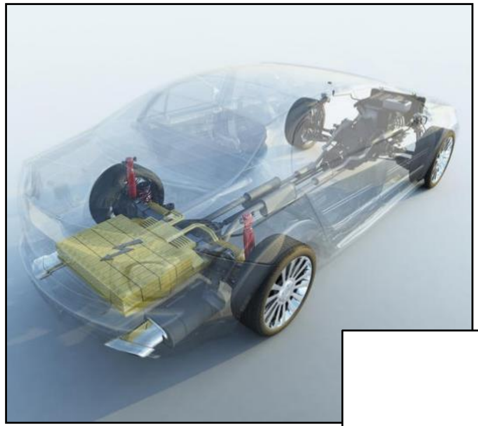
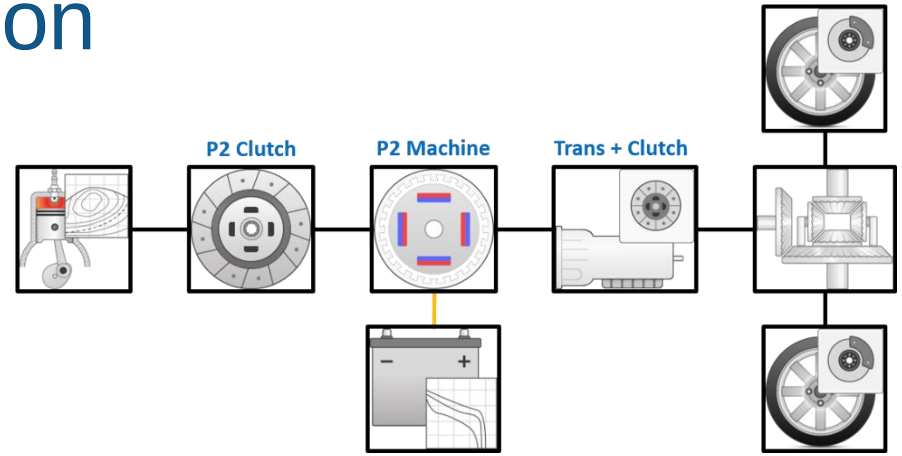
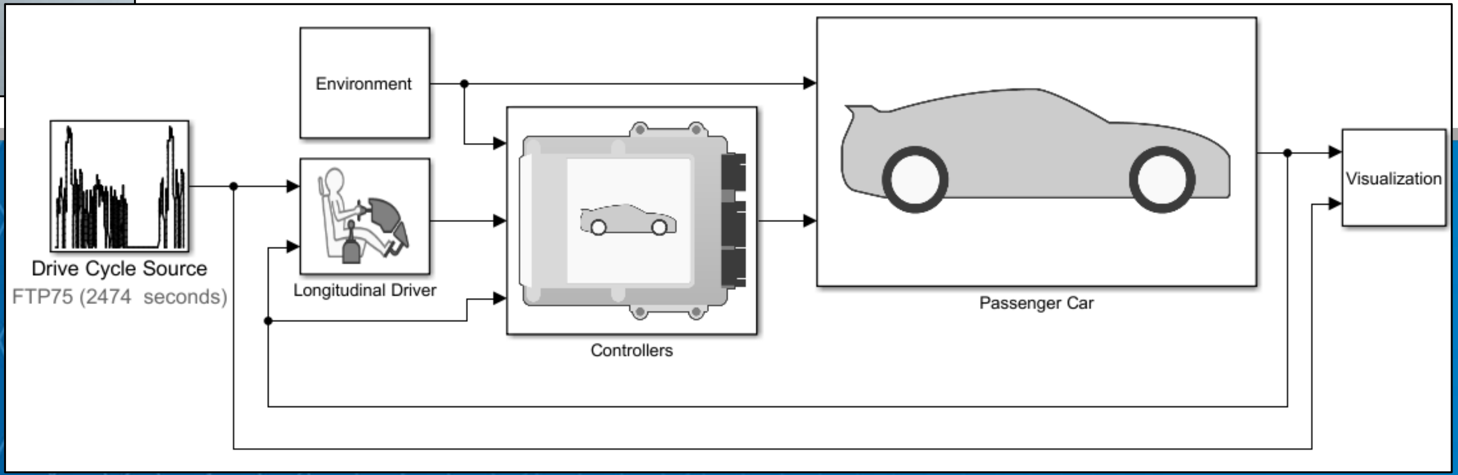
# Electrified Powertrain Design Exploration

MathWorks Automotive Conference

May 2nd, 2018





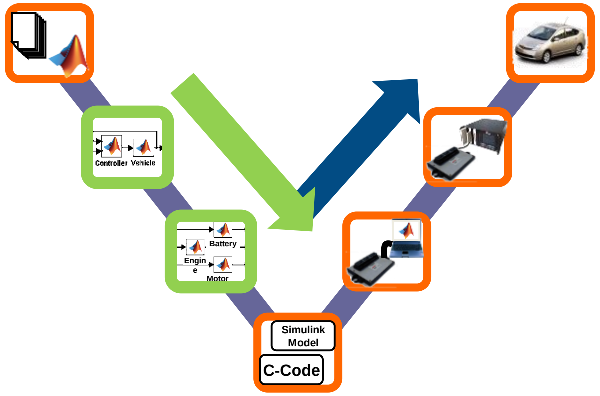

Kevin Oshiro
MathWorks

# Presenter

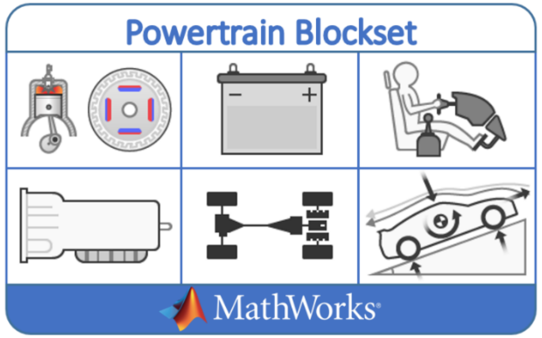
- Kevin Oshiro
  - MathWorks Application Engineering
  - Areas of interest:
    - Enabling Model-Based Design using physical modeling
    - Mechatronic systems / electrified powertrains
    - System level control strategies
    - Mentor for EcoCAR3 student competition
  - Previous experience at PACCAR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

# Key Points

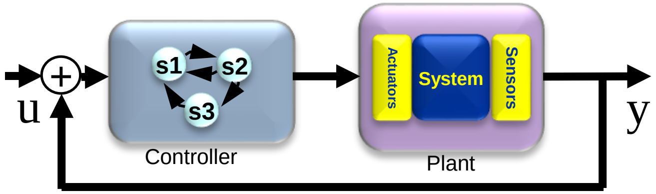
- Efficient plant modeling enables Model-Based Design (MBD)




- 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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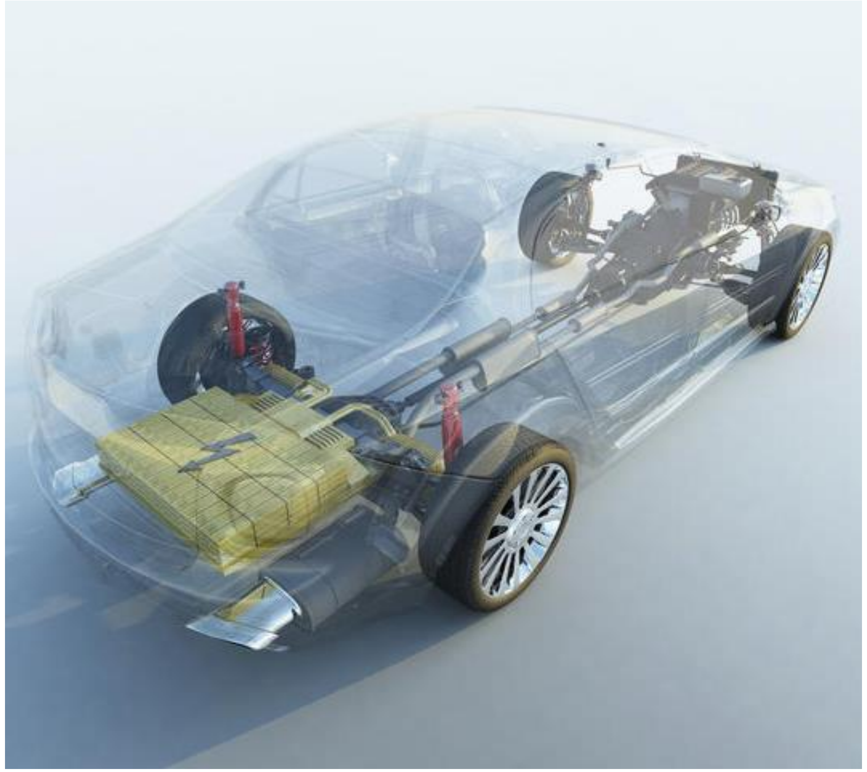
# Challenges with HEV Design

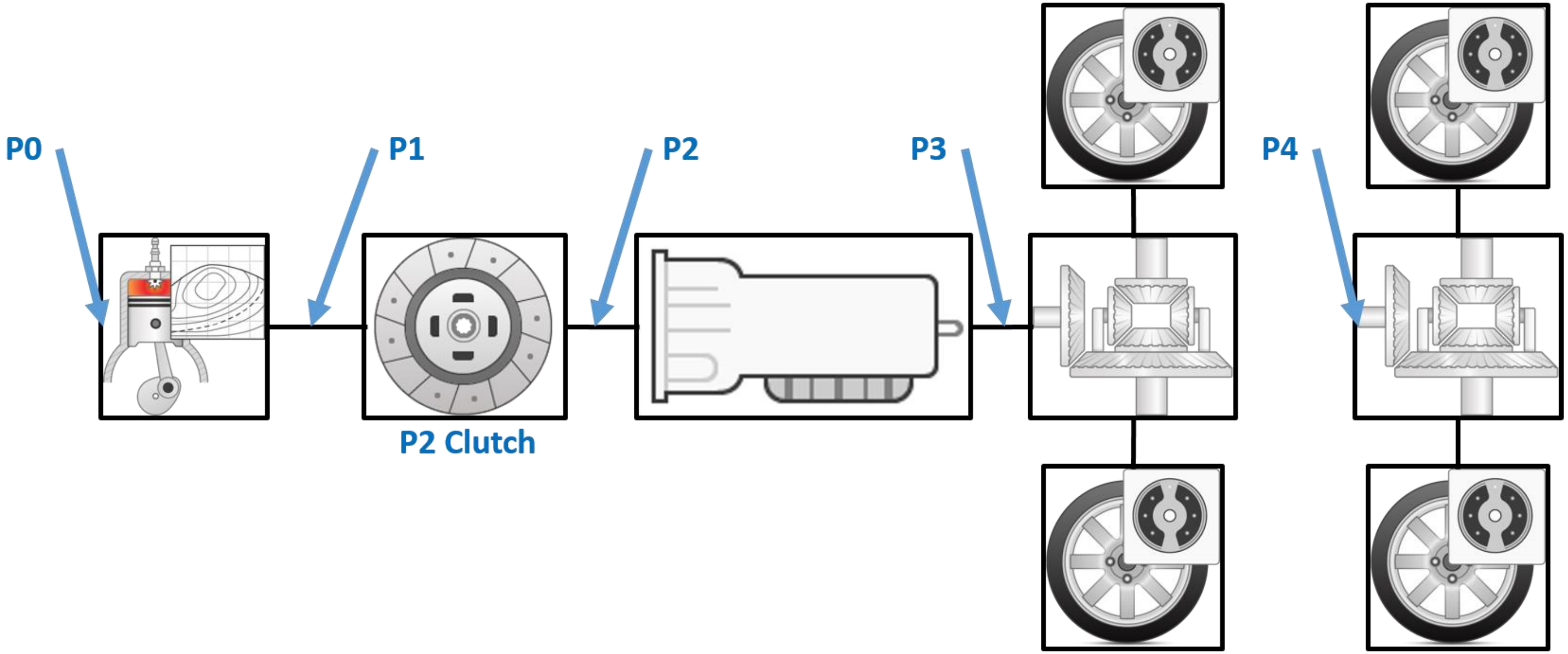
- Architecture / topology selection
- Selection and sizing of components
- Complexities in modeling plant and controllers



- 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



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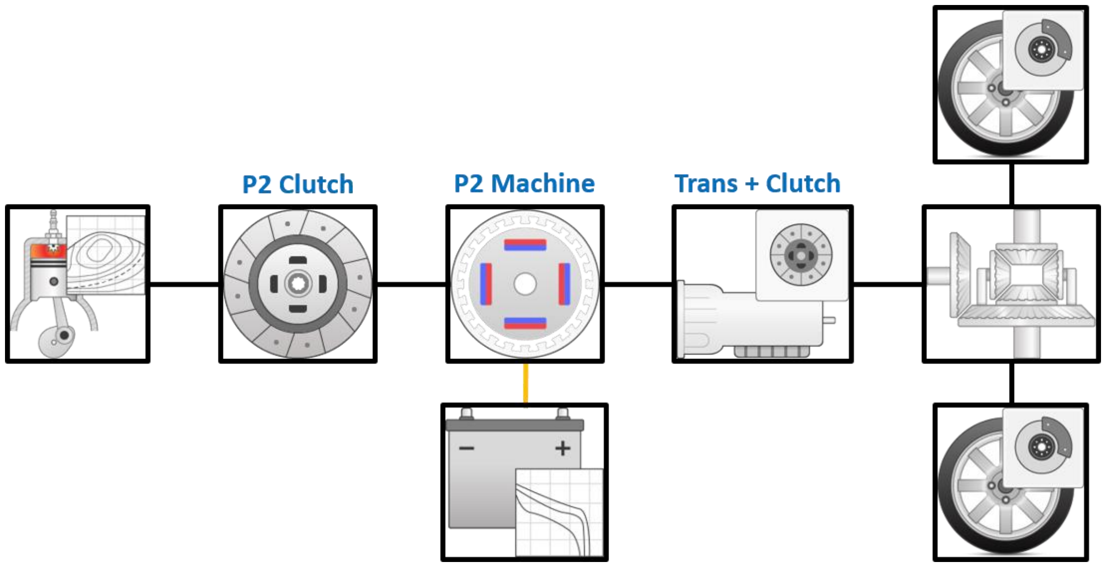
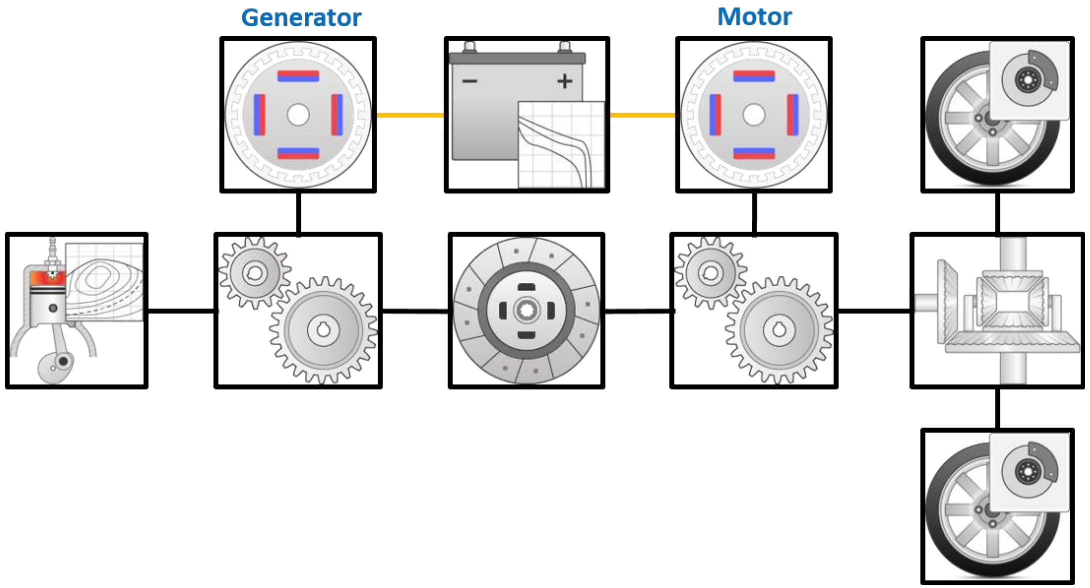
- Parallel / Series-Parallel HEV Architecture
  - P# = Electric machine locations
  - Multiple combinations (i.e. P2, P1/P4, etc.)
  - Intrinsic pros/cons for each location

P2

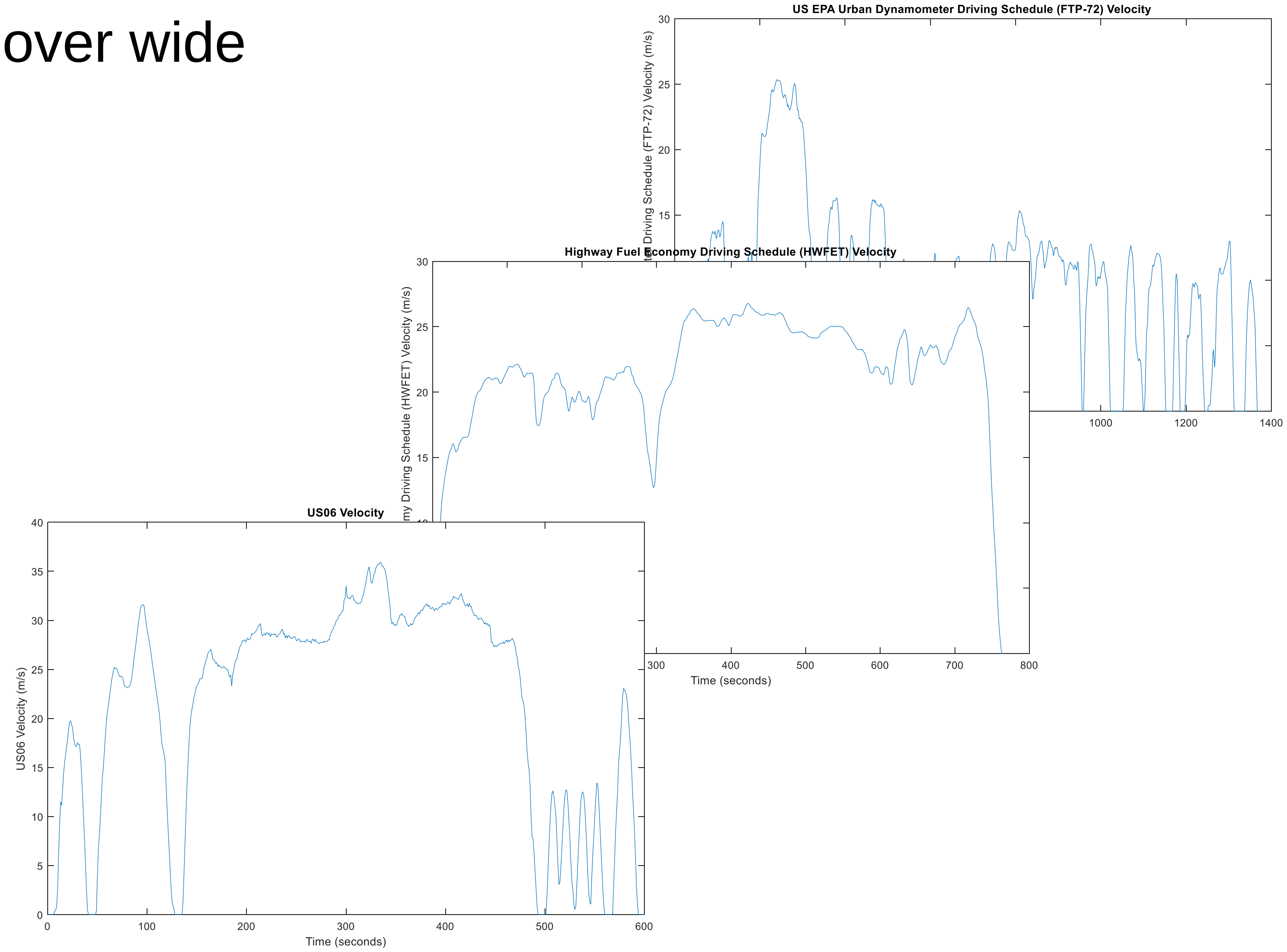



P1 / P3



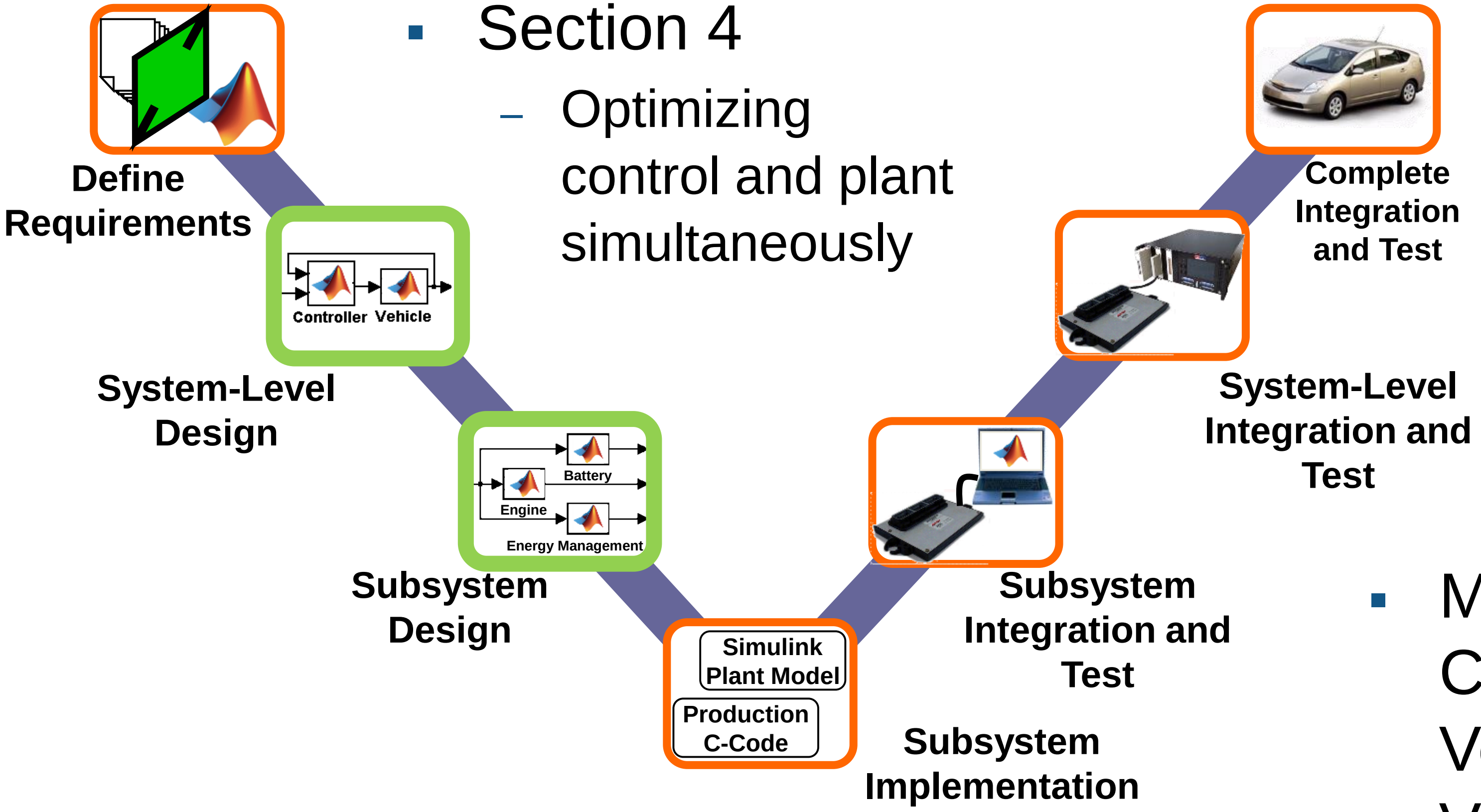
# Challenges with HEV Design – Example

- 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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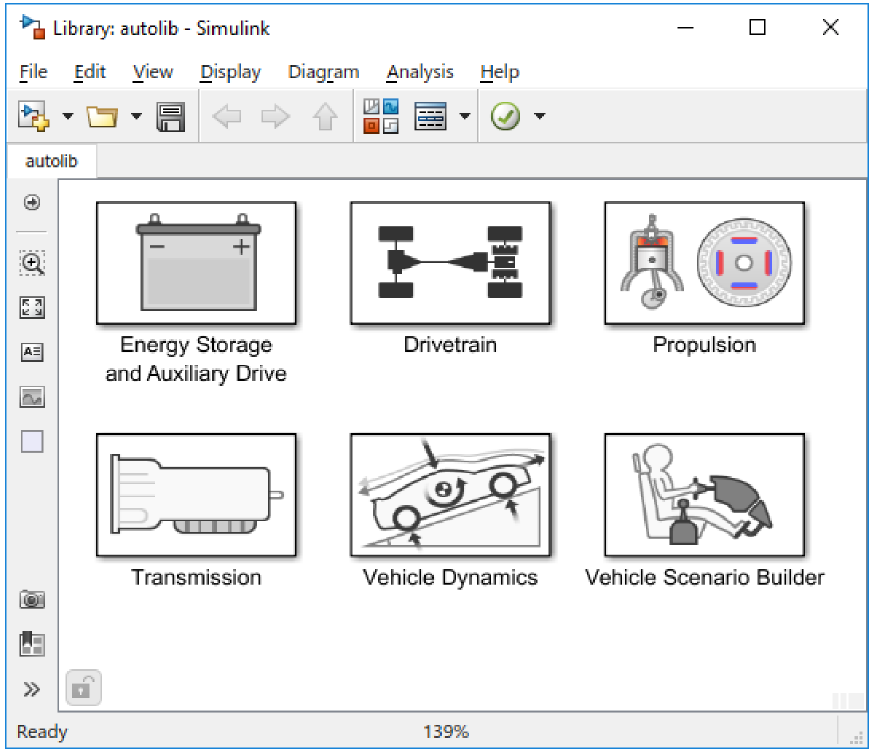
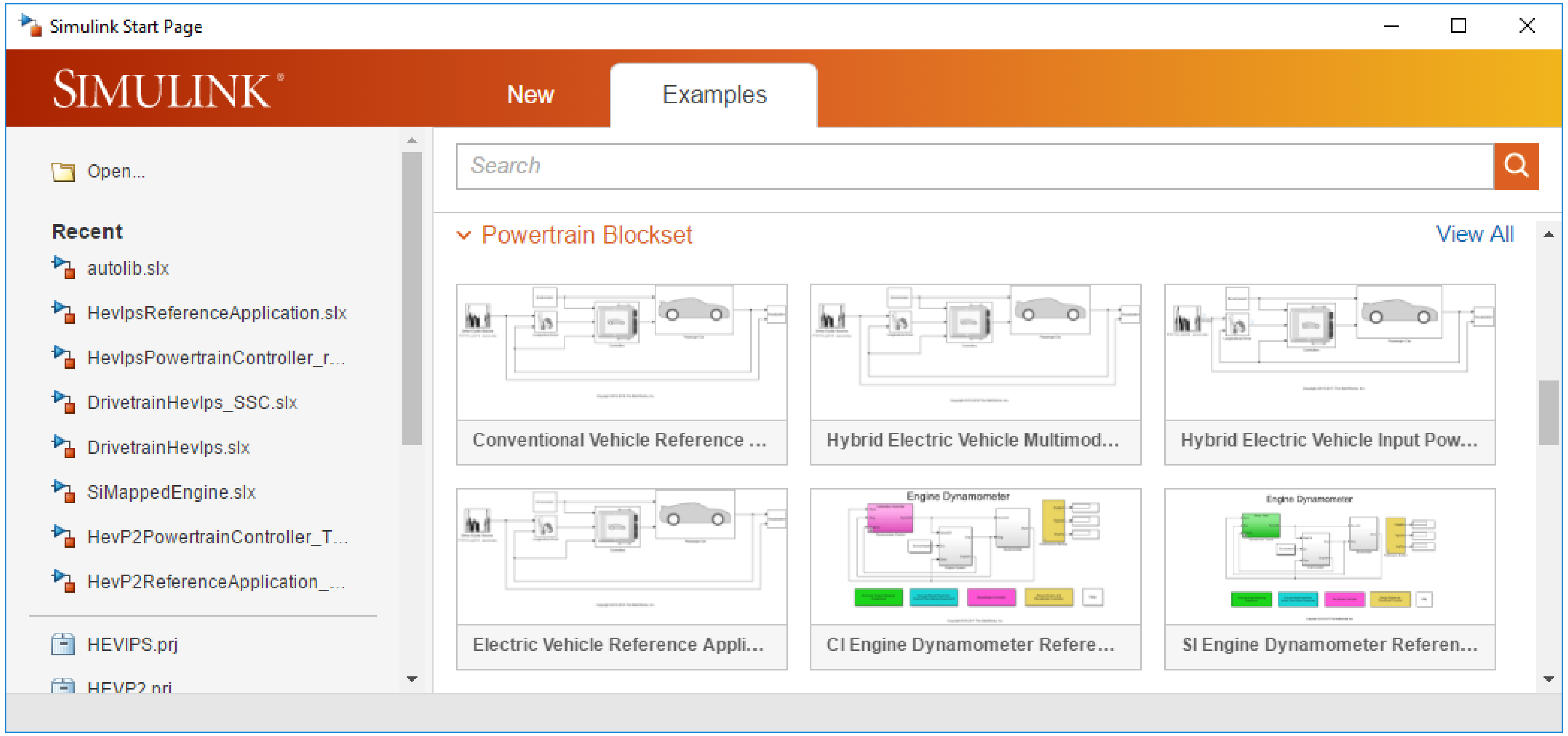
# Powertrain Blockset Features

## Library of blocks

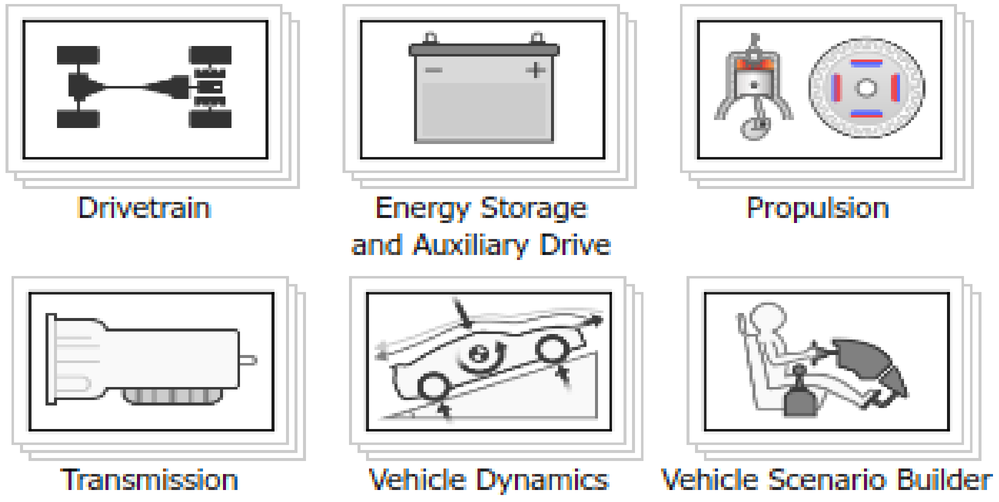


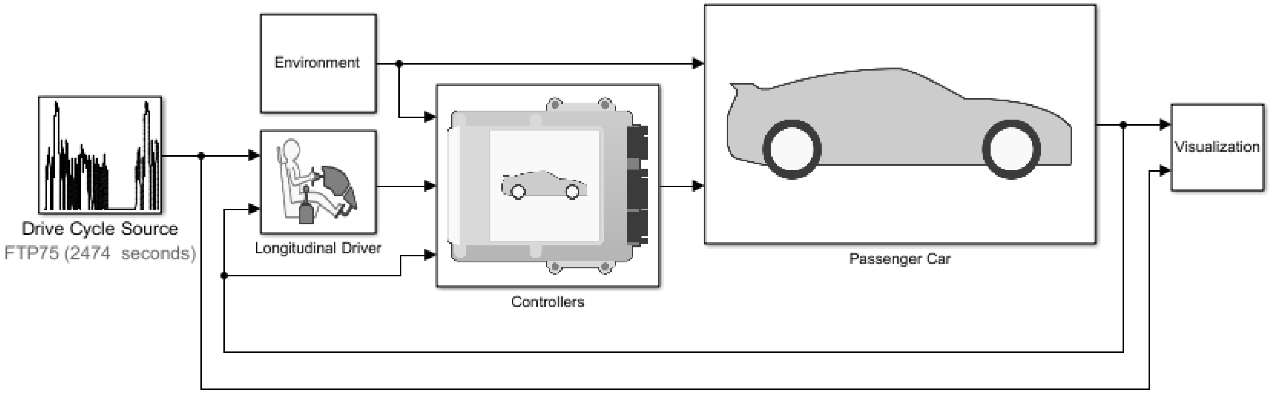

## Pre-built reference applications



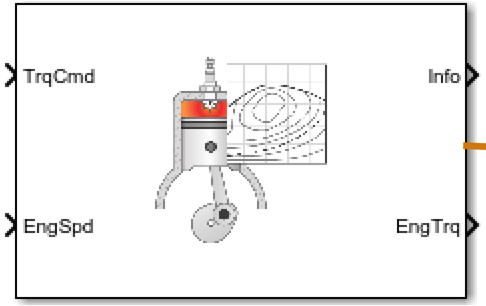
# Powertrain Blockset Benefits

- 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

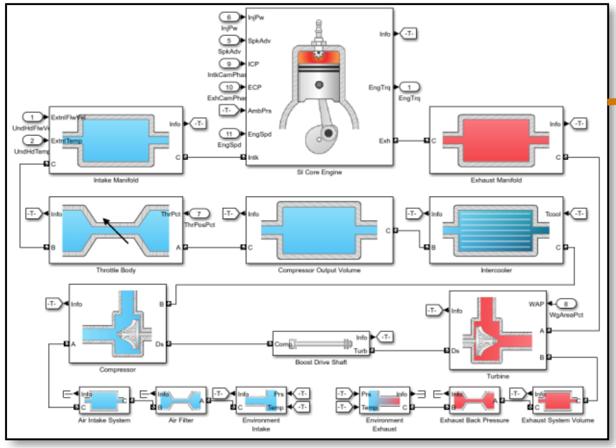


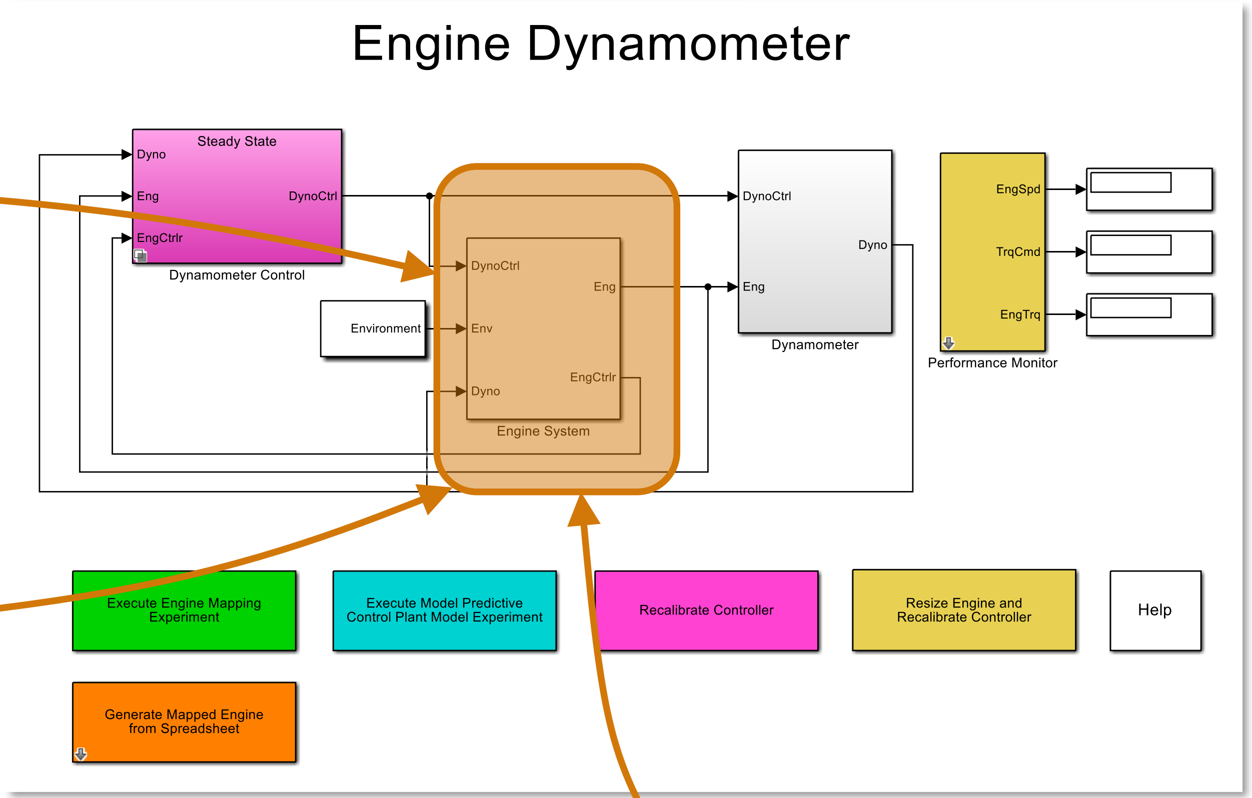
# Powertrain Blockset – Engine Models

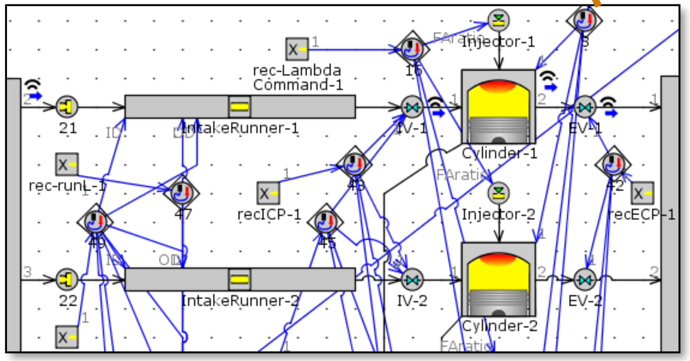



Use Powertrain Blockset *mapped* engine blocks with your own data



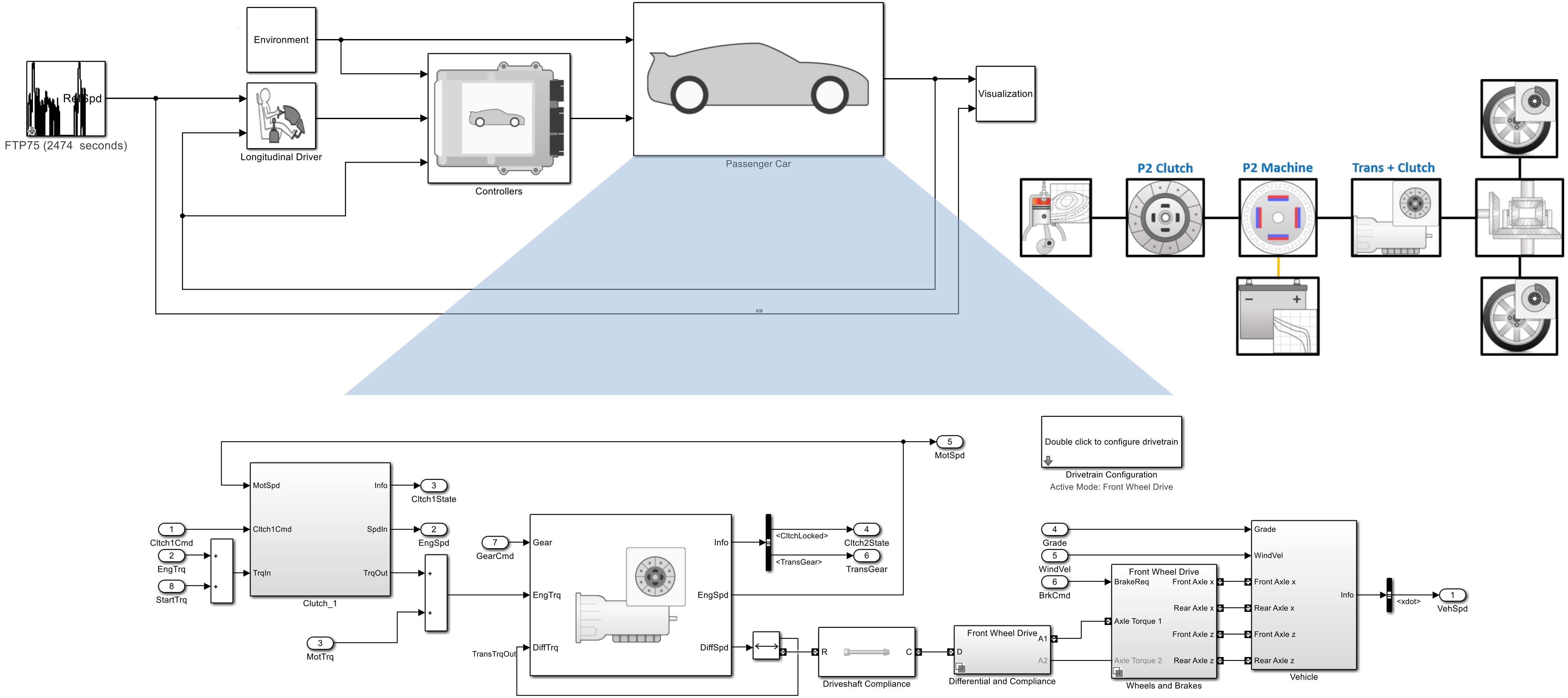

Create *dynamic* engine models using Powertrain Blockset library components




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

# Powertrain Blockset – P2 Reference Application

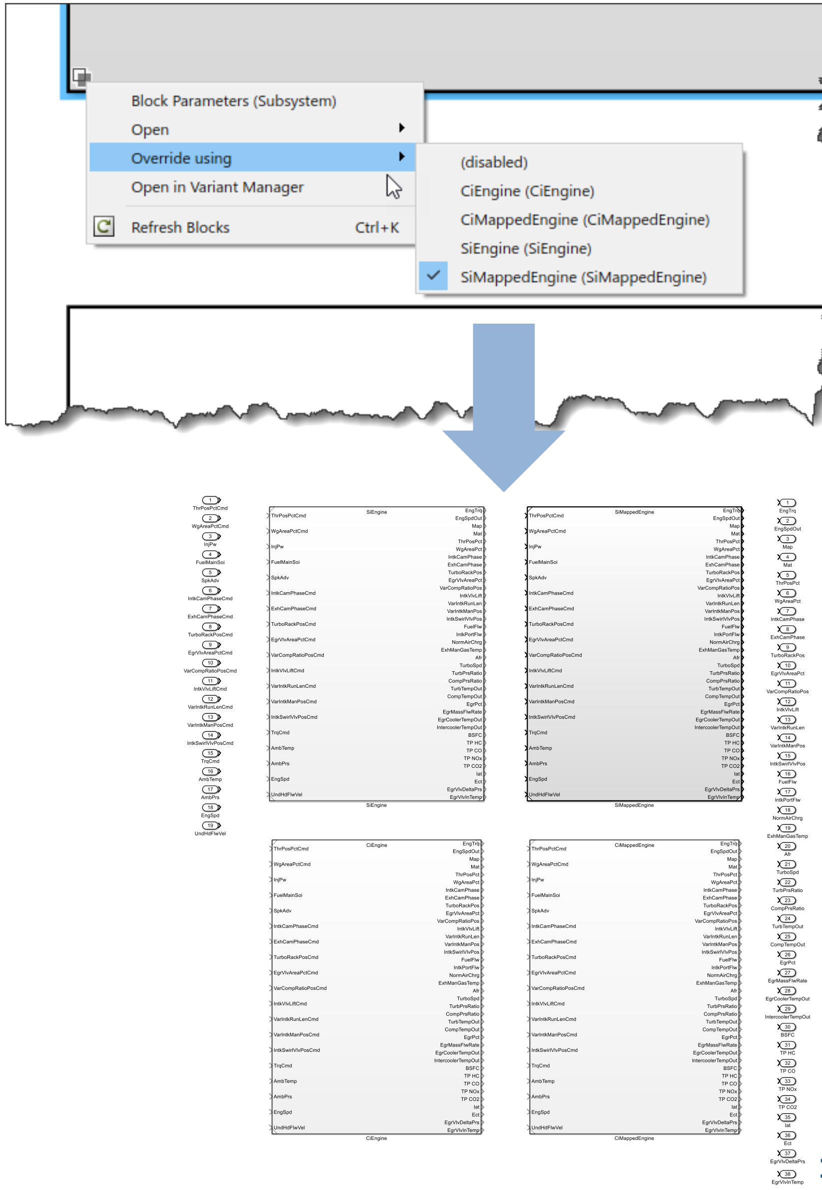


# HEV Modeling Best Practices – Getting Started

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

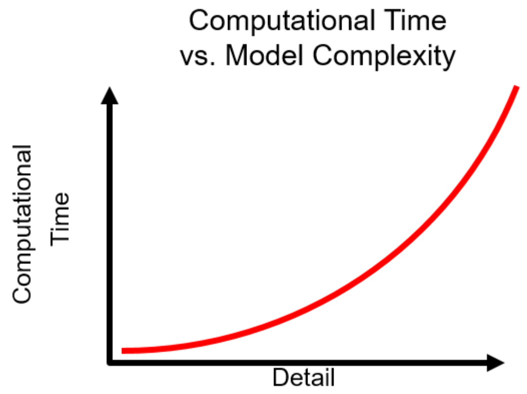
- For system level simulation, start with a PTBS reference application
  - Model architecture
    - Uses referenced models and variant subsystems for modularity
    - Input / Output layers separate from application layer
    - Utilizes Simulink Projects for model organization

- Parameterize / customize subsystems for your needs

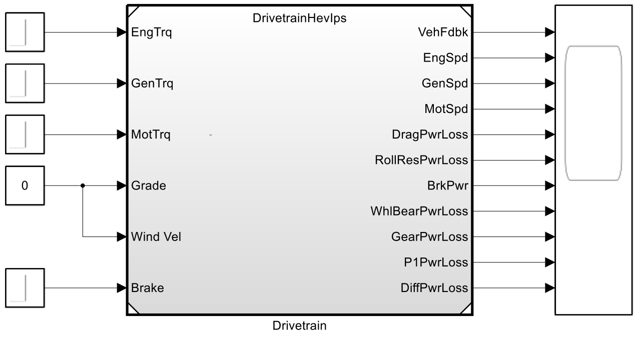


# HEV Modeling Best Practices – New Models

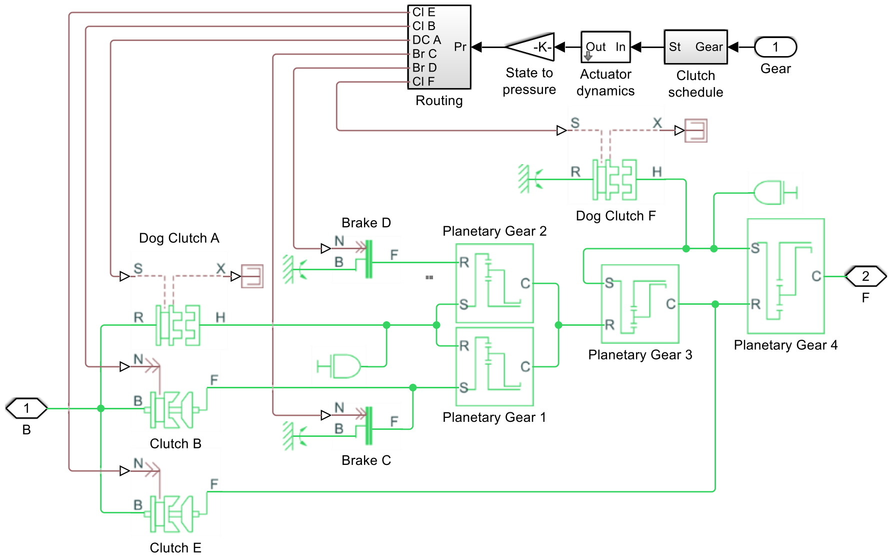
- Use appropriate modeling fidelity for purpose




- 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



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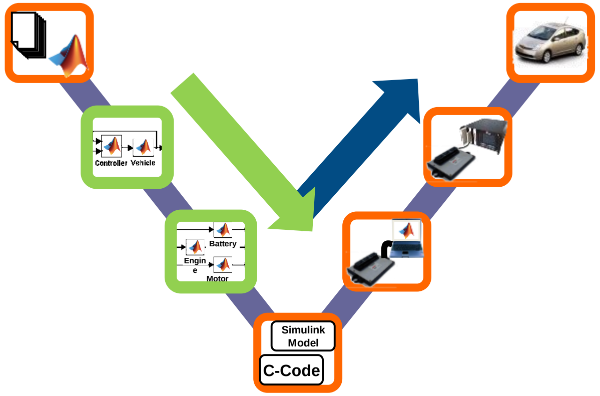
- Efficient plant modeling enables Model-Based Design (MBD)

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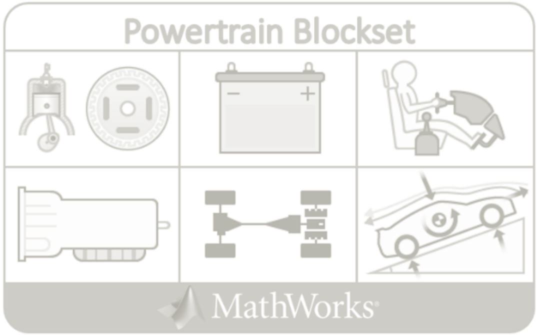
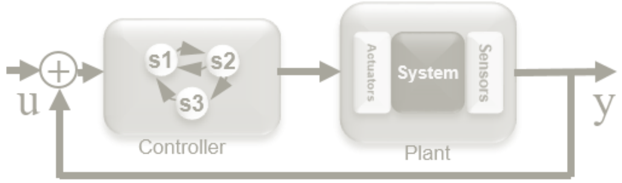



- Design / optimize plant and controls together as a system



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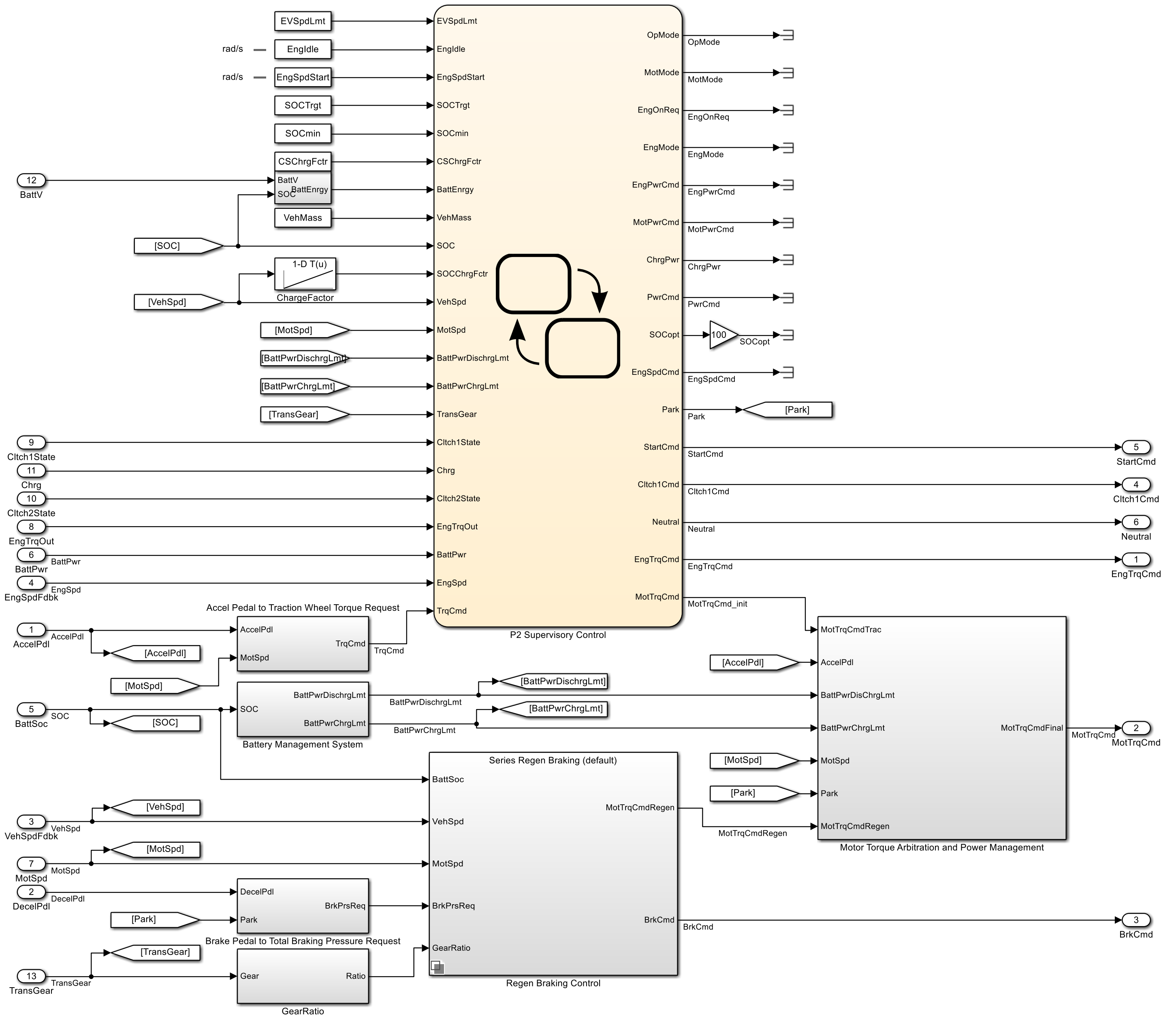
# Powertrain Control – HEV Supervisory Control

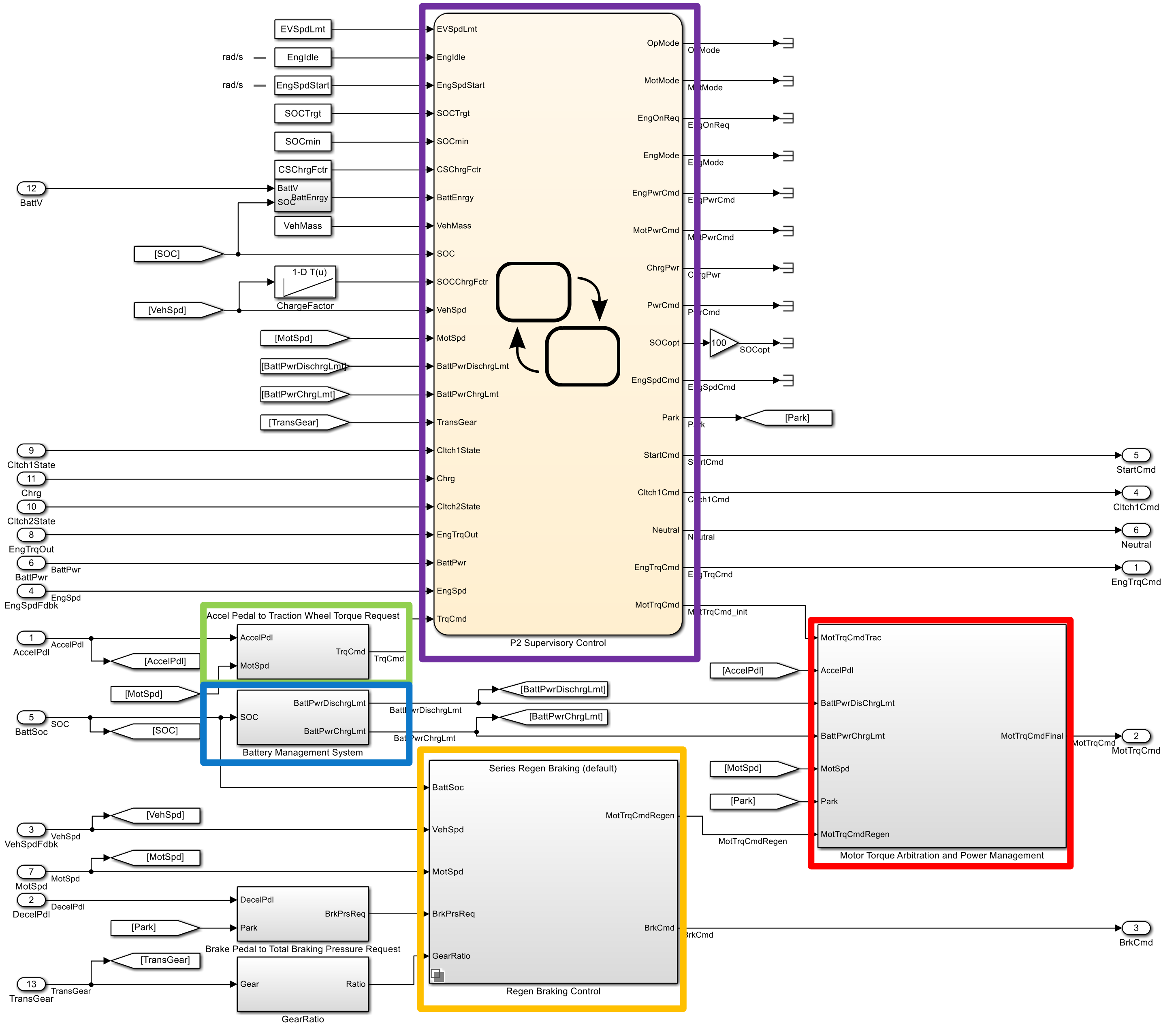
- HEV system level controller included in Reference Applications
- Rule-based
- Simulink / Stateflow
- Real-time implementable
- Customize as needed



# 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

SAE International
2011-01-2451
Published 06/01/2012

doi:10.4271/2011-01-2451
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

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

– Engine Power Calculation

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

– Minimum Eng On Power

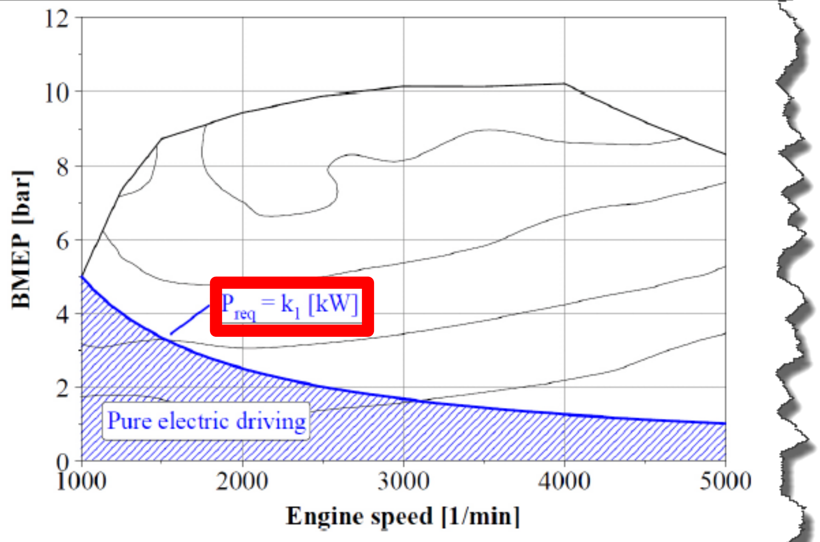
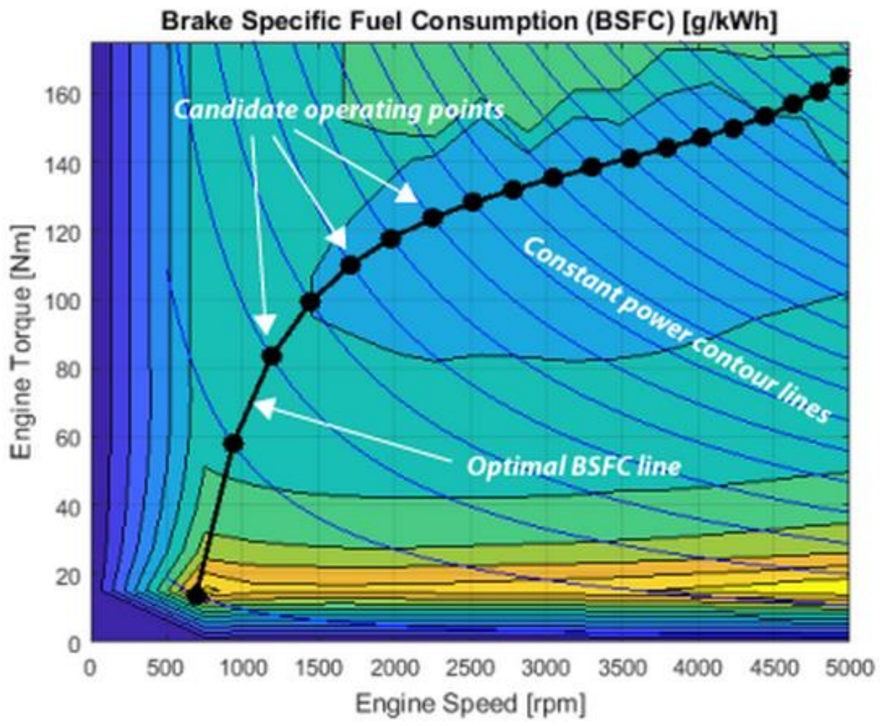
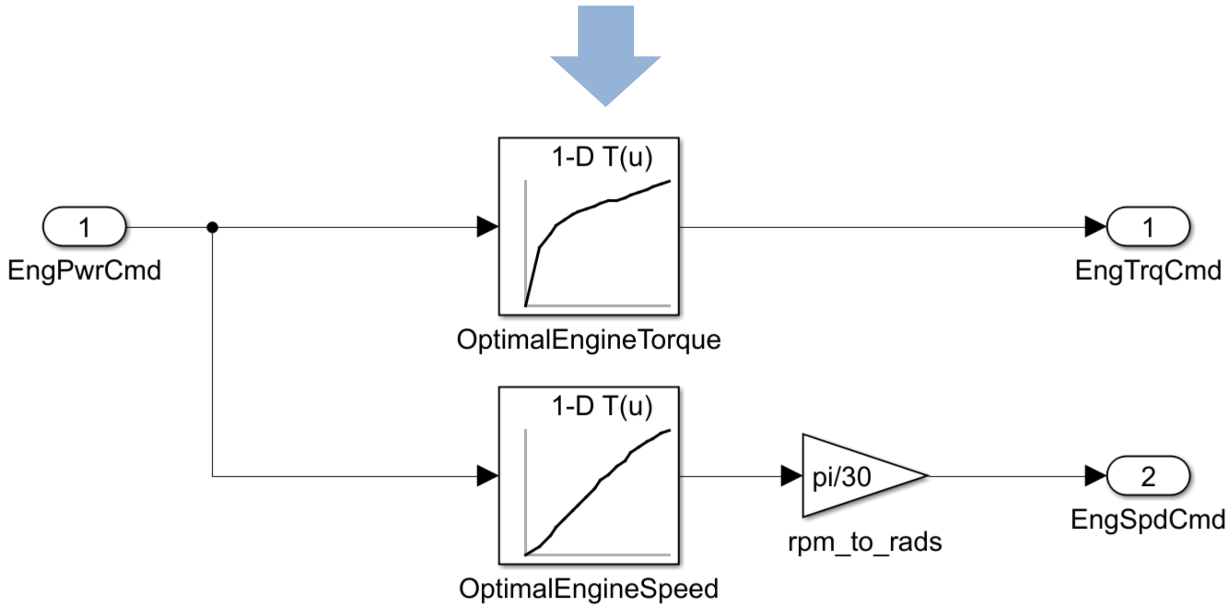



*Figure 5. Hybrid operating strategy: parameter $k_1$*

# Engine Control – HEV Mode

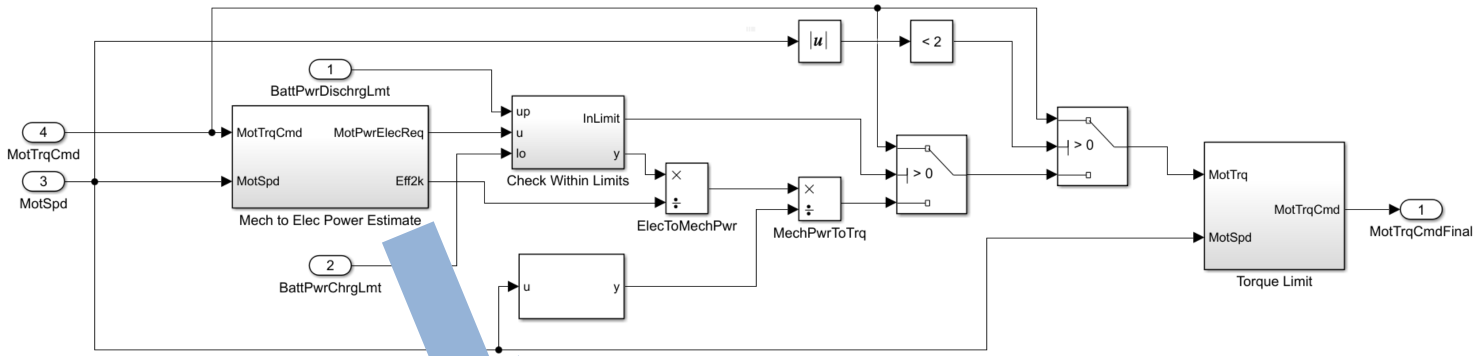
- Optimization algorithm used to find minimum BSFC line
- Results placed in lookup tables
- For an engine power command
  - Stationary mode can operate directly on this line
  - PHEV mode will attempt to operate on this line
- Good example of combining optimization w/ rules

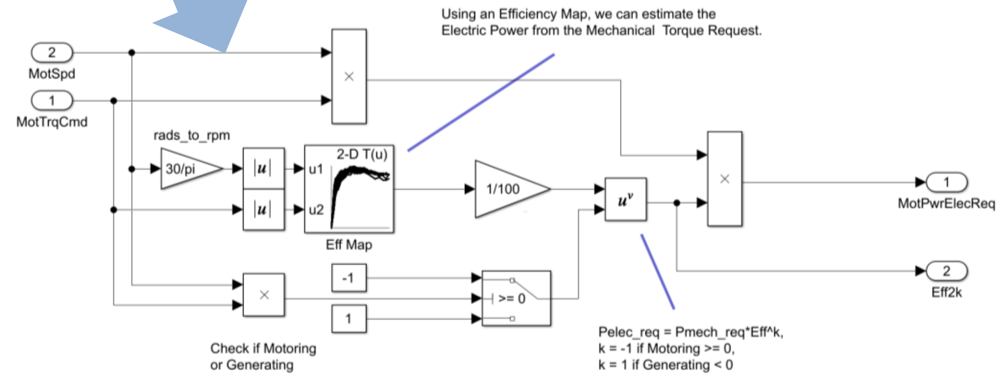


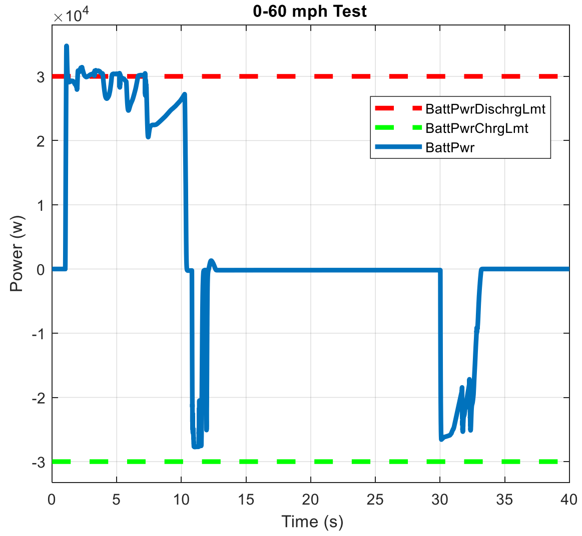



# Powertrain Control – Power Management

- 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

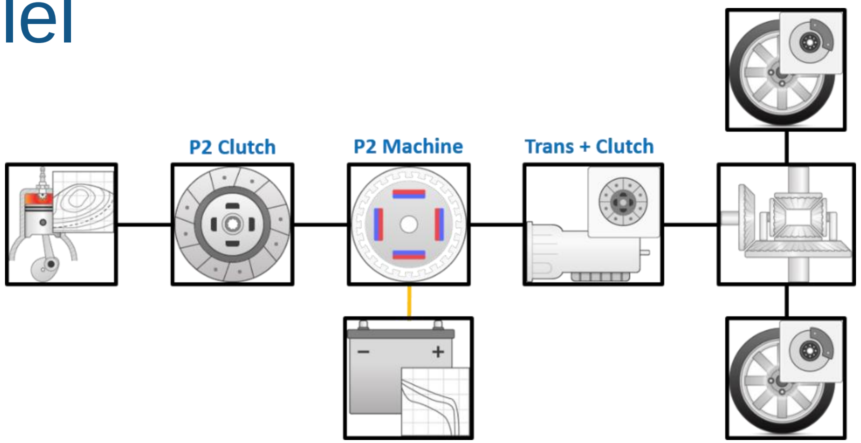


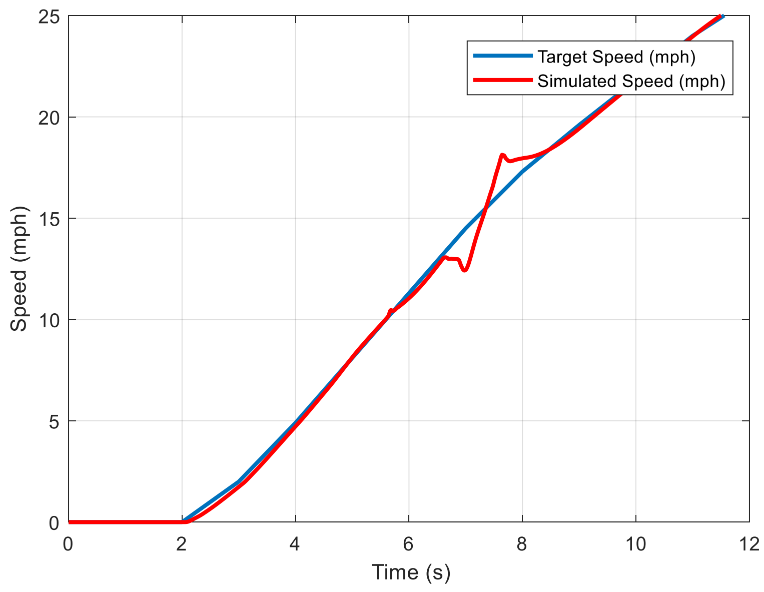



# Starting the ICE in a P2 HEV: EV → Parallel

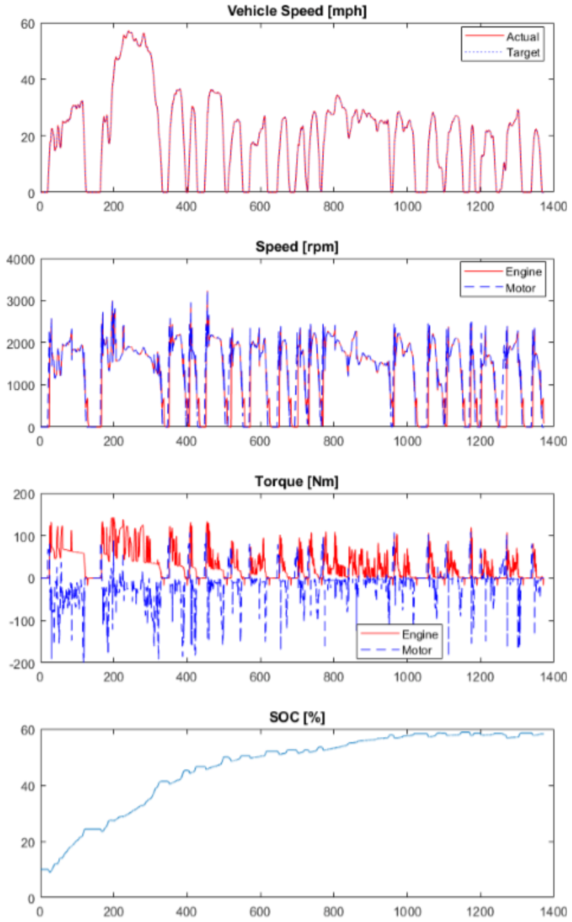
- “Bump” start
  - Can cause driveline disturbance
- “Shuffle” clutches
  - Process takes ~400-500 ms, causes vehicle speed to decrease
- Use low voltage Starter (or P0 machine)
  - Implemented in P2 Reference Application
  - 12V starter cranks ICE → ICE speed match mode → close P2 clutch

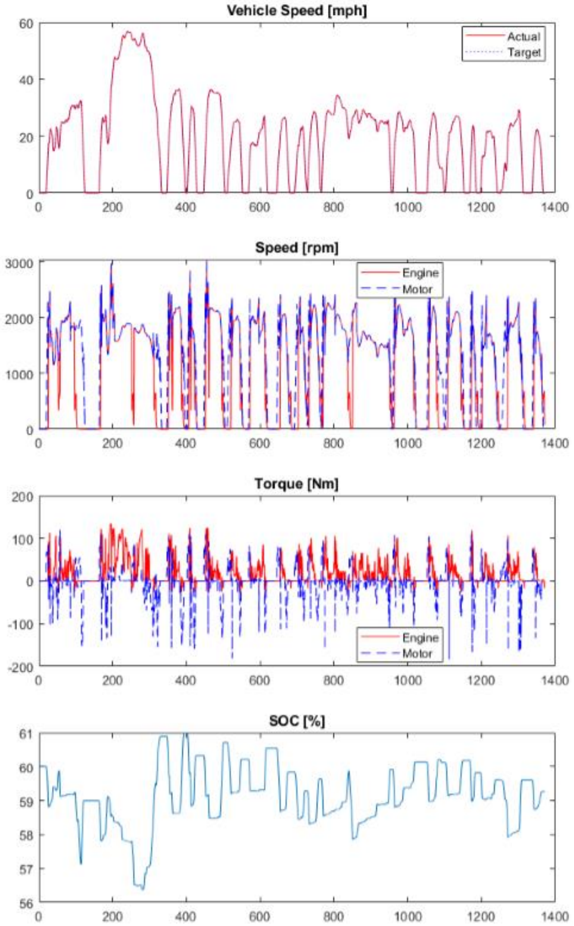


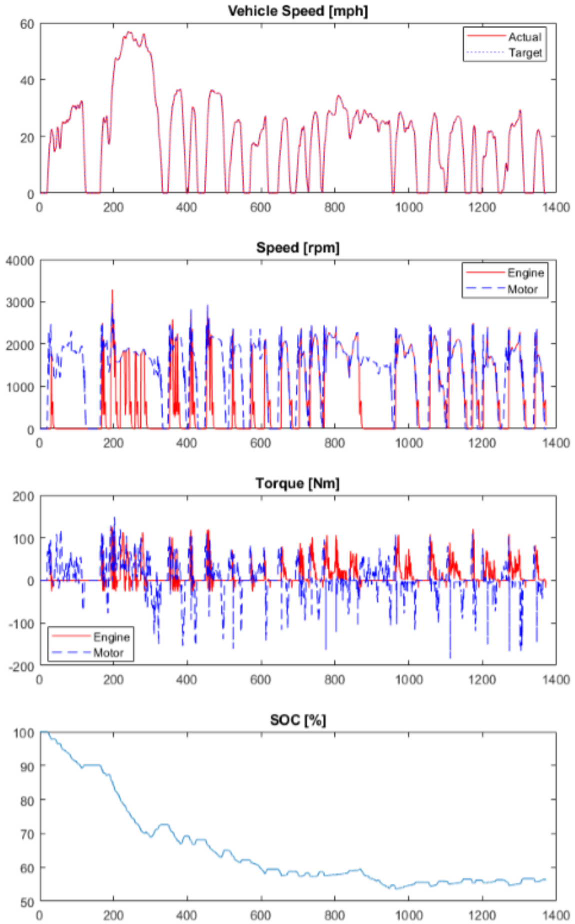



# Assessing Performance

- 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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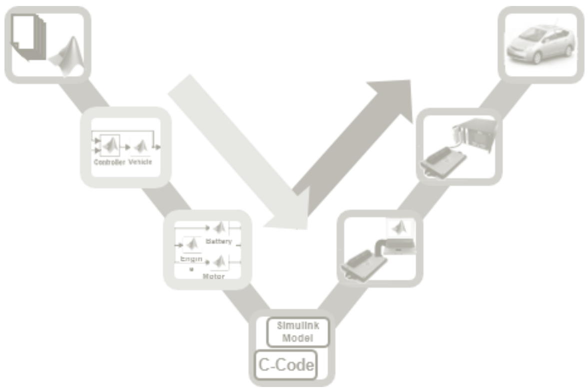


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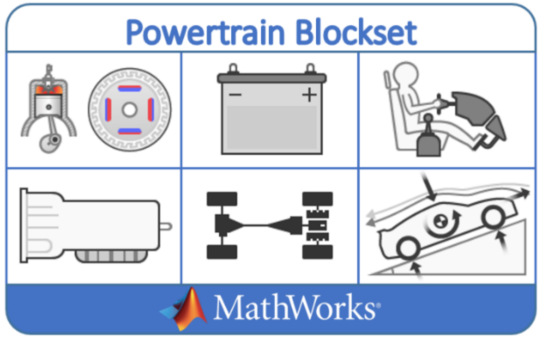


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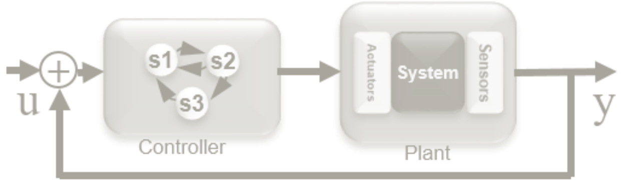

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# Optimization Introduction

***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

$$Ax \leq b$$

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

$$l \leq x \leq u$$

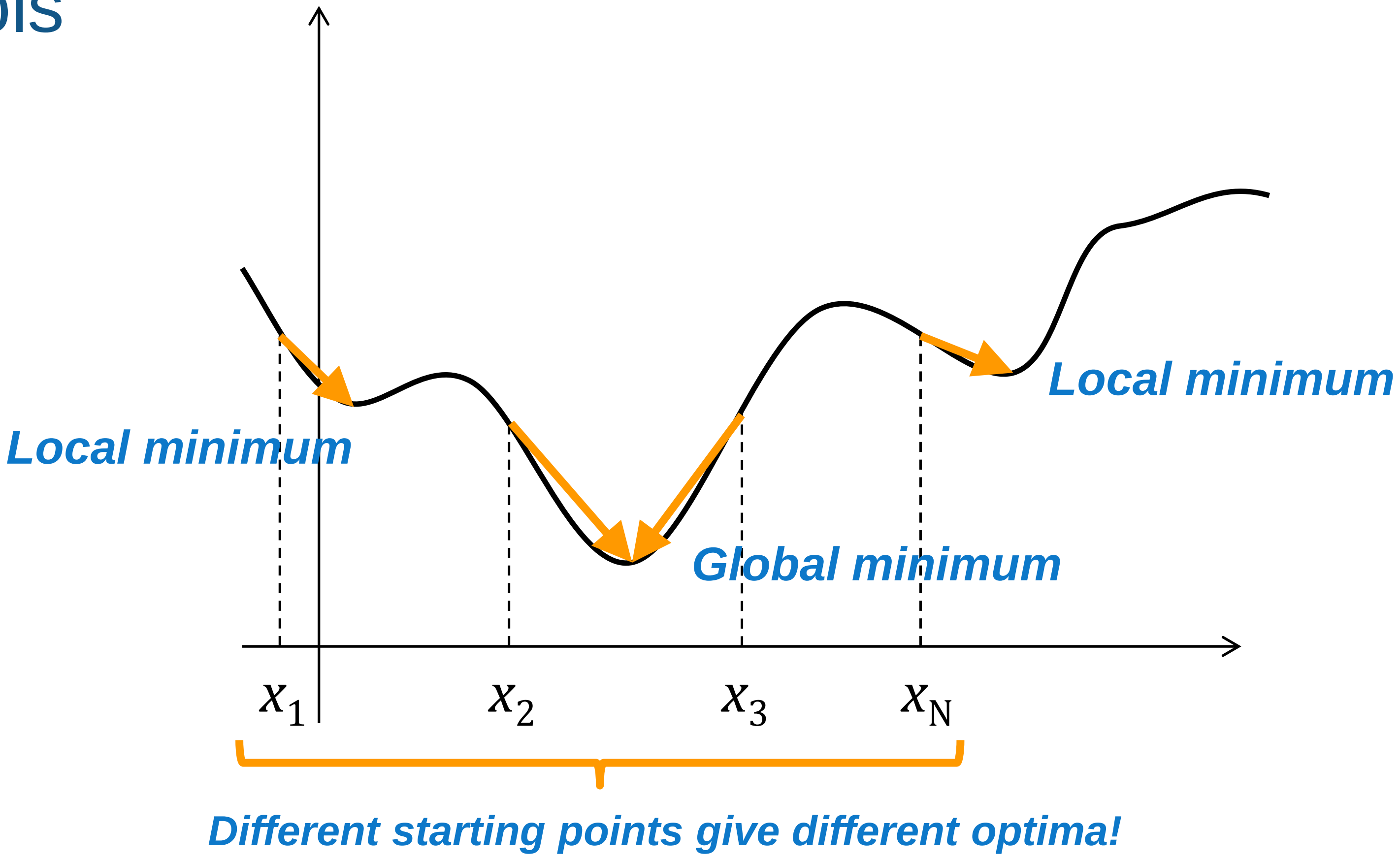
Nonlinear constraints

$$c(x) \leq 0$$

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

# 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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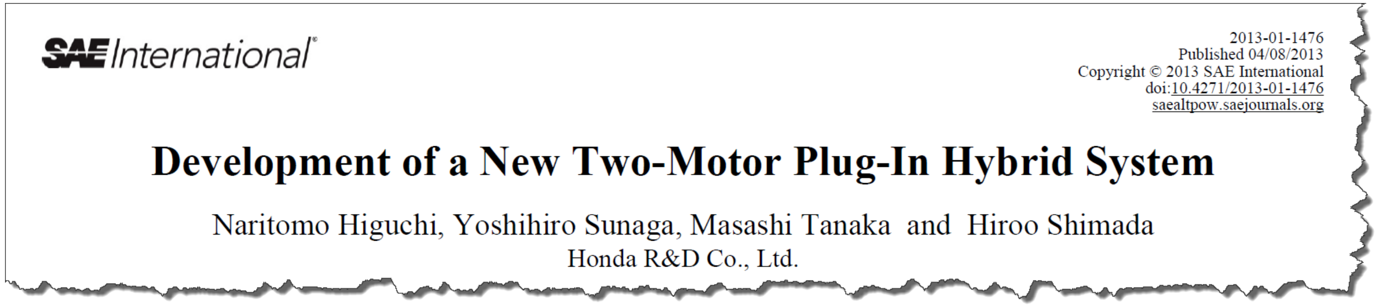
# Multi-Mode HEV Review



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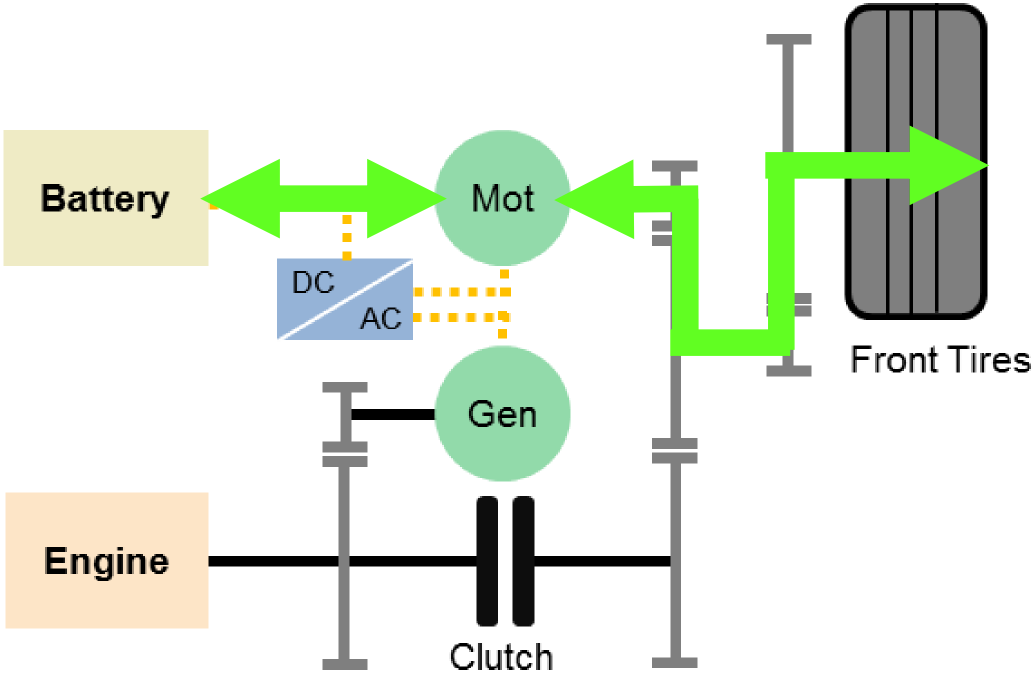
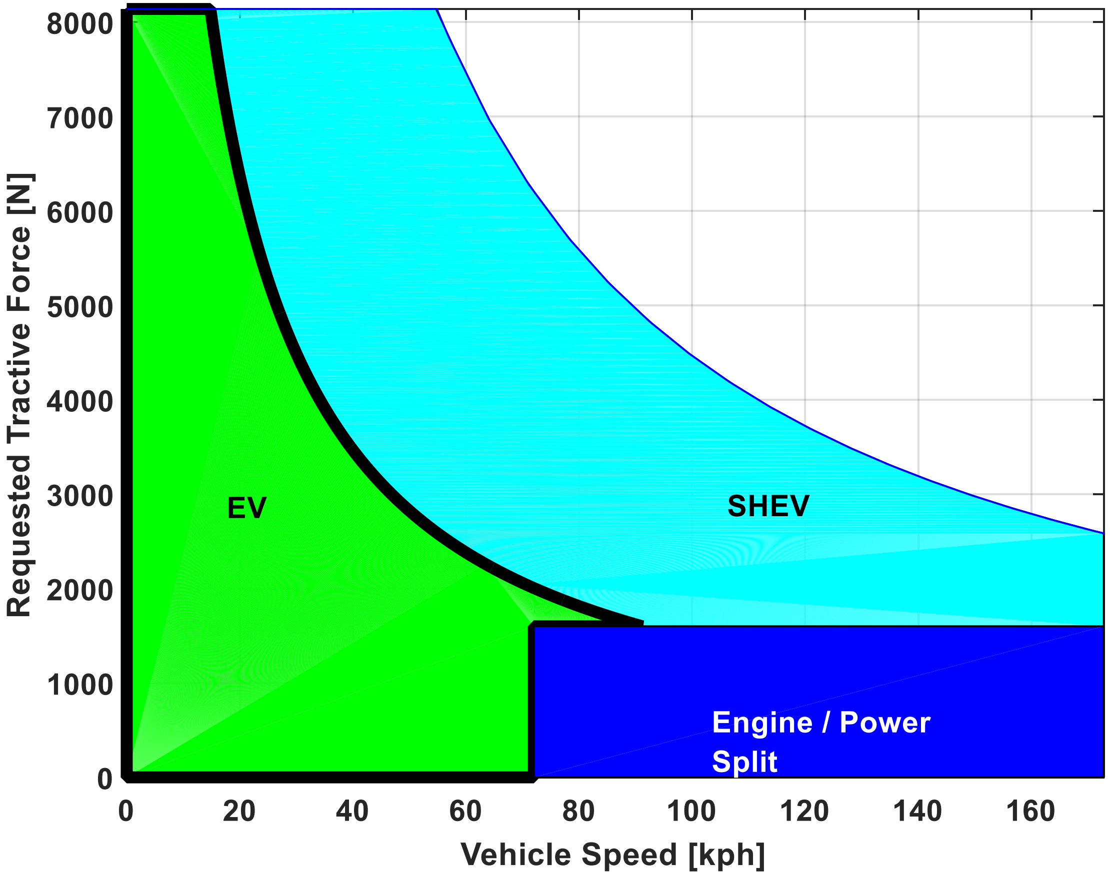
**Development of a New Two-Motor Plug-In Hybrid System**

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




**EV Mode**



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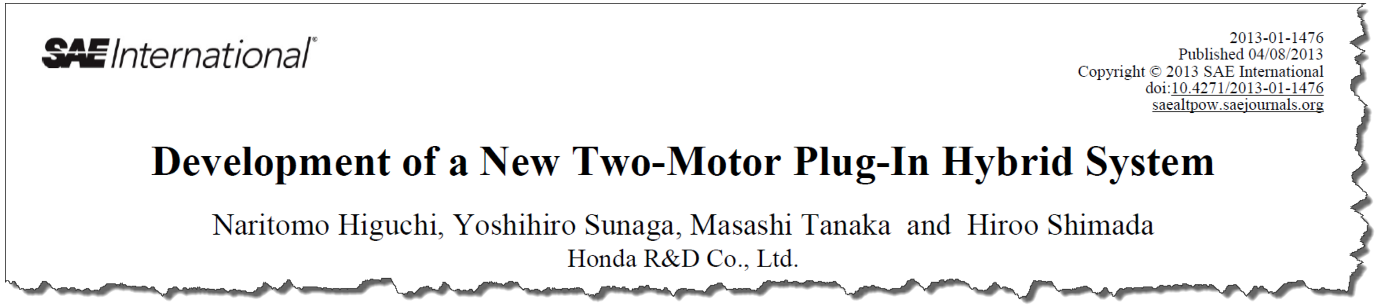

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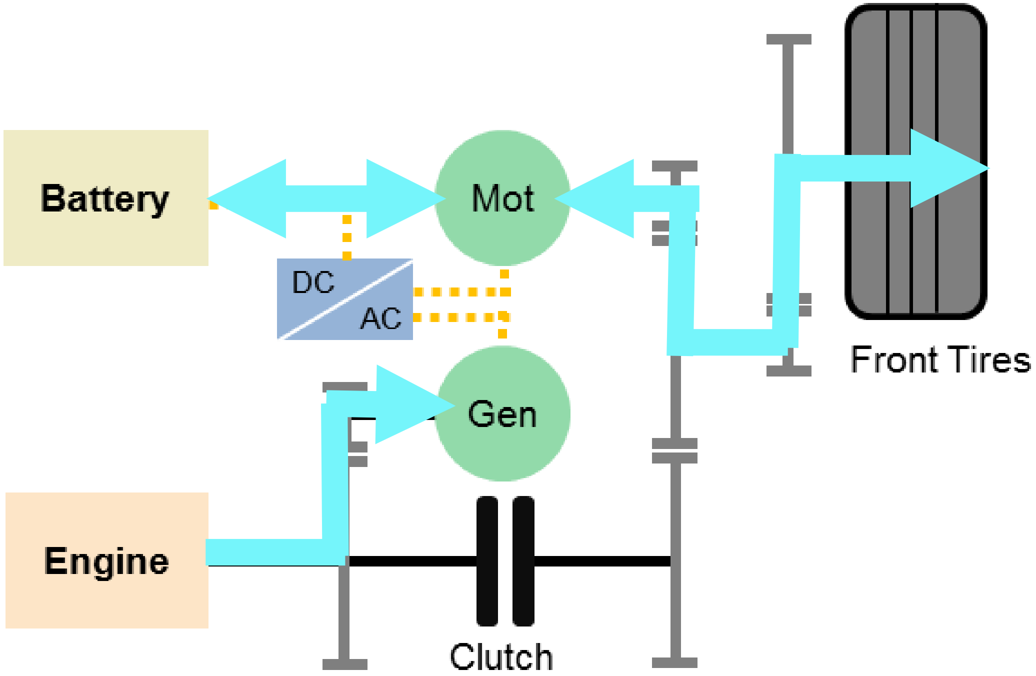
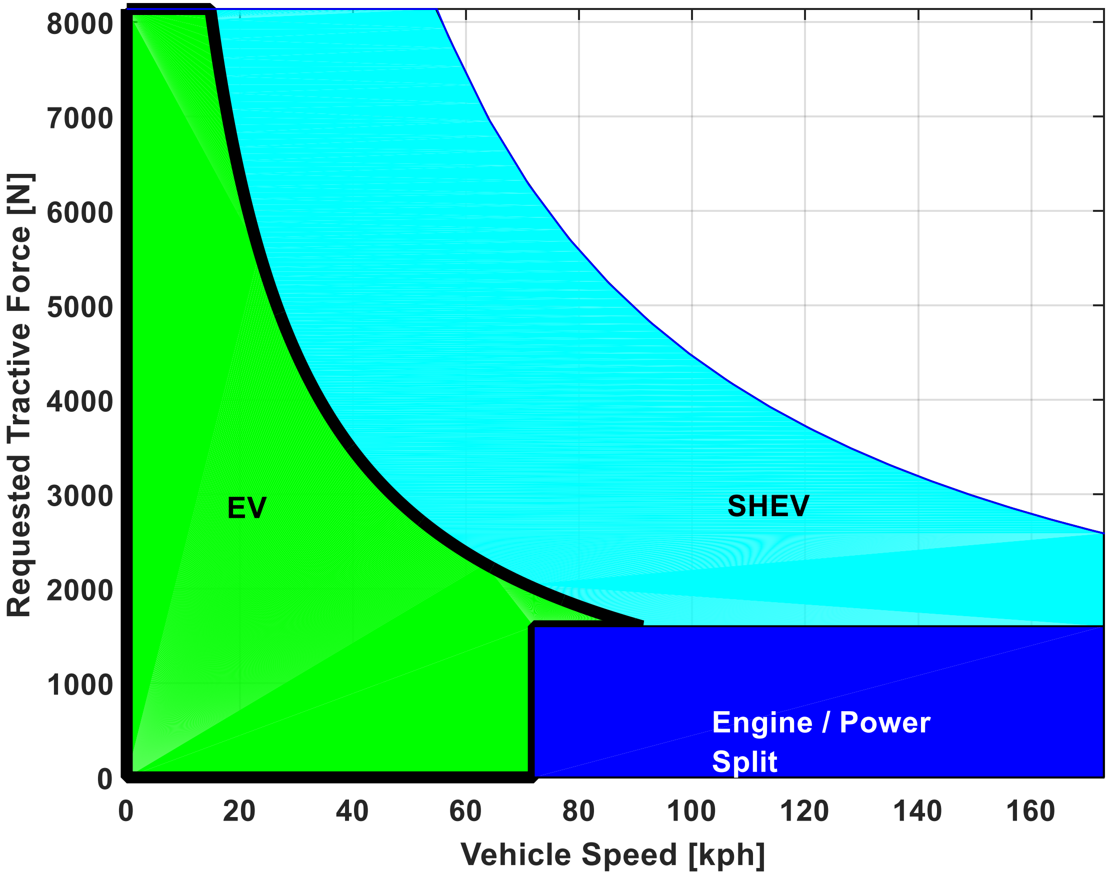



SHEV Mode



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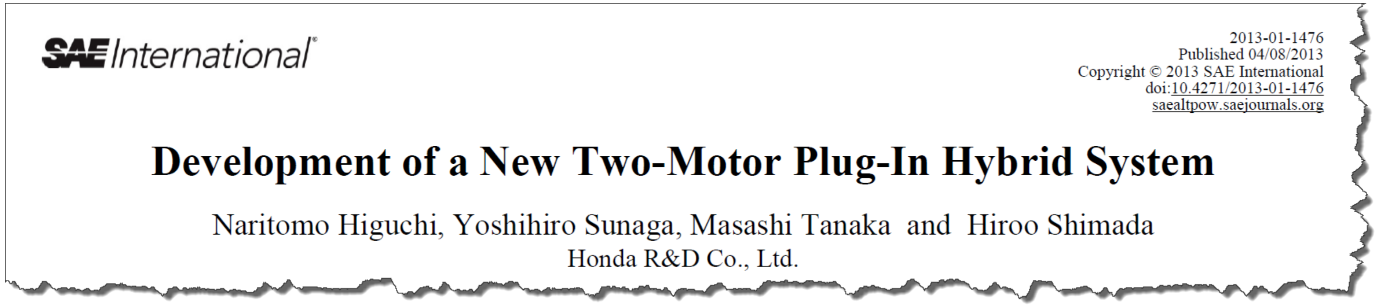
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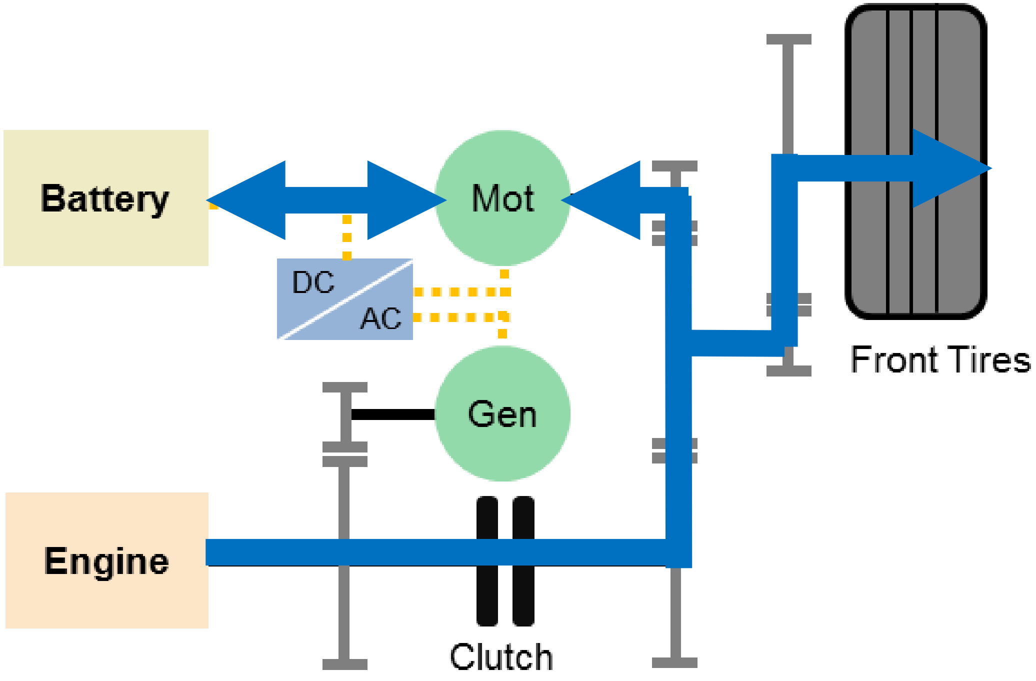
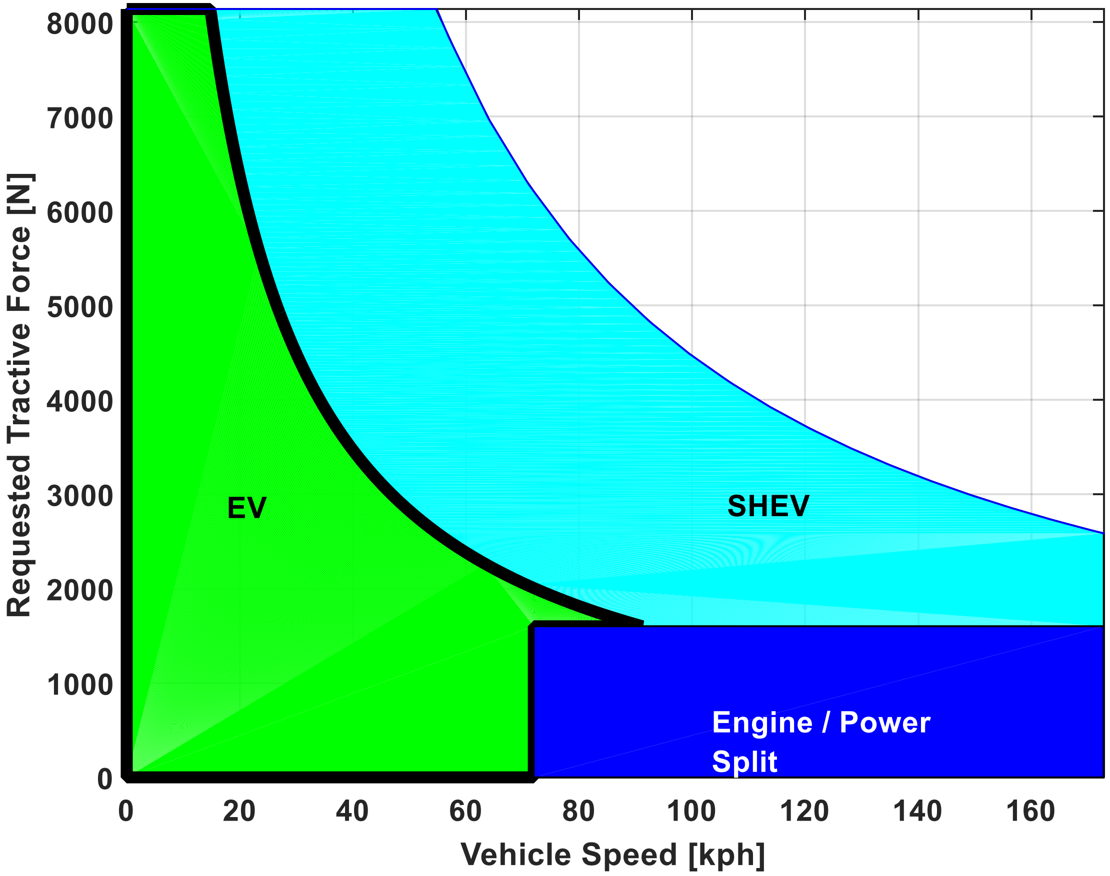
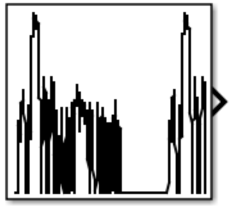


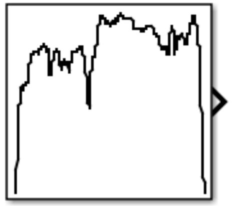

## Engine Mode



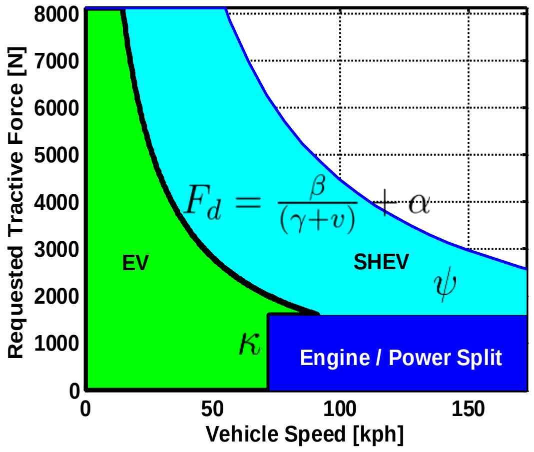
# Design Optimization Problem Statement

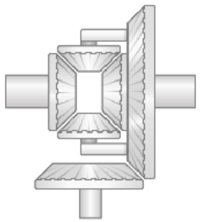
- Maximize MPGe
  - FTP75 and HWFET
  - Weighted MPGe = 0.55(FTP75) + 0.45(HWFET)


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



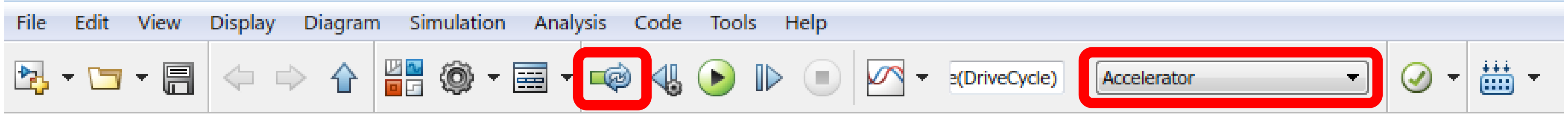


*Differential Ratio*

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

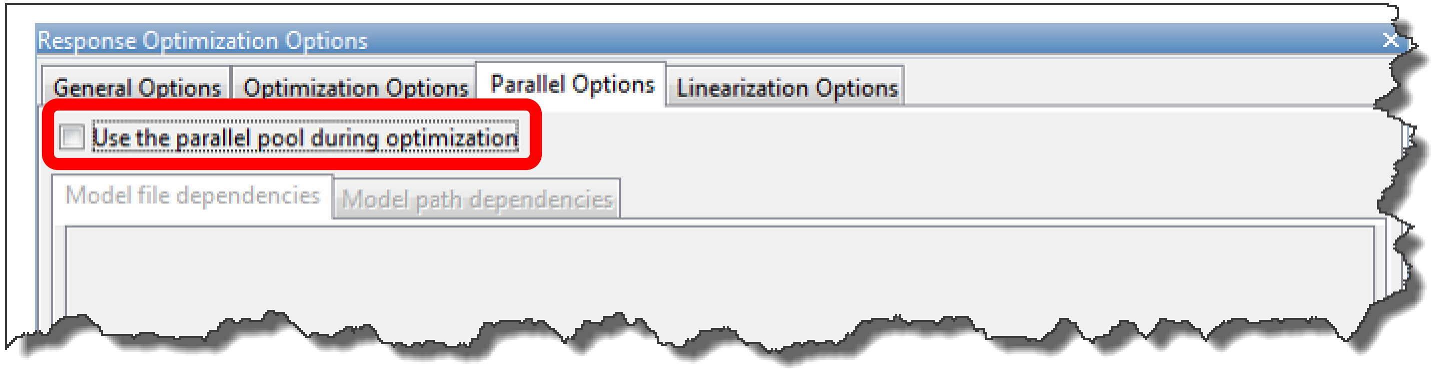

Lenovo ThinkPad T450s
Dual Core i7 2.60GHz
12 GB RAM

# Simulink Design Optimization

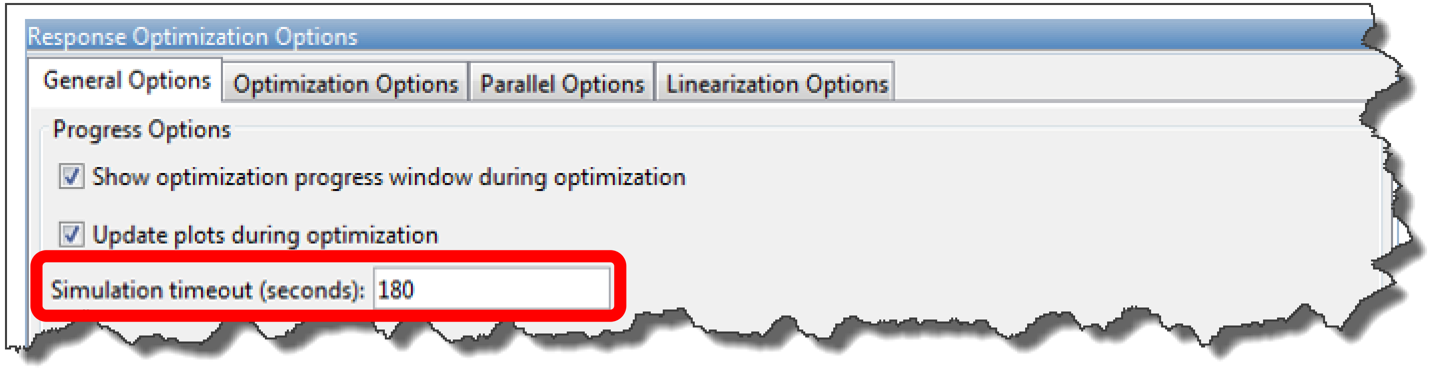
- Speed Up Best practices
  - Accelerator mode
  - Fast Restart




  - Use Parallel Computing Toolbox

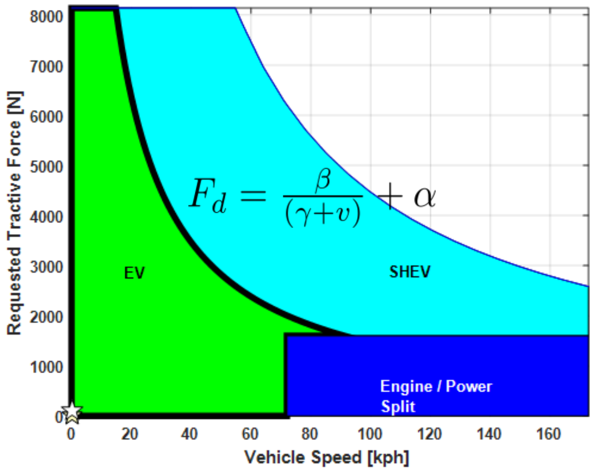


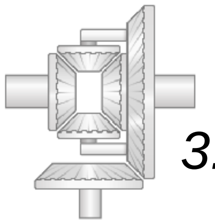

  - Specify Simulation timeout



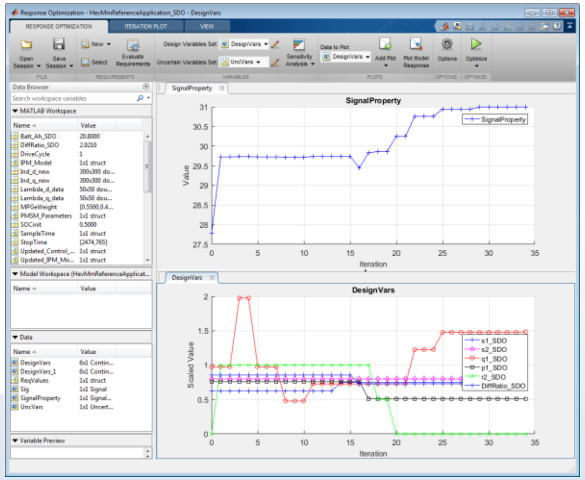
# Optimization Results

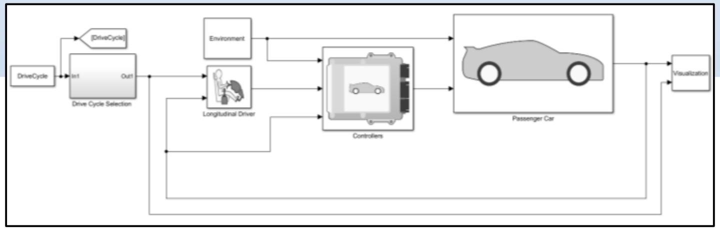
## Simulink Design Optimization → Response Optimization



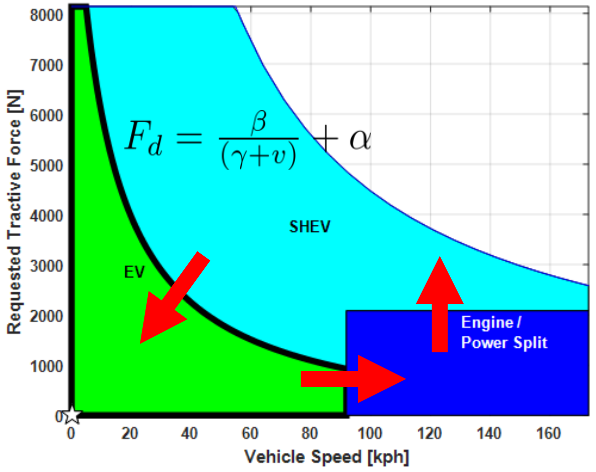
3.42:1

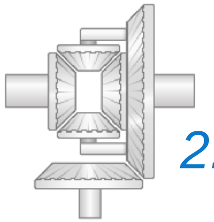



~ 12 Hours

+ 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

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doi:10.4271/2011-01-2451
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

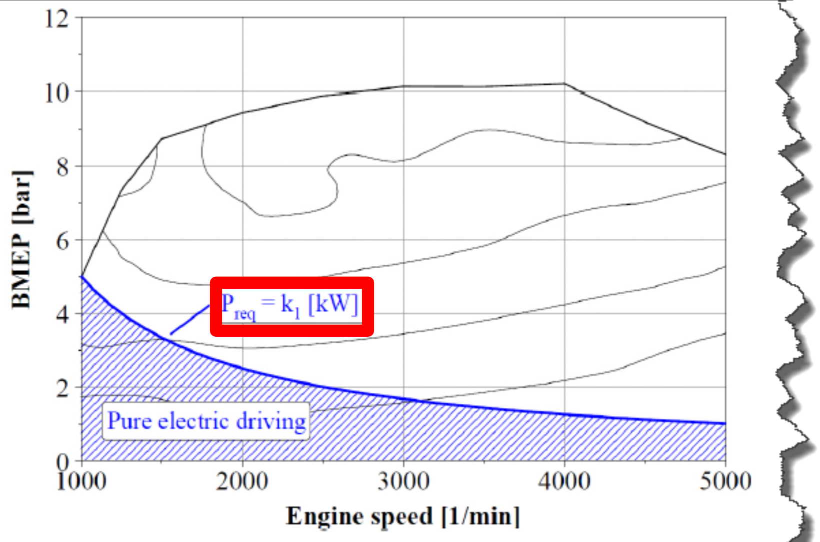
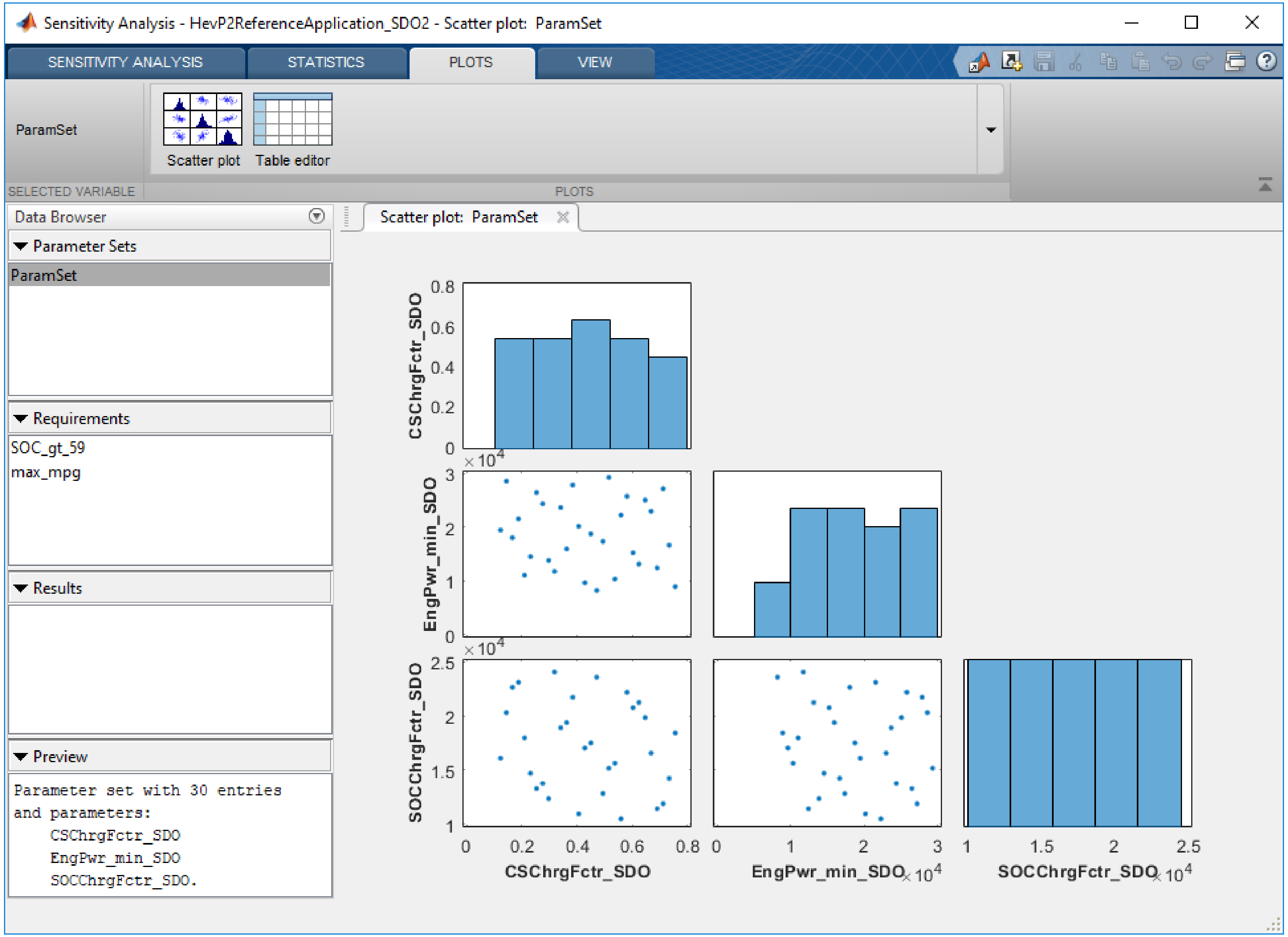



*Figure 5. Hybrid operating strategy: parameter $k_1$*

# Sensitivity Analysis

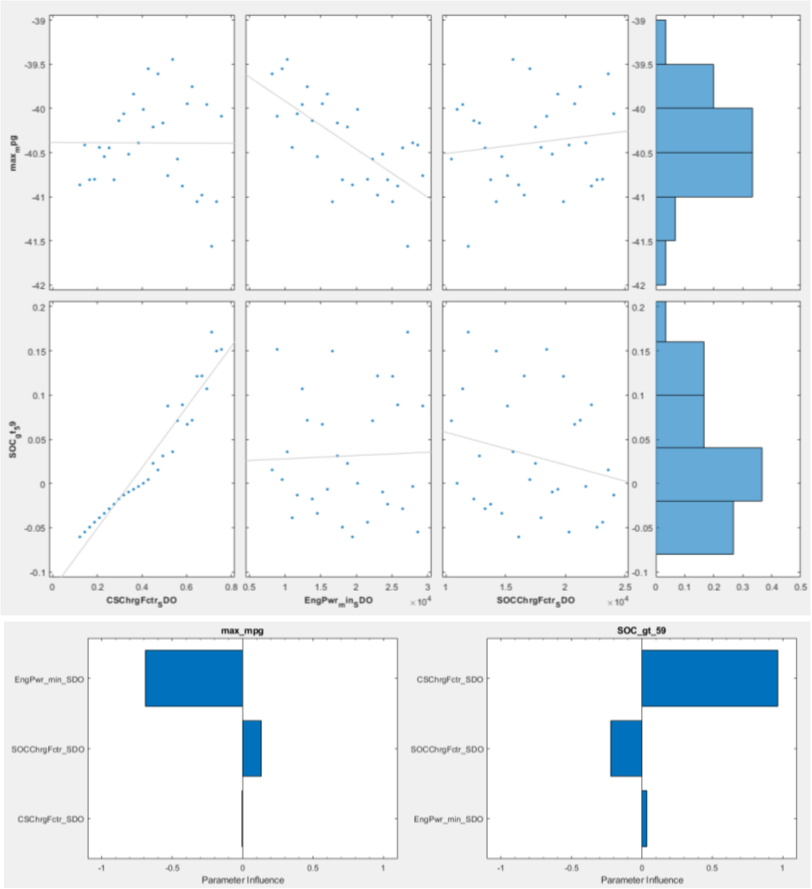
- Determine sensitivity of fuel economy and ability to charge sustain to changes in design parameters

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

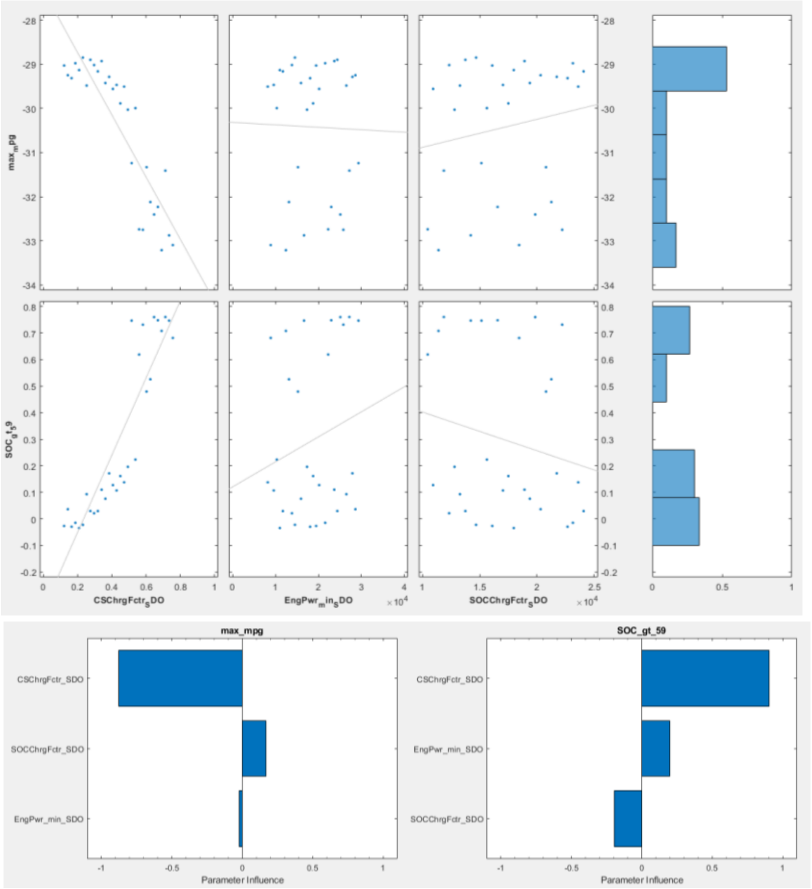


# Sensitivity Analysis – Results

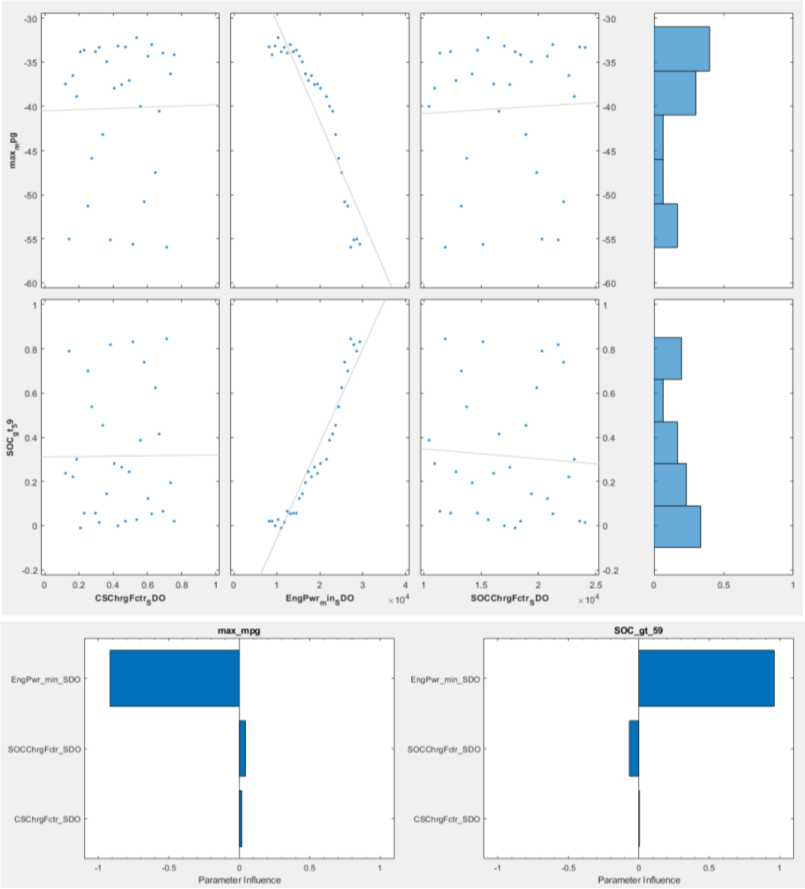
- HWFET




- US06




- FTP72




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

– CS Factor highest correlation for charge sustaining and max mpg

– 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 |

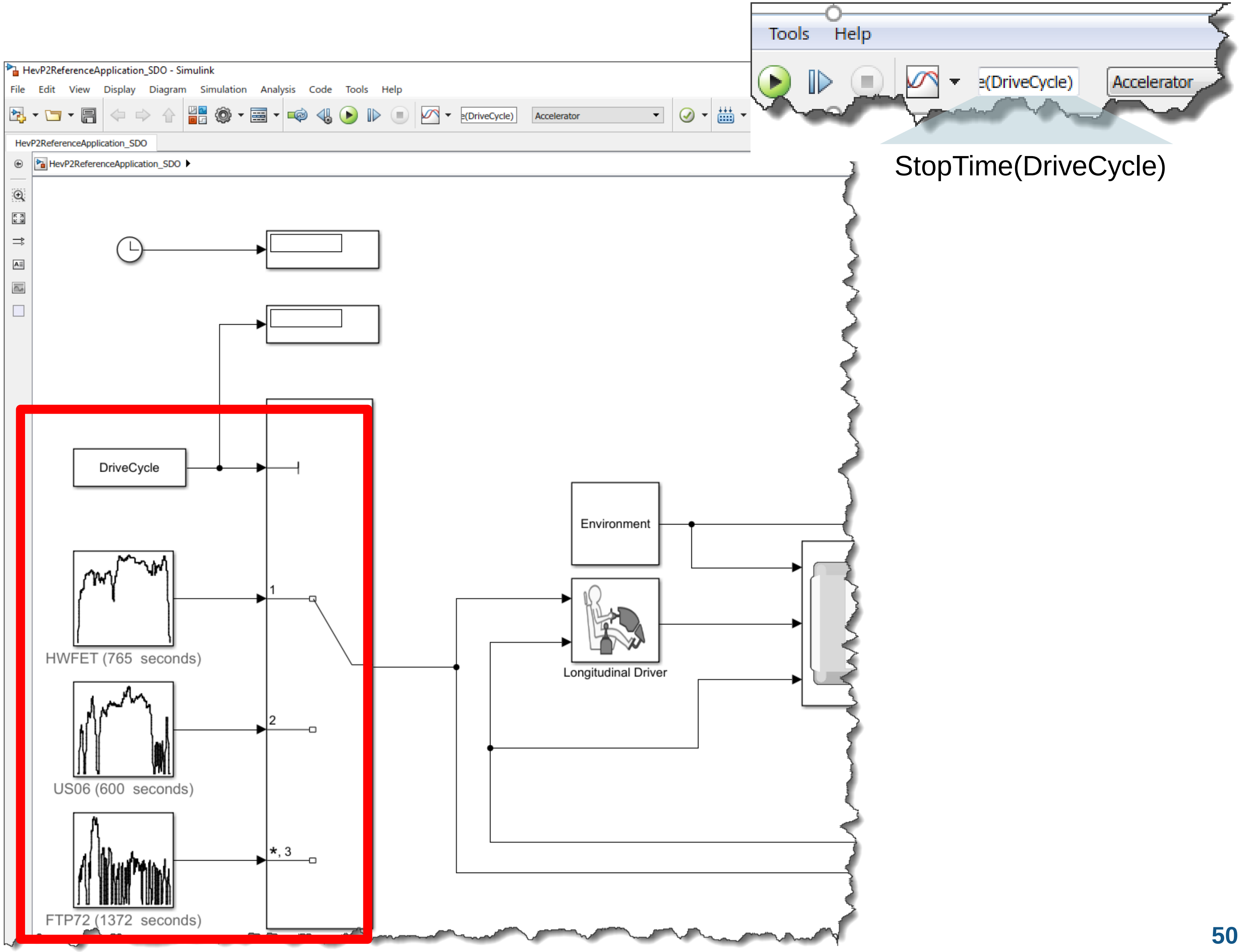
  - Note the variation in the 3 design variables

- 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

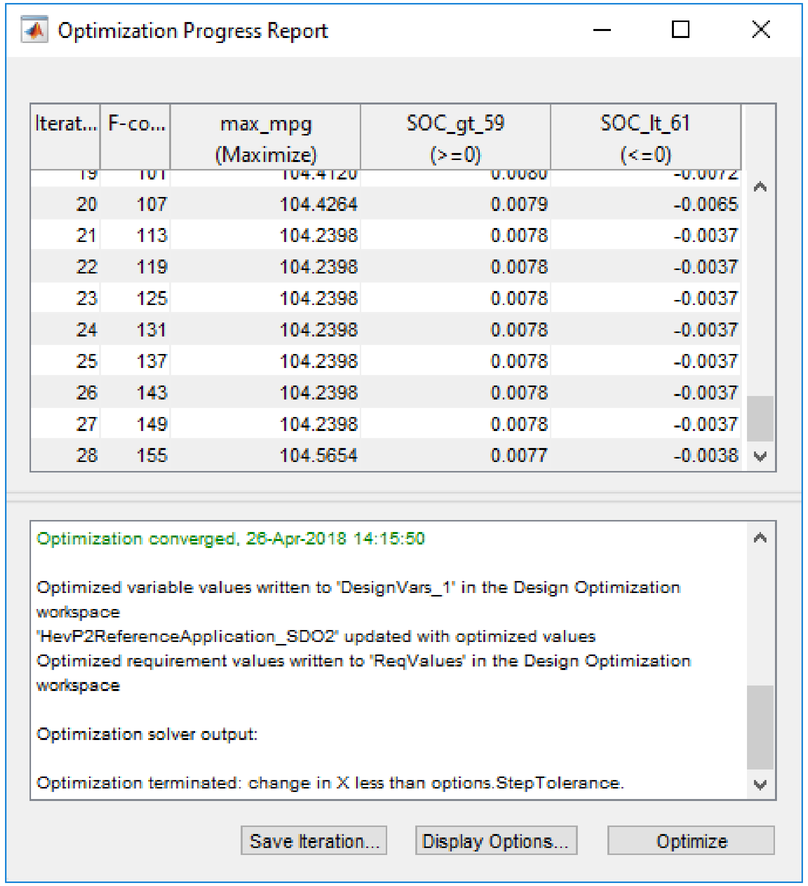
- Find optimal design parameters that satisfy multiple objectives and constraints simultaneously

- 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



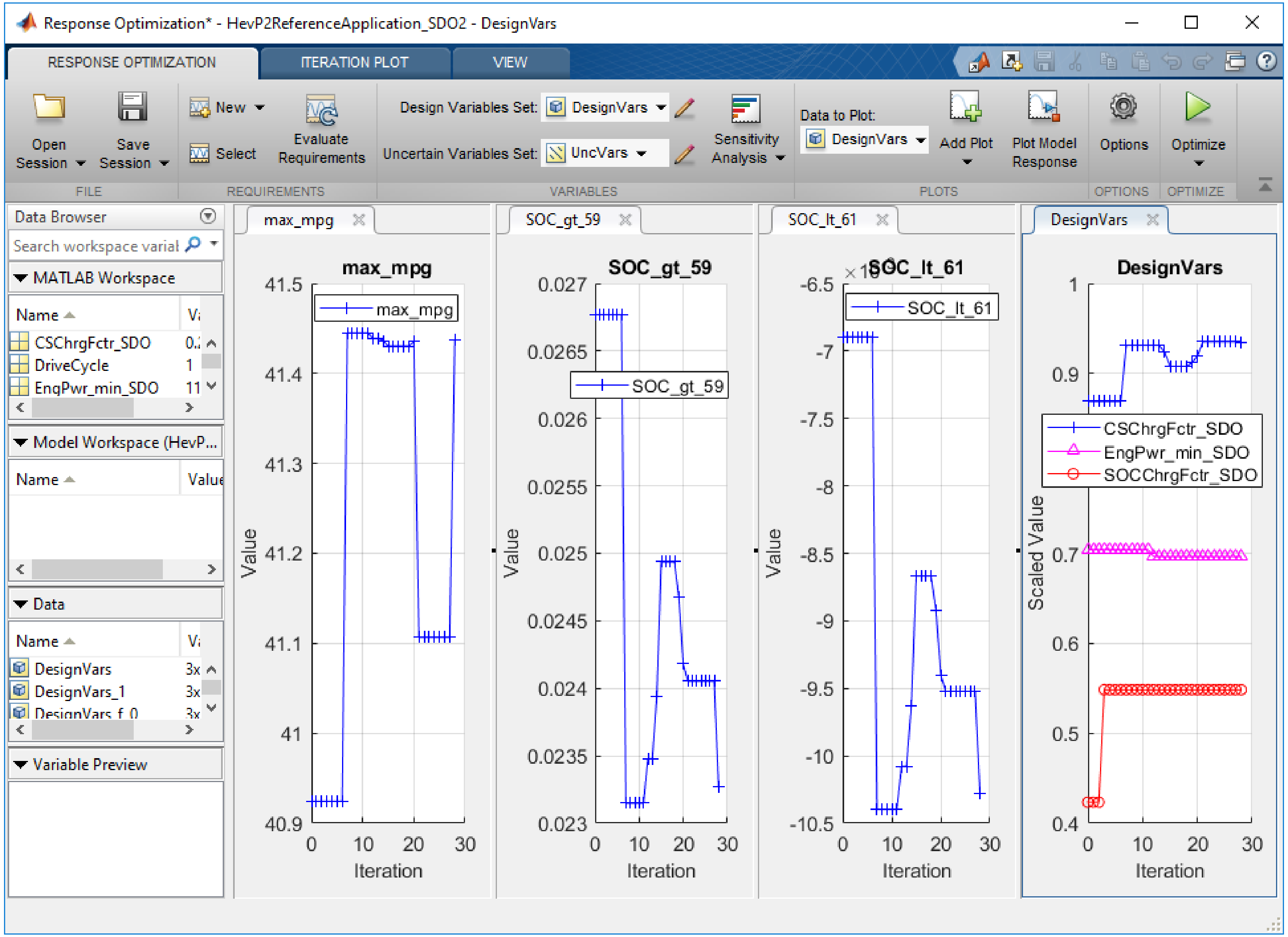
# Response Optimization – Results

1. View Results



| Iterat... | F-co... | max_mpg (Maximize) | SOC_gt_59 (>=0) | SOC_lt_61 (<=0) |
|---|---|---|---|---|
| 19 | 101 | 104.4120 | 0.0080 | -0.0072 |
| 20 | 107 | 104.4264 | 0.0079 | -0.0065 |
| 21 | 113 | 104.2398 | 0.0078 | -0.0037 |
| 22 | 119 | 104.2398 | 0.0078 | -0.0037 |
| 23 | 125 | 104.2398 | 0.0078 | -0.0037 |
| 24 | 131 | 104.2398 | 0.0078 | -0.0037 |
| 25 | 137 | 104.2398 | 0.0078 | -0.0037 |
| 26 | 143 | 104.2398 | 0.0078 | -0.0037 |
| 27 | 149 | 104.2398 | 0.0078 | -0.0037 |
| 28 | 155 | 104.5654 | 0.0077 | -0.0038 |





# SDO – Response Optimization

- Summary

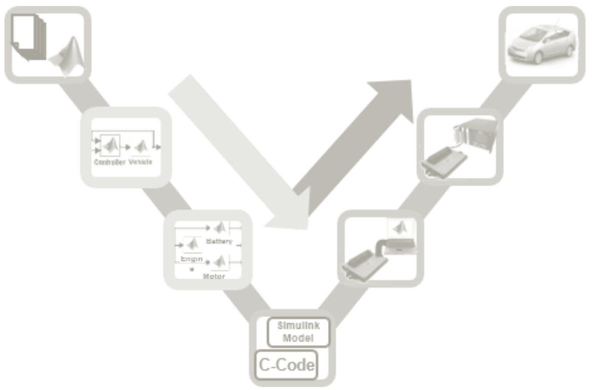
| Sensitivity Analysis | | | | | |
|---|---|---|---|---|---|
| | Charge Sustaining Factor | minimum Engine Power | SOC Factor | mpg | delta SOC (%) |
| HWFET | 0.1219 | 19453 | 16094 | 40.87 | 2.56 |
| US06 | 0.1656 | 18047 | 22656 | 29.31 | 0.76 |
| FTP72 | 0.2094 | 11016 | 17969 | 33.82 | -0.39 |

| 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 |

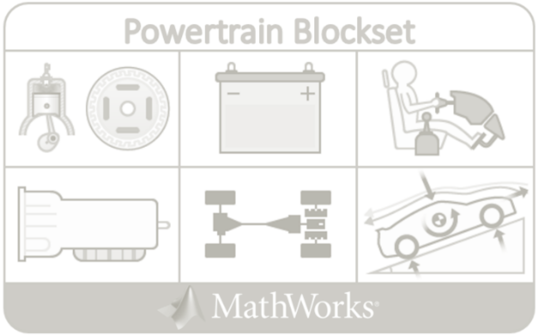
- ***Found single set of design variables to maximize mpg and charge sustain!***

# Key Points

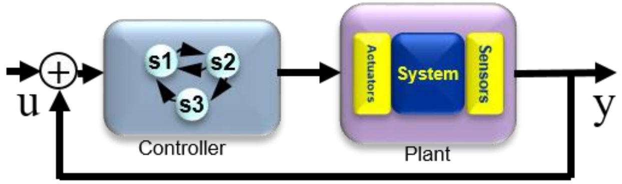
- Efficient plant modeling enables Model-Based Design (MBD)




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




- Design / optimize plant and controls together as a system



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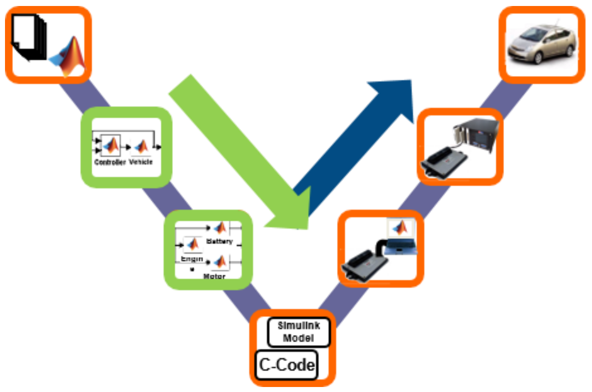


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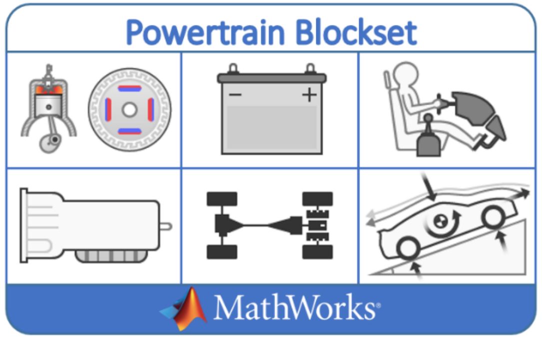


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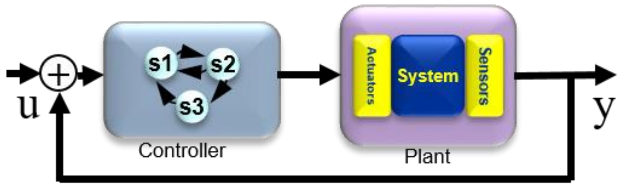

# Thank You