turbocharger.

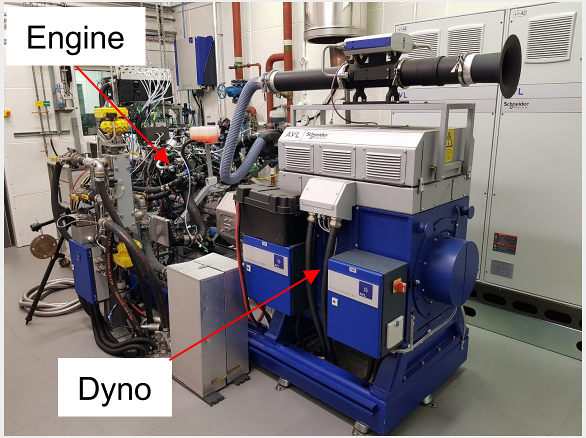


Basic Engine Test Infrastructure

Test Cells incorporate a variety of specialised equipment:

- Dynamometer ‘Dyno’
- Test Cell Management/Control System
- Heat Rejection Management
- Fuel Supply, Conditioning, Metering
- Ventilation System
- Exhaust Extraction
- Shop Air
- Instrumentation
- Specialist equipment (e.g. emissions analysers)

Example: L’boro Test Cell 7



Emissions Measurement - Gaseous

- CO, CO2 (intake & exhaust), NO, NO_2, NOx, HC, O_2, AFR.
- Uses: Aftertreatment development, EGR measurement.
- Accuracy, reliability, robustness are very important.
- Large rack mount benches have been the industry standard.
- These are modular and can be configured as required.
- Heated lines, pre-filtering, individual analysers for each gas.
- Calibration gases (gas bottle racks required to calibrate).
- Ease of maintenance: Complex units and OEM's will typically will have a service contract with the supplier.

- **Response times**: traditional emissions benches typically slow response times **(e.g. 1-5 …+ sec)** which means they **provide only partial insight in fast transients!**

https://www.horiba.com/en_en/products/detail/action/show/Product/mexa-one-41/

Examples:

- Horiba MEXA-ONE System (or the older 7000 series)
- AVL AMA i60

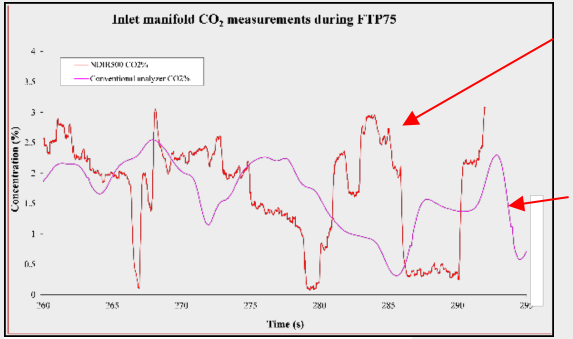
Emissions Measurement - Gaseous

Fast Emissions Measurement:

Fast e.g.:
- ECM 5210 NOx sensor **(200ms)**
  - We use for transient engine out NOx measurement
- ECM 5230 % EGR Measurement System **(<1 sec)**

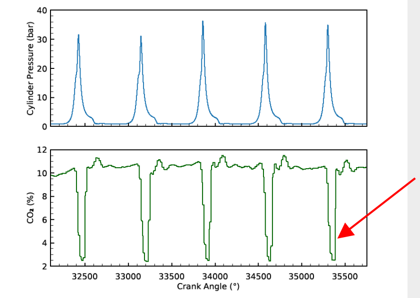
Ultra-Fast e.g.:
- Cambustion NDIR Fast CO/CO2 **(T_{90-10} 8ms)**
  - We use for Fast EGR measurement for EGR system characterisation.
- Cambustion CLD500 Fast NOx Analyser **(T_{90-10} 2ms)**
  - We use to optimise engine out NOx during transients.

Cambustion Fast NDIR Co & CO2 Analyser



Cambustion NDIR

Conventional analyser (e.g. Horiba Mexa)



Cambustion NDIR is fast enough to resolve the CO2 residual in cylinder during a cycle at low engine speeds!

Emissions Measurement - Particulates

Examples of Common Specialised Engine Particulate Measurement Systems:

AVL 415S Smoke Meter

- Soot Concentration: FSN or mg/m^3
- Based on filter paper method.
- Good reproducibility.
- Steady-state measurements.
- **Single measurement requires several seconds.**
- Large and light duty engines.

AVL 483 Micro Soot

- Soot Concentration: mg/m^3
- Photo-acoustic principle.
- High sensitivity (0.01µg/m^3 , large measurement range (engine out or tailpipe).
- Designed for transient.
- **$T_{90\text{-}10}$ ~1000ms.**
- Sensitive to soot only (non-volatile PM).

AVL 439 Opacity Meter

- Opacity: %
- Light intensity method.
- **Transient measurements (10Hz).**
- Low maintenance and suited for transient R&D.

Cambustion DMS 500

- Real time measurement of particle size distributions, number and mass
- Ideal for transient PN R&D
- **$T_{10\text{-}90\%}$ 200ms**

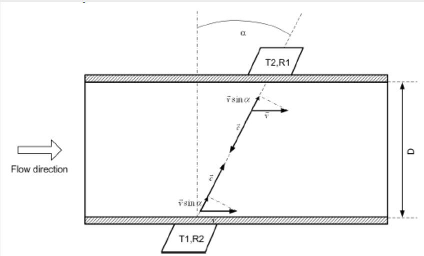
Slow → Fast

Fast Measurements

- Fast measurement devices are increasingly in use to meet requirements for RDE and WLTP.
- Currently at L'boro we are using these cutting edge devices for dynamic optimisation of GDI engine calibration.

- **Examples**: devices for fast flow measurement:
  - AVL Flowsonix Air-Mass Meter (t_{90} < 10ms)
    - Ultrasonic transit-time differential method
    - Small influence on the ICE due to small pressure drop
    - Measurement uncertainty: +/- 1% of reading, ~ £35k
  - Sentronics FlowSonic LF Fuel Meter (up to 2.2 kHz measurement rate)
    - Developed for F1 and WEC for the FIA
    - Measurement Uncertainty: +/- 0.5% of reading
    - Repeatability +/- 0.15%
    - Compact (~300g) , no moving parts, ~ £10k
  - Horiba EXFM-One Exhaust Mass Flow meter ($t_{10\text{-}90}$ <500ms)
    - Ultrasonic method for measuring exhaust gas flow rates directly from a vehicle or engine, ~ £35k

AVL Flowsonix Air Mass Meter:



Interaction between the speed of sound c and the velocity of flow v accelerates the ultrasonic pulse on one of the paths (in flow direction) and decelerates the pulse on the other

Sentronics FlowSonic LF Fuel Meter

Horiba EXFM-ONE Exh Flow Meter

Measurement: Other

Other measurements which can undertaken:

- Blow-by (flow rate of engine crank case gasses into engine intake)
- Vibration
- Thermal Imaging
- Electrical (power analyser to measure electrical ancillary efficiency)
- Optical in-cylinder
- Oil sample (oil rheology, soot contamination)

Measurement: Calibration of instrumentation

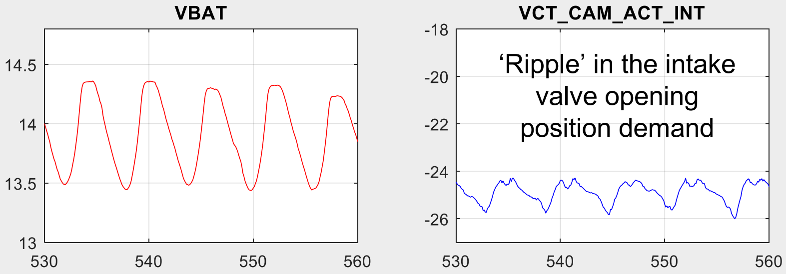
- Calibration of instrumentation and measuring equipment is very important.
- Temperature and pressure sensors can become faulty or drift and it is important to correct before any critical data may be lost or be unusable.
- Frequency of calibration dependent on the instrumentation, the type of use and the purpose of the test.
- Emissions analysers need to be regularly calibrated to ensure accuracy as they can drift due to changes in ambient conditions (e.g. emissions benches can require calibration several times a day to ensure accuracy).

Finally - Details Matter!

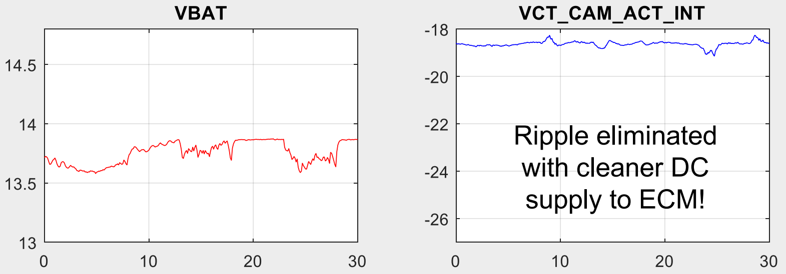
Case Study 1: ECU DC Voltage Fluctuation

- It was found recently when testing an engine at L'boro that the cam control actuators were cycling at a regular frequency.
- Investigation identified that the problem was caused by a fluctuation of the DC voltage of the ECU.
- Traced issue to the charging behaviour of the battery charger used which was causing a DC ripple of ~ 1V.
- Solution was to use the engine alternator to charge the 12V battery which gave a +/- 0.2V DC voltage at the ECM

Before:



After:

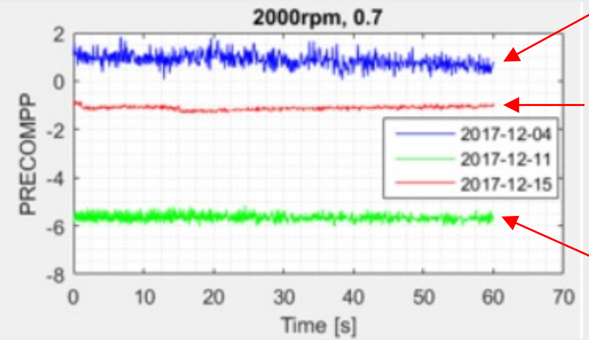


Finally - Details Matter!

Case Study 2: Sensor signal noise problem identification and resolution:

- High frequency noise observed on some instrumentation channels which was traced to a switched mode power supply powering the pressure sensors.
- Supply voltage from the power supply contaminated with high frequency noise.
- Changed to high quality laboratory linear power supply.
- **Benefit**: avoided resorting to low-pass signal filtering which would be detrimental as it adds a time delay to the signal and would remove some of the signal dynamics which may be important.

Example: Turbocharger compressor inlet pressure signal clean-up (N.B. different engine operating conditions):



Original pressure transducer signal.

Final cleaned-up signal (no filtering used!).

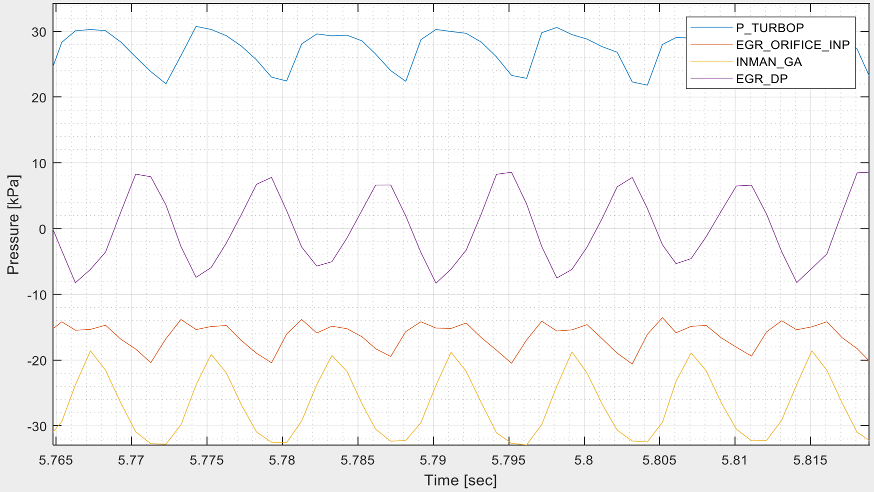
Intermediate stage signal clean-up.

Data Collection

Steady-State Testing:

- In steady-state testing data can often (but not always!) be time-averaged either by the test system when making a measurement or done in post processing e.g. over 60 sec – 'a Measurement'.
- Sample rates can often be **1Hz to 10Hz** (but not always!).
- Emphasis is normally on accuracy and repeatability over time rather than precise time alignment of signals.
- Stabilisation time prior to measurement is important in some types of test (typically 5-10 min.)
- **Transport delays**: emissions apparatus will have a transport delay (time for sample to reach detector and for the instrument to give a reading) and this can often be ignored in steady-state testing.

Example: EGR System Pressure Measurement at 5000rpm, GDI engine (**1Khz sampling**):



Measured period of Intake and Exhaust. pressure: (5000rpm/60)/2 x 3 = 125 cycles per sec => 1/125 = **0.008s**
i.e. measuring the EGR path pressure pulsations

Data Collection

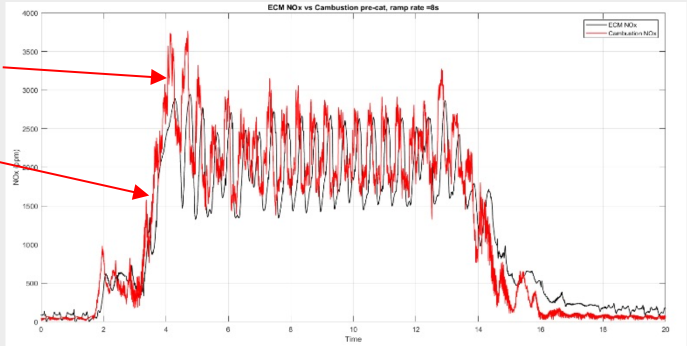
Transient Testing:

- Time synchronisation of measurements is very important for transient testing.
- Potentially measuring signals with **time resolution of 10ms or higher** and which need to be time synchronised e.g. ignition angle, fast emissions, intake and exhaust pressures etc.
- Data acquisition hardware needs to be capable **of synchronised data acquisition.**
- Basics: Nyquist theorem, sample at least twice as fast as fundamental frequency interested in. (use 1Khz sampling to resolve intake/exhaust pressure pulsations).
- **Use of signal filtering needs to be carefully designed as it can introduce delays or remove signal components of interest!!!**
- **Transport delays are important!!!**

0 to 140Nm ramp – pre-catalyst NOx: 8 sec

Cambustion CLD500 Fast NOx Analyser (T90-10 2ms)

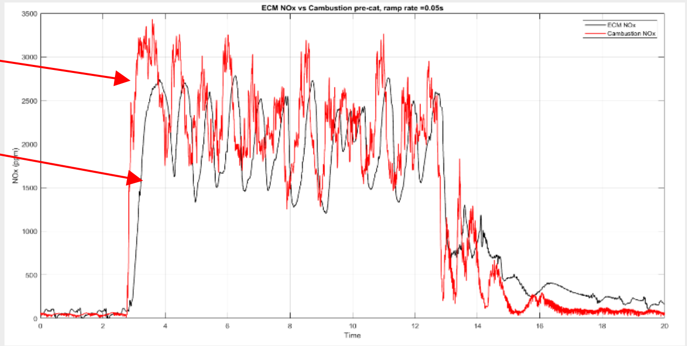
ECM 5210 NOx sensor (T90-10 ~200ms)



0 to 140Nm ramp – pre-catalyst NOx: 0.05 sec

Cambustion CLD500 Fast NOx Analyser (T90-10 2ms)

ECM 5210 NOx sensor (T90-10 ~200ms)



Synchronisation and Data Processing

Different Sample Rates & Files – Synchronisation

- Common (sometimes unavoidable) to have multiple systems recording data at different rates and in different files.
- Data processing approaches which re-sample data are often used to combine such data into a single data set.

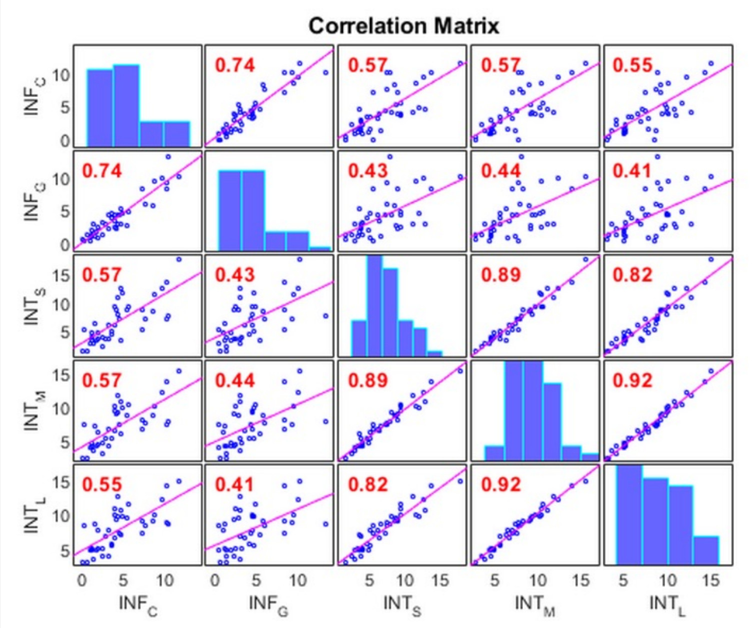
Examples:

- On Test Cell 7 we sample in excess of 600 channels between 1ms to 100ms) and produce single data files 100s MB (several GB a day).
- A single cylinder pressure data file sampled at 0.5 CAD and several hundreds of cycles is 20 MB.
- On Test Cell 8 the imaging camera captures 10,000 frames per sec (roughly 1 GB data per sec).

At Loughborough we largely use **MATLAB** for test engine data post processing:

- Automated scripts to re-sample data and to time-correct data.
- Convert data into TABLE objects enables very convenient data processing tools in MATLAB to be used to quickly plot and analyse large data sets.
- Many useful functions in MATLAB e.g. corrplot(x).

e.g. MATLAB: corrplot(x)



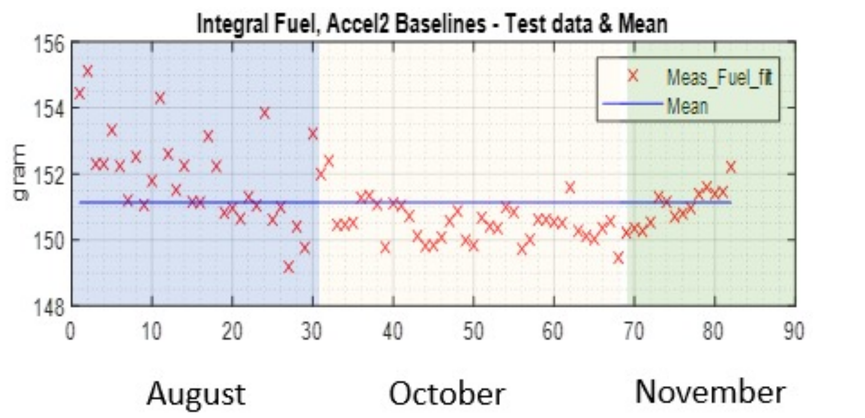
Repeatability

- **Measurement repeatability is very important especially when developing solutions for fuel consumption reduction.**
- **Fuel consumption measurement repeatability to <0.5% is very challenging.**

- Very difficult to achieve good repeatability even in a test cell:
  - Changes in ambient conditions.
  - Changes in instrument calibration over time (drift).
  - Engine performance change over time.
  - Fuel quality consistency, oil viscosity change.

- Try to minimise the number of uncontrolled factors:
  - Closed loop control of engine coolant temp, inter-cooler air out temp, oil cooler temp, fuel supply temp.
  - Adds lots of complexity and cost to system and to tests.

Example: Total fuel consumption (grams) over a 2 minute section of WLTC repeated between August and November 2018 on test cell 7:



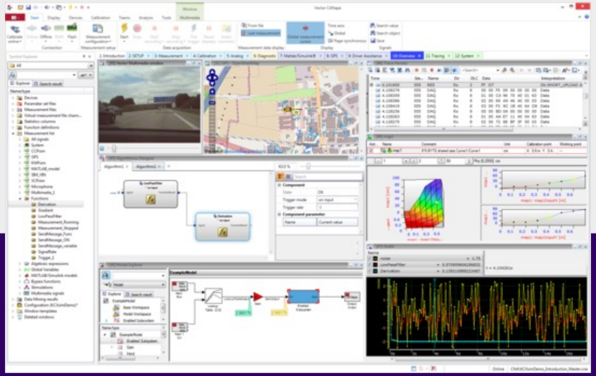
~4g/ 151g = 2.6% change over 4 month period

ECU Calibration Hardware & Software

- ECU calibration requires parameterisation of 100s – 1000s of ECU parameters (scalars and maps).
- One OEM has said that there are >10,000 calibration parameters in their strategy.
- **Several specialist software & hardware systems available:**
  - **ETAS**
  - **ATI Vision**
  - **Vector CANape**
- All provide a very similar interface and OEMs often will use one specific software and have agreements in place with supplier.
- Communication with ECU: usually **CAN, XCP etc**.
- These systems also provide additional useful features:
  - APIs to external software (e.g. MATLAB) – enables external application integration e.g. MATLAB scripts.
  - External hardware modules for data acquisition (e.g. CSM modules).
  - Rapid prototyping environment for deployment of prototype controls to the engine (can compile Simulink models to run within ATI vision and CANape).

ATI Vision

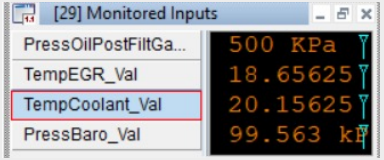
Vector CANape



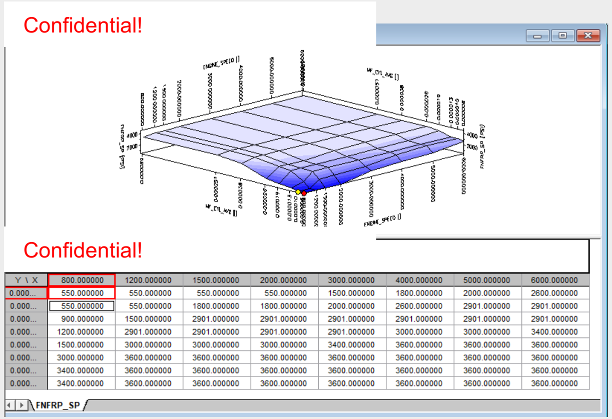
ECU Calibration Hardware & Software

- Software such as ATI Vision and Vector CANape have similar functionality and interface elements for interaction with ECUs:

Scalars: e.g. ECU reported sensor signals values (CANape):

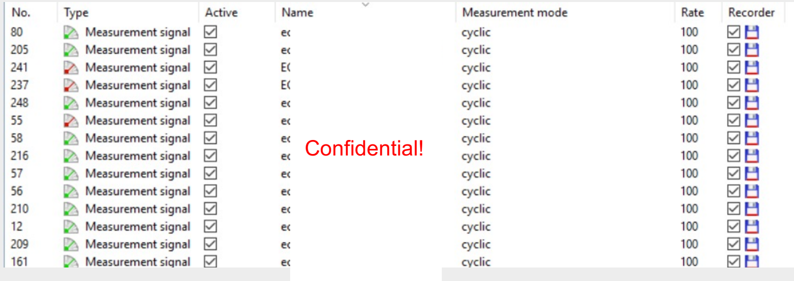


Maps: Calibration map view and editing (ATI Vision):



Y \ X	800.000000	1200.000000	1500.000000	2000.000000	3000.000000	4000.000000	5000.000000	6000.000000
0.000...	550.000000	550.000000	550.000000	550.000000	1500.000000	1800.000000	2000.000000	2600.000000
0.000...	550.000000	550.000000	1800.000000	1800.000000	2000.000000	2600.000000	2901.000000	2901.000000
0.000...	900.000000	1500.000000	2901.000000	2901.000000	2901.000000	2901.000000	2901.000000	2901.000000
0.000...	1200.000000	2901.000000	2901.000000	2901.000000	2901.000000	3000.000000	3000.000000	3400.000000
0.000...	1500.000000	3000.000000	3000.000000	3000.000000	3400.000000	3600.000000	3600.000000	3600.000000
0.000...	3000.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000
0.000...	3400.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000
0.000...	3400.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000	3600.000000

Measurement signals: which can be ECU based sensor signals, ECU estimators (e.g. engine torque), ECU control system parameters, ECU diagnostic parameters etc. (CANape):



No.	Type	Active	Name	Measurement mode	Rate	Recorder
80	Measurement signal	☑	ec	cyclic	100	☑
205	Measurement signal	☑	ec	cyclic	100	☑
241	Measurement signal	☑	E(	cyclic	100	☑
237	Measurement signal	☑	E(	cyclic	100	☑
248	Measurement signal	☑	ec	cyclic	100	☑
55	Measurement signal	☑	ec	cyclic	100	☑
58	Measurement signal	☑	ec	cyclic	100	☑
216	Measurement signal	☑	ec	cyclic	100	☑
57	Measurement signal	☑	ec	cyclic	100	☑
56	Measurement signal	☑	ec	cyclic	100	☑
210	Measurement signal	☑	ec	cyclic	100	☑
12	Measurement signal	☑	ec	cyclic	100	☑
209	Measurement signal	☑	ec	cyclic	100	☑
161	Measurement signal	☑	ec	cyclic	100	☑

Comment: at Lboro we are normally given by the OEM **the required a file (.vst for ATI Vision), (.A2L, .db for Vector CANape)** which you import into the calibration software and which tells the software the names of available ECU parameters & maps and their detailed properties so that the software can then interact with them. In some cases a special development ECU is required and sometimes there are security protocols in place which needs specialist software tools from the OEM to unlock the communication. CANape/Vision software is specialist and typically £5k to £10K for a single license.