Estimation and Control of Diesel Engine Processes Utilizing Variable Intake Valve Actuation

U.S. DEPARTMENT OF ENERGY
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DEARBORN
DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE

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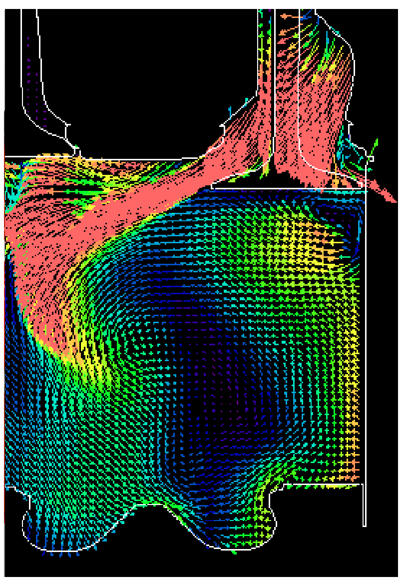
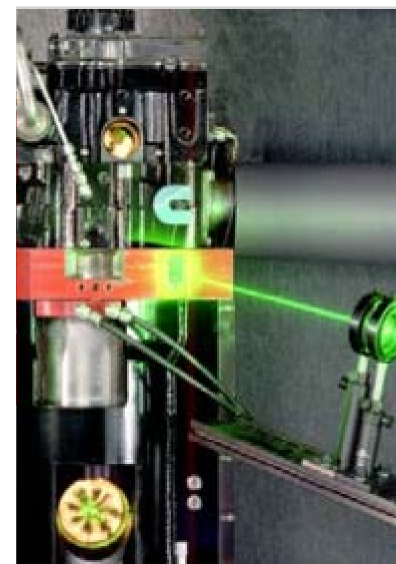
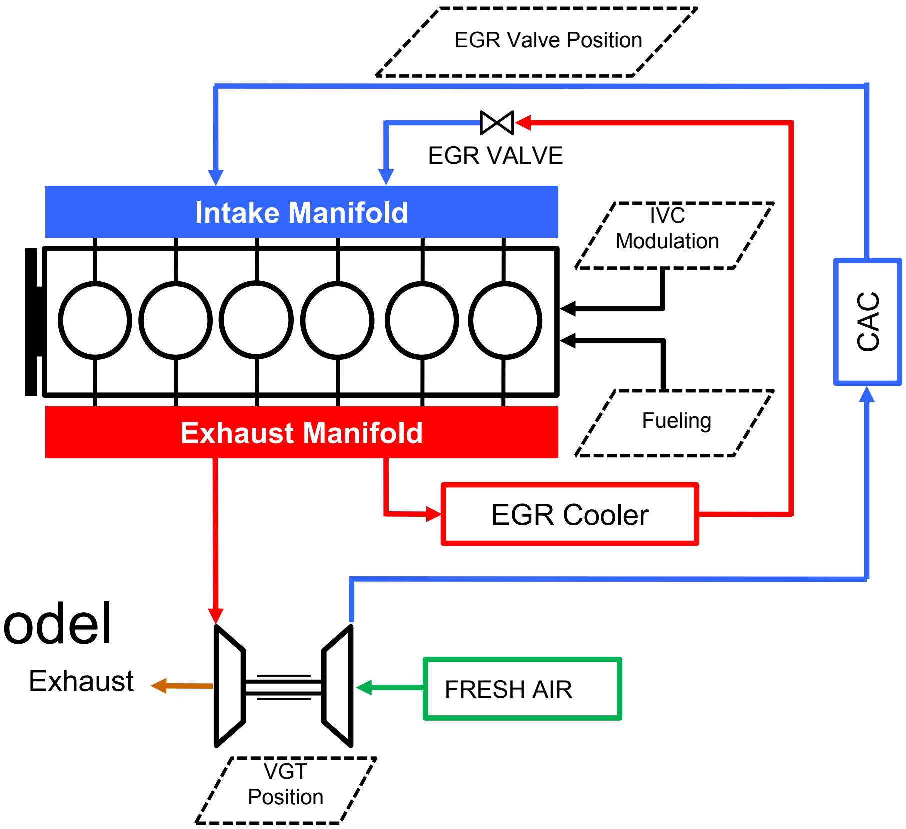




Presentation Overview

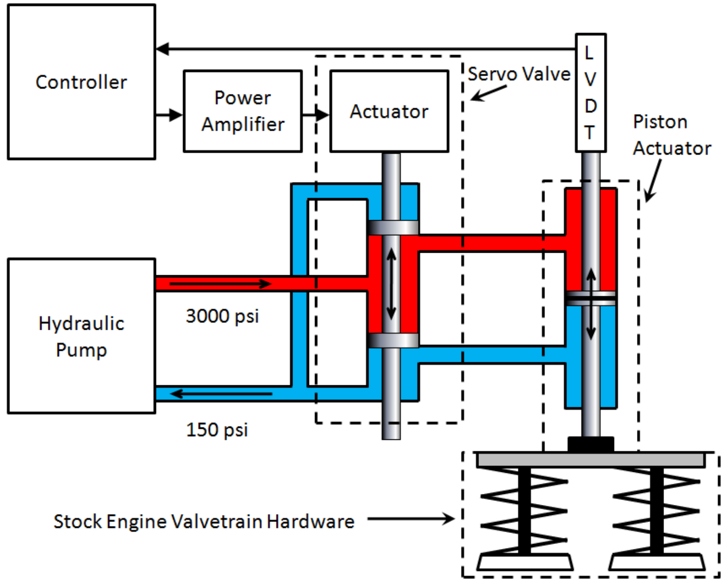
- Experimental Test Bed
- Model Based Approach
- Gas Exchange Model
  - Manifold Filling Dynamics
  - Volumetric Efficiency
  - Oxygen Fraction Dynamics
- Combustion Model
  - PCCI Combustion Timing Model
- Controller Development
  - PCCI Combustion Timing
- Summary

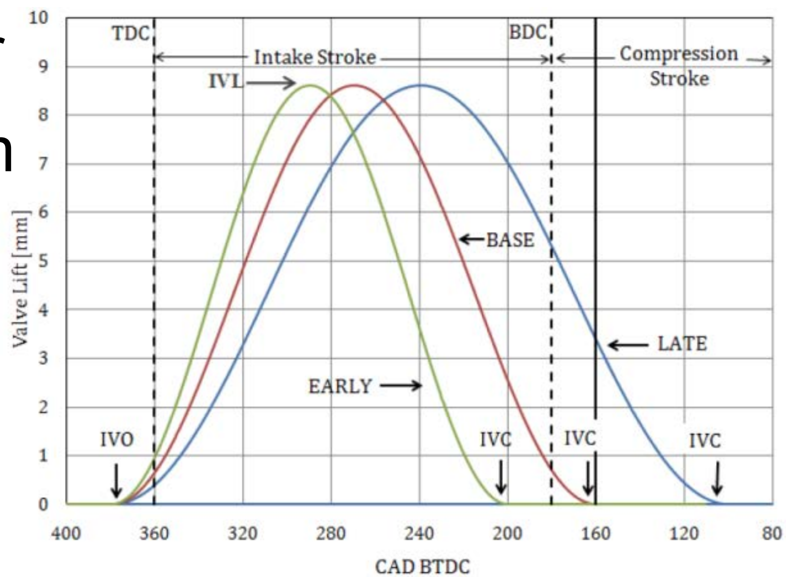


Experimental Test Bed

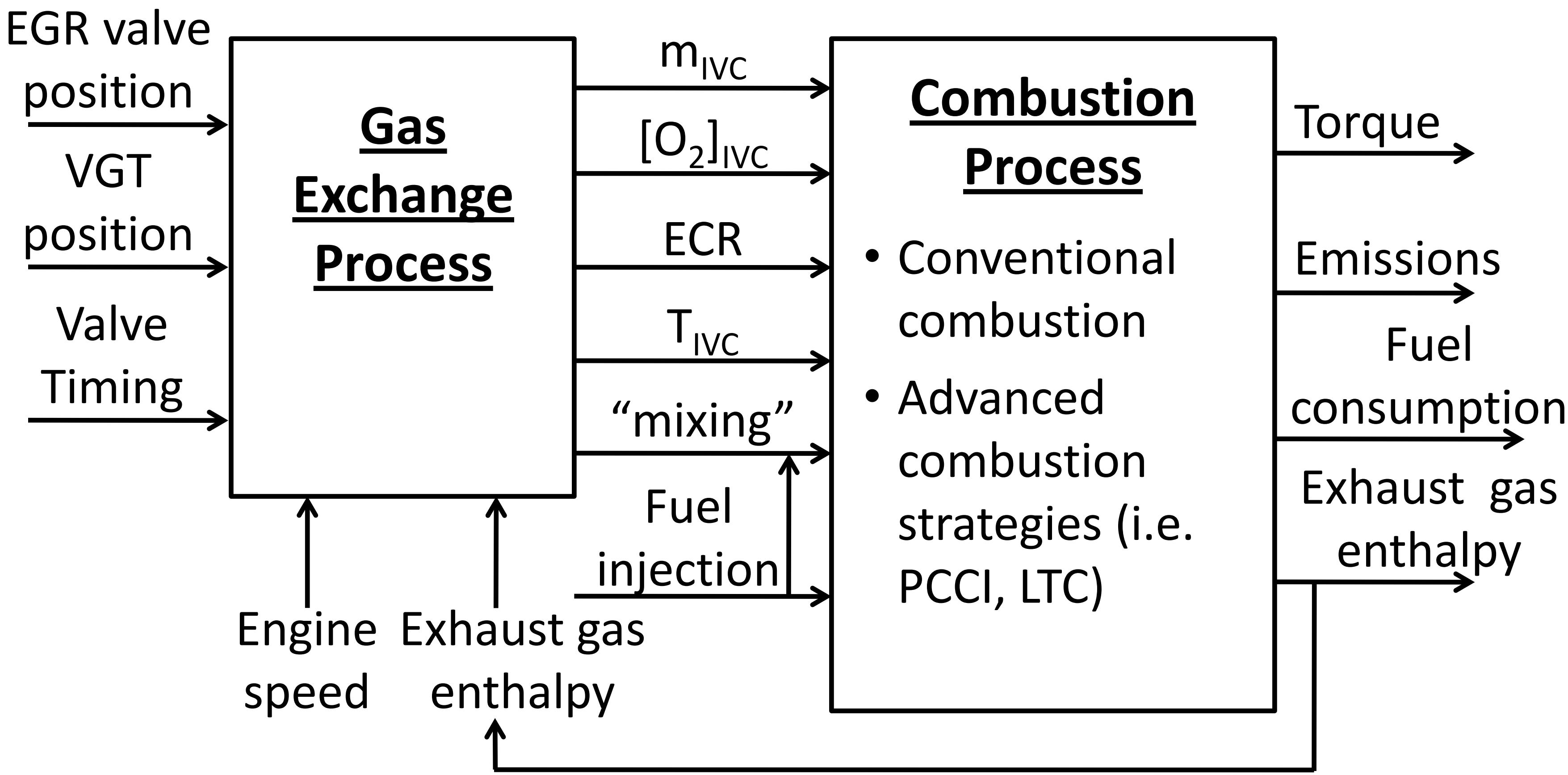
2010 Cummins ISB

- 360 HP (268 kW)
- 17.3:1 Compression Ratio
- Common Rail Fuel Injection
- Air-Handling System
  - Exhaust Gas Recirculation Valve
  - Variable Geometry Turbocharger
- Variable Valve Actuation System
  - Electro-Hydraulic System
  - Cylinder Independent
  - Cycle-to-cycle





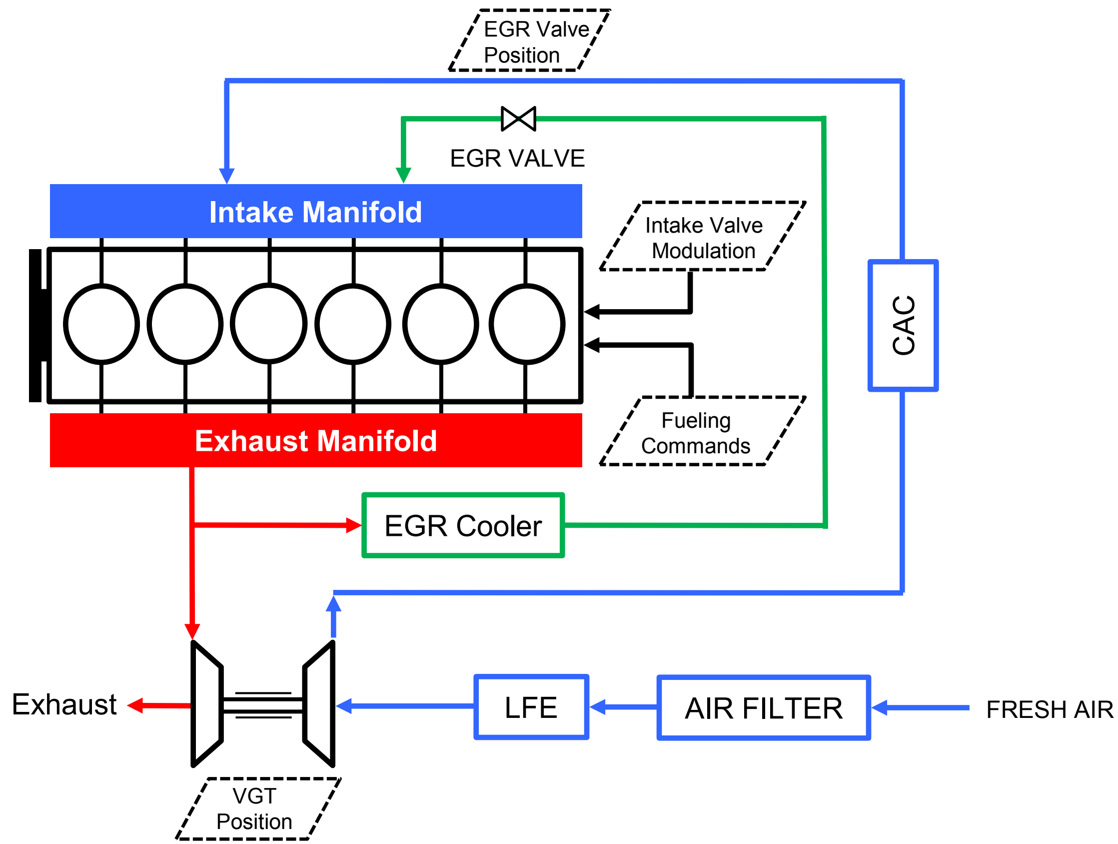
Model Based Approach



- Physically-based generalizable models
- Validated experimentally
- Validated via analysis (math-based stability, convergence rate, and sensitivity/uncertainty analysis)

Gas Exchange Model

- 5 Model States
  - Intake Manifold
    - Pressure
    - Temperature
  - Exhaust Manifold
    - Pressure
    - Temperature
  - Turbo Shaft Speed



Gas Exchange Model

Intake Manifold State Equations

$$\dot{p}_{im} = \frac{\gamma_{im} R_{im}}{V_{im}} \left(W_{egr} T_{egr} + W_c T_{cac} - W_e T_{im} \right)$$

$$\dot{T}_{im} = \frac{R_{im} T_{im}}{P_{im} V_{im}} \left[W_{egr} \left(\gamma_{im} T_{egr} - T_{im} \right) + W_c \left(\gamma_{im} T_{cac} - T_{im} \right) + W_e \left(T_{im} - \gamma_{im} T_{im} \right) \right]$$

Exhaust Manifold State Equations

$$\dot{p}_{em} = \frac{\gamma_{exh} R_{exh}}{V_{em}} \left[\left(W_e + W_f \right) T_{exh} - W_{egr} T_{em} - W_t T_{em} \right]$$

$$\dot{T}_{em} = \frac{R_{em} T_{em}}{P_{em} V_{em}} \left[\left(W_e + W_f \right) \left(\gamma_{em} T_{exh} - T_{em} \right) + W_{egr} \left(T_{em} - \gamma_{em} T_{em} \right) + W_t \left(T_{em} - \gamma_{em} T_{em} \right) \right]$$

Turbocharger Speed State Equation

$$\dot{\omega}_{tc} = \frac{\eta_m P_{turb} - P_{comp}}{I_{turb} \omega_{tc}}$$

$$P_{turb} = W_{turb} c_{p,exh} \eta_t T_{em} \left[1 - \left(\frac{p_{amb}}{p_{em}} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

$$P_{comp} = \frac{W_{comp} c_{p,amb} T_{amb}}{\eta_c} \left[\left(\frac{p_{cac}}{p_{amb}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

Gas Exchange Model

Volumetric Efficiency Model

$$W_e = \rho_{im}\eta_{vol}V_d\frac{N}{2}$$

$$\eta_{vol} = \frac{\left(P_{im}\left(\frac{V_{ivc_{eff}}}{V_{ivc}}\right)^k V_{ivc}c_v - P_{em}V_{ivo}c_v - P_{em}\left(V_{evc}-V_{ivo}\right)c_p + P_{im}\left(V_{ivc_{eff}}-V_{ivo}\right)R - h_{ivo-ivc}\left(T_{wall}-T_{im}\right)A_{s_{ivo-ivc}}R\right)}{P_{im}V_d c_p}$$

Exhaust Enthalpy Model

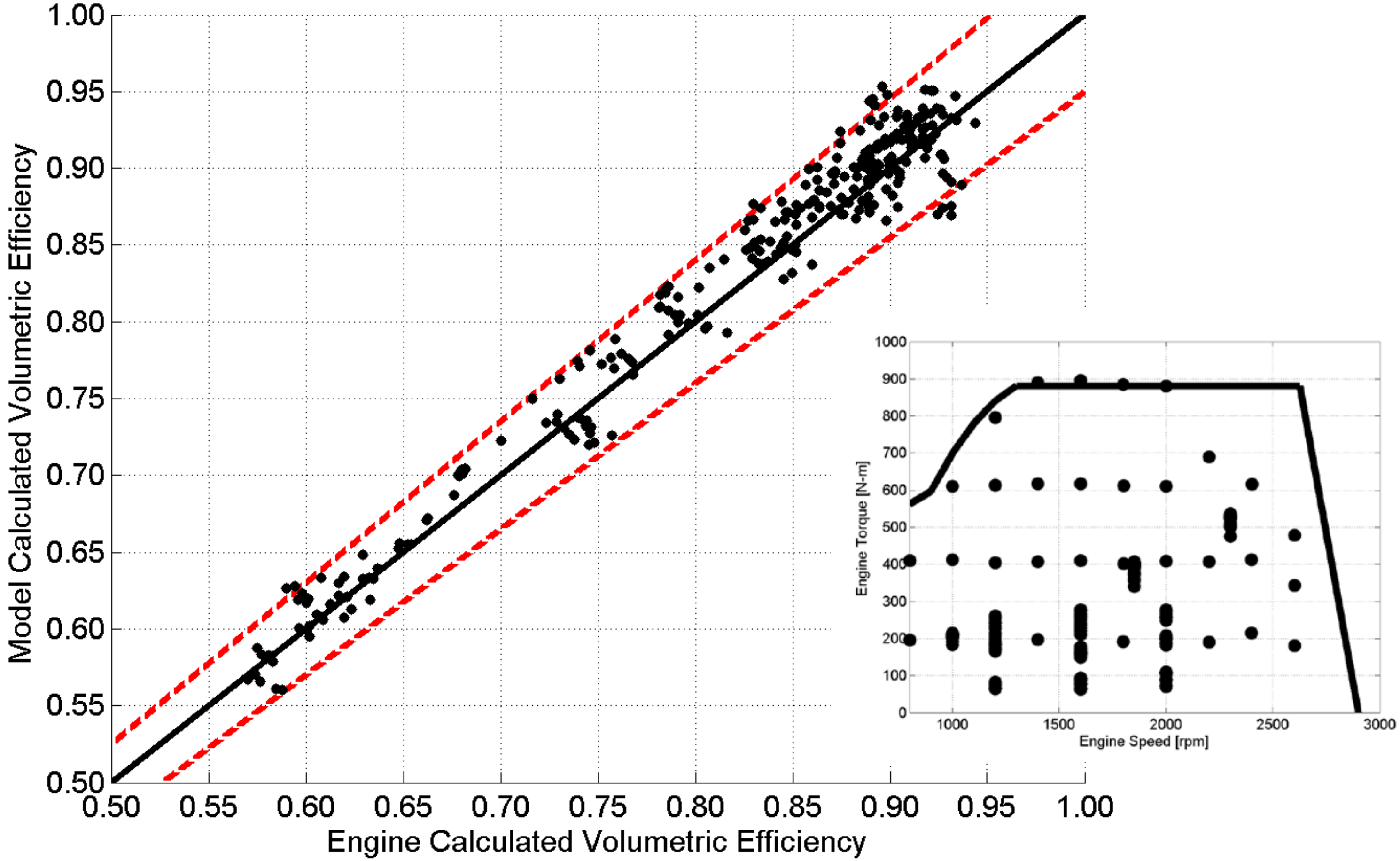
$$T_{evo} = \frac{p_{im}}{m_c R_{im}}\frac{ECR^{k_a}}{V_{evo}^{k_e-1}}\left(\frac{k_e-1}{k_e}\frac{\left(a\cdot N+b\right)m_f Q_{LHV}}{P_{im}ECR^{k_a}}+V_{tdc}\right)^{k_e}$$

Analytical Turbocharger Performance Functions

$$W_c = f\left(PR_c, N_{turb}\right) \quad W_t = f\left(PR_t, N_{turb}\right)$$

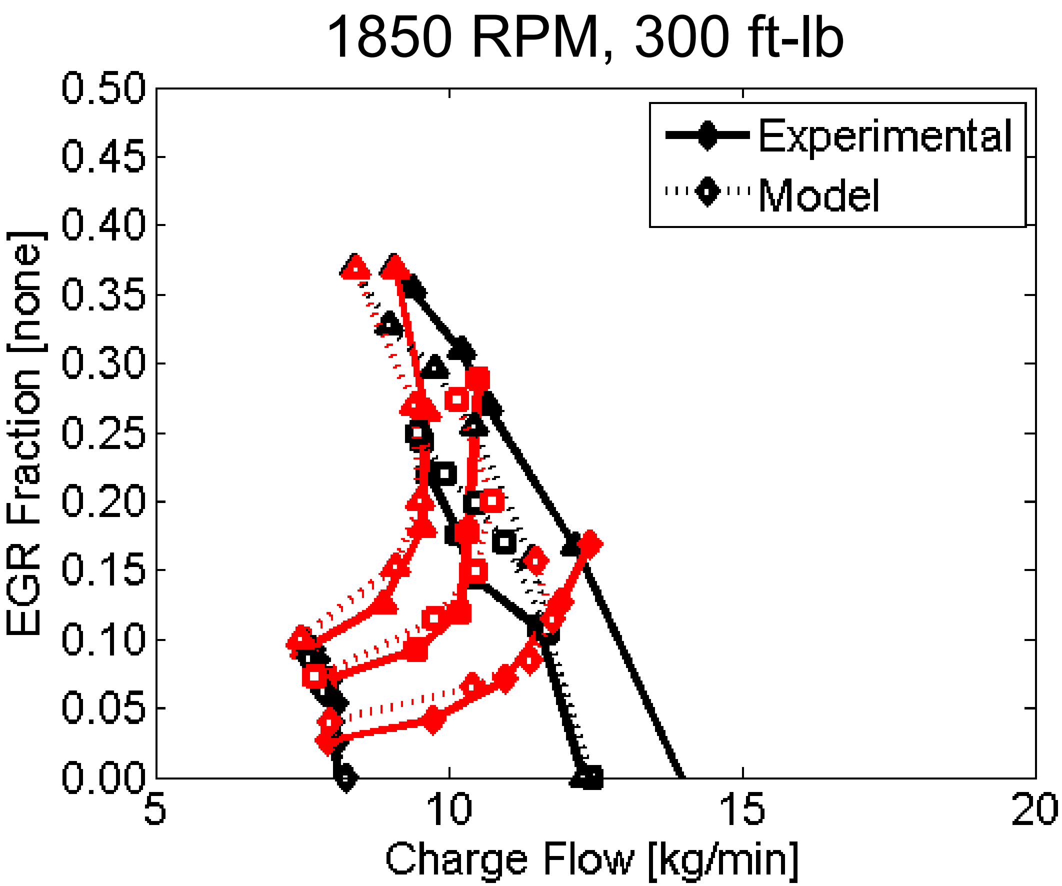
$$\eta_c = f\left(PR_c, N_{turb}\right) \quad \eta_t = f\left(PR_t, N_{turb}\right)$$

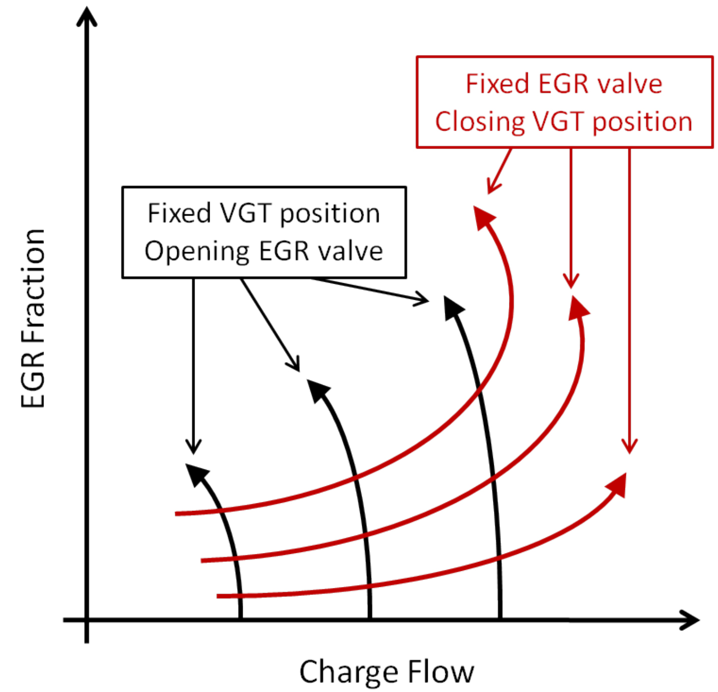
Volumetric Efficiency Model Results



± 5% Lines 2.5% RMS Error

Gas Exchange Model Results

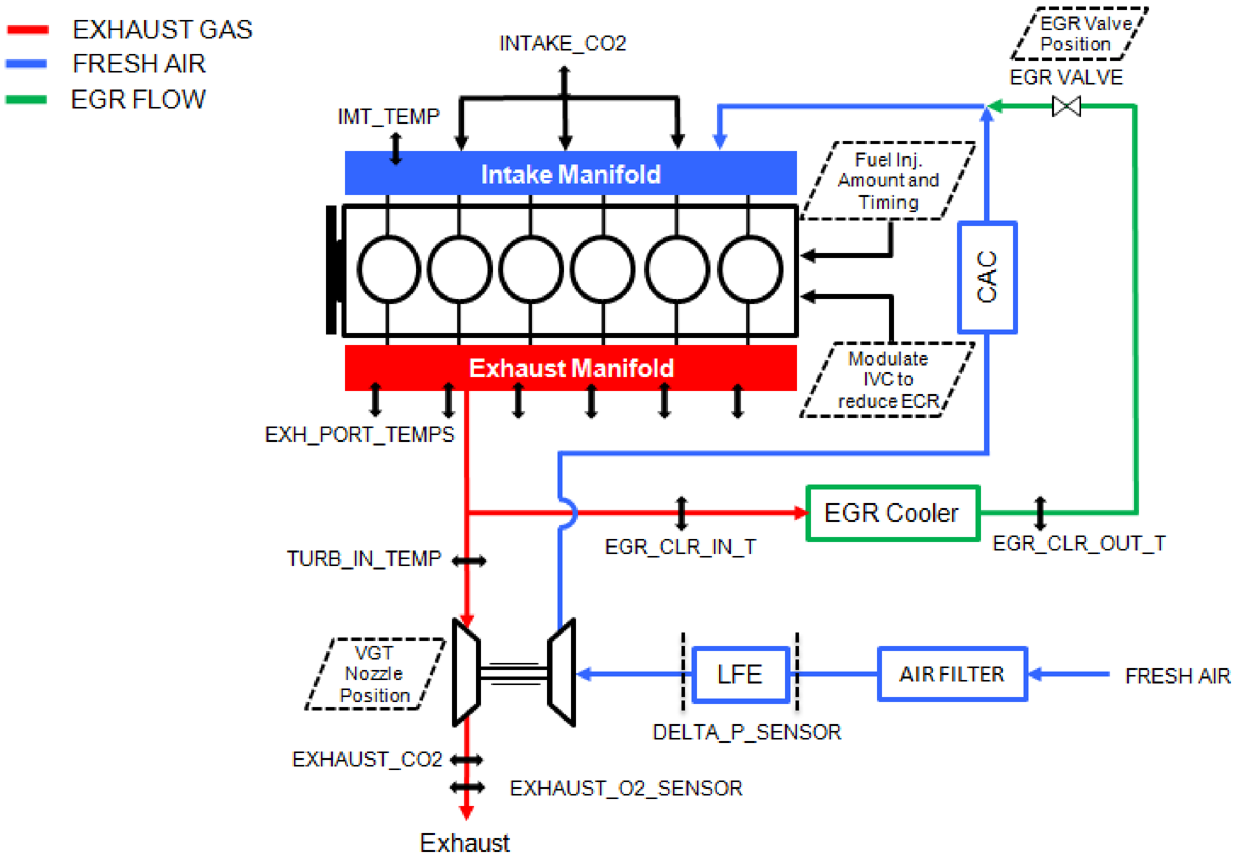




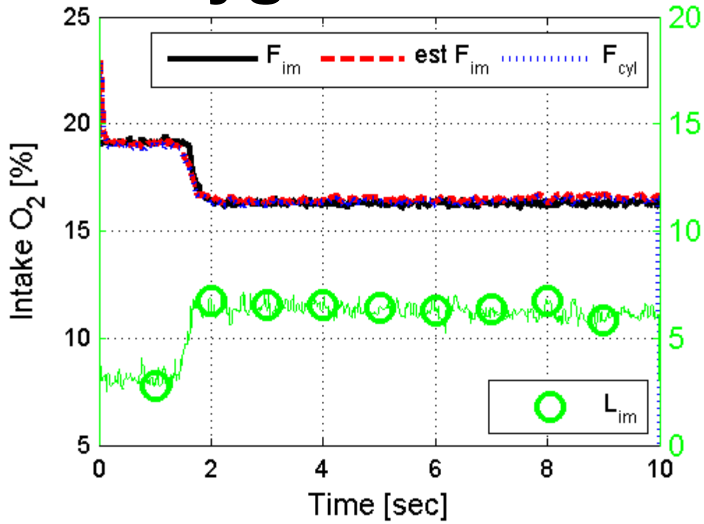
Gas Exchange Model

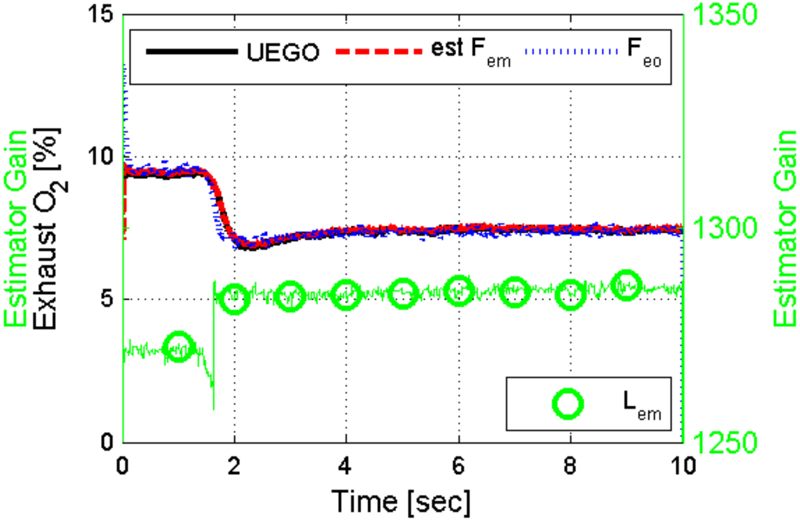
$$\dot{F}_{im} = \frac{RT_{im}}{P_{im}V_{im}}\left[F_{amb}W_c + F_{em}W_{egr} - F_{im}W_e\right]$$

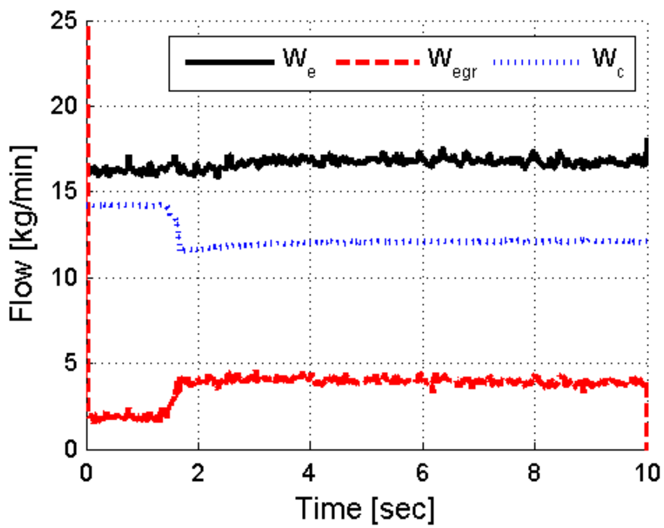
$$\dot{F}_{em} = \frac{RT_{em}}{P_{em}V_{em}}\left[F_{eo}\left(W_e + W_f\right) - F_{em}W_{egr} - F_{em}W_t\right]$$

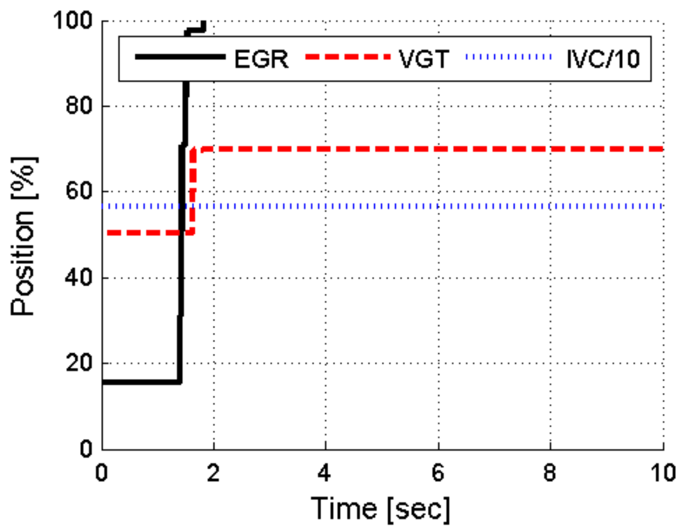


Oxygen Fraction Estimator Results









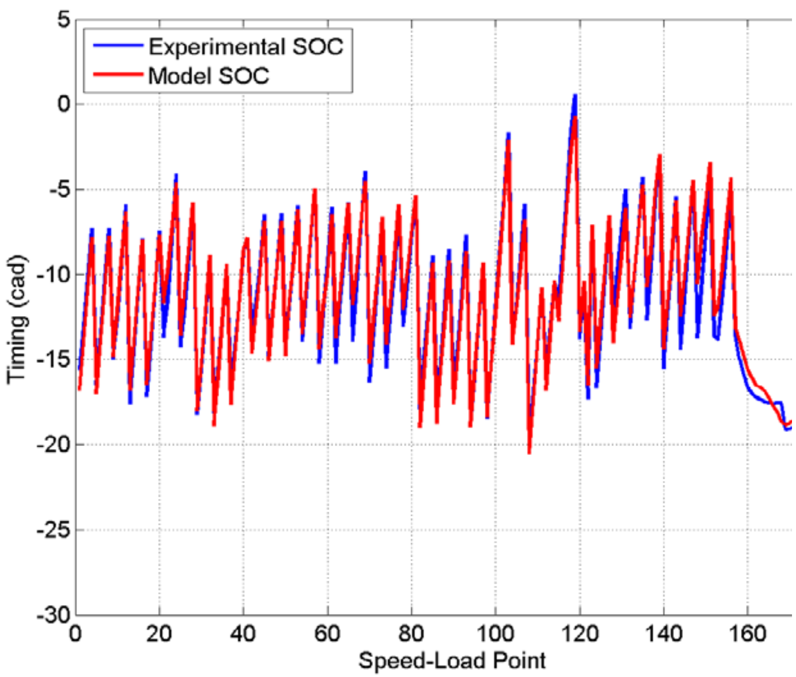
Innovation You Can Depend On

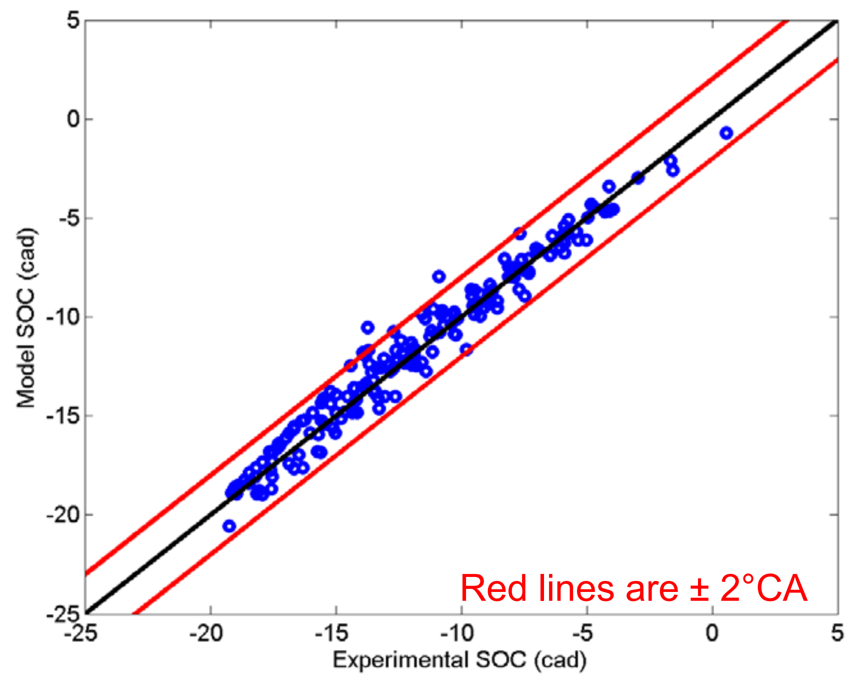
PCCI Combustion Timing Model

Start of Combustion Prediction

$$SOC = \tau_{elec} + \tau_{hyd} + \tau_{id} + SOI_{ecm}$$

$$SOC = 1.2 + 0.0018\omega + 0.006\omega\left(0.051\chi_{O_2}{}^{-1.14}\overline{P}^{-0.51}e^{\left(\frac{2100}{\overline{T}}\right)}\right) + SOI_{ecm}$$





PCCI Combustion Timing Model

- What needs to be controlled to control PCCI combustion timing?

$$SOC = 1.2 + 0.0018\omega + 0.006\omega\left(0.05\left(\chi_{O_2}\right)^{-1.14}\bar{P}^{-0.51}e^{\left(\frac{2100}{\bar{T}}\right)}\right) + SOI_{ecm}$$

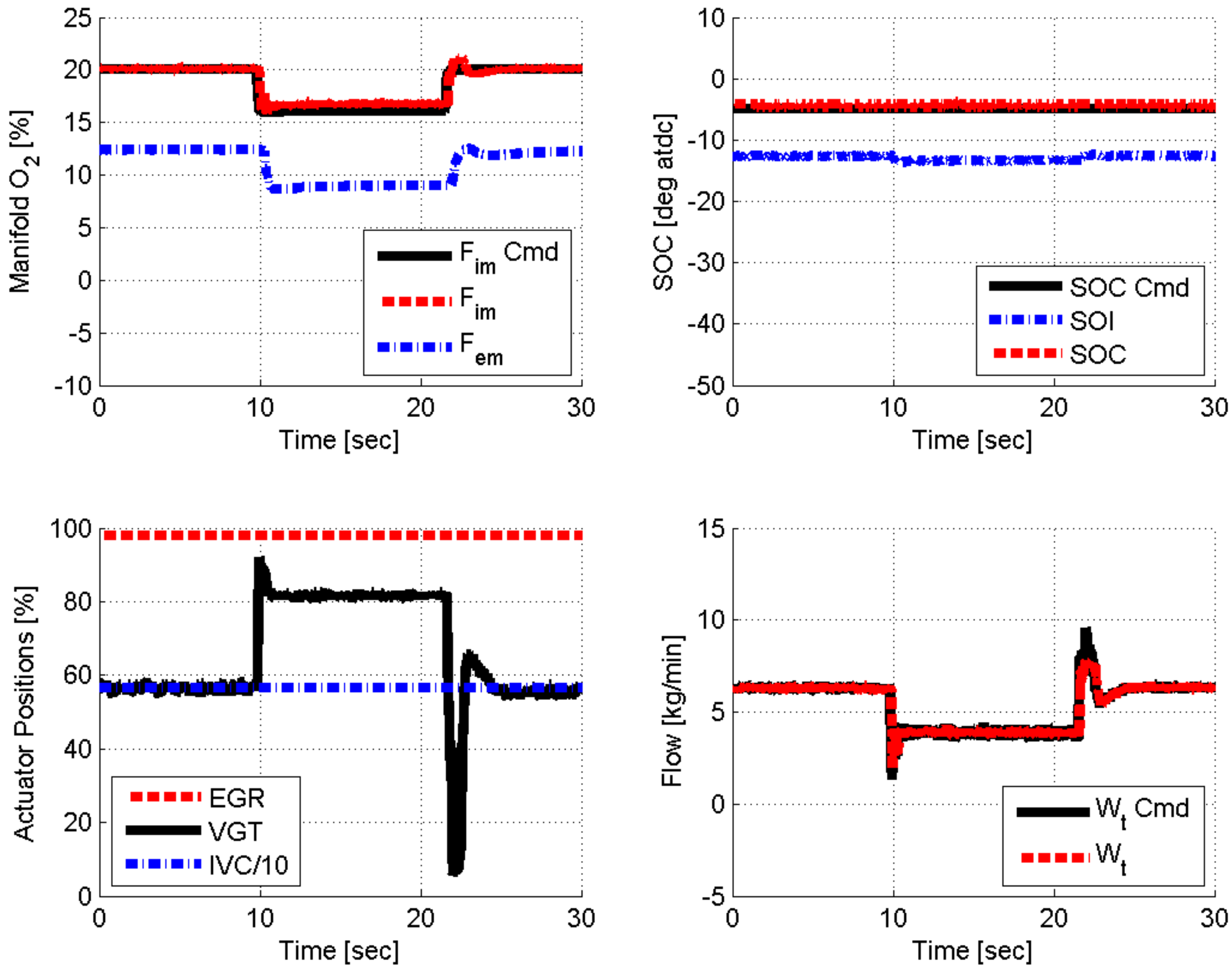
- Can we separate dynamics?

Slower dynamics driven by gas exchange process

Faster dynamics driven by fuel injection process

PCCI Combustion Timing Controller

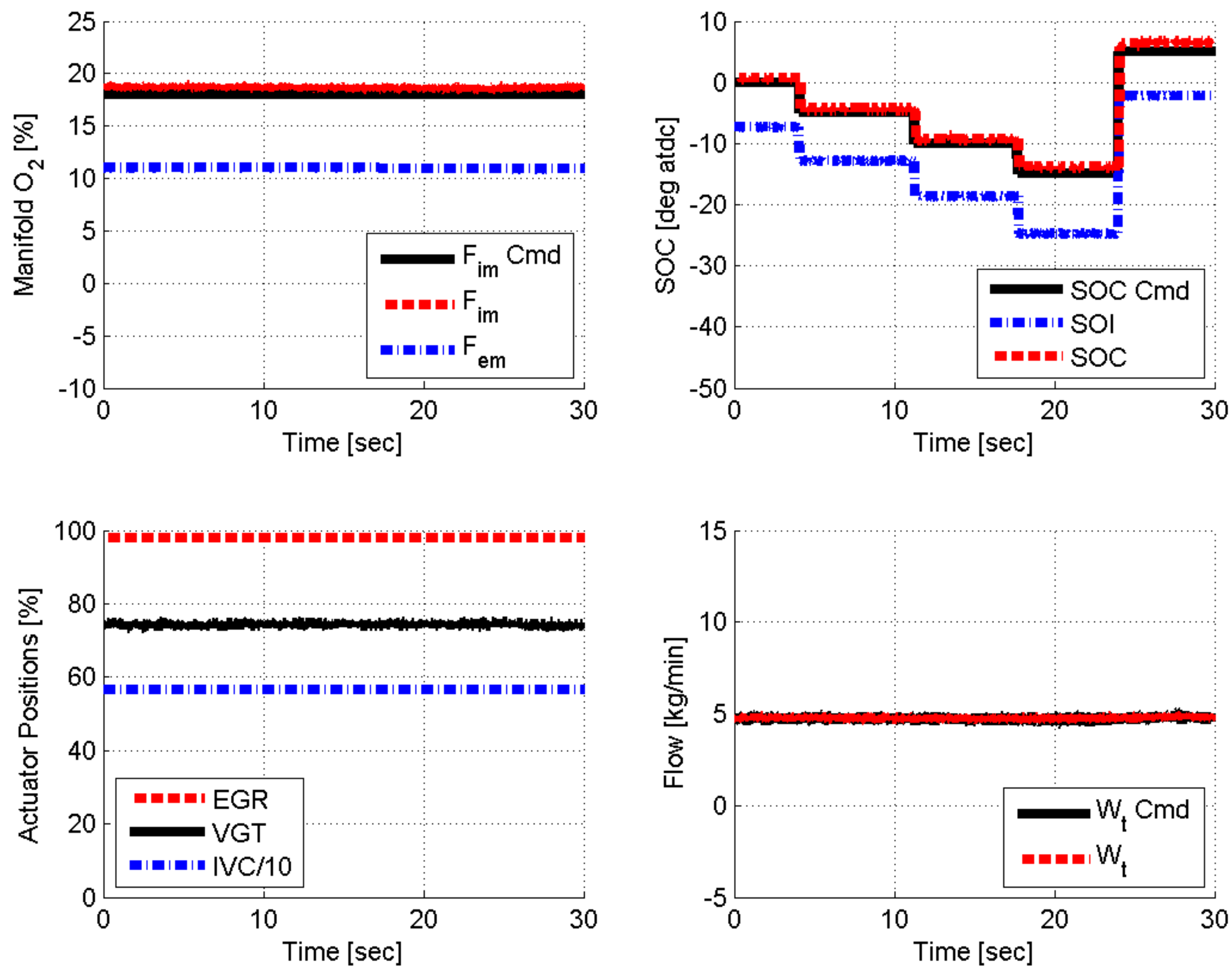
1600 rpm & 140 ft-lbf
F_{im} Command Step Change



Innovation You Can Depend On

PCCI Combustion Timing Controller

1600 rpm & 140 ft-lbf
SOC Command Step Change



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