Cold-start calibration
HFR500 fast FID

Accurate ‘real-time’ HC mass emissions
without a CVS tunnel….

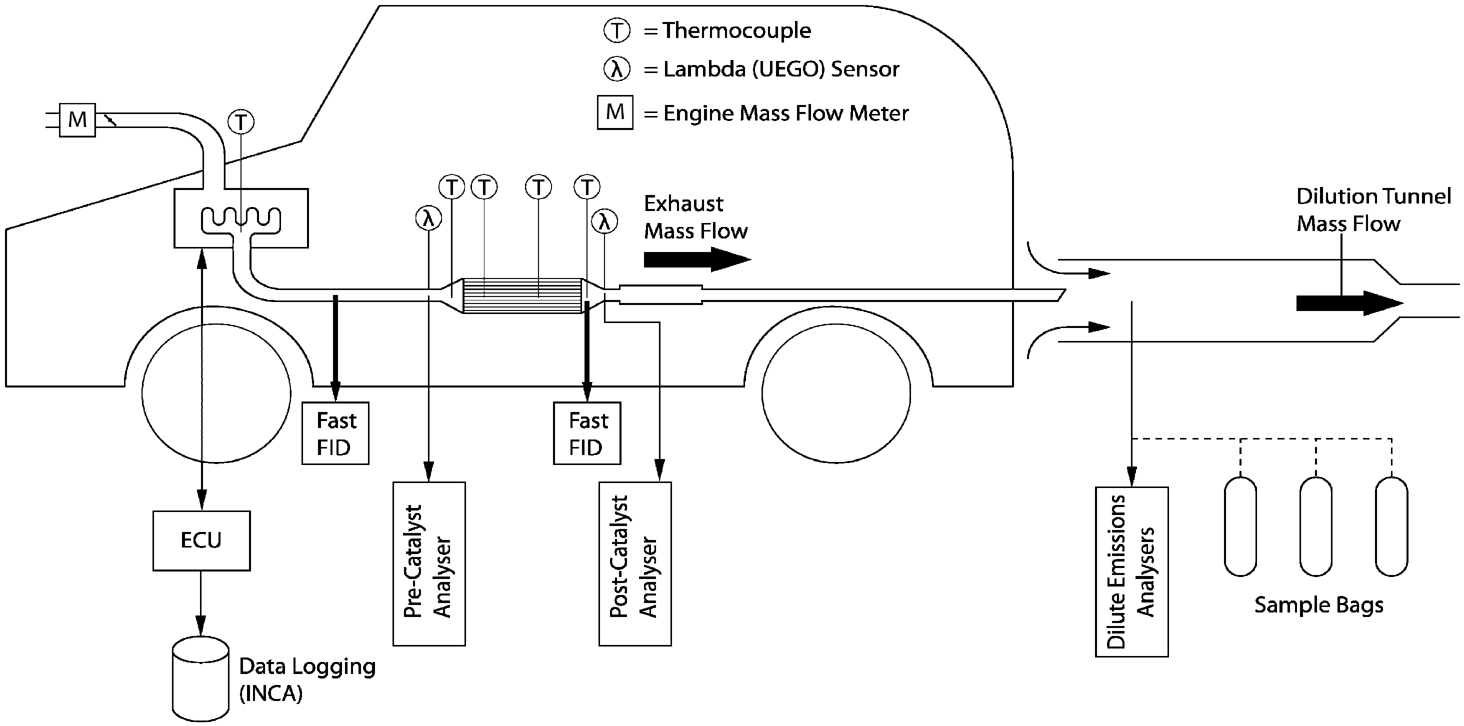
Contents

Introduction - Rationale

- Why do we need fast emissions analysis for cold start ?
  - In order to study the effects of transient events
  - To understand the combustion, exhaust port and catalyst processes
  - To quantify the effect of individual events
  - To prioritise calibration effort towards problem areas
- In order to provide the associated ***mass flow*** data
  - Data must be measured directly from the exhaust system (engine-out, after catalyst, preserving transient features)
  - Exhaust mass flow rate, and HC are changing rapidly
  - Both of these parameters are required in order to calculate HC mass flow

Introduction – Instrumentation/ data

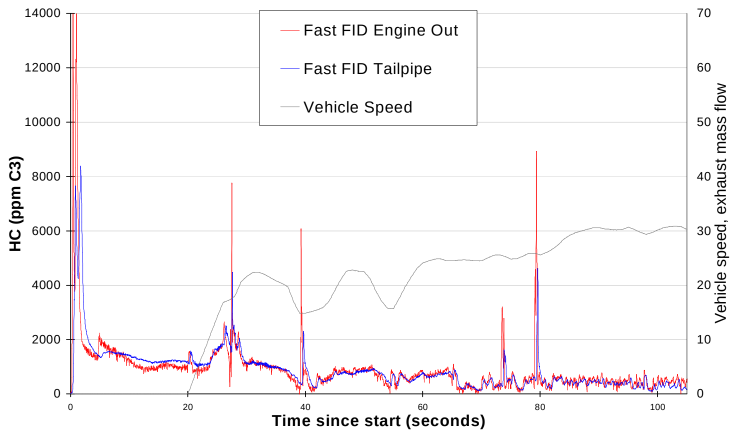
- Introduction to the instrumentation and data to be recorded



- Emissions are recorded with two different methods:
  - Exhaust gas measurements from inside the vehicle exhaust system (‘raw’ or ‘direct’)
  - For comparison, measurements from the diluted exhaust gas in the CVS tunnel (‘dilute’)

Introduction – Concentration and mass

- Important parameters
  - **Gas concentrations** from Emissions analysers



  - The fundamental measure of pollutants as a fraction of the exhaust gas

- **Mass flow rate** of exhaust gas
  - This is needed to convert **concentration** to **mass**, from parts per million (**ppm**) or percent (%) to grams (**g)** for pollutants

HC concentration measurement with the Fast FID

- Pre and post cat sample location
- Maintenance
- ‘Good practice’

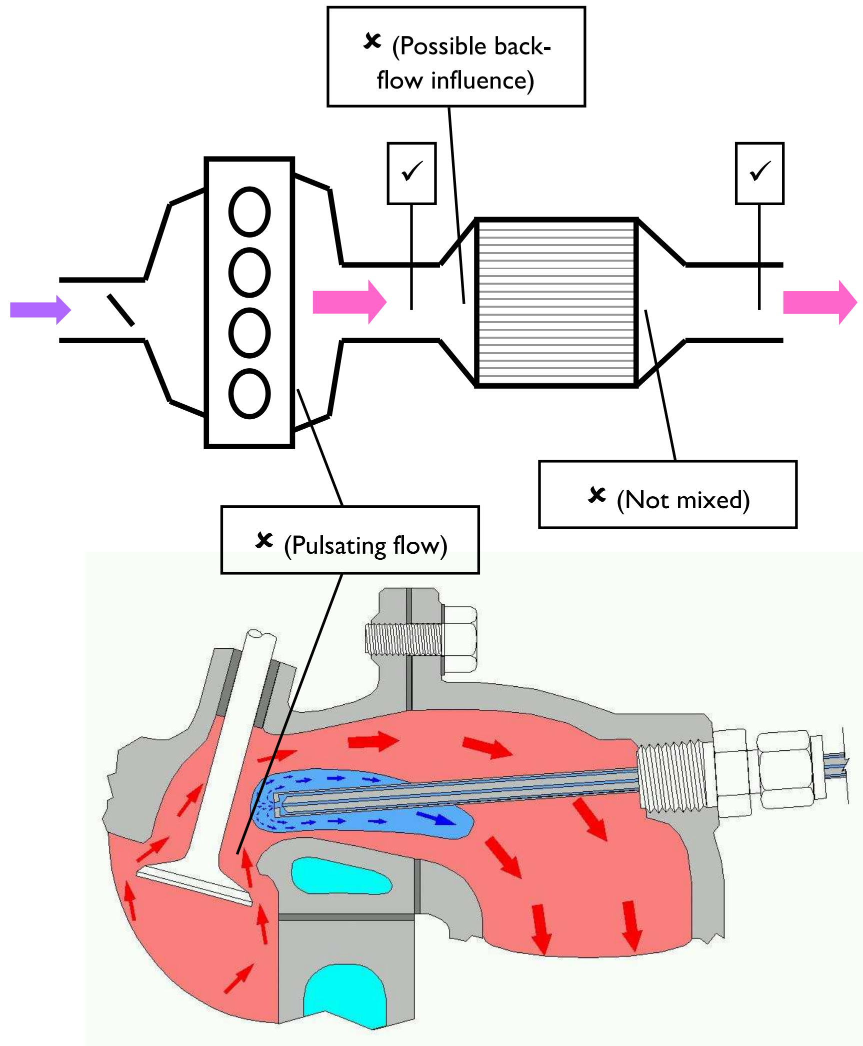
Sample point selection criteria

For general cold-start application we need:

- ‘Representative’ **HC concentrations**
  - Gas should be representative of the ‘average’ mixture
  - We should use a location in the pipe for a mixed sample (not sample from a particular area of catalyst)
  - Turbo can be helpful to mix the gas

- ‘Representative’ **Exhaust mass flow**
  - For example, the flow in the exhaust port is pulsing faster than the engine air meter can measure. If this is the case, (HC x flow rate) calculation does not work, even if number of cylinders is accounted for….
  - Post cat in the pipe is suitable.

- Point measurements can be useful……
  - For example to investigate the performance across the catalyst due to poor flow distribution
  - For case studies see SAE papers 2004-01-1489 and 2005-01-1095

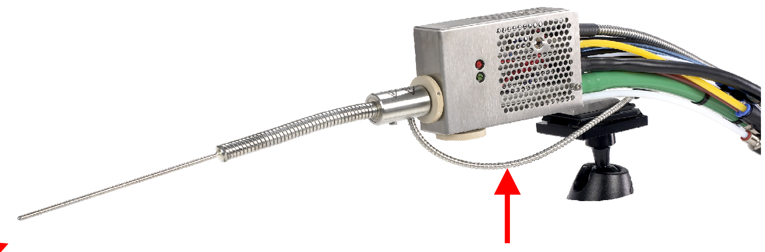


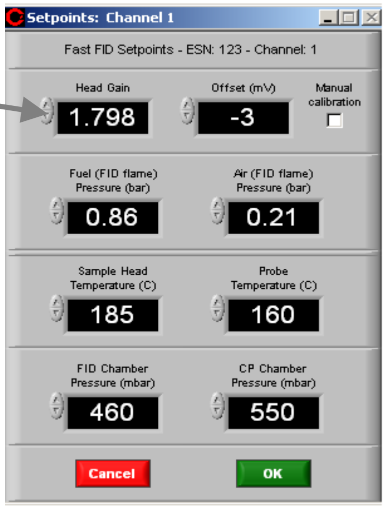
Fast FID basics - Maintenance

Daily recommended maintenance

- Daily check & cleaning while cold, sample line can be removed for cleaning

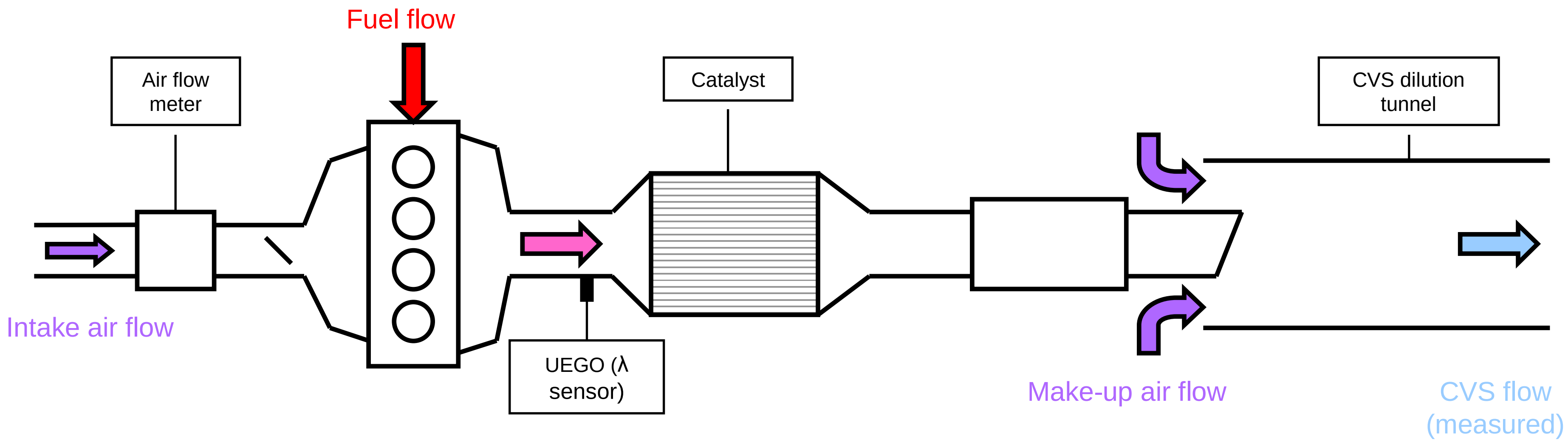
- Check of 'head gain' indicates correct operation – should be repeatable and close to a value of 1, high numbers indicate the sample system may be blocked





- Review of pre-requisites for good experimental practice
  - Span & zero checks before and after testing
  - Dynamic calibration (leak check)
  - Linearity check done
  - Comparison with bench analyser readings
  - Look at maintenance manual

Exhaust mass flow (intake air flow + fuel flow)



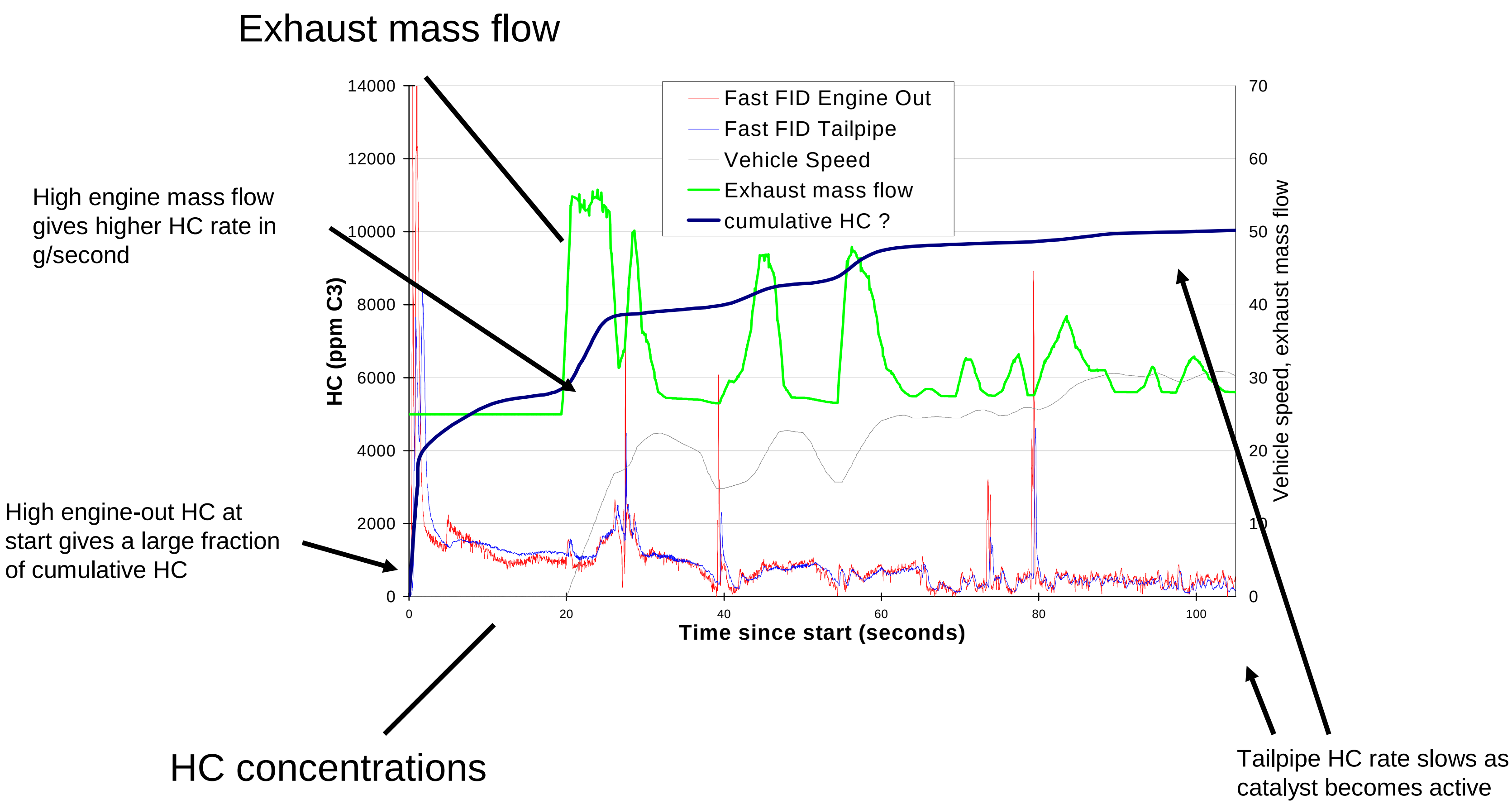
To make correct measurements, exhaust flow rate should be calculated at similar response time to the measured pollutant values.

For fast FID:

- Air Flow from engine air meter is preferred (fast measurement)
- Fuel flow = mass air flow / (λ x stoichiometric air-fuel ratio)

Schematic diagram of HC mass calculation

- Illustration of calculation of HC mass – FTP cycle



Emissions analysis – HC mass flow calculation

- Calculation of HC mass flow rate

  - Mass flow rate of HC is:

Exhaust mass flow rate x (ppm HC / 1,000,000) x molar mass [HC] / molar mass exhaust

Flow rate X Fraction HC X Relative mass HC

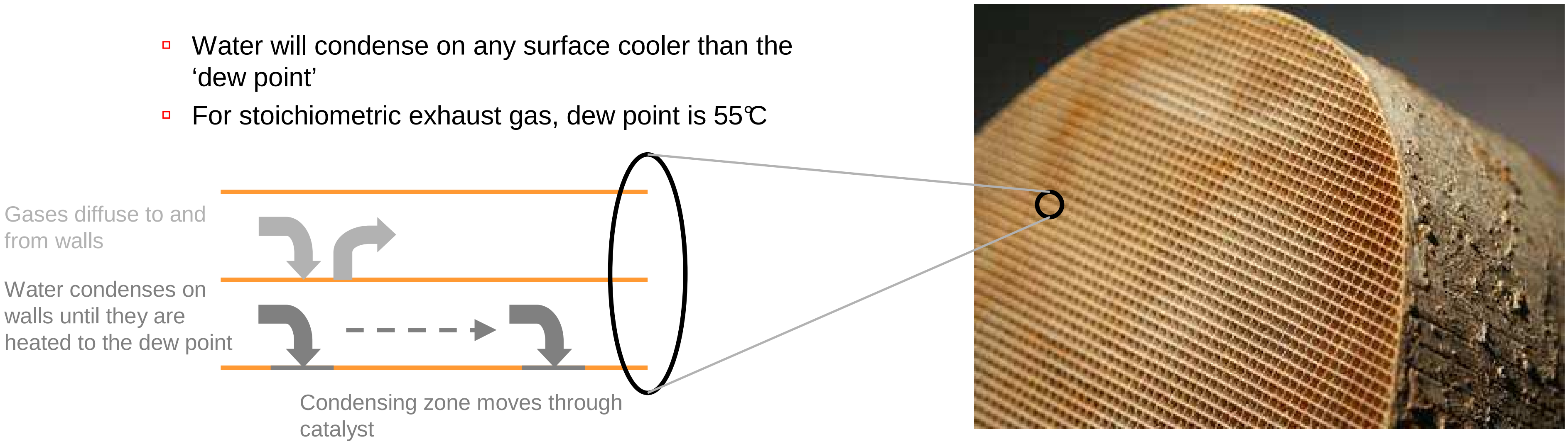
  - Molar mass of exhaust ~ 29 – varies slightly with fuel

  - Molar mass HC is defined in legislation, for European gasoline regulations for C1:
    - Stage 4 fuel molar mass for THC = 13.86, assumes C:H 1:1.86 in exhaust
    - Stage 5 fuel molar mass for THC = 13.93, assumes C:H 1:1.93 in exhaust

Wet/ dry measurement compensation for cold-start

Effect of catalyst on exhaust gas water content

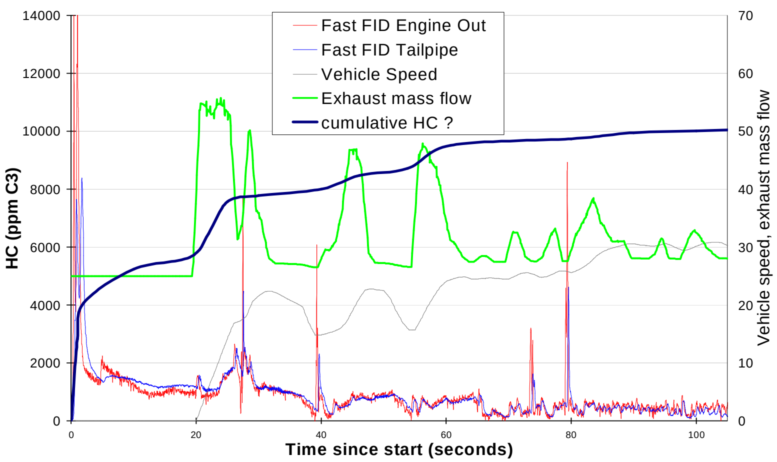
- Catalyst has extremely large surface area
    - Water will condense on any surface cooler than the ‘dew point’
    - For stoichiometric exhaust gas, dew point is 55℃



    - As the catalyst temperature rises to 55C from the front, the condensation point moves through the brick
    - Therefore, the water content at the catalyst **exit** is ~12% lower than the inlet until the exit of the catalyst is > 55℃ (Gas conc is therefore 13% higher)
- To correspond with CVS measurements, the exhaust concentration measurement needs to be reduced by ~12% until the water stops condensing (determined by thermocouple at catalyst exit)
- The re-evaporation of the water occurs over a generally longer time-scale and the errors associated with the increased flow at catalyst exit are negligible.

Emissions analysis – Mass HC processing

- Create Excel workbook
- Calculate exhaust mass flow
- Calculate mass flow rate of HC
- Make water correction
- Integrate mass flow of HC into g



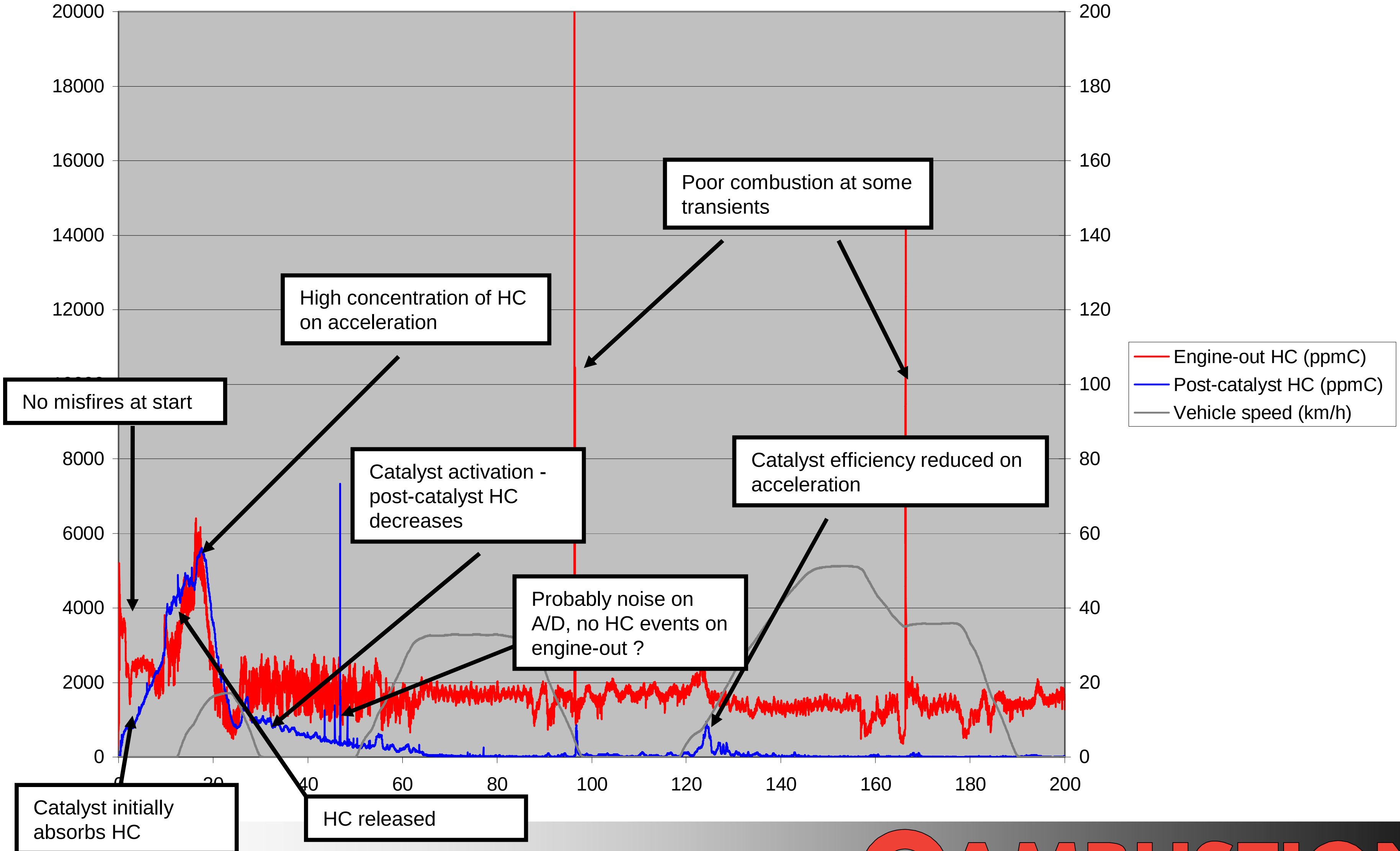
CAMBUSTION

Case study – Cold start and NEDC on 4 cyl 2.0l PFI engine

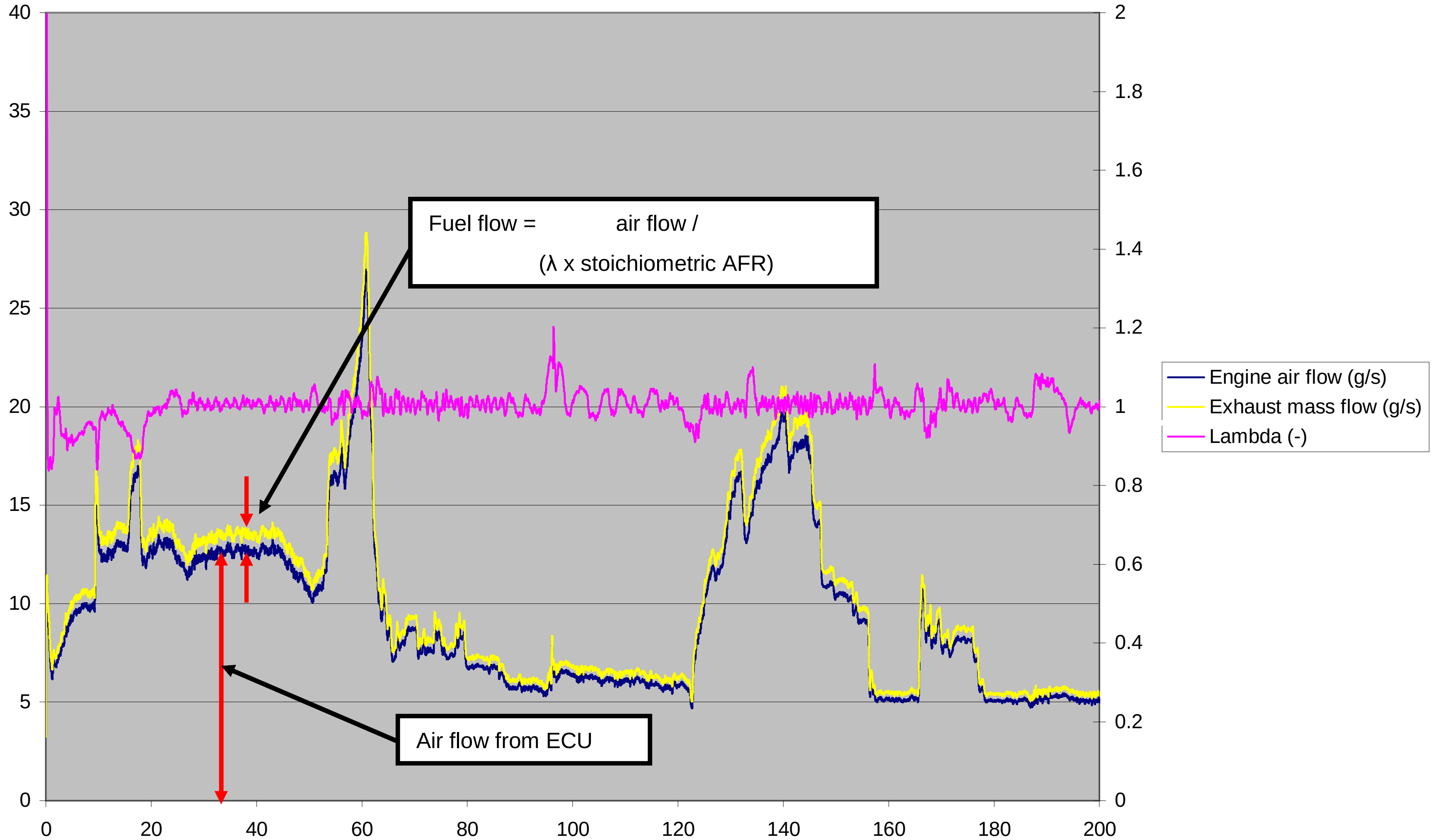
Now that we have covered the theory we can ……

- Examine raw HC data for general information
- Determine exhaust gas flow
- Time alignment of data
- Calculate ‘engine out’ HC flow rate (g/s)
- Calculate catalyst out HC flow rate (g/s)
- Integrated (modal) mass to quantify the contribution of individual events to cycle total
- Use this information, together with the HC concentrations, to diagnose problem areas
- Use information from other sensors and ECU parameters to find the cause of the events

Case study – Transient HC features on raw data vs time



Case study - Determine exhaust mass flow



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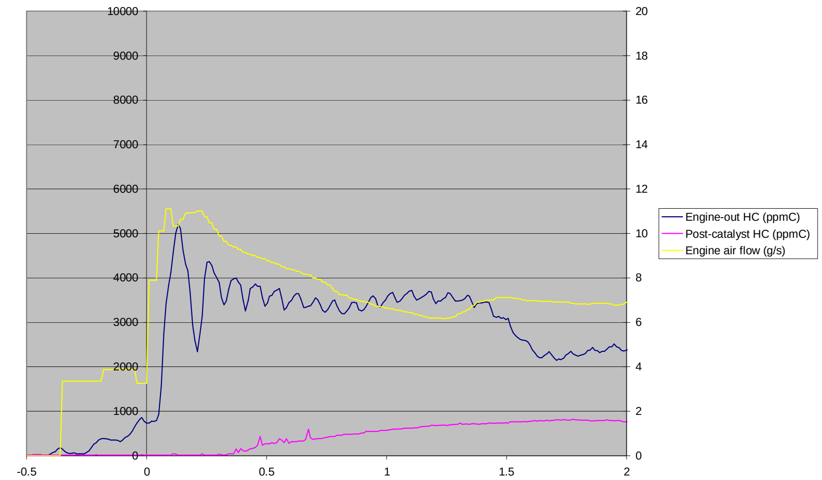
Case study – Time alignment/ datalogging

- Exhaust flow rate and HC concentrations both change rapidly
  - It is important that the analyser is fast enough to resolve the changes in HC
  - If the mass flow is not measured accurately this will cause errors
  - If there is a time delay between the mass and HC measurement, the result will be wrong!

- Important if different data sources used
  - For example ECU data and A/D system

- Logging frequency must match
  - To avoid time alignment errors

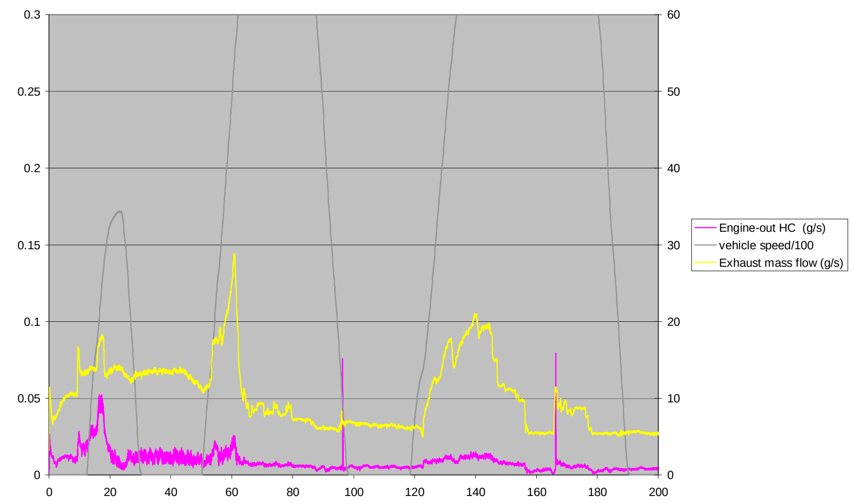


Case study – Engine-out HC flow rate (g/s)

- Multiply HC fraction of exhaust by exhaust flow rate
  - Make sure the units are correct
  - Convenient to have mass flow in g/s
  - HC is in ppm (C1), so divide by 1,000,000

- But HC molecular weight is not the same
  - Exhaust gas approximately 29g/mol
  - FID counts carbon atoms (C1 or C3)
  - Legislation decides how much H2 to add
  - C1 is 13.86 g/mol for Stage 4

- Therefore multiply result by 13.86/29
  - 3 x 13.86 / 29 if data is ppm C3



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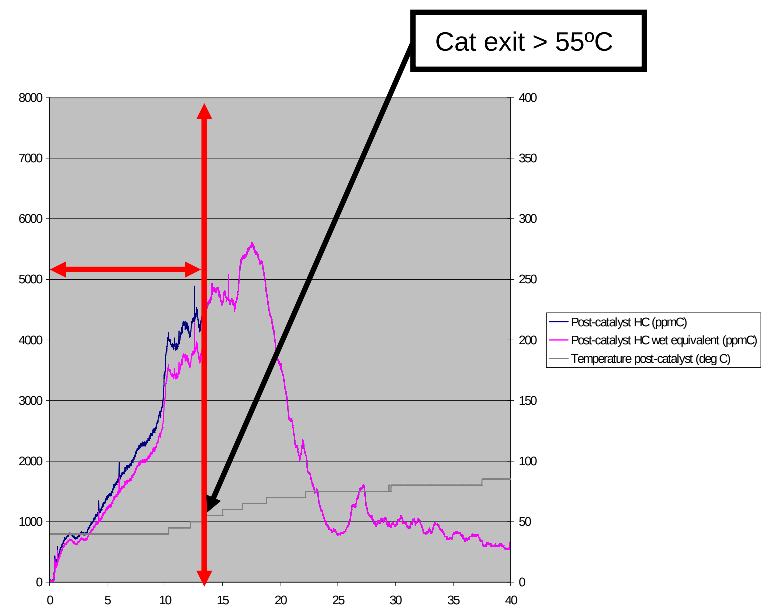
Case study – Post catalyst HC flow rate (wet/ dry correction)

- Mass flow is correct for ‘wet’ ppm
  - When gas is dried, ppm will indicate higher
  - For stoichiometric exhaust, approx 12.5% water
  - Reduce ppm value by 12.5%
  - This will convert to approx ‘wet’ value

- When catalyst stops drying
  - Correction no longer needed
  - Indicated by temperature > 55 ℃
  - In this case, around 15 seconds from start

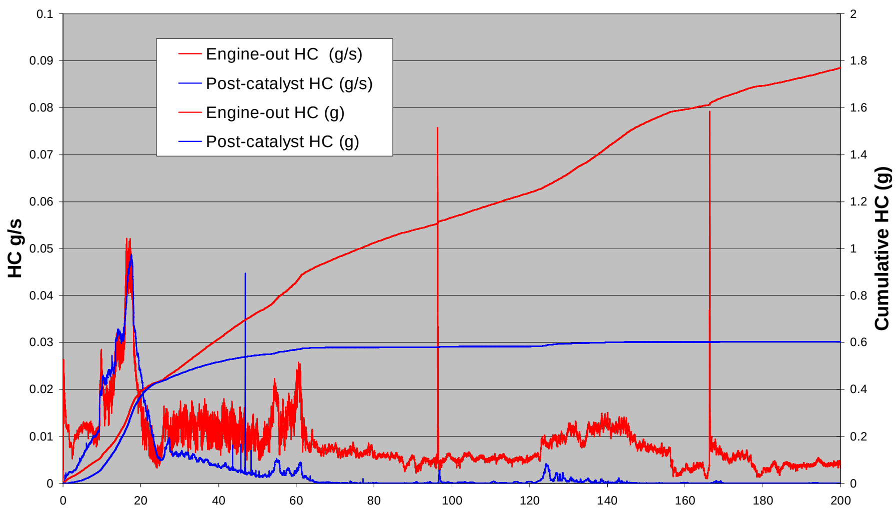
- More accurate equations can be used
  - But effects are small

- Same equation as for engine-out



Case study – Integrated (modal) HC emissions

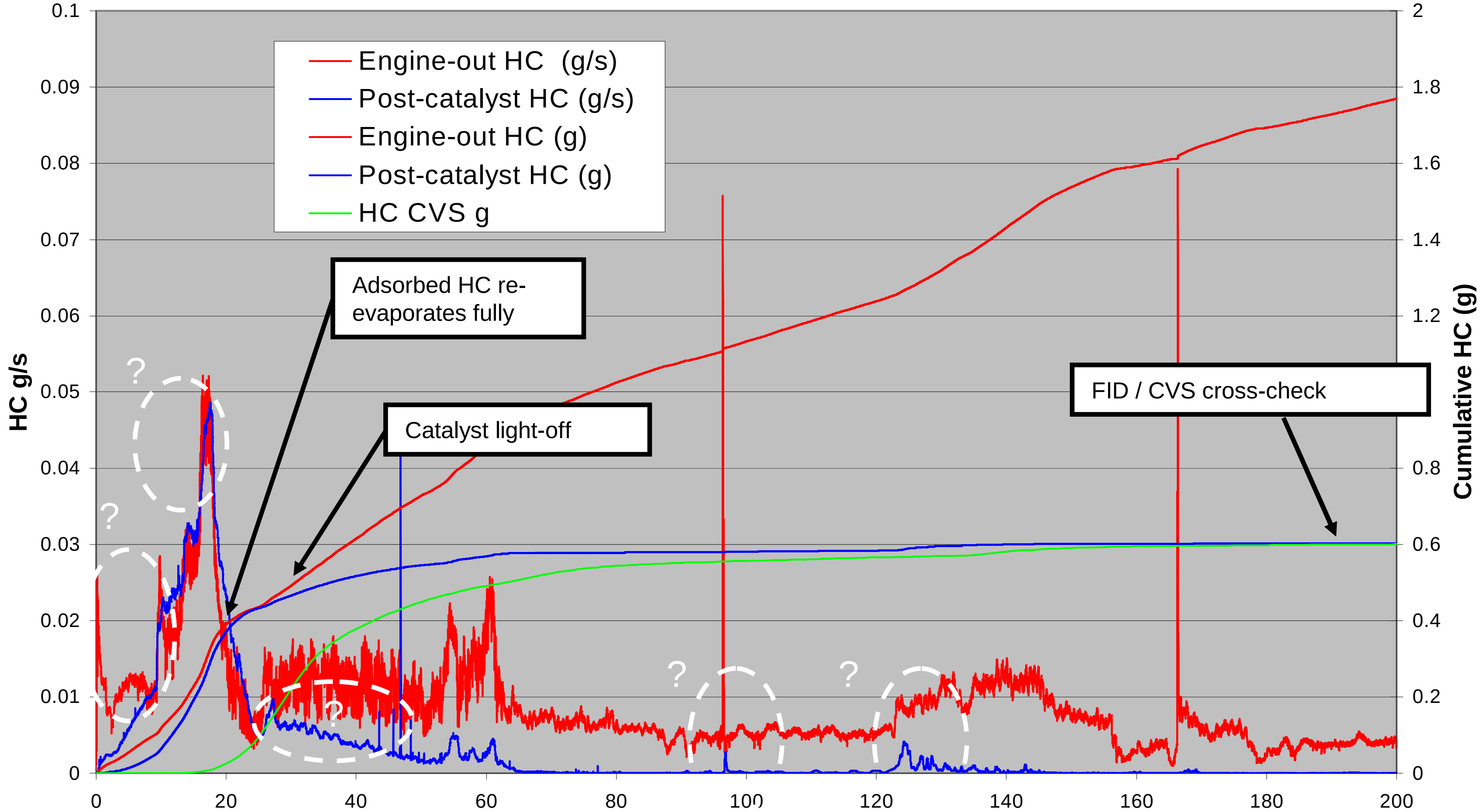
- Engine out and post-catalyst:
- For each data point
  - Add g/s value x time per point (dT) to previous value
  - If CVS emissions available, may be used for cross-check on post-catalyst HC



Interpretation of data - Overview

- Now we have HC data in g/s and g
  - Individual events and features can be examined
  - FID will help to understand the processes (ppm)
  - Mass data will identify the contribution to cycle HC emissions
- Engine-out HC can clearly be associated with transient events
  - Real-time HC data allows accurate analysis
- What can we see in the example data set ?
  - Calibration was for test purposes only !
  - Identify high g/s portions
    - are they caused by high HC ?
    - or by high exhaust mass flow

Interpretation of data – General observations



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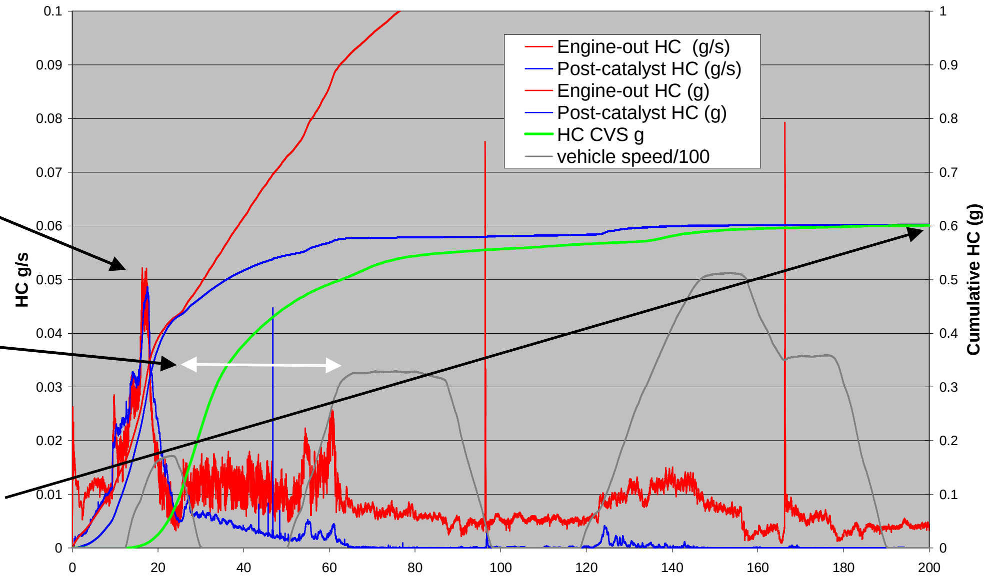
Interpretation of data – significant features

- We can see obvious features:
  - Catalyst HC absorbtion / desorbtion
  - Catalyst light-off
  - CVS emissions (second-by-second / bag) agree with Fast FID/ exhaust mass integration
    - Typical accuracy +/- 5%

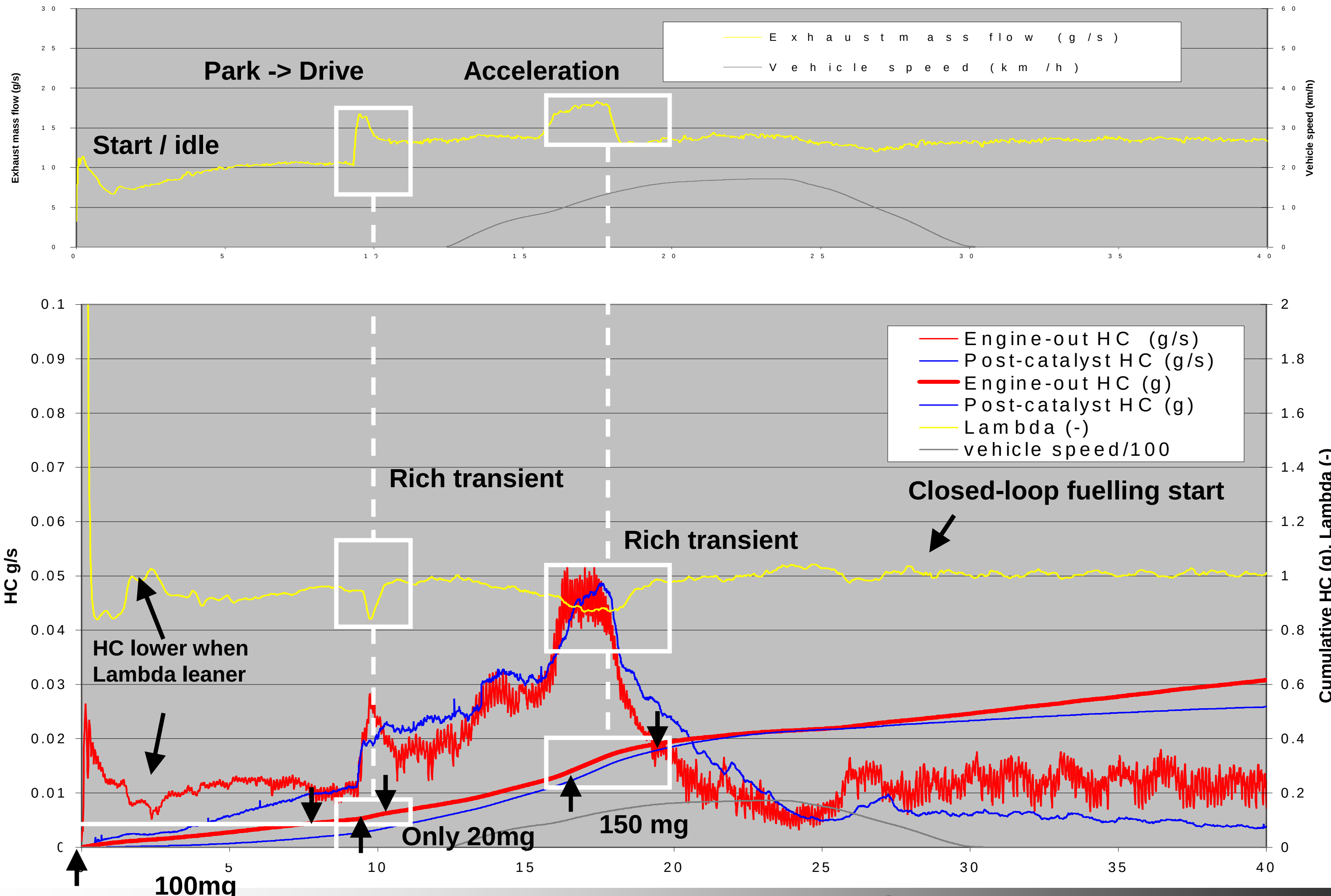


- We can prioritise events using the g HC they cause
  - Concentrate on **engine-out HC** when catalyst is inactive

- But there are more features we need to investigate to find the reasons
  - Add other data from ECU
  - Lambda sensor
  - Temperature measurements

Interpretation of data – Before catalyst light-off

Approximately 60% of cycle HC emissions in 25 seconds



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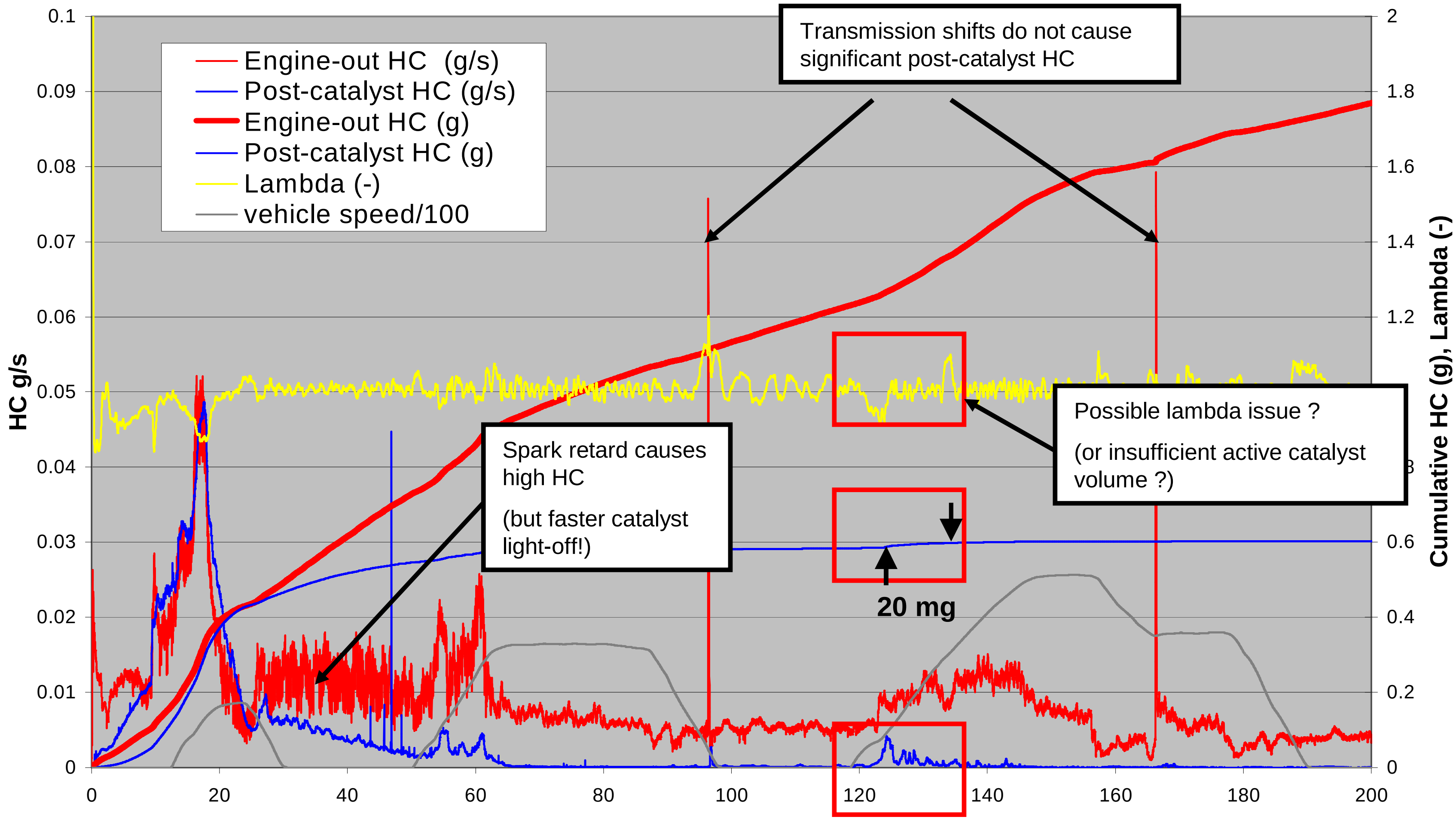
Interpretation of data – Phase 1

Can begin to look at post-catalyst HC once catalyst is active



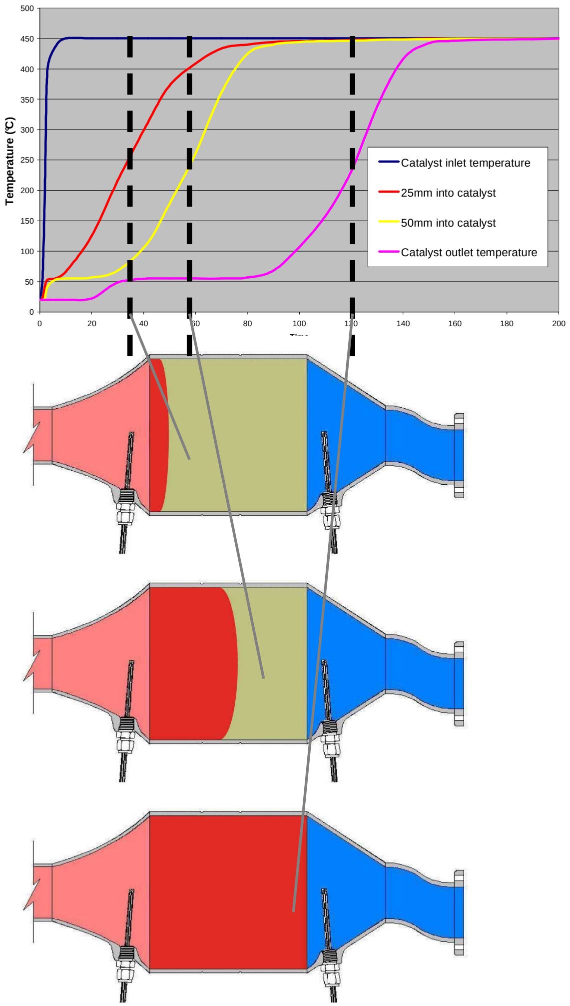
CAMBUSTION

Interpretation of data – Strategy for HC reduction

- Principles are easy to understand:
  - Use fast HC data to find the large contributions to cycle total
  - ‘Zoom in’ on these areas to examine closely
  - Use HC information and other signals to understand the cause
- Calibration engineers can then decide what to change
  - Subject to constraints and project targets

Catalyst warm-up – Light-off process/ Location

- How does the catalyst light off ?
  - Catalyst inlet temperature must be hot enough to activate the catalyst
  - Exhaust flow convects the heat through the catalyst
  - Once the front of the catalyst is hot enough to become active, the volume of active catalyst increases
  - After the catalyst becomes active, additional heat is generated by exothermic reactions
  - It is beneficial to have the catalyst active from the earliest possible time, to minimise emissions and take advantage of exotherm
  - High exhaust flow can cause ‘breakthrough’ of emissions
- Location – close coupled/ under body
  - The above can affect the packaging – the nearer to the exhaust valve the better (Beware… may become too hot at high load)

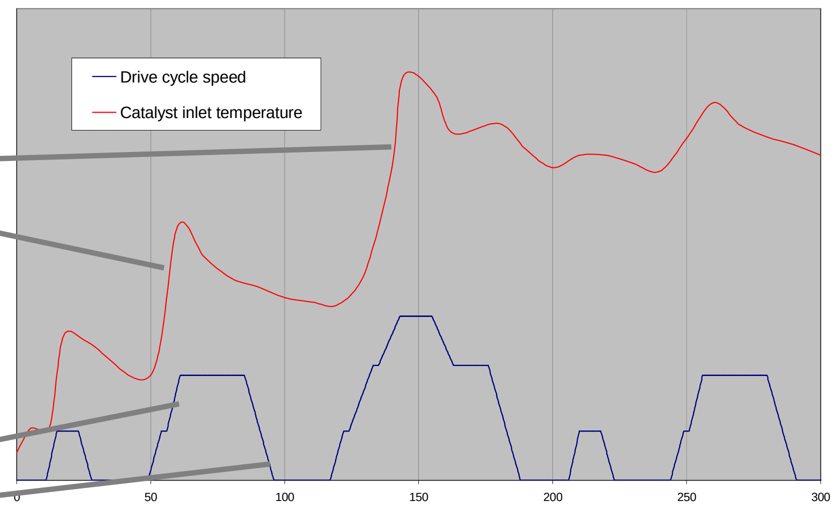


Catalyst warm-up – Drive-cycle effect

Influence of drive cycle on catalyst light-off and emissions

- What is the objective ? – sufficient volume of **active** catalyst as soon as possible
- We have seen that the energy flow to the catalyst is controlled by the **inlet temperature** and **exhaust mass flow**
- Catalyst heating is therefore influenced by the drive cycle
- Inlet temperature and mass flow both increase with engine load, when the vehicle is accelerating

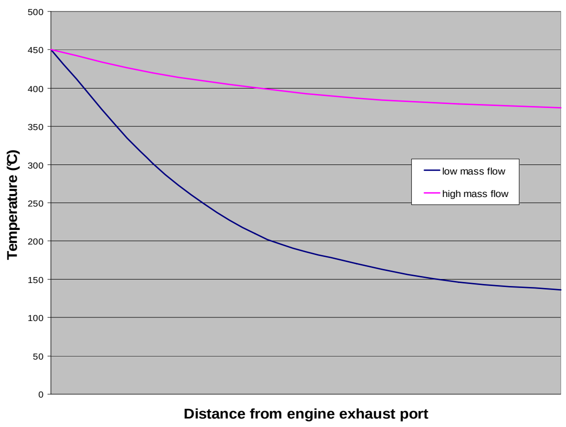
If we fail to light off on acceleration, we must wait until the next available increase in engine load



European cycle has accelerations followed by decelerations to idle

Catalyst warm-up – Exhaust flow effect

- The importance of exhaust mass flow
  - Strongly affects catalyst temperature
    - Exhaust manifold walls are ‘cold’ for this phase, large temperature difference between gas and pipe
    - Temperature loss between engine and catalyst is reduced at higher mass flows
    - Speed of heating of catalyst (energy flow) is proportional to mass flow

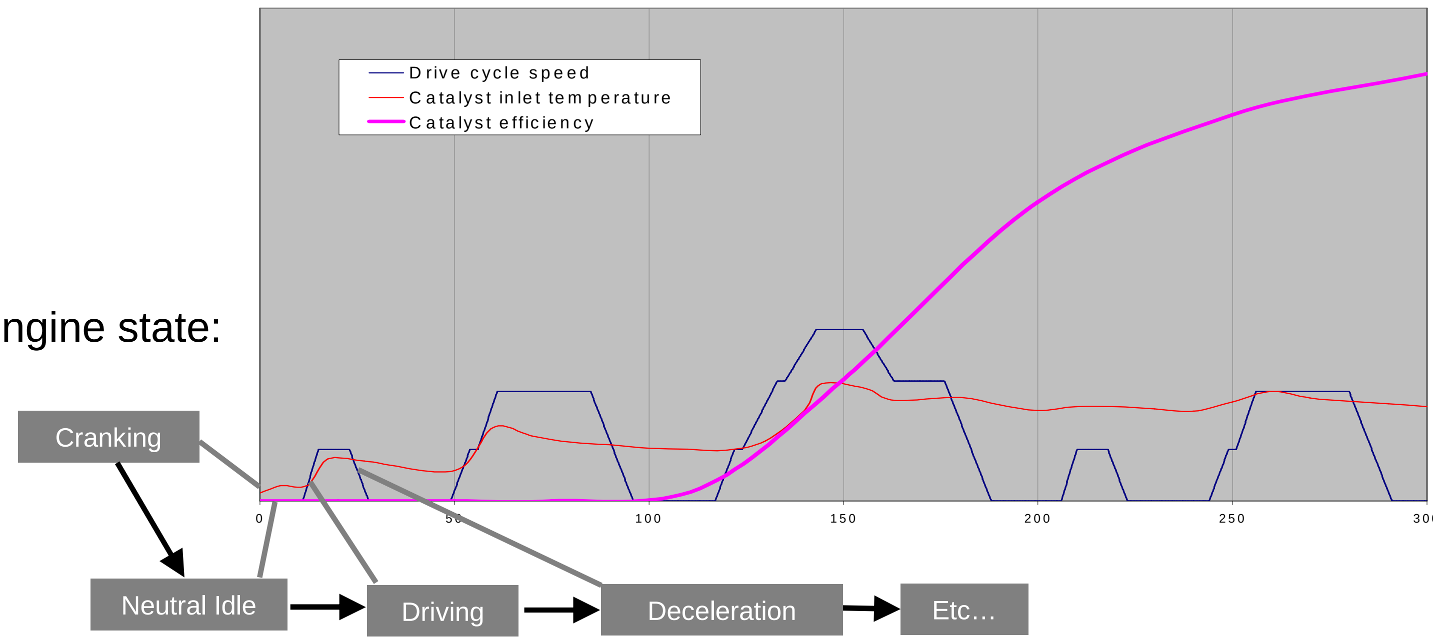


- Some other cautions
  - Cautions regarding exhaust gas oxygen sensors (especially cranking / misfire)
    - Large amount of unburned reactants mean the UEGO sensor is unable to fully react all the fuel and air – result will indicate leaner than actual lambda value
  - Cautions regarding measurement of gases pre-catalyst if backflow is possible
    - Retarded spark (for catalyst heating) can cause exhaust flow to reverse for part of the engine cycle due to pressure fluctuations
    - Sampling near to the inlet face of an active catalyst can cause HC reading to be lower than engine-out
  - UEGO sensors and heated probes can heat the exhaust system (and affect the cold start)
    - Switch on as late as possible !

Cold start optimisation principles – Important phases

- Decision of which phases of the cycle to concentrate on

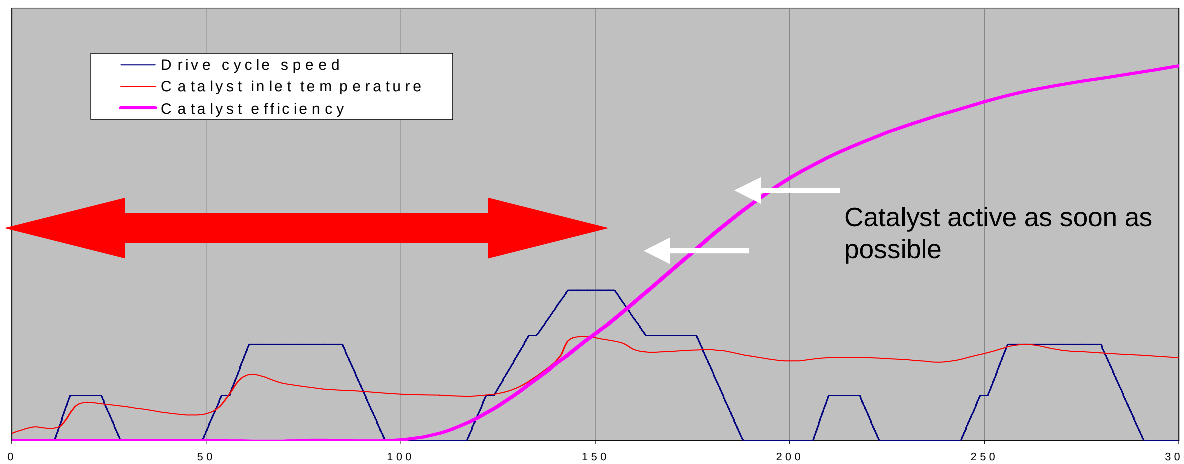
- Catalyst state: Inactive → Fully active
- Engine temperature: Cold → Hot
- Engine state:



Cold start optimisation principles – Catalyst light-off

- Assess relative contributions to HC for each area, concentrate on area where catalyst is inactive !
- Catalyst state:

Inactive → Fully active



Optimising the warmed-up phase is for future presentation

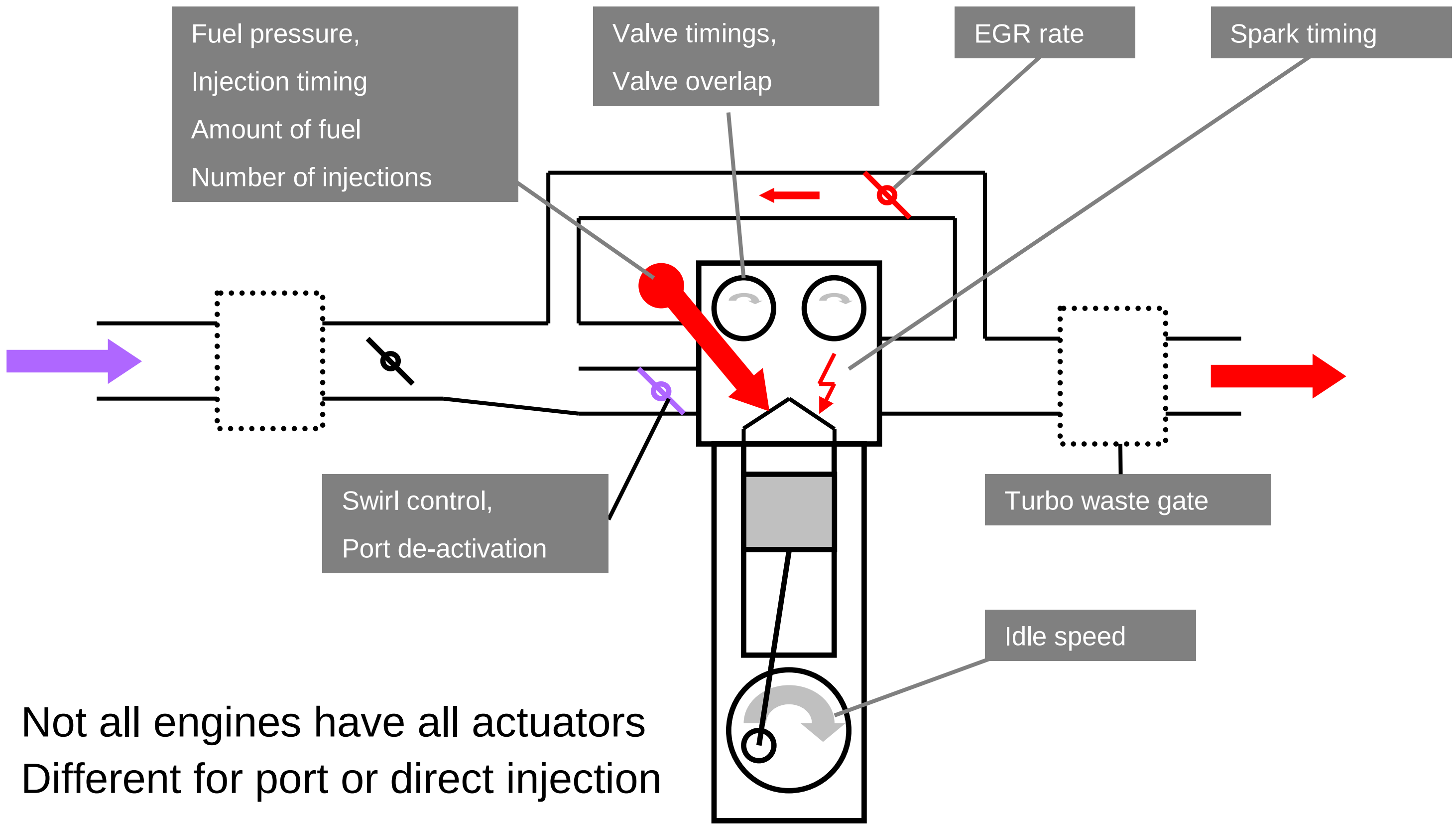
NB Fine lambda control (0.001 λ) affects CO, NOx ….

- Fuelling control state:

Cranking → Open-loop (no oxygen sensor) → Closed-loop– as catalyst lights (using oxygen sensor) → Fine lambda control using post-catalyst sensor

Opportunities to improve calibration – variables/ actuators

- Engine actuators – example engine



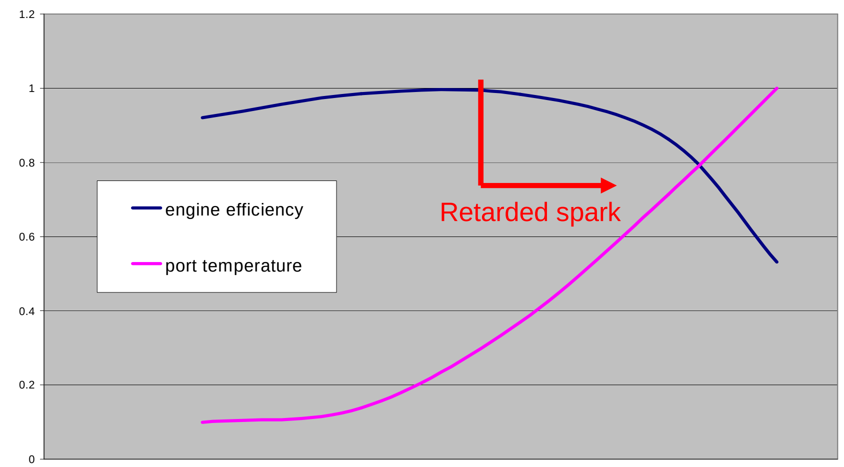
- Not all engines have all actuators
- Different for port or direct injection

NB – ensure that 'adaptive' parts of strategy are not active during calibration
(fuel injectors and air flow meter)

Opportunities to improve calibration – Spark timing

- Actuators that can be adjusted

- Spark timing
  - Key parameter for engine combustion
  - Later spark means less torque, **higher exhaust port temperature**
  - Less torque per unit fuel means **higher exhaust mass flow** for same torque
  - Higher exhaust port temperatures can oxidise HC and CO to **reduce engine-out pollutants**
  - **Be careful – higher mass flow means engine-out HC concentration must be reduced to avoid increasing HC mass (g)**



- Retarded spark timing can improve engine-out HC, but may cause combustion instability
  - May result in misfire or unacceptable idle
  - Less efficient use of fuel increases fuel consumption

Opportunities to improve calibration – Fuelling/ injection

- Actuators that can be adjusted

- Fuelling control
  - **Air-fuel ratio** is key for **combustion**
  - Ignition is affected by vaporised fuel only

  - **Lambda** (λ) is important for engine-out HC, CO, NOx and **catalyst performance**
  - Exhaust port reactions are strongly affected by λ

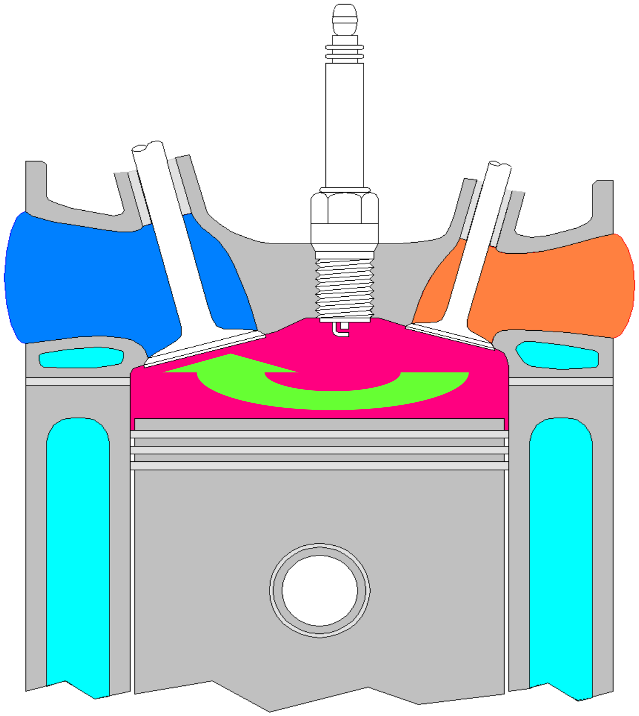
- Injection timing & number of injections
  - What to do before ECU has synchronised (found crank position and stroke information) ?
  - Inject onto open or closed valve ?

  - Multiple injections may be possible with direct injection engines
  - Some fuel injected early to vapourise, some fuel injected late to provide rich region at spark

Opportunities to improve calibration – Valve timing

Actuator that can be adjusted:

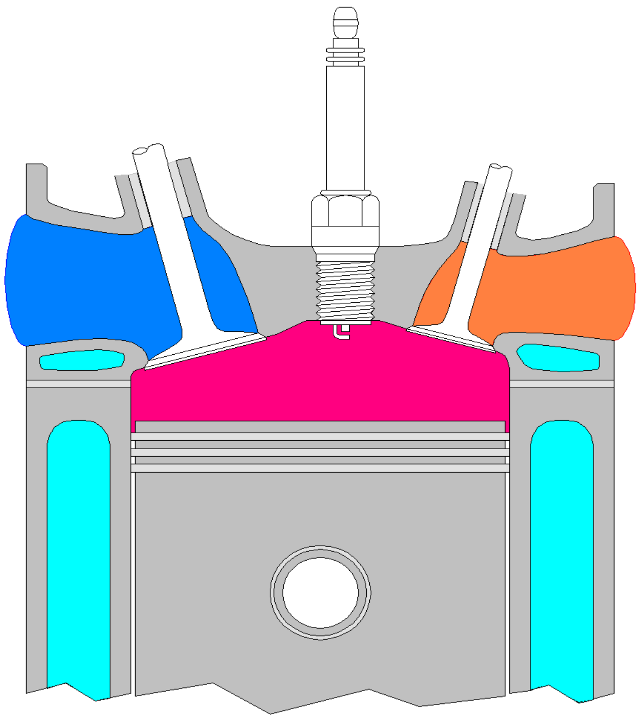
- Valve timing
  - Usually large valve overlap is detrimental to emissions performance
  - During cold stat it is possible that the back-flow from exhaust to inlet is **helpful**
  - Backflow heats up inlet valve and inlet port
  - Helps to vaporise fuel



Opportunities to improve calibration – Other possibilities

Actuators that can be adjusted:

- Inlet port de-activation (swirl control)
    - Controls mixture motion in cylinder
    - Affects combustion, emissions and optimum spark timing (MBT)
- External EGR
    - Not usually useful in crank & idle ?
- Turbo setting
    - Opening waste-gate may reduce heat loss of exhaust gas
- Others…



Important factors for calibration development

Catalyst condition – representative of mid-life vehicle condition ?

- ‘Optimal’ calibration depends on catalyst !

Repeatability - vehicle and the drive cycle should be repeatable as possible

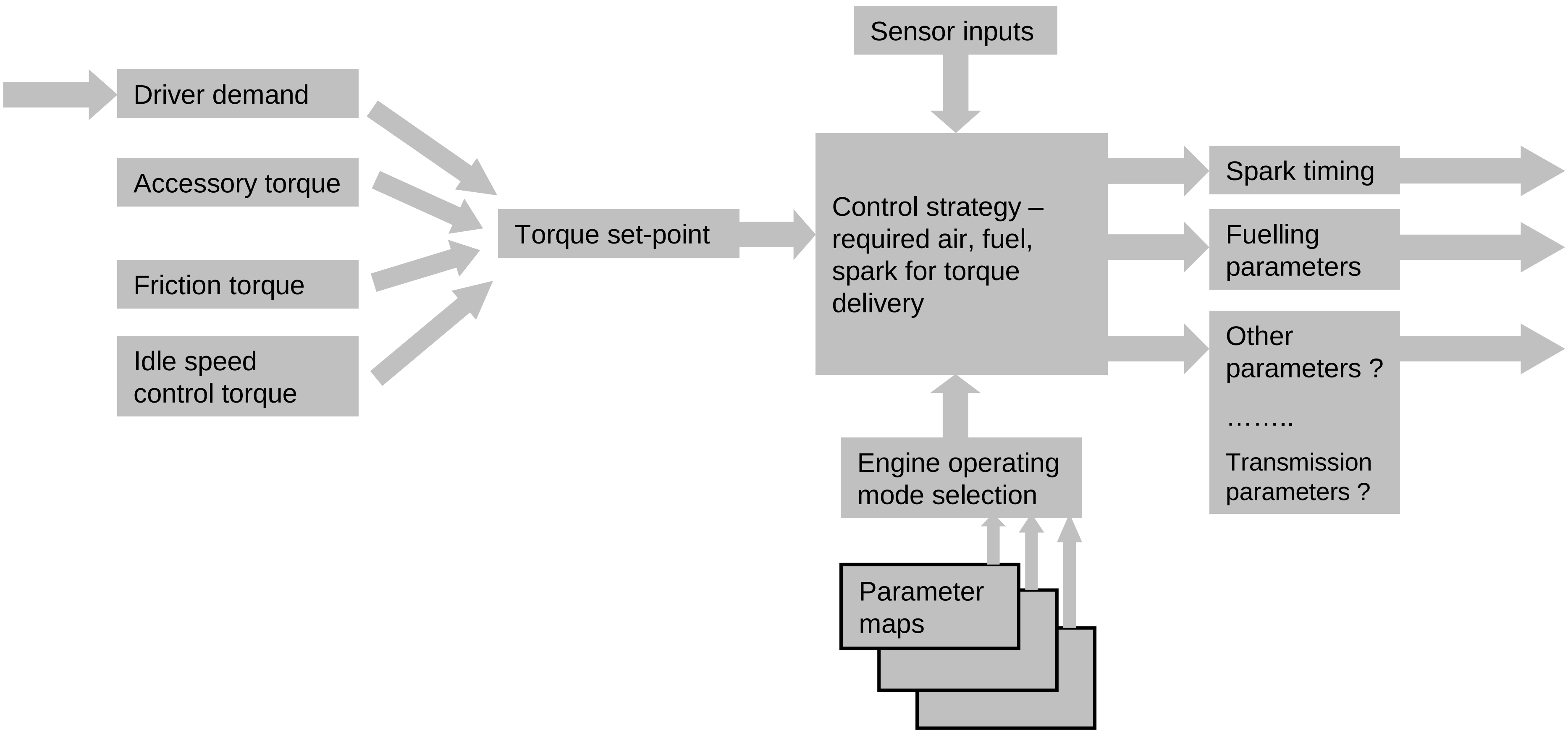
- We can then make valid comparisons between calibrations
  - Engine and transmission temperature – additional cooling for short soak times
  - Catalyst temperature – may also need additional cooling
  - Driver repeatability (robot ??)
  - Battery charge state – important for cranking repeatability and alternator load
  - Vehicle must be run until fully warmed up each time to ensure inlet manifold conditions are repeatable
  - Fuel specification

Record keeping, file archiving

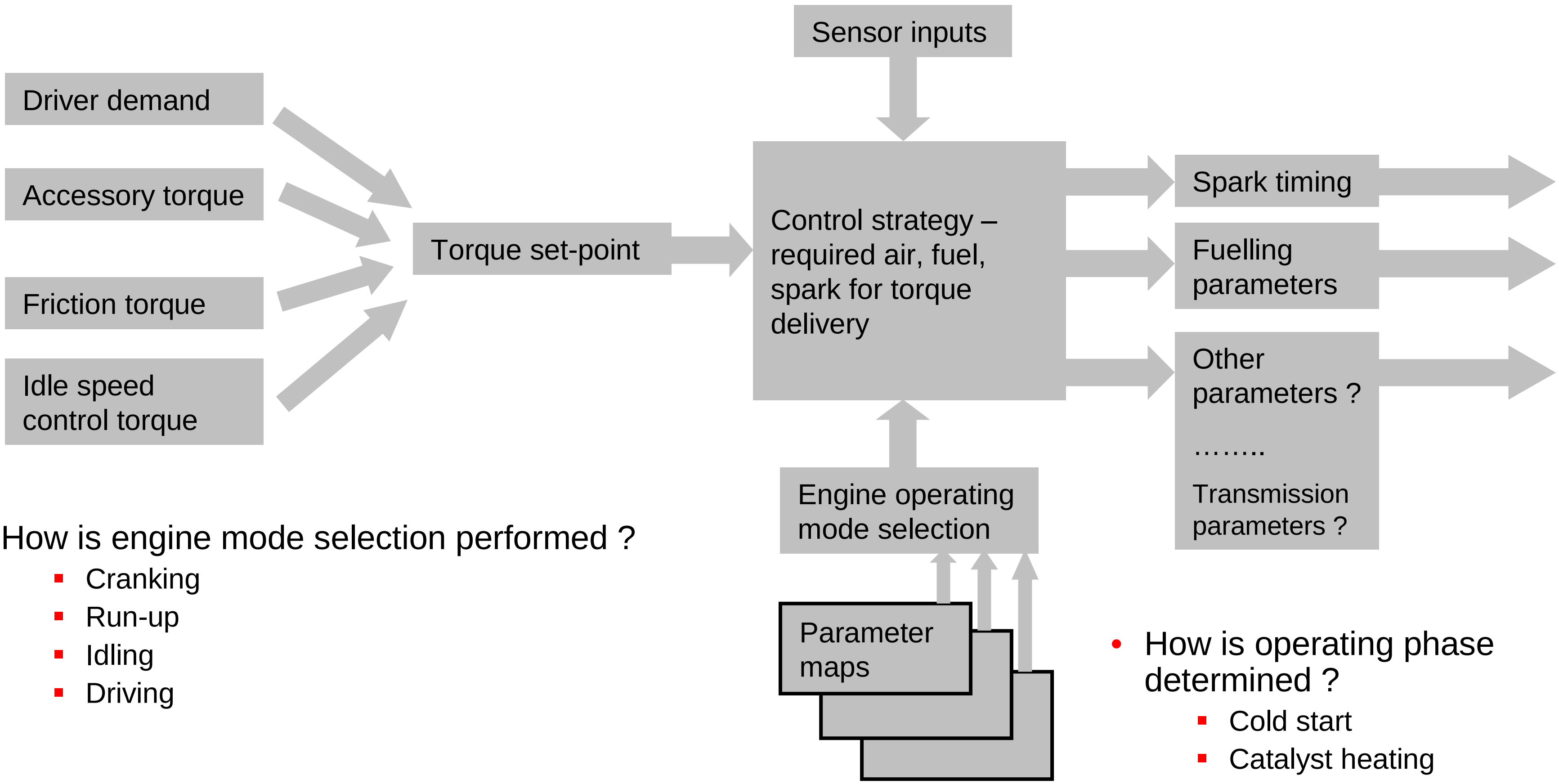
- Record all calibration changes
- Engine coolant temperature at start
- Environmental conditions: temperature, pressure, humidity
- Record any changes to vehicle, engine, exhaust system

Opportunities to improve calibration – ECU strategy overview

- ECU strategy and parameter maps



Opportunities to improve calibration – Generic operation modes



- How is engine mode selection performed ?
  - Cranking
  - Run-up
  - Idling
  - Driving

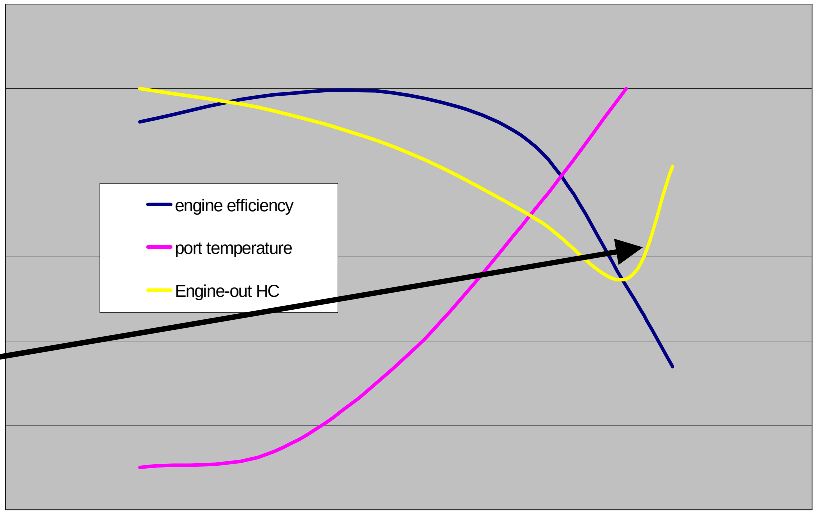
- How is operating phase determined ?
  - Cold start
  - Catalyst heating
  - 'Closed loop' fuel control

Opportunities to improve calibration – Maps/ primary variables

- Identify map axes, primary variables for control
  - Usually engine torque (load) and engine speed
- Identify parameter maps for:
  - Idle speed selection in catalyst heating and idle modes
    - Adjusts mass flow (higher speed = higher mass flow)
    - May also affect combustion quality
  - Charge (air) control & spark timing
    - Will be different in different operating modes ?
  - Engine fuelling
    - Initially should be lean of stoichiometric ($\lambda > 1.00$) to minimise HC, CO from combustion
    - NOx is usually less important during cold start phase
    - What controls fuelling when oxygen sensor is cold (inactive) ?
    - What controls fuelling compensation for transients ?
  - Control parameters for catalyst heating
    - Spark timing controlled in catalyst heating mode
    - What condition terminates catalyst heating (model) ?
  - Other actuators
    - Valve timing,
    - Intake port deactivation
    - ……. ?

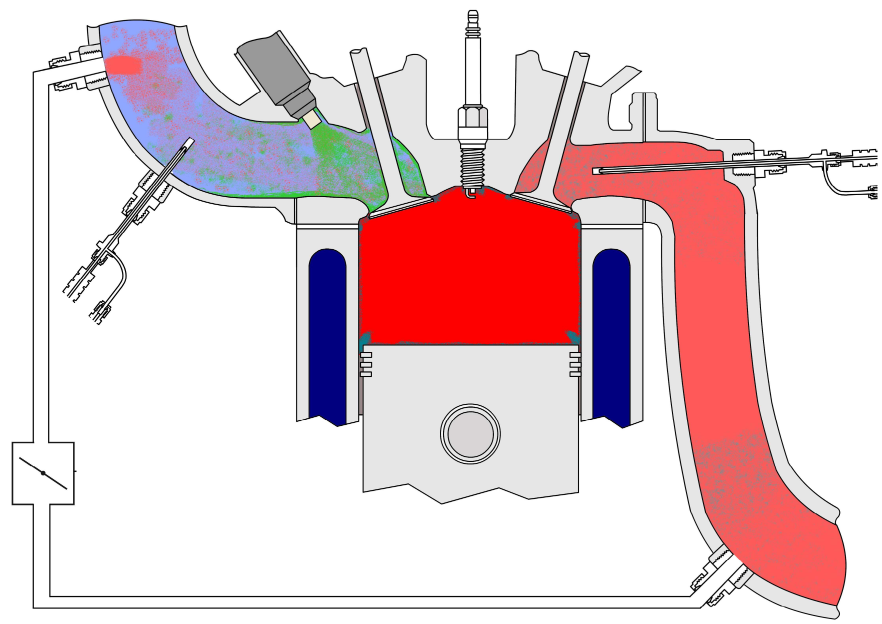
Opportunities to improve calibration – Limitations

- Limitations on calibration values
  - Customer acceptance
    - What are customer expectations of idle quality, noise, vibration ?
  - Combustion
    - Spark timing cannot be retarded indefinitely
    - Misfire will cause unacceptable idle / drive quality and increase in emissions
  - External requirements
    - Spark retard causes increased inlet manifold pressure to provide the increased air flow
    - This reduces available vacuum for brake servo
    - Maximum idle speed may be limited for auto transmission due to 'creep'
    - Is fuel economy satisfactory ?



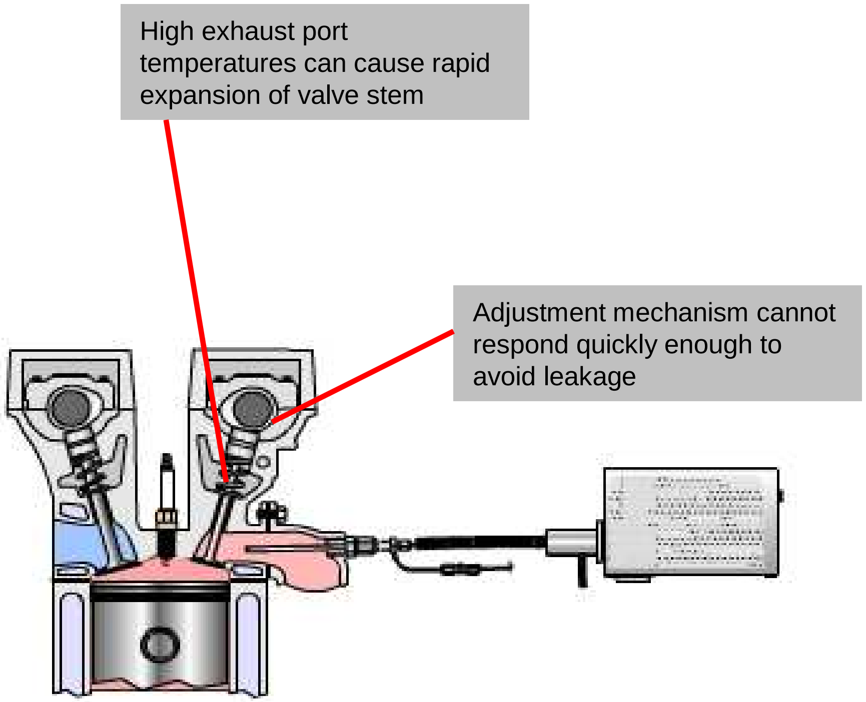
Opportunities to improve calibration – Limitations

- Limitations on calibration values
  - Actuator limitations
    - Valve timing may be fixed until oil pressure is high enough to allow movement
    - EGR system and turbo waste gate may be operated by vacuum
    - Cranking fuel pressure may be limited, especially for direct injection engines



Opportunities to improve calibration – Limitations

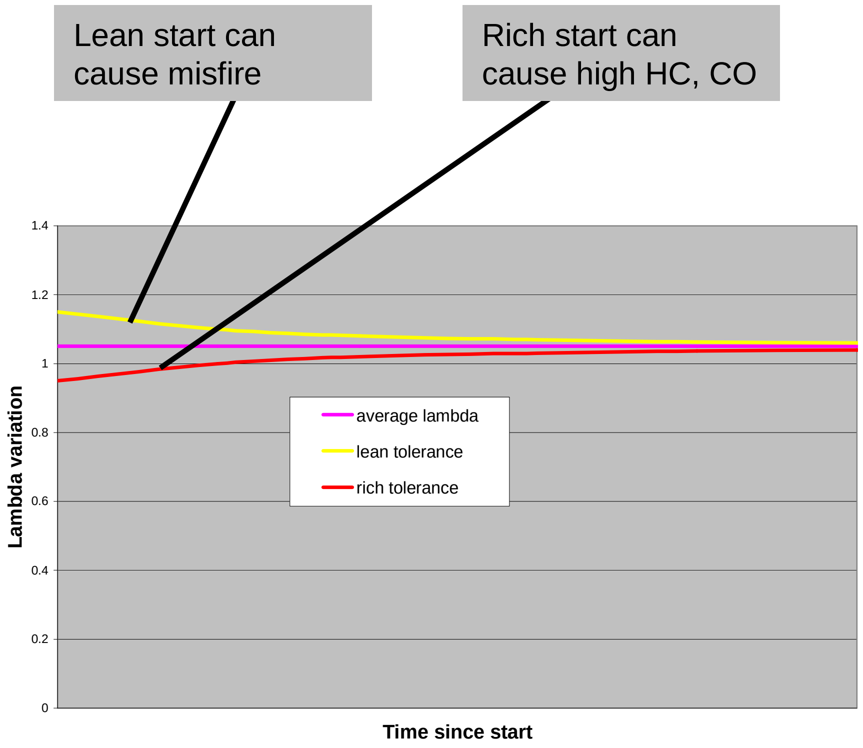
- Limitations on calibration values - continued
  - What else can go wrong ?
  - Unexpected things, for example exhaust valve leakage
    - Case study example SAE 971638
  - Can cause high HC emissions
  - Identifiable using fast FID but…..
    - Mass flow integration is not accurate in this location as the mass flow is intermittent and pulsating, and cannot be accurately time-aligned with the FID signals



Opportunities to improve calibration – tolerance/ variability

- Introduction to testing high and low tolerance envelope

- We must be careful to avoid settings that are too close to stability limits
  - The engine may stop in different position each time, this will affect when the control system becomes synchronised next time the engine is started, and affect the crank / start
  - Normally we should perform several tests to see if the engine behaves repeatably
  - Usually worst variation in lambda is at the crank/ start
- We must allow for the vehicle tolerance envelope (sensor variability, measurement error etc)
- Variations in components (especially fuel injectors) can cause large variations between different vehicles
- Lean and rich limit examples should be tested….



Conclusions

- We have covered the theory & practice of cold-start study using fast FID
  - To measure the HC produced by the engine
  - To study the effect of calibration on engine-out and tailpipe HC

- Fast HC analysers are a useful tool
  - Help to identify problem areas
  - Help to determine the cause of emissions problems
  - Cold- start calibration without the use of a CVS facility is demonstrated