Hybridisation and splitting of a crank angle resolved internal combustion engine using a mean value intake for real-time performance

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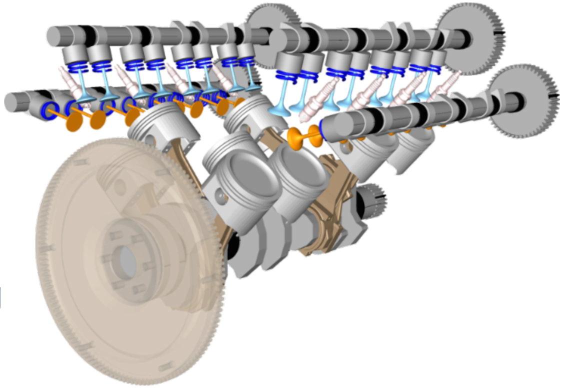
Agenda

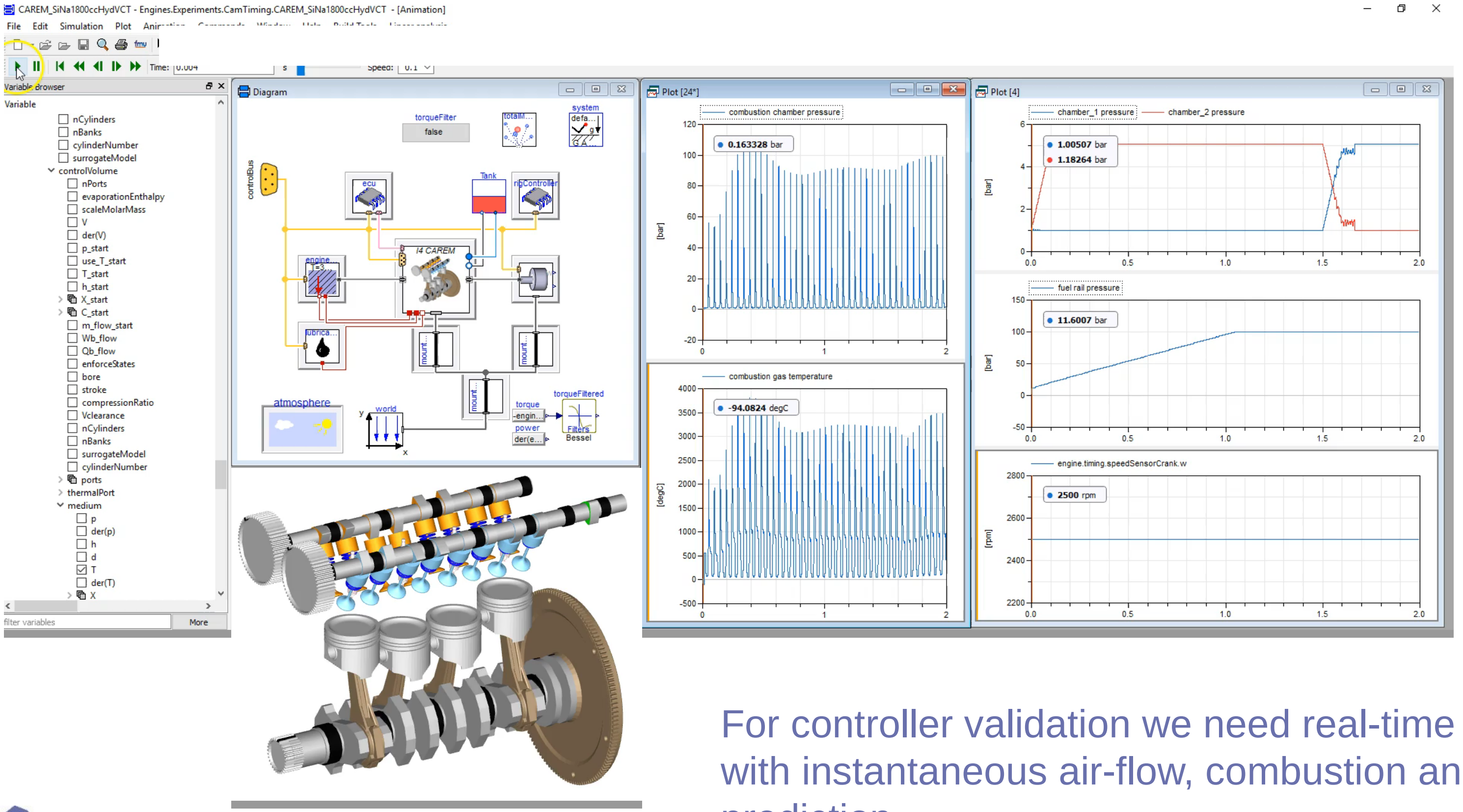
- Who are Claytex?
- What is Crank Angle Resolved Engine Model (CAREM)?
- Splitting CAREM to run on multi-core processor, with/without feedback loops.
- What is Mean Value Engine Model (MVEM)?
- Use of MVEM in CAREM combustion simulation.
- Performance evaluation of MVEM with CAREM combustion in Dymola.
- Real-Time performance evaluation of MVEM with CAREM combustion on hardware.
- Calibration of MVEM using controller design.
- Automation of calibration process.
- Summary.

Who are Claytex?

- Model-based engineering analysis consultancy
  - Innovators in CAE process
  - Leading the way on zero-prototype development
  - Specialists in high-fidelity real-time simulation
  - Users of Dymola and Modelica since 1999
- Provider of software solutions for systems engineering
  - Dymola distributors since 2003
  - Dassault Systemes partner since 2008
  - rFpro system integrator and distributor since 2009
- Modelica library and FMI tool developers
- Dassault Systemes Certified Education Partner
- Offices in the UK, USA and South Africa
- Major customers include Automotive OEM’s, suppliers and Motorsport teams (Formula 1, NASCAR, Indycar, Formula E)



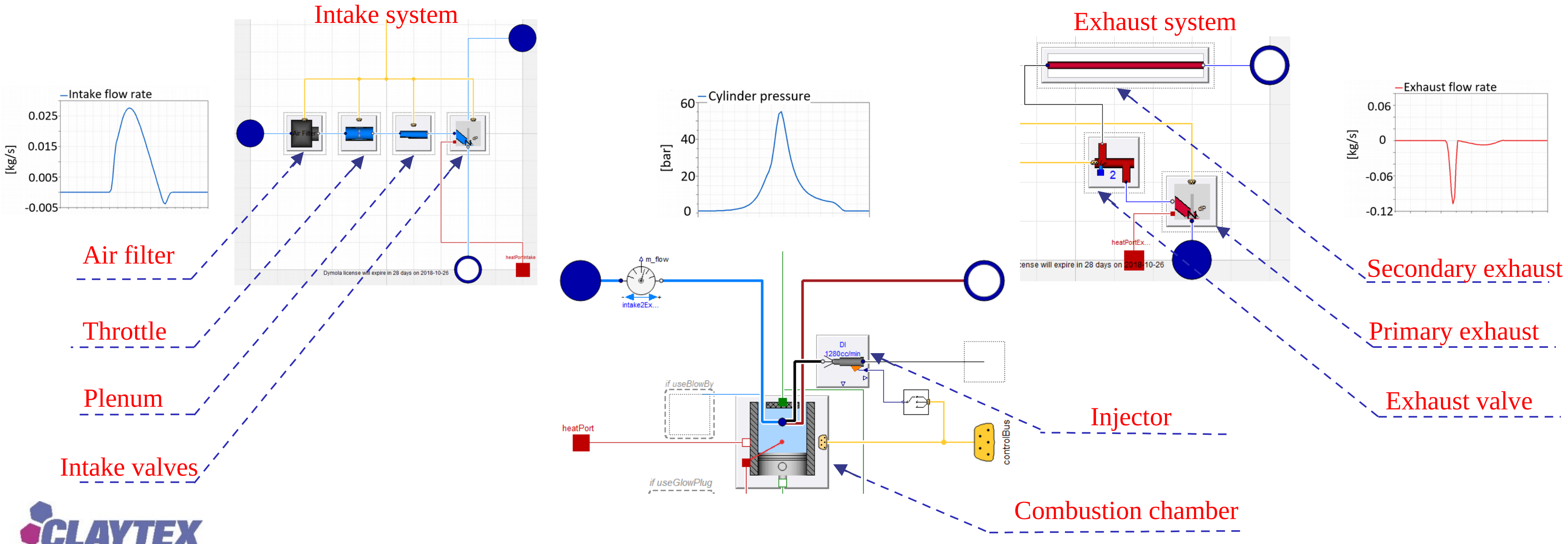
For Engines



For controller validation we need real-time engine models with instantaneous air-flow, combustion and torque prediction

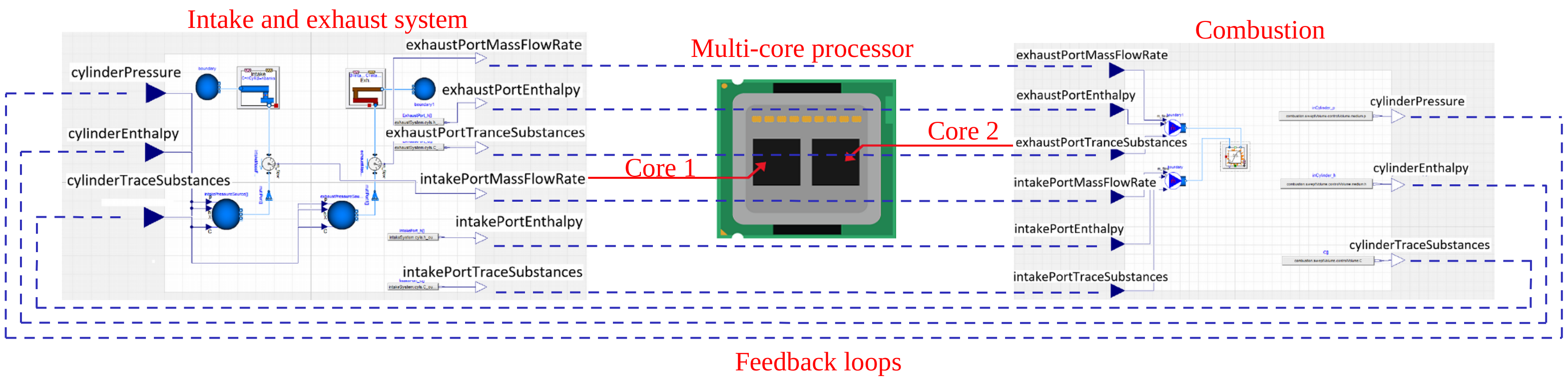
Crank angle resolved engine Model (CAREM)

- What is Crank Angle Resolved Engine Model?
  - Predicts the instantaneous torque and air flow through the engine
  - 1D thermofluid components (valves, orifices, volumes) to model instantaneous quantities (pressure, temperature, mass flow rate, species) through intake, exhaust and combustion chamber



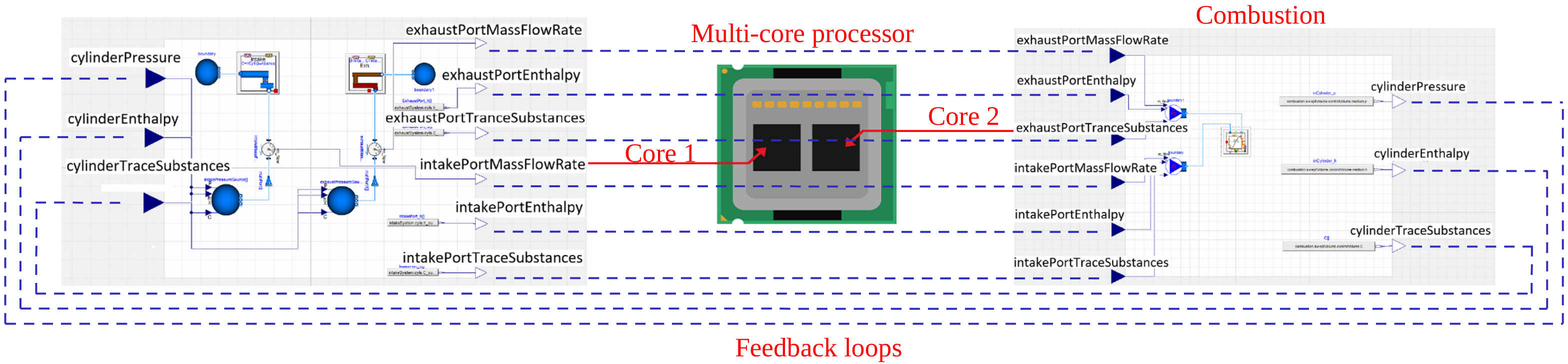
Real-time using multiple cores

- Real-time simulation of CAREM
  - To achieve accurate results from the combustion model time steps of less than 200 microseconds is required (50-100 is better) due to the fast pressure and temperature transients
  - Most HiL systems now have multiple cores
- An engine model can be thought of as a number of tightly couple systems:
  - Intake, exhaust, combustion and mechanics
- One approach is to split the model so that each part runs on its own core



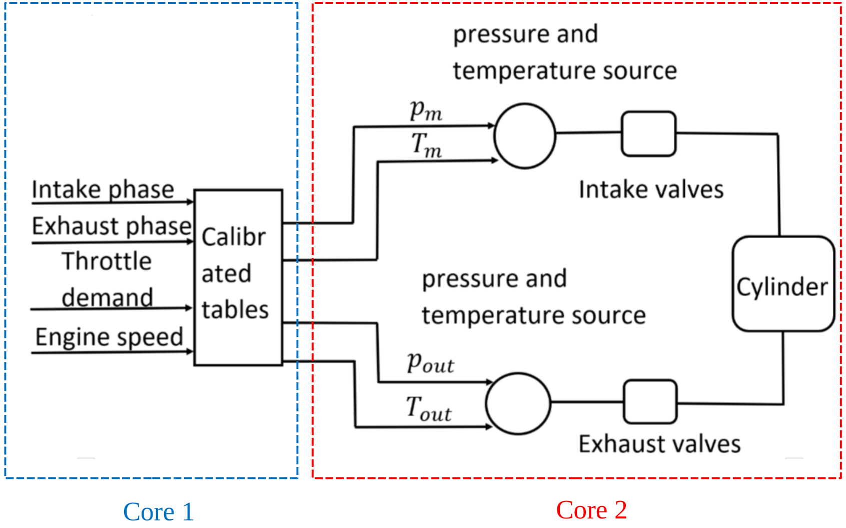
Problems with this approach

- Feedback loop
  - The intake and exhaust systems running on core 1 and the combustion running on core 2 are highly interconnected, i.e. have feedback loops
  - The outputs of intake and exhaust system model are fed into the combustion model whose own outputs are in turn fed back as inputs to the intake and exhaust systems
- This leads to delays in the feedback loop
  - As these form part of a discontinuous and nonlinear system it can render real-time performance unattainable and/or inaccurate



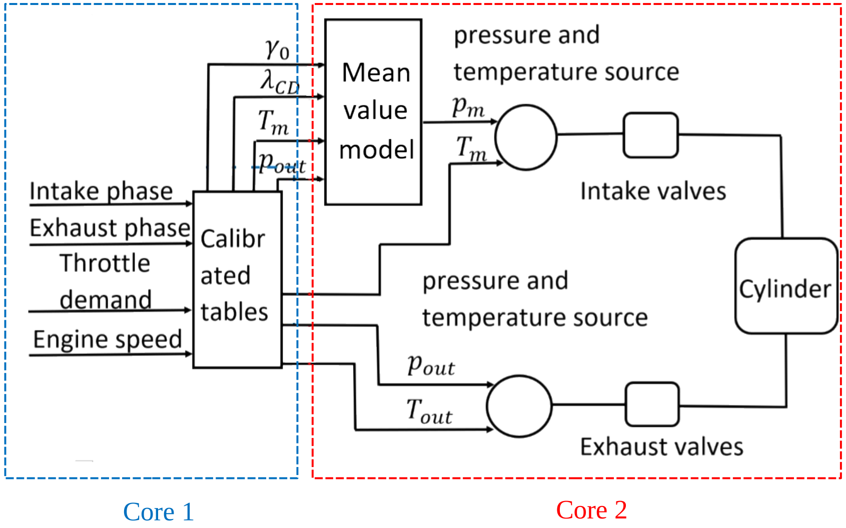
A potential solution

- Replace the intake and exhaust system models with tables
  - Intake and exhaust systems are calibrated off-line for each operating point
  - The calibrated model is then used to replace fluid based intake and exhaust systems.
- However, the fixed boundary conditions and interpolation between calibration points in the tables reduce the accuracy of the resulting simulation



Refining this approach

- Fluid dynamics of the intake and exhaust is much slower than the combustion dynamics
- Introduce a mean value model into the combustion part of the model
- What is a mean value model ?
  - Cycle averaged continuous model
  - neglects the reciprocating behaviour of the engine
  - based on reduced mass and energy balance equations
  - Physical model that runs faster than CAREM, which makes it suitable for real-time applications
- Mean value model now calculates change in pressure based on mass and energy balance
  - Inputs are mass flow rate through throttle and volumetric efficiency from calibration tables

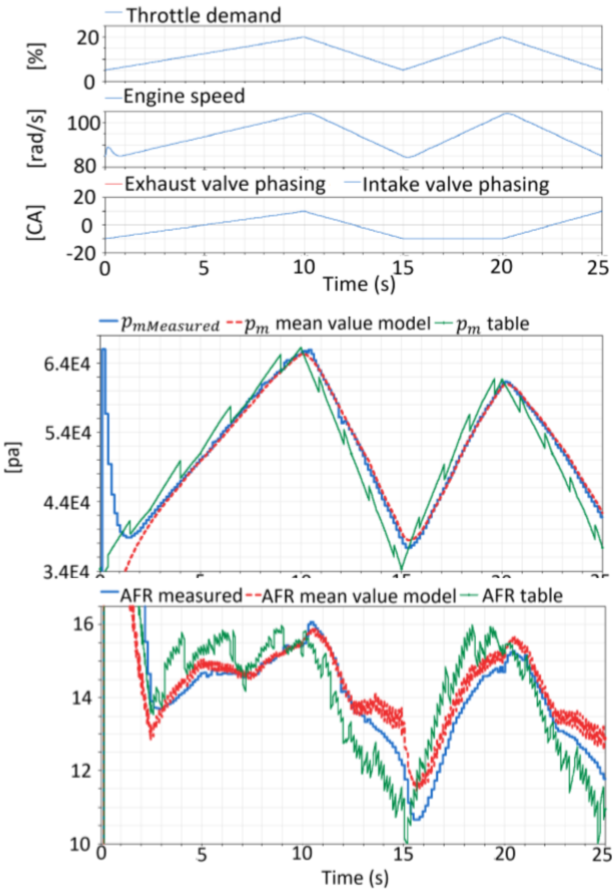


Performance evaluation

- Comparison of full CAREM model and the new approaches
- For both MVEM based scheme and non-MV based scheme
  - MVEM based scheme (red dotted)
  - Non-MVEM, table based scheme (green solid)
  - Full CAREM intake model (blue solid).
- Tables calibration at the following operating points

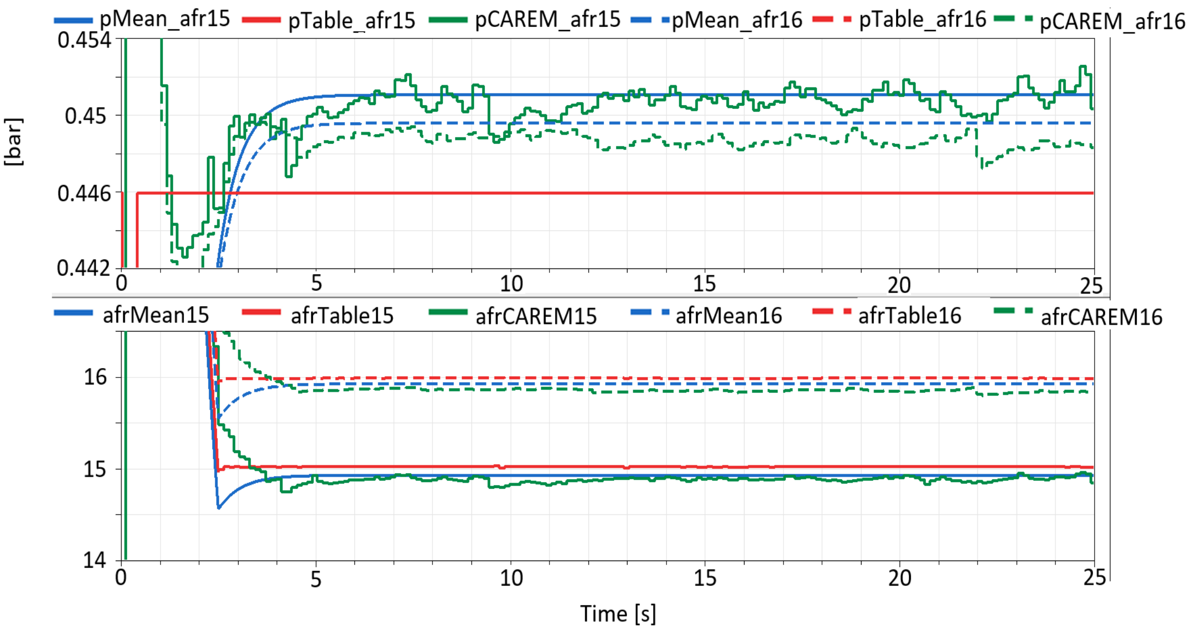
Calibration inputs	*calibration points*
Throttle opening (percent)	5, 8, 11, 14, 17, 20
Engine speed (rpm)	800, 850, 900, 950, 1000
Intake phasing (CA)	-10, -5, 0, 5, 10
Exhaust phasing (CA)	-10, -5, 0, 5, 10

- These results are with a 3% calibration interval for throttle opening
- Increasing the throttle opening to 10% calibration intervals can maintain the same level of accuracy between MVEM and CAREM models



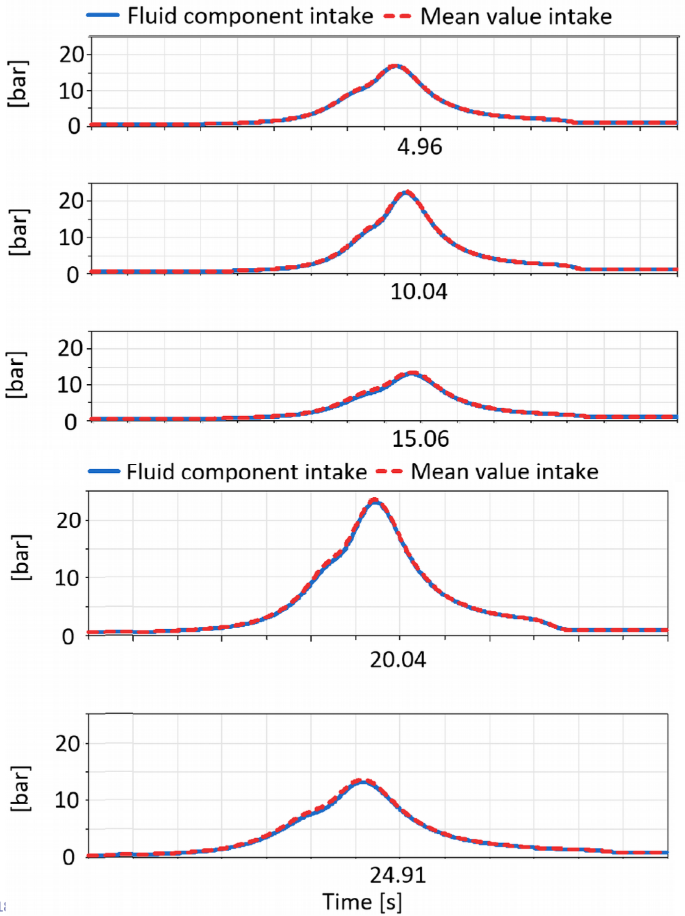
AFR dependent MVEM

- The MVEM is formulated such that AFR variation can be compensated by the model
- Two results with AFR=15 and AFR=16
- Plenum pressure decreases due to leaner AFR
- Without calibration against leaner AFR, MVEM intake with CAREM combustion is able to calculate the decreased plenum pressure due to learner AFR
- Without the MVEM component, the plenum pressure remains insensitive to AFR variation unless the calibration tables include this extra dimension



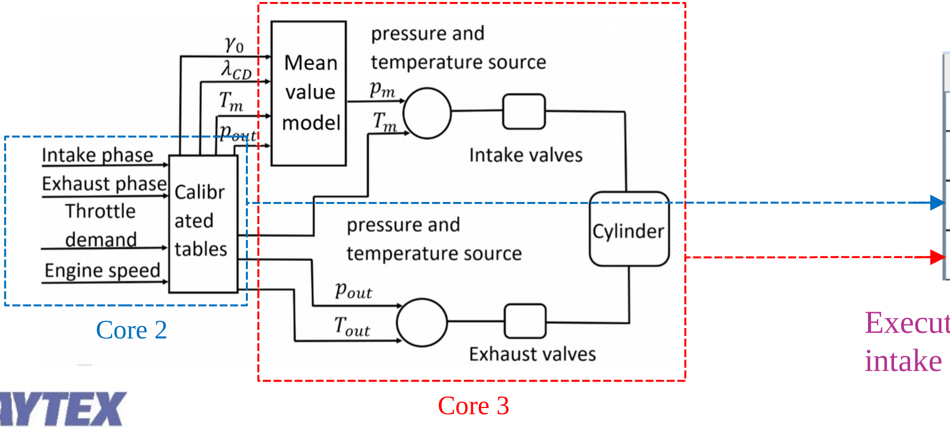
Cylinder pressure profile from MVEM intake with CAREM combustion

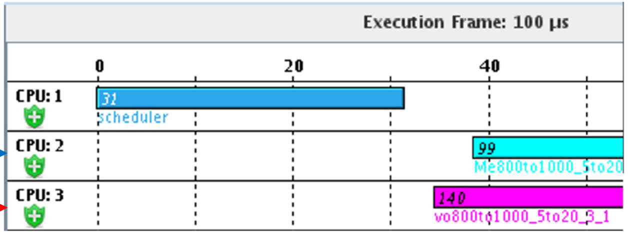
- Comparison of in-cylinder pressures at different operating points
  - Hybrid approach compared to full, non-real-time CAREM model



Allocating on hardware

- Hardware specification
  - A quad-core Concurrent test rig, each core having 2.5 GHz clock rate and 3.9 GB Ram, with RedHawk Linux operating system is used to evaluate the real-time performance of the MVEM intake with CAREM combustion.
- Core 2 runs the mechanical components (pistons, crankshaft, camshaft), ECU (generate command for throttle opening, valve phasing, speed, injection and spark timing), and calibrated tables.
- Core 3 runs CAREM combustion with MVEM intake
- The execution frames for two models on separate core are shown in the plot on the right below. Model in core 3 consumes more computational resources than in Core 2.

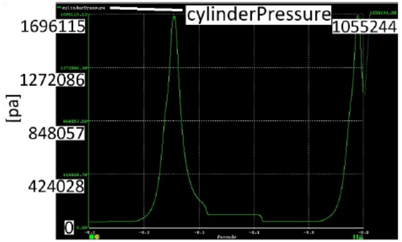




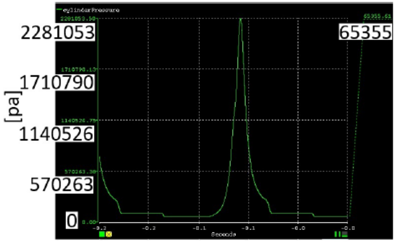
Execution frame for mechanical model on core 2 and MVEM intake with CAREM combustion on core 3

Real-time performance of MVEM intake with CAREM combustion on hardware

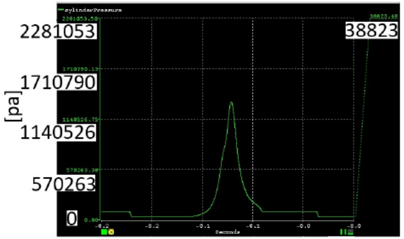
- Running MVEM intake with CAREM combustion on Concurrent to examine cylinder pressure trace
  - For the experiment shown in slide 9, the same experiment is run in Concurrent with model allocation shown in previous slide.
  - The model is running at 100 µs.
  - Cylinder pressure trace of the MVEM intake with CAREM combustion at different time instant are recorded on hardware.
  - It is seen cylinder pressure recorded on hardware shows the same level of accuracy as the models running in Dymola



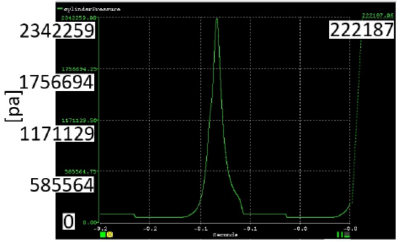
5s



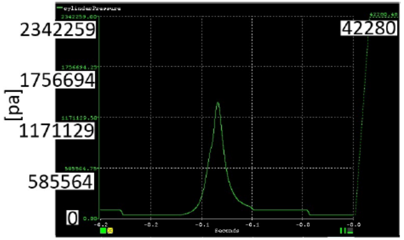
10s



15s



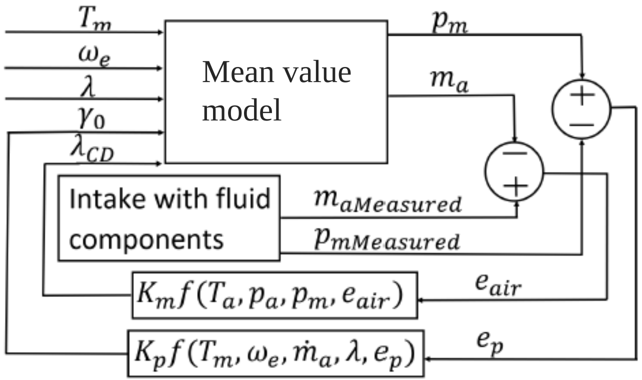
20s



25s

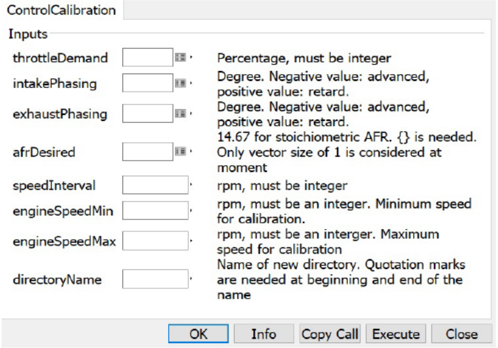
Calibration of MVEM using control design

- Controllers can be designed to calibrate the models
- These work to minimize the error of plenum pressure (p_m) and mass flow into cylinder ($\dot{m}_a$) between MVEM and CAREM engine models by controlling calibration parameters
- The controllers are designed to cancel out the nonlinear terms and the closed loop system is governed only by linear systems with control gains K_m and K_p.
- Features of calibration using control design
  - Convergence of the errors does not depend on initial value of calibrated parameters, γ_0, λ_{CD} because the closed loop is a linear system.
  - No iteration is needed as errors are guaranteed to converge in each simulation execution.
  - Errors converge within 2s of simulated time, typically taking less than 5s to run the simulation at each operating

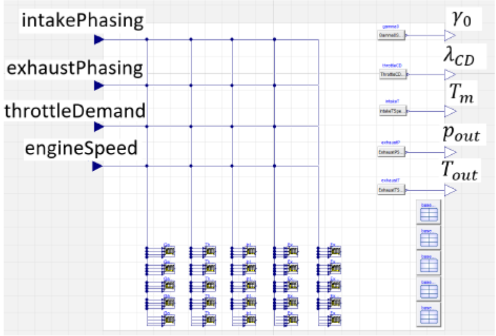


Automated calibration for MVEM

- A function can be created to automatically calibrate MVEM for all the operating points user has specified
- In the automatically generated calibration tables, the number of rows corresponds to the number of engine speed points. The number of columns corresponds to the number of calibration parameters.



Function for automated calibration



Automatically generated calibration tables

Summary

- It has been shown that the MVEM is efficient and accurate to be used for CAREM simulation on hardware for real-time performance
- The MVEM can account for AFR variation, so number of calibration points against AFR can be reduced
- Calibration using controller design is efficient
  - On average it takes 2 to 5 seconds to run 2 second of simulation to calibrate MVEM for each calibration point
  - This is practically acceptable, given the amount of operating points to be calibrated.
- Automated calibration has been implemented to improve efficiency and accuracy