Model-Based Design and Hardware-in-the-Loop Simulation for Clean Vehicles

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Outline of Presentation

- **Background and Motivation**
- **Model-Based Approach for Embedded Control System Design**
- **Hardware-In-the-Loop (HIL) Simulation**
- **Single Shaft Parallel Hybrid Electric Vehicle (HEV) and Electronic Control Unit (ECU) Network**
- **HIL Simulation of Parallel HEV**
- **Conclusions**

Background and Motivation

Fuel Economy & Emission Standards

Vehicle Population

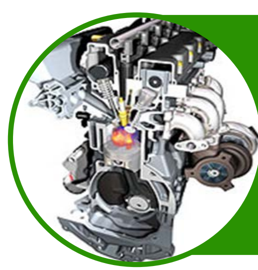
- ***750, 000, 000+*** vehicles in the world
- Expected ***2 billions*** by the year of 2020

Fuel Consumption

- The transportation sector in the U.S. accounts for two-thirds of our petroleum use

Environmental Emission

- Transportation produces 33% of US CO_2 output



Technologies & Challenges

- Hybrid, electric, fuel cell , and renewable energy vehicles
- Complex powertrain and control system

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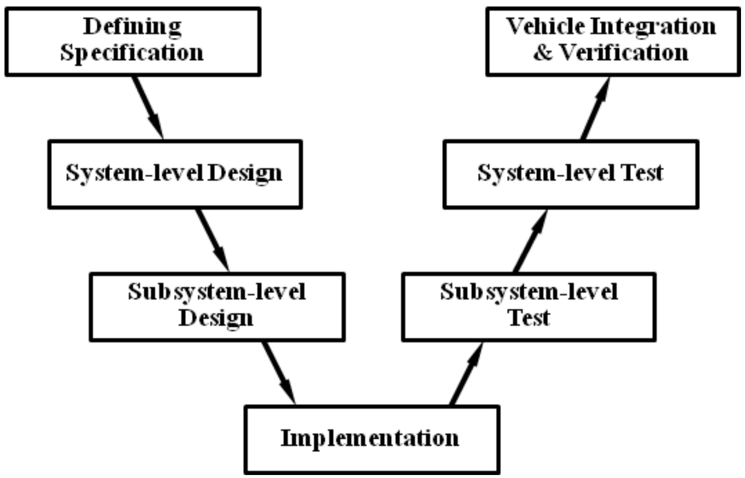
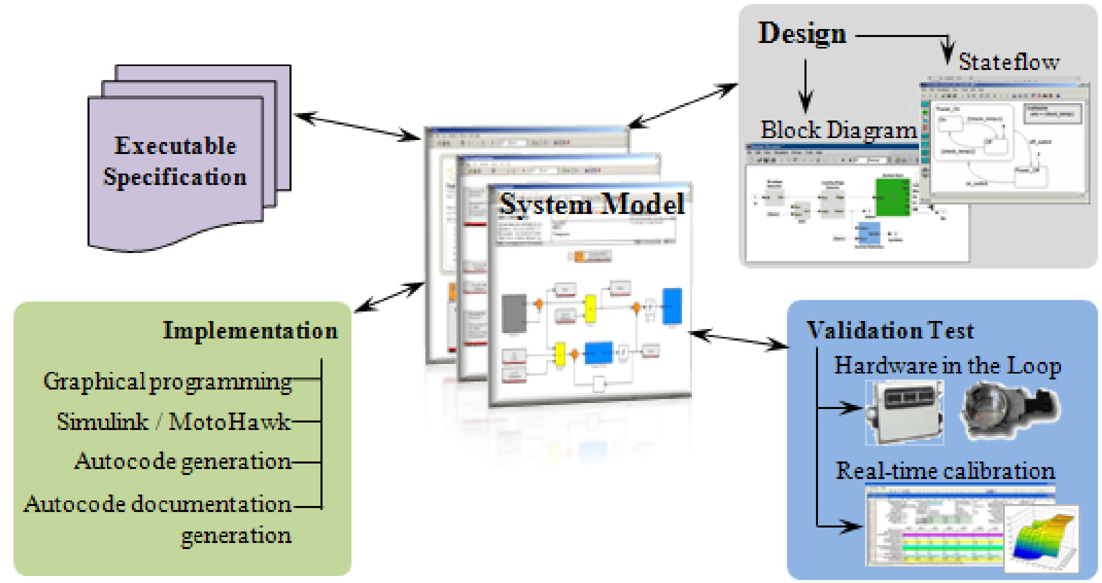
Model-Based Approach for Embedded System Design





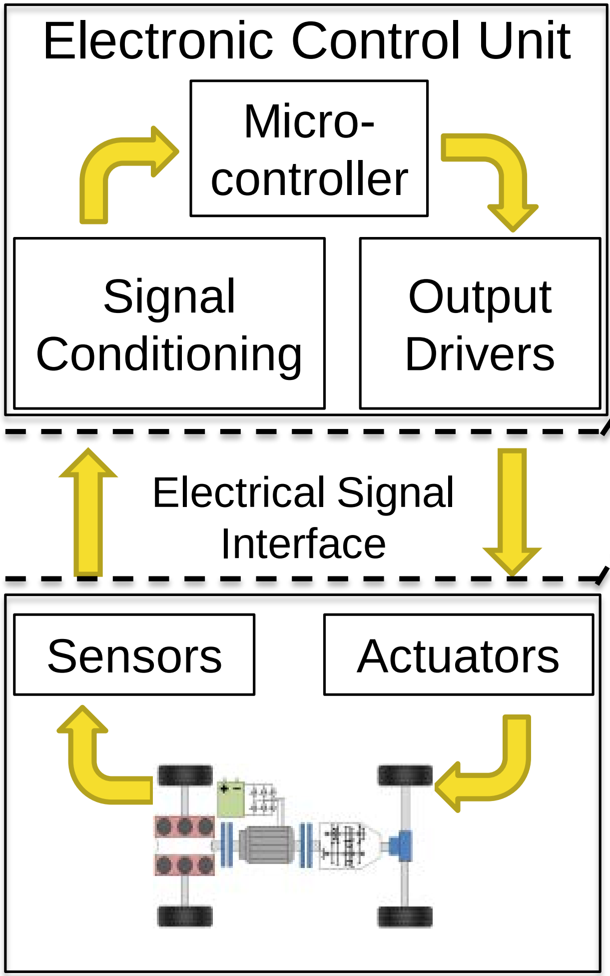
Conventional V-model: a plan-driven process. The design process follow the defined development stages in order

Model-based Design: provide an integrated environment for design, simulation, automatic code generation, and validation.

Salient Features of Model-Based Embedded System Design Approach

- Platform for representing entire system: control strategy and plant models
- Graphical representation: use graphical language to describe implementation details
- Time saving: minimize software development time and maximize software re-use. No hand coding, production quality code is automatically generated
- Integrated development and validation cycles
- Communication among the team members is made easier

Hardware-In-the-Loop (HIL) Simulation



Automotive Plant Model

Real World

MotoTron Engine ECU

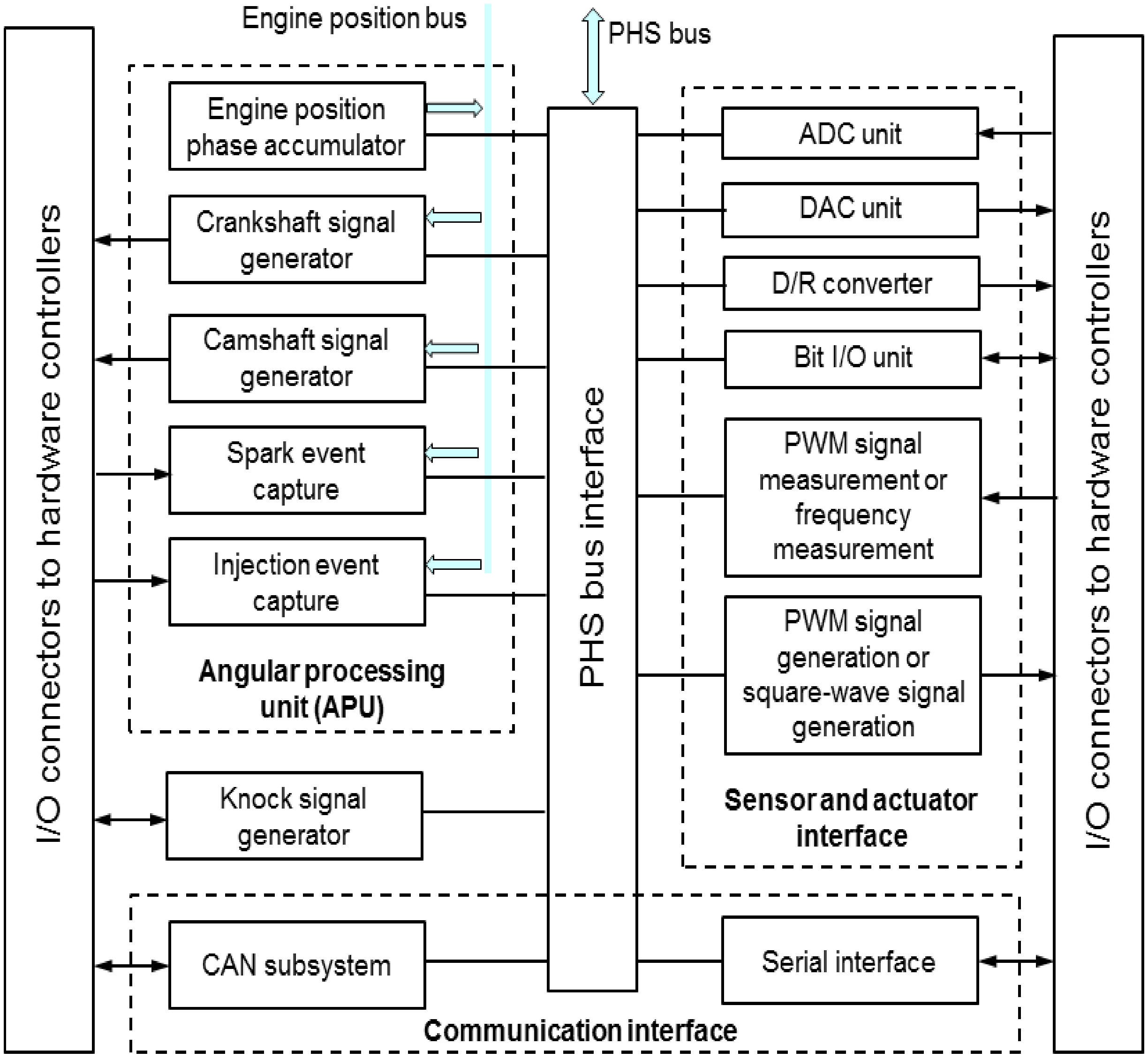
MicroAutoBox Motor ECU

dSPACE HIL Simulator

HIL System

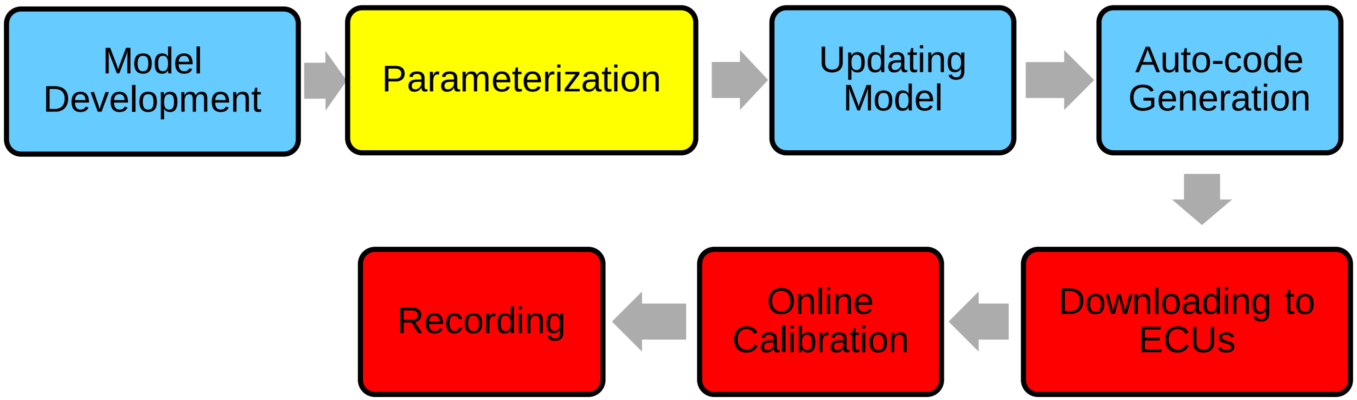
- Generate an environment where ECU assumes that it is running with a real physical system.
- HIL simulator simulates the physical system that is under test. It generates plant sensor signals and capture actuator signals from ECU.
- Used to test control strategies to be implemented on ECUs.

dSPACE HIL I/O Interface



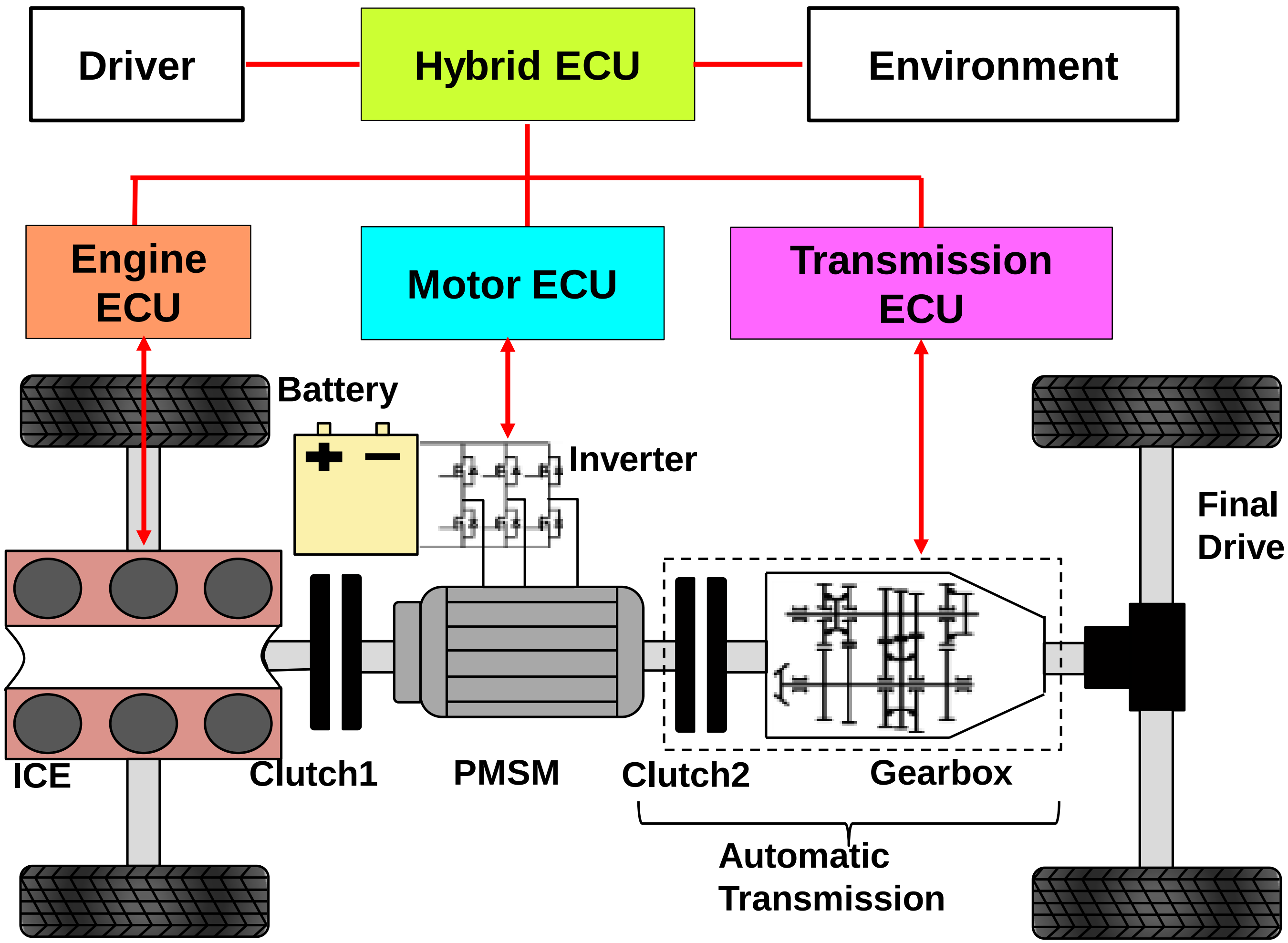
PHS-Peripheral High Speed

Model Development and HIL Simulation Process



- Colors indicate the different softwares used in the steps.
- Blue : Simulink/Stateflow/dSPACE blocksets/Real-time Workshop
  Model building, modification, and auto-code generation
- Yellow : dSPACE ModelDesk
  Model Parameterization
- Red : dSPACE ControlDesk Next Generation
  Real Time Calibration, Data Recording, File Export

Single Shaft Parallel HEV Powertrain Architecture and ECU Network



- **Vehicle level ECU:**

  Hybrid ECU

- **Low level ECU:**

  Engine ECU
  Motor ECU
  Transmission ECU

dSPACE Parallel HEV Model

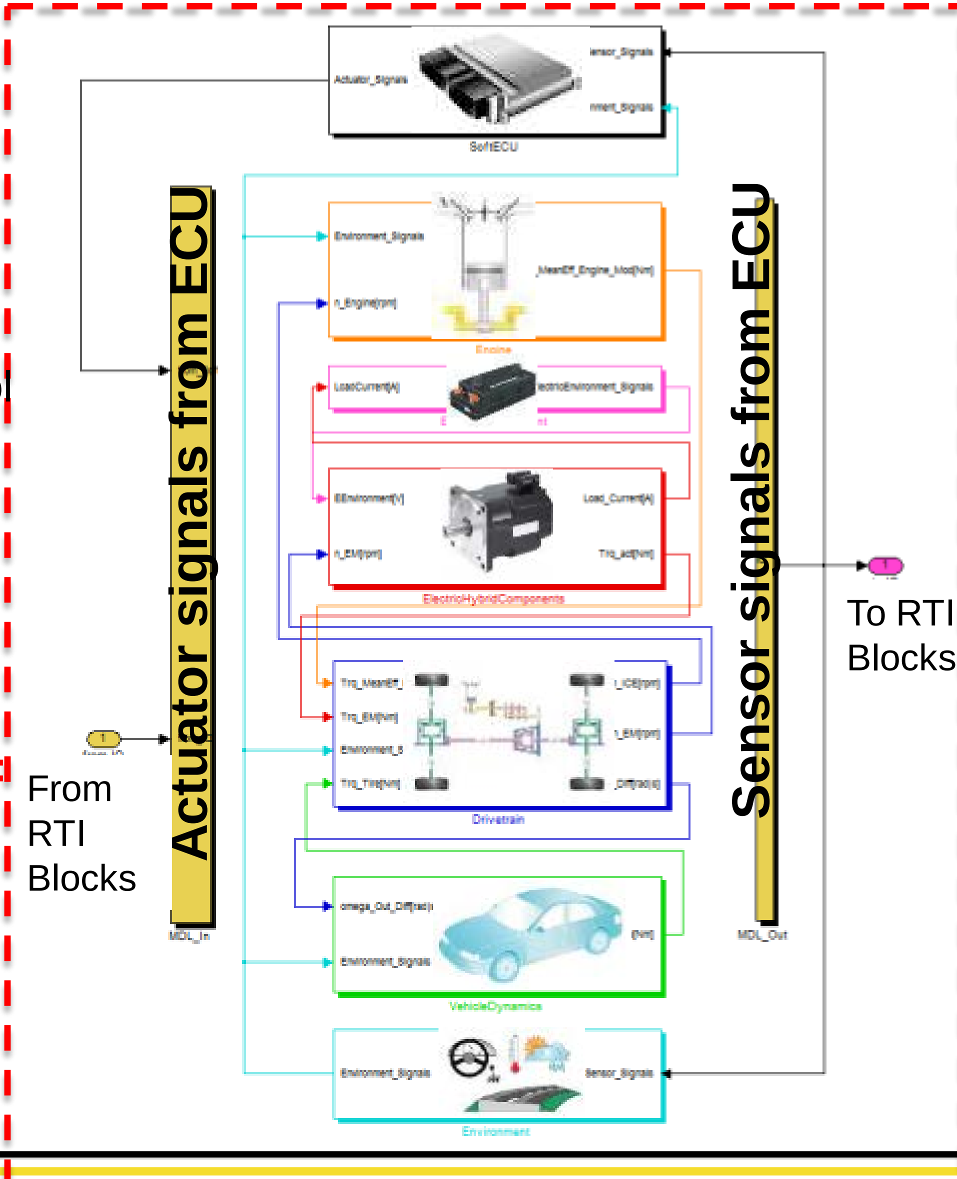
From MotoTron ECM:

- Ignition angle
- Injection angle and duration
- Throttle valve, EGR valve, pressure control valve position, and PWM control signal

From MicroAutoBox II:

- Three phase PWM signals

Actuator Signals



To MotoTron ECM:

- Engine torque request
- Engine speed
- Engine keys
- Intake manifold pressure and temperature
- Coolant temperature
- Rail pressure
- ……

To MicroAutoBox II:

- Motor Torque Request
- Motor Speed
- Three phase current
- DC bus voltage

Sensor Signals

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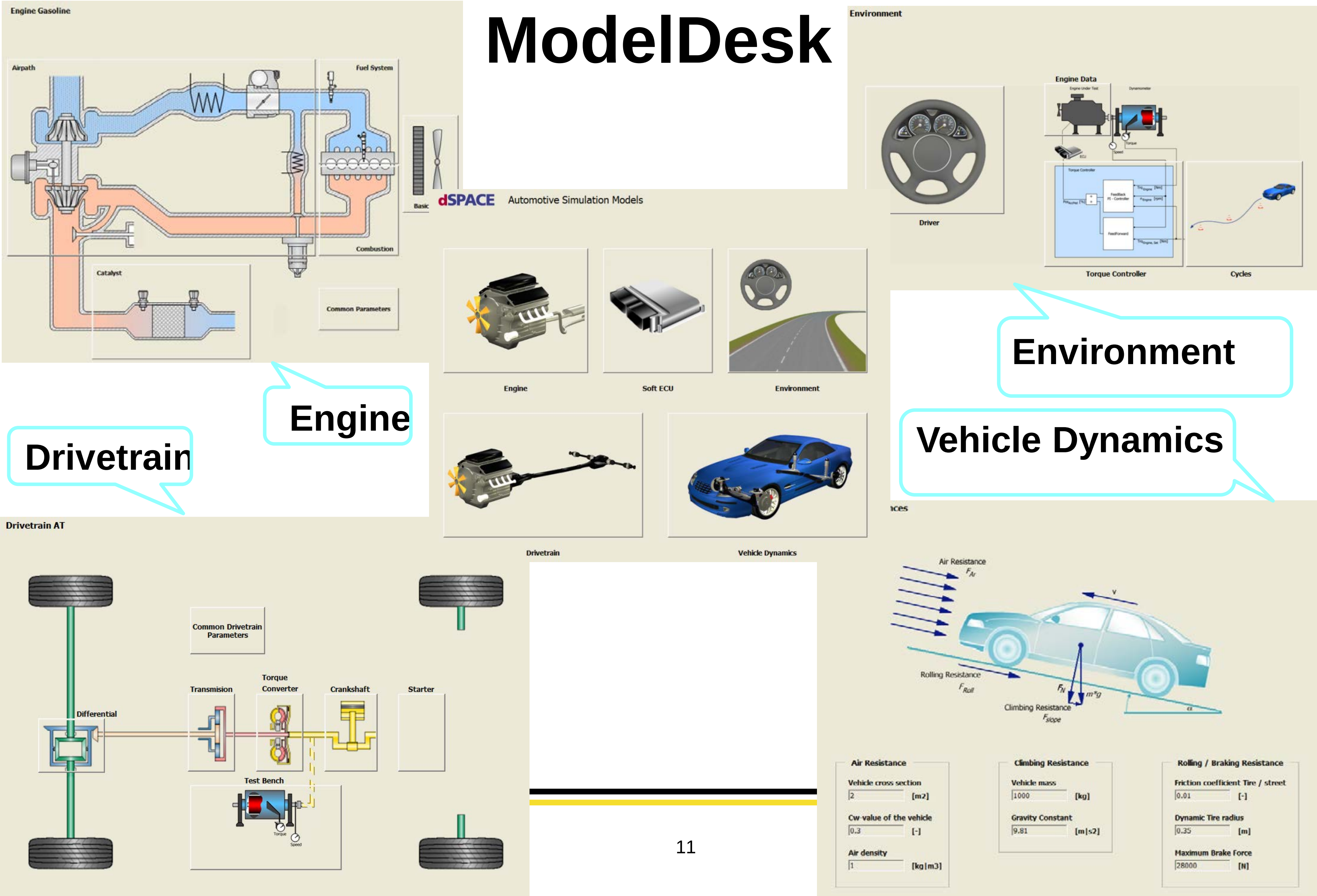
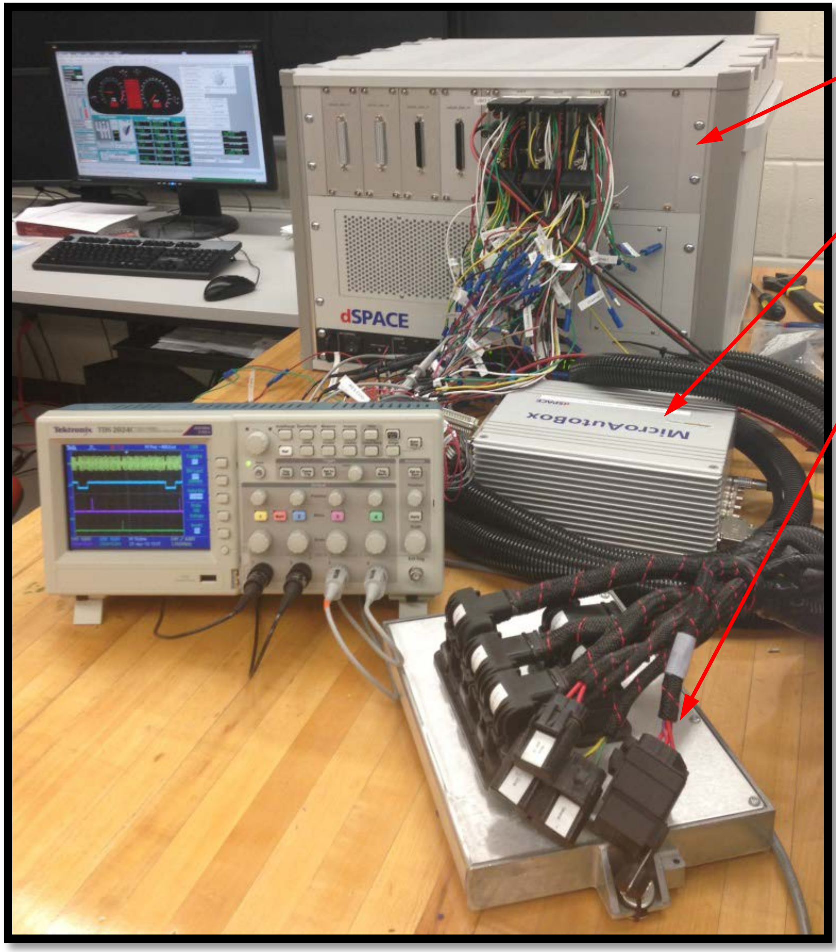
dSPACE HIL Simulator

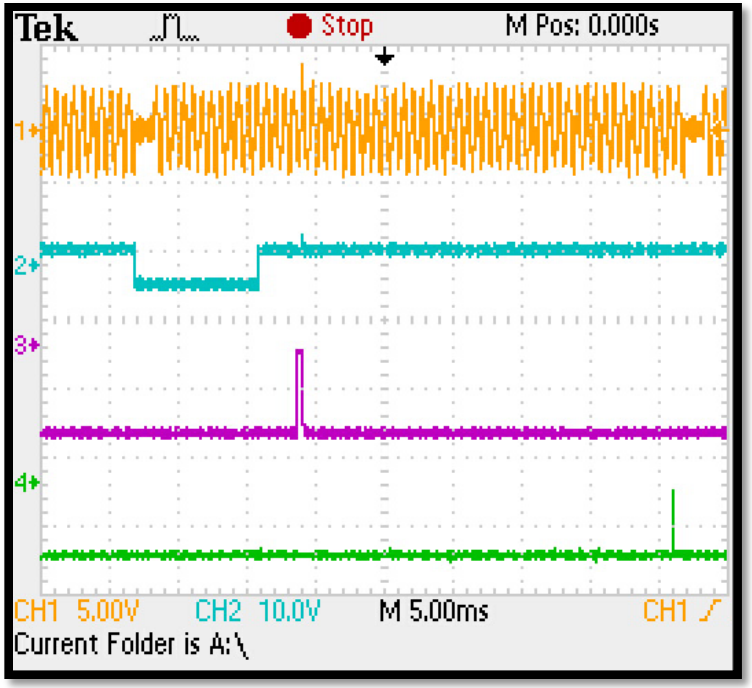
Parameterize HEV Model Using ModelDesk



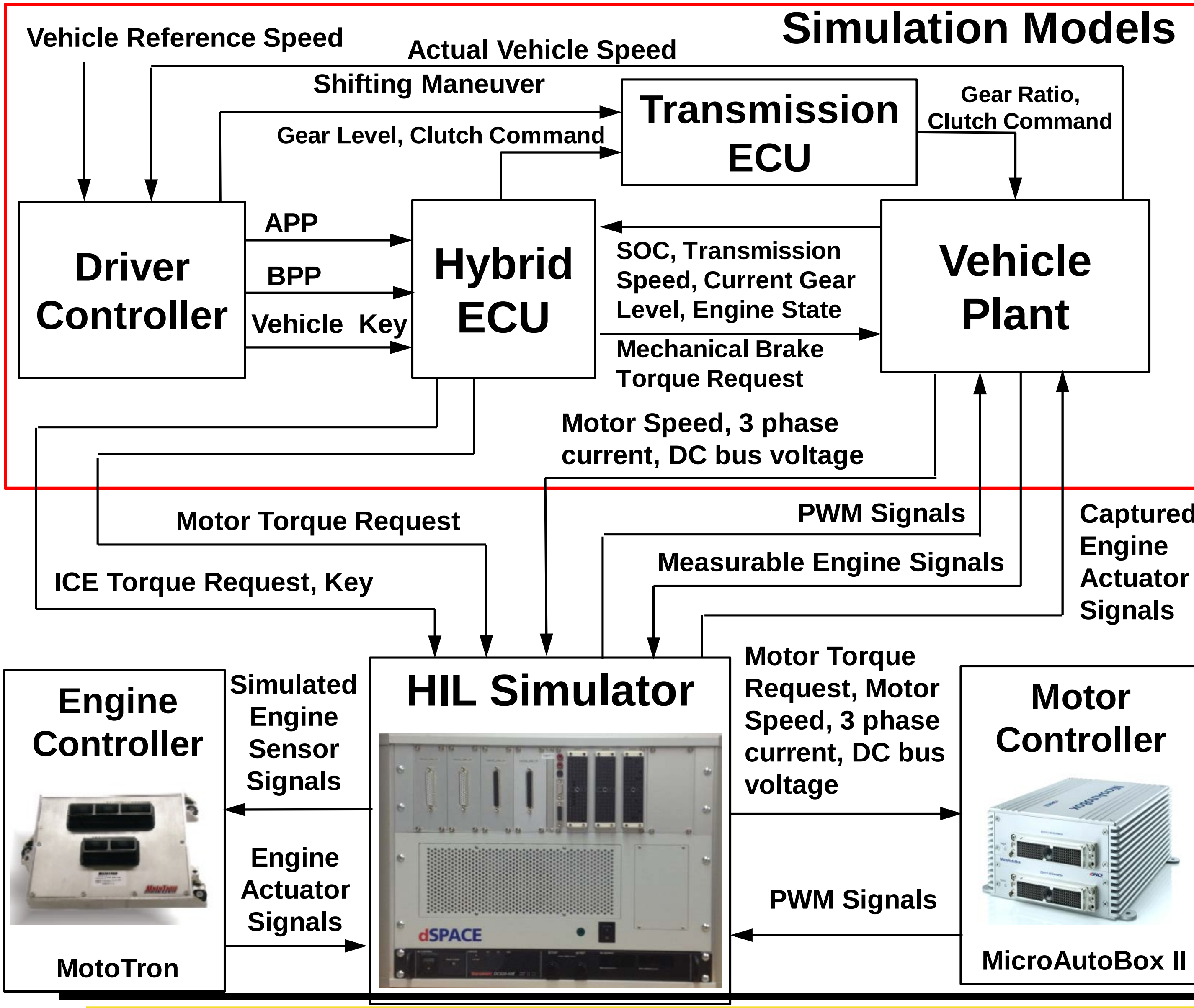
HIL Setup for the Parallel HEV



- dSPACE HIL simulator
- MicroAutoBox II for motor controller
- MotoTron 128 pin ECM for engine controller



Signal for the Parallel HEV



Signals between Engine Controller and Vehicle Plant

Sensor signals:

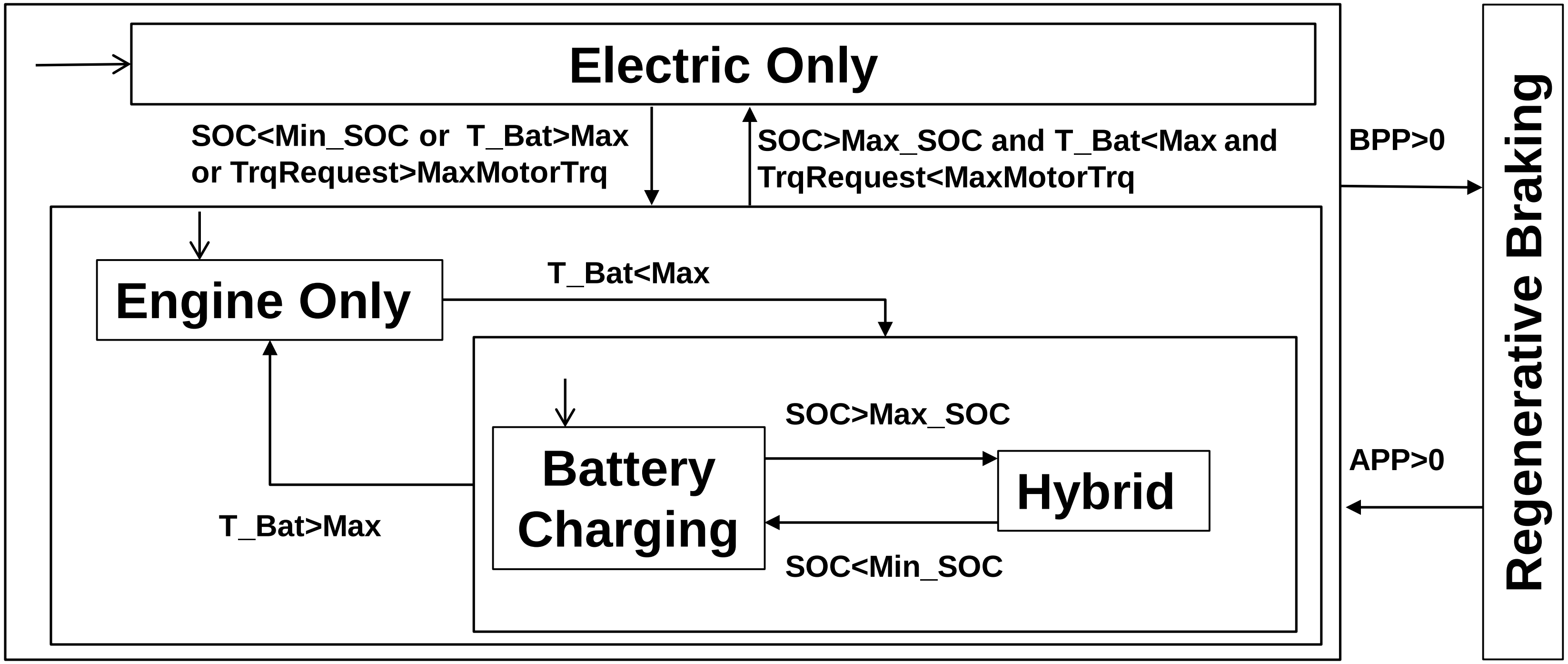
- AFM through throttle
- engine speed
- intake manifold pressure and temperature
- EGR valve position
- coolant temperature
- injection pressure…

Actuator signals:

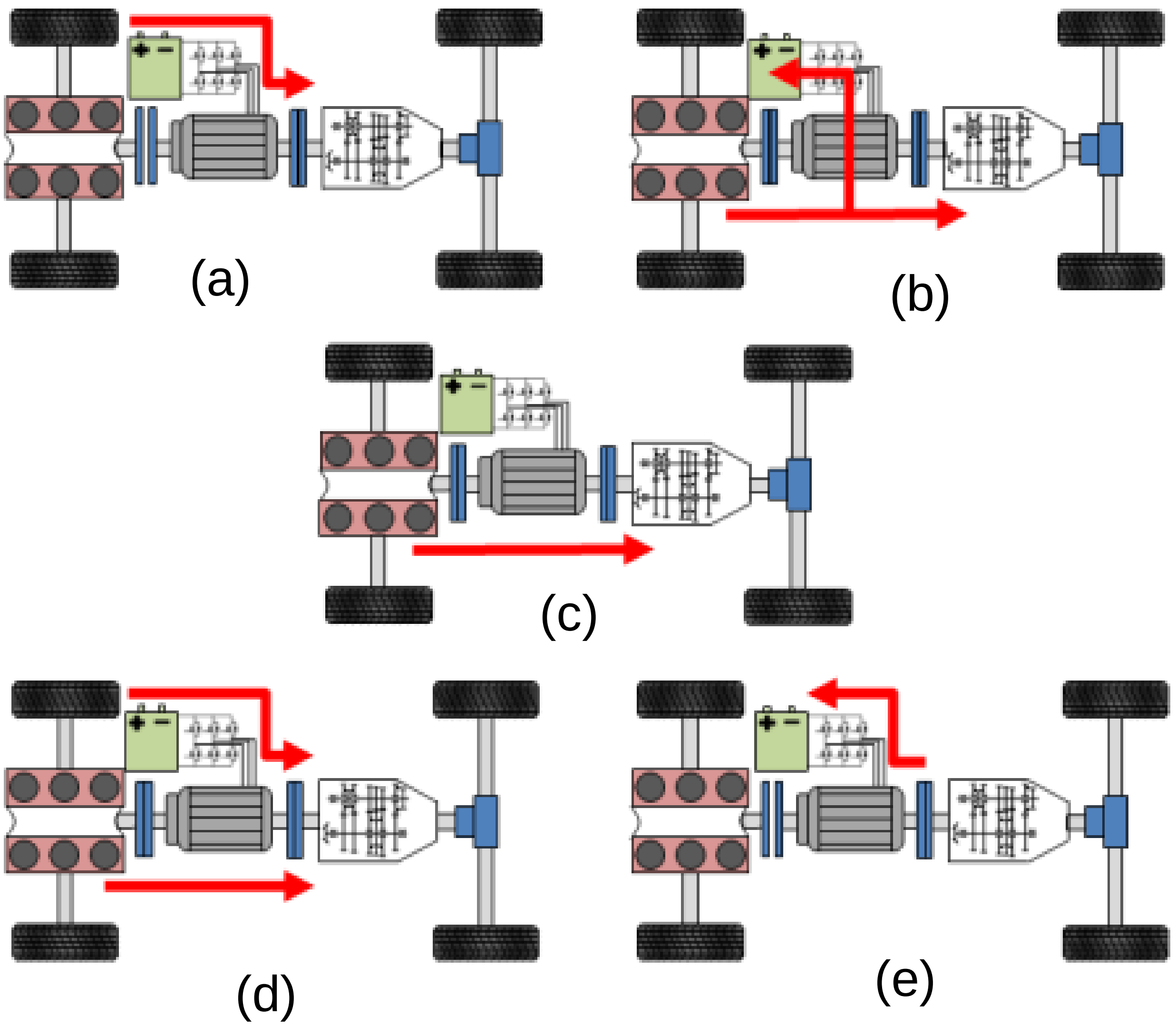
- Ignition angle and duration
- injection angle and duration
- throttle valve, EGR valve, and pressure control valve position PWM control signal

Hybrid ECU

- Vehicle operating mode control
- Split powertrain torque between engine and electric machine to achieve maximum fuel economy
- Control regenerative braking to recover as much energy as possible and ensure braking performance at the same time

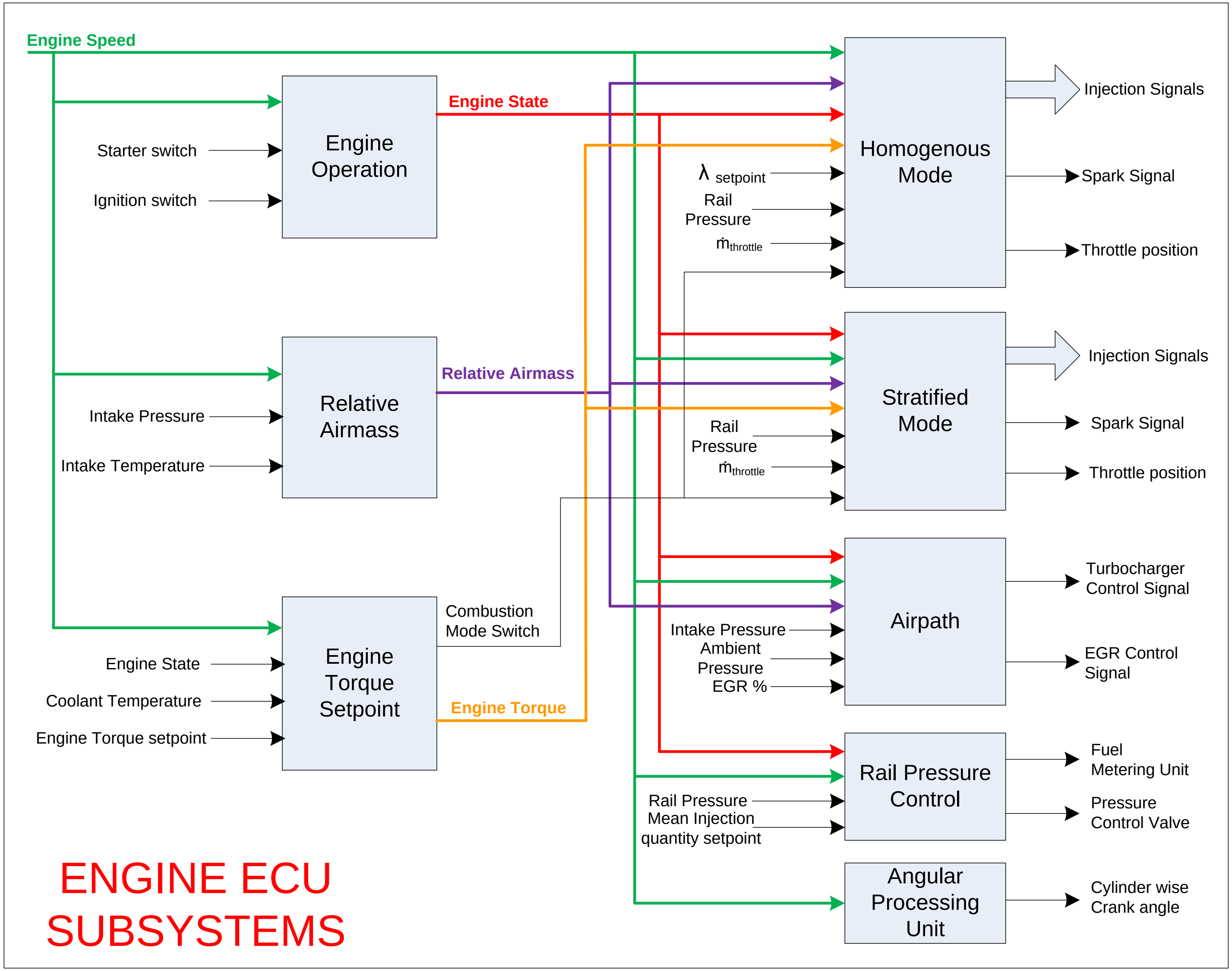


Vehicle Mode and Energy Flow



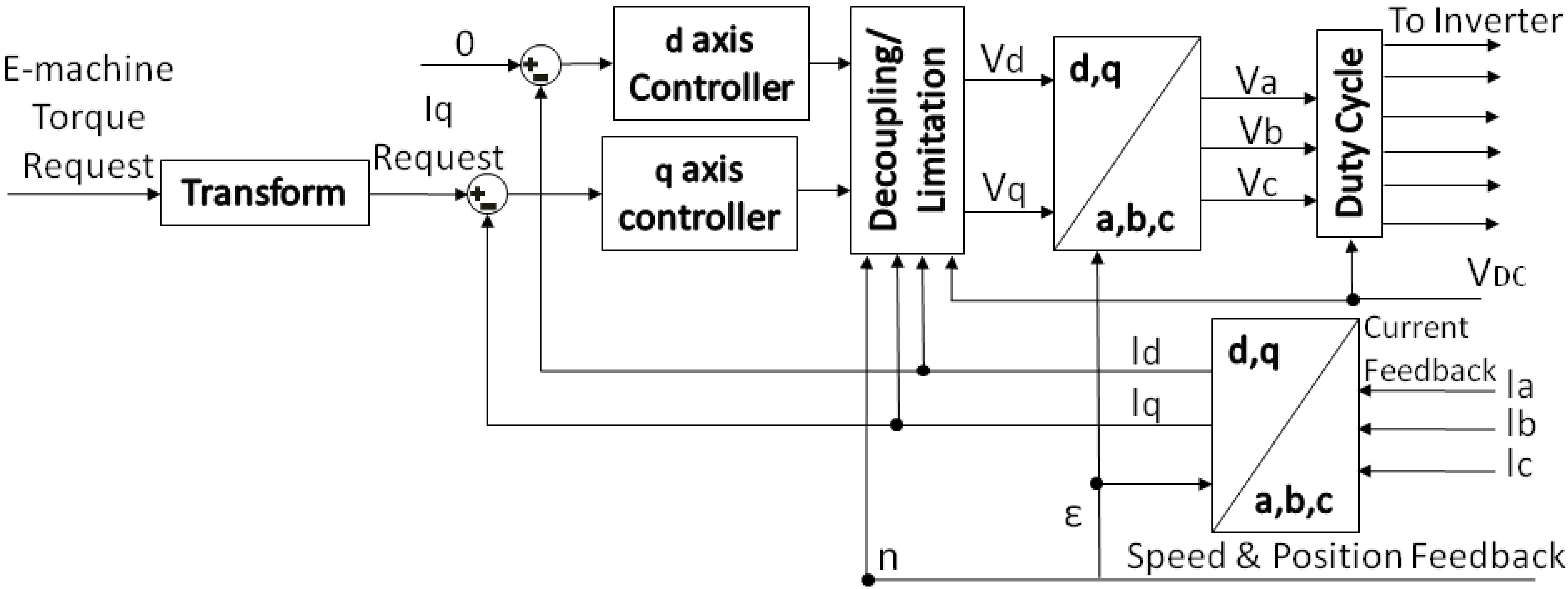
(a) Electric only mode
(b) Battery charging mode
(c) Engine only model
(d) Hybrid mode.
(e) Regenerative braking mode

Overview of Engine ECU

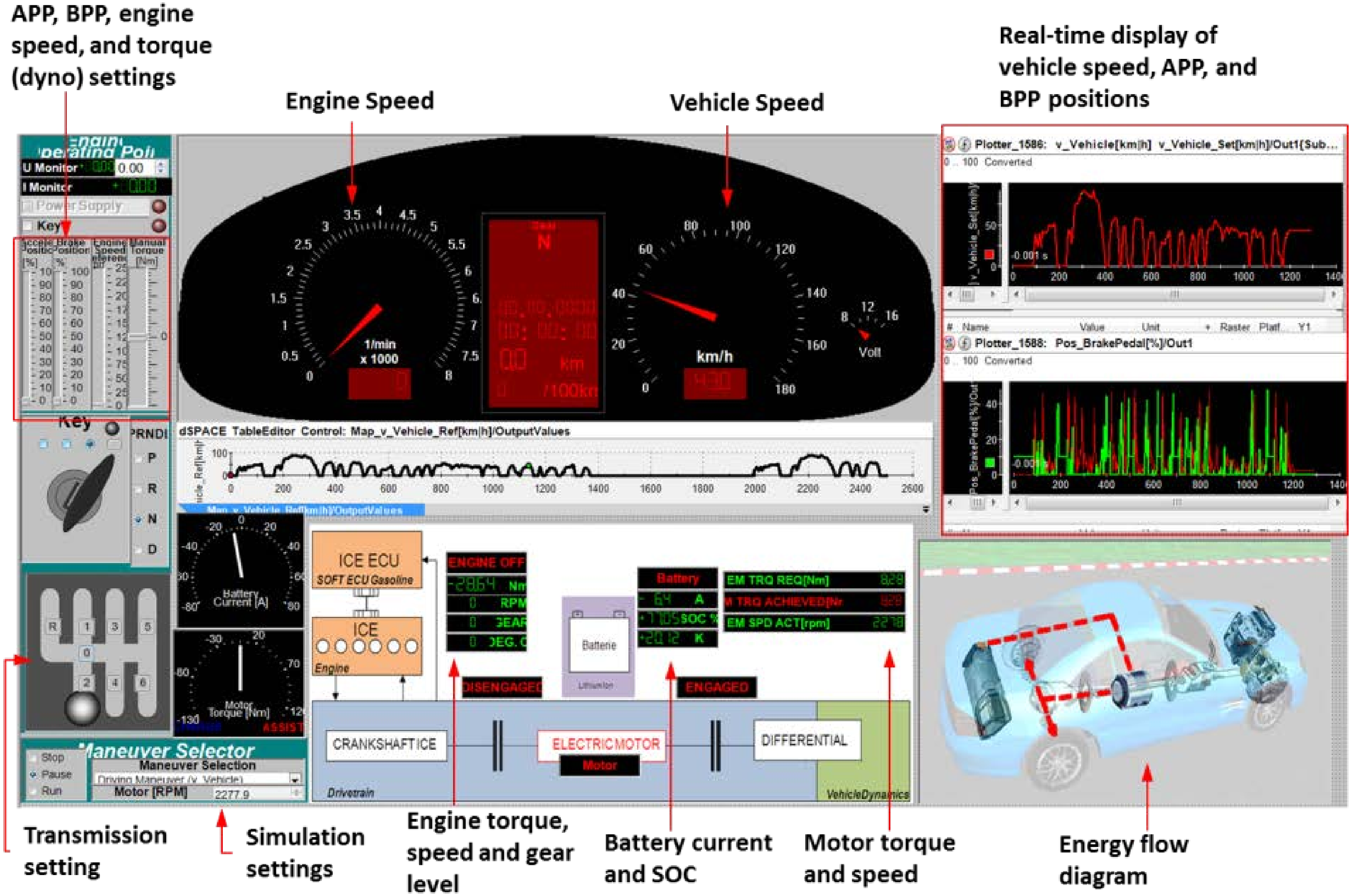


- Injection signals
- Ignition signals
- Throttle position
- Turbocharger control signal
- EGR control signal
- Rail pressure control signals
- Engine position

Motor Controller



dSPACE Experiment Software - ControlDesk

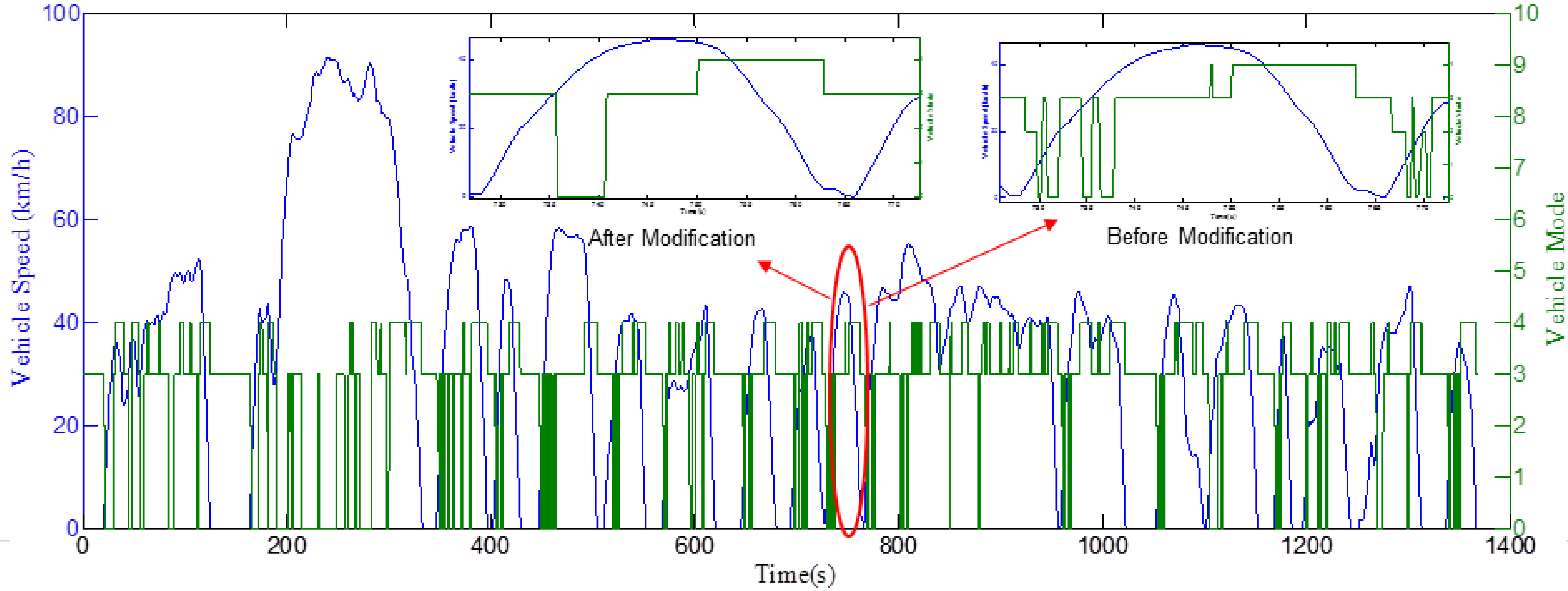


Simulation Results: Vehicle Mode Control

#	Vehicle Mode
0	Battery charging
1	Engine only
2	Hybrid mode
3	Motor only
4	Regenerative breaking

- Hybrid ECU control logic is modified to avoid frequent mode change.
- Improved vehicle performance is shown in enlarged subfigures.

Vehicle operation modes in UDDS drive cycle



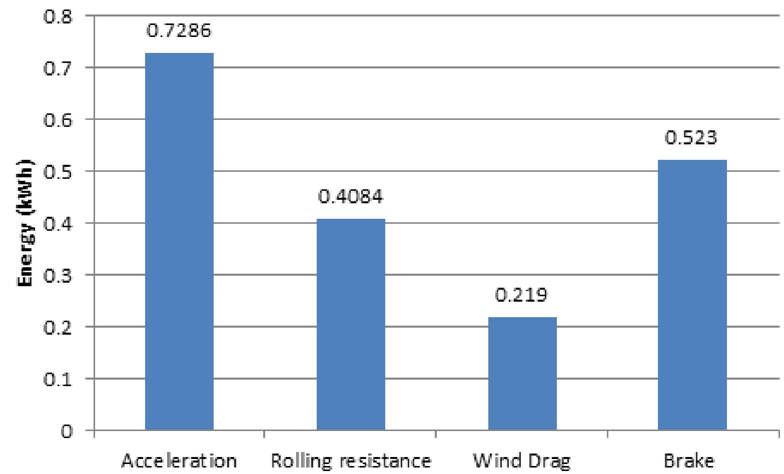
Simulation Results: Power and Energy Distribution

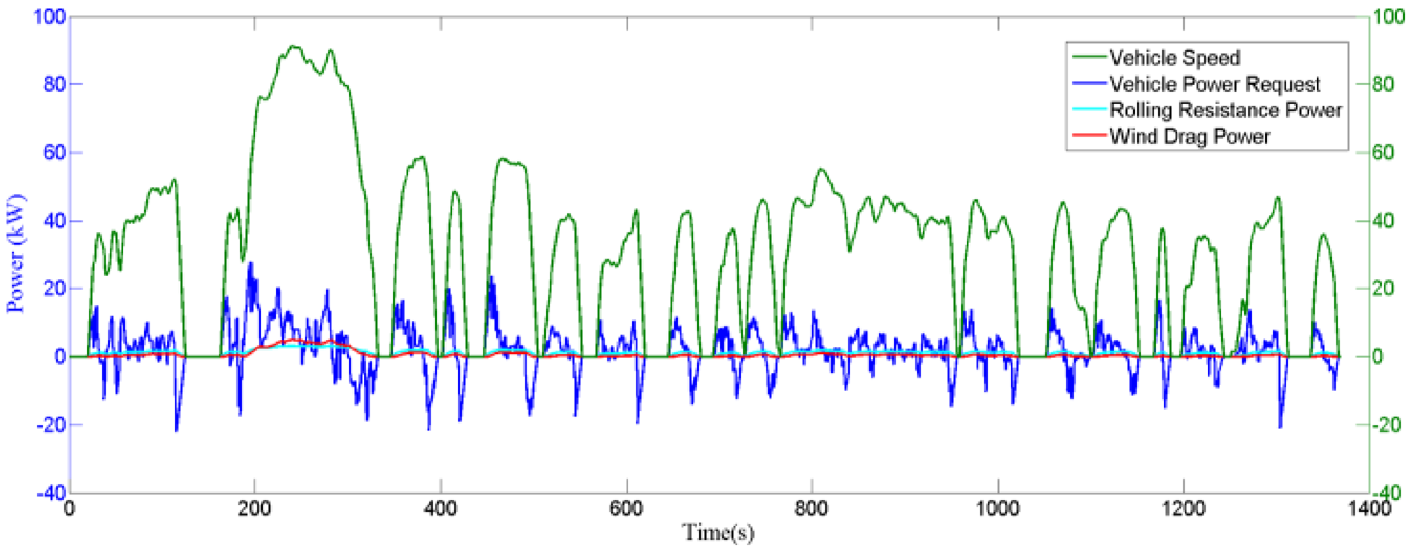
$$\sum F_x = ma = F_T - F_{roll} - F_{Wd} - F_{Gf}$$

$$P_{req} = F_T \cdot v = (ma + F_{roll} + F_{Wd} + F_{Gf}) \cdot v$$

$$F_{roll} = mg\cos\theta\, f_r \qquad F_{Wd} = \frac{1}{2}\rho c_d A v^2 \qquad F_{Gf} = mg\sin\theta$$

Rolling resistance | Wind drag | Gravitational force

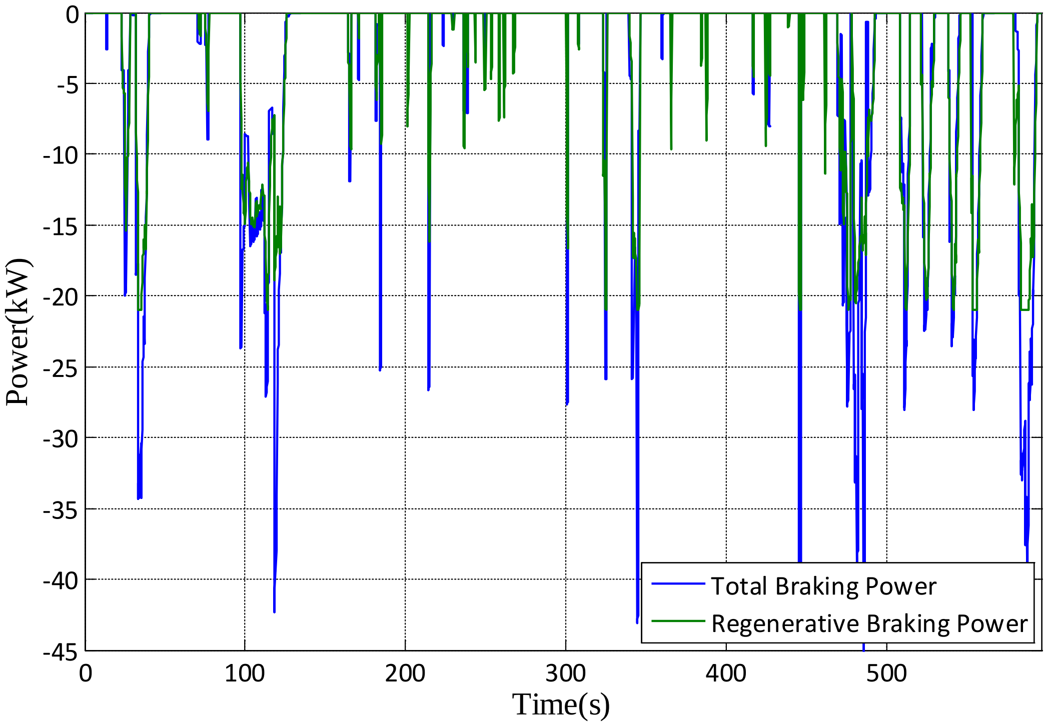




Vehicle power request, rolling resistance power, and wind drag power over a UDDS drive cycle

Simulation Results: Regenerative Breaking

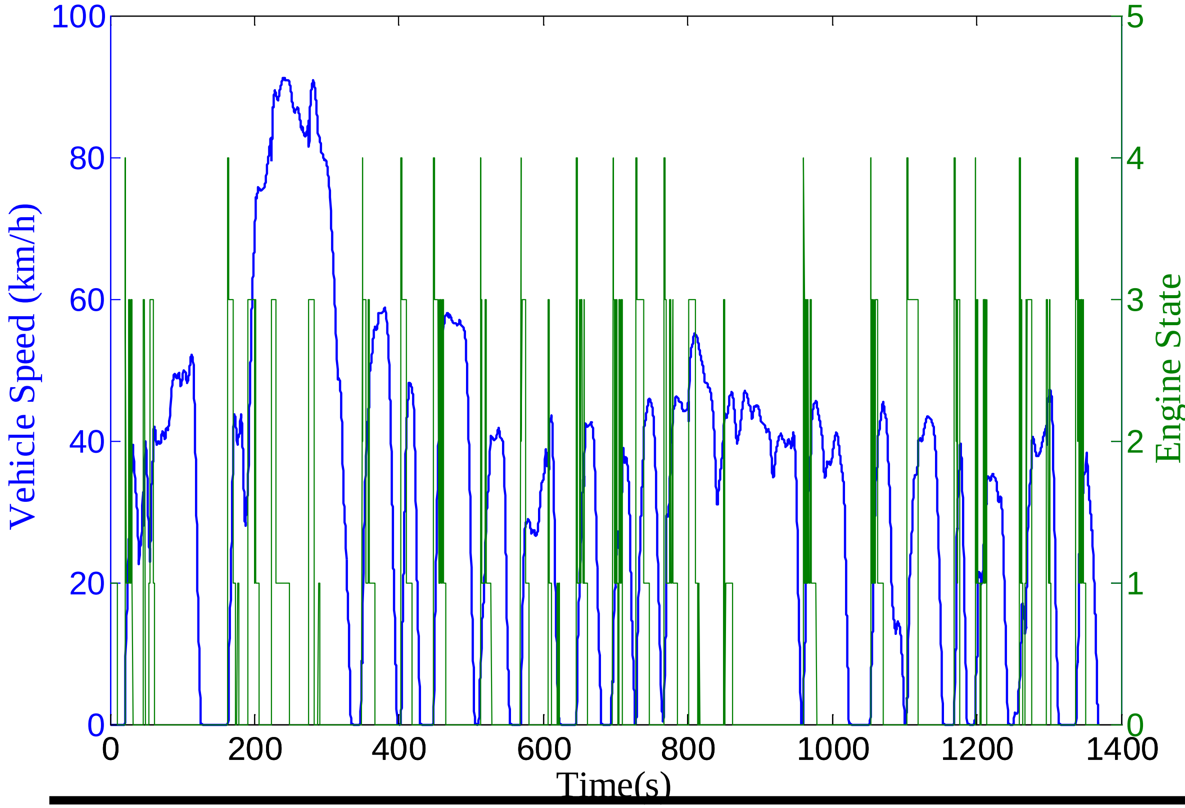
- Designed to recover as much as possible
- Disabled when *v* < 0.1 km/h or SOC reached charging limit
- Limited by maximum motor power
- 81% braking energy was recovered, total 0.4638 kWh



Braking power in US06 drive cycle

Simulation Results: Engine States

State value	1	2	3	4
Engine state	Idling	Engine Traction only	Traction & charging Battery	Traction with motor

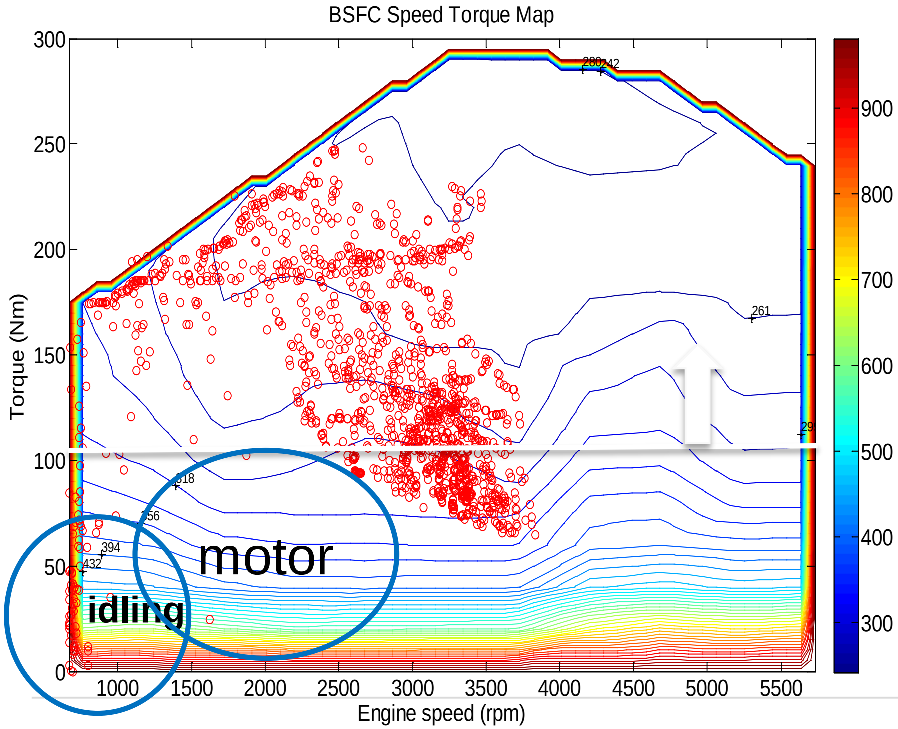


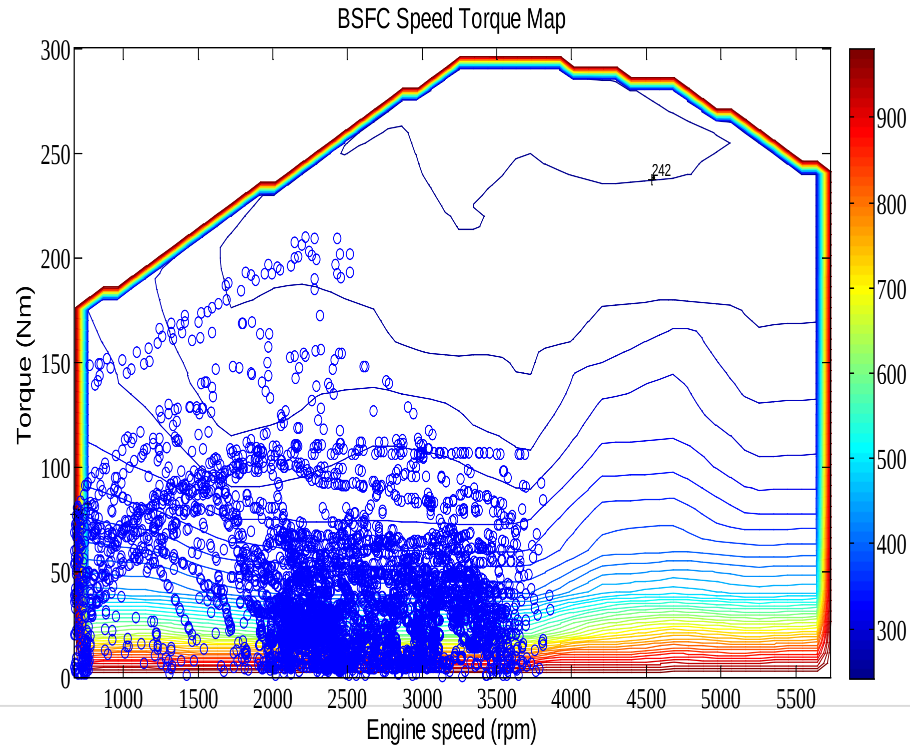
Engine On	30.8%
Engine idling	53.3%

Engine states in UDDS drive cycle

Simulation Results: Engine Operating Region

- Engine operating points: HEV (left), conventional vehicle (right)
- Motor provides traction when torque demand below 100 Nm.





Conclusions

- Model-based design allows ECU development with vehicle plant models in the same environment.
- Hardware-in-the-loop simulation enable very short development times with parallel control system validation.
- Model-based design HIL simulation are suitable for the development of complex control systems for the clean vehicles.

Acknowledgements

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WHERE DISCOVERIES BEGIN

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