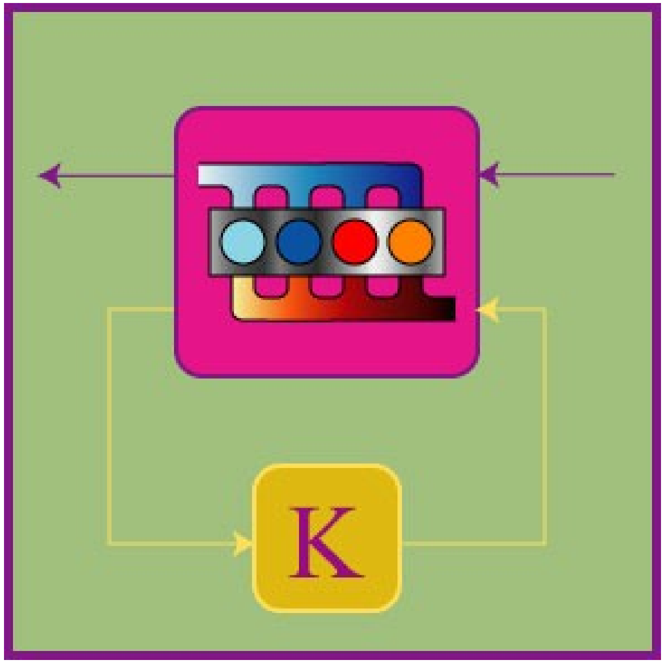
Control Opportunities in Automotive Engine Management



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Outline

- Introduction – Engine Control at Cambridge
  - Facilities
  - Previous Work
- Overview of control applications in modern diesel engines
- Areas of potential for control development within the current project.

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PART 1
Introduction

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Personnel

- Keith Glover FRS, FREng, Professor of Control Engineering
- Nick Collings, FREng, Professor of Applied Thermodynamics
- Alex Darlington, PhD – Research Associate on EPSRC grant
- Dariusz Cieslar, MSc – PhD student on EPSRC grant.

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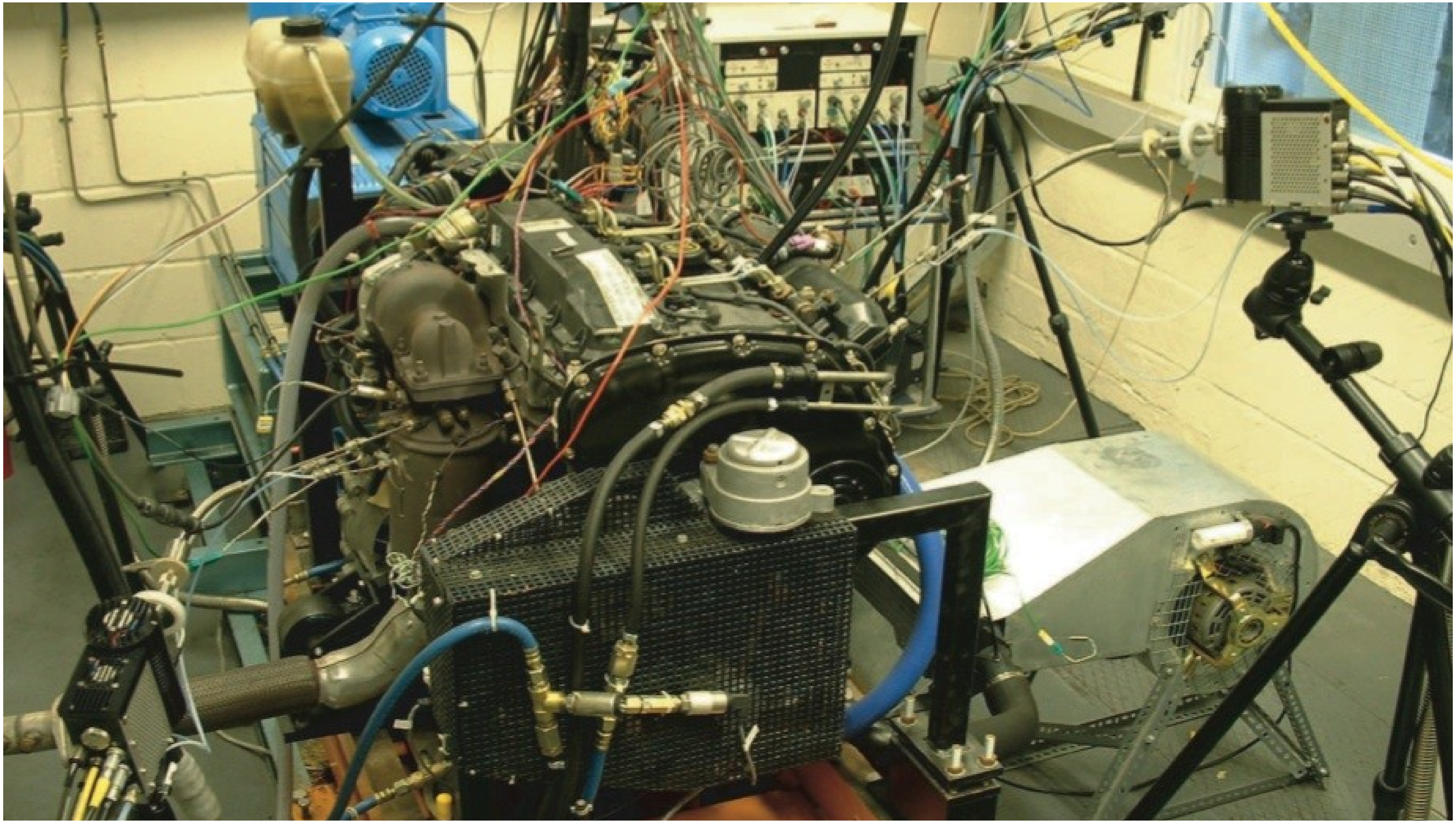
Cell Facilities



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Dedicated Equipment - Test Cell 2

- Transient AC Dynomometer 125kW
- AVL 733 Dynamic Fuel Flow
- Celesco Opacimeter
- UEGO
- dSpace rapid prototyping system
- 4 channel AVL indicating system
- Temperature and pressure measurements

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Shared Equipment

- Cambustion fast NOx/CO2/CO/HC
- Horiba EXSA 1500 NOx/CO2/CO/HC/O2
- AVL 415 Smoke meter
- In-cylinder gas sampling valves
- Fast UEGO (~10ms) measurements
- Mass spectrometer/GC

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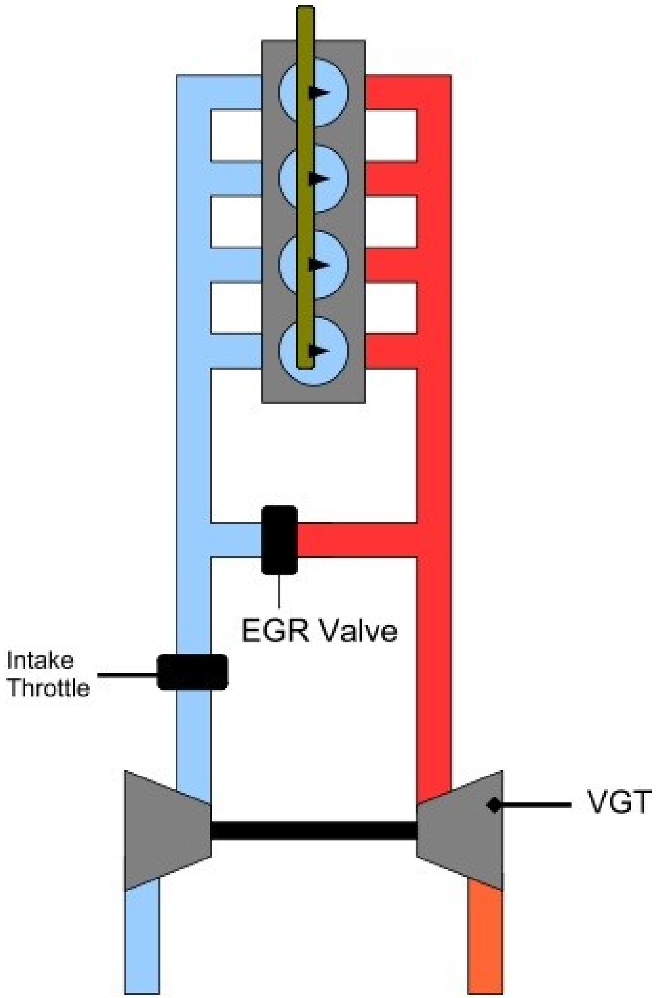
Previous Engine Controls Work

- Diesel air-path modelling and control
  [Calibratable linear parameter-varying control of a turbocharged diesel engine - Jung, M.; Glover, K - Control Systems Technology, IEEE Transactions on]
- Modelling and measurement of in-cylinder charge properties using novel in-cylinder sampling
  [A Simple Diesel Engine Air-Path Model to Predict the Cylinder Charge During Transients: Strategies for Reducing Transient Emissions Spikes – Darlington, A; Glover, K; Collings, N – SAE Transactions 2006-01-3373]
- Catalyst modelling and control
  [The Role of Oxygen Storage in NO Conversion in Automotive Catalysts – Cornelius, S; Collings, N; Glover, K – Topics in Catalysis, Springer]

Previous Engine Controls Work

- DPF modelling and control
  [Safe Operation and Control of Diesel Particulate Filters Using Level Set Methods – Swift, S; Glover, K; Collings, N - Recent Advances in Learning and Control (Book Chapter) – ISBN 978-1-84800-154-1]
- Idle speed control
  [An application of coprime factor based anti-windup and bumpless transfer control to the spark ignition engine idle speed control problem – Ford, R; Glover, K - Decision and Control, 2000. Proceedings of the 39th IEEE Conference on]
- VVT modelling and control
  [Identification of the Twin Independent Variable Cam Timing Engines for AFR Control – Genc, U; Glover, K – ASME Journal of Dynamic Systems, Measurement, and Contro]

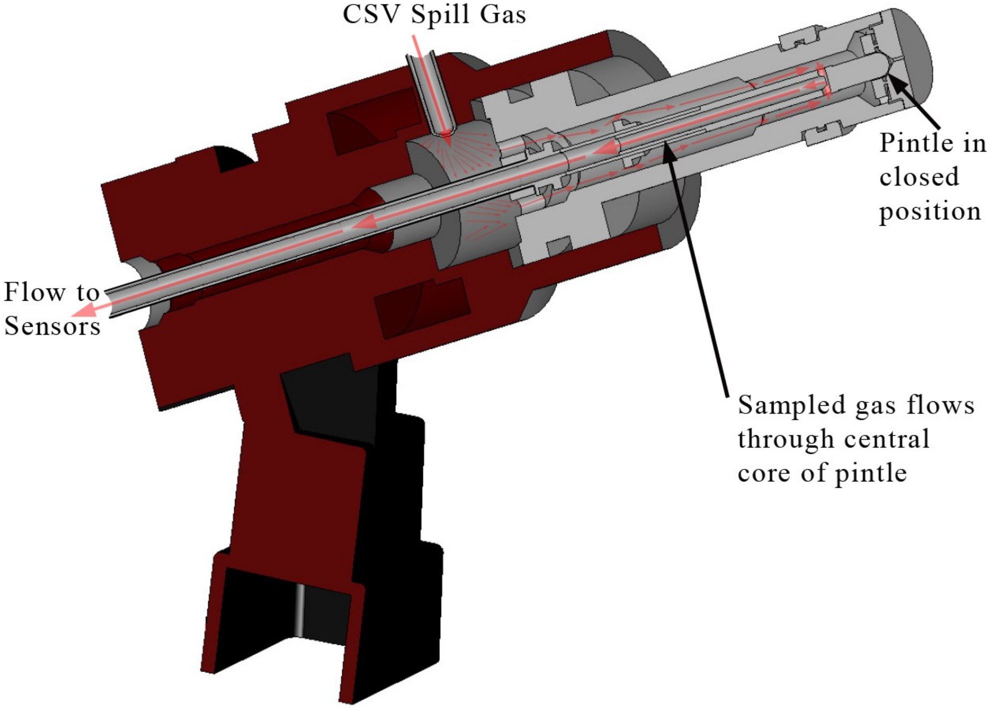
Diesel Air-path Charge Modelling



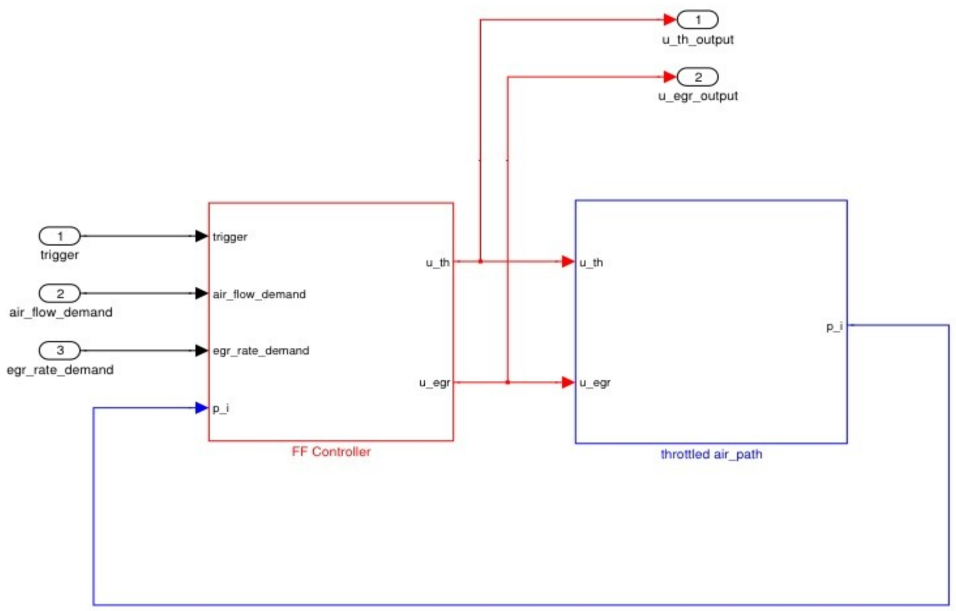
- Aim: to achieve the fastest possible transition in the in-cylinder charge properties
- Mean value engine model developed to capture the system dynamics
- Coordinated use of the throttle and EGR valve required to ensure correct air mass and burned gas fraction of the pre-compression charge

In-cylinder sampling

- To aid development of the models and allow direct verification, a novel in-cylinder sampling system was developed and used
- A GDI fuel injector was connected to one of the cylinders and opened for a short duration during the compression stroke
- Sample gas was fed to high speed CO2 analyser



Feed-Forward Implementation



- A feed-forward controller was implemented
- Direct inversion of the model (considering the actuator saturation) was used to obtain a rapid response in the cylinder charge composition
- Air-flow and EGR rate demands were mapped to throttle and EGR valve actuator positions

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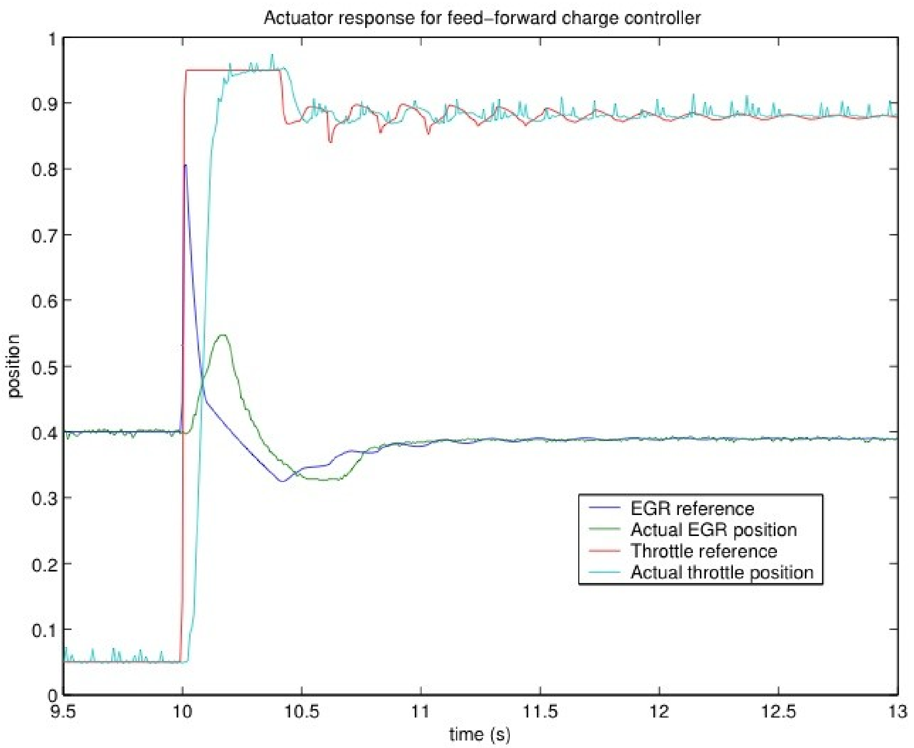
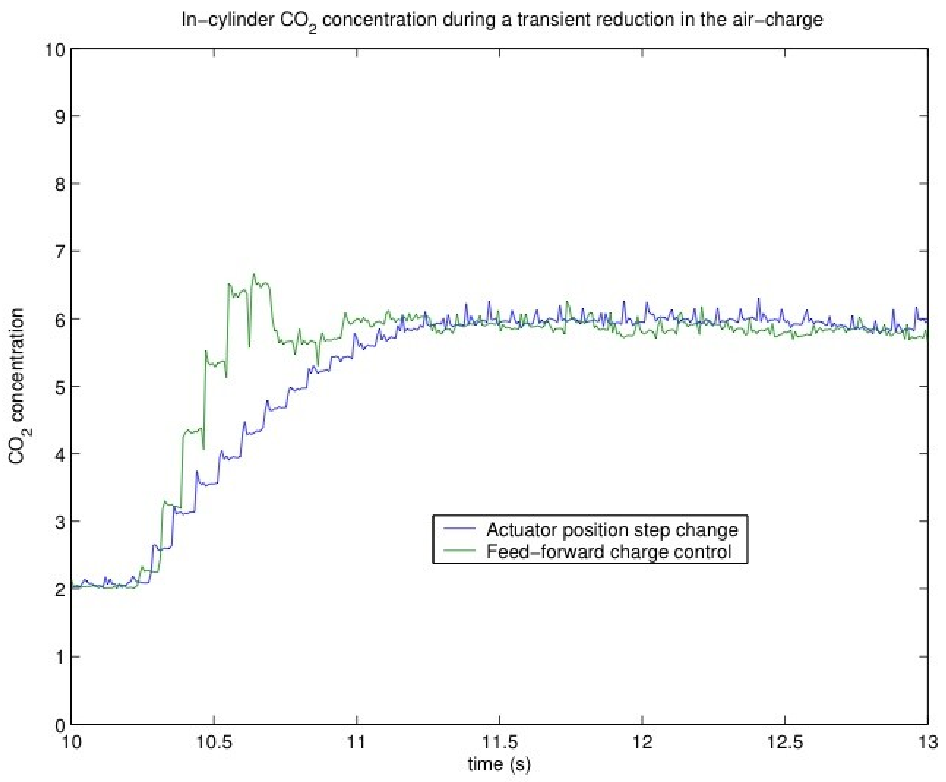
Results





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PART 2
Current Diesel Control

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Control in modern Diesel Engines

- Feedback control (or related signal processing activities) is used in a number of ways on modern Diesel engines:
  - Engine speed control
  - Engine torque control
  - Fuel pressure control
  - Cylinder balancing
  - Supervision of aftertreatment systems
  - Exhaust temperature control
  - Air-charge control

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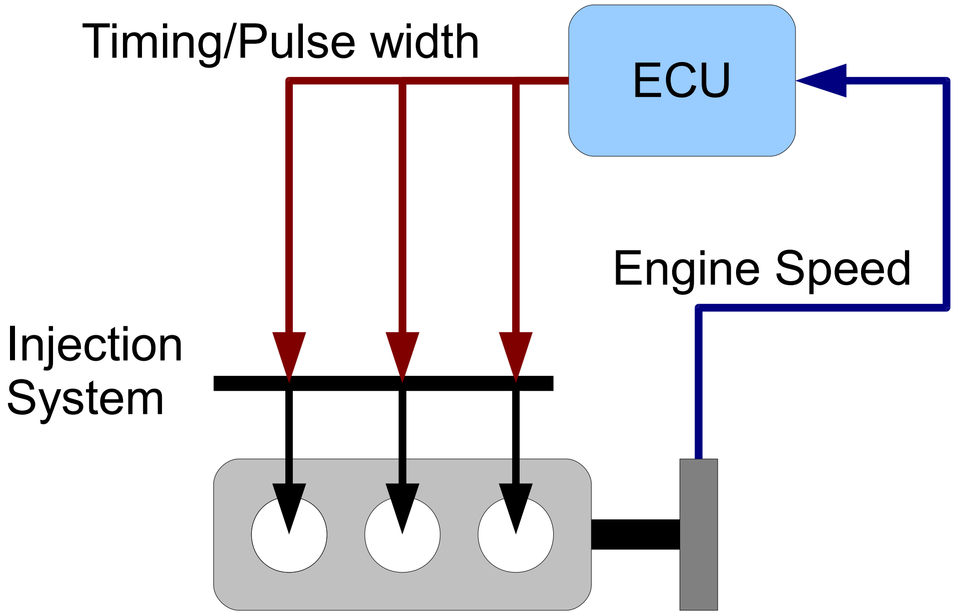
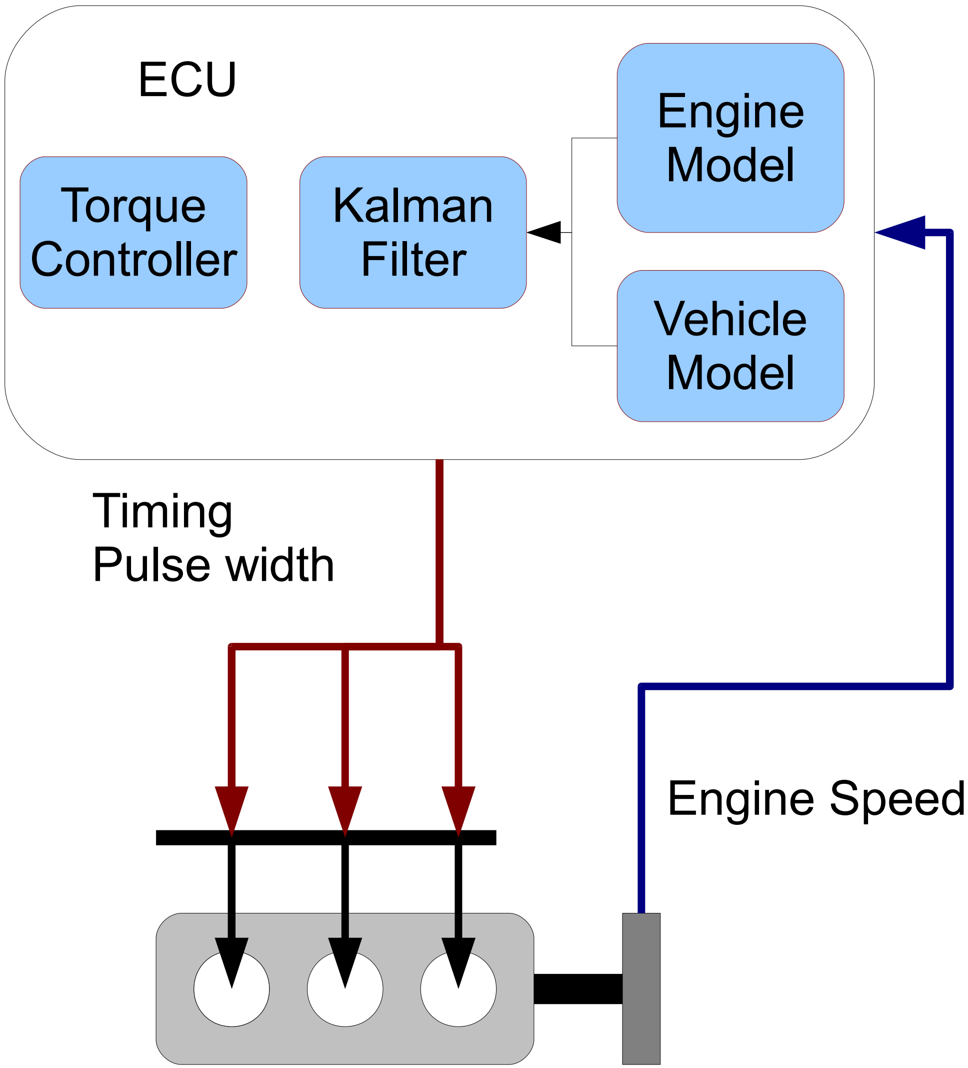
Engine Speed Control



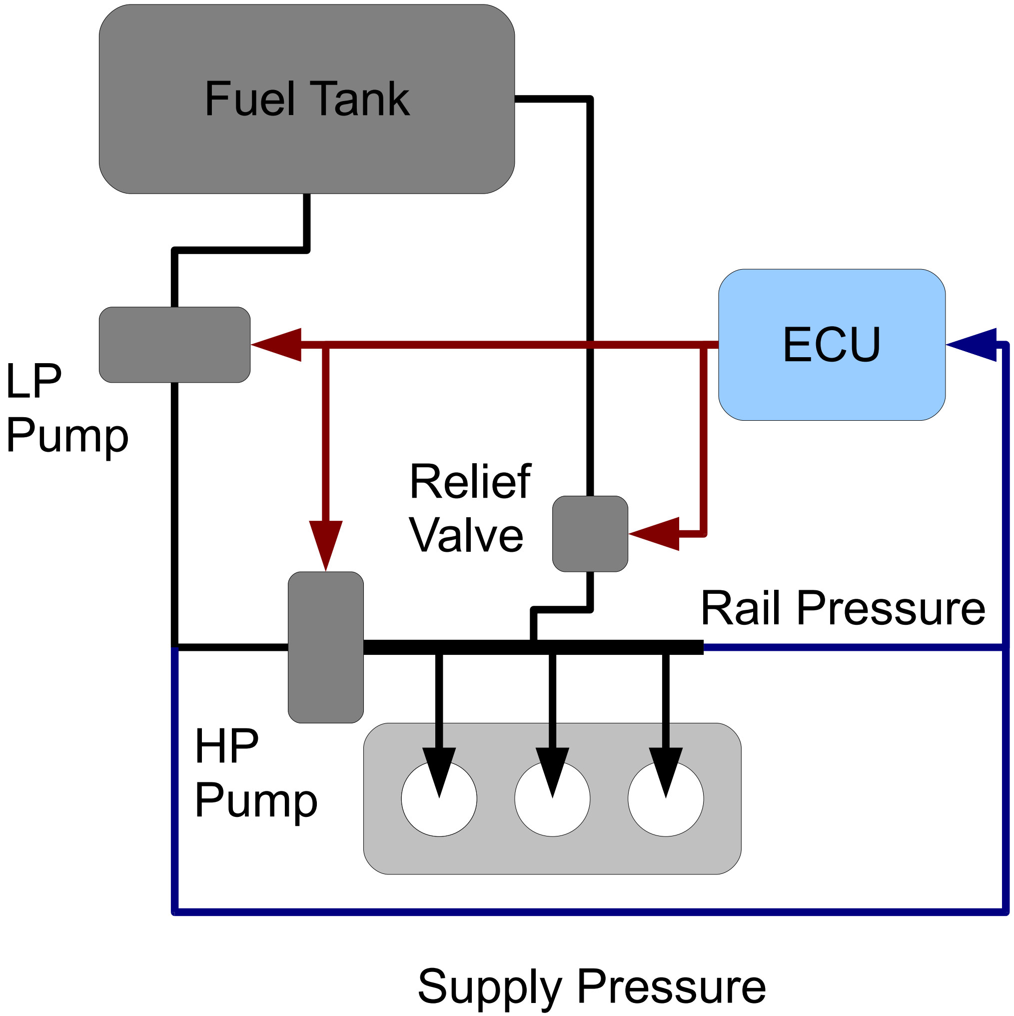
- At some operating conditions we wish to control the engine speed:
- Idle/pull-away to prevent stall
- Engine protection to prevent over-speed
- Gear-shift to aid smooth driving

Engine Torque Control



- At some operating conditions we wish to control the engine torque:
- Gear-shift in automatic cars
- Smooth engagement of ancillaries (e.g. air-con)
- Vehicle safety systems (e.g. traction control)

Fuel Pressure Control



- The fuel system in modern diesels operates at extreme pressure (2000 atm.)
- Significant impact on engine emissions, noise and durability

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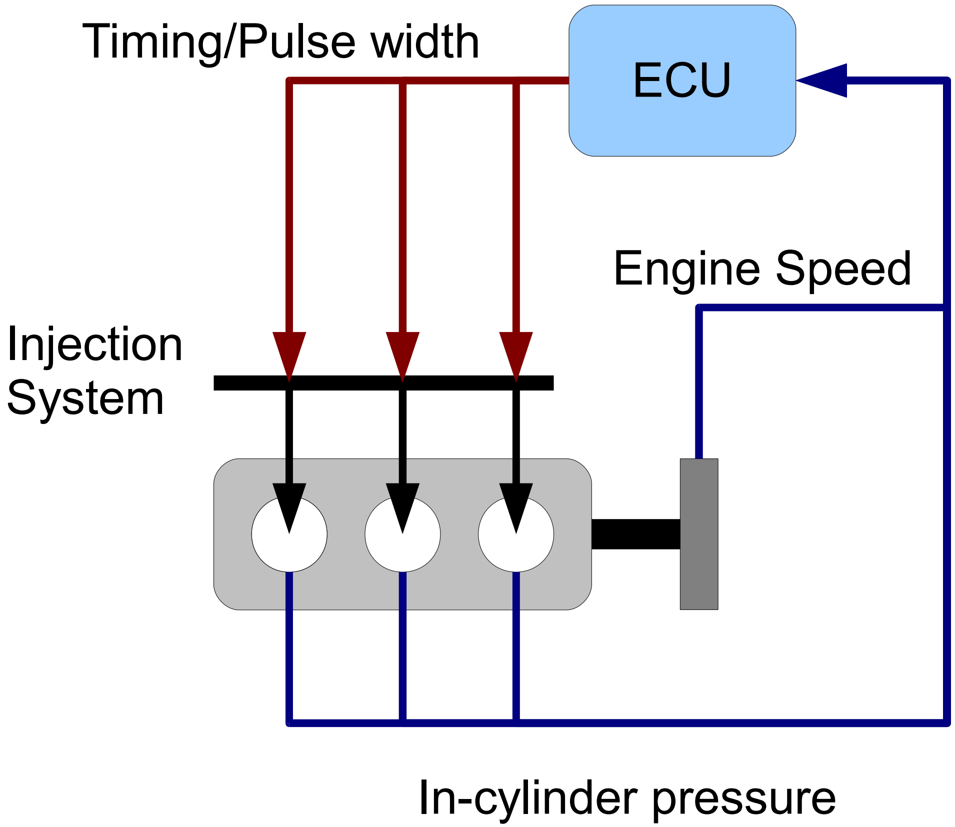
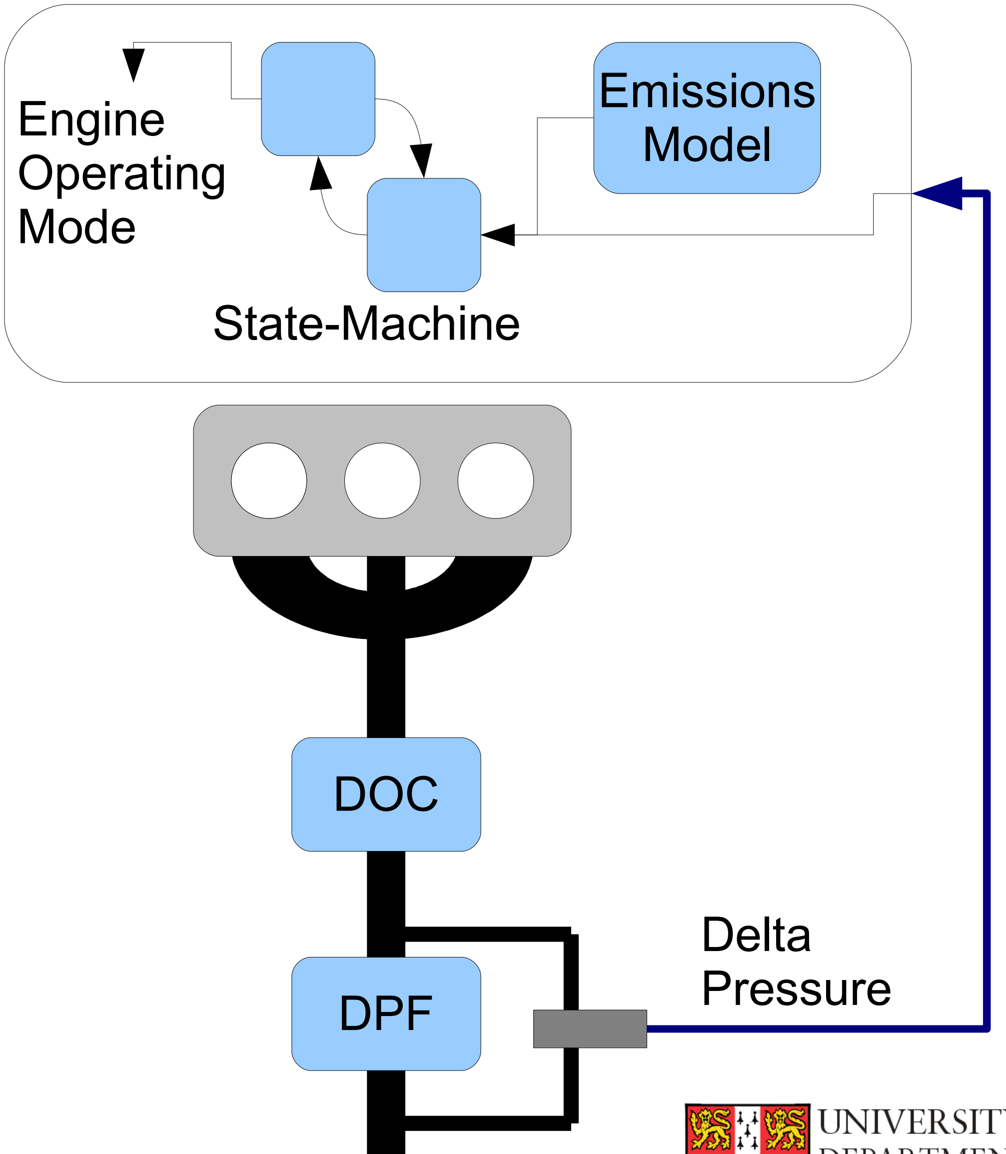
Cylinder Balancing



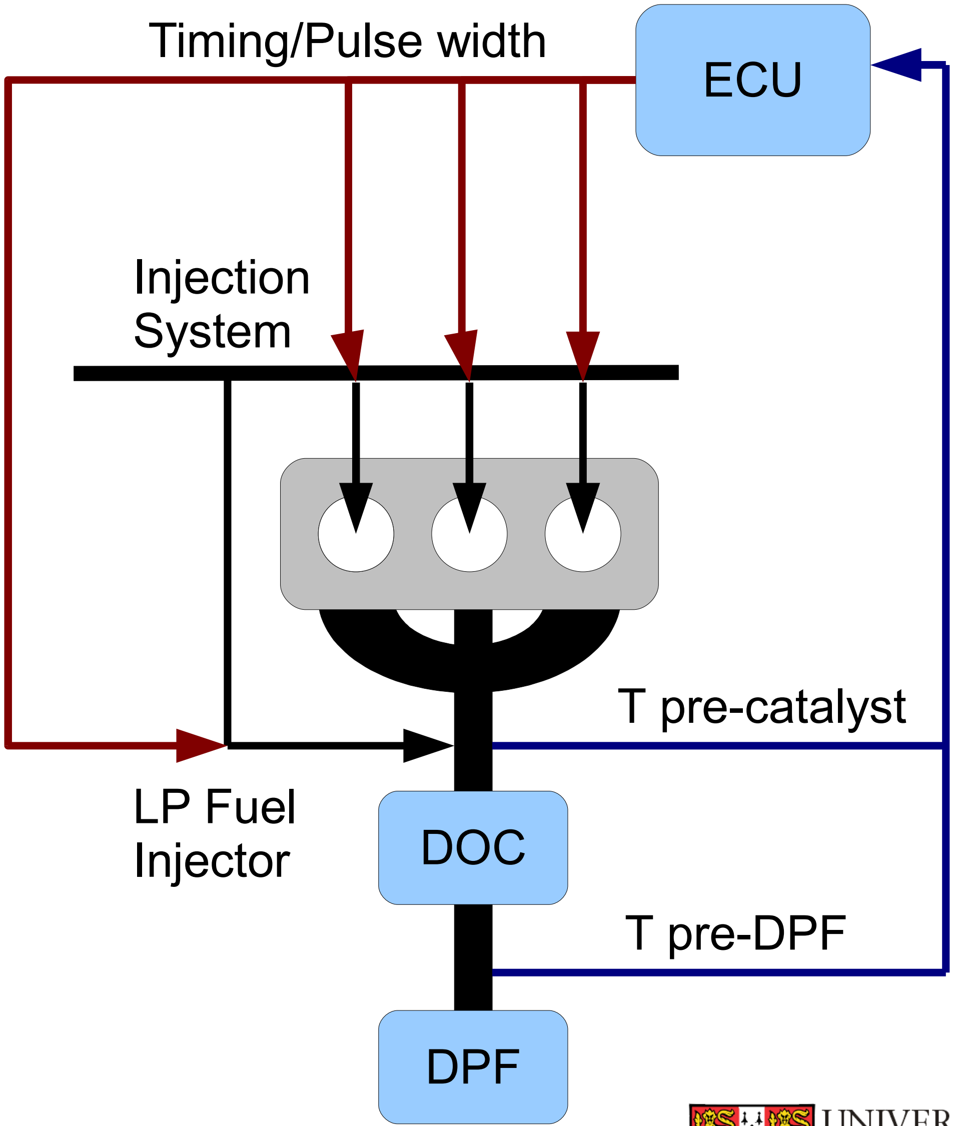
- Idle quality can be improved by measuring variations in engine speed and adjusting the fuel injected to each cylinder
- Emissions levels can be reduced by using feed-back from in-cylinder pressure transducers to give correct combustion phasing in every cylinder

Supervising Aftertreatment



- Modern aftertreatment systems (such as DPFs) require the engine to be periodically operated in a different mode to regenerate the system.
- A supervisory controller must monitor the condition of the aftertreatment system and optimise fuel economy without compromising safety.

Exhaust Temperature Control



- When the engine operates in DPF regeneration mode the temperature of the gas entering the DPF must be maintained at a certain setpoint.
- This is accomplished in 2 stages. Firstly by altering the combustion to increase engine out-temperatures.
- The remainder of the temperature increase is given by oxidising fuel over the catalyst

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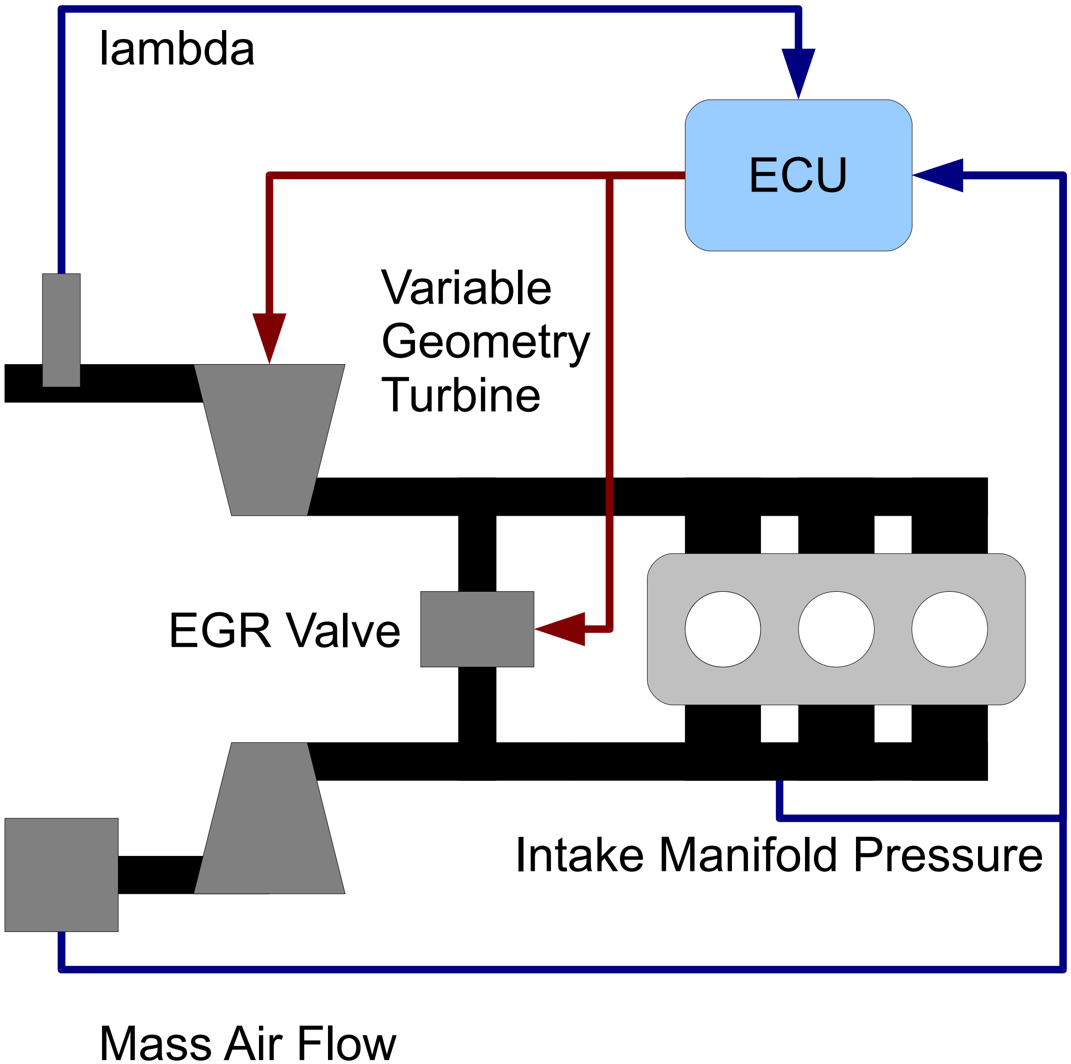
Air-Charge Control



- Typically, the EGR valve is used to regulate the air-flow to the engine and the turbine to regulate the intake manifold pressure
- A slower adaptation of the setpoints based on the signal from the lambda sensor helps to improve robustness to drift in the fuel system.

Feedback Control in Perspective

- Although essential for acceptable operation of the engine, feedback control represents only a very small part of the ECU
- In terms of lines of code or memory: diagnostics accounts for somewhere in the region of 90%
- In terms of calibration effort (10 man years total?): diagnostics, steady-state setpoints and climate corrections account for somewhere in the region of 90%

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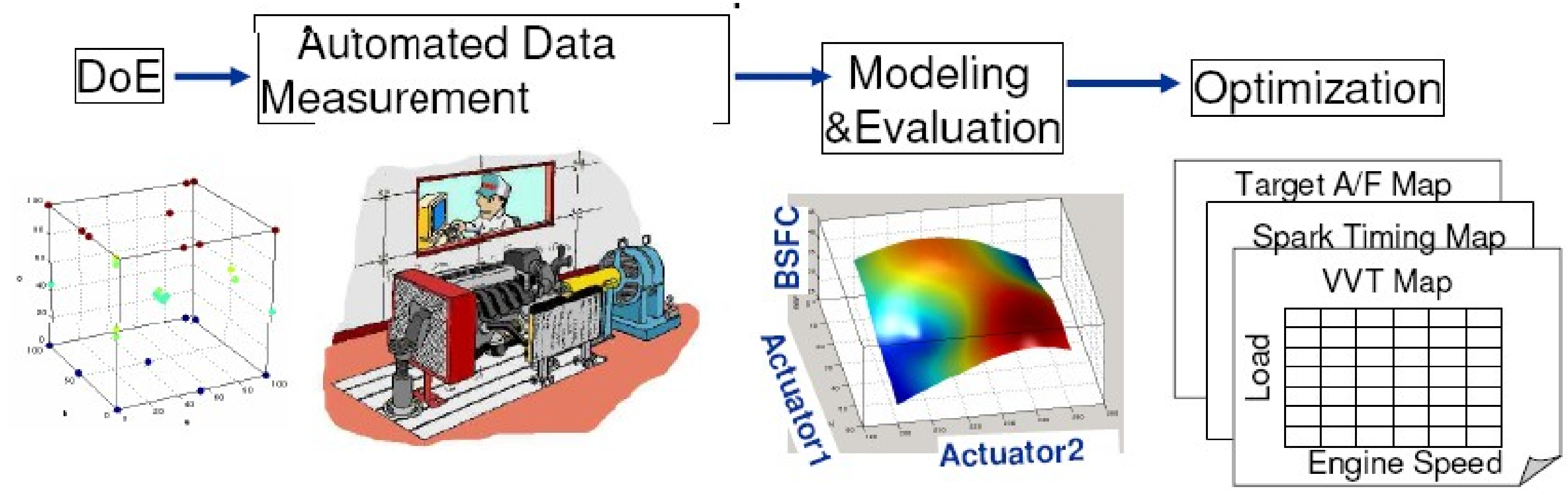
Scale of the steady-state calibration task

- Find an optimum trade-off in terms of emissions, fuel consumption, noise and combustion stability by varying:
  - Timing and quantity of up to 7 injections
  - Fuel rail pressure
  - Swirl valve and EGR cooler positions
  - Mass air-flow and intake pressure
- 4 objectives and up to 19 inputs

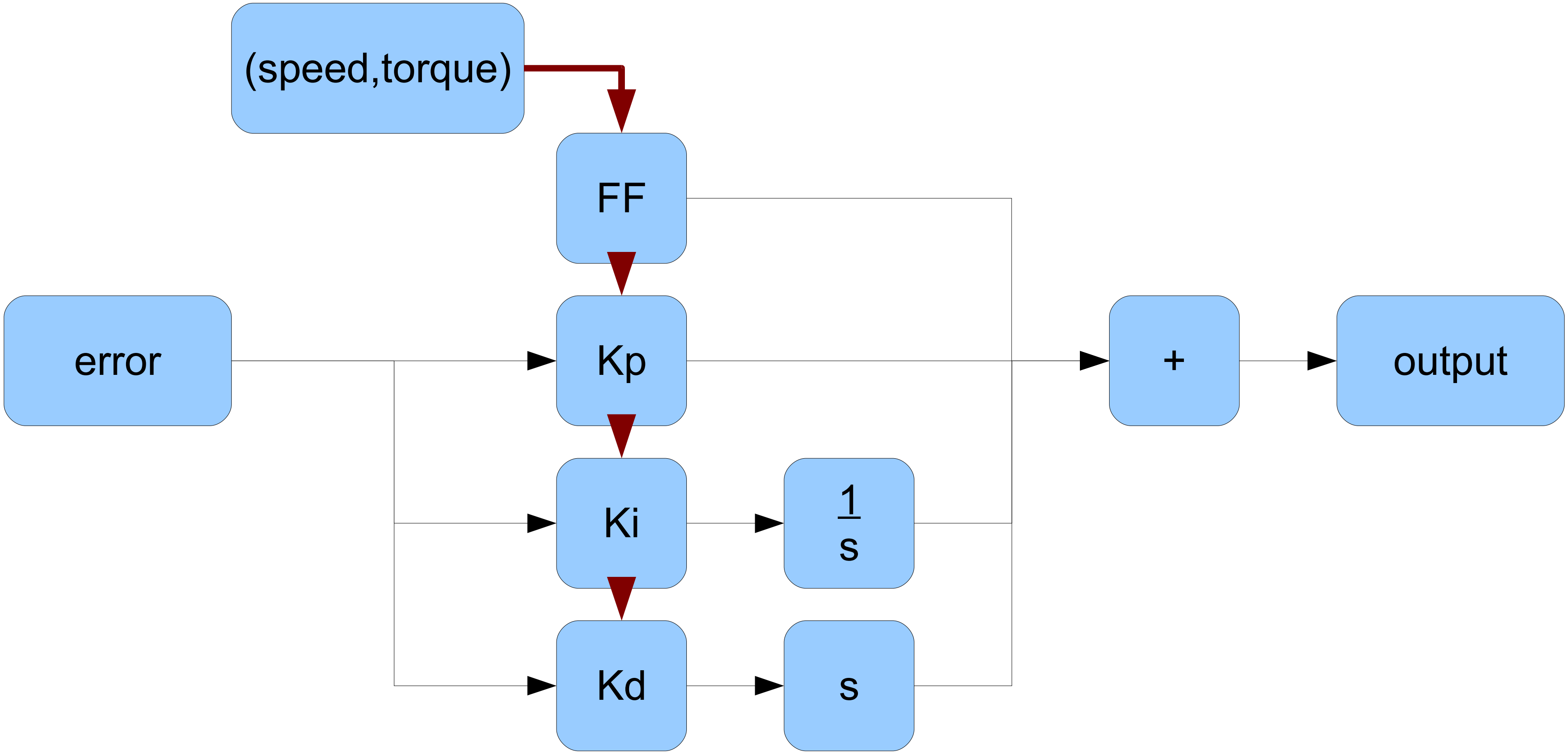
Steady-state calibration task



- Now repeat the process for operating points covering the whole engine operating range
- And do the same thing for 2-5 different operating modes.
- Then calibrate all of the above for hot/cold and high altitude operation.

Air-path control structure

- Most commonly a collection of gain-scheduled feed-forward and feed-back control loops:



Disadvantages of this approach

- Tuning gains is something of an art and benefits from (requires) experienced calibrators.
- Gains need to be adjusted/checked under all operating modes and conditions, steady-state and transient.
- Difficult to finalise controller calibration before the steady-state calibration has been completed

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Advantages of this approach

- Very rapid to implement slow but stable controllers that allow the base calibration to continue.
- Relatively quick for experienced calibrators to get acceptable performance.
- Changes are local, so fixing a problem in a particular operating mode at a particular operating point has minimal or zero effect on performance under other conditions.
- In practice, the changes in calibration and operating mode tend to require relatively minor changes in the controller gains.

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What should alternatives offer?

- At least some of:
  - Better performance
  - Easier calibration
  - Improved robustness
- One alternative that has been applied in production vehicles is based on much more physical models.

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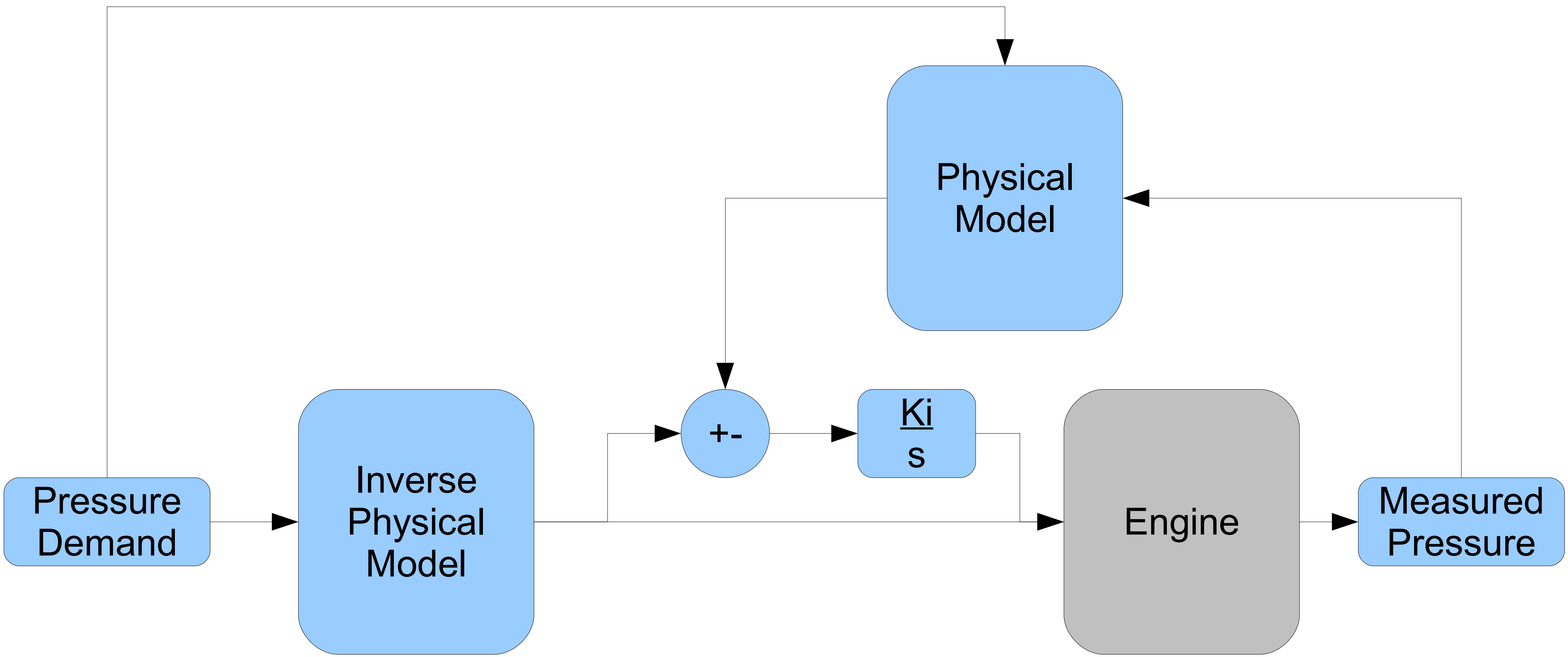
Model-based control



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Advantages of model-based control

- Feedback element is reduced to a single gain for all conditions/modes
- Strong feed-forward action gives fast response
- The inverse model includes the system dynamics and actuator saturation and reduces any integrator wind-up effects.
- Many of the model elements are physically based and in principle provided by component suppliers

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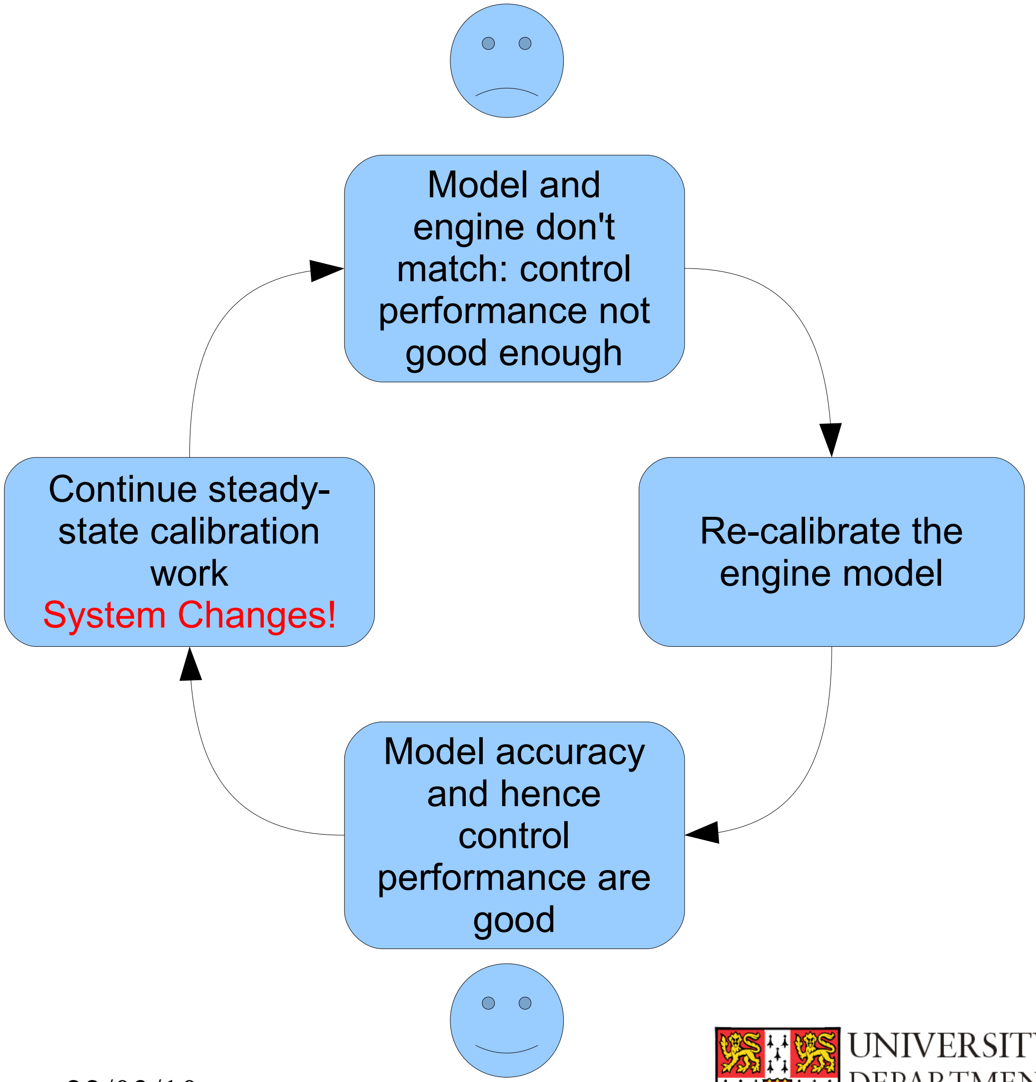
Potential calibration issues



- In practice there is the danger of falling into the following calibration cycle
- The models rely on many mapped parameters.
- These maps must change to reflect the current calibration for the controller to perform correctly

Further questions

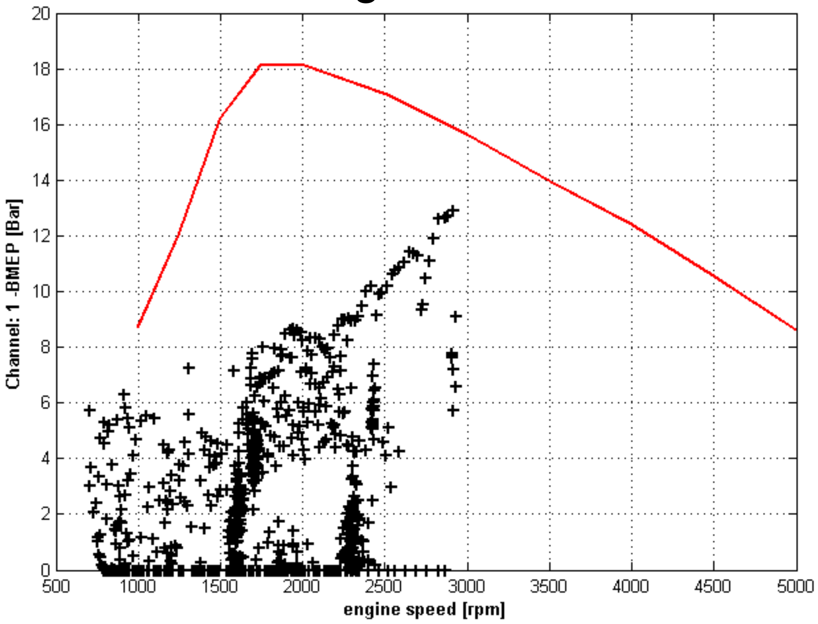
- Although more physical, the models still involve many mapped parameters with limited accuracy when extrapolating outside the mapped areas.
- Calibrating the models takes substantial time, possibly more than conventional controllers.
- Many of the model parameters are global, making changes will necessitate re-testing (and could adversely affect) performance in areas that were previously satisfactory.

PART 3
Research Directions

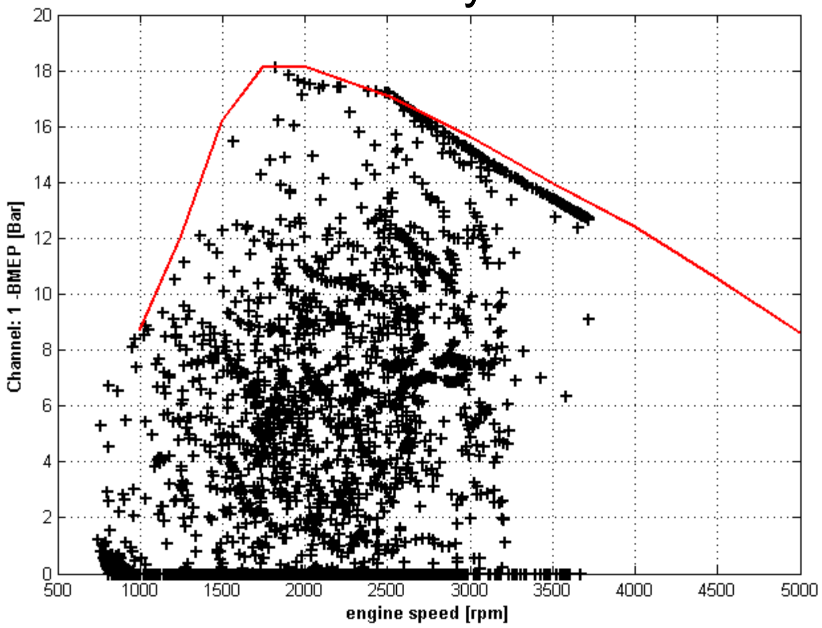
Legislation and CO_2

- Before discussing some possibilities for reducing CO2 emissions, it is worth mentioning that due to the way cars are tested, only a small part of the engine operating map is considered in official figures.

Legislation



Reality?

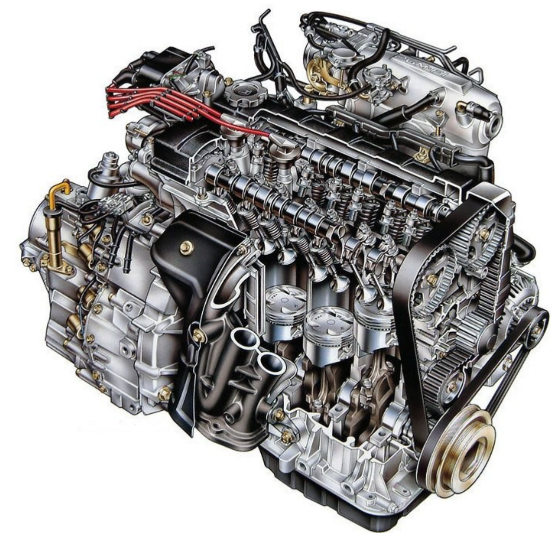


How will CO_2 be reduced?

- Base engine design:
  - Reducing frictional losses
- Alternative combustion (HCCI)
- Flexible valve-trains
- Cylinder deactivation
- Alternative fuels
- Downsizing

Downsizing

40%
Reduction
In Engine
Displacement



Fuel Consumption reduced by over 20%

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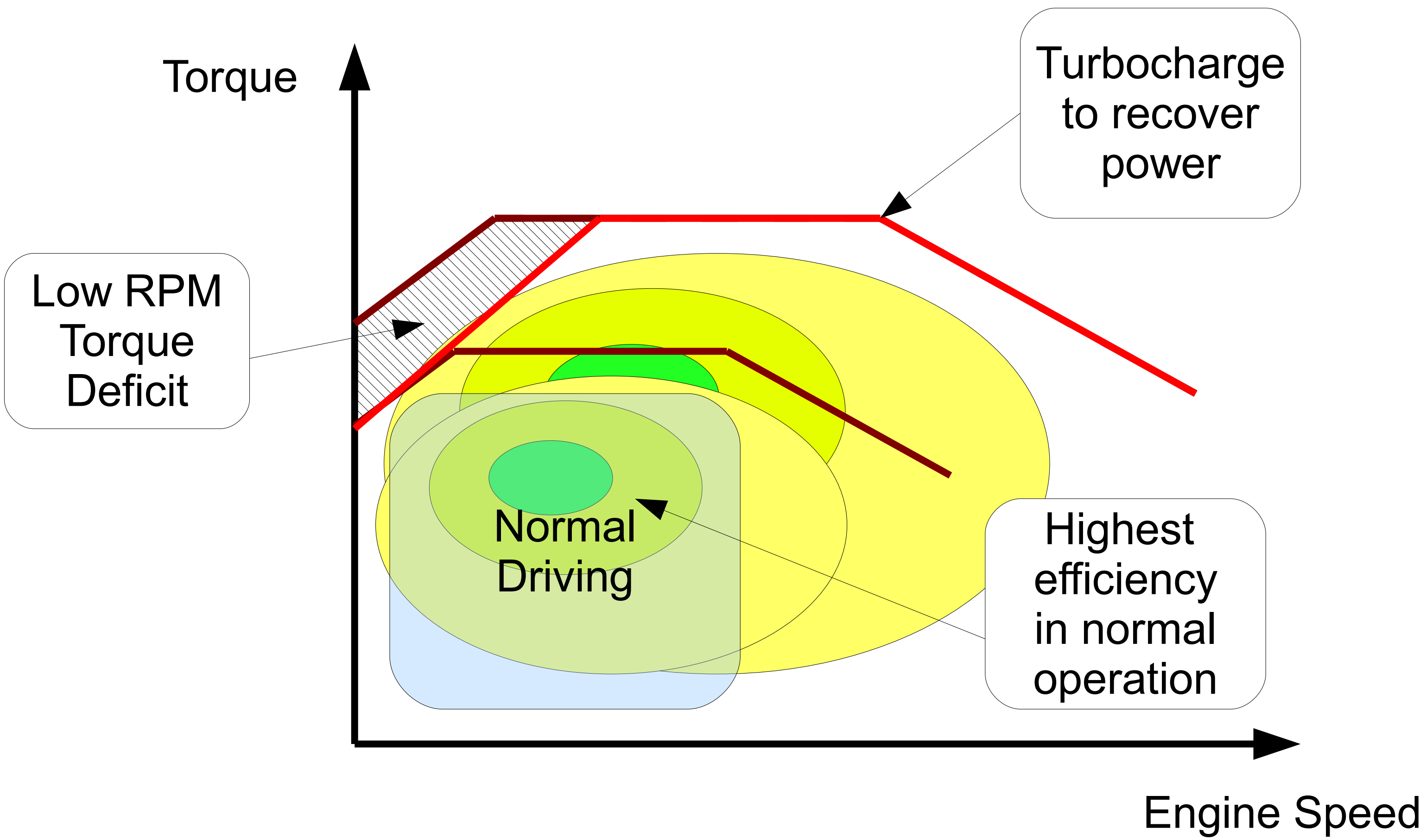
Shifting the operating point



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Challenges with Downsizing

- In addition to the innate loss of low-end torque, the turbocharger inertia will exacerbate the problem during transient manoeuvres
- For SI engines, the high efficiency requirements necessitate a high compression ratio engine. In combination with high levels of boost this can result in catastrophic Megaknock

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Recovering Low RPM Torque

- It is likely some additional technology will be used to help fill the torque deficit introduced by engine downsizing:
  - Electric turbochargers
  - Electric superchargers
  - Compressed air boost assistance
  - Mild hybridisation (Integrated Starter-Generators)

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Control Implications

- Considering these technologies naturally leads to some questions that fit within the control framework:
  - What is the optimum achievable transient performance using these new technologies in combination with the existing actuators?
  - When should the transitions between assisted and non-assisted engine operation take place?
  - How can the transitions between modes be managed to ensure smooth operation from the driver's perspective?

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Mode switching is already important

- Mode switching examples:
  - Homogeneous to/from stratified
  - HCCI to/from SI
  - Cam schedules
  - DPF regeneration
  - Start/stop
  - NOx/SOx purging
  - V4 to/from V8
  - 4-stroke to/from 2-stroke

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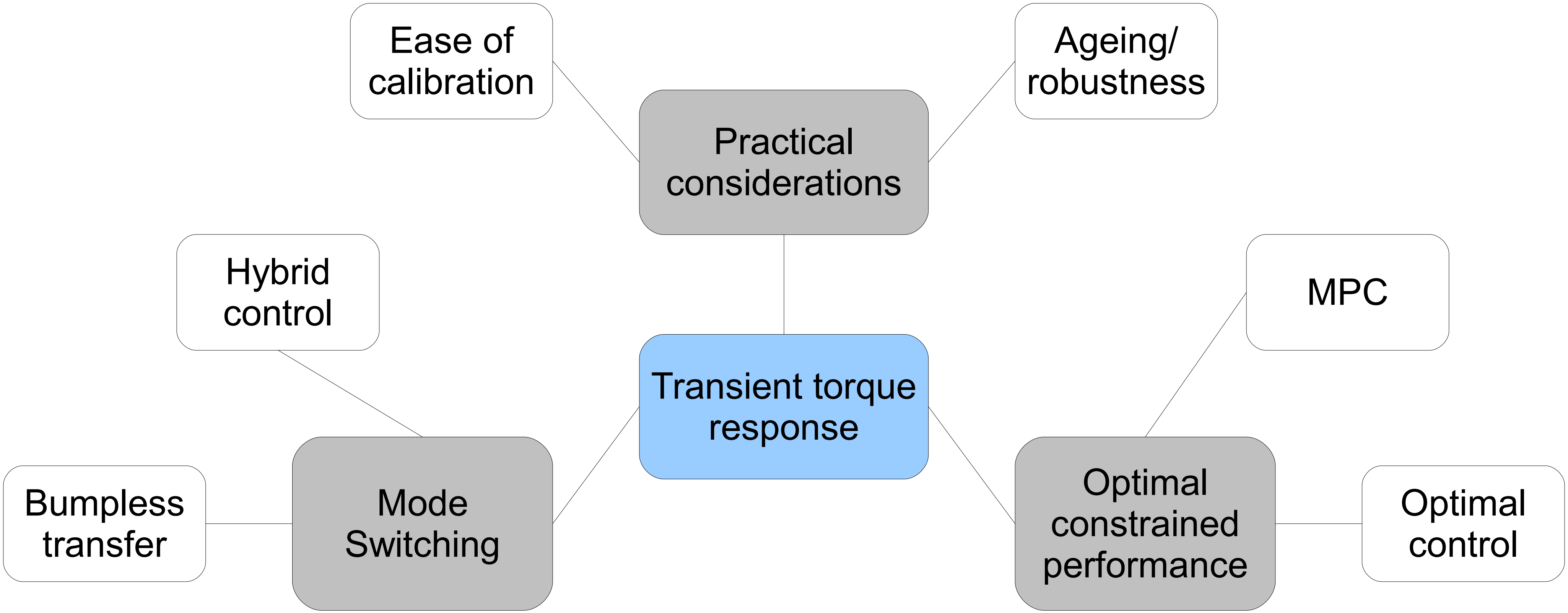
Links to Control Areas



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