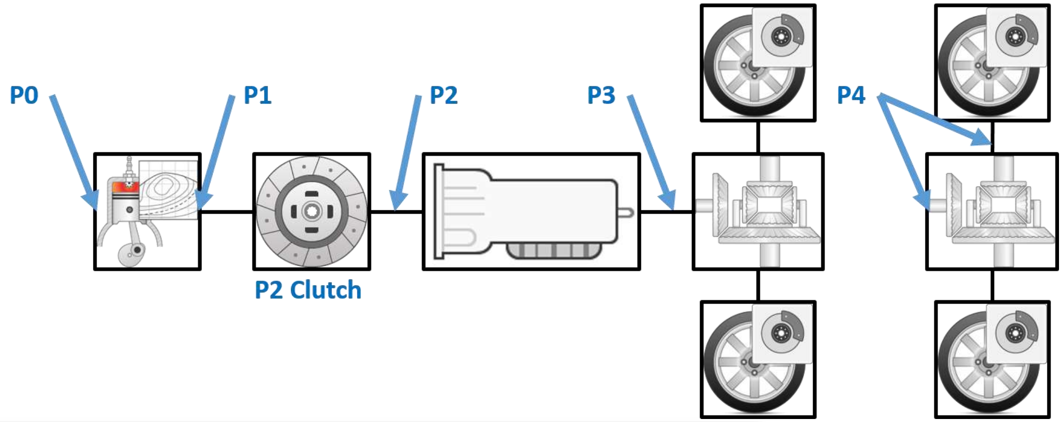
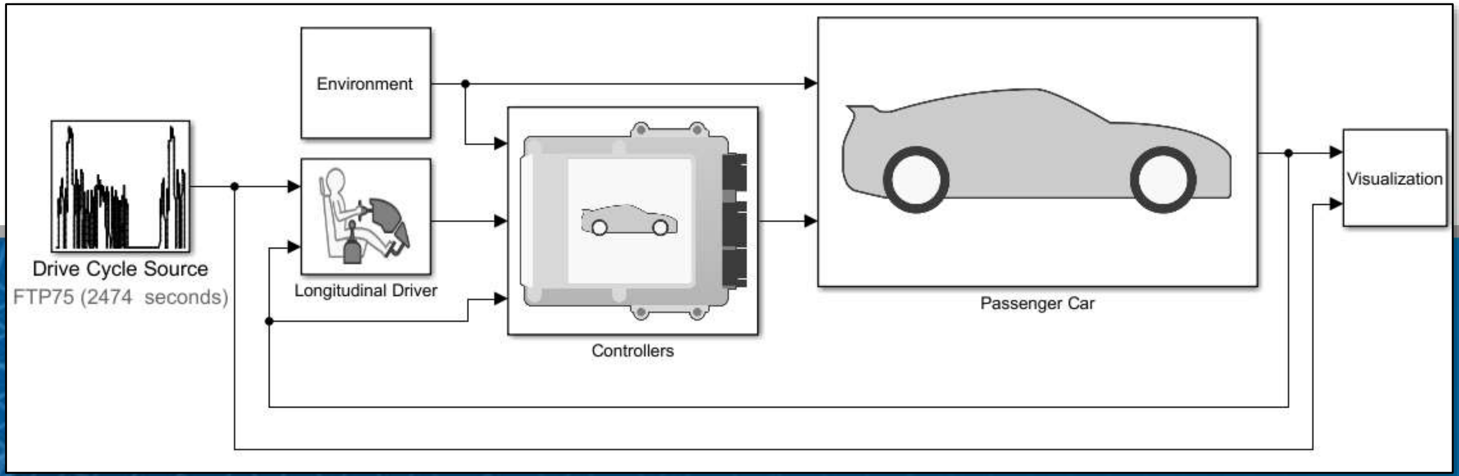
# Full Vehicle Simulation for Electrified Powertrain Selection




MathWorks Automotive Conference

April 30, 2019



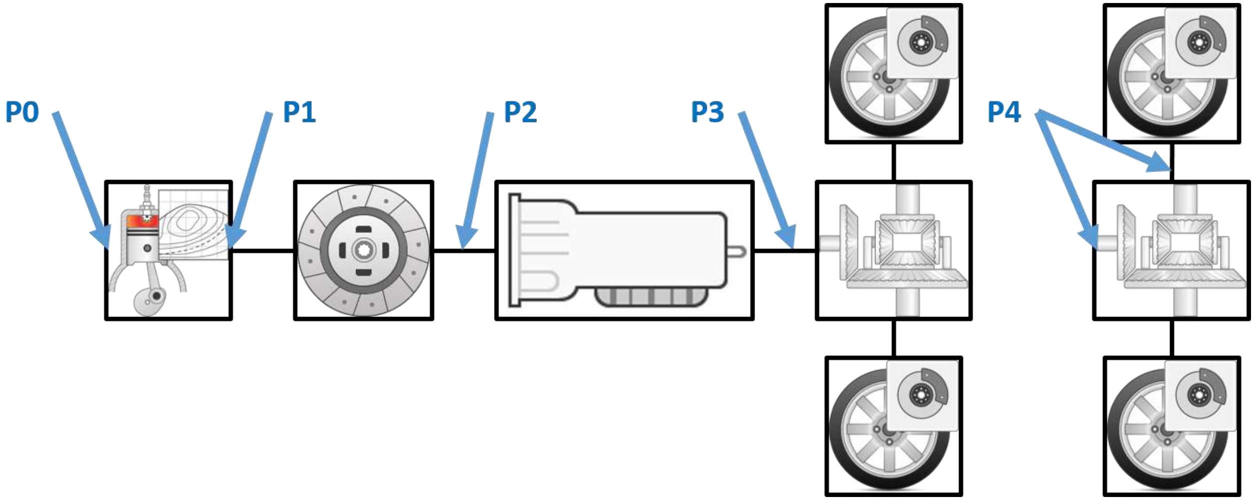


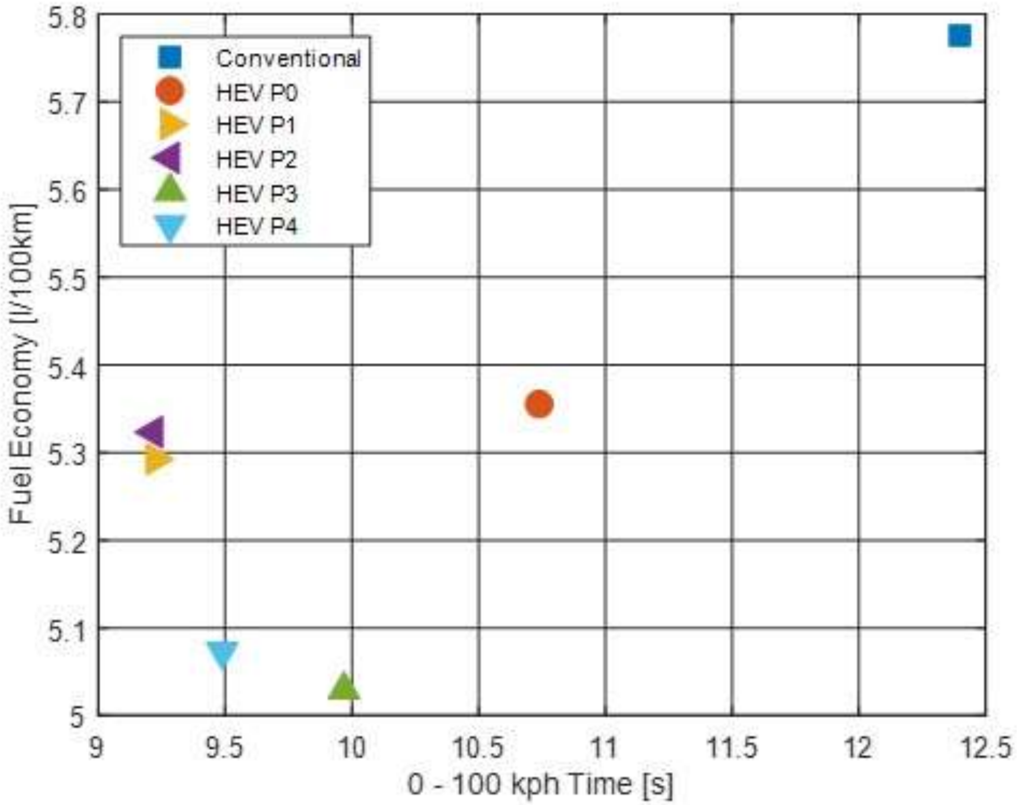
Mike Sasena, Product Manager

Kevin Oshiro, Application Engineering

# 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”?

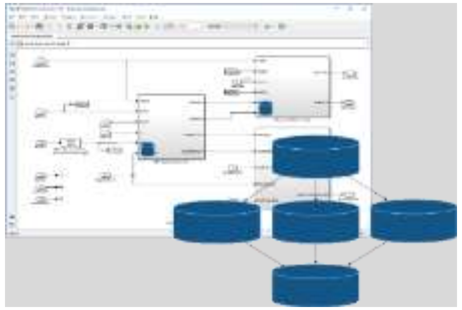
- Plant model + closed-loop control algorithms
  – Production code out of scope for today’s presentation (OBD, timing, etc.)

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

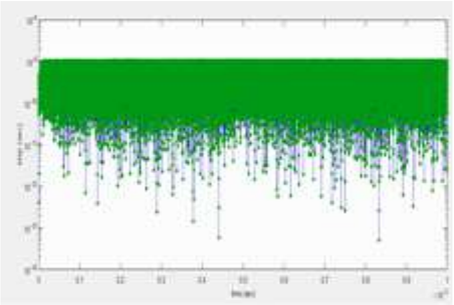
- Heterogeneous modeling environment
  – Support for inclusion of 3rd party simulation tools (S-function, FMU, …)

# Simulink as a Simulation Integration Platform

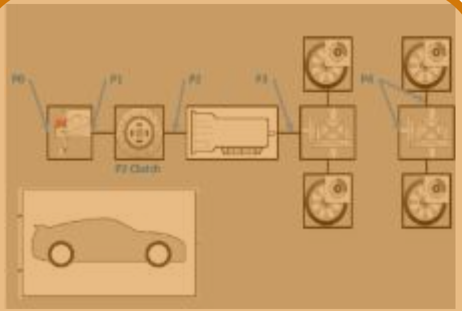
**Focus of this talk**



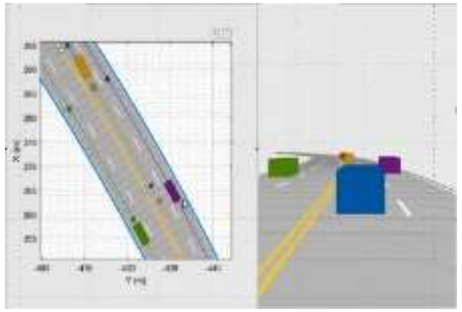
**Data Management**



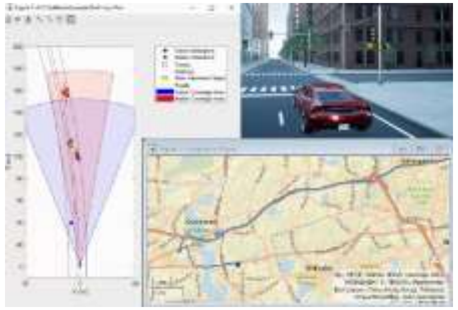
**Solver Technology**



**Vehicle Configuration**



**Multi-actor Scenarios**



**Visualization**

MODELICA

GT

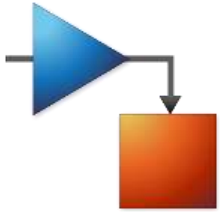
Delft-Tyre

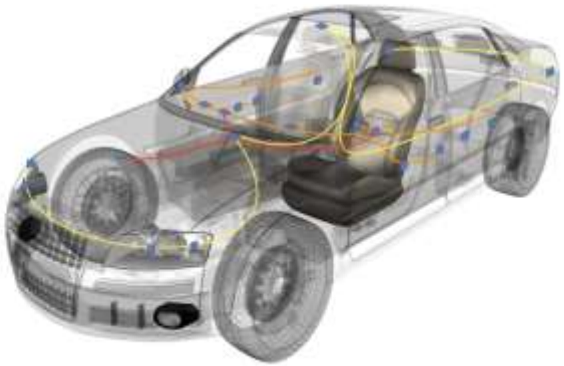
C++

fmi


IPG AUTOMOTIVE


# 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?

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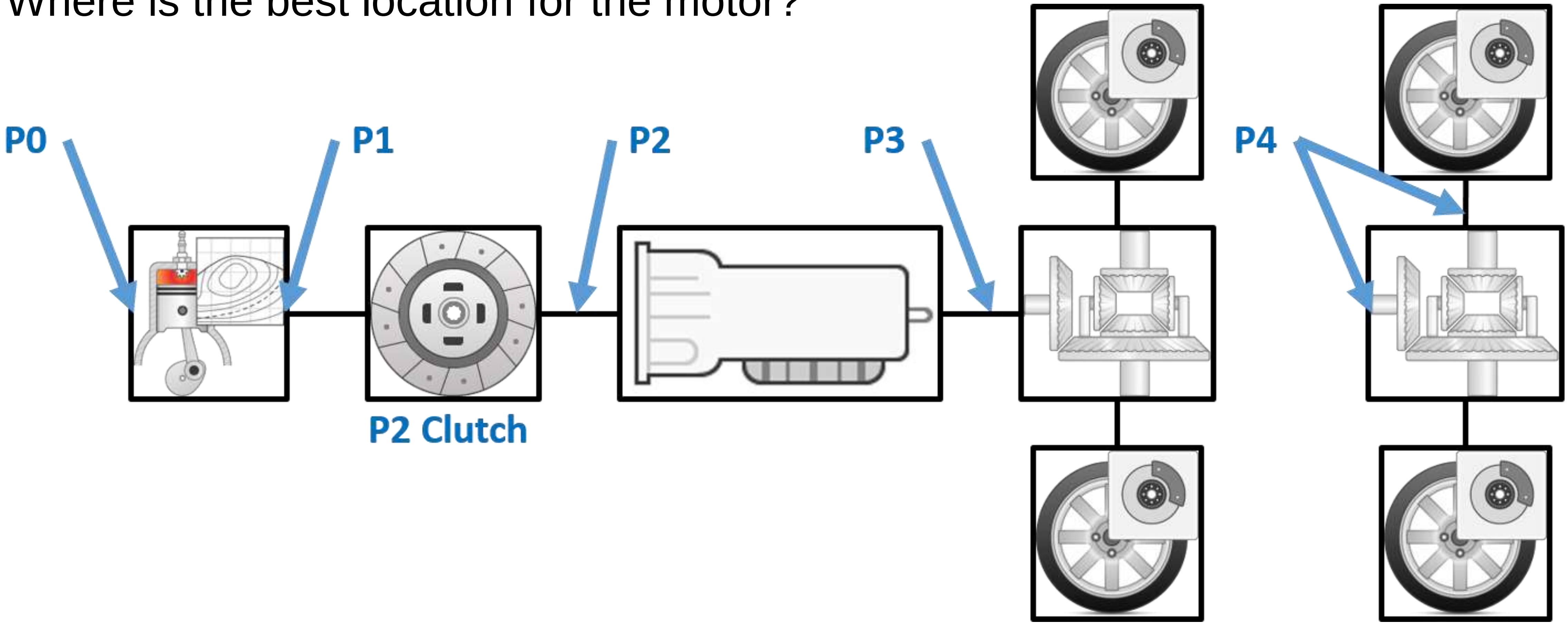
# Electrified Powertrain Selection

- 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 ($t_{0\text{-}60mph}$)

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

# Agenda

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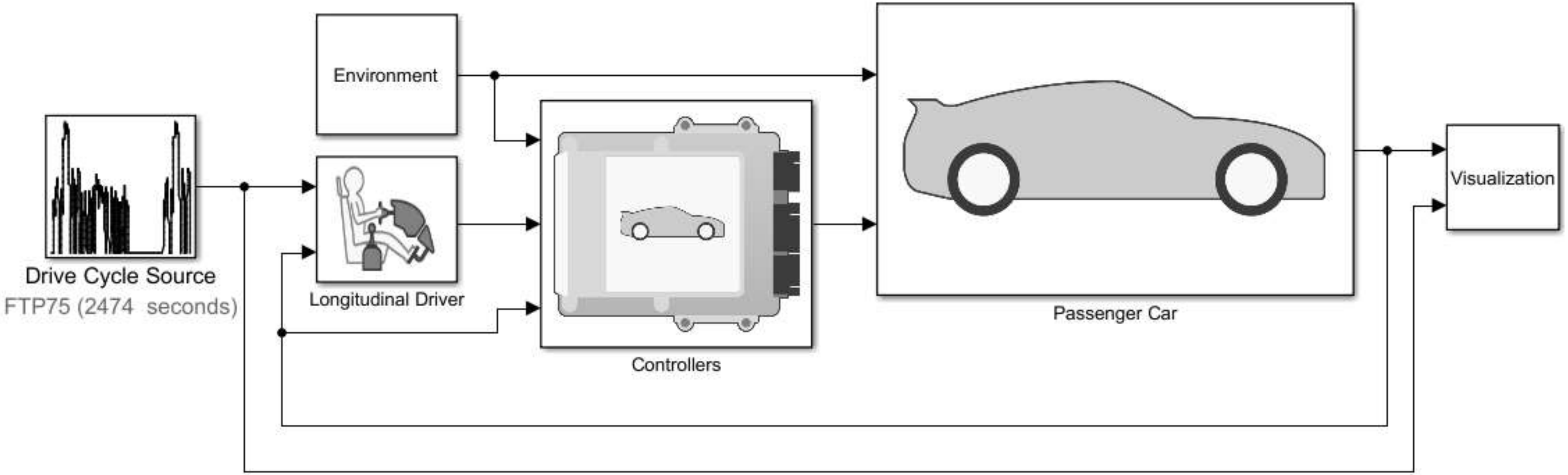
# Powertrain Blockset

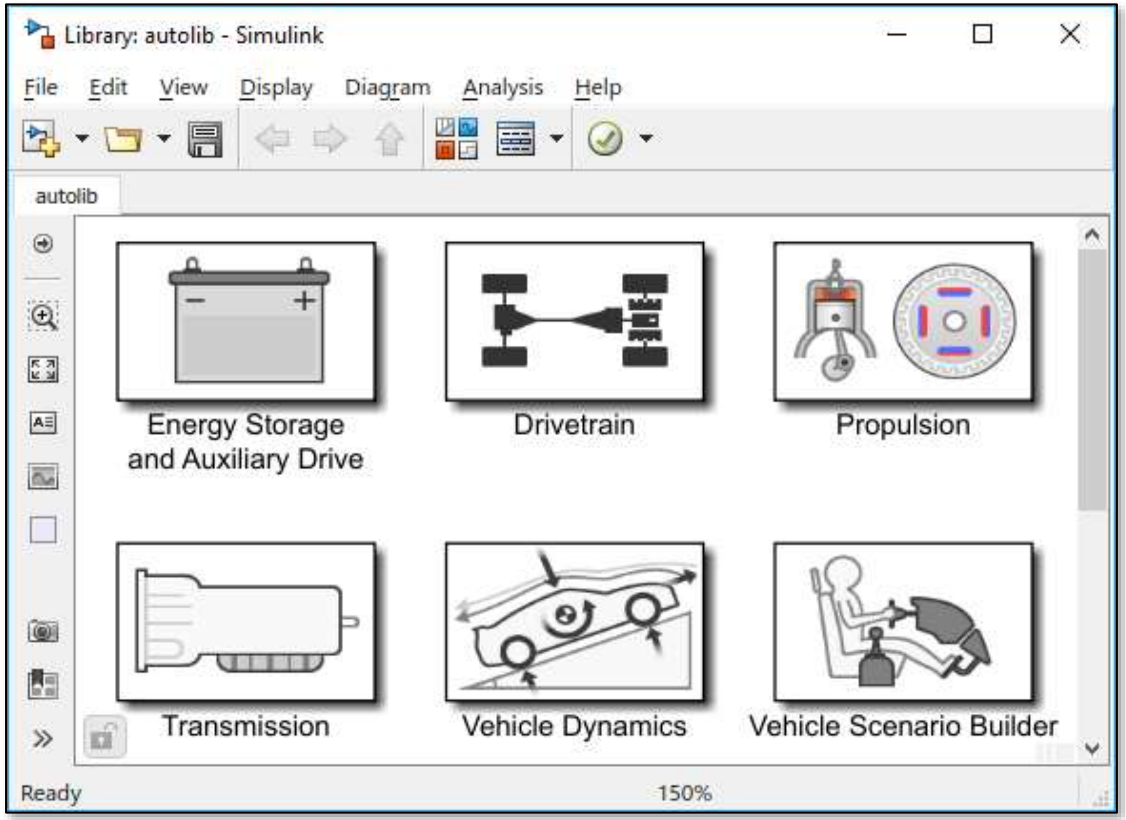
- Goals:
  - Provide starting point for engineers to build **good plant / controller models**
  - Provide **open** and documented models
  - Provide very **fast**-running models that work with popular HIL systems



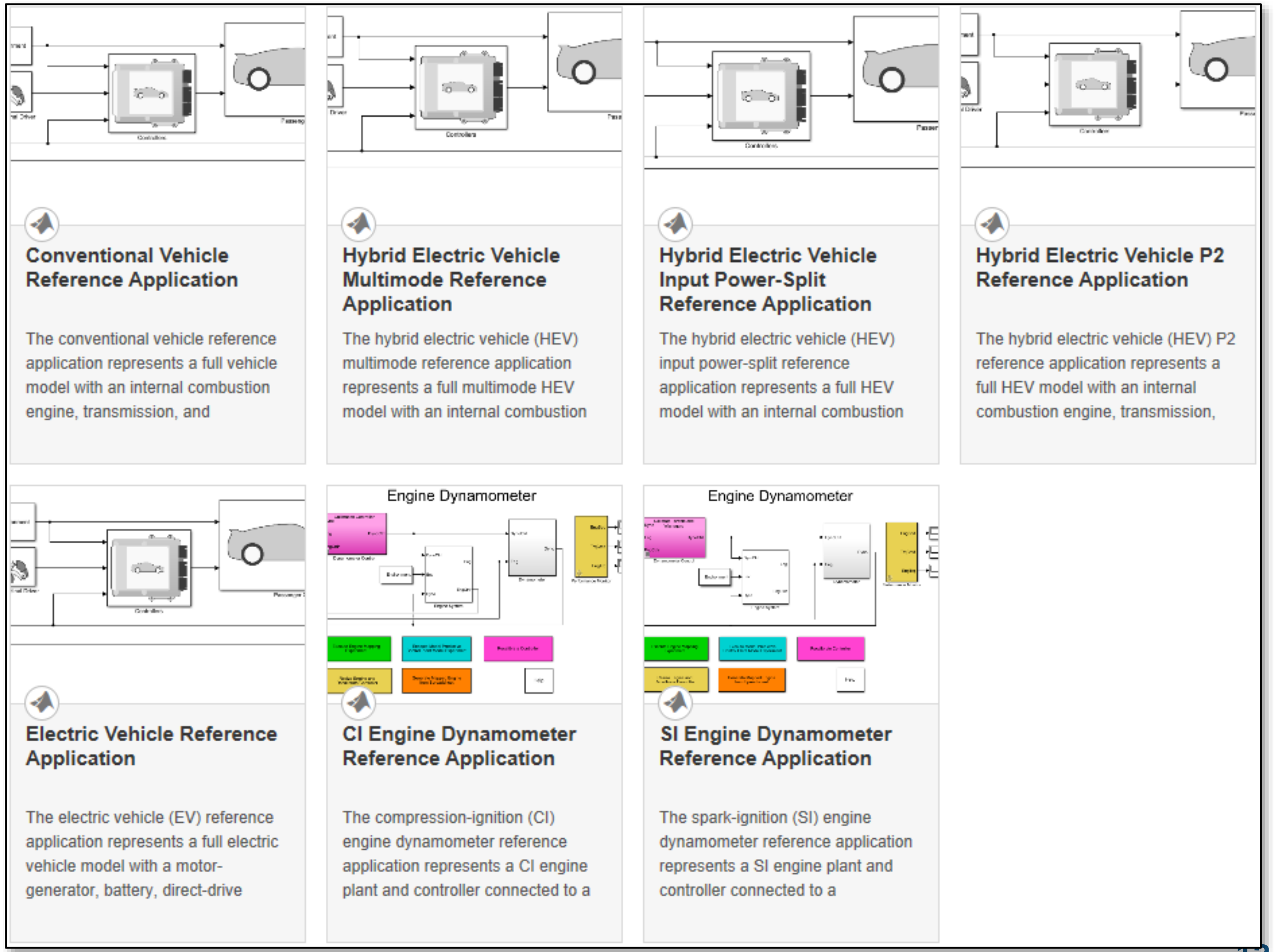

***Lower the barrier to entry for Model-Based Design***

# Powertrain Blockset Features

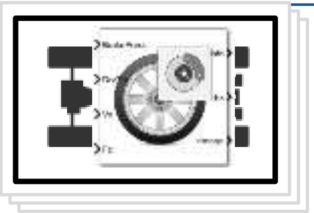
## Library of blocks



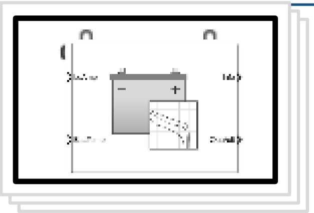

## Pre-built reference applications



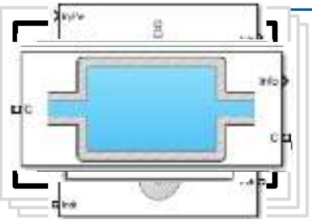
MathWorks



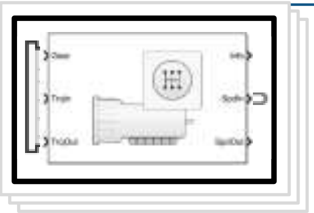
Drivetrain



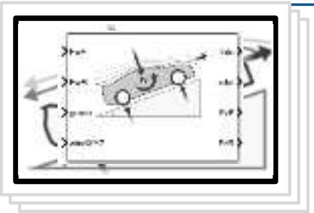
Energy Storage and Auxiliary Drive



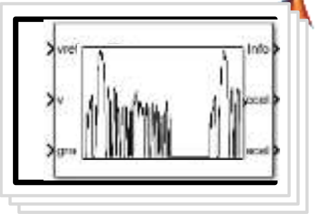
Propulsion



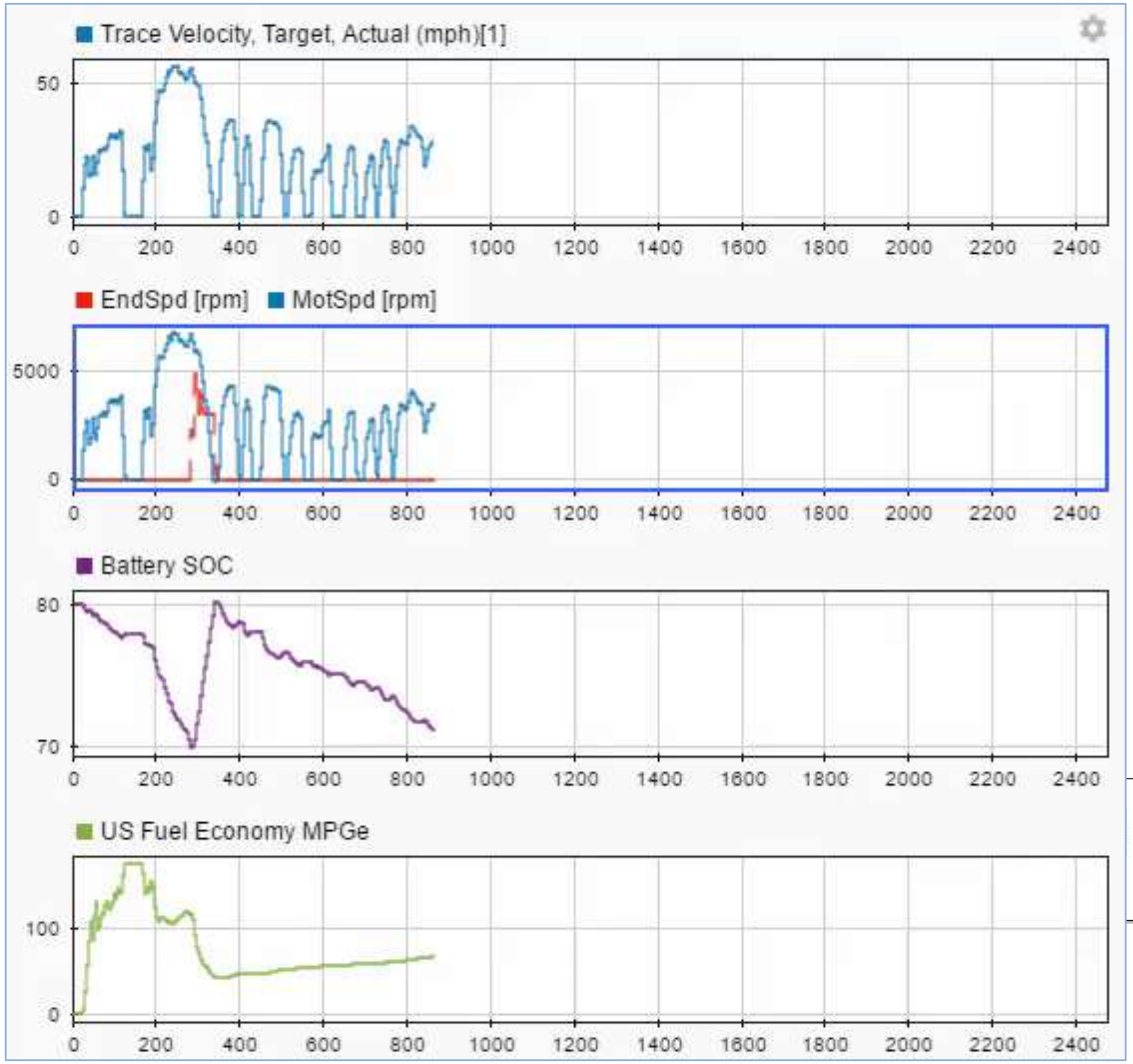
Transmission

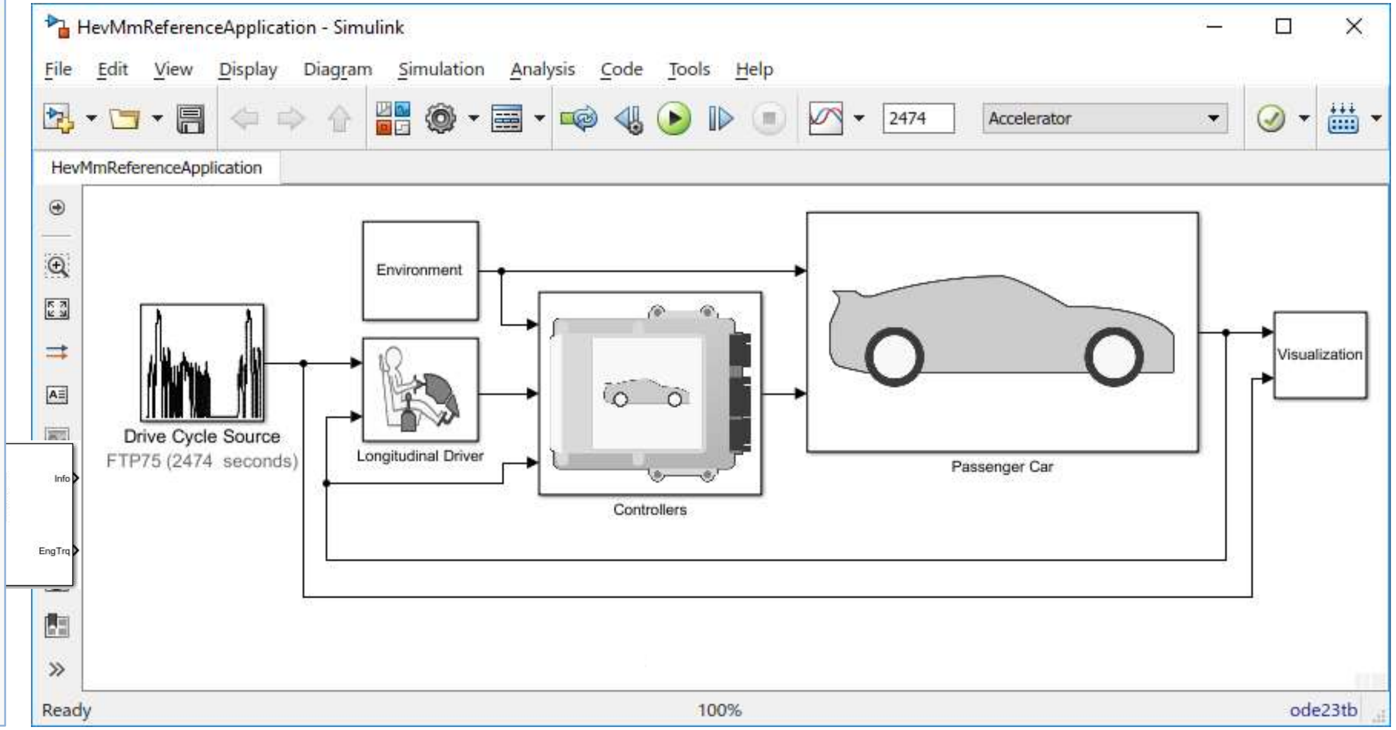


Vehicle Dynamics



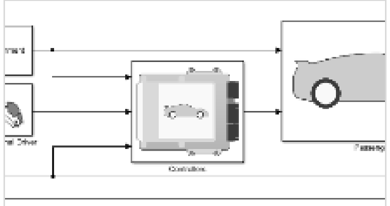
Vehicle Scenario Builder



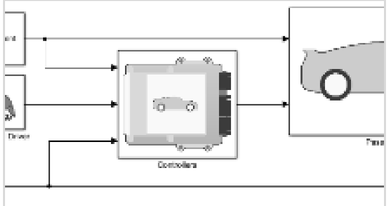
# Reference Applications

## Full Vehicle Models



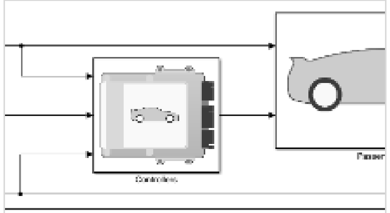
**Conventional Vehicle Reference Application**

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



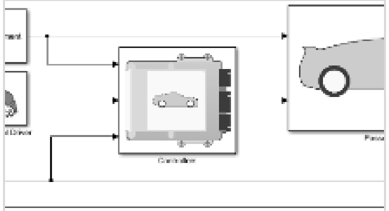
**Hybrid Electric Vehicle Multimode Reference Application**

The hybrid electric vehicle (HEV) multimode reference application represents a full multimode HEV model with an internal combustion



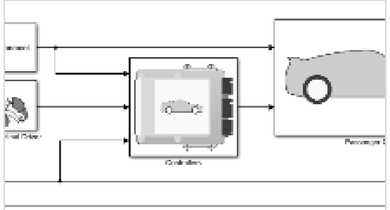
**Hybrid Electric Vehicle Input Power-Split Reference Application**

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**

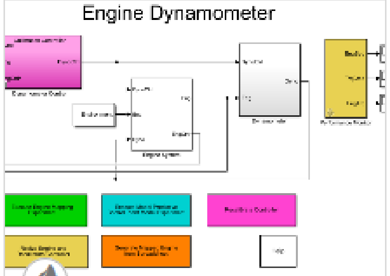
The hybrid electric vehicle (HEV) P2 reference application represents a full HEV model with an internal combustion engine, transmission,



**Electric Vehicle Reference Application**

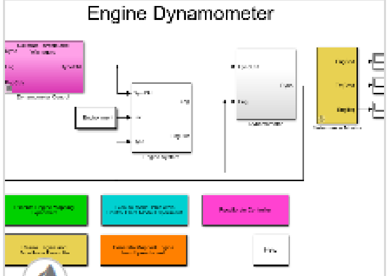
The electric vehicle (EV) reference application represents a full electric vehicle model with a motor-generator, battery, direct-drive

## 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

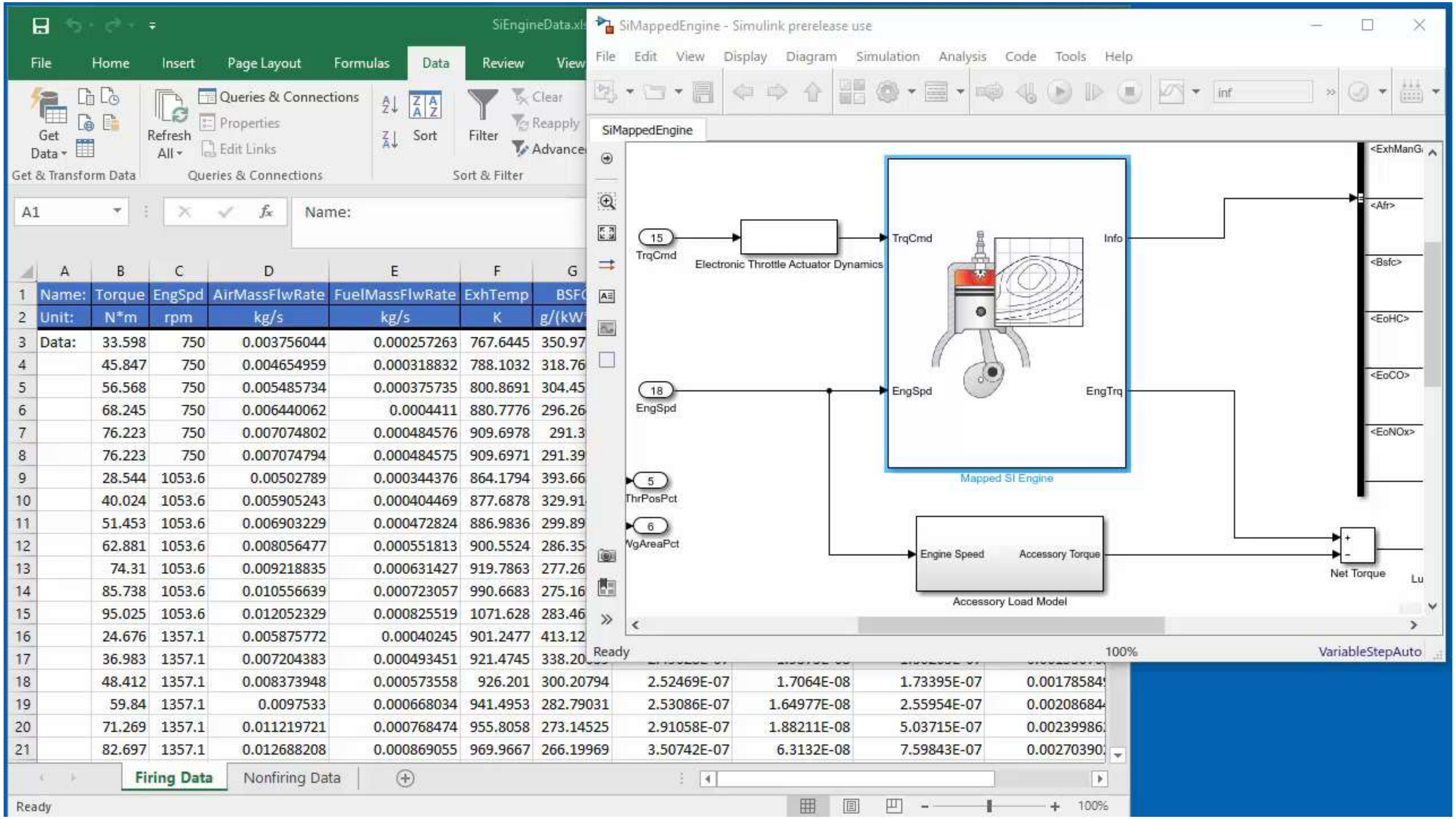



**SI Engine Dynamometer Reference Application**

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



| | A | B | C | D | E | F | G | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Name: | Torque | EngSpd | AirMassFlwRate | FuelMassFlwRate | ExhTemp | BSFC | | | | |
| 2 | Unit: | N*m | rpm | kg/s | kg/s | K | g/(kW | | | | |
| 3 | Data: | 33.598 | 750 | 0.003756044 | 0.000257263 | 767.6445 | 350.97 | | | | |
| 4 | | 45.847 | 750 | 0.004654959 | 0.000318832 | 788.1032 | 318.76 | | | | |
| 5 | | 56.568 | 750 | 0.005485734 | 0.000375735 | 800.8691 | 304.45 | | | | |
| 6 | | 68.245 | 750 | 0.006440062 | 0.0004411 | 880.7776 | 296.26 | | | | |
| 7 | | 76.223 | 750 | 0.007074802 | 0.000484576 | 909.6978 | 291.3 | | | | |
| 8 | | 76.223 | 750 | 0.007074794 | 0.000484575 | 909.6971 | 291.39 | | | | |
| 9 | | 28.544 | 1053.6 | 0.00502789 | 0.000344376 | 864.1794 | 393.66 | | | | |
| 10 | | 40.024 | 1053.6 | 0.005905243 | 0.000404469 | 877.6878 | 329.91 | | | | |
| 11 | | 51.453 | 1053.6 | 0.006903229 | 0.000472824 | 886.9836 | 299.89 | | | | |
| 12 | | 62.881 | 1053.6 | 0.008056477 | 0.000551813 | 900.5524 | 286.35 | | | | |
| 13 | | 74.31 | 1053.6 | 0.009218835 | 0.000631427 | 919.7863 | 277.26 | | | | |
| 14 | | 85.738 | 1053.6 | 0.010556639 | 0.000723057 | 990.6683 | 275.16 | | | | |
| 15 | | 95.025 | 1053.6 | 0.012052329 | 0.000825519 | 1071.628 | 283.46 | | | | |
| 16 | | 24.676 | 1357.1 | 0.005875772 | 0.00040245 | 901.2477 | 413.12 | | | | |
| 17 | | 36.983 | 1357.1 | 0.007204383 | 0.000493451 | 921.4745 | 338.20 | | | | |
| 18 | | 48.412 | 1357.1 | 0.008373948 | 0.000573558 | 926.201 | 300.20794 | 2.52469E-07 | 1.7064E-08 | 1.73395E-07 | 0.00178584 |
| 19 | | 59.84 | 1357.1 | 0.0097533 | 0.000668034 | 941.4953 | 282.79031 | 2.53086E-07 | 1.64977E-08 | 2.55954E-07 | 0.00208684 |
| 20 | | 71.269 | 1357.1 | 0.011219721 | 0.000768474 | 955.8058 | 273.14525 | 2.91058E-07 | 1.88211E-08 | 5.03715E-07 | 0.00239986 |
| 21 | | 82.697 | 1357.1 | 0.012688208 | 0.000869055 | 969.9667 | 266.19969 | 3.50742E-07 | 6.3132E-08 | 7.59843E-07 | 0.00270390 |

# What's New in R2019a ?

## Energy Accounting and Reporting

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

Live Editor - GenerateEnergyReport.mlx | Project - HEVIPS

### Run Simulation

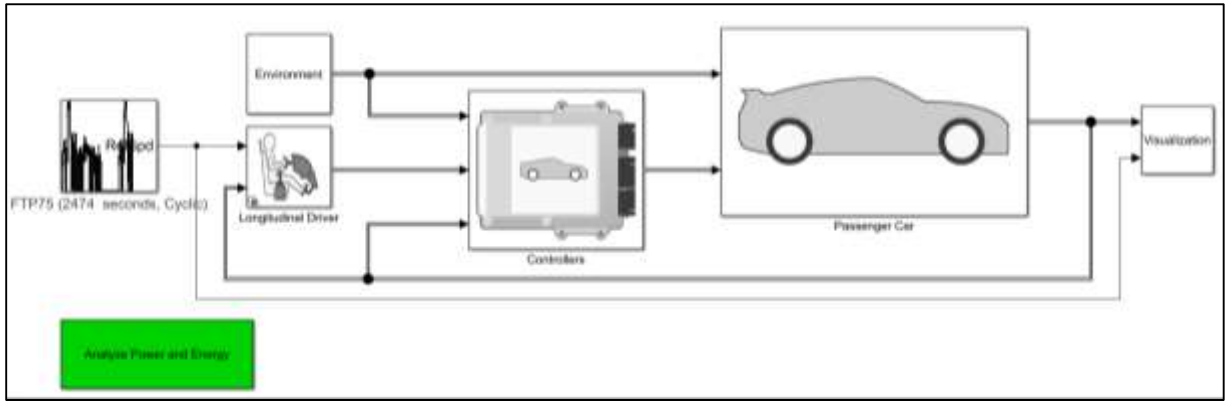
Click **Run** to create an `autoblks.pwr.PlantInfo` object that analyzes the model energy consumption. Use the `PwrUnits` and `EnrgyUnits` properties to set the units.

After you run the simulation, the live script provides the energy summary. You can use the results to analyze energy and power losses at the component and system level. For more information, see Explore the Hybrid Electric Vehicle Input Power-Split Reference Application.

```
SysName = 'HevIpsReferenceApplication';
VehPwrAnalysis = autoblks.pwr.PlantInfo(SysName);
VehPwrAnalysis.PwrUnits = 'kW';
VehPwrAnalysis.EnrgyUnits = 'MJ';
```

Use `run` method to turn on logging, run simulation, and add logged data to the object.

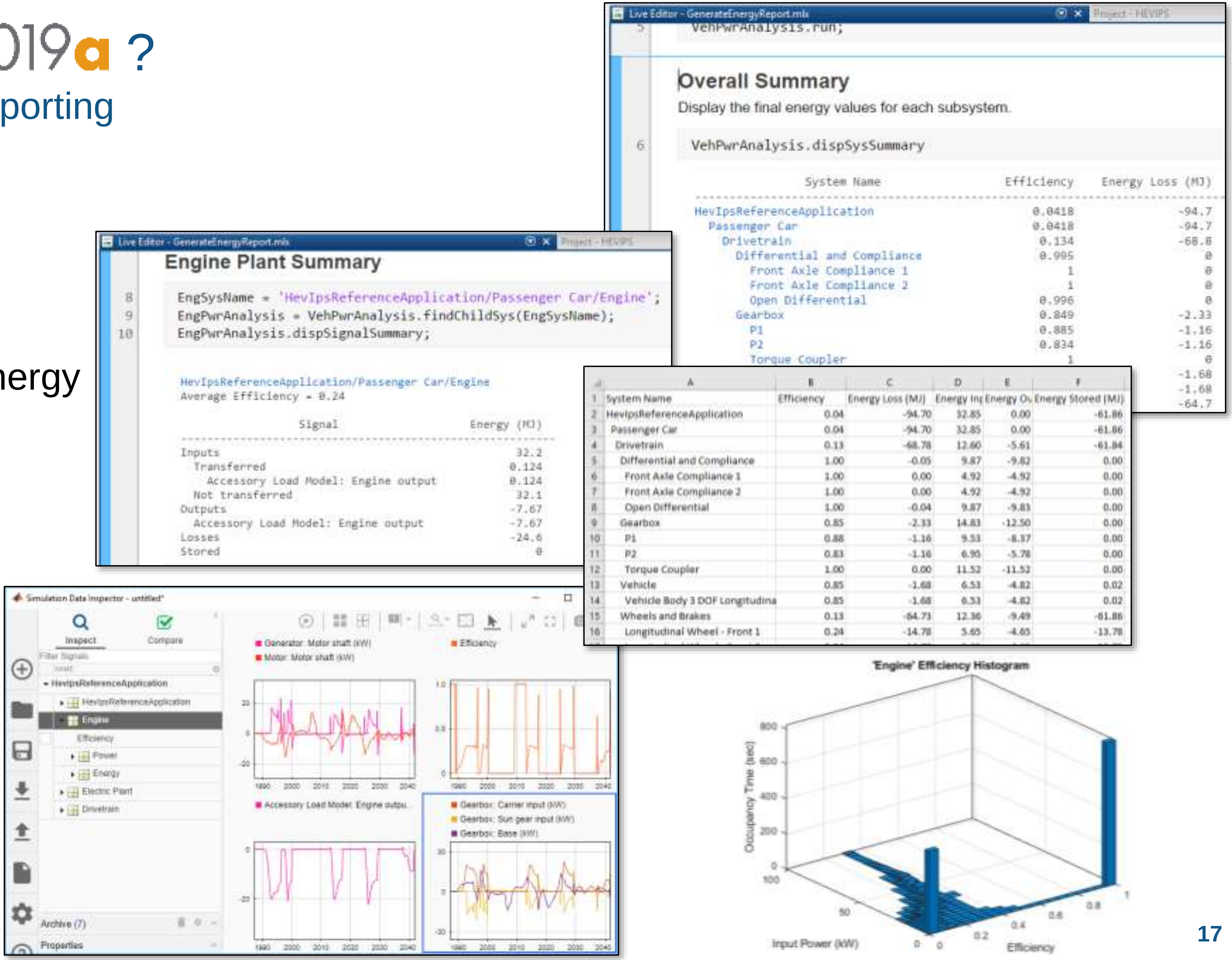
```
VehPwrAnalysis.run;
```



# 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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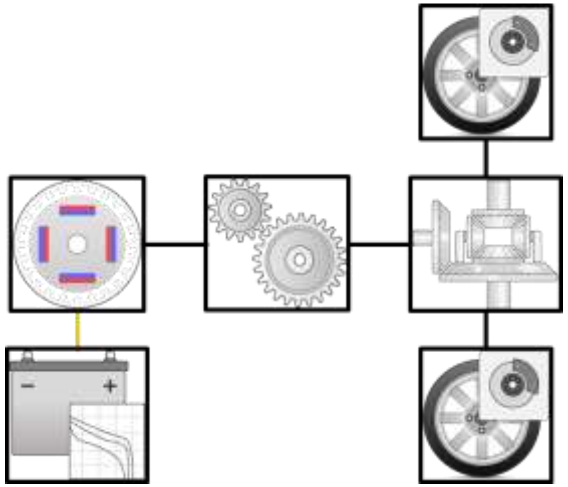
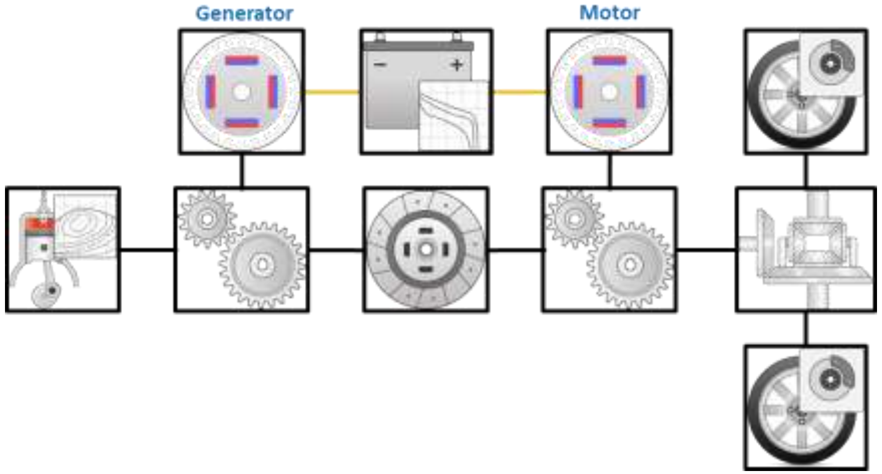
# EV / HEV Configurations Shipping with Powertrain Blockset

Pure EV



- Released in: R2016b
- Similar powertrains:
  - Nissan Leaf
  - Tesla Model 3
  - Chevy Bolt

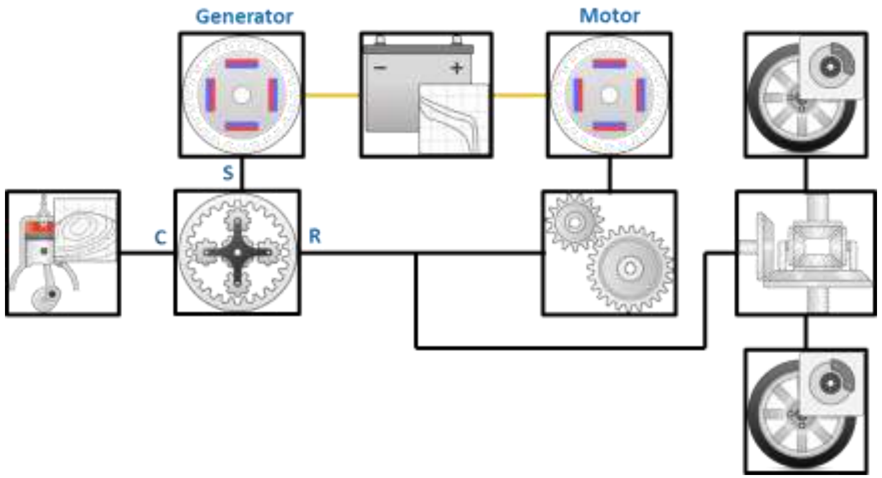
Multi-mode HEV → P1/P3




- Released in: R2016b
- Similar powertrains:
  - Hybrid Honda Accord

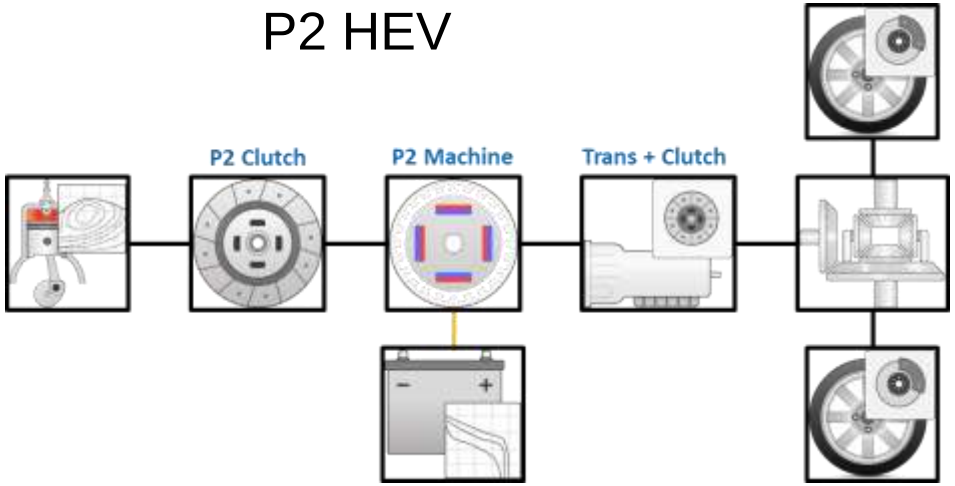
# EV / HEV Configurations Shipping with Powertrain Blockset

Input Power-Split HEV




- Released in: R2017b
- Similar powertrains:
  - Toyota Prius
  - Lexus Hybrid
  - Ford Hybrid Escape

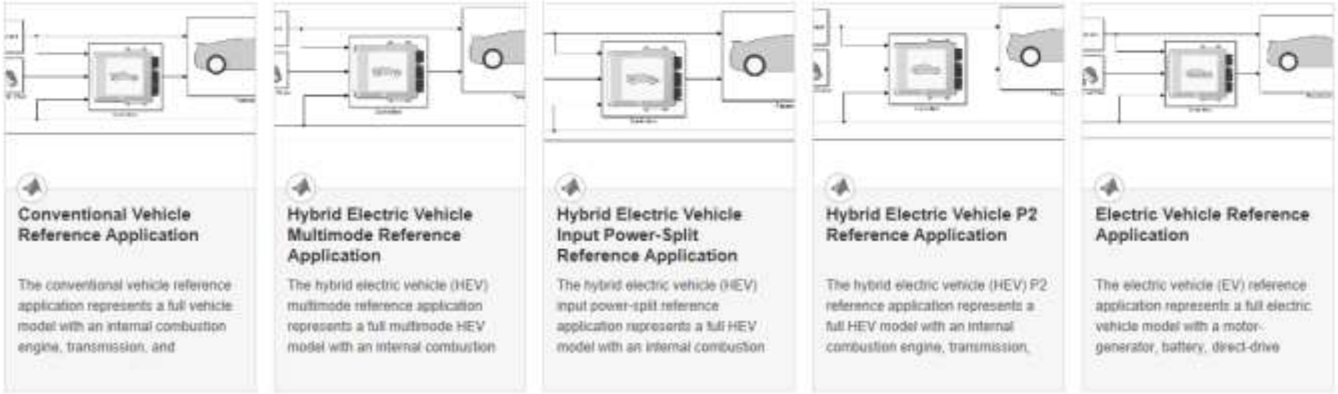
P2 HEV




- 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

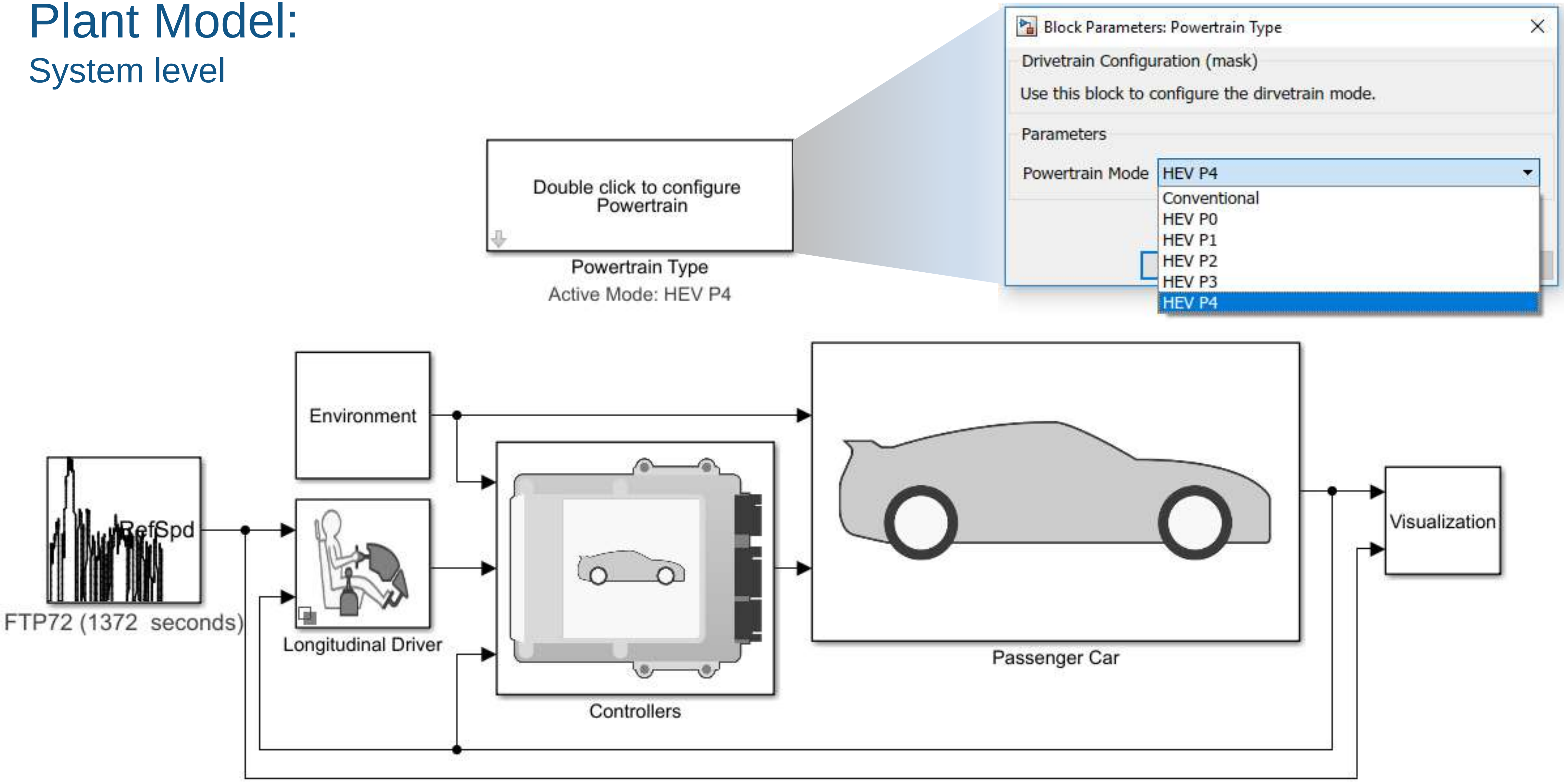
3. Customize the controllers
   – Parameterize the controllers
   – Customize supervisory control logic
   – Add your own controller variants

4. Perform closed-loop system testing
   – Sensitivity analyses
   – Design optimization
   – MIL / SIL / HIL testing

# Initial HEV Architecture Study

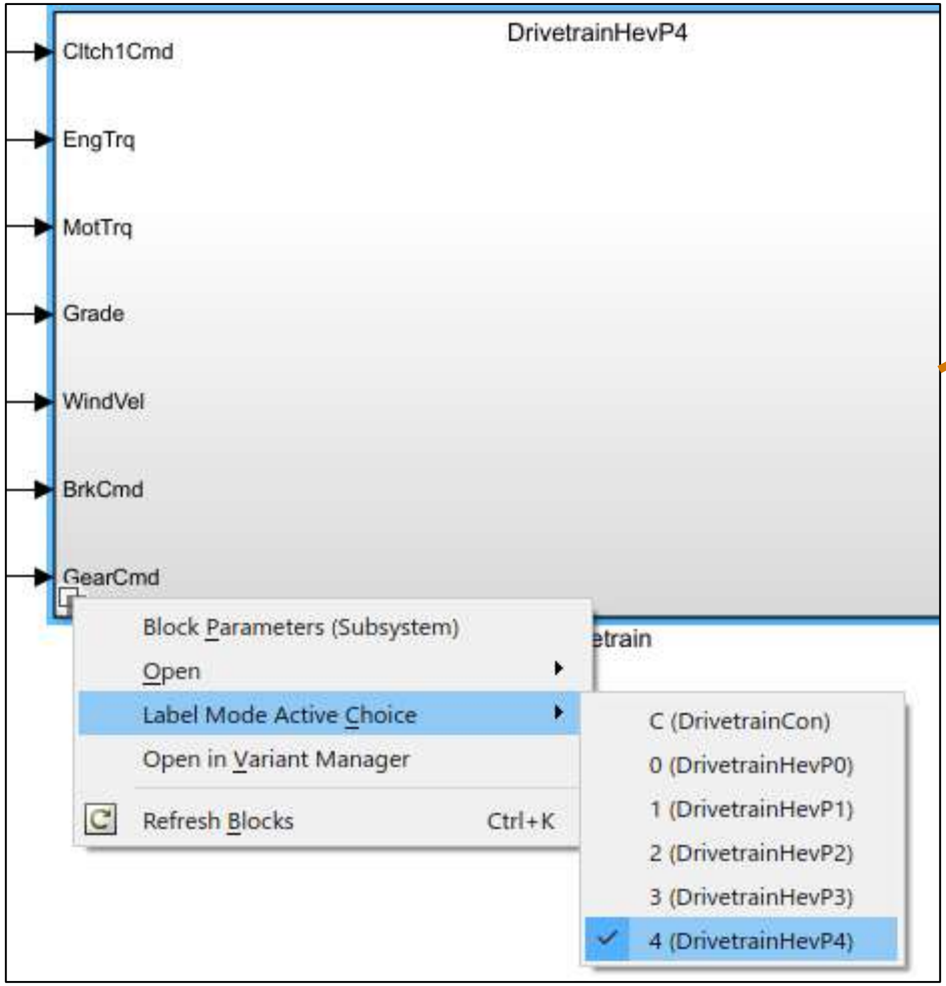
- EcoCAR Mobility Challenge
  - Student competition for 12 North American universities
  - Collaboration of industry, academia and government research labs
  - Improve fuel economy through hybridization and enable level 2 automation capabilities
- MathWorks provided Powertrain Blockset reference applications:
  - Plant models for P0 – P4 architectures
  - Supervisory controller
- Generic versions of the models used for this study

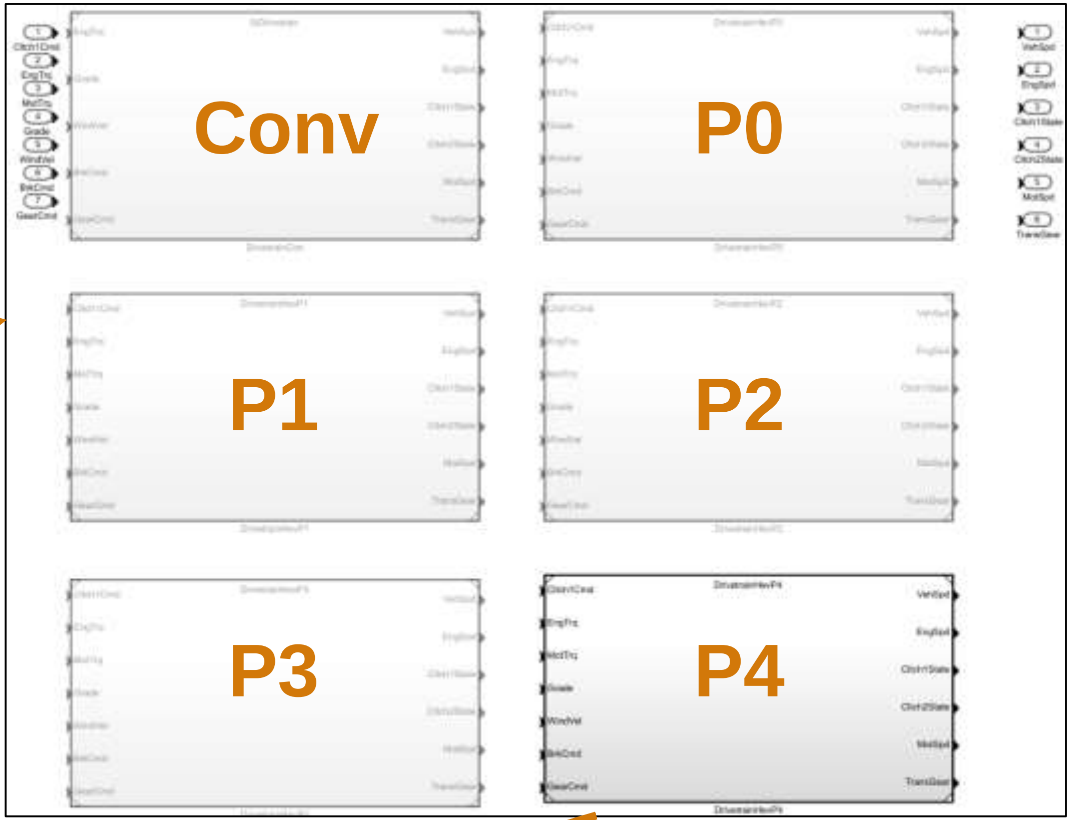
# Plant Model:
## System level

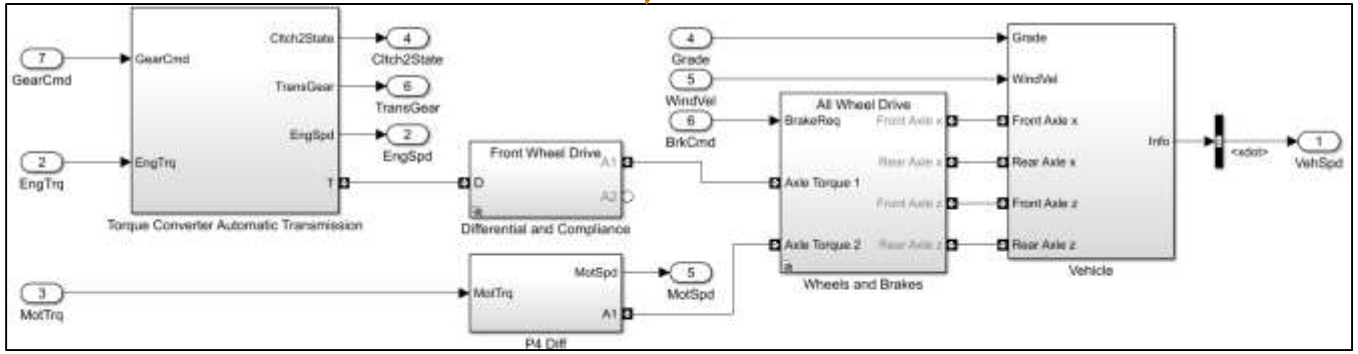


# Plant Model:

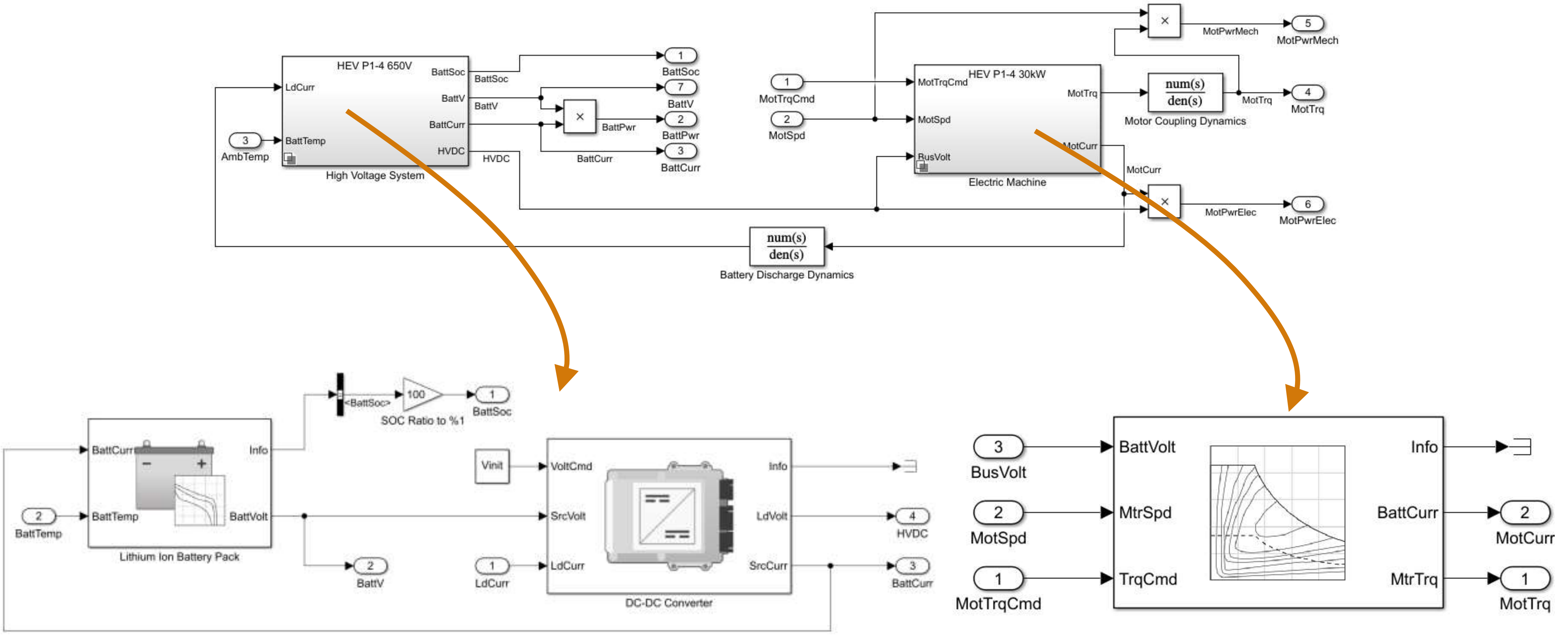
## Driveline Subsystem



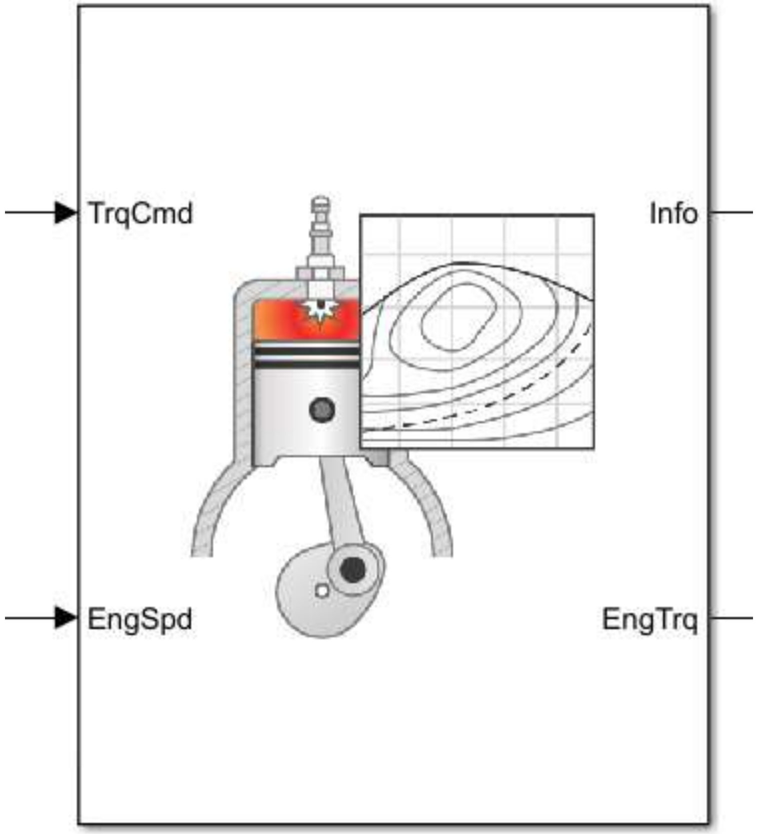
# Plant Model:
## Electrical Subsystem



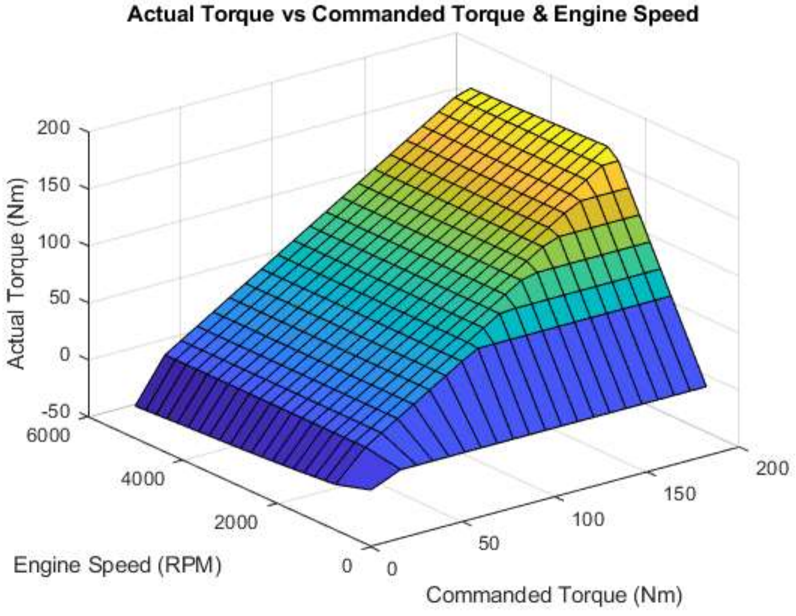

650 V Battery & DC-DC Converter
(smaller sizing for P0)

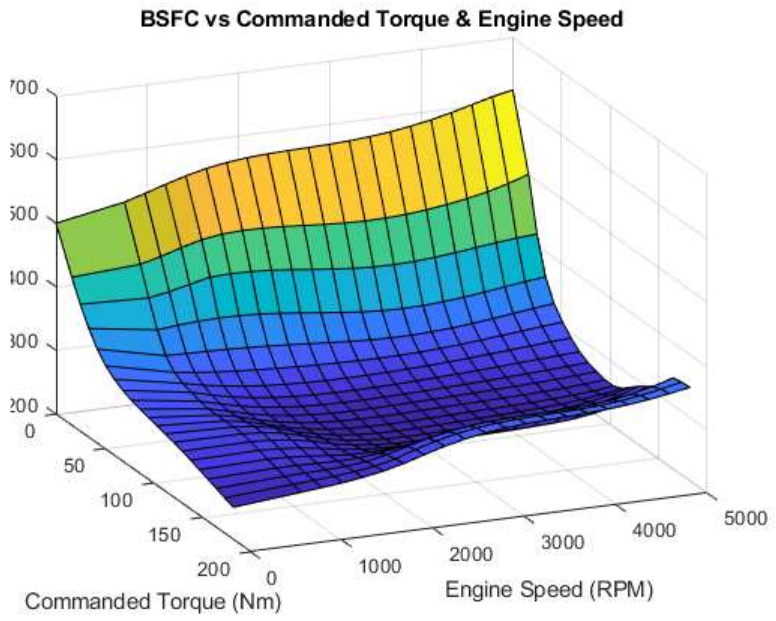
30 kW Motor
(10 kW for P0)

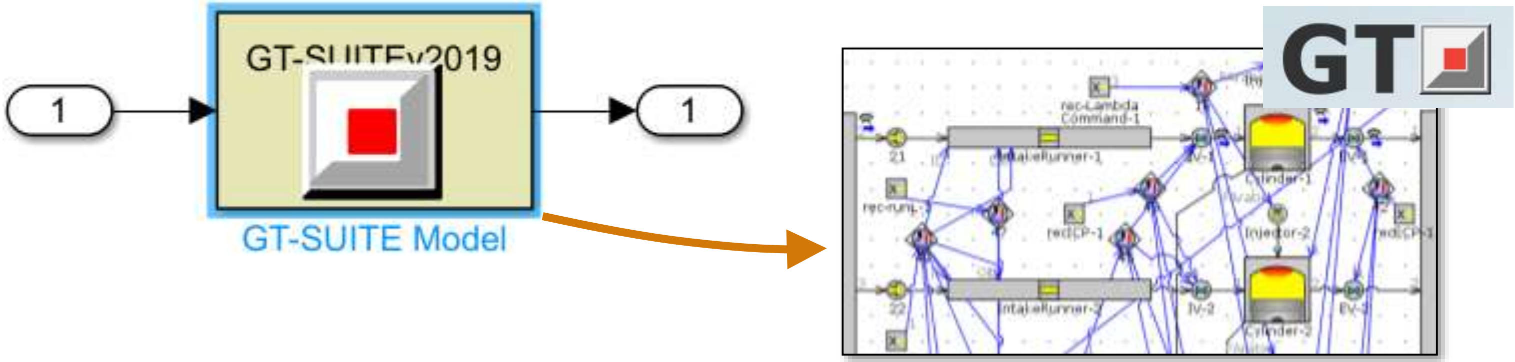
# Plant Model:
## Engine Subsystem




1.5l Gasoline Engine

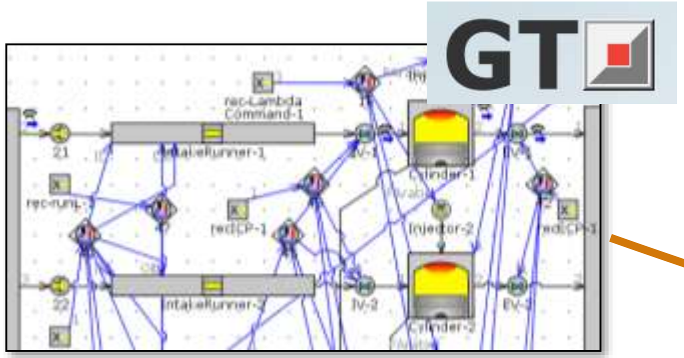


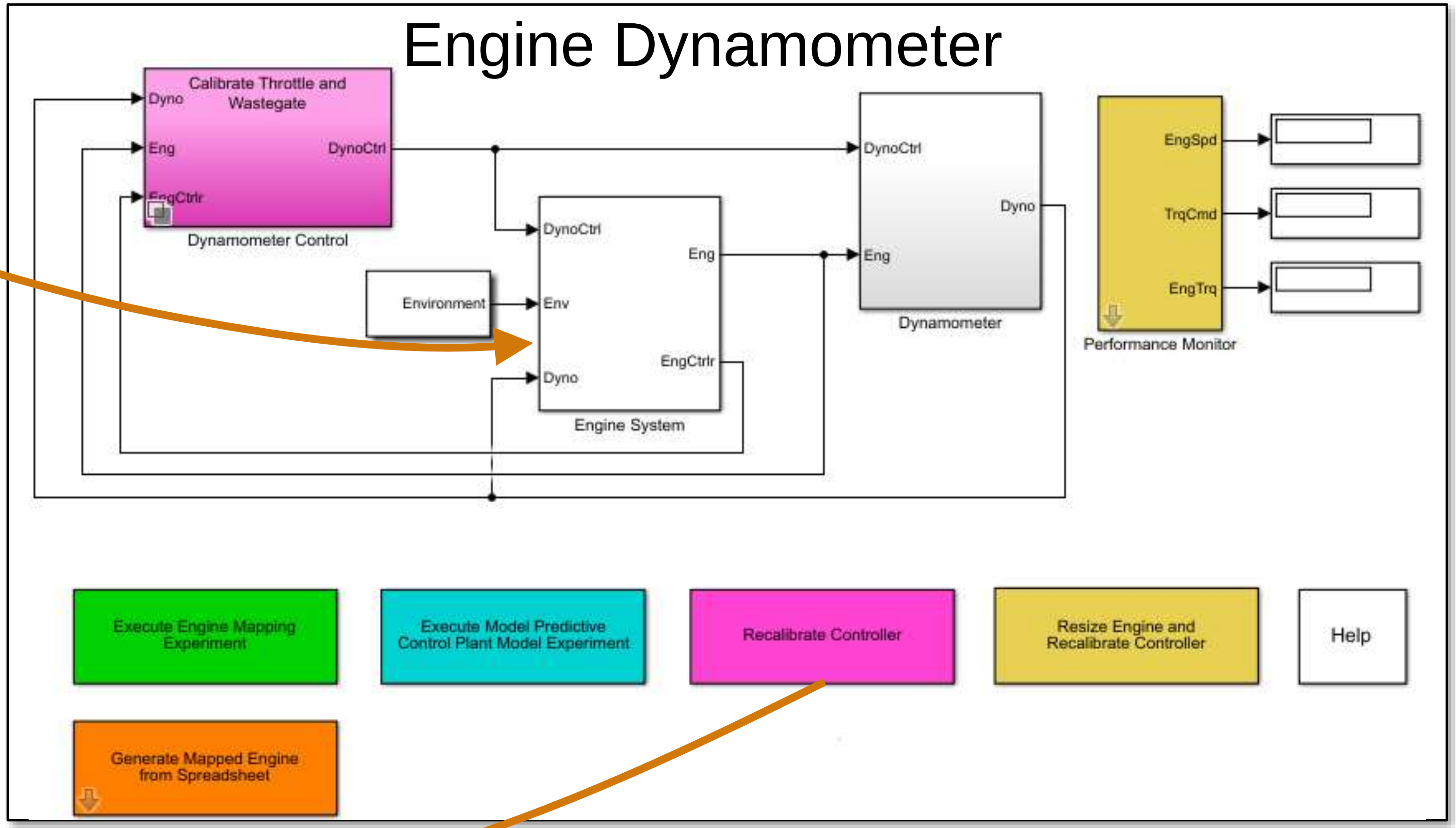



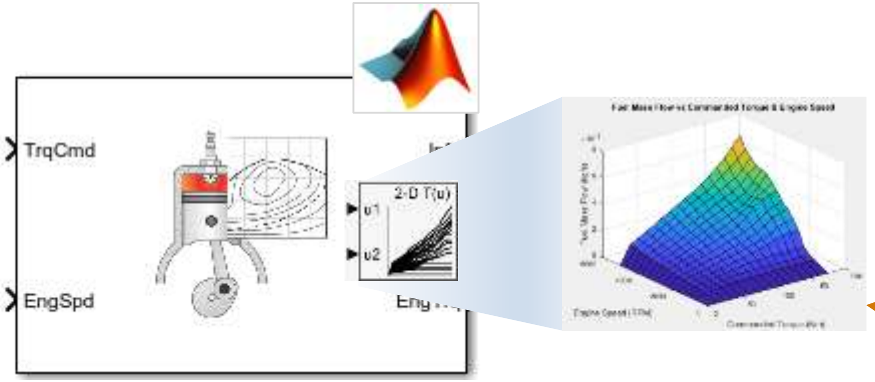

Maps generated from GT-POWER®

# Controls-oriented Model Creation




Detailed, design-oriented model

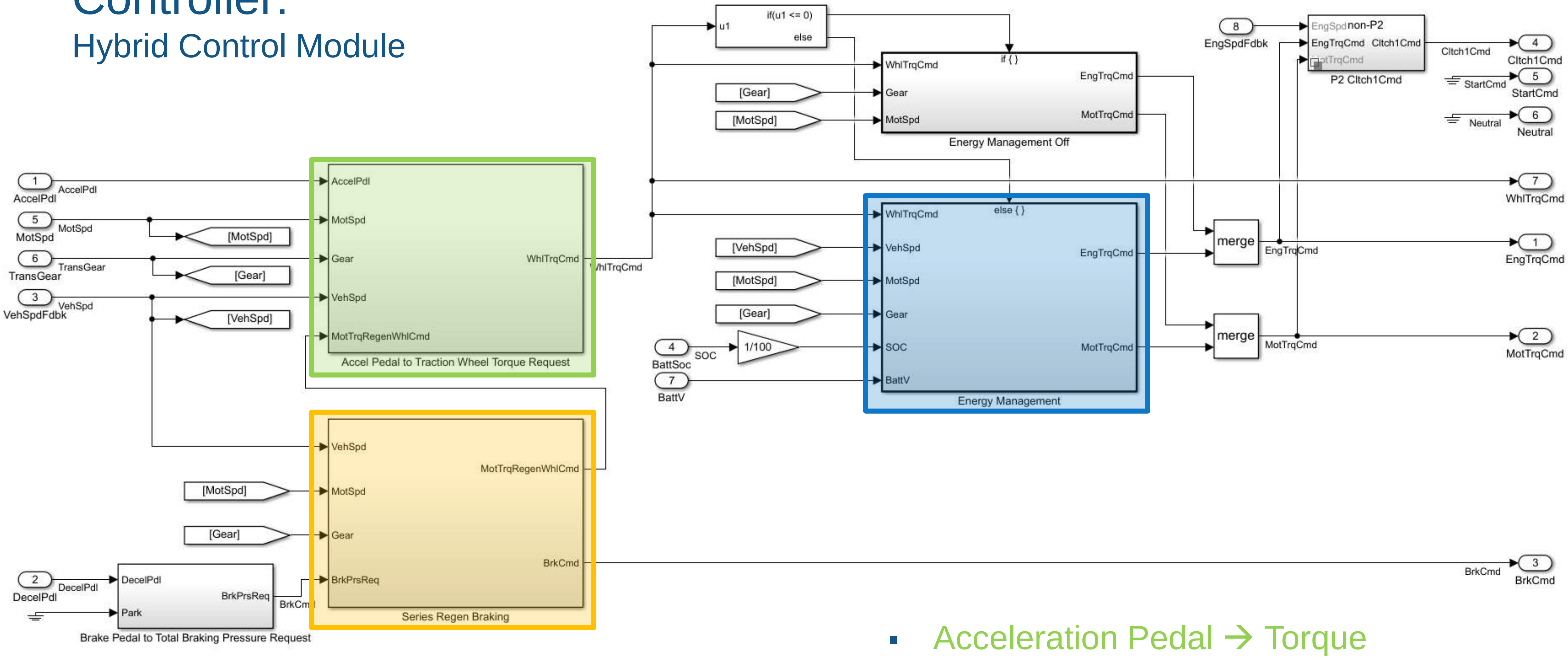



Fast, but accurate controls-oriented model

# 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:

$$\tau_{min}(\omega) \leq \tau_{act} \leq \tau_{max}(\omega)$$

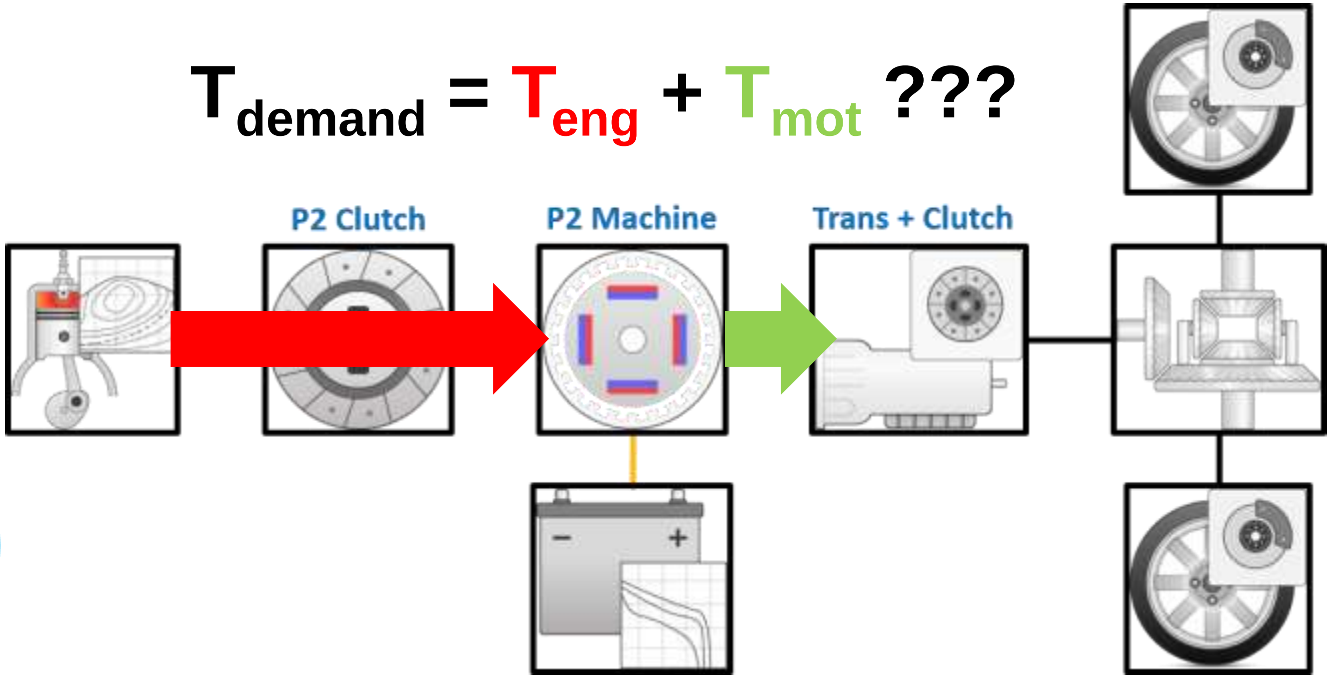
$$P_{chg}(SOC) \leq P_{batt} \leq P_{dischg}(SOC)$$

$$I_{chg}(SOC) \leq I_{batt} \leq I_{dischg}(SOC)$$

$$SOC_{min} \leq SOC \leq SOC_{max}$$

- Attempt to minimize energy consumption, maintain drivability

$T_{demand} = T_{eng} + T_{mot}$ ???



# Equivalent Consumption Minimization Strategy (ECMS)

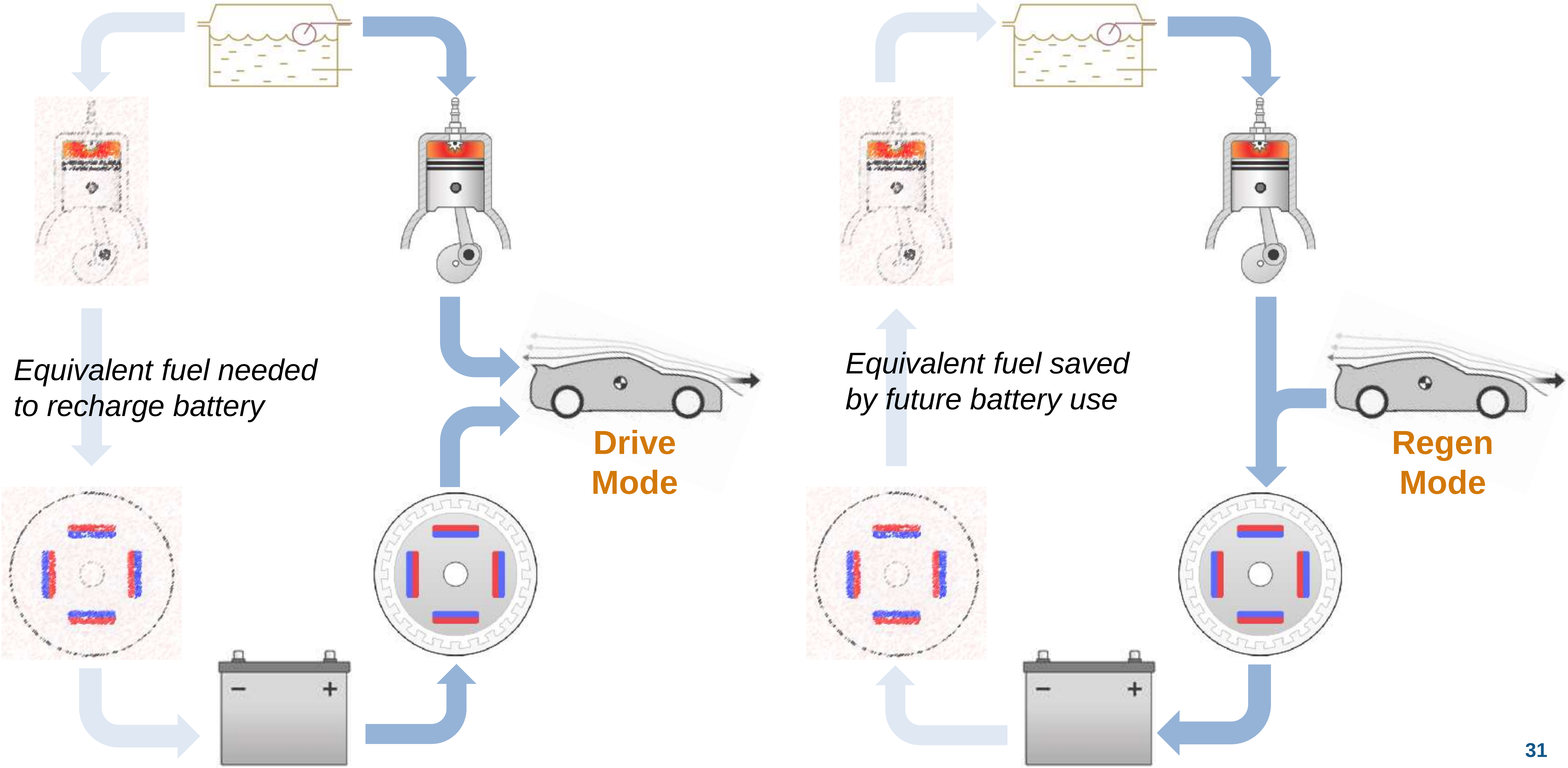
- What is ECMS?
  - Supervisory control strategy to decide when to use engine, motor or both
  - Based on analytical instantaneous optimization

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

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)

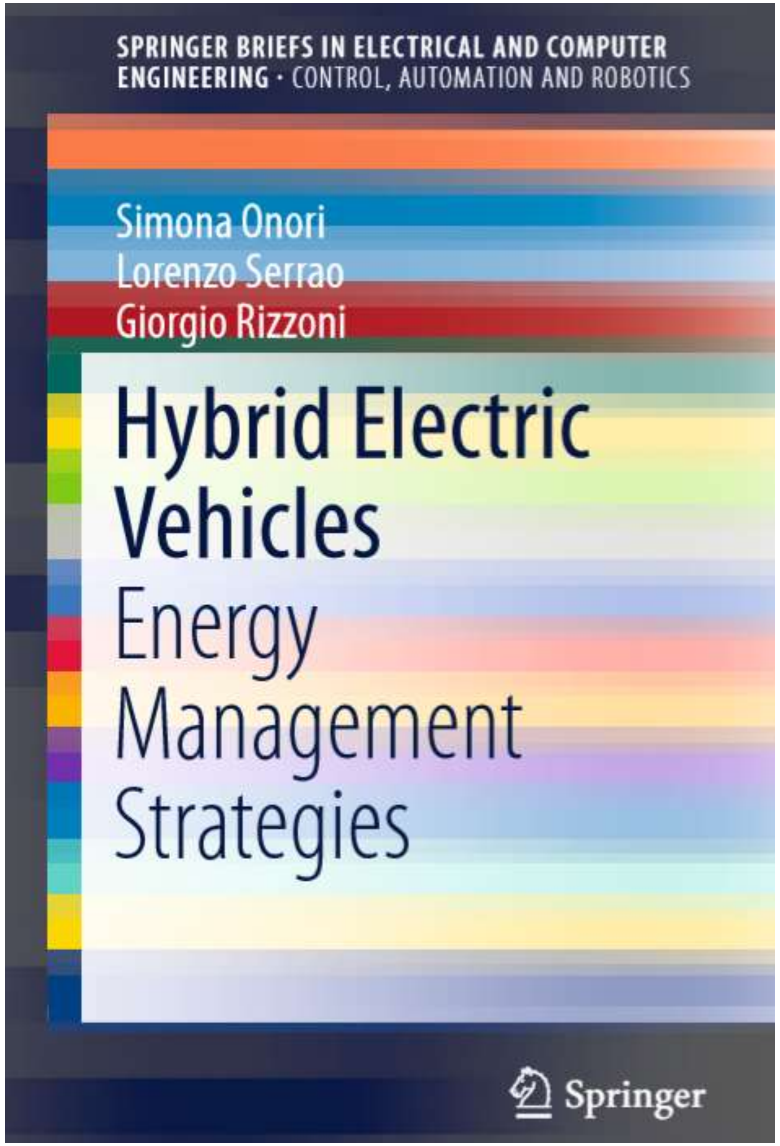
# Equivalent Consumption Minimization Strategy (ECMS)



# Equivalent 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
2. Check constraints, determine infeasible conditions
3. Calculate and minimize cost function

$$\begin{bmatrix} Trq\,Cmd \\ 0 \\ -Min\,Mot\,Trq \\ \vdots \\ +Max\,Mot\,Trq \end{bmatrix}$$

$$\tau_{min}(\omega) \le \tau_{act} \le \tau_{max}(\omega)$$

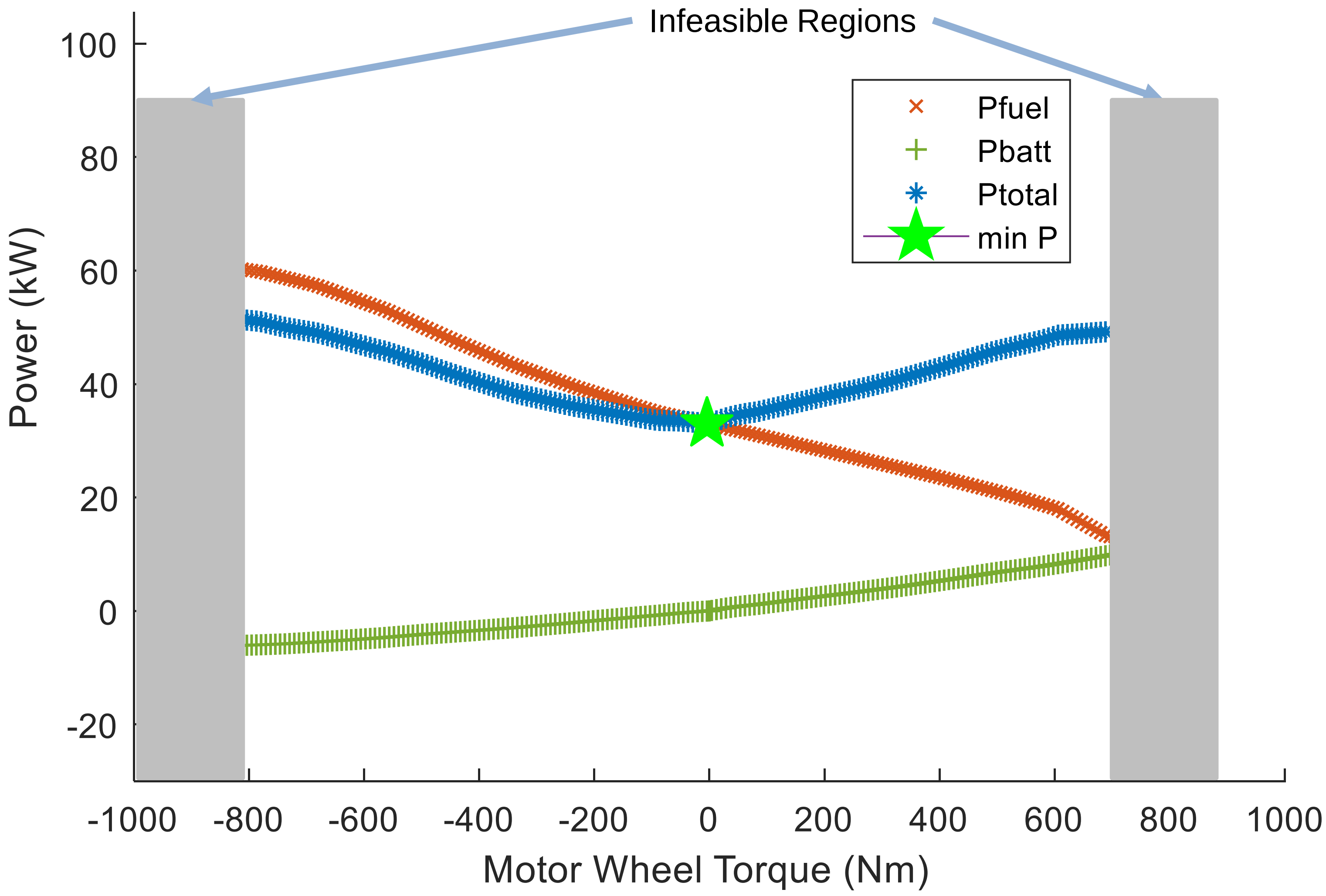
$$P_{chg}(SOC) \le P_{batt} \le P_{dischg}(SOC)$$

$$I_{chg}(SOC) \le I_{batt} \le I_{dischg}(SOC)$$

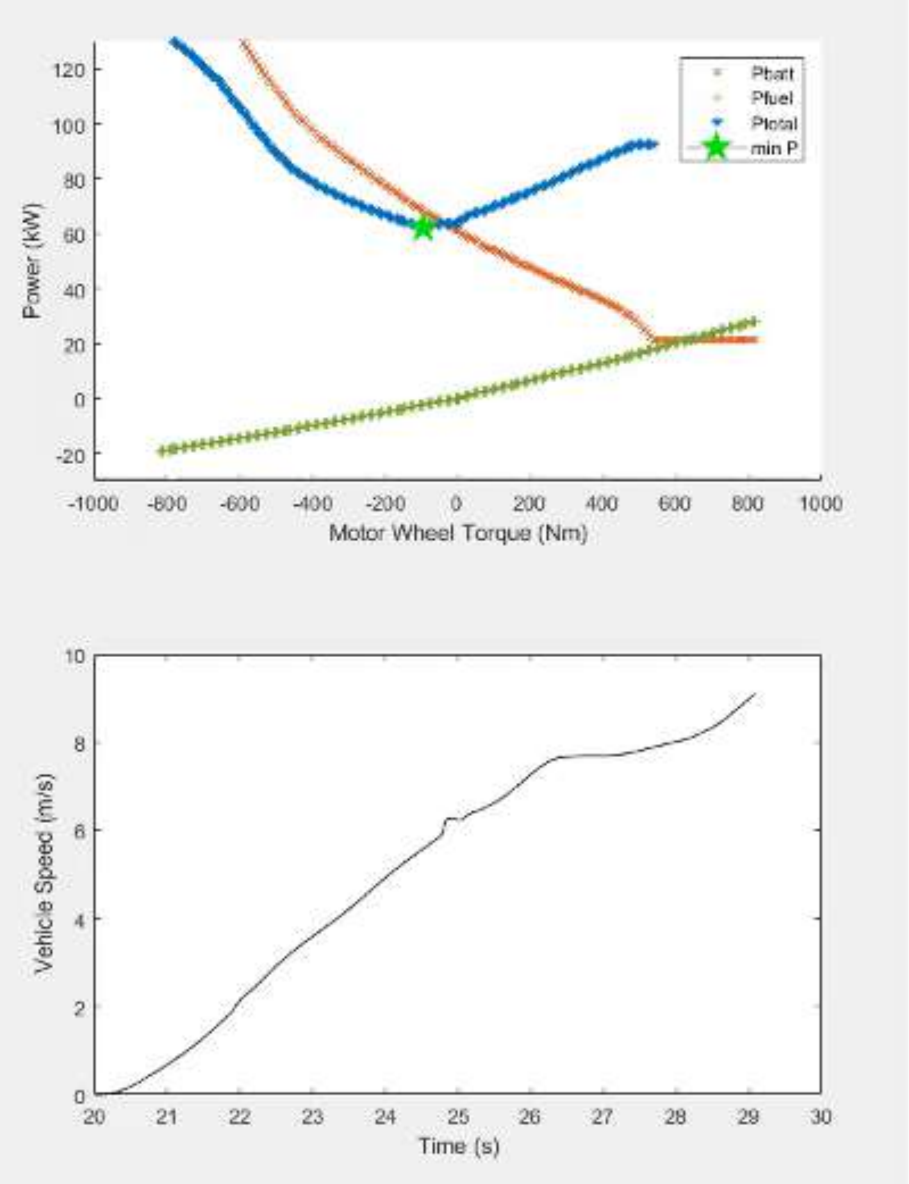
$$SOC_{min} \le SOC \le SOC_{max}$$

$$\min P = P_{fuel} + s \cdot P_{\mathrm{batt}}$$

# Equivalent Consumption Minimization Strategy (ECMS) Process



# Equivalent Consumption Minimization Strategy (ECMS) Process



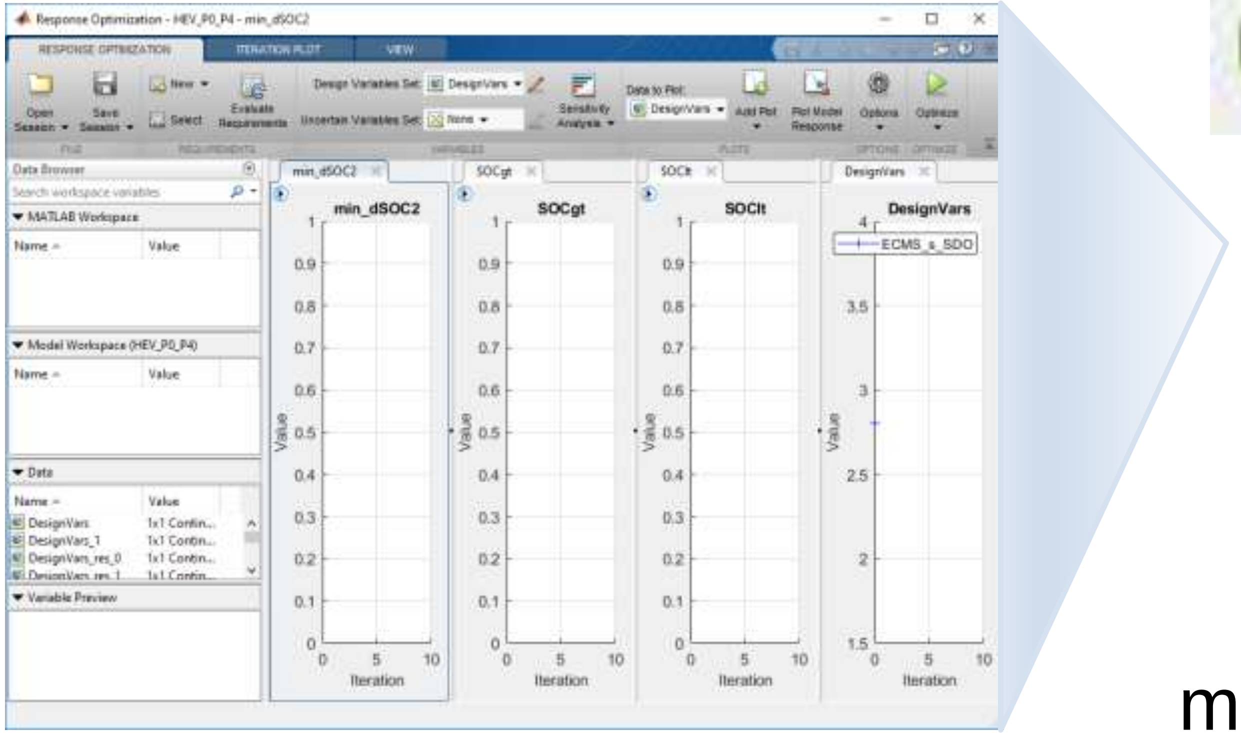
# Agenda

- Context
- Case study description
- Tools used
- Plant model and controls
- Results
- Next steps

# 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 $\Delta$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

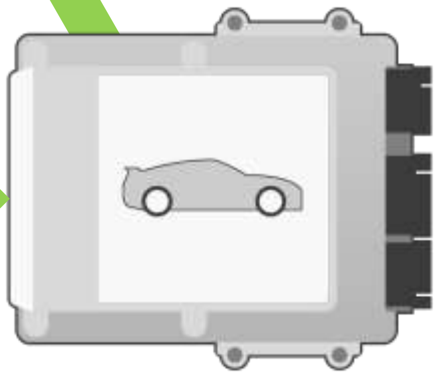
# Charge Sustain Iteration Process





$\min \Delta SOC^2$

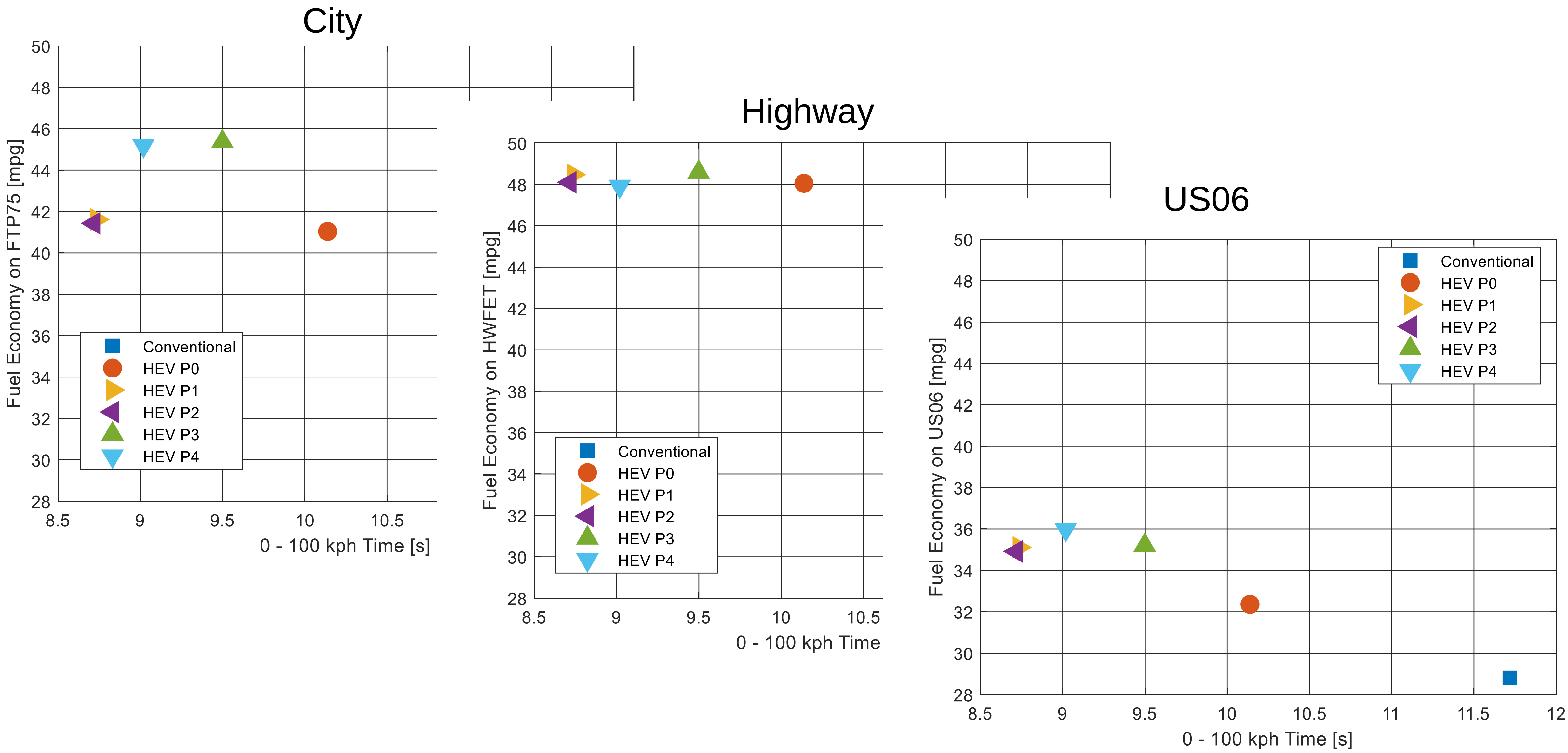
Update ‘s’



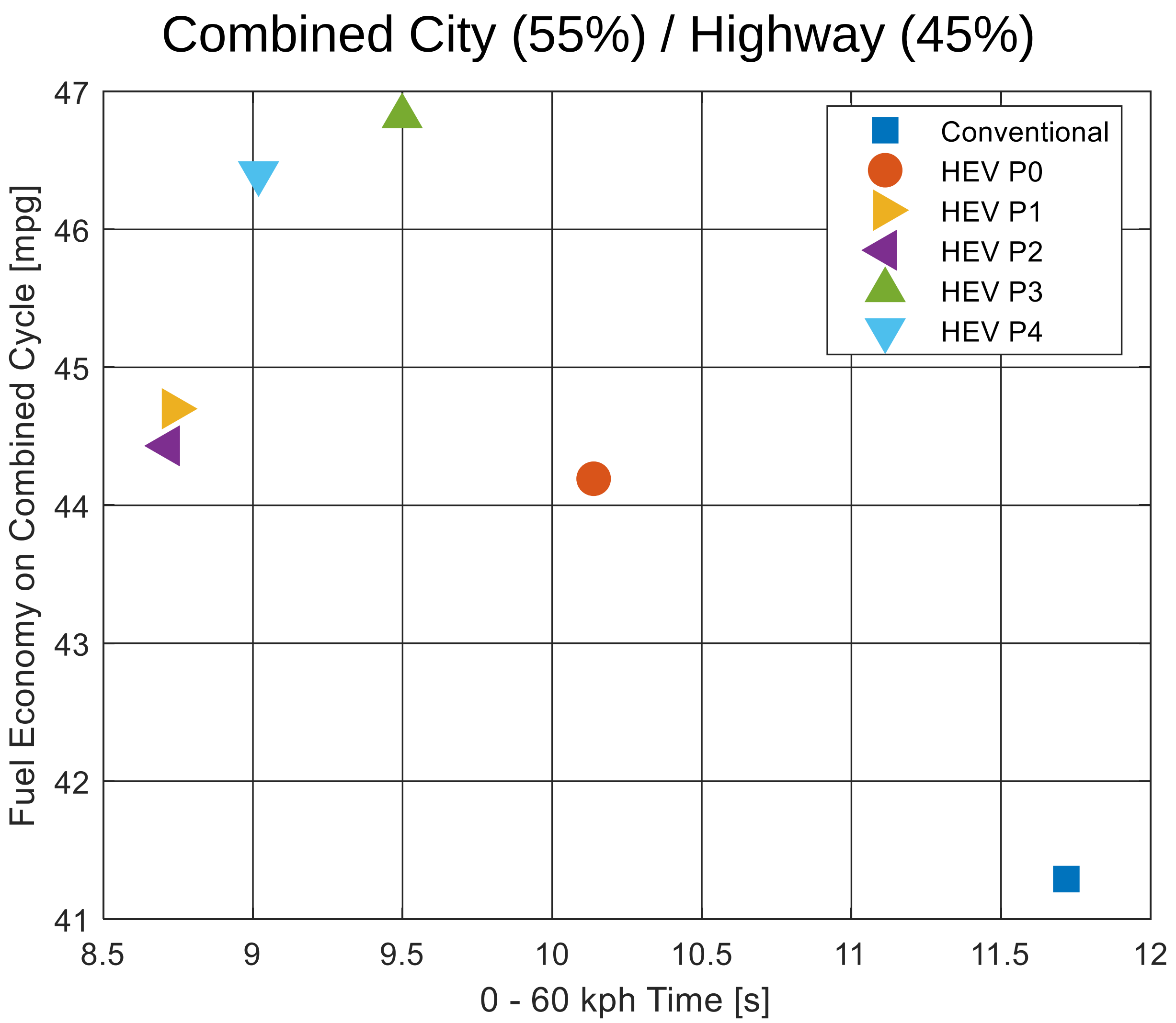
## Simulink Design Optimization

- Optimization / Global Optimization
- Parallel Computing

# Architecture Comparison Results



# Architecture Comparison Results

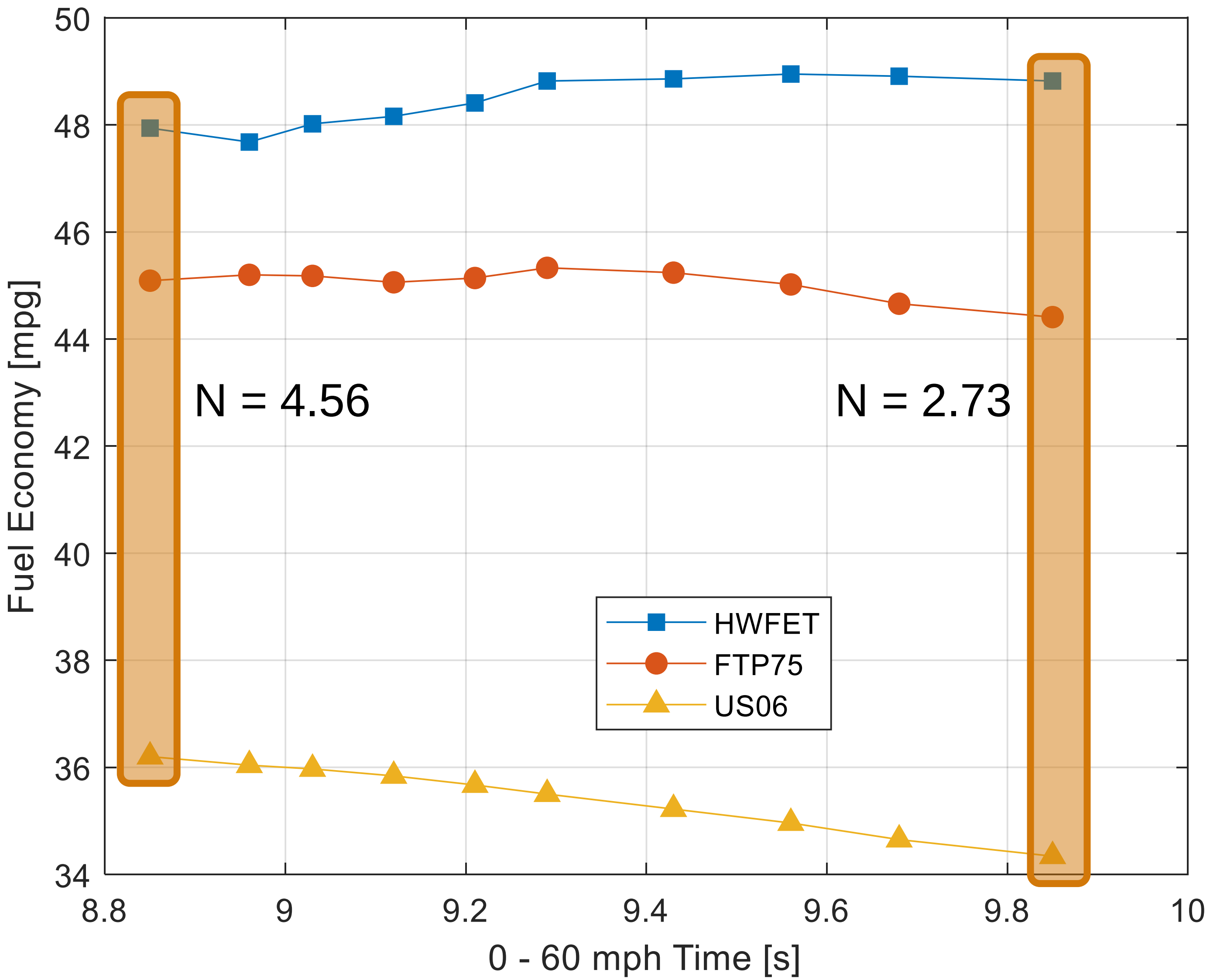



- Placing motors closer to the drive wheel:
  - Improves fuel economy (better regen efficiency)
  - Degrades performance (lower mechanical advantage)

- Simulation allows you to <u>quantify</u> 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

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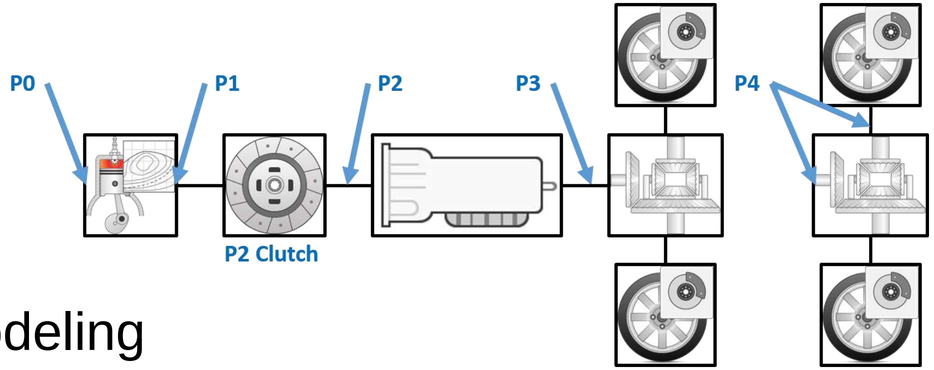
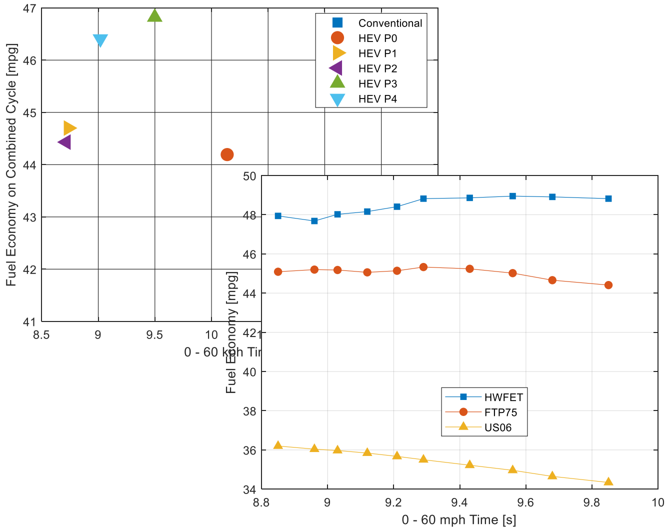
# Summary

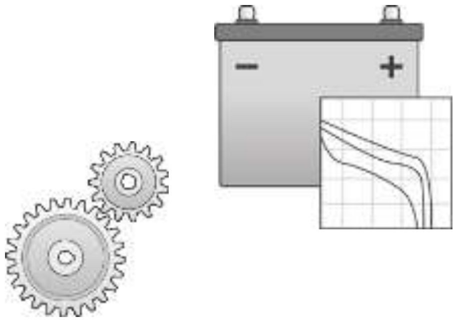



- Assembled full vehicle simulation
  - Powertrain Blockset as framework for vehicle level modeling
  - Mapped engine models auto-generated from design-oriented engine model
  - ECMS for supervisory controls provides a fair comparison between P0 – P4 variants

- 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

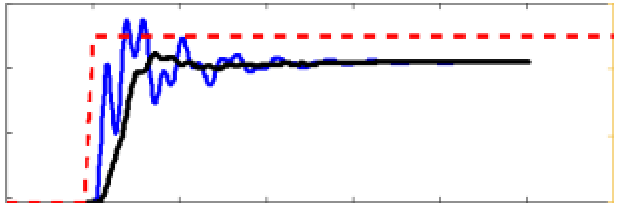


# Next Steps

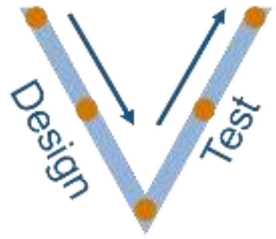


- Widen the scope of powertrain selection study
  - Search over design parameters (gear ratios, battery capacity, etc.)
  - Include two-motor HEV's, with modified ECMS controls

- 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

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