Model-Based Powertrain and Engine Control

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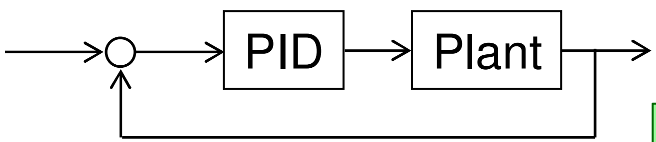
Outline

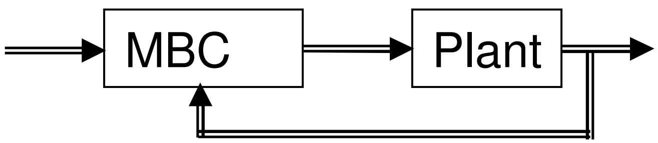
- ❑ Background
- ❑ Model-based control frame work
- ❑ Modeling
  - Crank-resolved engine/powertrain model
  - Control oriented charge-mixing model
- ❑ Control Applications
  - Optimal control: HCCI model transition control
  - LPV (Gain-scheduling) control of cam phaser
  - Adaptive control of LNT regeneration
- ❑ Conclusions

Background

Traditional SISO Control

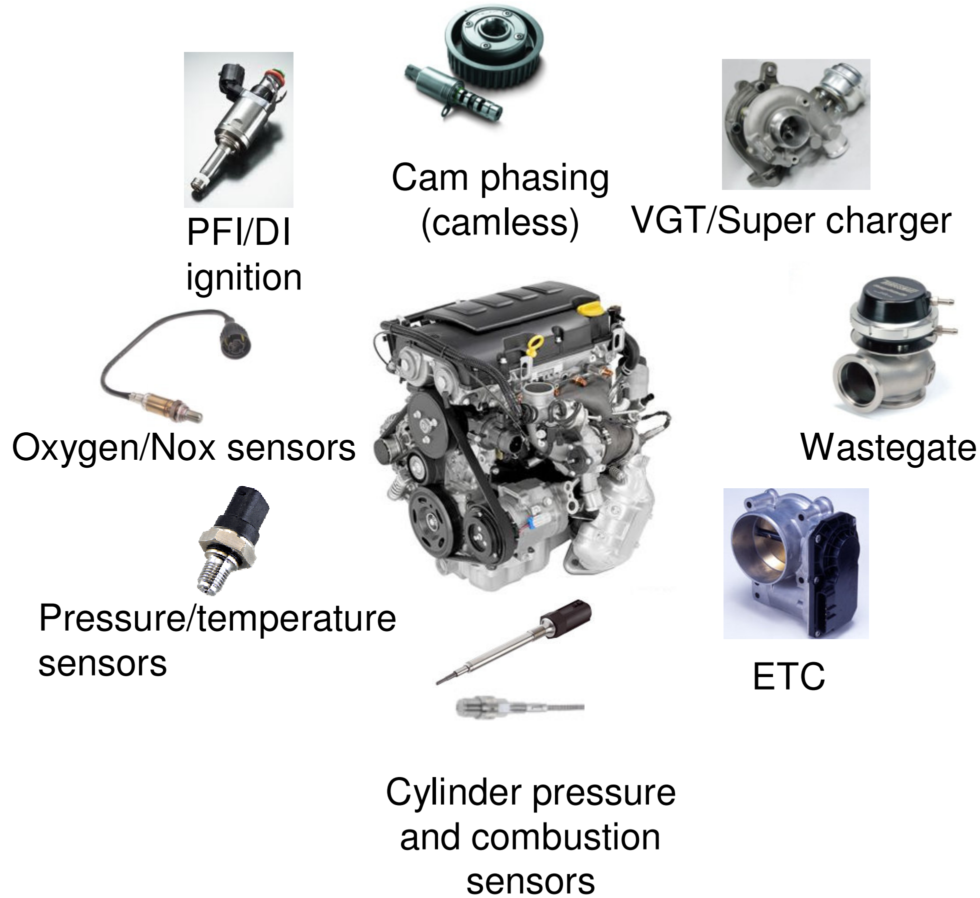


MIMO Control System



Engine system has the following characteristics:

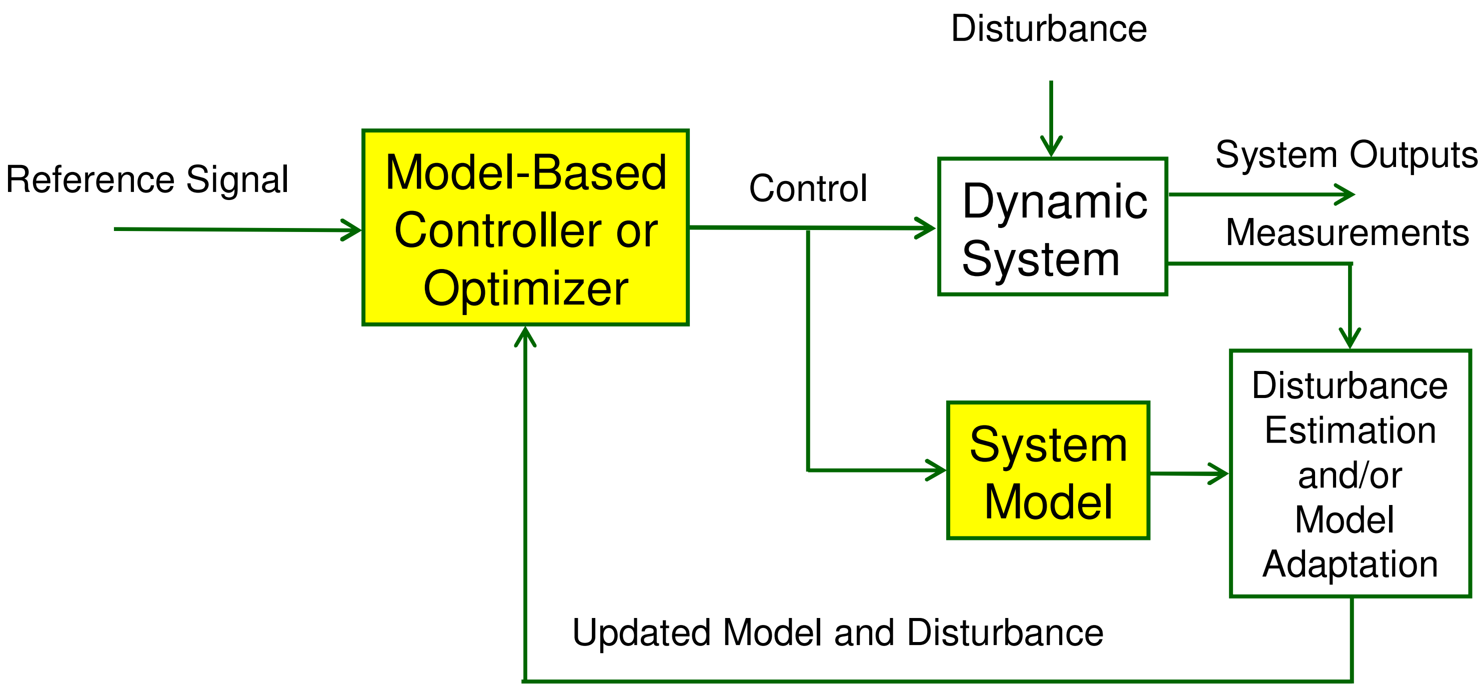
- ❑ Highly nonlinear
- ❑ Parameter (time) varying
- ❑ System parameters changes as engine aging
- ❑ Time and event based control
- ❑ Complicated flow and thermal dynamics
- ❑ Robustness (fuel, altitude, etc.)



Model-Based Control (MBC) is a **necessity**

Model-Based Control Framework

Generic form of the model-based control

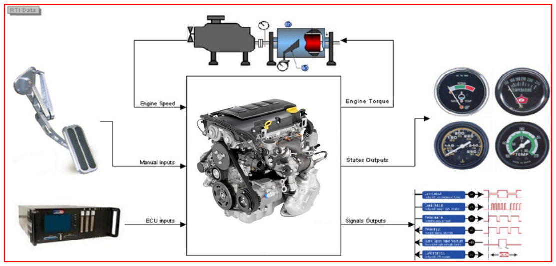


Two key components of model-based control:

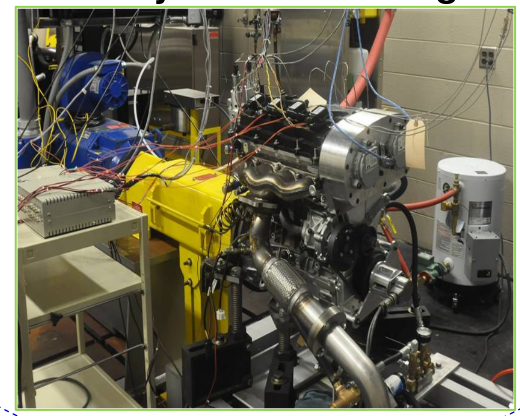
- ❑control oriented model capable of real-time simulation, and
- ❑model based controller and optimizer

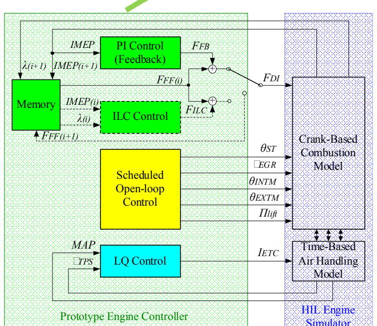
Model-Based Control (development roadmap)

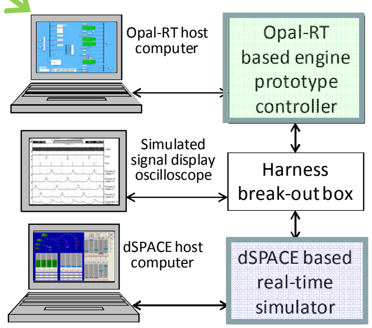
Control-oriented engine models developed with GT-Power simulations



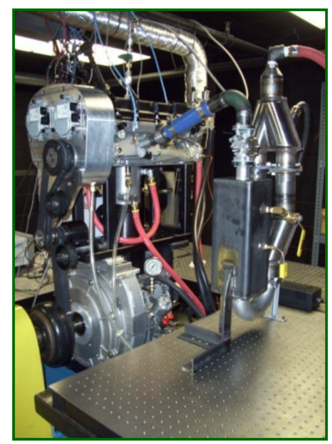
Multi-cylinder metal engine







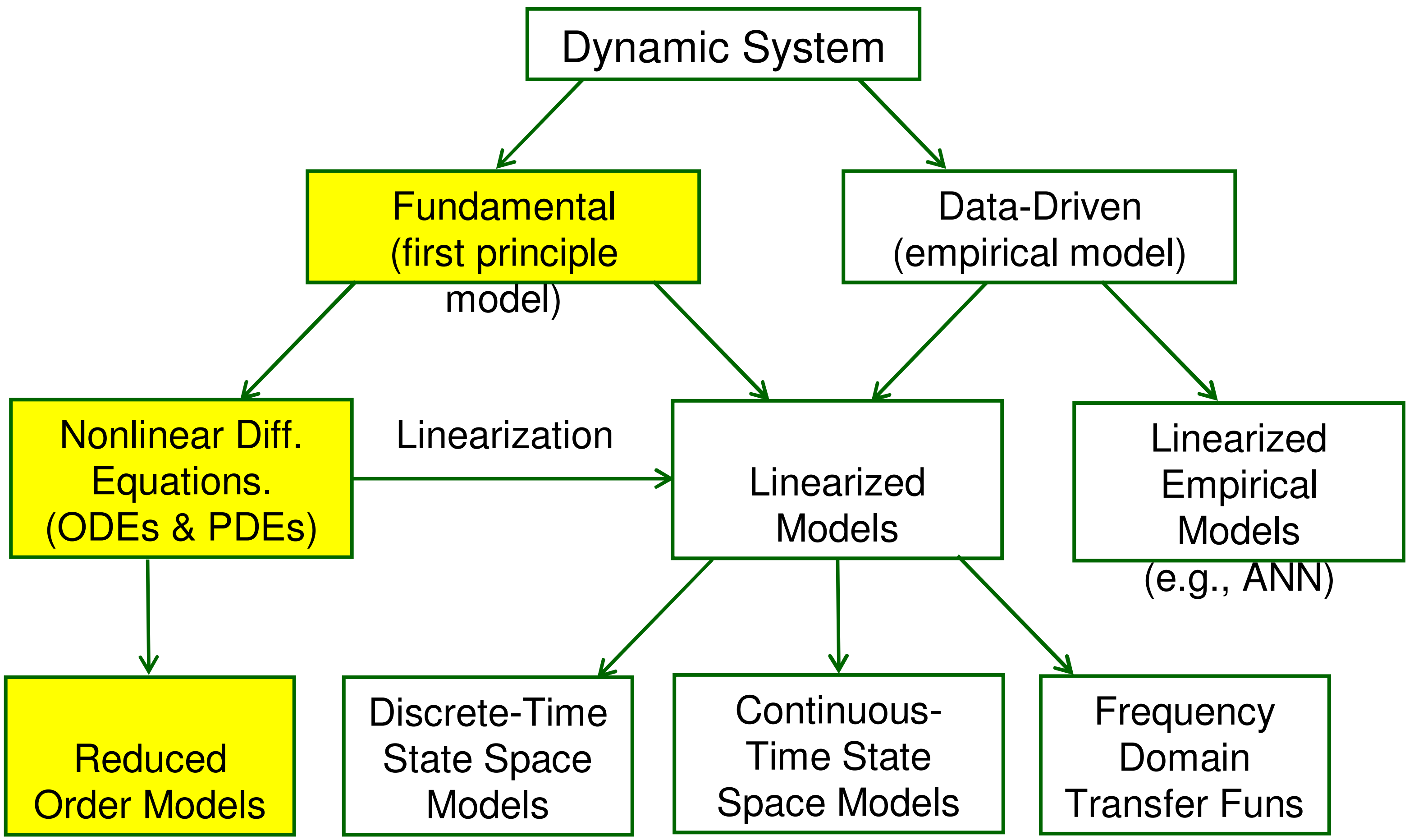
Single cylinder optical engine



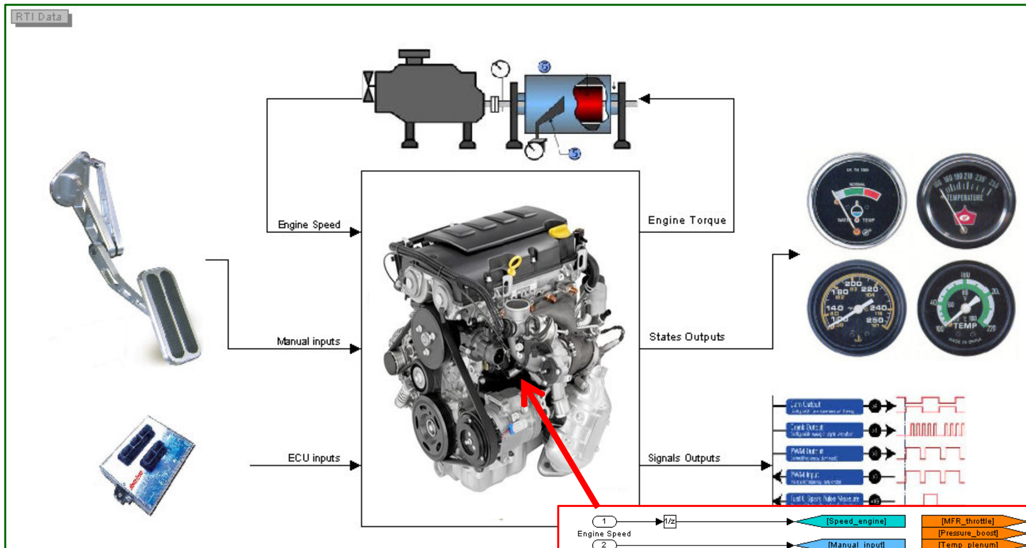
Model-based control strategy

HIL simulation to validate the control strategy

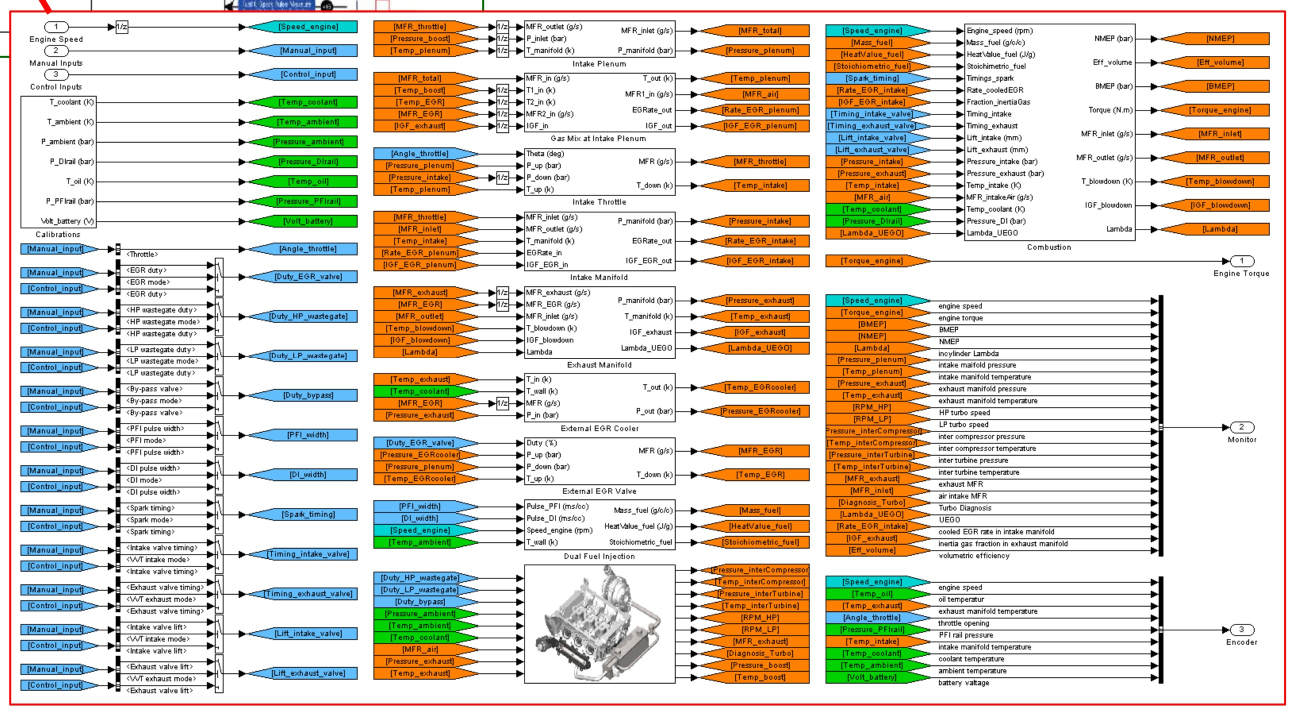
Control-Oriented Modeling



Crank-Resolved Engine Model



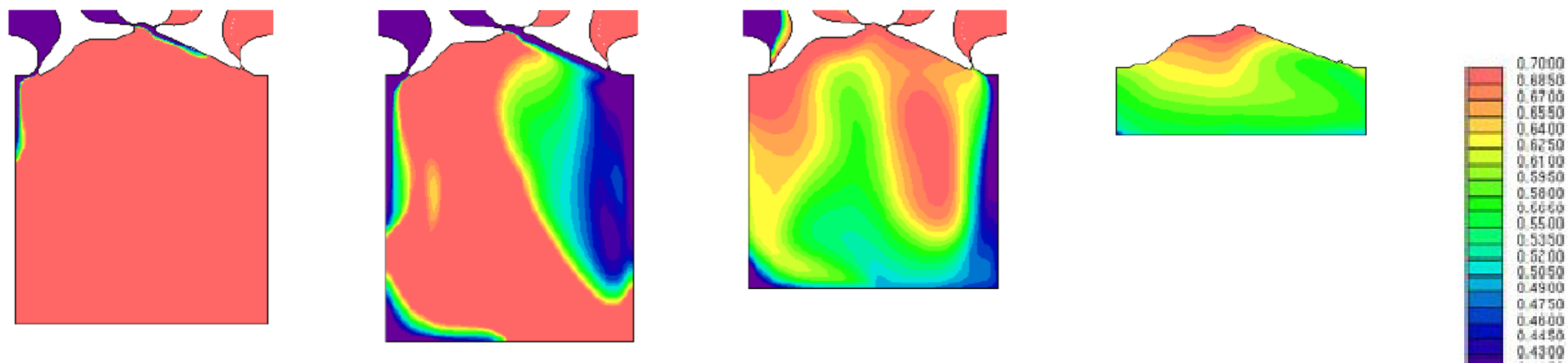
- ❑ Crank-based in-cylinder pressure and temperature;
- ❑ Simple in-cylinder charge mixing model;
- ❑ Event-based fuel, ignition, and torque calculation with mean manifold dynamics.
- ❑ Real-time simulation up to 5000RPM



Physics-based modeling: charge mixing (1)

Background

- HCCI combustion assumes Homogeneous Charge before compression ignition, while in practice it is Heterogeneous, especially with high EGR.
- One-zone control-oriented HCCI combustion model, developed earlier, assumes that the thermodynamic characteristics is uniformly distributed in the cylinder, leading large prediction error of the start of combustion (SOC).
- To accurately predict the SOC, it is proposed to use a two-zone HCCI combustion model for predicting SOC, which involves two-zone charge mixing and HCCI modeling.



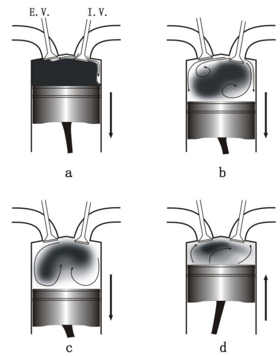
140° after exhaust TDC | 180° after exhaust TDC | 120° before comb TDC | 60° before comb TDC

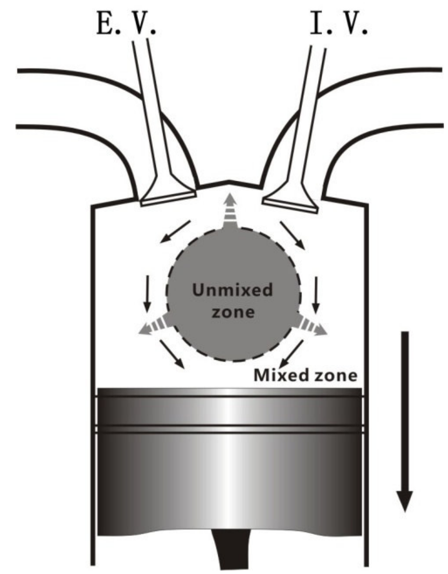
* M. Shen, "Simulation of in-cylinder flow and composition distribution of a gasoline HCCI engine with variable valve actuation," MS Thesis, Tianjin University, July, 2006.

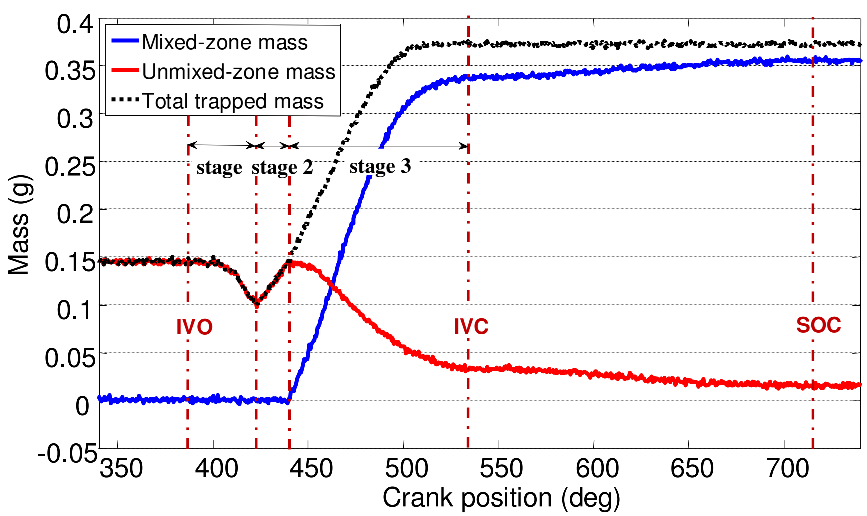
Physics-based modeling: charge mixing (2)

Charge mixing modeling - three phases:

- ❑ Backflow phase: when in-cylinder pressure is higher than manifold pressure;
- ❑ Backflow returning: when in-cylinder pressure is lower than manifold pressure;
- ❑ Fresh charge phase.





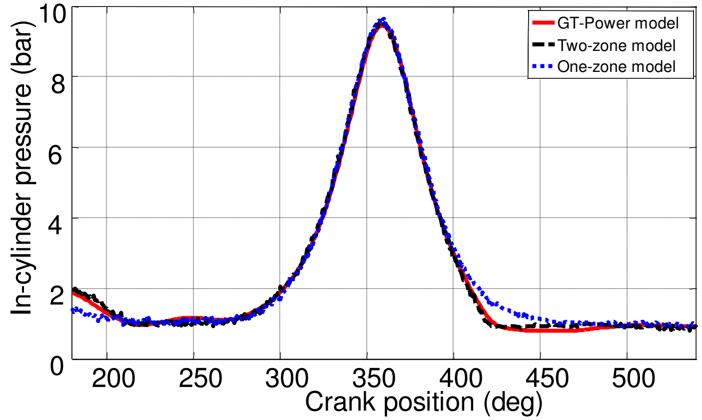


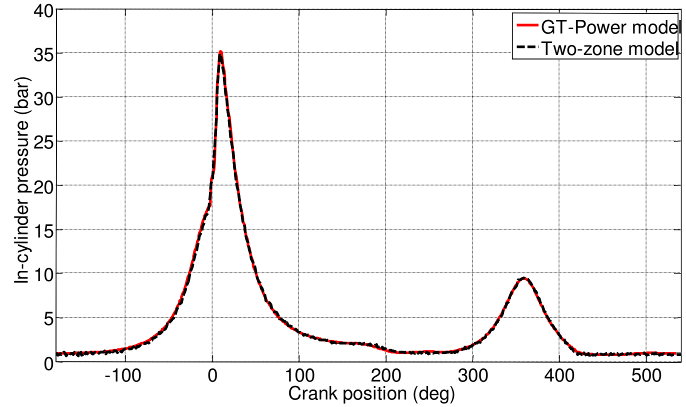
Mass transfer between fresh charge and residual is assumed to be mainly due to

Diffusion
- Molecular diffusion
- Laminar diffusion
- **Turbulent diffusion**

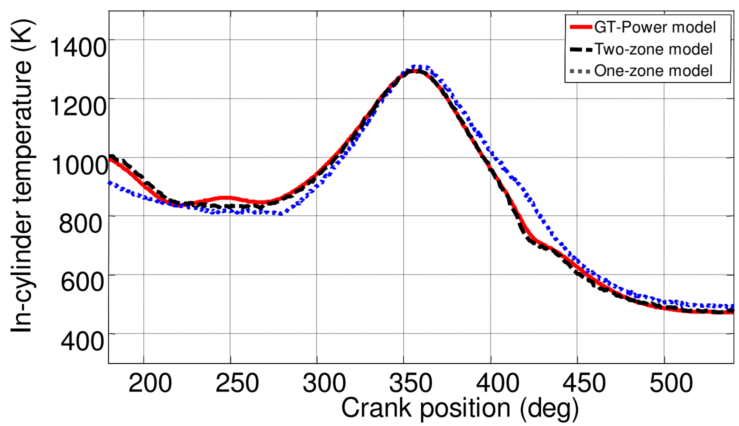
* S. Zhang, G. Zhu, and Z. Sun, "A control-oriented charge mixing and two-zone HCCI combustion model," *Submitted to IEEE Transactions on Vehicular Technology* (*Feb., 2013*).

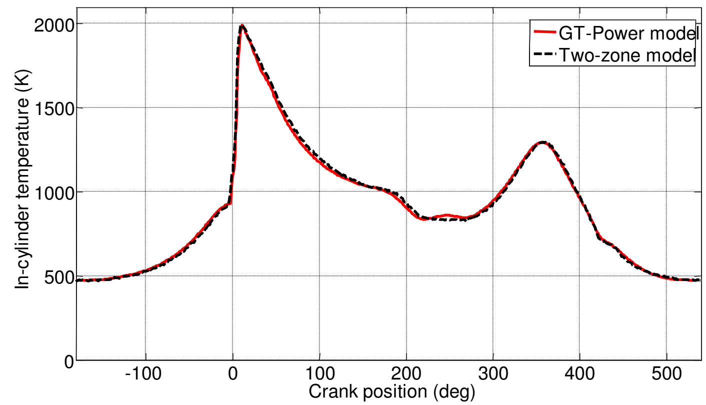
Physics-based modeling: charge mixing (3)





Pressure

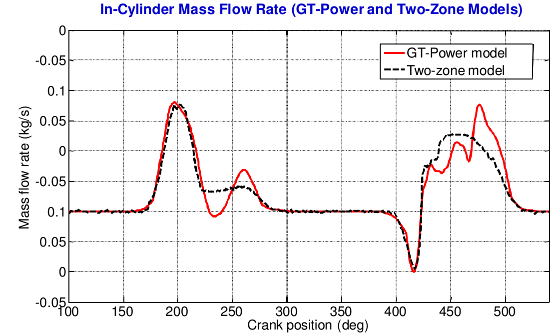




Temperature

Model	FUEL (MG)	SOC	IMEP
GT-Power	13.2	2	4.2
Two-zone model	13.2	2	4.22
One-zone model (w/ flow dynamics)	13.2	4	4.23
One-zone model (w/o flow dynamics)	13.2	8	4.36

In-Cylinder Mass Flow Rate (GT-Power and Two-Zone Models)



Hybrid powertrain – HIL simulations

Mototron based supervisory controller

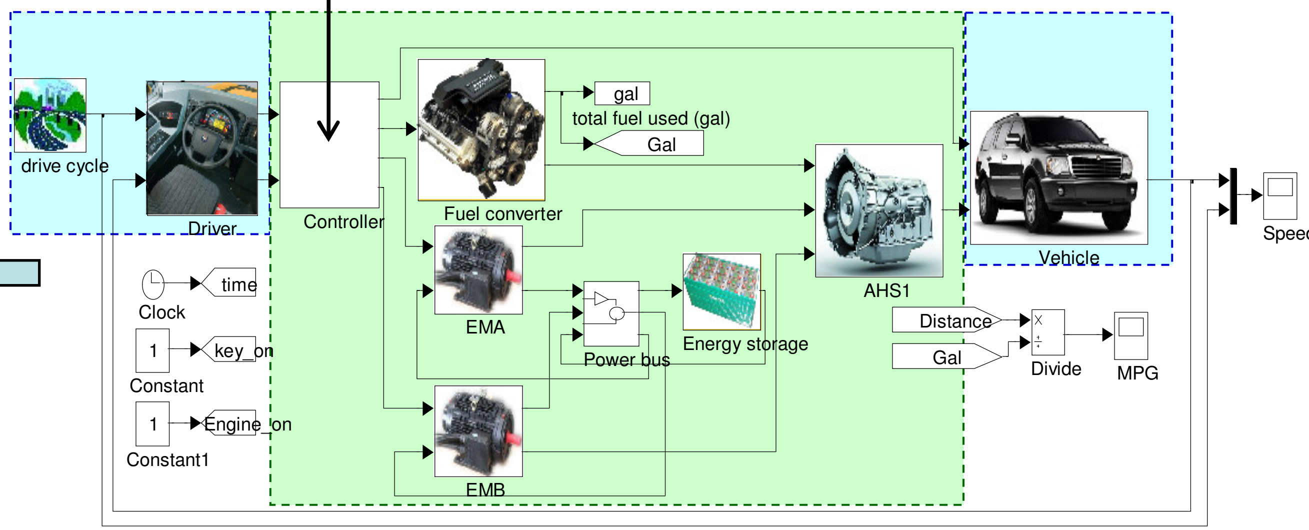
Hybrid powertrain supervisory control for the best fuel economy using real-time equivalent fuel consumption optimization

CAN

TruckSim + Driver Model

Hardware in the dyno room

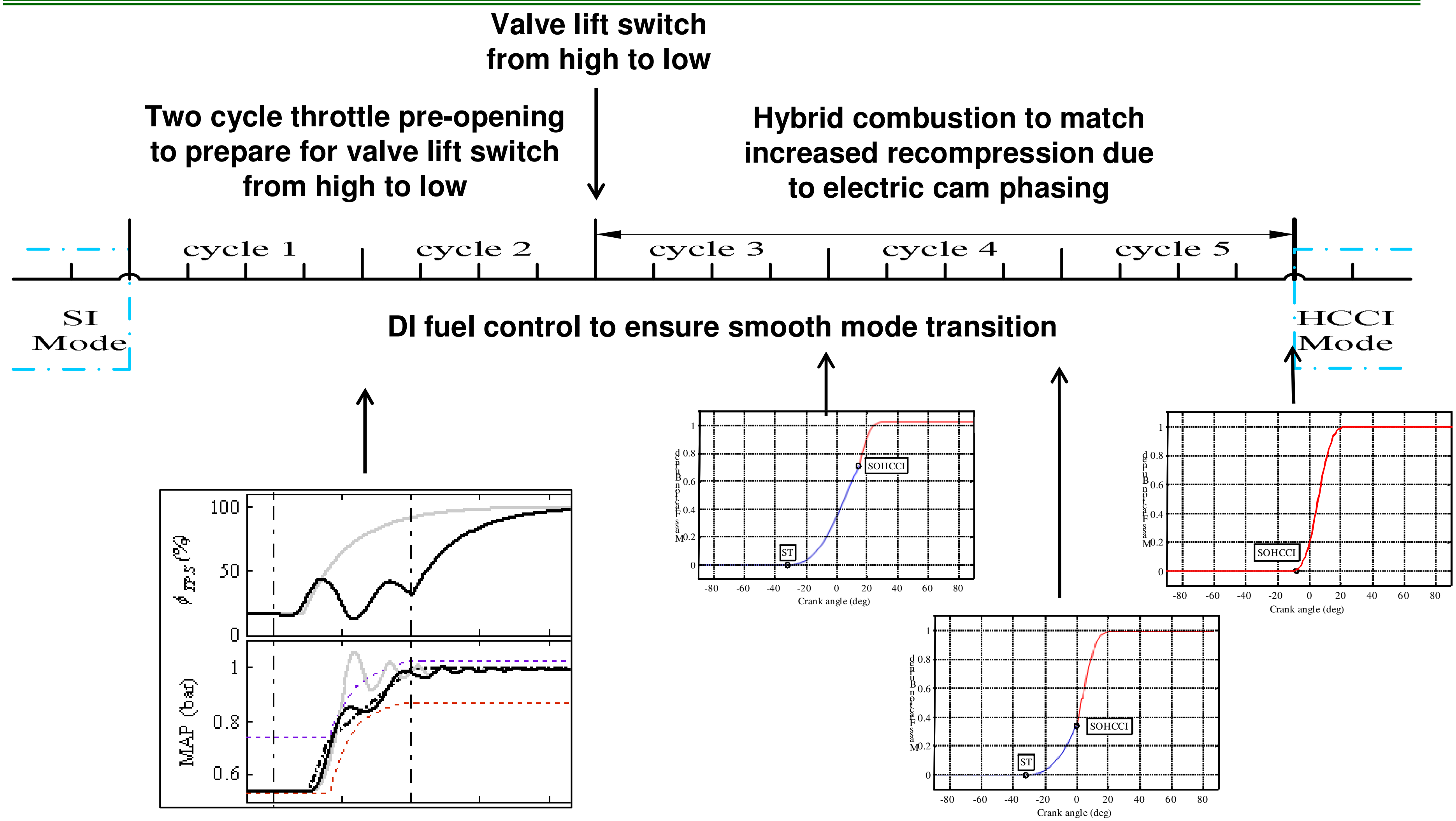
TruckSim + Driver Model



Opal-RT based real-time simulator

Real-time hybrid powertrain modeling for the hardware-in-the-loop (HIL) simulation applications

Optimal Control: HCCI Mode Transition



LQ Optimal throttle control to maintain desired AFR

Hybrid combustion that starts with SI and ends with HCCI combustion

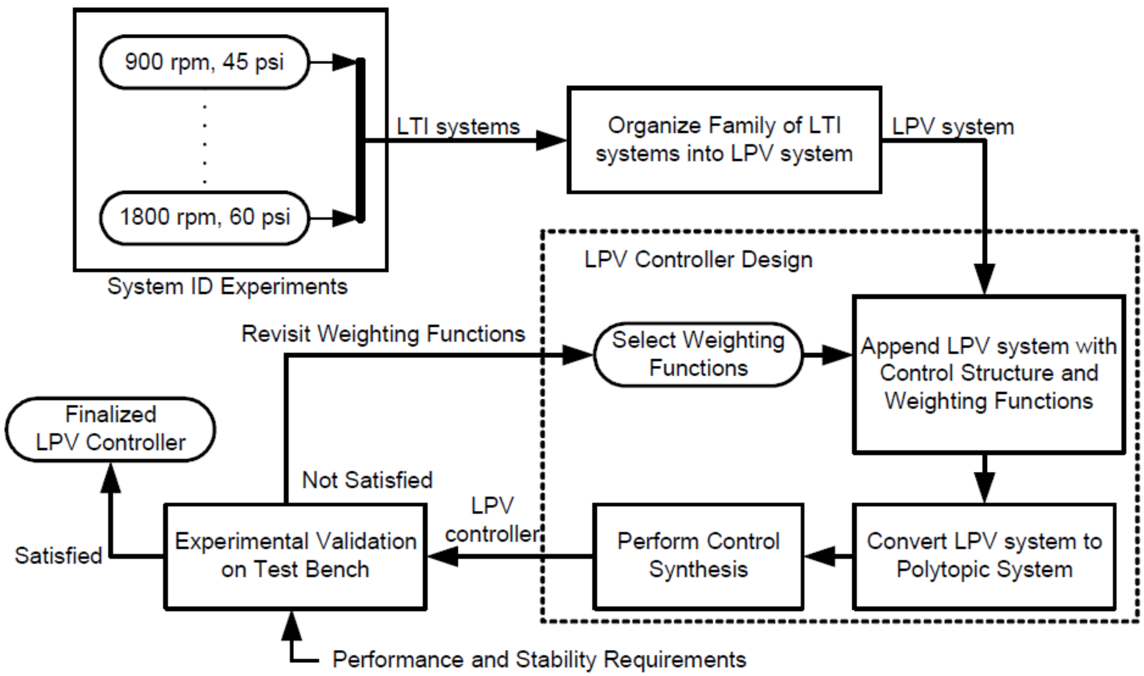
* X. Yang and G. Zhu, "SI and HCCI combustion mode transition control of a multi-cylinder HCCI capable SI engine," *IEEE Transaction on Control System Technology* (*Accepted in May, 2012,* DOI: 10.1109/TCST.2012.2201719)

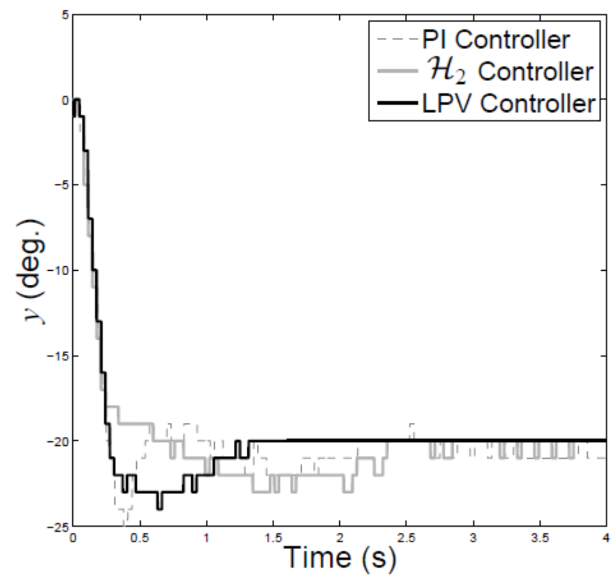
LPV (Gain-Scheduling) Control

- Traditionally, the PID control gains are tuned by calibration engineers in test cell or field.
- Control design based upon a linear system model whose parameters are a function of measurable parameters; and the resulting controller parameters are also a function of these measurable parameters.
- Closed loop system stability and performance are guaranteed

VVT example

$$
\begin{aligned}
x_c(k+1) &= A_c(\theta)x_c(k) + L(\theta)z(k) \\
u(k) &= K(\theta)x_c(k)
\end{aligned}
$$

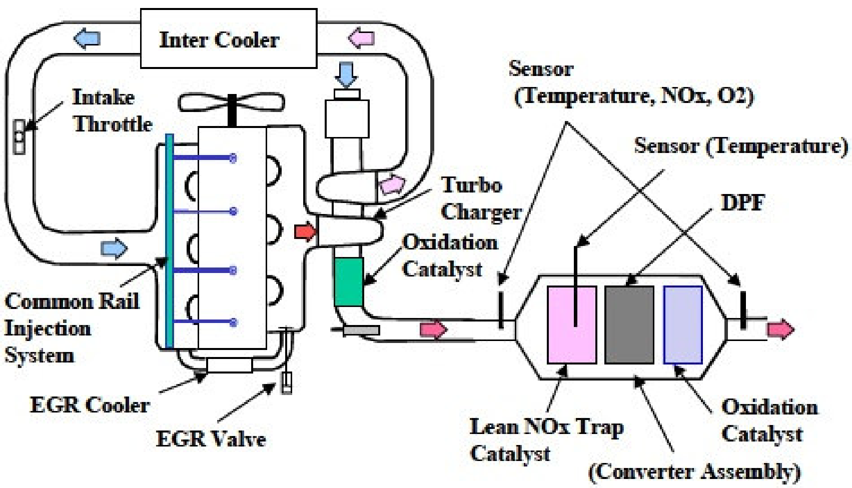


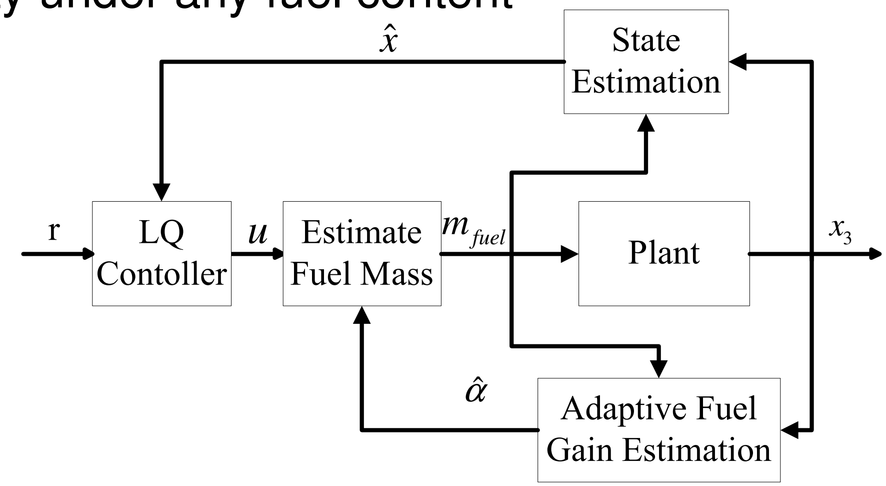


* A. White, Z. Ren, G. Zhu, and J. Choi, "Mixed H_∞ and H_2 LPV control of an IC engine hydraulic cam phase system," *IEEE Transaction on Control System Technology, Vol. 21, Issue. 1, 2013, pp. 229-238* (DOI 10.1109/TCST.2011.2177464)..

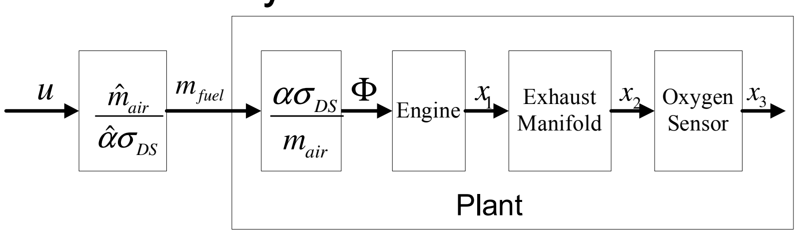
Adaptive Control: AFR during LNT regeneration

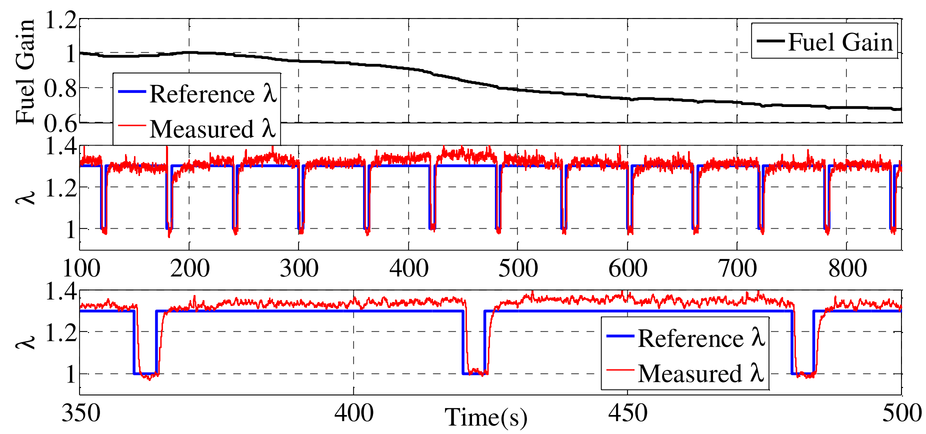
- ❑ Biofuel content is estimated online with guaranteed convergence
- ❑ Optimal air-to-fuel ratio (AFR) tracking control as a function of biofuel content
- ❑ Guaranteed closed loop system stability under any fuel content





System Model





- X. Chen, Y. Wang, I. Haskara, and G. Zhu, "Optimal air-to-fuel ratio tracking control with adaptive biofuel content estimation for the LNT regeneration," *IEEE Transaction on Control System Technology* (*Accepted in March, 2013, DOI: 10.1109/TCST.2013.2252350*).

Conclusions

- Model-based powertrain/engine control becomes a necessity due to the significant increment of number of sensors/actuator and high system nonlinearity.
- Control-oriented powertrain and engine modeling is moving towards first-principle based with reduced complexity (e.g., engine charge-mixing model)
- Powertrain and engine models used for the HIL (hardware-in-the-loop) simulations will be capable of simulating the physical systems at different detail level. The improved computing technology enables more and more first-principle based simulations.
- Model-based control, such as adaptive control, model predictive control, linear parameter varying (gain-scheduling) control, will be the future powertrain and control technologies

Other Research Activities

- Closed loop combustion control of internal combustion engines (SI, HCCI, and CI)
- Adaptive and model reference control of hydraulic and electric valve actuation
- Closed loop system identification and control of automotive systems
- Hybrid powertrain system control and optimization
- Automotive system modeling for hardware-in-the-loop (HIL) simulations
- Combustion control and optimization for ethanol engines
- Variable displacement engines
- Ionization based combustion diagnostics and control
- TEG (thermo-electric generator) system management
- Application of the smart material to automotive systems
- LPV (linear parameter varying) optimal control with hard constraints