Full Vehicle Simulation for Electrified Powertrain Selection

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Key Points

- Customize pre-built vehicle models to assess electrified powertrain variants
- Apply optimal control techniques to make fair comparisons
- Quantify tradeoffs between fuel economy and acceleration performance
Agenda

- Context
- Case study description
- Tools used
- Plant model and controls
- Results
- Next steps
What Is Meant By “Full Vehicle Simulation”?

- Plant model + closed-loop control algorithms
  - Production code out of scope for today’s presentation (OBD, timing, etc.)

- Right balance of accuracy / speed
  - Sufficient detail for attribute analysis (fuel economy, performance, drivability, …)
  - Fast enough for design optimization (much faster than real-time)

- Heterogeneous modeling environment
  - Support for inclusion of 3rd party simulation tools (S-function, FMU, …)
Simulink as a Simulation Integration Platform

Focus of this talk

Data Management  
Solver Technology  
Vehicle Configuration  
Multi-actor Scenarios  
Visualization

Simulink
Full Vehicle Simulation Track

1. **Full Vehicle Simulation for Electrified Powertrain Selection**
   For a given vehicle class, how can I use simulation to select a hybrid powertrain that meets my requirements?

2. **Model-Based Design of Electric Powertrain Systems**
   For a given powertrain, how can I use simulation to develop and calibrate motor controls?

3. **Objective Drivability Calibration**
   For a given vehicle, how can I use simulation to calibrate the ECU for improved drivability?
Agenda

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Electrified Powertrain Selection

- Considering variants of single motor, parallel hybrids
- Where is the best location for the motor?
Problem Statement

- Minimize:
  - Fuel consumption (mpg for drive cycles Highway, City, US06)
  - Acceleration time ($t_{0-60mph}$)

- Subject to:
  - Actuator limits for motor & engine
  - Velocity within 2 mph window of drive cycle target velocity
  - SOC within $[SOC_{\text{low}}, SOC_{\text{high}}]$
  - $|SOC_{\text{final}} - SOC_{\text{init}}| < \text{tol} \rightarrow \text{requires iteration on supervisory control parameter}$
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Powertrain Blockset

- **Goals:**
  - Provide starting point for engineers to build **good plant / controller models**
  - Provide **open** and documented models
  - Provide very **fast**-running models that work with popular HIL systems

*Lower the barrier to entry for Model-Based Design*
Powertrain Blockset Features

Library of blocks

- Energy Storage and Auxiliary Drive
- Drivetrain
- Propulsion
- Transmission
- Vehicle Dynamics
- Vehicle Scenario Builder

Pre-built reference applications

- Conventional Vehicle Reference Application
- Hybrid Electric Vehicle Multimode Reference Application
- Hybrid Electric Vehicle Input Power-Split Reference Application
- Hybrid Electric Vehicle HEV Reference Application
- Electric Vehicle Reference Application
- CI Engine Dynamometer Reference Application
- SI Engine Dynamometer Reference Application
Reference Applications

Full Vehicle Models

Conventional Vehicle Reference Application
The conventional vehicle reference application represents a full vehicle model with an internal combustion engine, transmission, and

Hybrid Electric Vehicle Multimode Reference Application
The hybrid electric vehicle (HEV) multimode reference application represents a full multimode HEV model with an internal combustion

Hybrid Electric Vehicle Input Power-Split Reference Application
The hybrid electric vehicle (HEV) input power-split reference application represents a full HEV model with an internal combustion

Hybrid Electric Vehicle P2 Reference Application
The hybrid electric vehicle (HEV) P2 reference application represents a full HEV model with an internal combustion engine, transmission,

Electric Vehicle Reference Application
The electric vehicle (EV) reference application represents a full electric vehicle model with a motor-generator, battery, direct-drive

Virtual Engine Dynamometers

CI Engine Dynamometer Reference Application
The compression-ignition (CI) engine dynamometer reference application represents a CI engine plant and controller connected to a

SI Engine Dynamometer Reference Application
The spark-ignition (SI) engine dynamometer reference application represents a SI engine plant and controller connected to a
What’s New in **R2018b**?

**Engine Test Data Import**
What’s New in R2019a?
Energy Accounting and Reporting

- Simulate
  - Turn on logging
  - Run simulation
  - Check conservation of energy
What’s New in R2019a?
Energy Accounting and Reporting

- **Simulate**
  - Turn on logging
  - Run simulation
  - Check conservation of energy

- **Report results**
  - System level summary
  - Subsystem detailed view
  - Excel export
  - Efficiency histogram
  - Time trace plots
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EV / HEV Configurations Shipping with Powertrain Blockset

- **Pure EV**

- **Multi-mode HEV → P1/P3**

- **Released in:** R2016b

- **Similar powertrains:**
  - Nissan Leaf
  - Tesla Model 3
  - Chevy Bolt

- **Released in:** R2016b

- **Similar powertrains:**
  - Hybrid Honda Accord
EV / HEV Configurations Shipping with Powertrain Blockset

- **Input Power-Split HEV**
  - Released in: **R2017b**
  - Similar powertrains:
    - Toyota Prius
    - Lexus Hybrid
    - Ford Hybrid Escape

- **P2 HEV**
  - Released in: **R2018b**
  - Similar powertrains:
    - Nissan Pathfinder
    - Hyundai Sonata
    - Kia Optima
Flexible Modeling Framework

1. Choose a vehicle configuration
   - Select a reference application as a starting point

2. Customize the plant model
   - Parameterize the components
   - Customize existing subsystems
   - Add your own subsystem variants

3. Customize the controllers
   - Parameterize the controllers
   - Customize supervisory control logic
   - Add your own controller variants

4. Perform closed-loop system testing
   - Sensitivity analyses
   - Design optimization
   - MIL / SIL / HIL testing
Initial HEV Architecture Study

- EcoCAR Mobility Challenge
  - Student competition for 12 North American universities
  - Collaboration of industry, academia and government research labs
  - Improve fuel economy through hybridization and enable level 2 automation capabilities

- MathWorks provided Powertrain Blockset reference applications:
  - Plant models for P0 – P4 architectures
  - Supervisory controller

- Generic versions of the models used for this study
Plant Model: System level
Plant Model: Driveline Subsystem
Plant Model: Electrical Subsystem

650 V Battery & DC-DC Converter
(smaller sizing for P0)

30 kW Motor
(10 kW for P0)
Plant Model: Engine Subsystem

1.5l Gasoline Engine

Maps generated from GT-POWER®
Controls-oriented Model Creation

Detailed, design-oriented model

Fast, but accurate controls-oriented model
Controller:
Hybrid Control Module

- Acceleration Pedal → Torque
- Regenerative Brake Blending
- Energy Management
HEV Energy Management

- Instantaneous torque (or power) command to actuators (engine, electric machines)
- Subject to constraints:
  \[ \tau_{\text{min}}(\omega) \leq \tau_{\text{act}} \leq \tau_{\text{max}}(\omega) \]
  \[ P_{\text{chg}}(SOC) \leq P_{\text{batt}} \leq P_{\text{dischg}}(SOC) \]
  \[ I_{\text{chg}}(SOC) \leq I_{\text{batt}} \leq I_{\text{dischg}}(SOC) \]
  \[ SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}} \]
- Attempt to minimize energy consumption, maintain drivability

\[ T_{\text{demand}} = T_{\text{eng}} + T_{\text{mot}} \]
Equivalent Consumption Minimization Strategy (ECMS)

- **What is ECMS?**
  - Supervisory control strategy to decide when to use engine, motor or both
  - Based on analytical instantaneous optimization

\[
\min P_{\text{equivalent}}(t) = P_{\text{fuel}}(t) + s(t) \cdot P_{\text{battery}}(t),
\]

where \( s(t) \) are the “equivalent factors”

- **Why use ECMS?**
  - Provides near optimal control if drive cycle is known a priori
  - Fair comparison between different HEV architectures (only tune equivalence factor)
  - Can be enhanced with adaptive methods (i.e. Adaptive-ECMS)
Equivalent Consumption Minimization Strategy (ECMS)

Equivalent fuel needed to recharge battery

Drive Mode

Equivalent fuel saved by future battery use

Regen Mode
Equivalent Consumption Minimization Strategy (ECMS)

- Collaborated with Dr. Simona Onori from Stanford University
- For more information on ECMS, refer to: https://www.springer.com/us/book/9781447167792
Equivalent Consumption Minimization Strategy (ECMS) Process

1. Create torque split vector

\[
\begin{bmatrix}
\text{Trq Cmd} \\
0 \\
-\text{Min Mot Trq} \\
\vdots \\
+\text{Max Mot Trq}
\end{bmatrix}
\]

2. Check constraints, determine infeasible conditions

\[
\tau_{\min}(\omega) \leq \tau_{\text{act}} \leq \tau_{\max}(\omega)
\]

\[
P_{\text{chg}}(SOC) \leq P_{\text{batt}} \leq P_{\text{disch}}(SOC)
\]

\[
I_{\text{chg}}(SOC) \leq I_{\text{batt}} \leq I_{\text{disch}}(SOC)
\]

\[
SOC_{\min} \leq SOC \leq SOC_{\max}
\]

3. Calculate and minimize cost function

\[
\min P = P_{\text{fuel}} + s \cdot P_{\text{batt}}
\]
Equivalent Consumption Minimization Strategy (ECMS) Process
Equivalent Consumption Minimization Strategy (ECMS) Process
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Methodology

- Generate Powertrain Blockset mapped engine from GT-POWER model

- Perform architecture evaluation
  - For each Px architecture (non-plug-in):
    - Iterate on s (controller parameter) to achieve $\Delta \text{SOC} \leq 1\%$ across each drive cycle
    - Assess fuel economy on city, highway and US06 drive cycles
    - Assess acceleration performance on Wide Open Throttle (WOT) test
  - Compare fuel economy and performance across P0 – P4 architectures

- Perform P4 axle ratio sweep
  - Assess attributes over a range of axle ratios
  - Compare fuel economy and performance across P4 axle ratios
Charge Sustain Iteration Process

Simulink Design Optimization

- Optimization / Global Optimization
- Parallel Computing

\[
\text{min } \Delta SOC^2
\]

Update ‘s’
Architecture Comparison Results

- Placing motors closer to the drive wheel:
  - Improves fuel economy (better regen efficiency)
  - Degrades performance (lower mechanical advantage)

- Simulation allows you to quantify the tradeoff

- ECMS provides a fair comparison of alternatives
P4 Ratio Sweep Results

- P4 axle is independent of ICE axle transmission ratios, shift maps, and final ratio
- Quantify tradeoffs
  - Higher ratios → Better for performance and FTP75 / US06 mpg
  - Lower ratios → Better for HWFET mpg
- Future study of 2-speed P4 axle

![Graph showing fuel economy vs. 0-60 mph time with N = 4.56 and N = 2.73]
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Summary

- Assembled full vehicle simulation
  - Powertrain Blockset as framework for vehicle level modeling
  - Mapped engine models auto-generated from design-oriented engine model
  - ECMS for supervisory controls provides a fair comparison between P0 – P4 variants

- Assessed fuel economy / performance across several variants
  - Iterated on controller parameter to identify charge neutral settings
  - Generated pareto curve to quantify tradeoffs
    - P0-4 HEV Architectures
    - P4 Axle Ratios
Next Steps

- **Widen the scope of powertrain selection study**
  - Search over design parameters (gear ratios, battery capacity, etc.)
  - Include two-motor HEV’s, with modified ECMS controls

- **Conduct more in-depth analysis**
  - Assess additional attributes of interest by including more design-oriented models (engine, aftertreatment, drivability, etc.)
  - Integrate control features from advanced development / production

- **Continue along the V-cycle**
  - Once field candidates are narrowed down to a few options, conduct more detailed electrification study (motor controls, battery design, etc.)
  - Once vehicle platform is selected, calibrate vehicle (drivability, etc.)
Thank You

Mike Sasena, PhD
Product Manager
msasena@mathworks.com

Kevin Oshiro, MS
Application Engineering
koshiro@mathworks.com