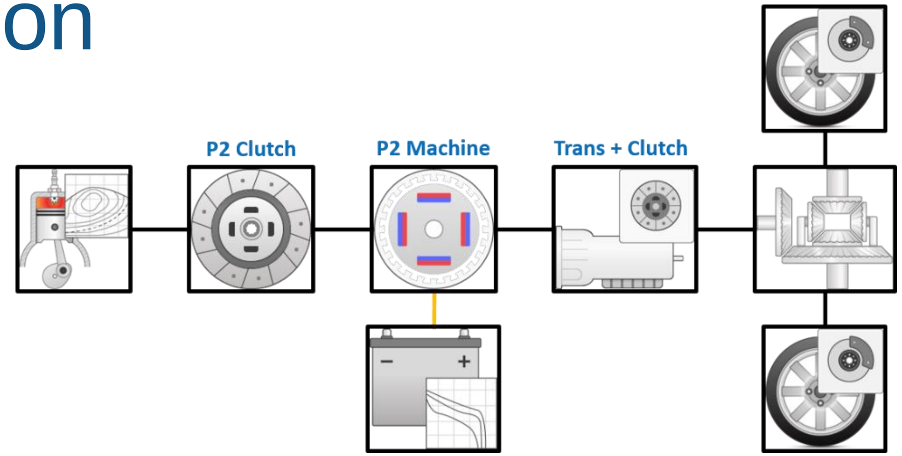
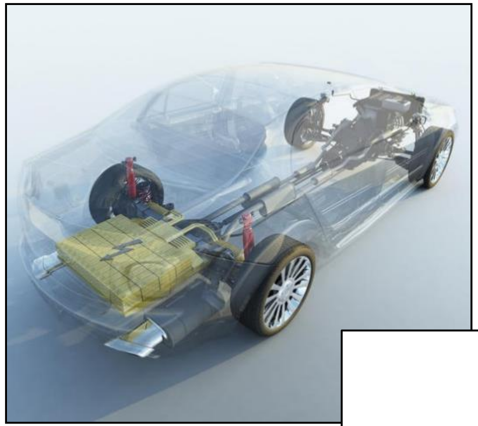
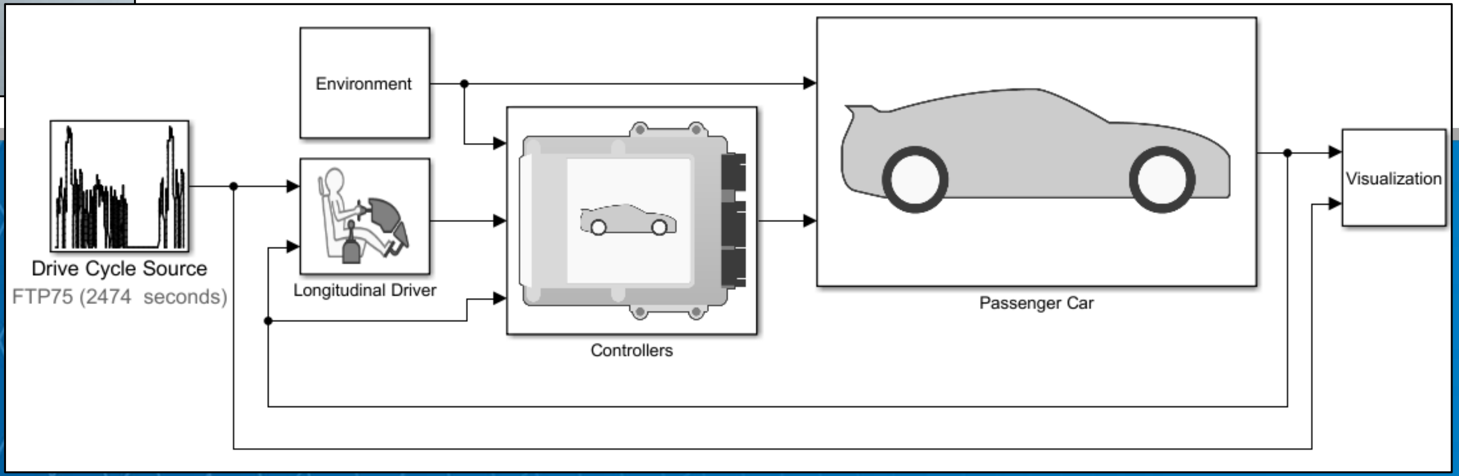
Electrified Powertrain Design Exploration



MathWorks Automotive Conference

May 2nd, 2018





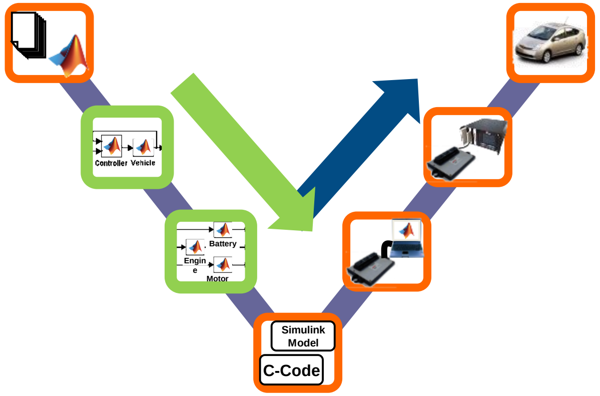
Kevin Oshiro
MathWorks

Presenter

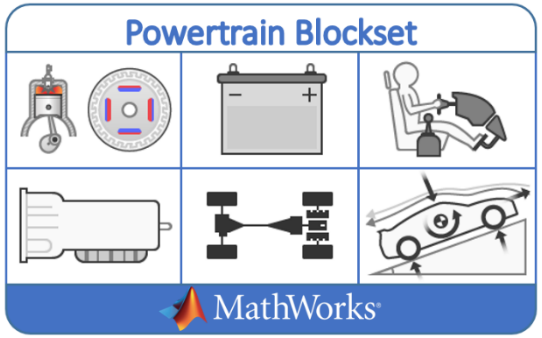
- Kevin Oshiro
  - MathWorks Application Engineering
  - Areas of interest:
    - Enabling Model-Based Design using physical modeling
    - Mechatronic systems / electrified powertrains
    - System level control strategies
    - Mentor for EcoCAR3 student competition
  - Previous experience at PACCAR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

Key Points

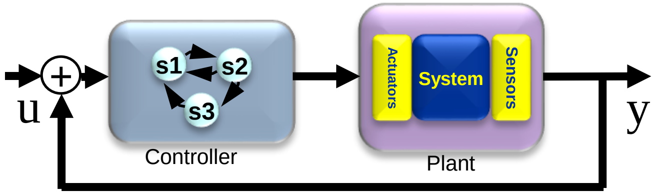
- Efficient plant modeling enables Model-Based Design (MBD)



- 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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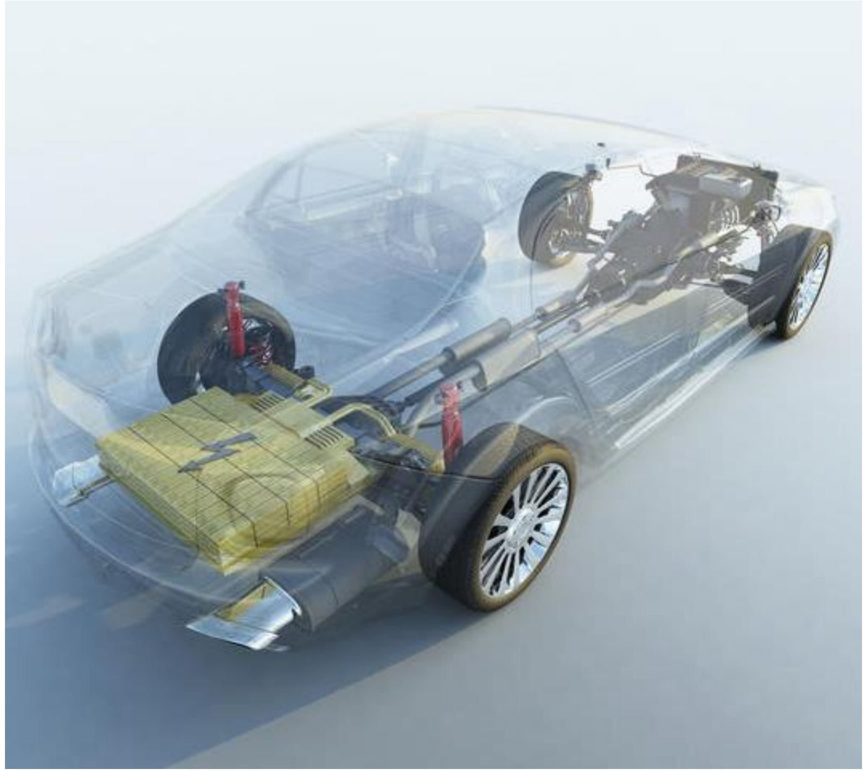
Challenges with HEV Design

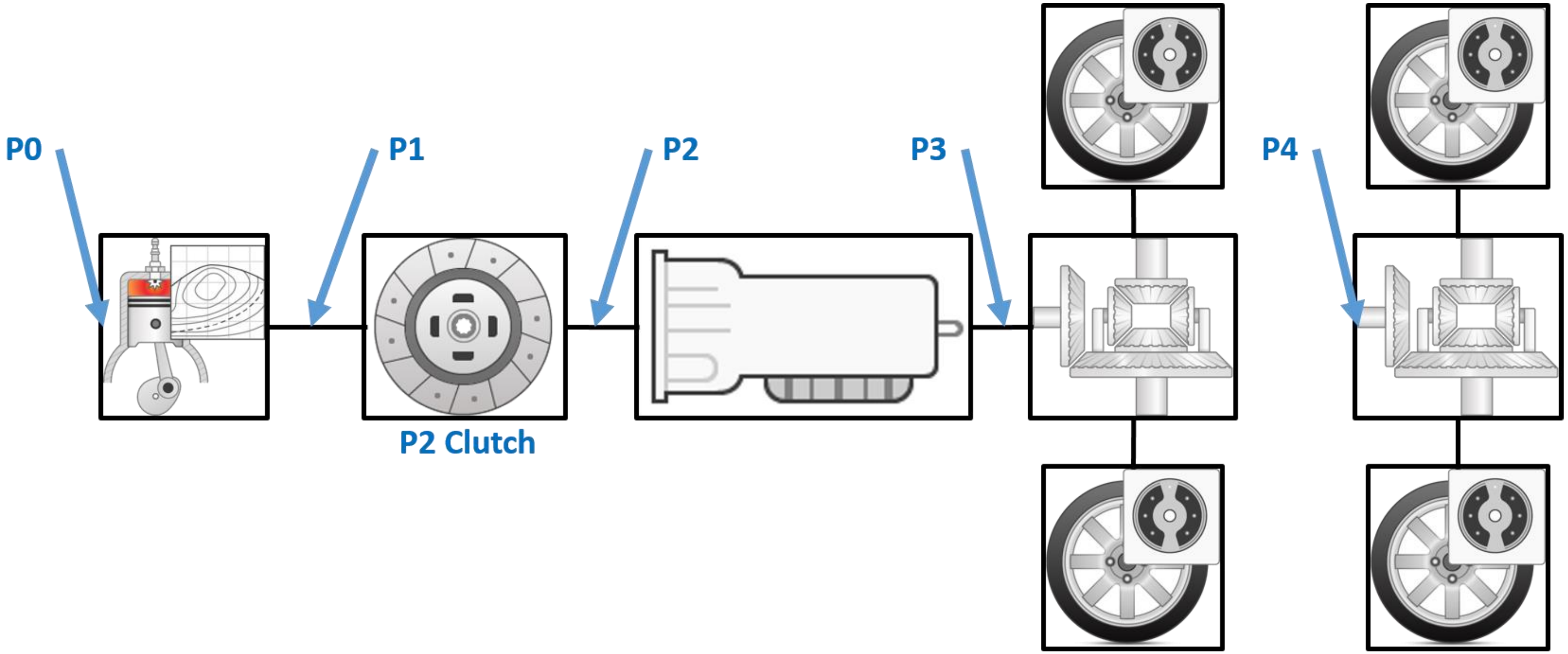
- Architecture / topology selection
- Selection and sizing of components
- Complexities in modeling plant and controllers



- How to optimize performance over wide range of conditions?
- Control algorithms real-time implementable

Challenges with HEV Design – Example

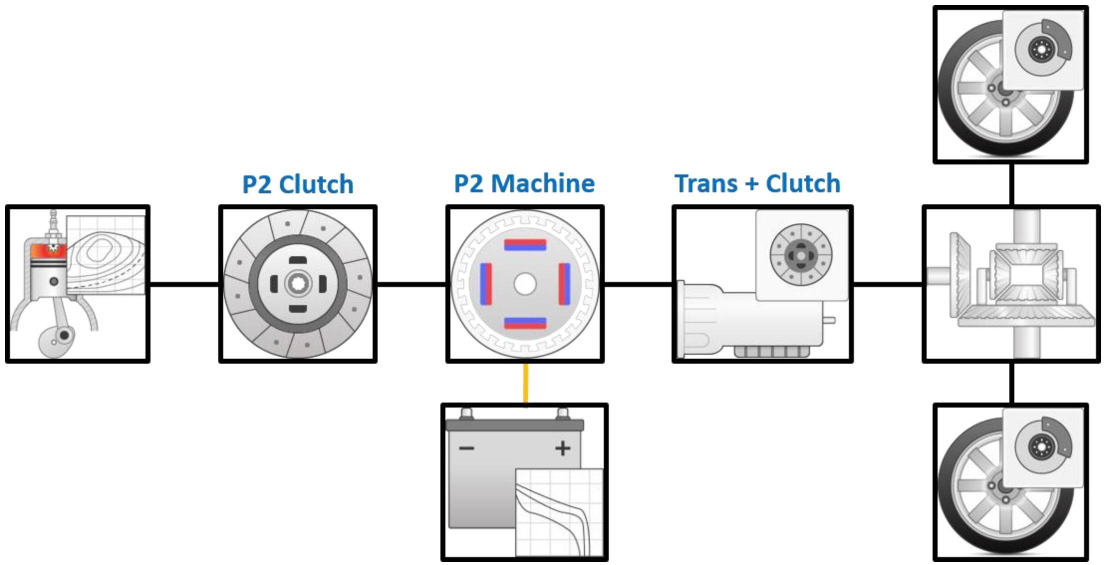
- Parallel / Series-Parallel HEV Architecture
  - P# = Electric machine locations
  - Multiple combinations (i.e. P2, P1/P4, etc.)
  - Intrinsic pros/cons for each location



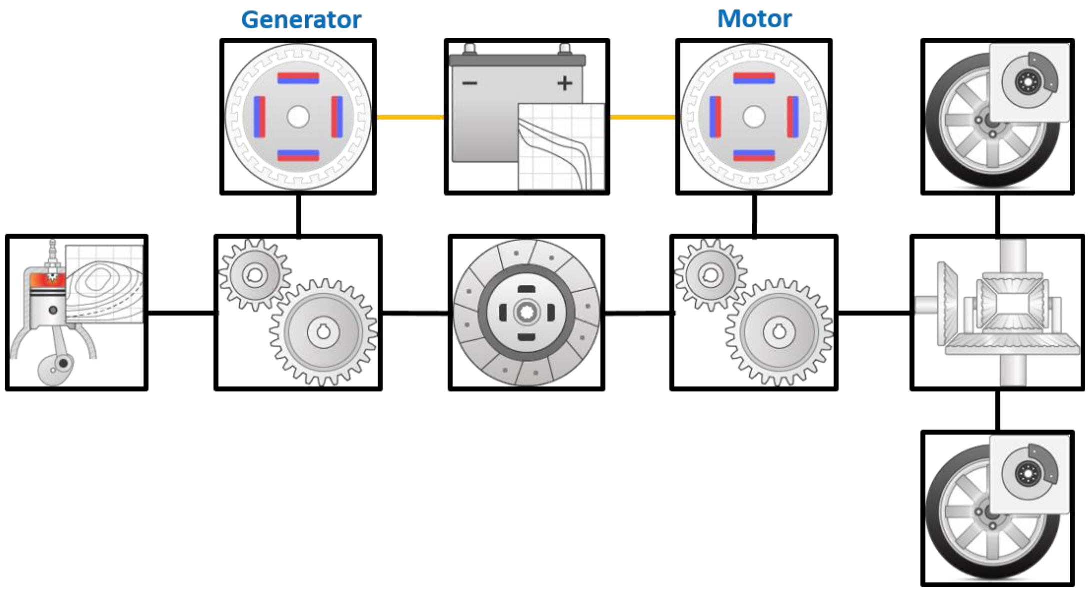
Challenges with HEV Design – Example

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

P2

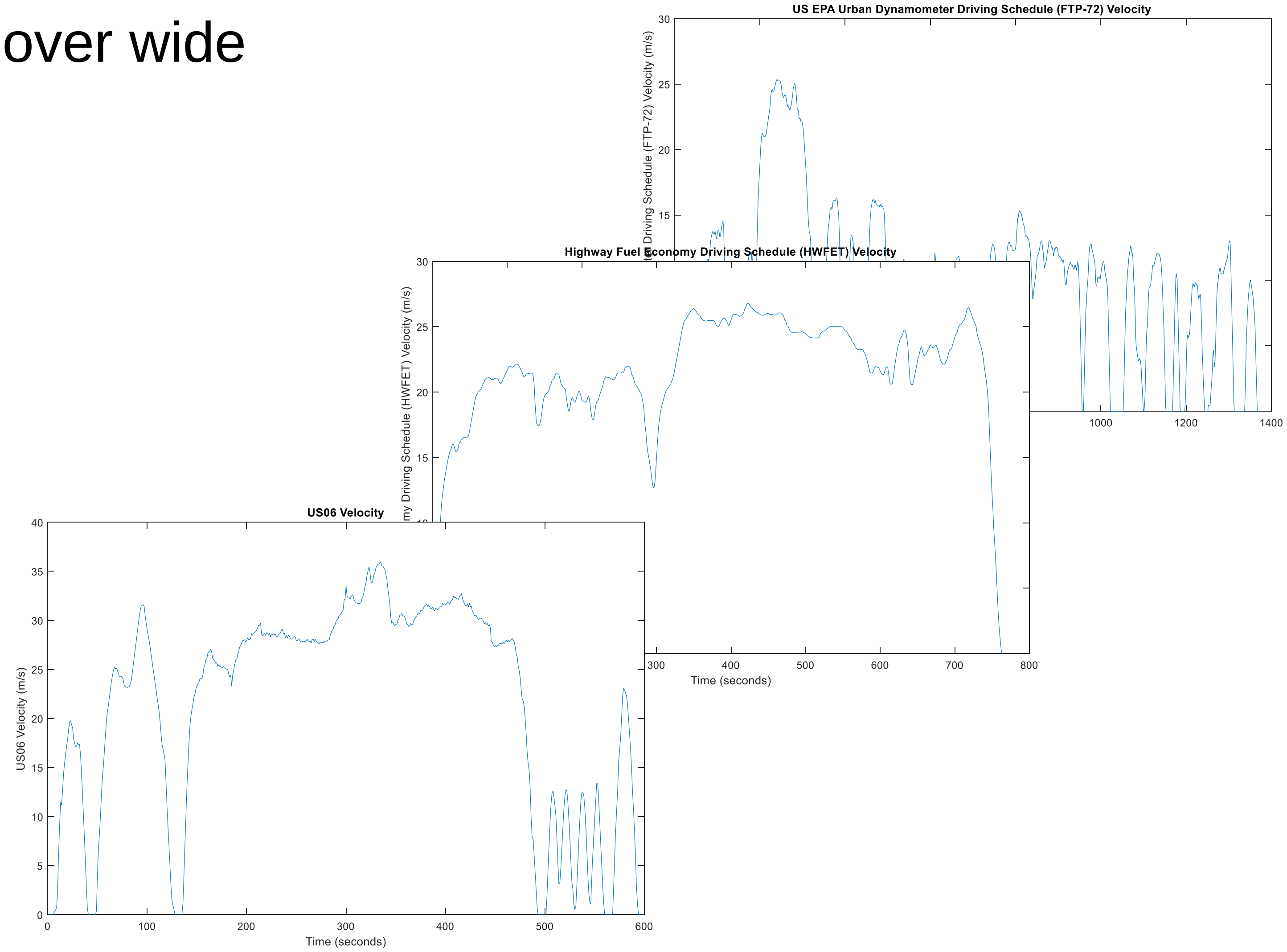


P1 / P3



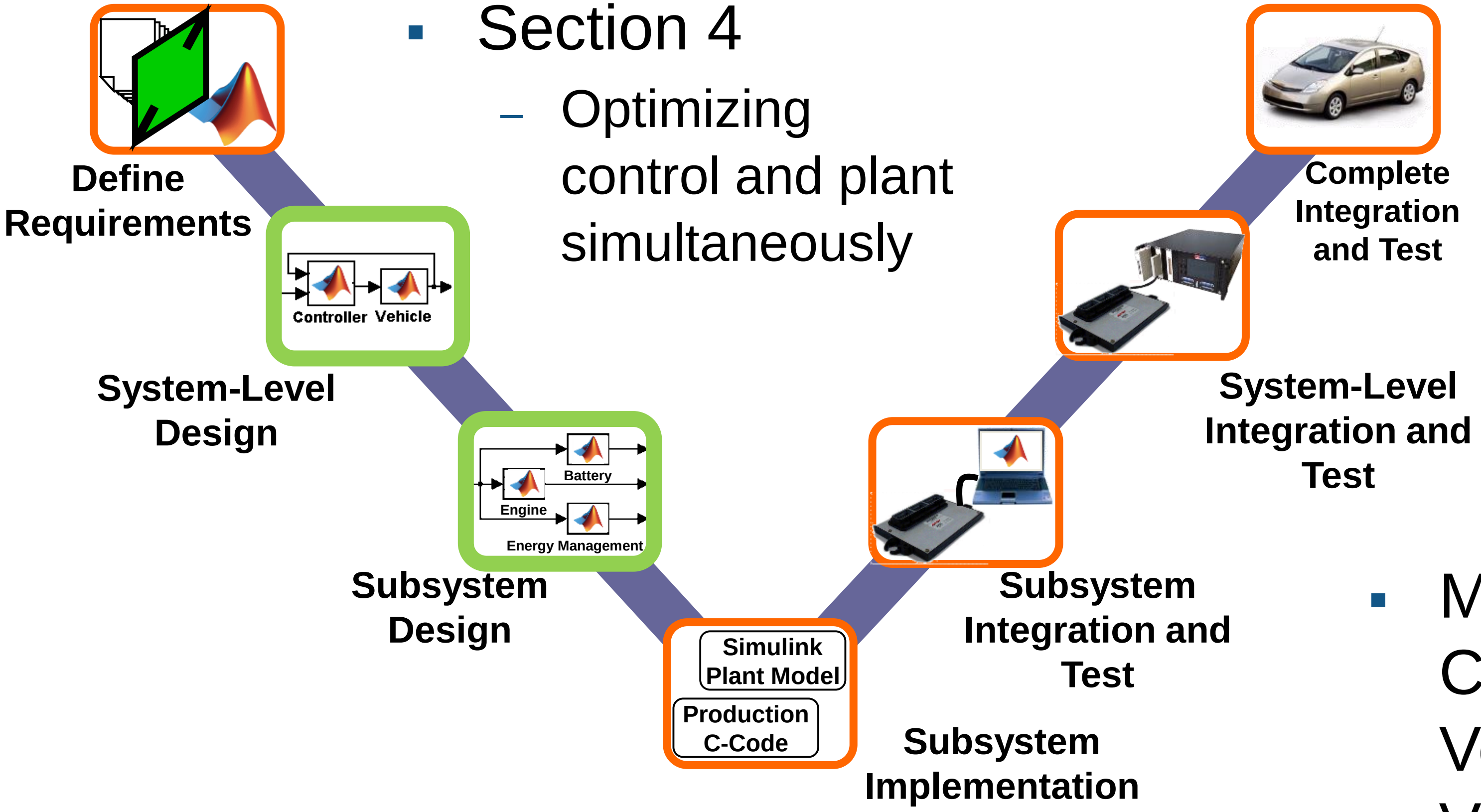
Challenges with HEV Design – Example

- 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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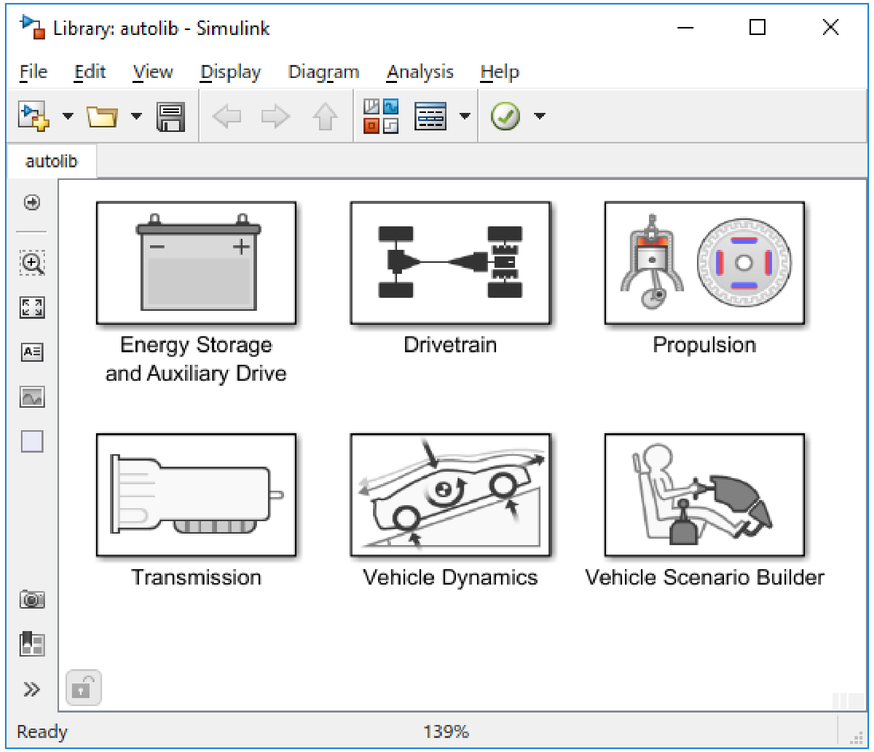
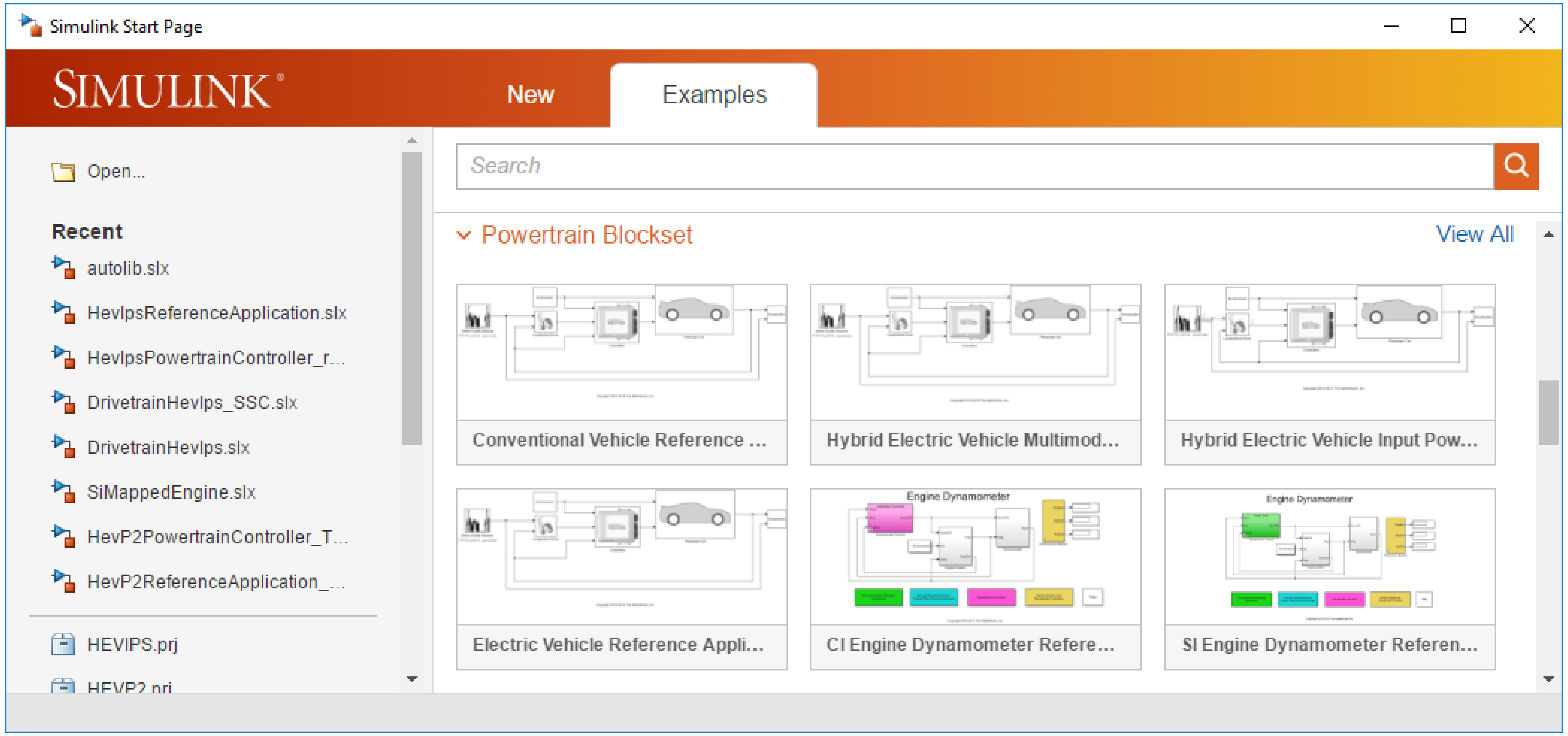
Powertrain Blockset Features

Library of blocks

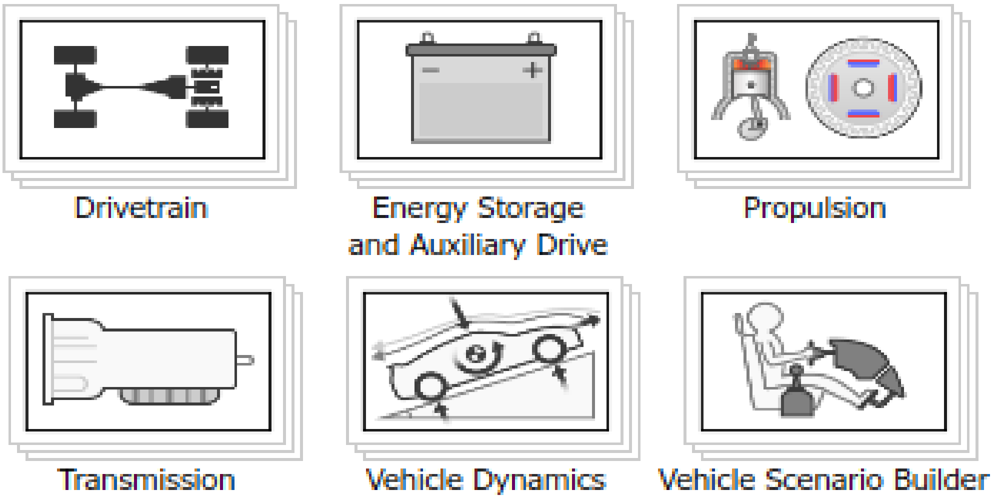


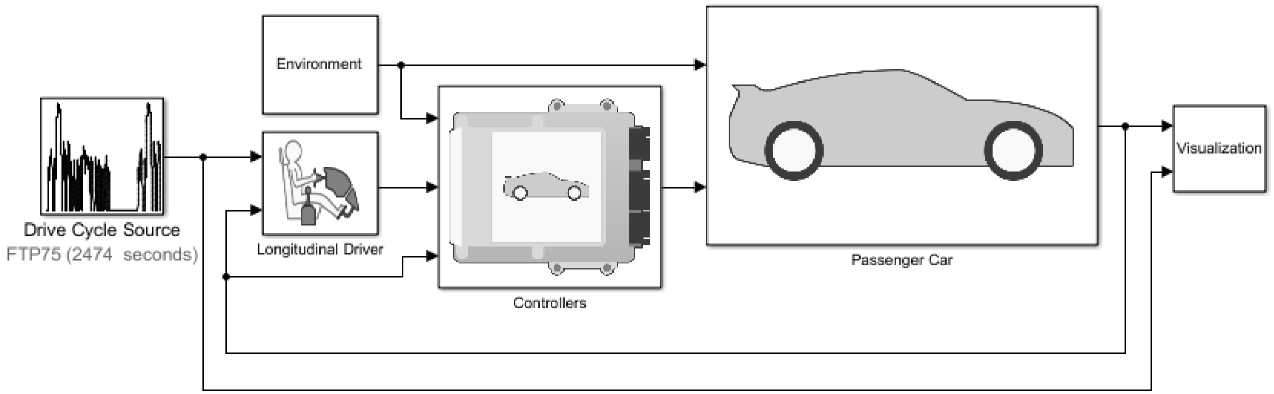
Pre-built reference applications



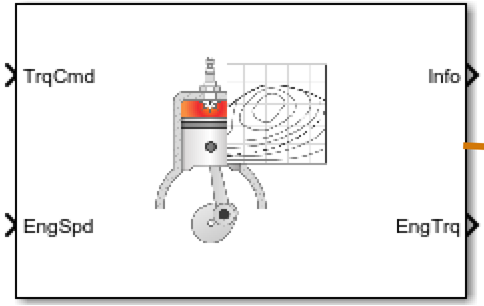
Powertrain Blockset Benefits

- 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

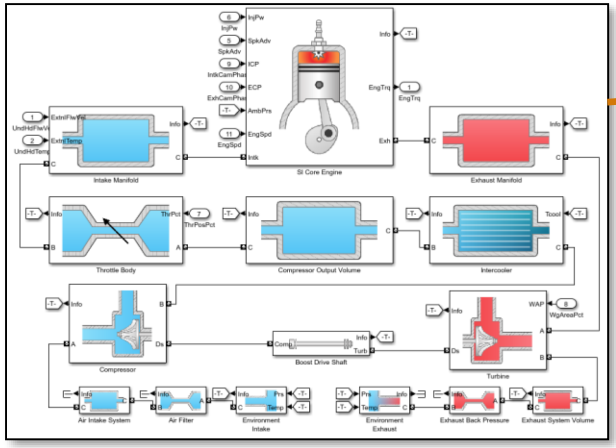




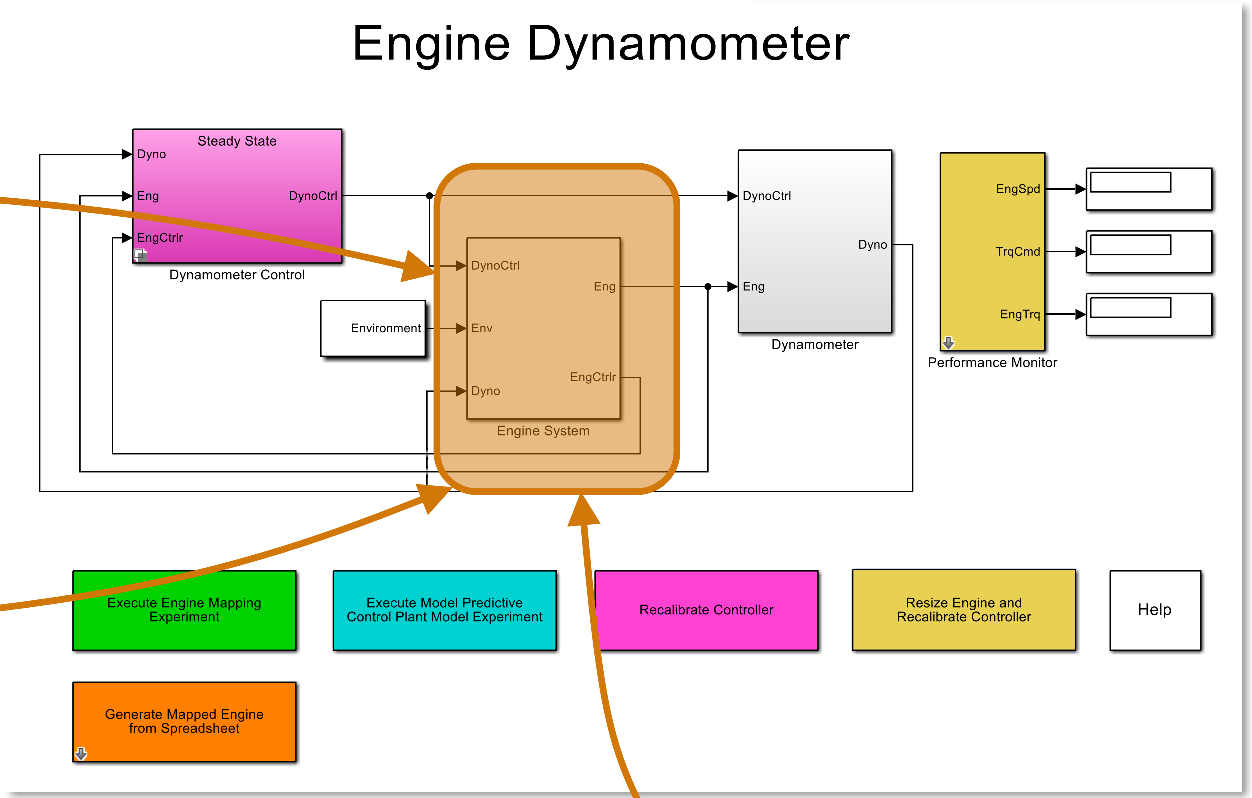
Powertrain Blockset – Engine Models

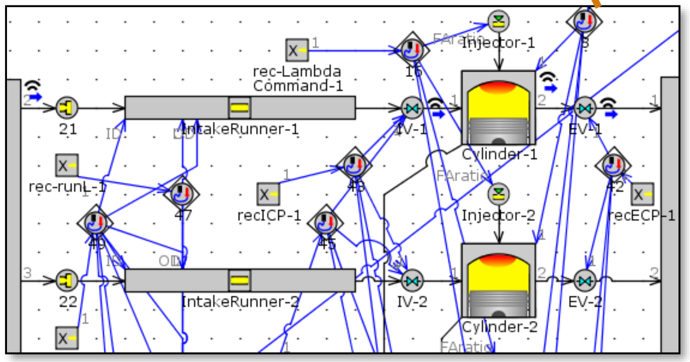


Use Powertrain Blockset *mapped* engine blocks with your own data



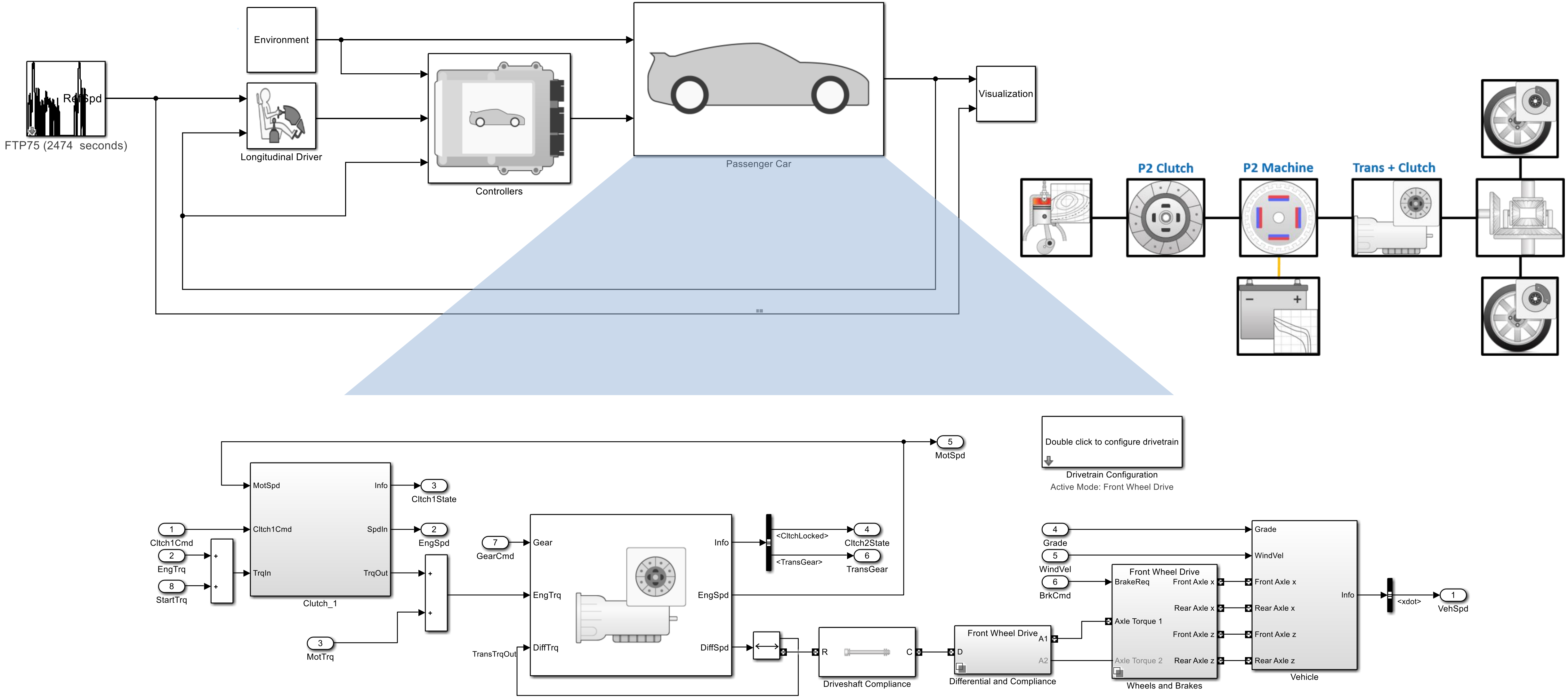
Create *dynamic* engine models using Powertrain Blockset library components





Connect in your own CAE model (e.g., GT-POWER)

Powertrain Blockset – P2 Reference Application

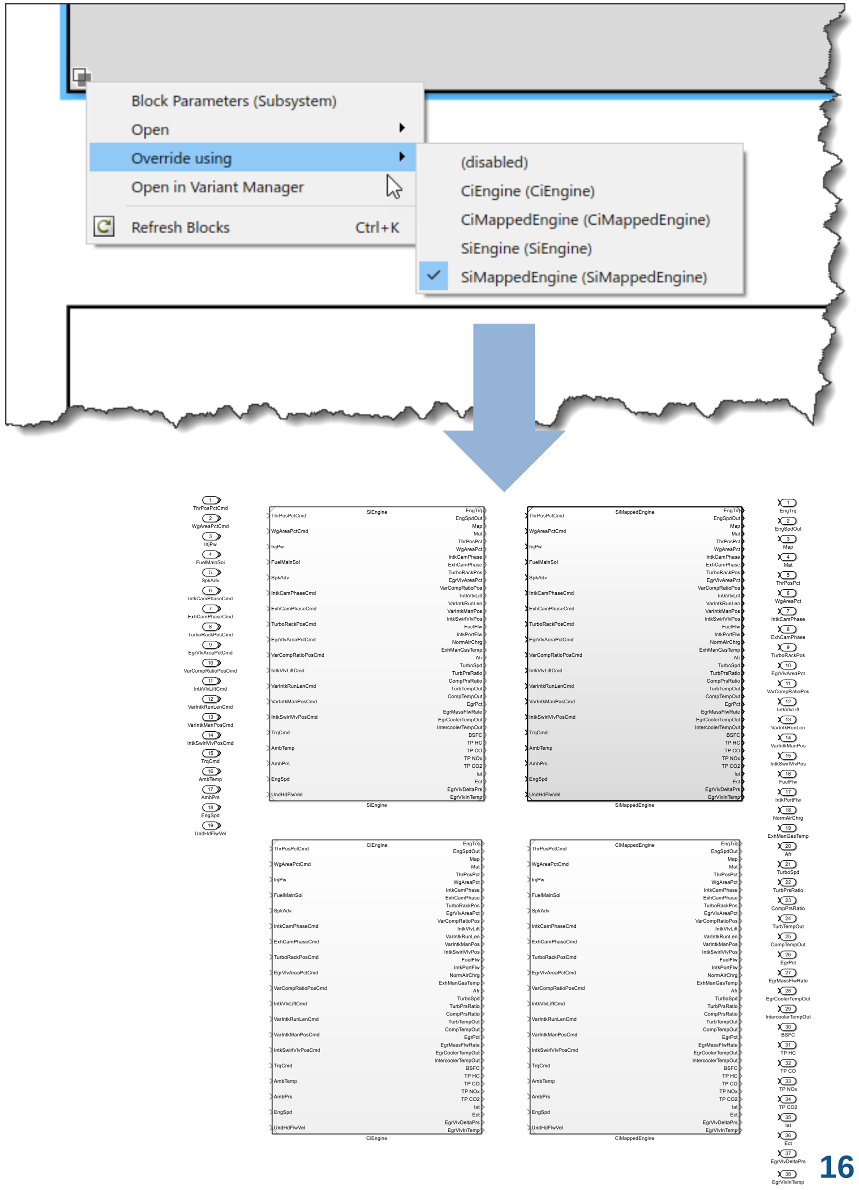


HEV Modeling Best Practices – Getting Started

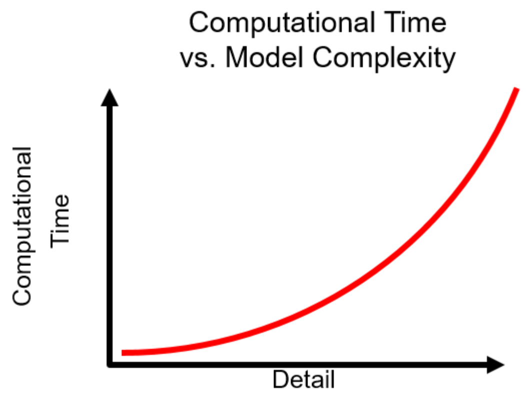
- Start with a template or example
  - Review examples in Help for Powertrain Blockset (PTBS) and Simscape Driveline

- 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

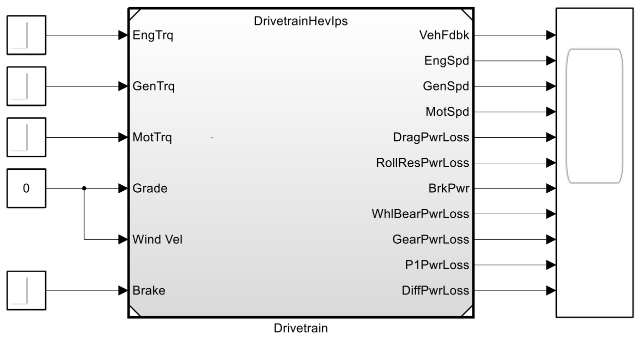
- Parameterize / customize subsystems for your needs



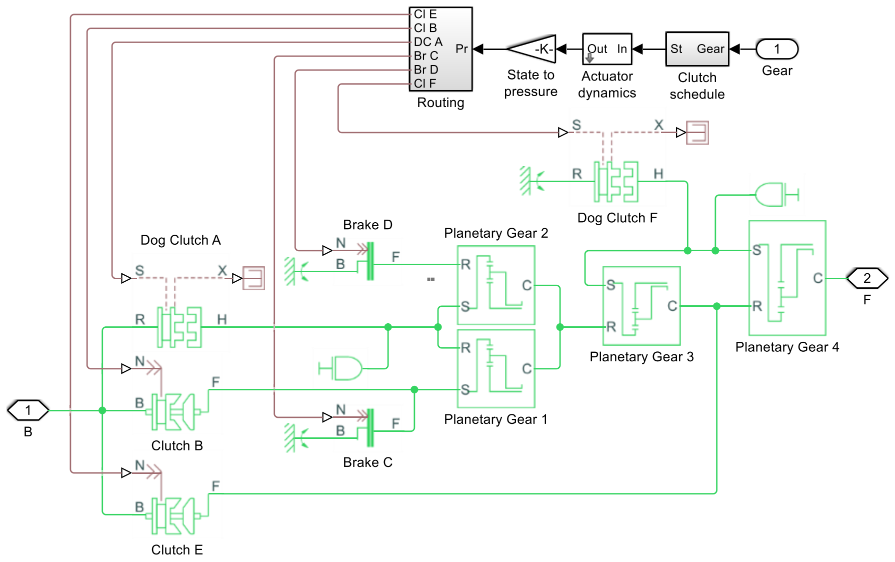
HEV Modeling Best Practices – New Models



- Use appropriate modeling fidelity for purpose



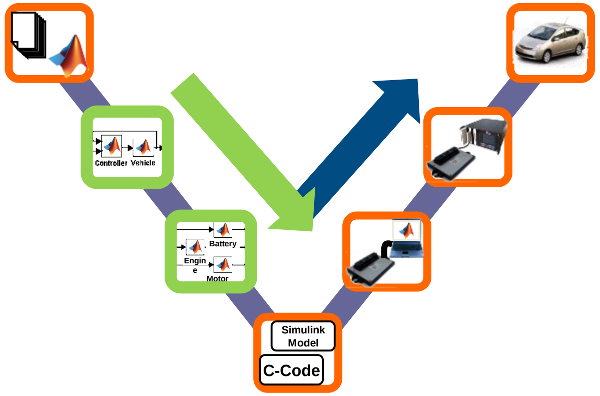
- Start small, build slowly, use “test harness” models
  - Ensure system is working properly before integrating into larger model
  - Can also use Simulink Test



- Use Simscape if:
  - Already have existing Simscape models
  - Multiple physical domains needed
  - Constructing complex topologies

Key Points

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



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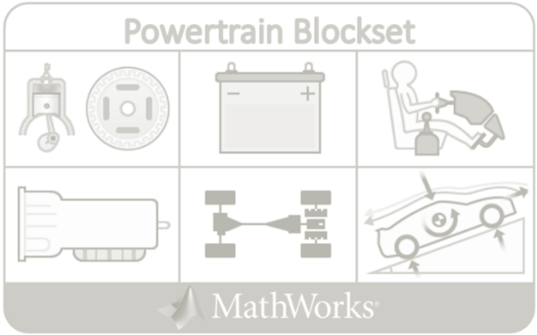
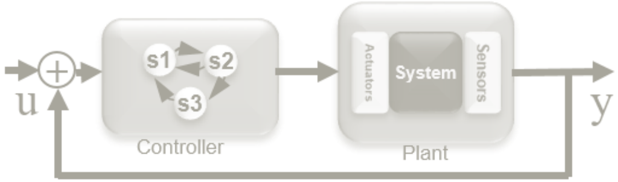


- Design / optimize plant and controls together as a system



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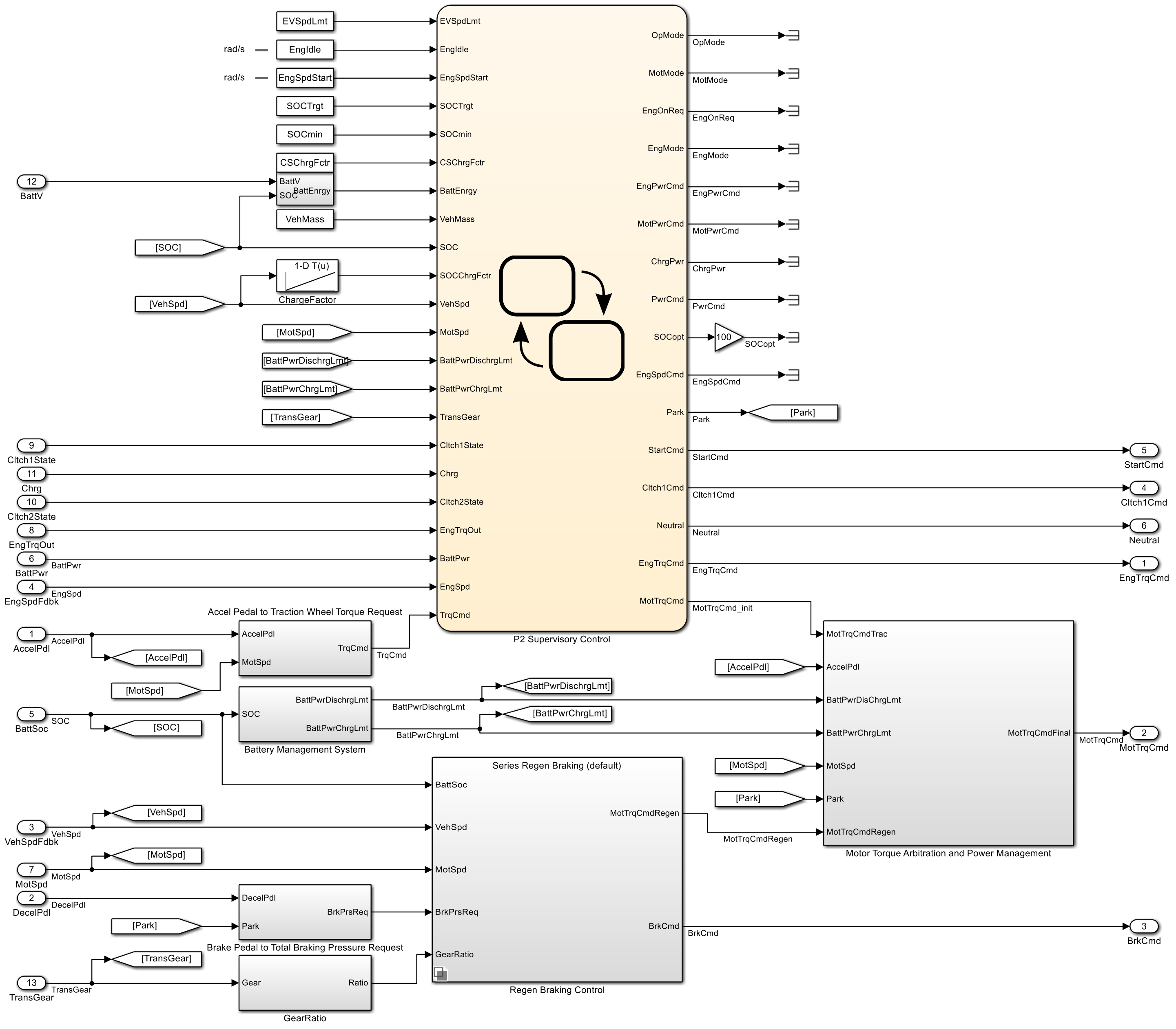
Powertrain Control – HEV Supervisory Control

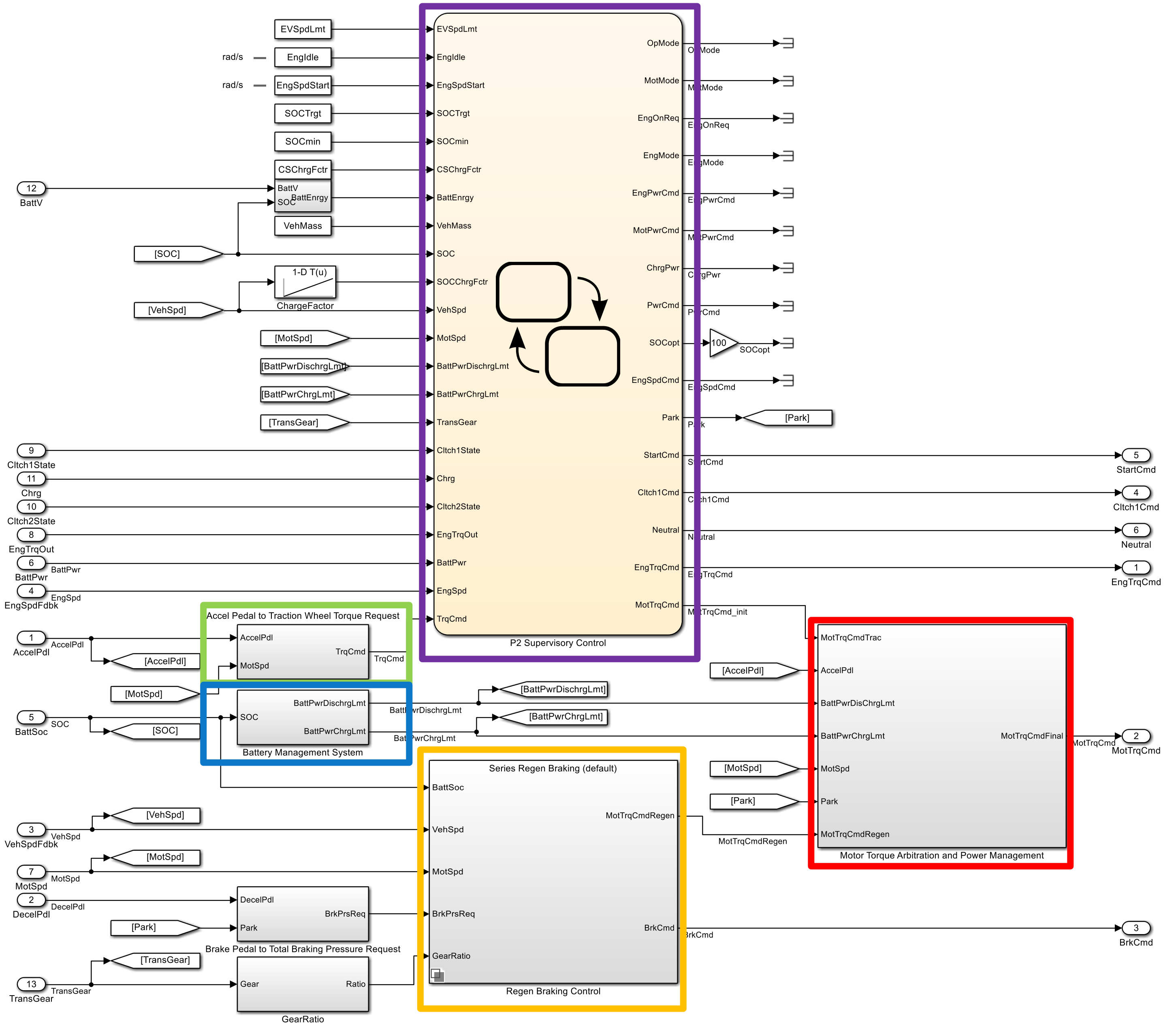
- HEV system level controller included in Reference Applications
- Rule-based
- Simulink / Stateflow
- Real-time implementable
- Customize as needed



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

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Optimization of Electrified Powertrains for City Cars

Andreas Balazs
Aachen Univ.

Edoardo Morra
Politecnico di Torino

Stefan Pischinger
FEV GmbH

– SOC Optimal calculation

$$SOC^*_{opt} = \frac{E_{batt}SOC_{opt} - \eta_{rech}\frac{1}{2}M_{veh}v_{veh}^2}{E_{batt}} \quad (2)$$

– Engine Power Calculation

$$P_{ICE,dem} = P_{dem,trac} + k_2 (SOC^*_{opt} - SOC_{act}) \quad (3)$$

– Minimum Eng On Power

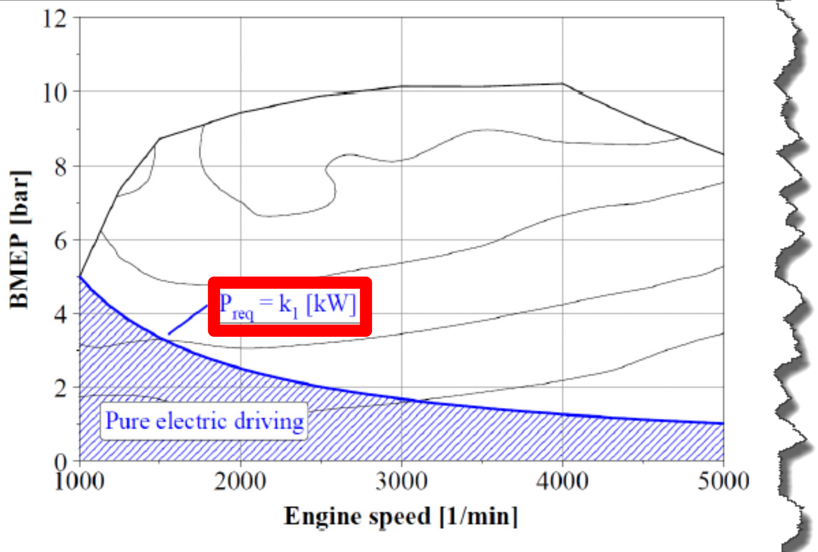
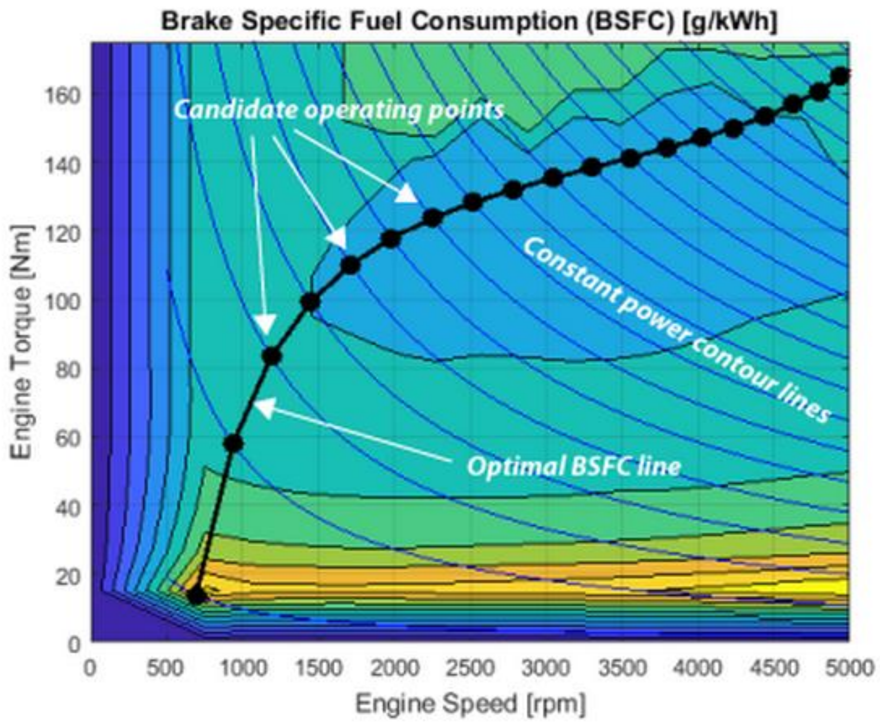
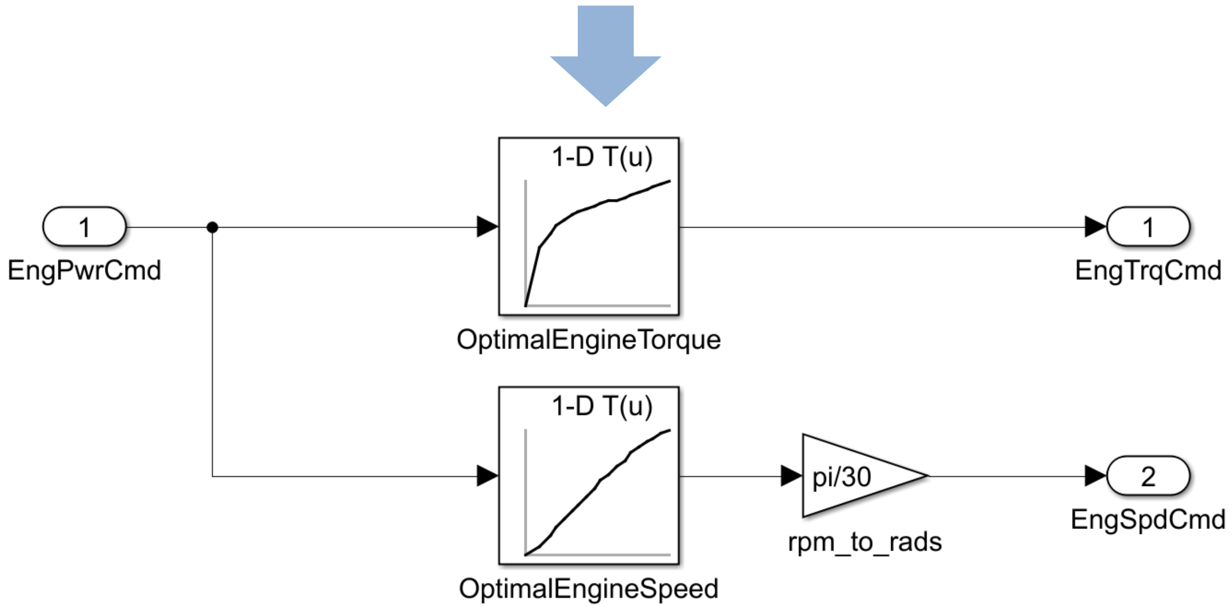


Figure 5. Hybrid operating strategy: parameter k_1

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



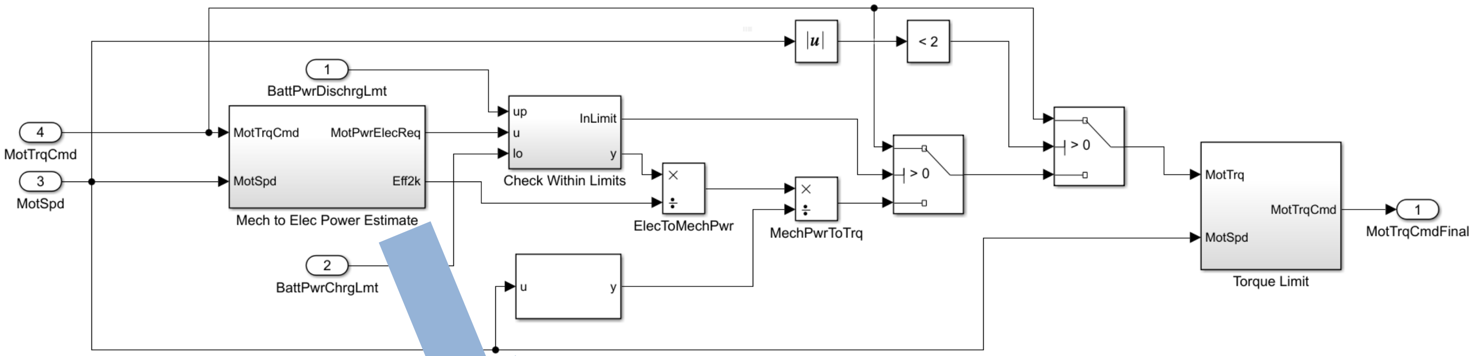


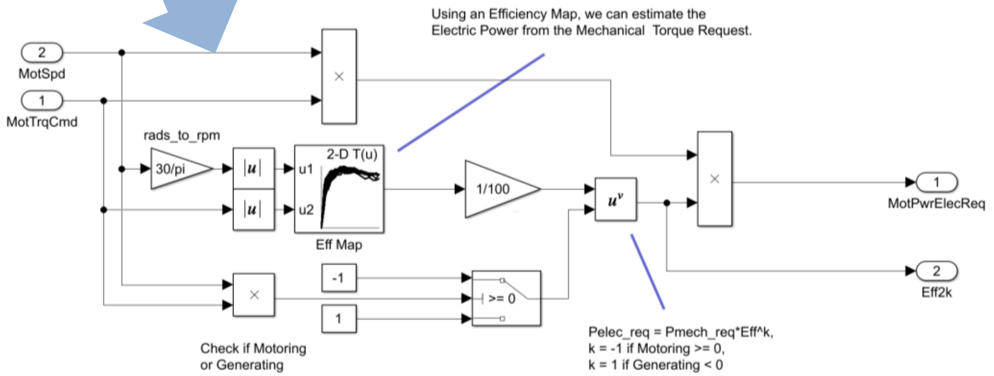
Powertrain Control – Power Management

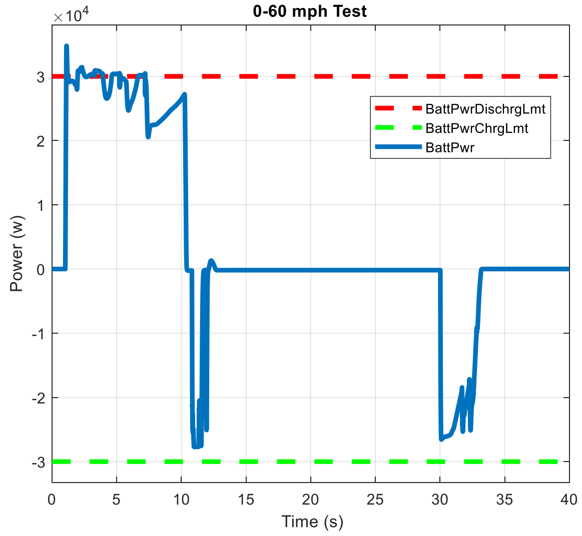
– Bound battery power within dynamic power limits of battery

– Convert mechanical power request to electrical power using efficiency map

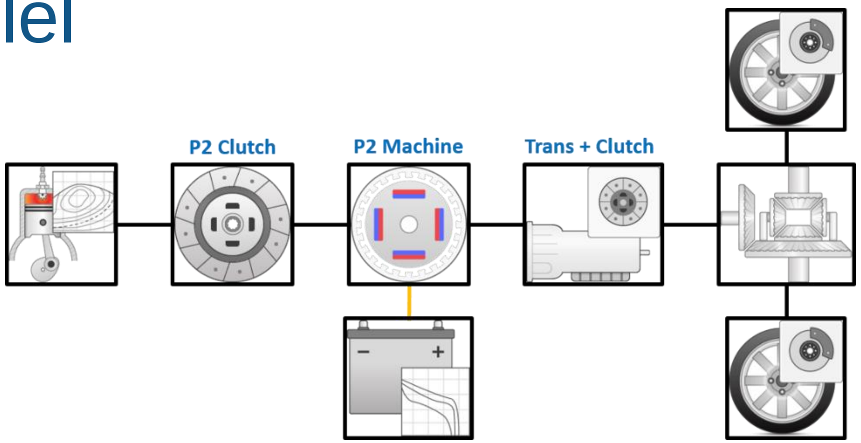
– Check if electric power request is within limits
  - OK → allow original mechanical power request
  - Not OK → use limit for electrical power, and convert to an allowable mechanical power request



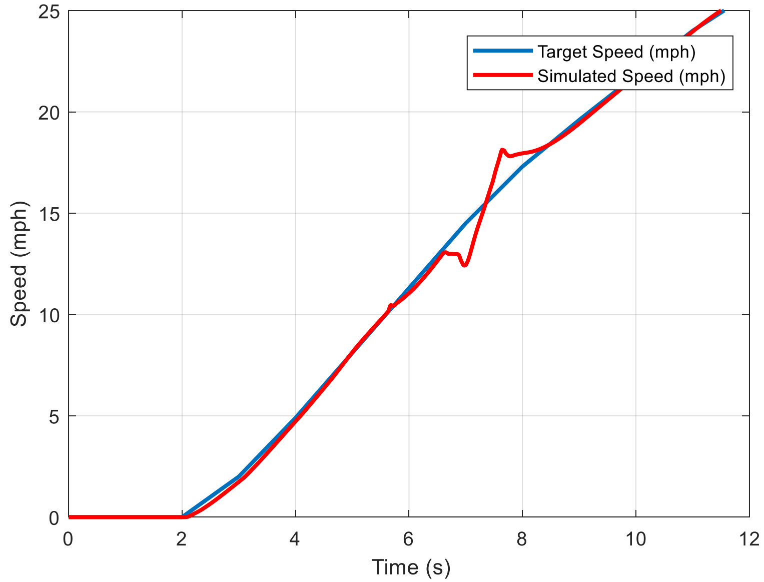




Starting the ICE in a P2 HEV: EV → Parallel

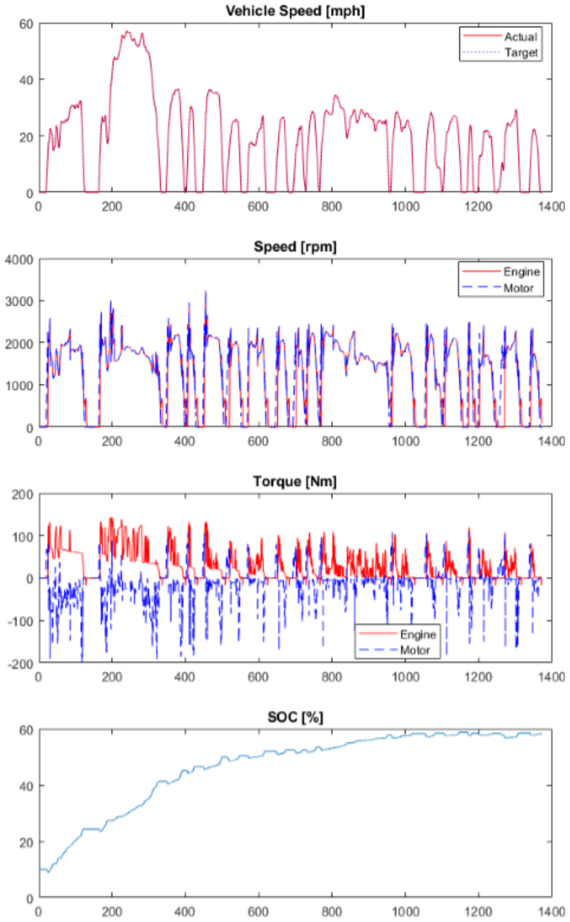


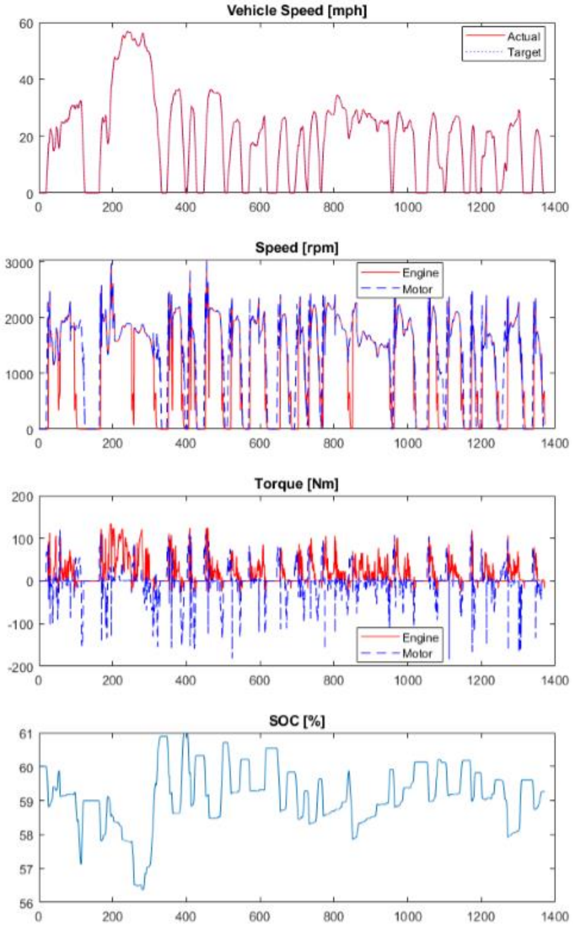
- “Bump” start
  - Can cause driveline disturbance
- “Shuffle” clutches
  - Process takes ~400-500 ms, causes vehicle speed to decrease
- Use low voltage Starter (or P0 machine)
  - Implemented in P2 Reference Application
  - 12V starter cranks ICE → ICE speed match mode → close P2 clutch

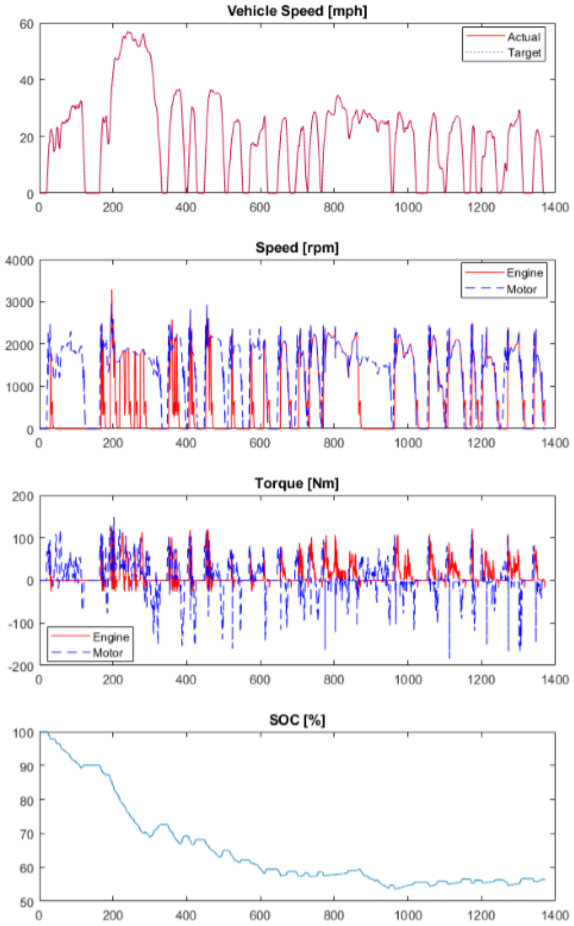


Assessing Performance

- 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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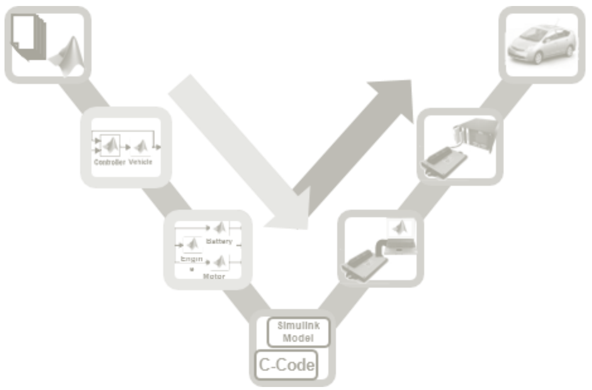

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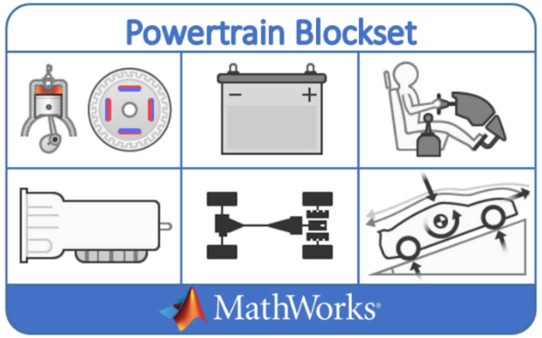

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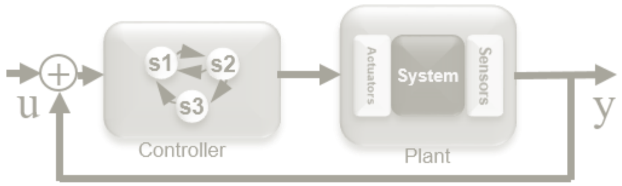

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Optimization Introduction

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

- 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

Objective Function

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

Linear or nonlinear

Design variables (discrete or integer)

Linear constraints

$$Ax \leq b$$

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

$$l \leq x \leq u$$

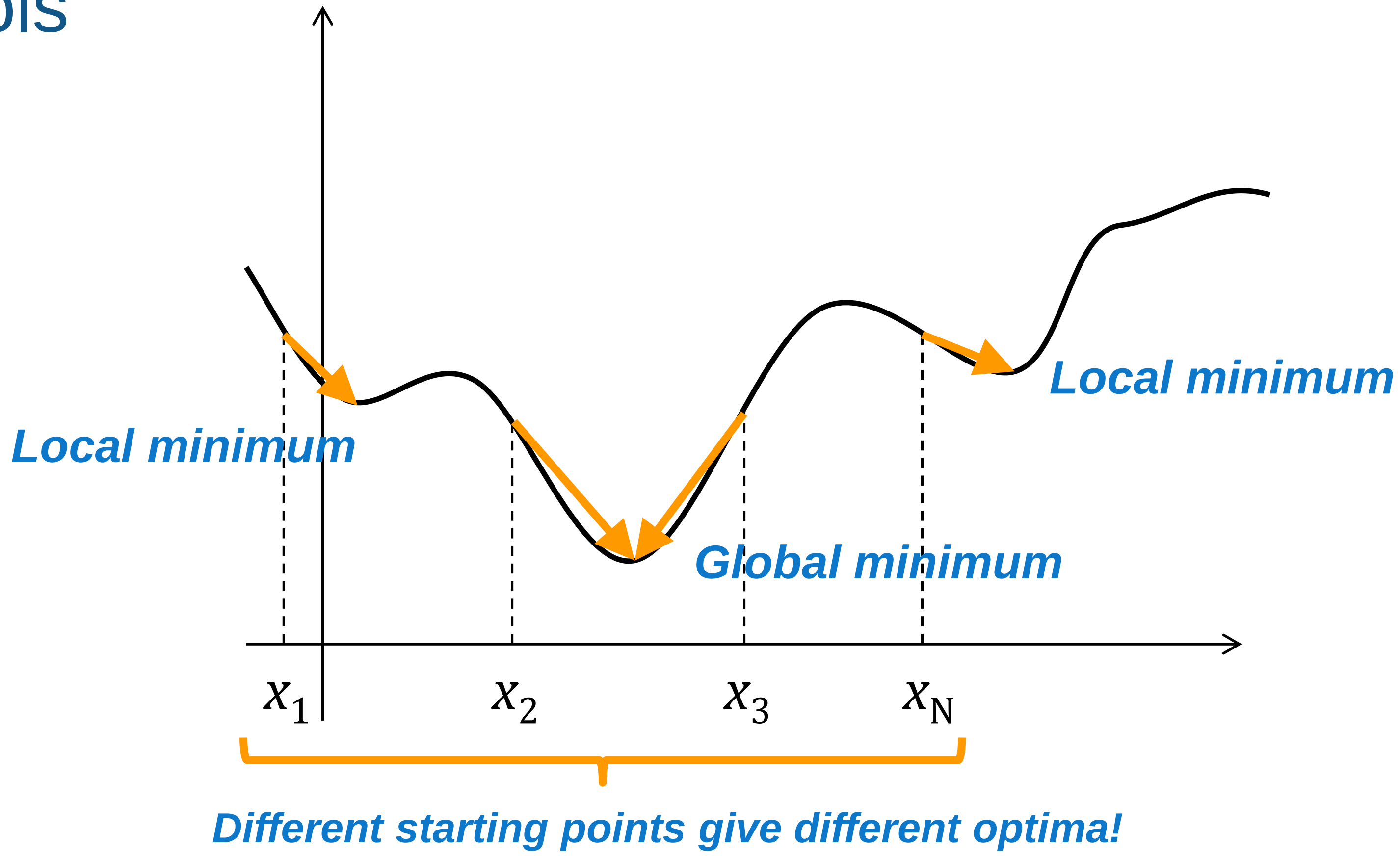
Nonlinear constraints

$$c(x) \leq 0$$

$$c_{eq}(x) = 0$$

MathWorks Optimization Tools

- [Optimization Toolbox]
  - MATLAB
- [Global Optimization Toolbox]
  - MATLAB
- [Simulink Design Optimization (SDO)]
  - ***User Interface***
  - Uses functions from toolboxes above



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

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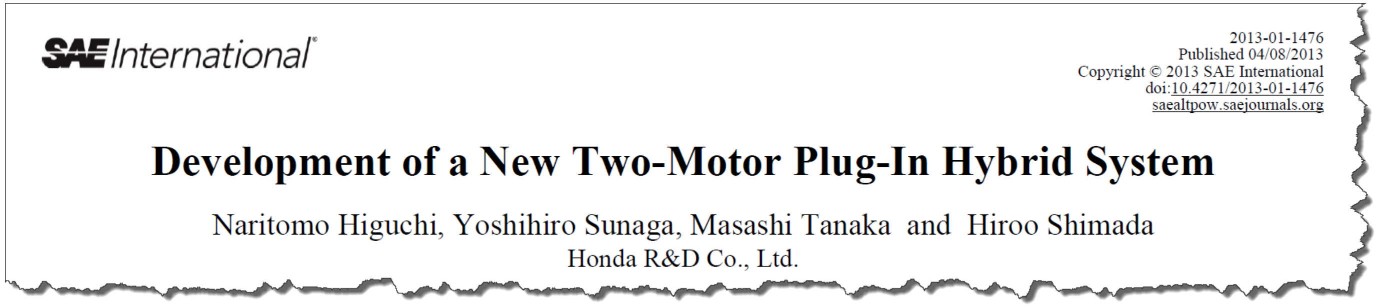
Multi-Mode HEV Review



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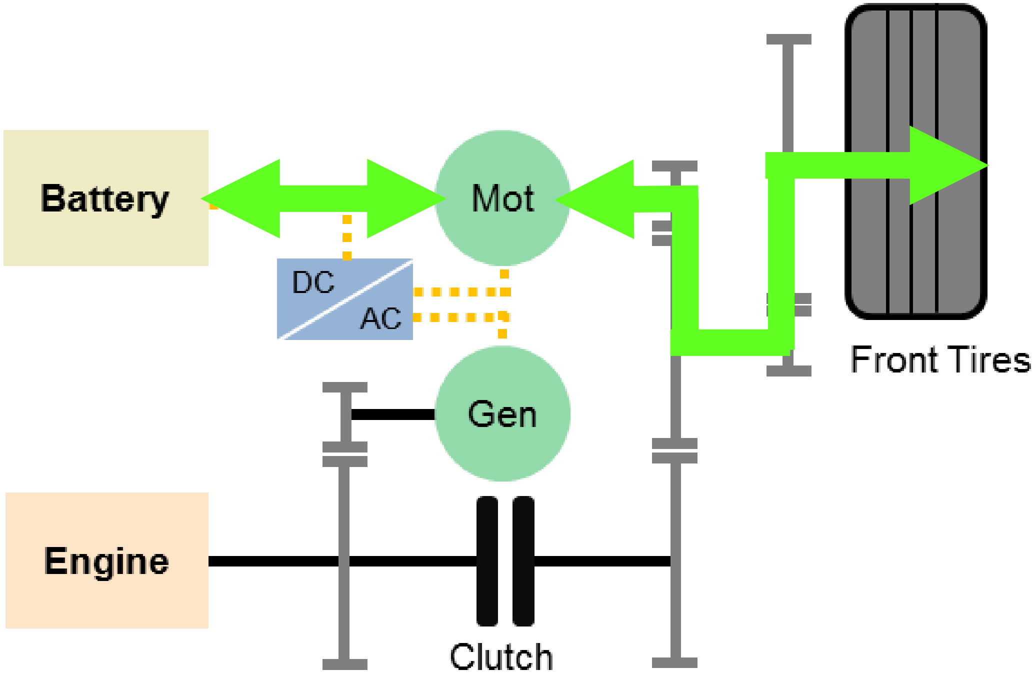
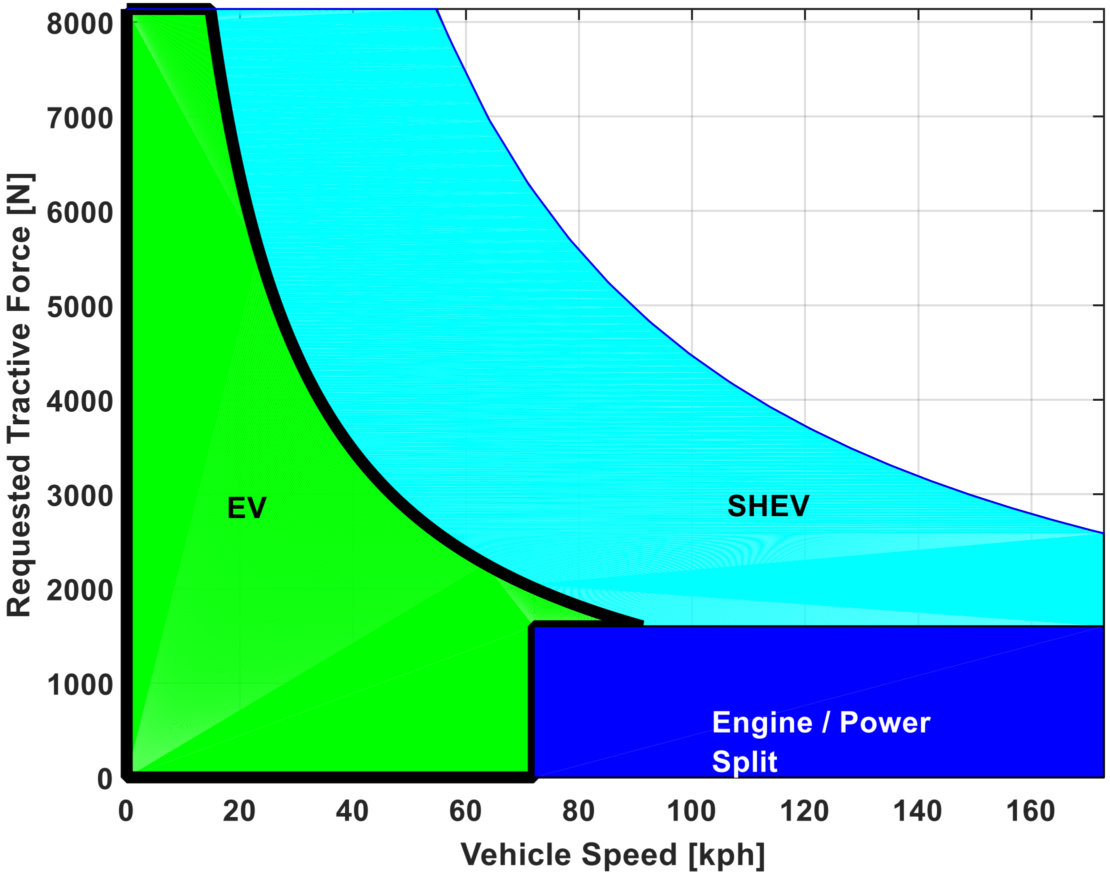
Development of a New Two-Motor Plug-In Hybrid System

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



EV Mode



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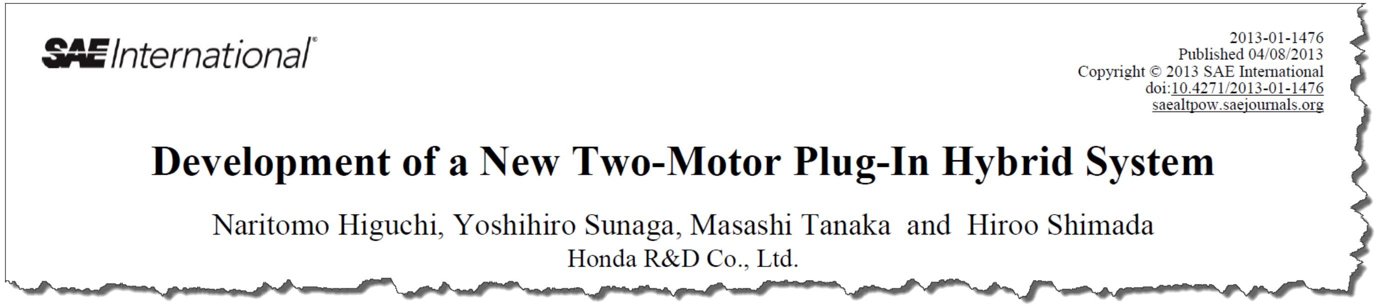
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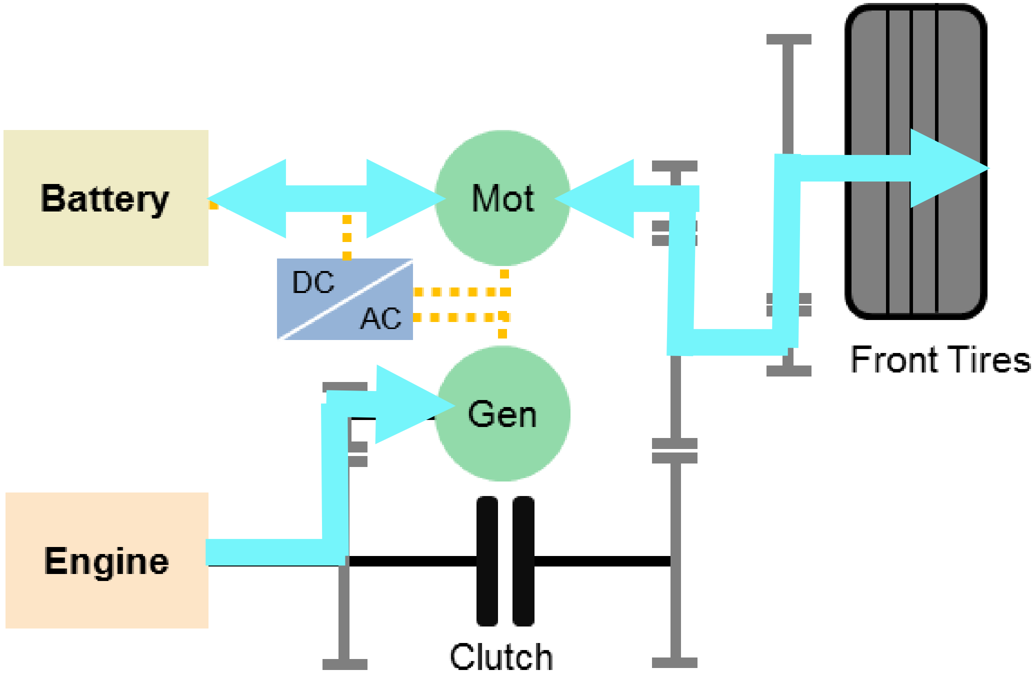
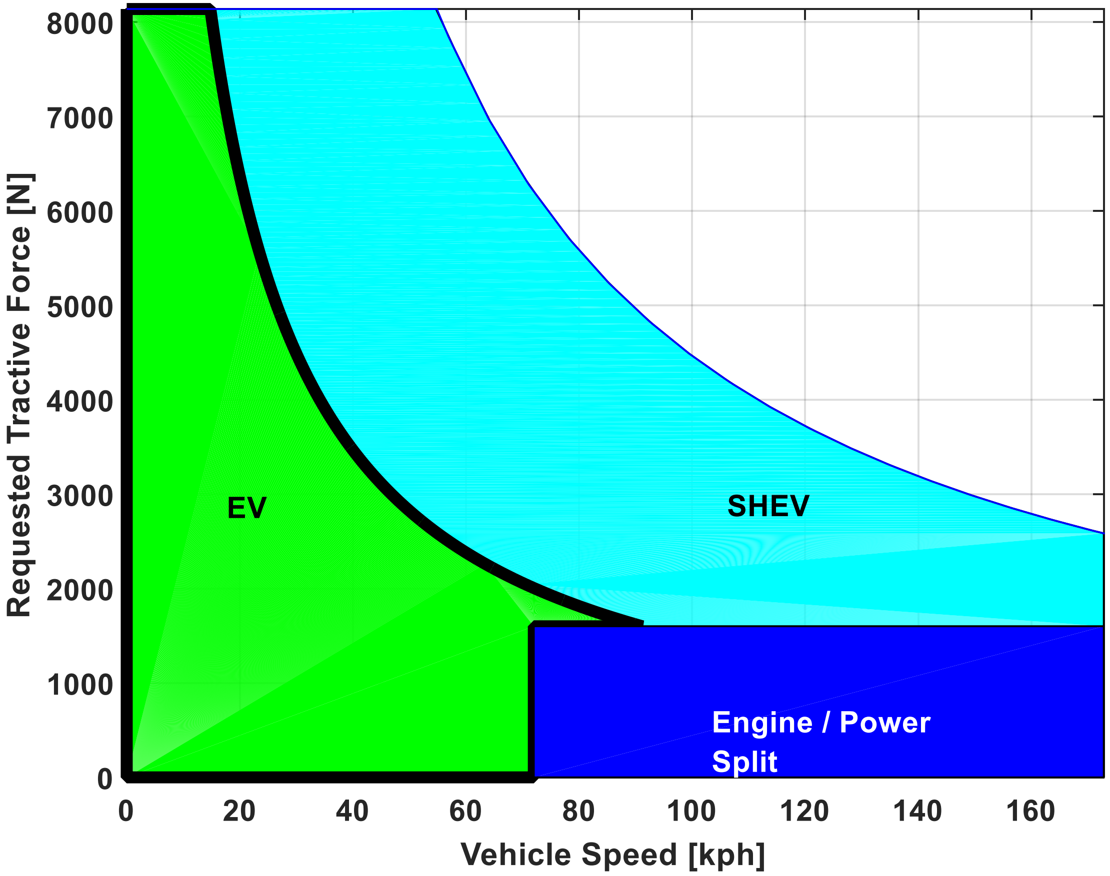


SHEV Mode



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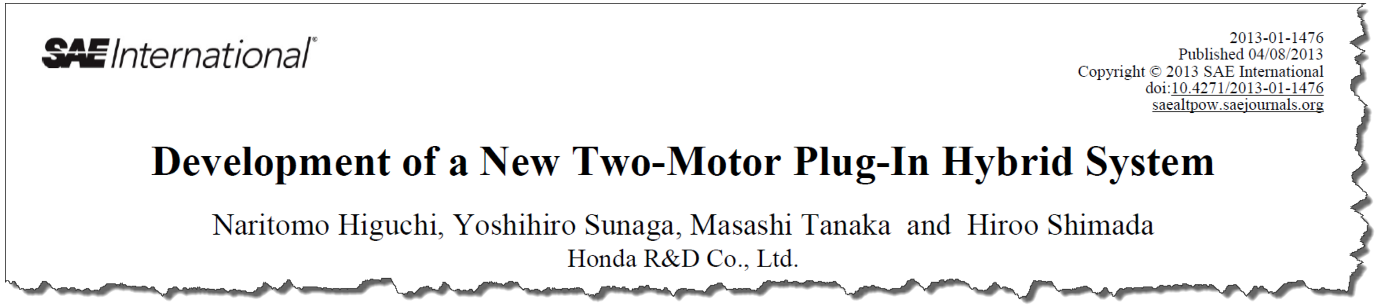

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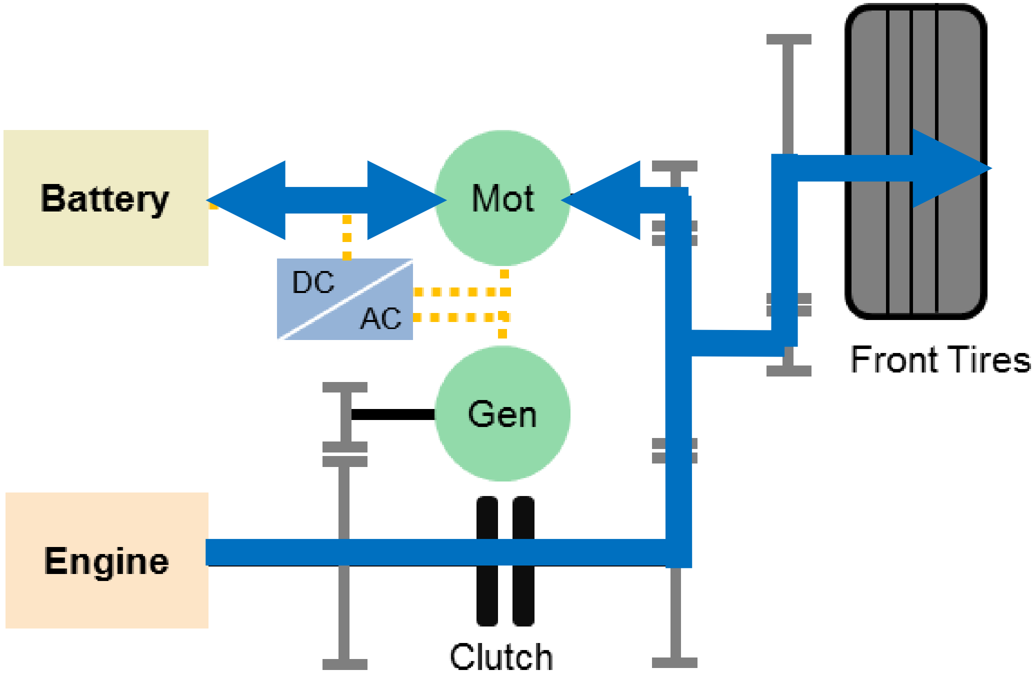
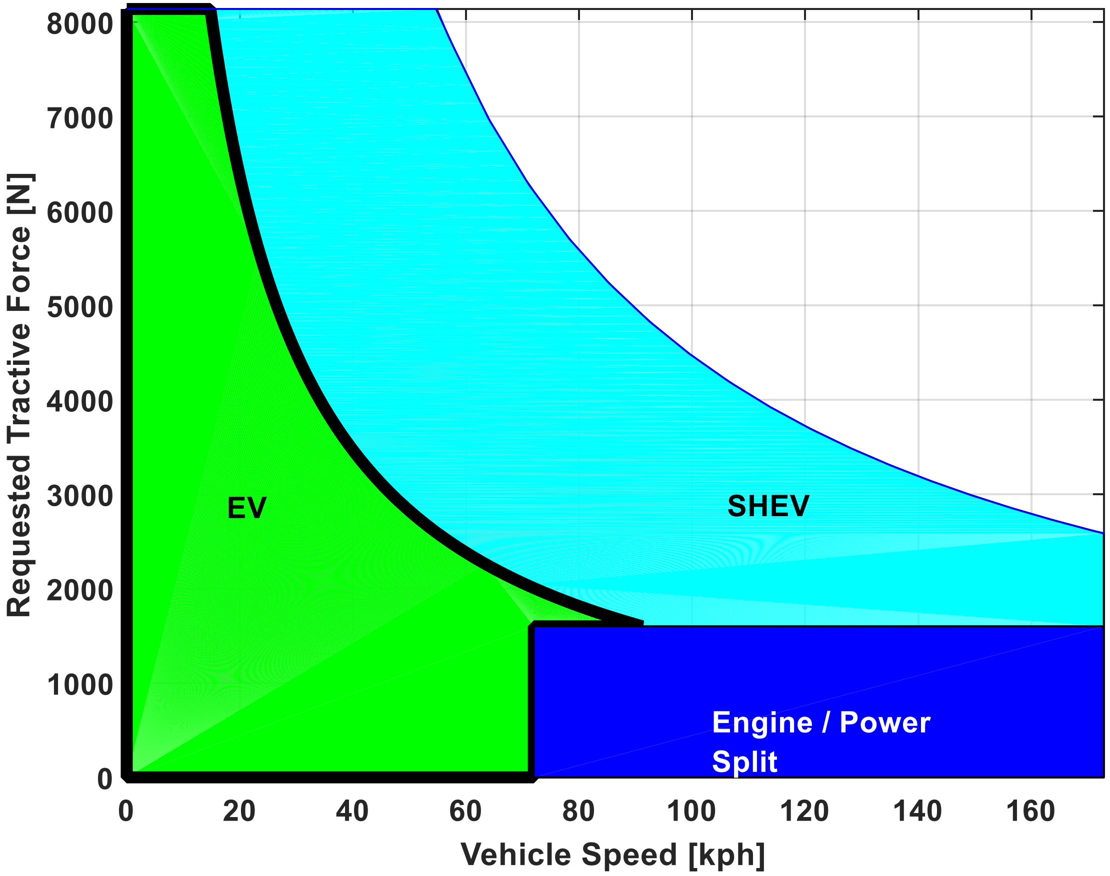
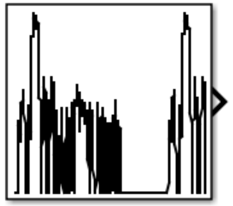


Engine Mode

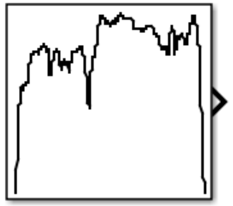


Design Optimization Problem Statement

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

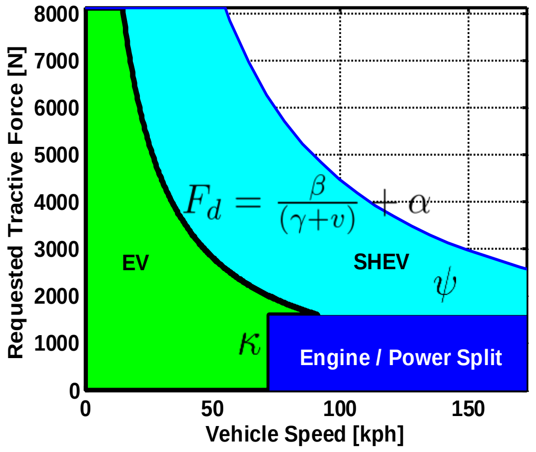


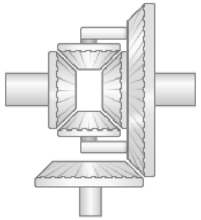
Drive Cycle Source1
FTP75 (2474 seconds)



Drive Cycle Source
HWFET (765 seconds)

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





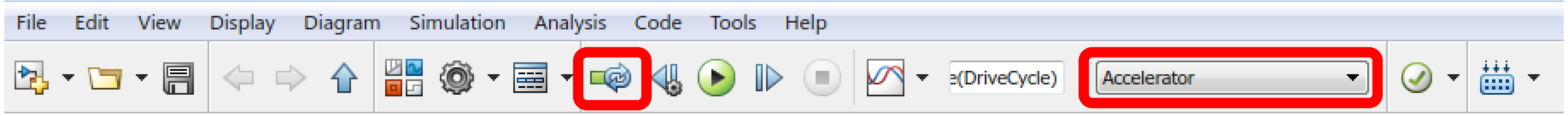
Differential Ratio

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

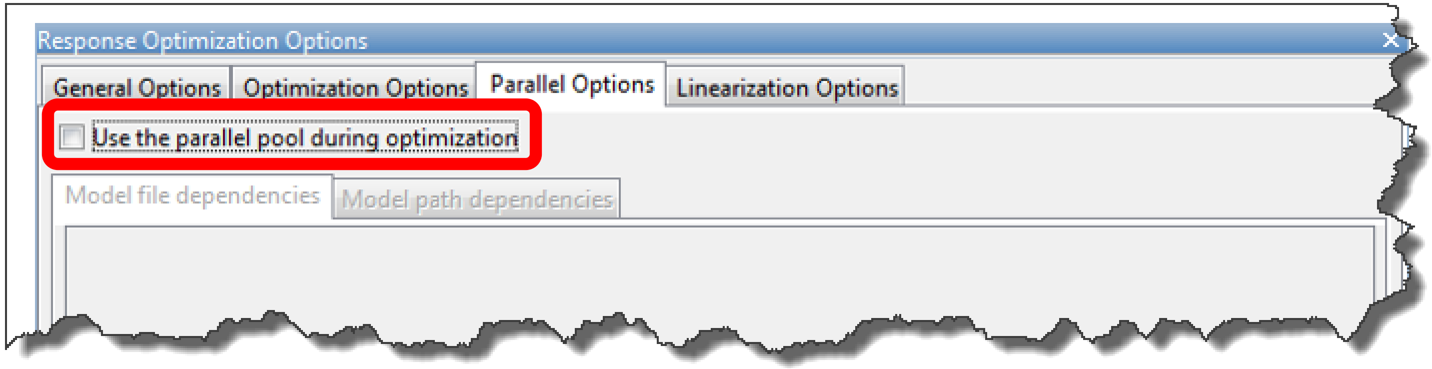
Lenovo ThinkPad T450s
Dual Core i7 2.60GHz
12 GB RAM

Simulink Design Optimization

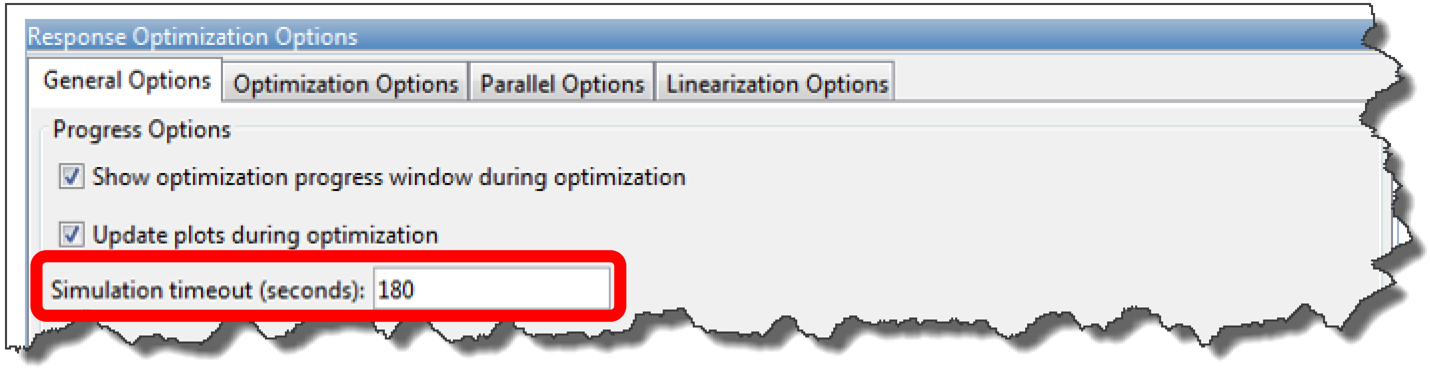
- Speed Up Best practices
  - Accelerator mode
  - Fast Restart



  - Use Parallel Computing Toolbox

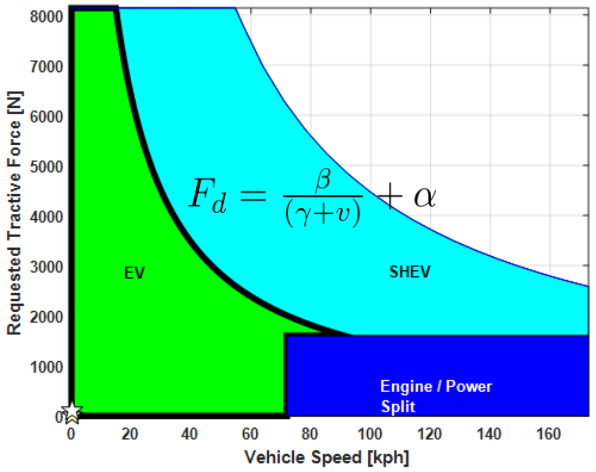


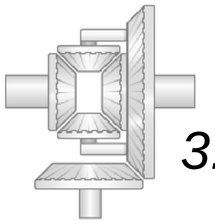
  - Specify Simulation timeout



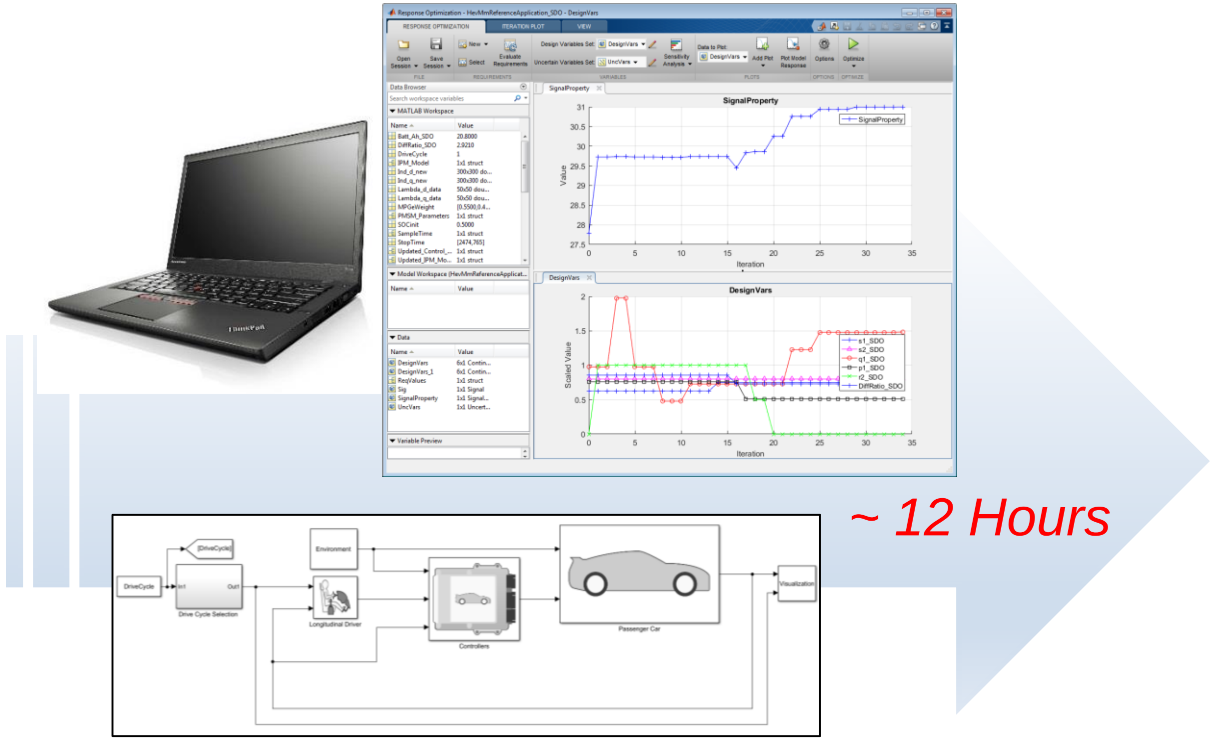
Optimization Results

Simulink Design Optimization → Response Optimization



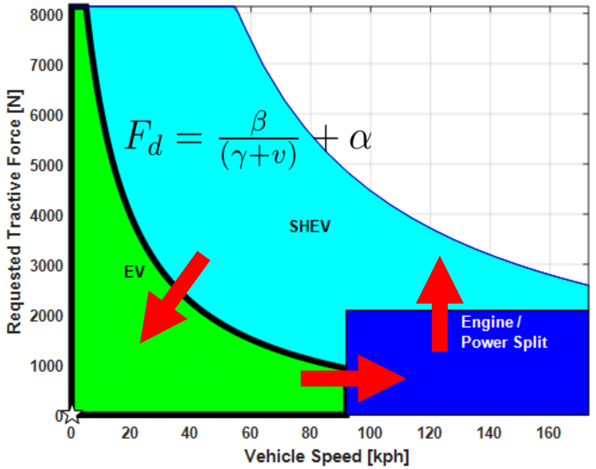


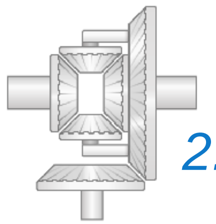
3.42:1



~ 12 Hours

+ 2% MPGe





2.92:1

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

Powertrain Control – Charge Sustaining / PHEV Power-Split

SAE International

2011-01-2451
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saealtpow.saejournals.org

Optimization of Electrified Powertrains for City Cars

Andreas Balazs
Aachen Univ.

Edoardo Morra
Politecnico di Torino

Stefan Pischinger
FEV GmbH

– SOC Optimal calculation

$$SOC^*_{opt} = \frac{E_{batt}SOC_{opt} - \eta_{rech}\frac{1}{2}M_{veh}v_{veh}^2}{E_{batt}} \quad (2)$$

– Engine Power Calculation

$$P_{ICE,dem} = P_{dem,trac} + k_2(SOC^*_{opt} - SOC_{act}) \quad (3)$$

– Minimum Eng On Power

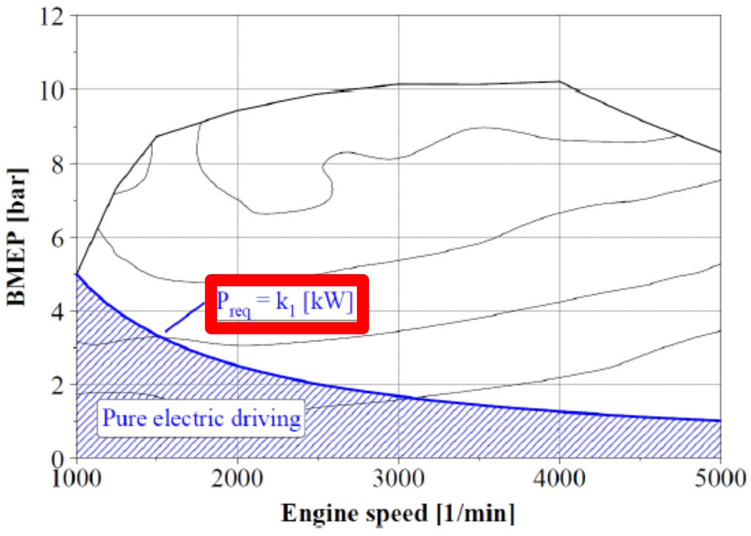
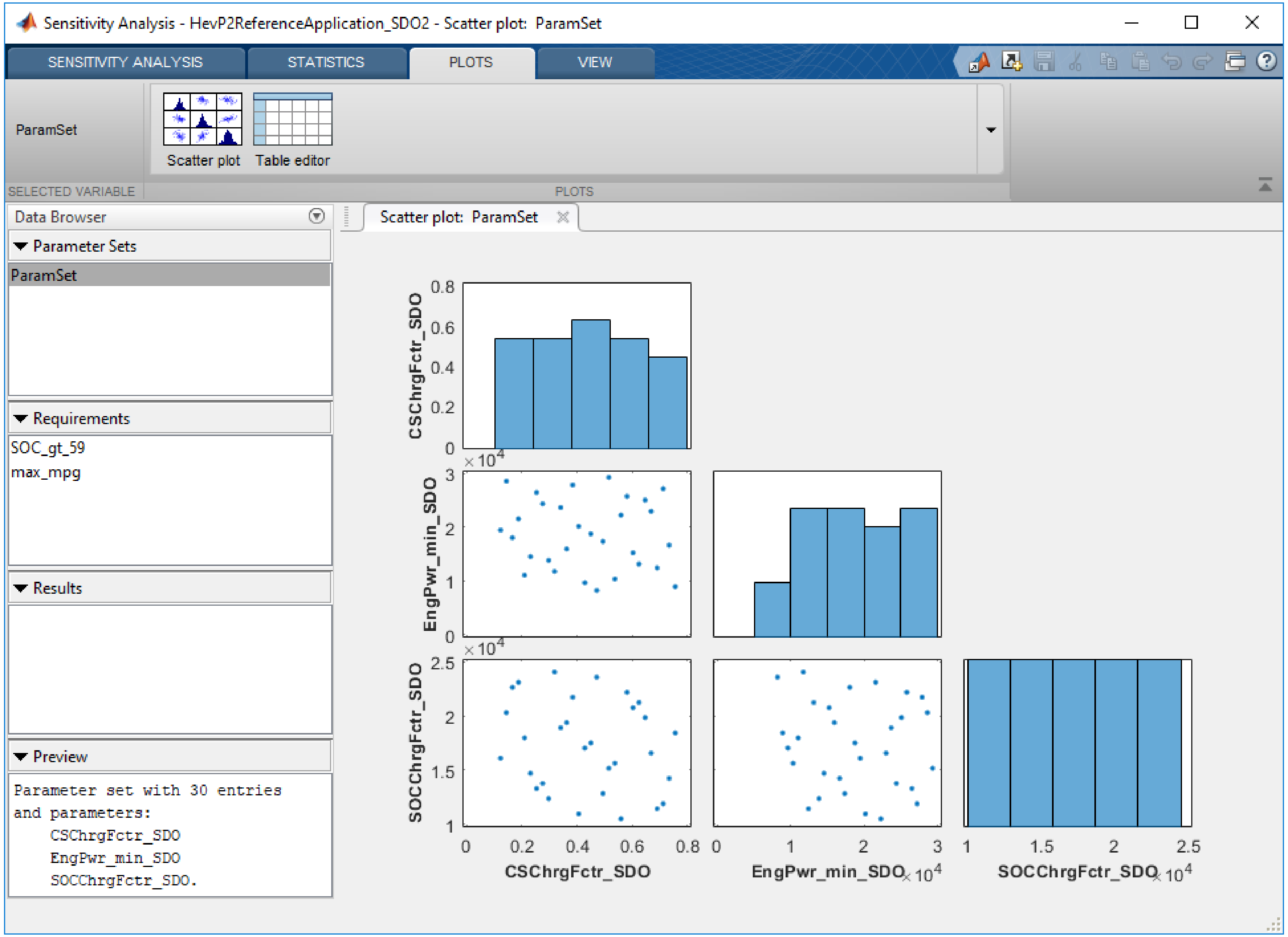


Figure 5. Hybrid operating strategy: parameter k_1

Sensitivity Analysis

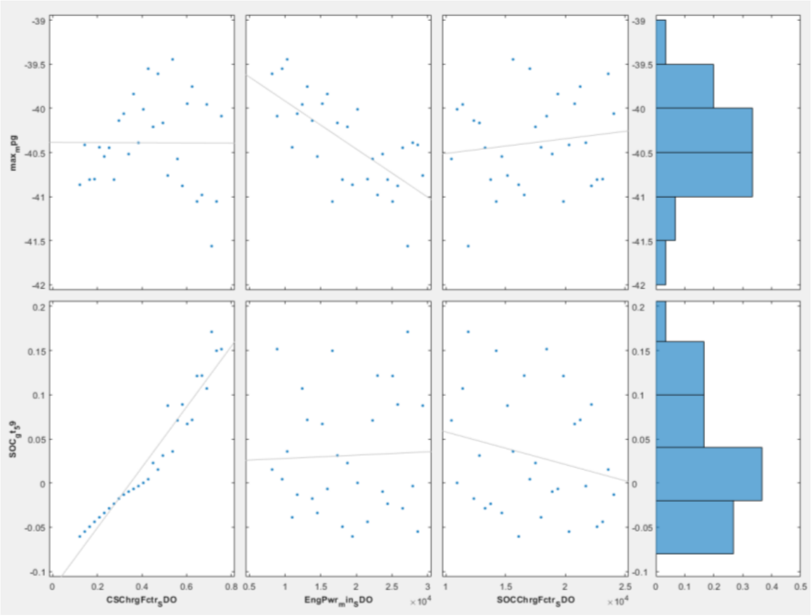
- Determine sensitivity of fuel economy and ability to charge sustain to changes in design parameters

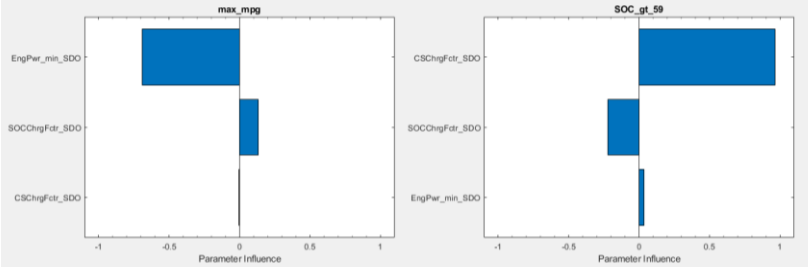
- Simulink Design Optimization UI
  - Create sample sets
  - Define constraints
  - Run Monte Carlo simulations
  - Speed up using parallel computing



Sensitivity Analysis – Results

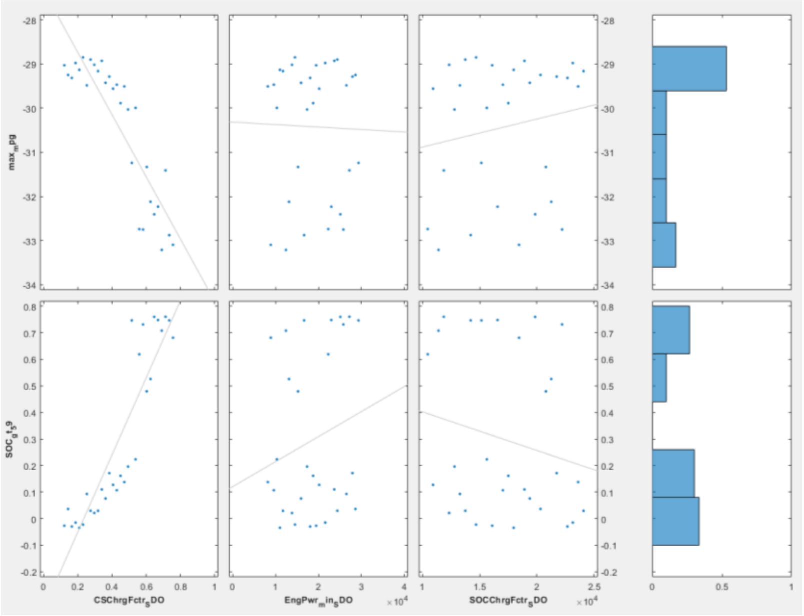
- HWFET

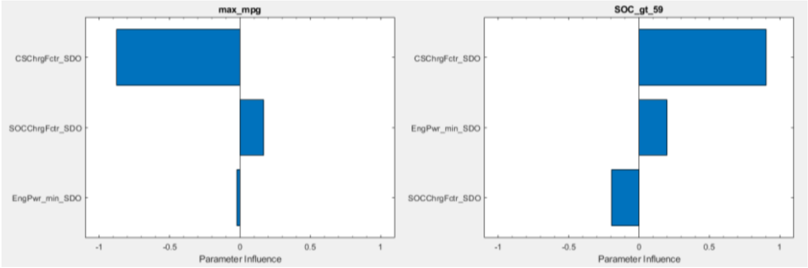




  - CS Factor highest correlation for charge sustaining
  - Min Engine Power highest correlation for max mpg

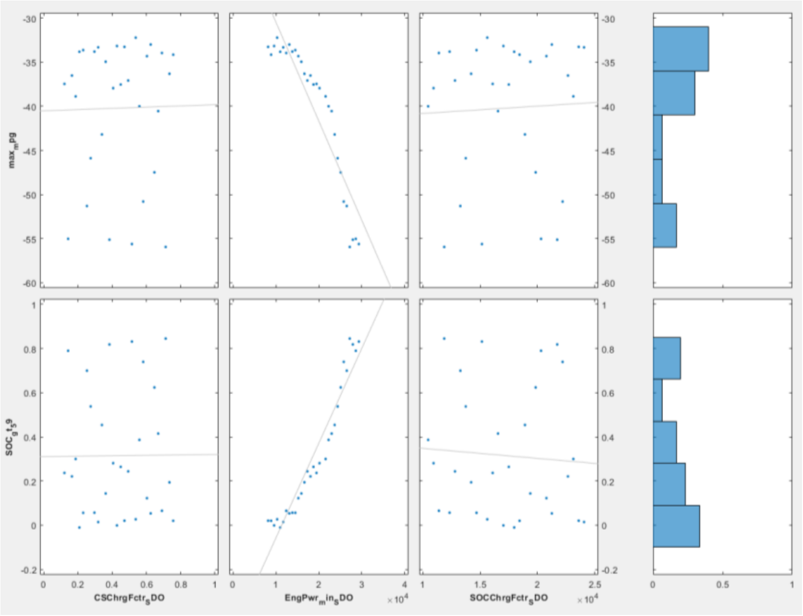
- US06

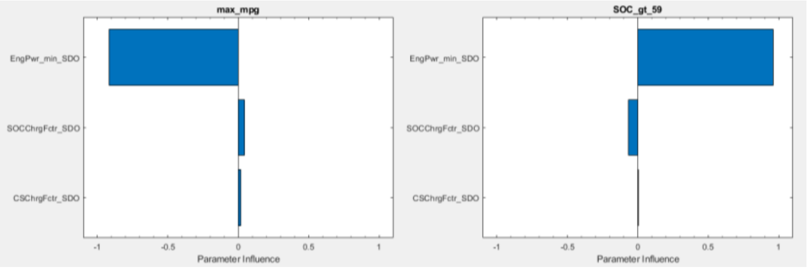




  - CS Factor highest correlation for charge sustaining and max mpg

- 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

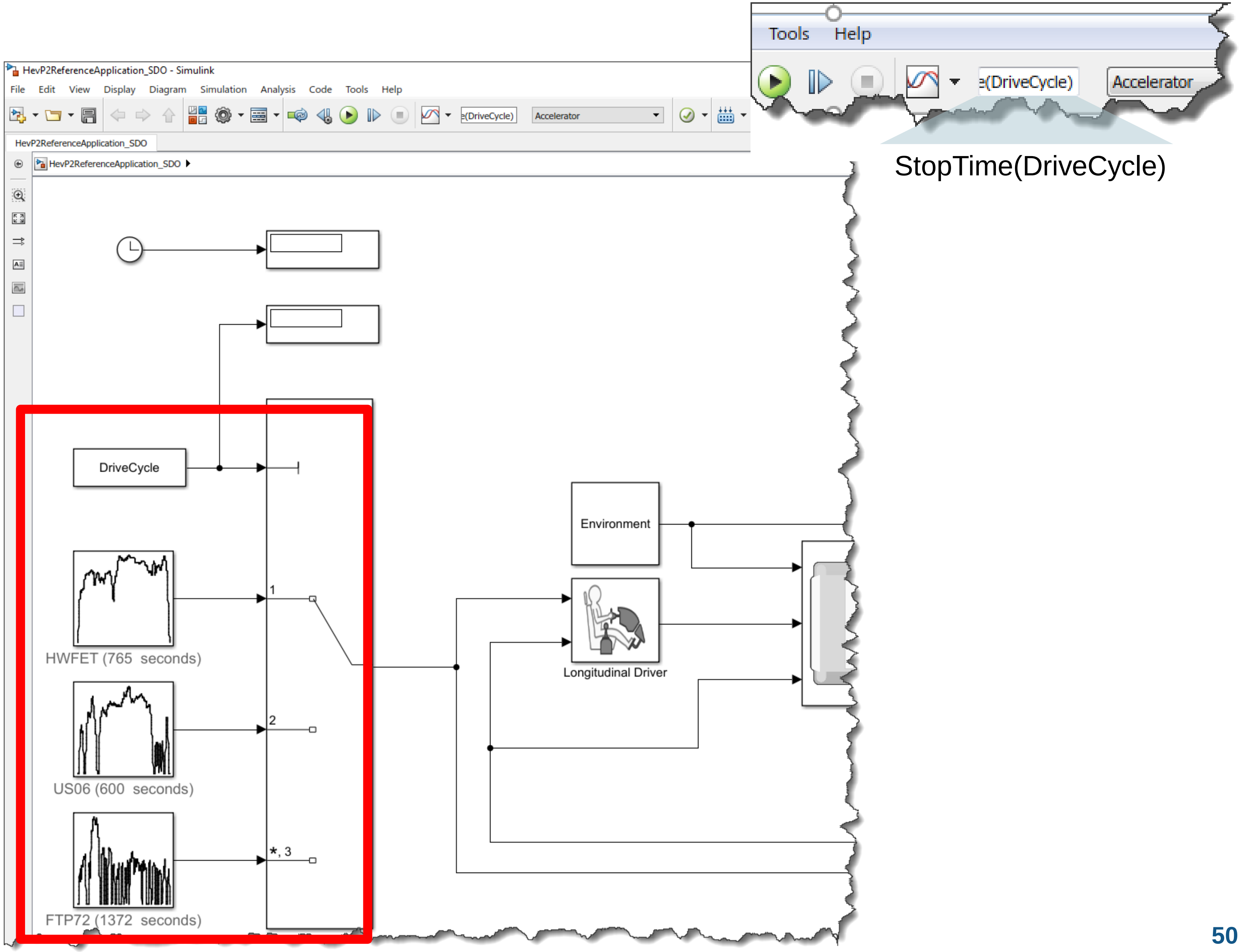
	Charge Sustaining Factor	minimum Engine Power	SOC Factor	mpg	delta SOC (%)
HWFET	0.1219	19453	16094	40.87	2.56
US06	0.1656	18047	22656	29.31	0.76
FTP72	0.2094	11016	17969	33.82	-0.39

  – 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

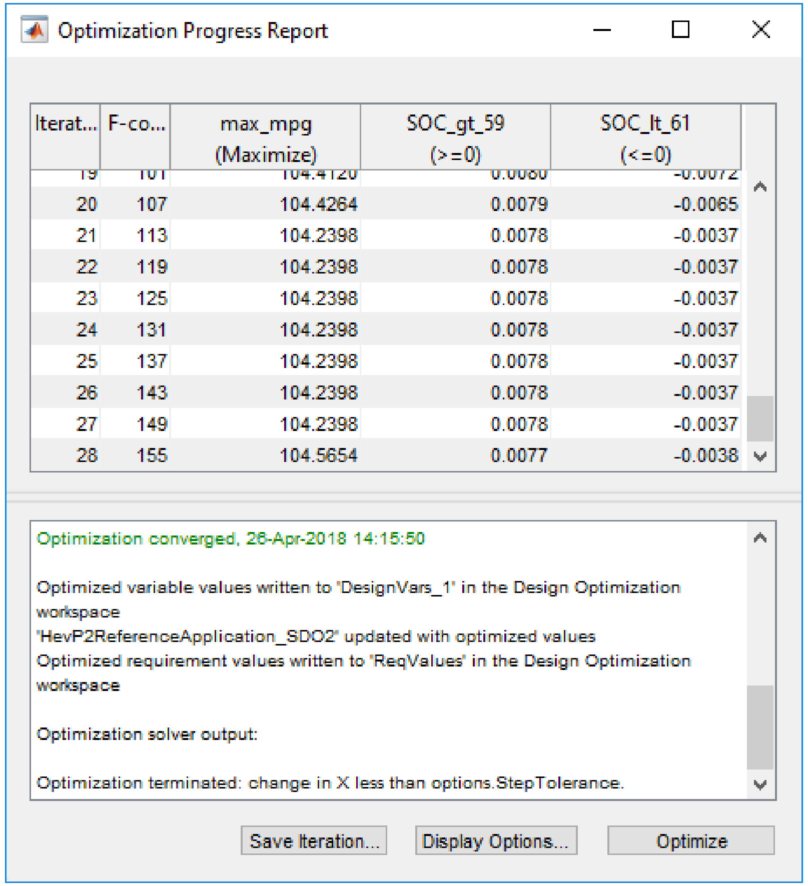
Response Optimization

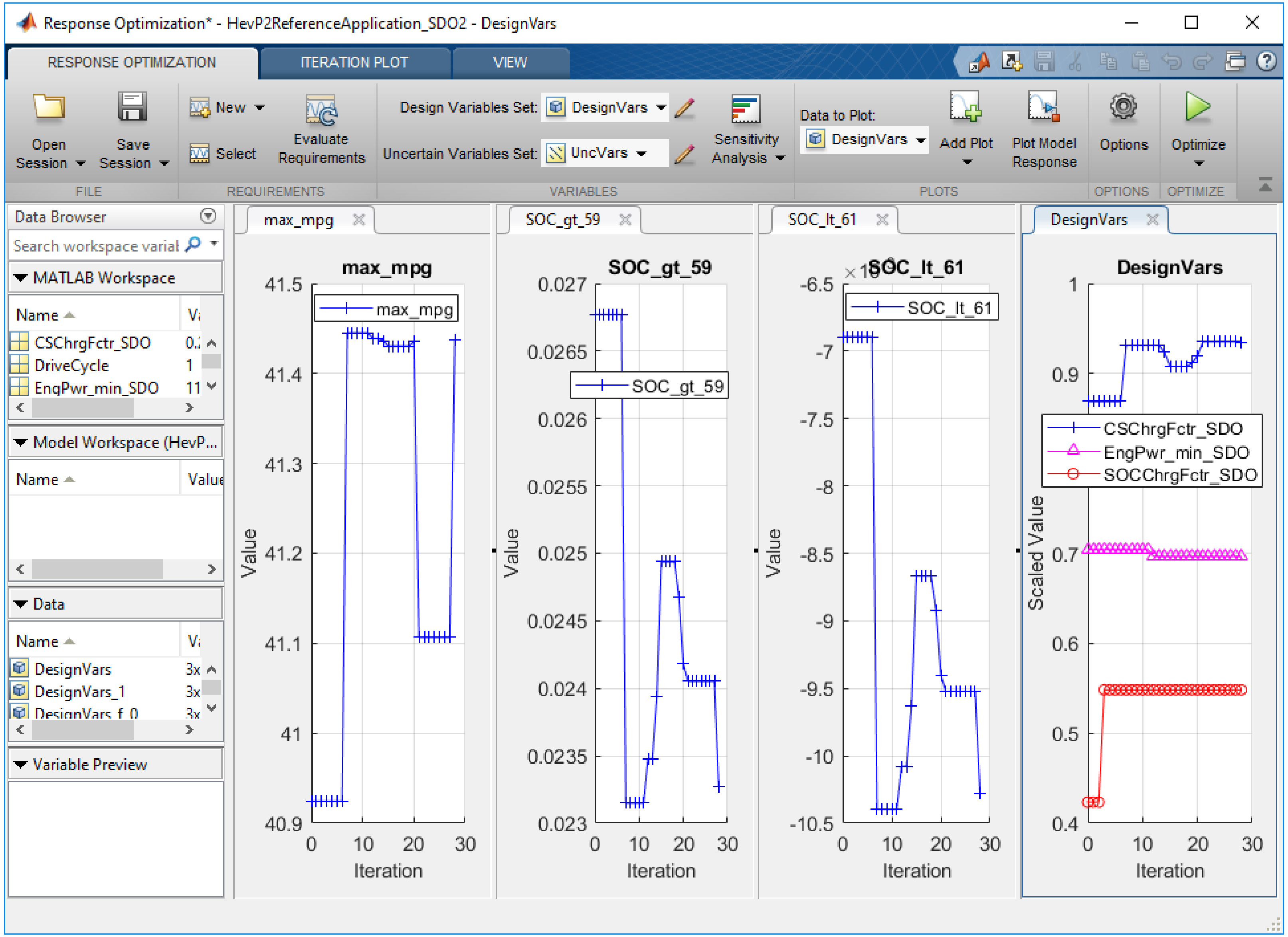
- Find optimal design parameters that satisfy multiple objectives and constraints simultaneously
- Simulink Design Optimization UI
  - Define design variables, objective functions, and constraints
  - Use ‘Uncertain Variable’ (Drive Cycle) to run all 3 cycles in 1 iteration
  - Speed up using parallel computing



Response Optimization – Results

1. View Results





SDO – Response Optimization

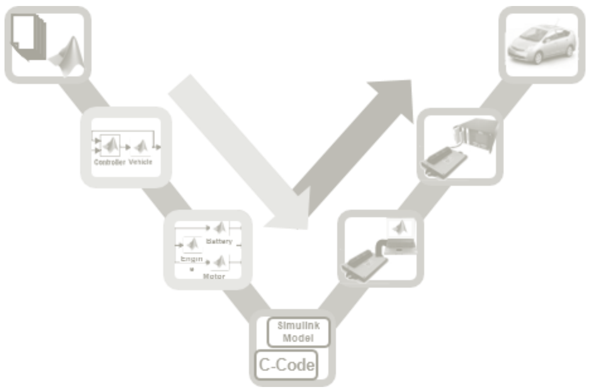
- Summary

Sensitivity Analysis					
	Charge Sustaining Factor	minimum Engine Power	SOC Factor	mpg	delta SOC (%)
HWFET	0.1219	19453	16094	40.87	2.56
US06	0.1656	18047	22656	29.31	0.76
FTP72	0.2094	11016	17969	33.82	-0.39
3 Cycle Response Optimization					
	Charge Sustaining Factor	minimum Engine Power	SOC Factor	mpg	delta SOC (%)
HWFET	0.2337	11408	17969	41.44	0.37
US06				29.14	0.78
FTP72				34	-0.55

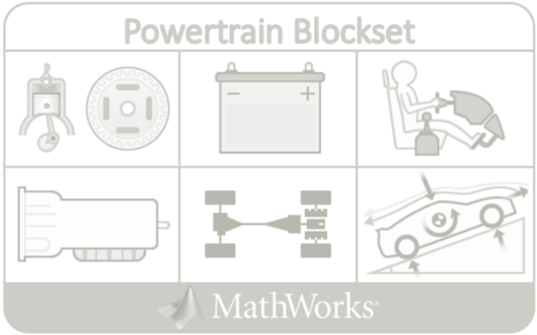
- ***Found single set of design variables to maximize mpg and charge sustain!***

Key Points

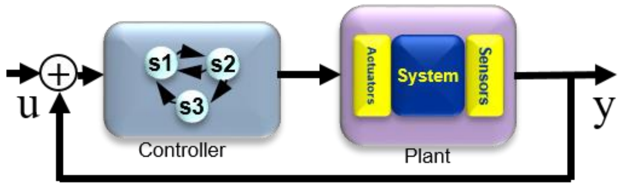
- Efficient plant modeling enables Model-Based Design (MBD)



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



- Design / optimize plant and controls together as a system



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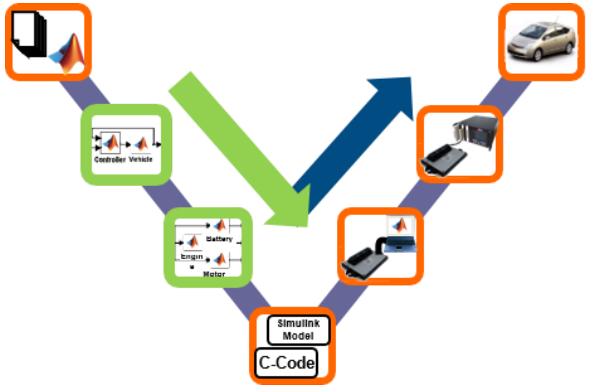

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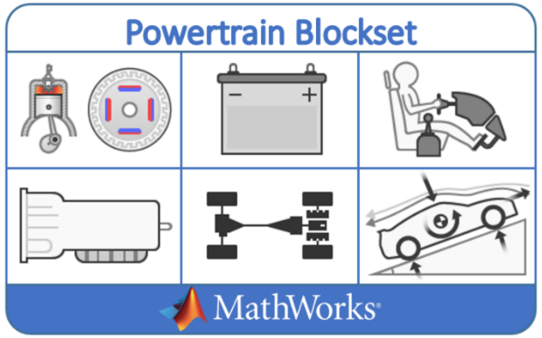

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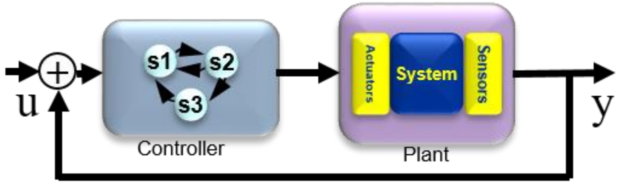

Thank You