Multi-strategy diesel after treatment control optimisation

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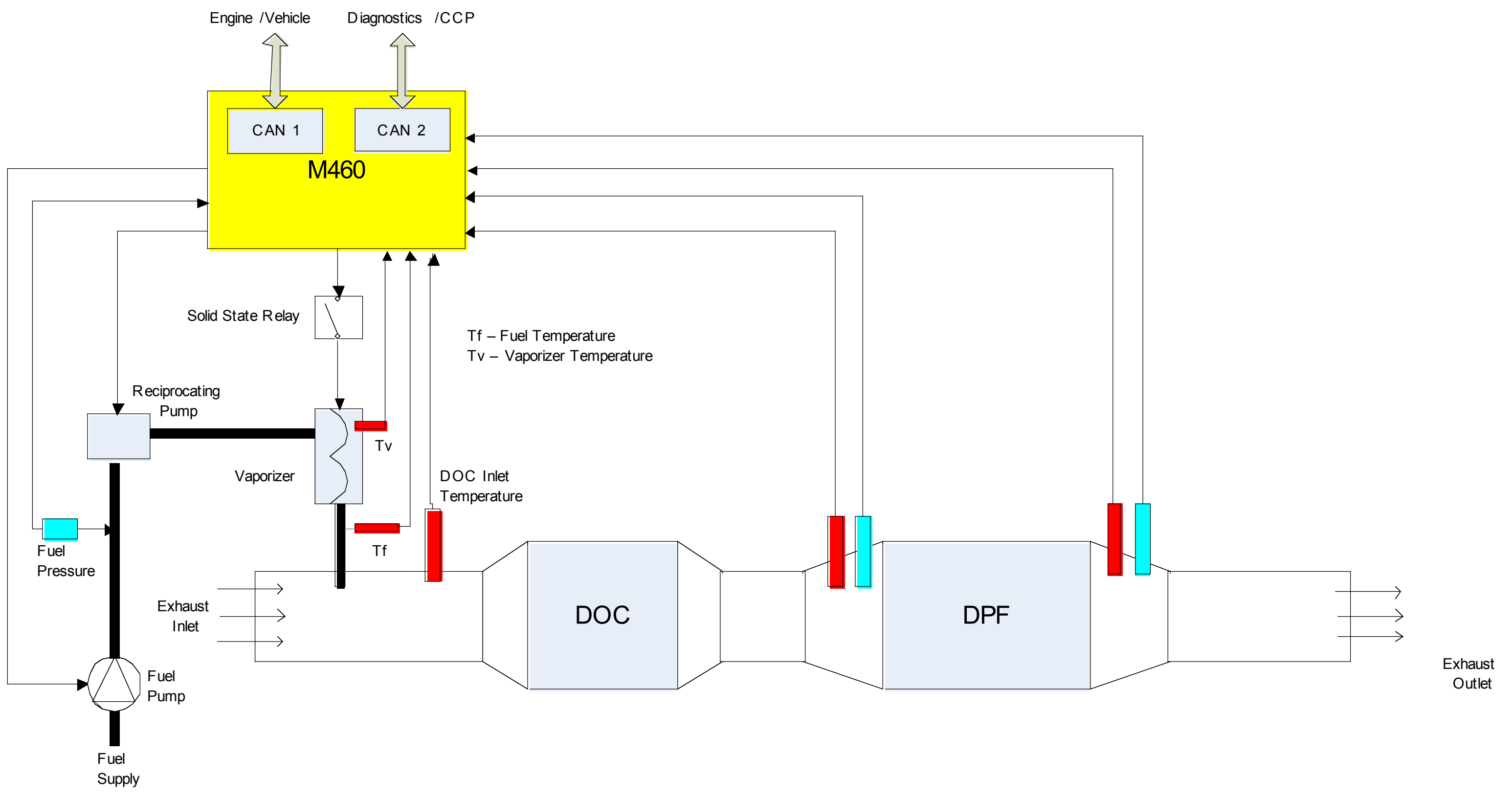
Multiple control strategies

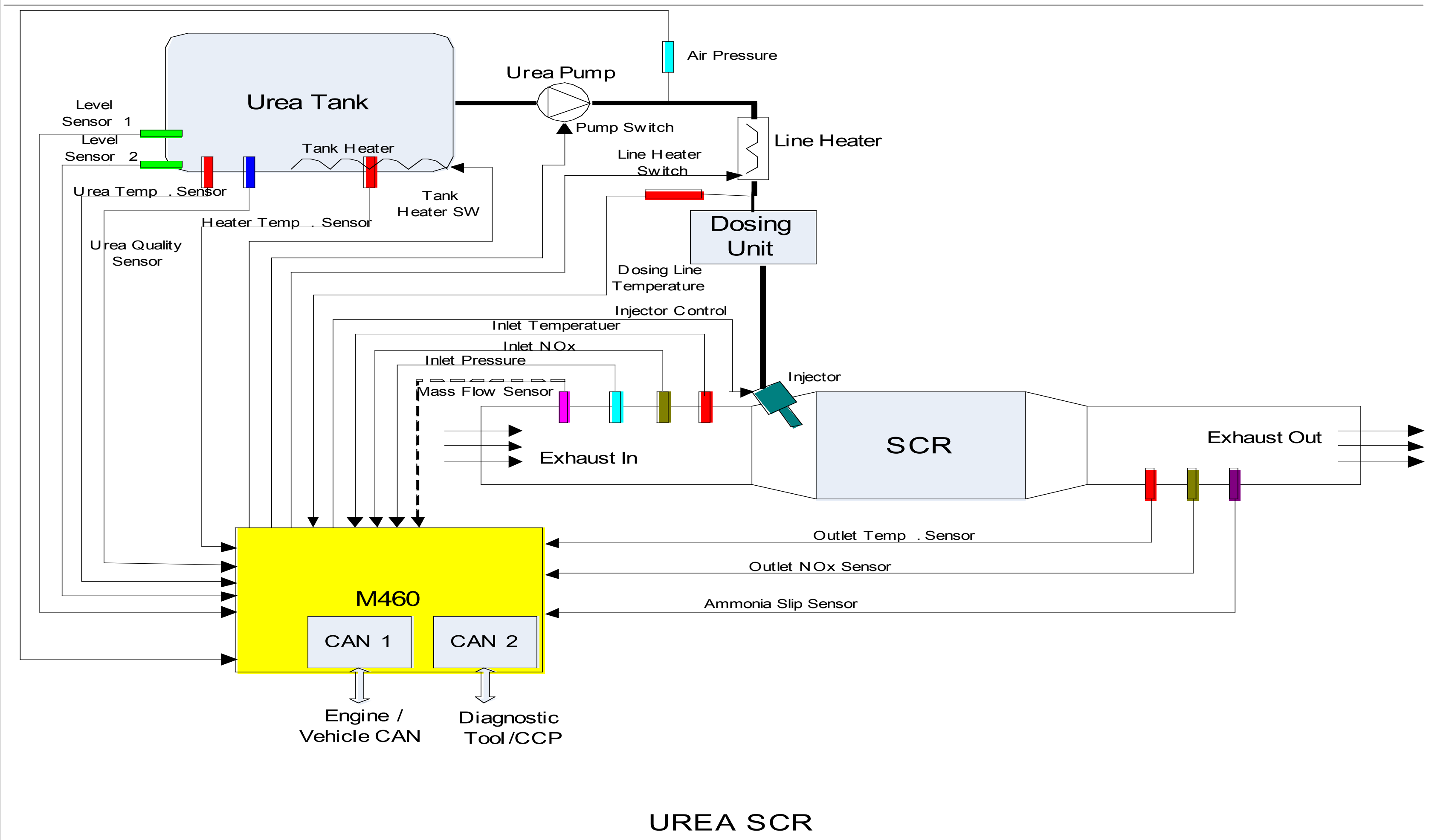
- DPF regeneration
  - fuel atomiser into DOC
  - fuel vaporiser into DOC
  - fuel burner
  - engine late injection…
  - low-load applications need more active regeneration
- NOx control
  - urea SCR
  - reformer, hydrogen SCR
  - lean NOx trap…
  - low-load/short duty applications struggle to keep SCR hot enough to work
- Different applications need different configurations
  - DPF, DPF + SCR, DPF + LNT?
  - SCR after DPF or SCR before DOC?
- Diversity is challenge for generic aftertreatment controls
  - system and strategy changes, porting to new applications

PM Aftertreatment Control Setup



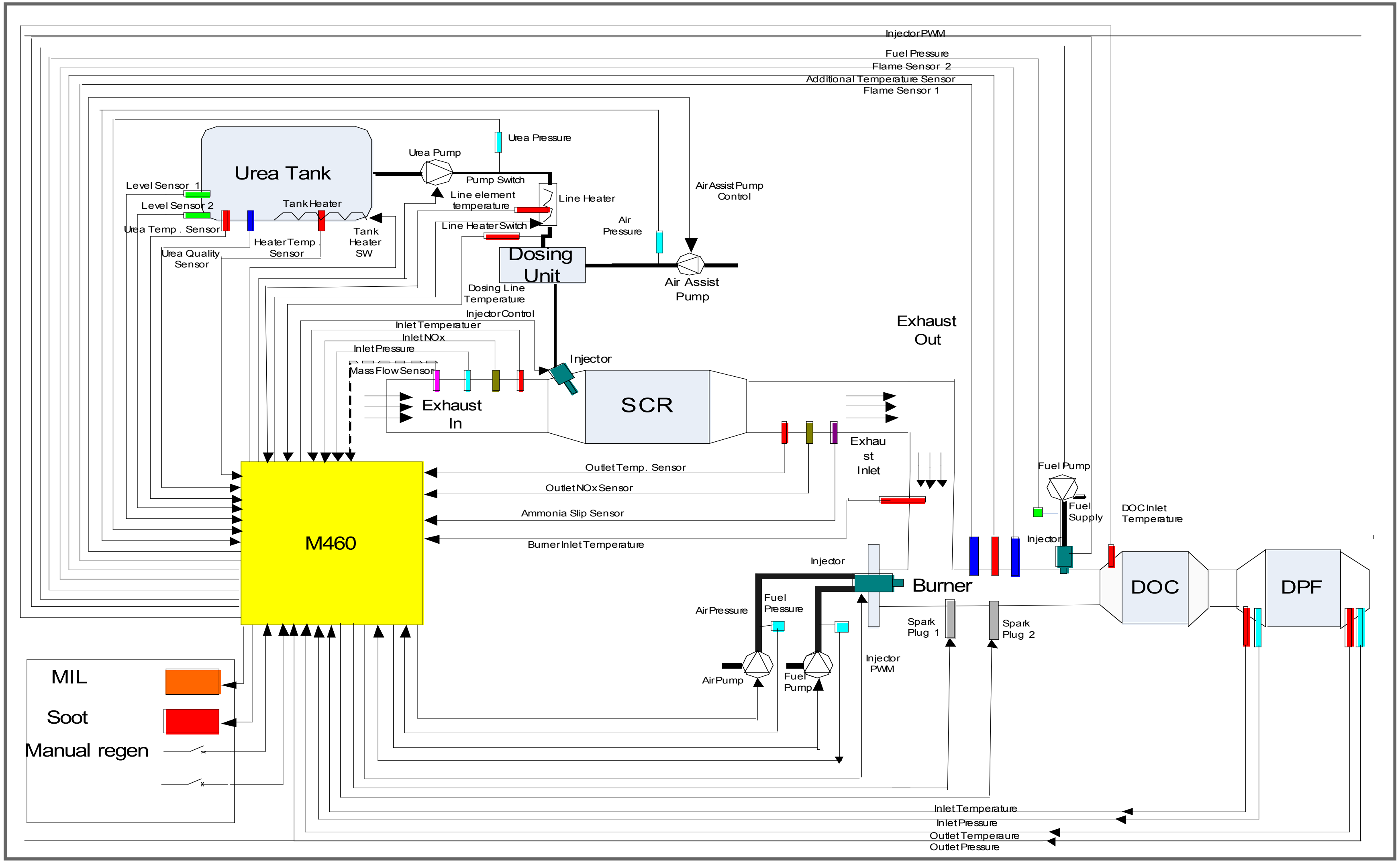
DPF WITH VAPORIZER

NOx Control Setup (urea SCR)



Most complex aftertreatment system

- this one has SCR *before* DOC



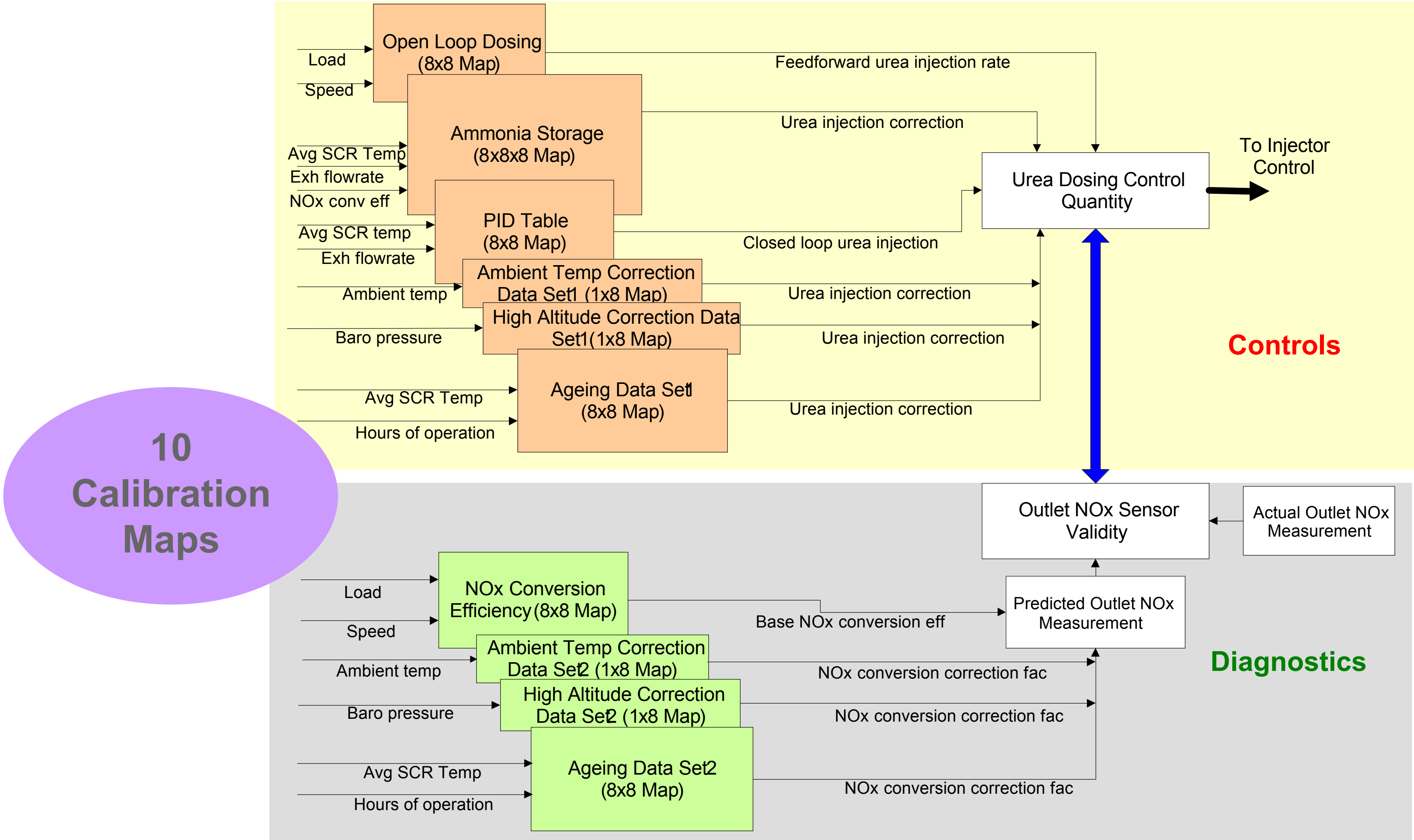
Maps versus models

- Maps: look up component outputs in tables
  - calibrated from exhaustive experiments with identical system configuration
  - high confidence but only if system remains the same as test system
- Models: use physical and chemical equations
  - thermal convection and conduction equations for the gases and the solid structure
  - diffusion and fluid flow equations to govern gas flow
  - chemical equations describe each different reaction
  - reaction rates limited by different factors in different regions
  - mass accumulation and depletion

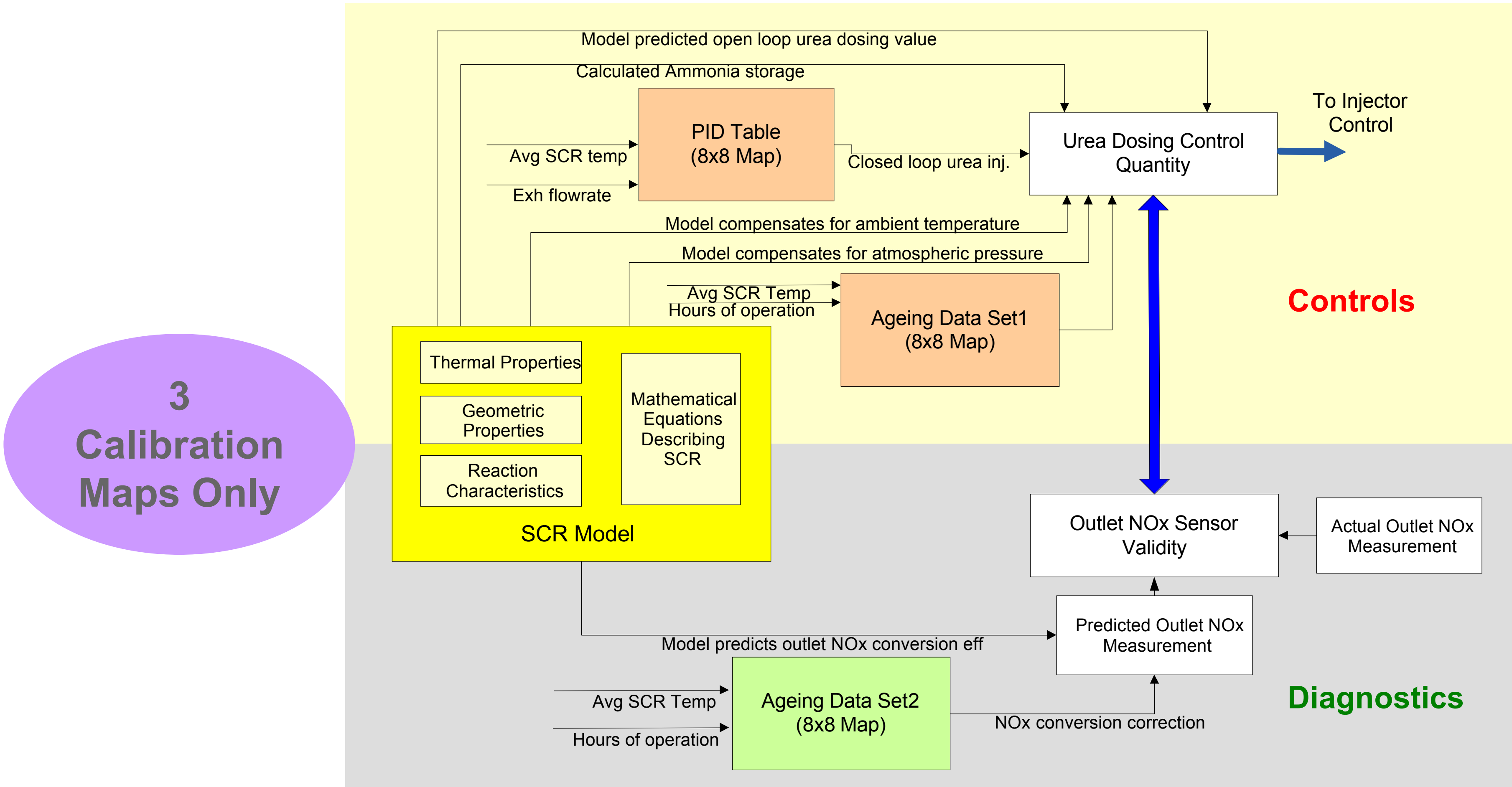
Model Based Approach (contd)

- Differing systems interact through downstream gas flow, e.g.
  - engine operating point affects gas mixture, mass flow and temperature
  - DOC temperature affects NO_2/NO ratio
  - NO_2 and DOC exit temperature affect DPF soot burn
  - remaining NO_2, NO and temperature affect SCR conversion...
- Complexity ensures that changes will occur during development!
- Model-based controls more adaptable to new "unexpected" configurations
  - don't need to tear up calibrations if new catalyst stage added or moved
  - robust models should have reasonable behaviour even outside expected areas used for calibration
  - less disruption to downstream implementation if upstream sensing or controls optimised or changed
  - minimal dyno time to re-validate after changes
- Model predictions provide OBD reality check for sensors

Map-based approach…



…and equivalent model-based approach

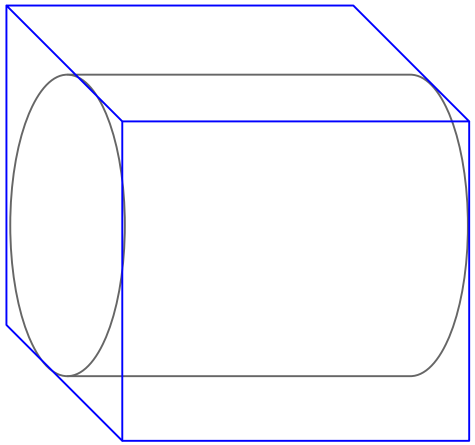


Model-based versus calibration: a continuum

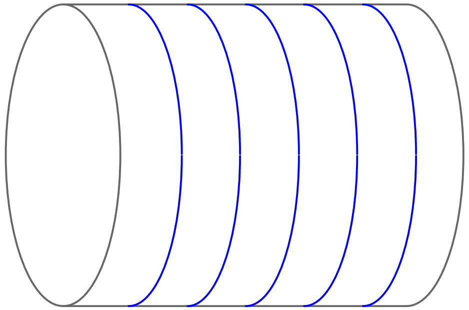
- Models still have calibration tables
  - exhaust gas composition from engine operating point
  - exhaust soot load from engine operating point
  - empirical catalyst aging factors
  - empirical chemical rate constants
- Map-based controls still have equations
  - multiple scale factors combined
  - trigger points (temperature, pressure) acted upon
  - closed-loop feedback in physical terms
- Model-based control:
  - maximises use of basic physics and chemistry
  - minimises empirical look-up tables
  - still needs basic data for physical catalyst sizes and material properties

Dimensionality of models – what is good enough?

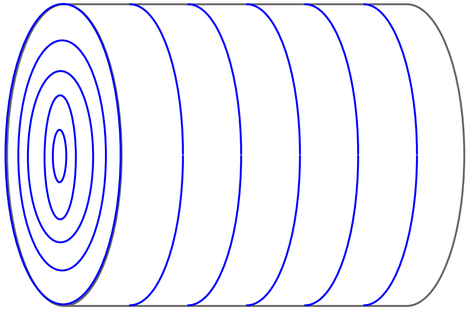
0-D: average scalar values represent entire catalyst



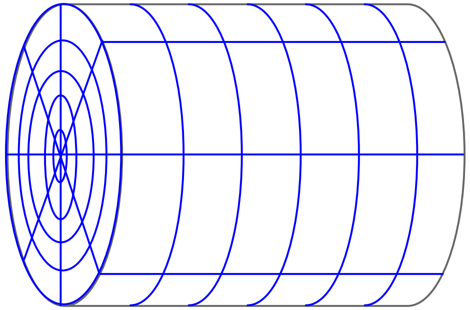
1-D: 'x' longitudinal slices; lengthwise behaviour modelled



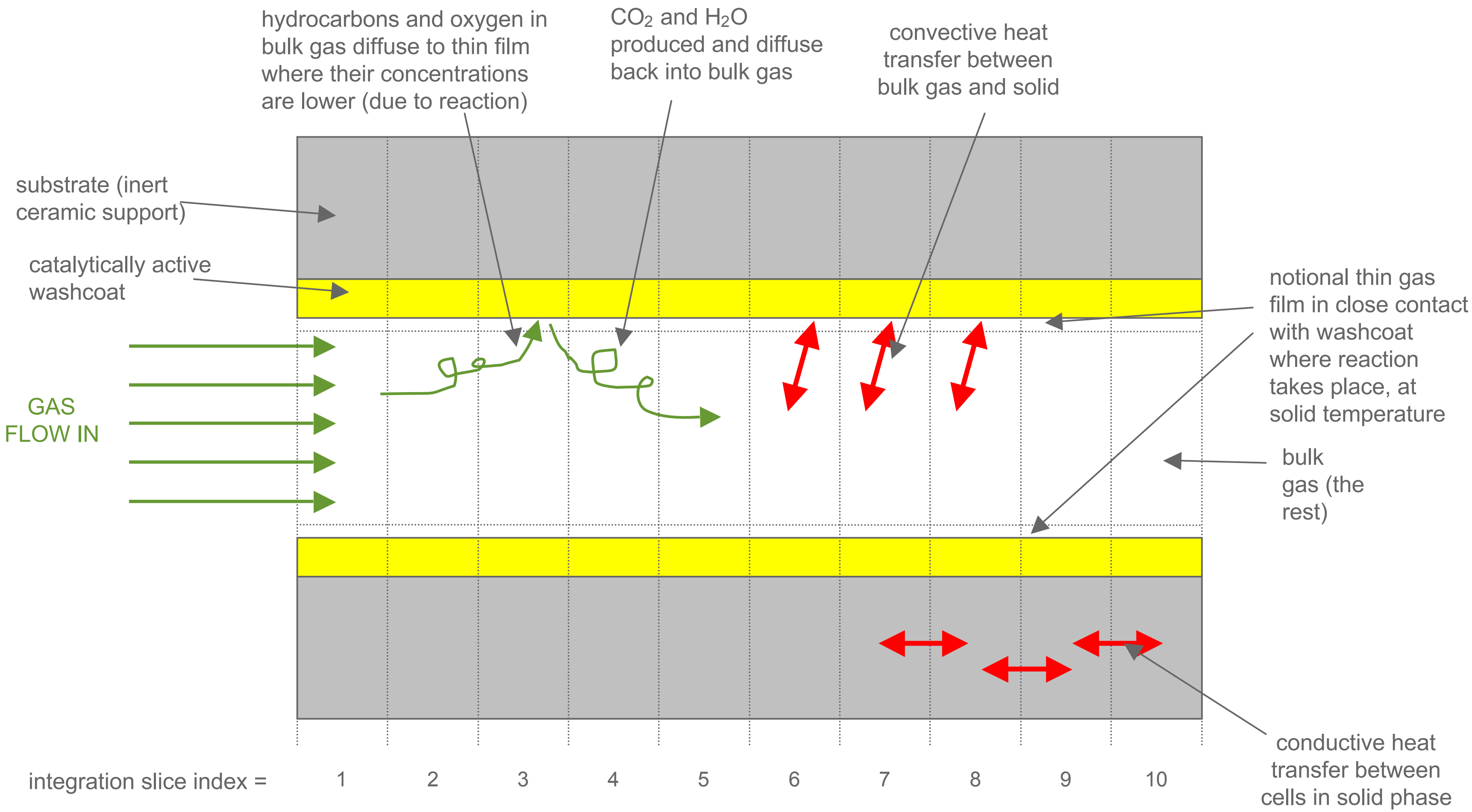
2-D: 'x' longitudinal slices and 'y' radial layers; radial behaviour modelled



3-D: 'x' longitudinal slices, 'y' radial layers, 'z' angular segments; radial asymmetry allowed



1-D DOC model principles

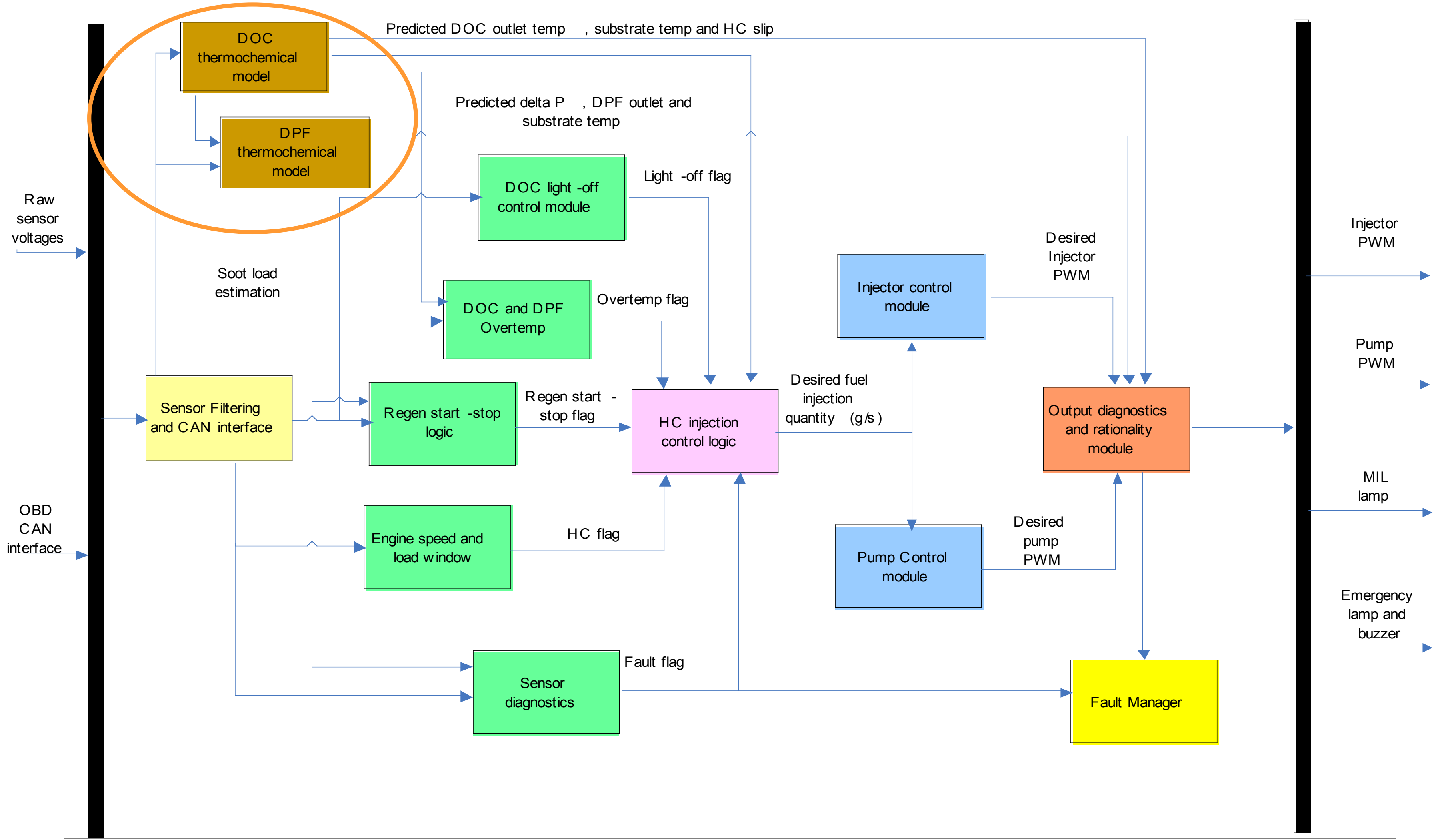


Theory into practice

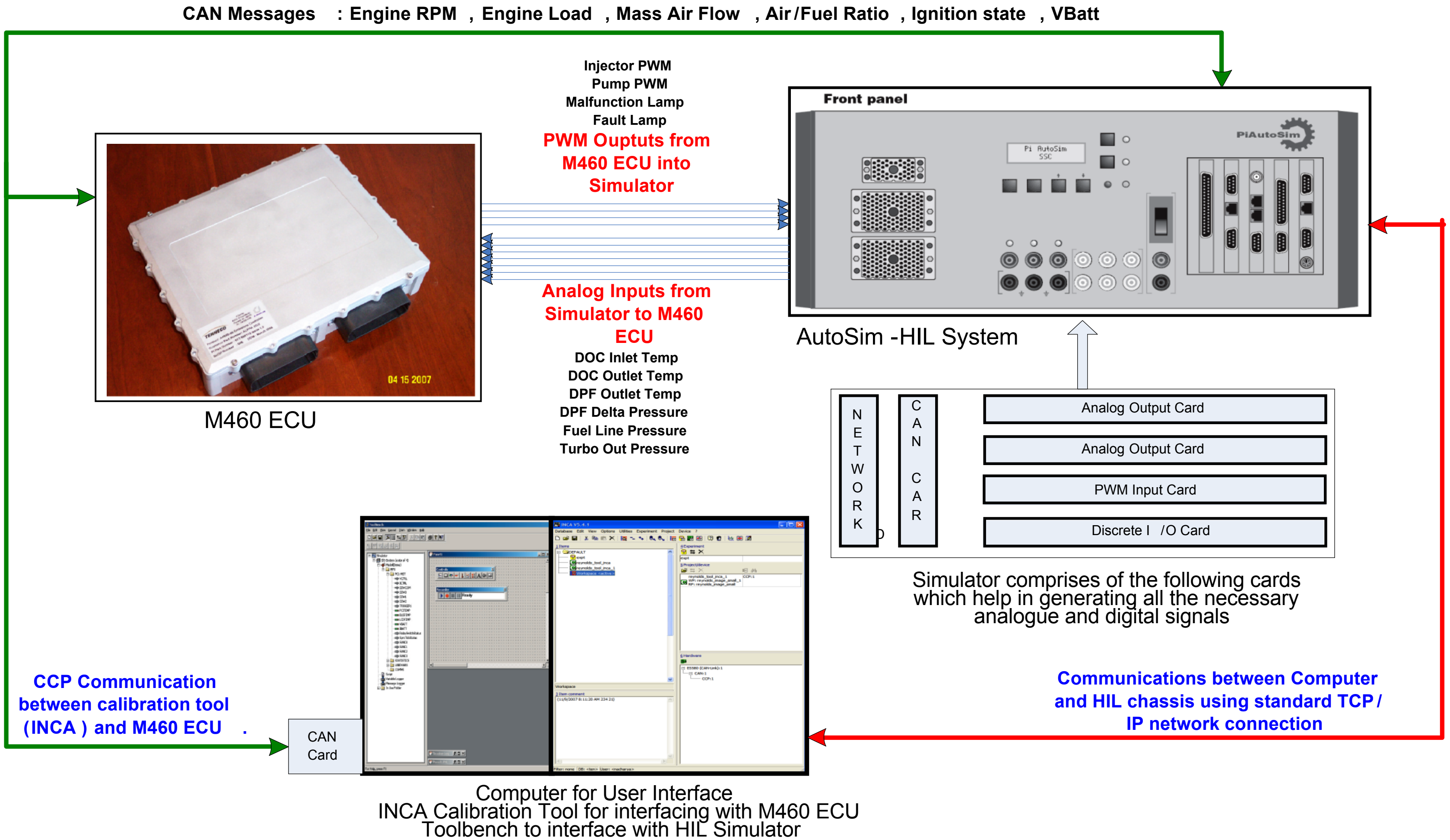
- 1-D DOC and 0-D DPF models implemented on generic controller
  - active DPF regeneration control using exhaust fuel injection into DOC
  - "virtual sensor" readings to actively control fuel dose and temperature
  - SCR under development
- Simulink model autocoded to C
  - 80 MHz MPC5534
  - 64 kB RAM
  - 512 kB code space, 256 kB calibration space
- Additional software:
  - control strategies that *use* the models
  - I/O processing
  - communications
  - fault detection and management
  - diagnostics

HCI Control Software Architecture

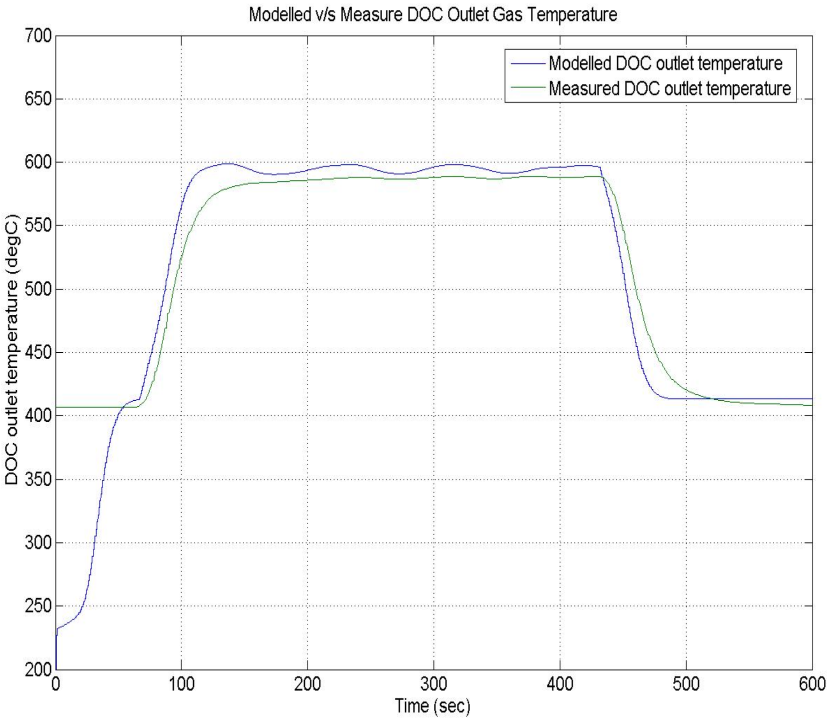
- models are only part of whole software system



HCI control strategy HIL testing...

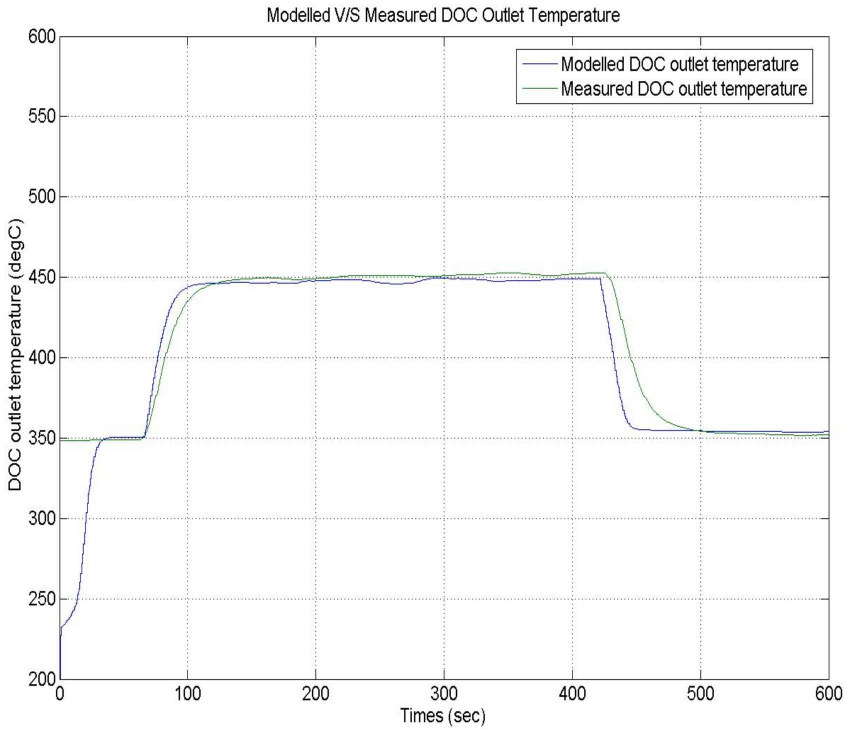


DOC model performance in steady-state dyno regeneration

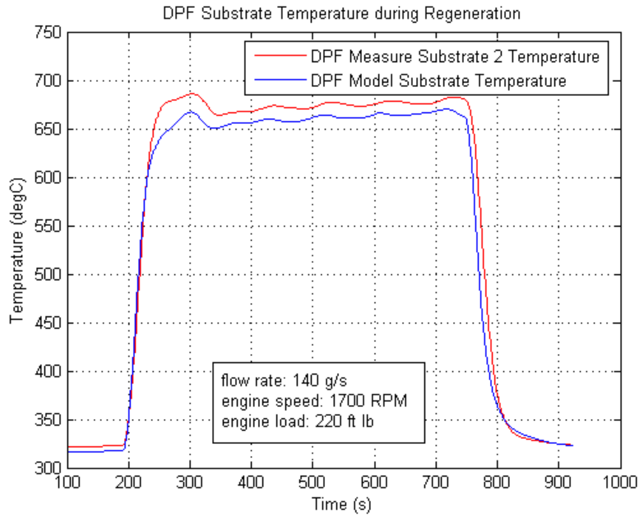


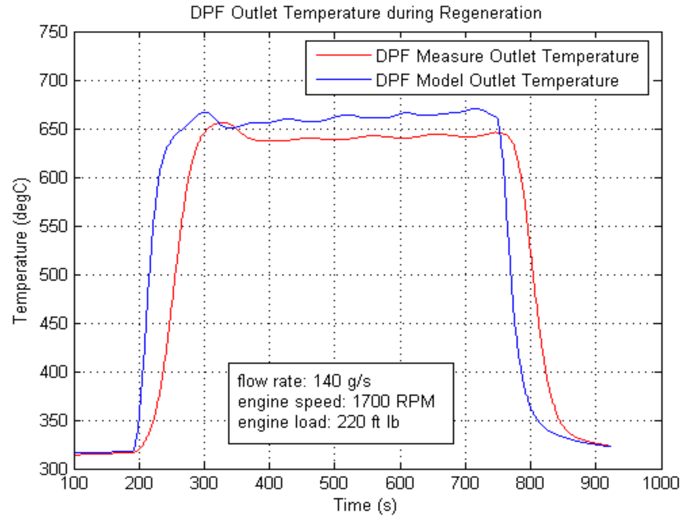
Comparison of predicted and measured DOC outlet temperature for 0.5 g/s fuel injection at 180g/s flowrate and DOC inlet 350°C (1800 RPM, 300 ft-lb)

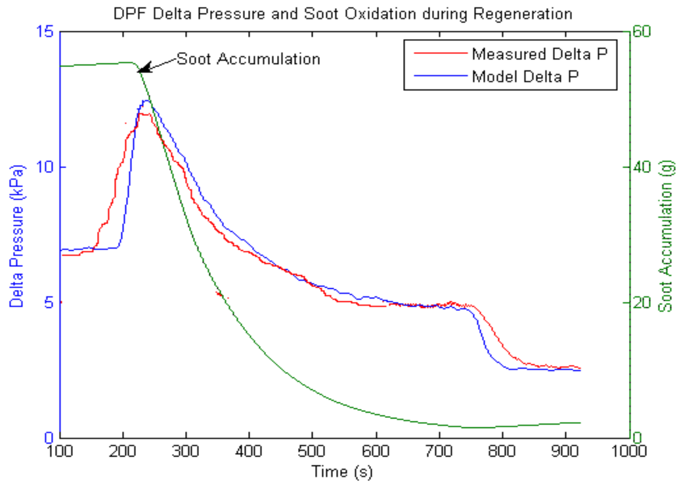
Comparison of predicted and measured DOC outlet temperature for 0.5 g/s fuel injection at 100g/s flowrate and DOC inlet 400°C (1300 RPM, 325 ft-lb)



DPF model performance in steady-state dyno regeneration

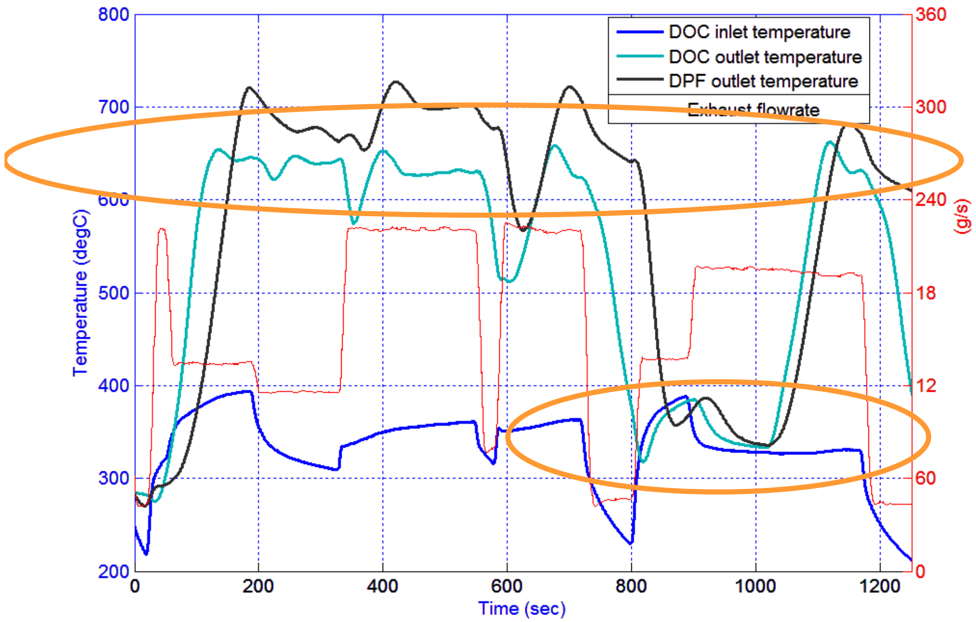


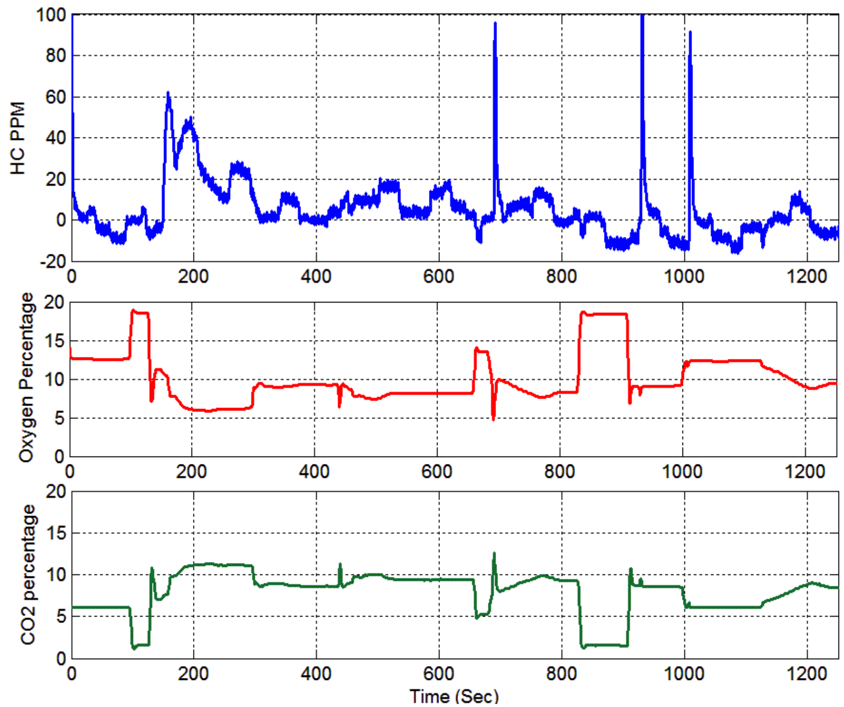




- Predict the DPF substrate and outlet temperature
- Accurately predict DPF ΔP
- Predict soot loading and unloading
- Simple 0D model surprisingly effective

Control strategy performance in transient tests on dyno

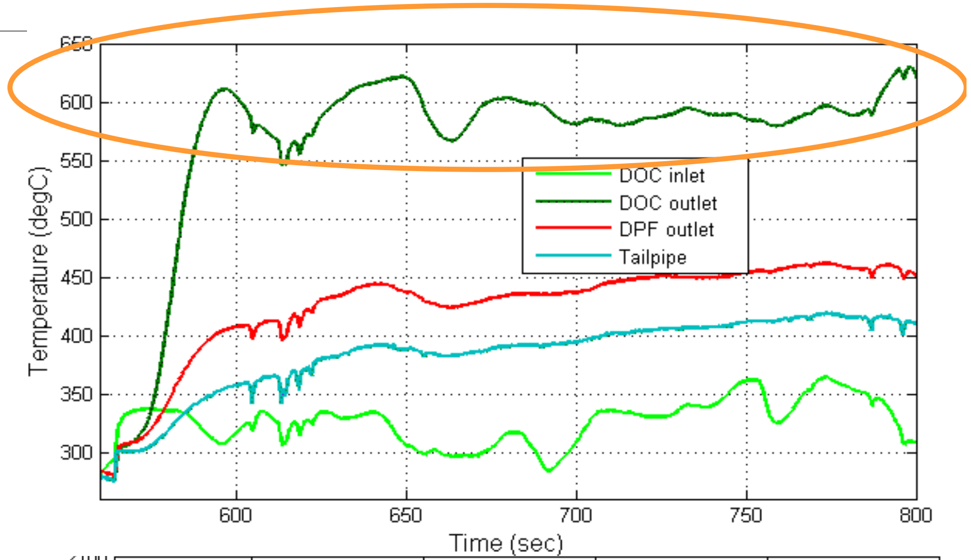


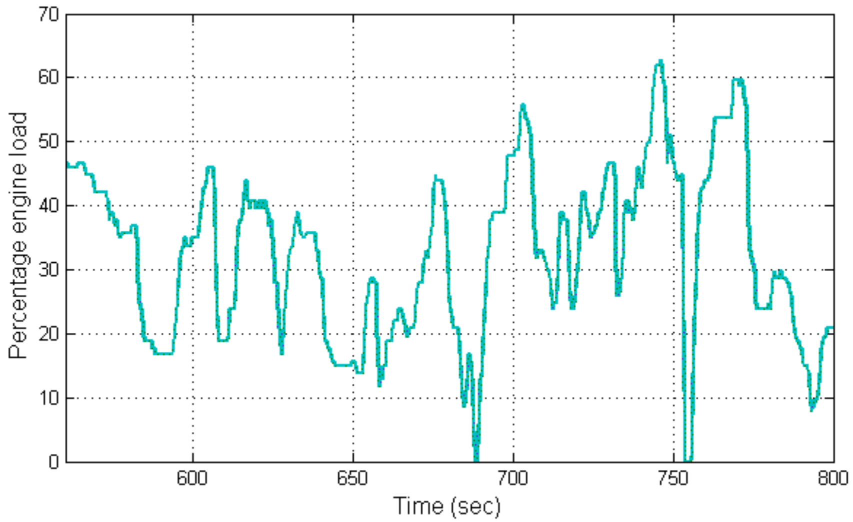


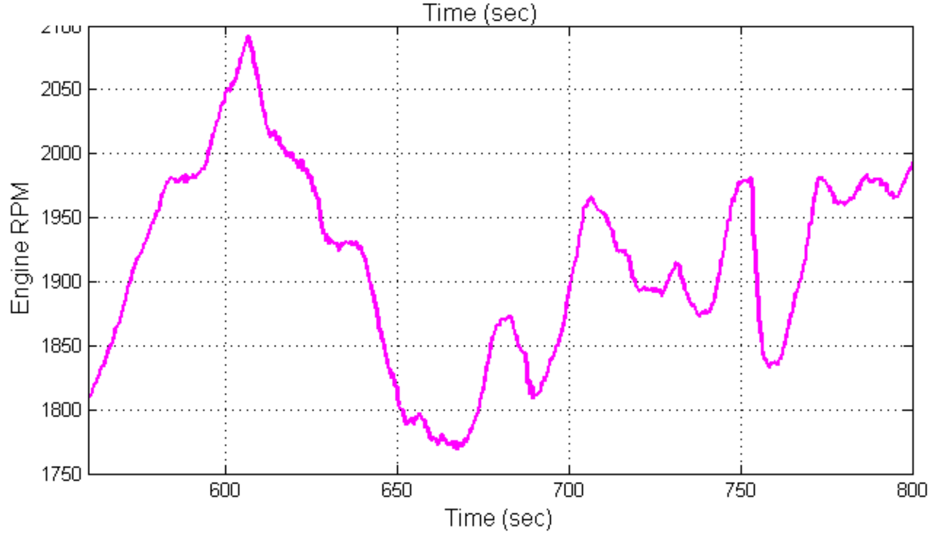
- 630C target DOC outlet once regeneration triggered
- had to pause during idle condition

On-road transient drive cycle performance

- Target is to control DOC outlet temp to a steady 600C during transient driving
- Successful despite varied drive cycle and transients







Conclusions

- Different vehicles need different aftertreatment configurations and control strategies
  - Models can be combined in different configurations without extensive recalibration
  - Different control strategies can be employed making use of model virtual sensor "measurements" depending on vehicle use profile
  - Allows re-use of generic software components
- 1-D DOC model sufficient to give good temperature prediction
  - can also use predicted output gas composition downstream
  - good enough to validate operation of output temperature sensor
  - control strategy can take advantage of expected fuel burn with known internal temperatures
- 0-D DPF model sufficient to predict temperature and soot
  - very simple model gives good delta pressure and temperature agreement with reality
- Models easily run within CPU constraints of general-purpose ECU
  - prototype experiments refined to production solution without slow optimisation
  - avoids risks of big jump from high-performance prototype to production hardware

References

- SAE 2009-01-2904 “Real Time Implementation of DOC-DPF Models on a Production-Intent ECU for Controls and Diagnostics of a PM Emission Control System”
- http://www.pi-shurlok.com