Full Vehicle Simulation for Electrified Powertrain Selection

MathWorks Automotive Conference

April 11, 2019

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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 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

- Data Management
- Solver Technology
- Vehicle Configuration
- Multi-actor Scenarios
- Visualization
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Electrified Powertrain Selection

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

▪ Maximize:
  – Fuel economy (l/100km for drive cycles Highway, City, US06)
  – Acceleration performance ($t_{0-100km/h}$)

▪ Subject to:
  – Actuator limits for motor & engine
  – Velocity within 3,2 km/h window of drive cycle target velocity
  – SOC within [$SOC_{\text{low}}, SOC_{\text{high}}$]
  – $|SOC_{\text{final}} - SOC_{\text{init}}| < tol \rightarrow \text{requires iteration on supervisory control parameter}$
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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 P2 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**
  - Released in: **R2016b**
  - Similar powertrains:
    - Nissan Leaf
    - Tesla Roadster
    - Chevy Bolt

- **Multi-mode HEV → P1/P3**
  - 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
EcoCAR: Mobility Challenge

- **What is it?**
  - 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

- **Work reused as starting point for powertrain for this work**
Plant Model:
System level
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
Plant Model: 
Electrical Subsystem

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

30 kW Motor
(10 kW for P0)
Plant Model:
Driveline Subsystem
Controller: Hybrid Control Module

- Accel Pedal $\rightarrow$ Torque
- Regenerative Brake Blending
- Energy Management
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

- **Why use ECMS?**
  - Provides near optimal control if drive cycle is known a priori
  - Can be enhanced with adaptive methods (i.e. Adaptive-ECMS)

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

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

- Generate Powertrain Blockset mapped engine from GT-POWER model

- For each $P_i$ architecture:
  - Using mapped engine model, iterate on $s$ (controller parameter) to achieve $dSOC < 1\%$ 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
Results

Fuel Economy on FTP75 [L/100km]
- Conventional
- HEV P0
- HEV P1
- HEV P2
- HEV P3
- HEV P4

Fuel Economy on HWFET [L/100km]
- Conventional
- HEV P0
- HEV P1
- HEV P2
- HEV P3
- HEV P4

Fuel Economy on US06 [L/100km]
- Conventional
- HEV P0
- HEV P1
- HEV P2
- HEV P3
- HEV P4
Results

- ECMS provides a fair comparison of alternatives

- 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
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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 strategy applicable to all P0 – P4 variants

- Assessed fuel economy / performance across several variants
  - Iterated on controller parameter to identify charge neutral settings
  - Generated pareto curve to quantify tradeoff between variants
Next Steps

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

- **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

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