Electrified Powertrain Design Exploration

MathWorks Automotive Conference

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Presenter

- Kevin Oshiro
  - MathWorks Application Engineering
  
  - Areas of interest:
    - Enabling Model-Based Design using physical modeling
    - Mechatronic systems / electrified powertrains
    - System level control strategies
    - Mentor for EcoCAR3 student competition
  
  - Previous experience at PACCAR (Kenworth R&D), Motorola
  
  - Education
    - MSEE, University of Washington
    - BSME, BSEE, Colorado School of Mines
Key Points

- Efficient **plant** modeling enables Model-Based Design (MBD)

- **Powertrain Blockset** provides HEV modeling framework, components, and controls

- Design / optimize **plant and controls** together as a system
Agenda

1. Motivation for modeling HEV’s
2. HEV plant modeling
3. Developing HEV controls
4. HEV design optimization
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Challenges with HEV Design

- Architecture / topology selection
- Selection and sizing of components
- Complexities in modeling plant and controllers
- How to optimize performance over wide range of conditions?
- Control algorithms real-time implementable
Challenges with HEV Design – Example

- **Parallel / Series-Parallel HEV Architecture**
  - **P#** = Electric machine locations
  - Multiple combinations (i.e. P2, P1/P4, etc.)
  - Intrinsic pros/cons for each location
Challenges with HEV Design – Example

- **Parallel / Series-Parallel HEV Architecture**
  - P# = Electric machine locations
  - Multiple combinations (i.e. P2, P1/P4, etc.)
  - Intrinsic pros/cons for each location

![Diagram of Parallel / Series-Parallel HEV Architecture]

- **P2**
  - P2 Clutch
  - P2 Machine
  - Trans + Clutch

- **P1 / P3**
  - Generator
  - Motor
Challenges with HEV Design – Example

- How to optimize performance over wide range of conditions?
  - Reduce energy consumption
  - Driveability requirements
    - Acceleration time
    - Gradeability
    - …
Solution – Model-Based Design (MBD)

- **Sections 2, 3**
  - Evaluate an architecture
  - Assess performance
  - Early closed loop control development

- **Section 4**
  - Optimizing control and plant simultaneously

- **Model reuse** - Code gen / HIL / Verification & Validation
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Powertrain Blockset Features

Library of blocks

Pre-built reference applications
Powertrain Blockset Benefits

- Accelerate your system development process
  - Open and documented library of component and subsystem models
  - Pre-built vehicle models
    - Industry grade models / architecture
    - Parameterize / customize
  - Fast-running models that are ready for HIL deployment
Use Powertrain Blockset *mapped* engine blocks with your own data.

Create *dynamic* engine models using Powertrain Blockset library components.

Connect in your own CAE model (e.g., GT-POWER).
Powertrain Blockset – P2 Reference Application
HEV Modeling Best Practices – Getting Started

- Start with a template or example
  - Review examples in Help for Powertrain Blockset (PTBS) and Simscape Driveline

- For system level simulation, start with a PTBS reference application
  - Model architecture
    - Uses referenced models and variant subsystems for modularity
    - Input / Output layers separate from application layer
    - Utilizes Simulink Projects for model organization

- Parameterize / customize subsystems for your needs
HEV Modeling Best Practices – New Models

- Use appropriate modeling fidelity for purpose

- Start small, build slowly, use “test harness” models
  - Ensure system is working properly before integrating into larger model
  - Can also use Simulink Test

- Use Simscape if:
  - Already have existing Simscape models
  - Multiple physical domains needed
  - Constructing complex topologies
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Powertrain Control – HEV Supervisory Control

- HEV system level controller included in Reference Applications
- Rule-based
- Simulink / Stateflow
- Real-time implementable
- Customize as needed
Powertrain Control – HEV Supervisory Control

- Major Functions
  - Accel Pedal → Torque
  - Regenerative Brake Blending
  - Battery Management System
  - Power Management
  - Supervisory Control (Stateflow)

- Only supervisory control system changes for different HEV architectures
  - Other functions are reusable
Powertrain Control – Charge Sustaining / PHEV Power-Split

- SOC Optimal calculation

\[
SOC_{\text{opt}} = \frac{E_{\text{batt}} \cdot SOC_{\text{opt}} \cdot \eta_{\text{e}} \cdot M_{\text{veh}} \cdot v_{\text{veh}}}{E_{\text{batt}}} \quad (2)
\]

- Engine Power Calculation

\[
P_{\text{ICE, dem}} = P_{\text{dem, trac}} + k_2 (SOC_{\text{opt}} - SOC_{\text{act}}) \quad (3)
\]

- Minimum Eng On Power

\[P_{\text{eng}} = k_1 \text{ [kW]}\]
Engine Control – HEV Mode

- Optimization algorithm used to find minimum BSFC line

- Results placed in lookup tables

- For an engine power command
  - Stationary mode can operate directly on this line
  - PHEV mode will attempt to operate on this line

- Good example of combining optimization w/ rules
Powertrain Control – Power Management

- Bound battery power within dynamic power limits of battery
- Convert mechanical power request to electrical power using efficiency map
- Check if electric power request is within limits
  - OK → allow original mechanical power request
  - Not OK → use limit for electrical power, and convert to an allowable mechanical power request
Starting the ICE in a P2 HEV: EV → Parallel

- “Bump” start
  - Can cause driveline disturbance

- “Shuffle” clutches
  - Process takes ~400-500 ms, causes vehicle speed to decrease

- Use low voltage Starter (or P0 machine)
  - Implemented in P2 Reference Application
  - 12V starter cranks ICE → ICE speed match mode → close P2 clutch
Assessing Performance

- Minimal vehicle speed tracking error
- Actuator torques not noisy
- Power doesn’t exceed limits for long periods
- SOC trends toward target
- Improved MPG over conventional vehicle
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Optimization Introduction

- Objective function – What you are trying to achieve?
  - Minimize measured signal

- Design variables – What parameters need to be adjusted?
  - Physical model parameters
  - Controller gains

- Constraints – What are the bounds or constraints of the design variables?
  - Min/Max values
  - Parameter dependencies

Minimizing (or maximizing) objective function(s) subject to a set of constraints

Objective Function

$$\min_{x} f(x)$$

Linear or nonlinear

Design variables (discrete or integer)

Linear constraints

$$Ax \leq b$$

$$A_{eq} x = b_{eq}$$

$$l \leq x \leq u$$

Nonlinear constraints

$$c(x) \leq 0$$

$$c_{eq}(x) = 0$$
MathWorks Optimization Tools

- **Optimization Toolbox**
  - MATLAB

- **Global Optimization Toolbox**
  - MATLAB

- **Simulink Design Optimization (SDO)**
  - **User Interface**
  - Uses functions from toolboxes above

Different starting points give different optima!
HEV Design Optimization Examples

- Example 1
  - Simultaneous control and hardware parameter optimization

- Example 2
  - Find single set of control parameters that work for different driving conditions
HEV Design Optimization Examples

- **Example 1**
  - Simultaneous control and hardware parameter optimization

- **Example 2**
  - Find single set of control parameters that work for different driving conditions
Multi-Mode HEV Review

Development of a New Two-Motor Plug-In Hybrid System

Naritomo Higuchi, Yoshhiro Sunaga, Masashi Tanaka and Hiroo Shimada
Honda R&D Co., Ltd.

Battery
Mot
Gen
Clutch

Front Tires

Requested Tractive Force [N]

Vehicle Speed [kph]

0 1000 2000 3000 4000 5000 6000 7000 8000

0 20 40 60 80 100 120 140 160

EV Mode
Multi-Mode HEV Review

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Honda R&D Co., Ltd.

SHEV Mode

Battery

Mot

Gen

Clutch

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Requested Tractive Force [N]

Vehicle Speed [kph]

EV

SHEV

Engine / Power Split

MathWorks
Multi-Mode HEV Review

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Engine Mode
Design Optimization Problem Statement

- Maximize MPGe
  - FTP75 and HWFET
  - Weighted MPGe = 0.55(FTP75) + 0.45(HWFET)

- Optimize Parameters:
  - 5 control parameters
    - EV, SHEV, Engine mode boundaries
  - 1 hardware parameter
    - Final differential ratio

- Use PC
  - Simulink Design Optimization (SDO)
  - Parallel Computing Toolbox (PCT)
Simulink Design Optimization

- Speed Up Best practices
  - Accelerator mode
  - Fast Restart
  - Use Parallel Computing Toolbox
- Specify Simulation timeout
Optimization Results

Simulink Design Optimization $\rightarrow$ Response Optimization

$F_d = \frac{\beta}{(\gamma + \psi)} + \alpha$

3.42:1

+ 2% MPGe

~ 12 Hours

2.92:1
HEV Design Optimization Examples

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Powertrain Control – Charge Sustaining / PHEV Power-Split

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- Minimum Eng On Power

**Figure 5. Hybrid operating strategy: parameter \( k_1 \)**
Sensitivity Analysis

- Determine sensitivity of fuel economy and ability to charge sustain to changes in design parameters

- Simulink Design Optimization UI
  - Create sample sets
  - Define constraints
  - Run Monte Carlo simulations
  - Speed up using parallel computing
Sensitivity Analysis – Results

- **HWFET**
  - CS Factor highest correlation for charge sustaining
  - Min Engine Power highest correlation for max mpg

- **US06**
  - CS Factor highest correlation for charge sustaining and max mpg

- **FTP72**
  - Min Engine Power highest correlation for maximizing mpg and charge sustaining
Optimization Process – Sensitivity Analysis

- **Sensitivity Analysis**
  - Best numbers in experiment that maximized mpg with minimum delta SOC

<table>
<thead>
<tr>
<th></th>
<th>Charge Sustaining Factor</th>
<th>minimum Engine Power</th>
<th>SOC Factor</th>
<th>mpg</th>
<th>delta SOC (%)</th>
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<td>33.82</td>
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- Note the variation in the 3 design variables

- **Next step:**
  - use Response Optimization to attempt to find a *unified* set of parameters to maximize mpg and minimize delta SOC over all 3 drive cycles
Response Optimization

- Find optimal design parameters that satisfy multiple objectives and constraints simultaneously.

Simulink Design Optimization UI
- Define design variables, objective functions, and constraints.
- Use ‘Uncertain Variable’ (Drive Cycle) to run all 3 cycles in 1 iteration.
- Speed up using parallel computing.
Response Optimization – Results

1. View Results
SDO – Response Optimization

- Summary

<table>
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3 Cycle Response Optimization

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- Found single set of design variables to maximize mpg and charge sustain!
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Thank You