Plug-in Hybrid Powertrain Modeling

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Why Plug-in?

Fuel Efficiency

More active participation of electric drive allows IC engine to operate near peak efficiency.

Greenhouse Gas Emissions

Increased drivetrain efficiency results in lower emissions. On average, a 15% reduction in CO_2 vs. conventional hybrids [1].

Operating Costs

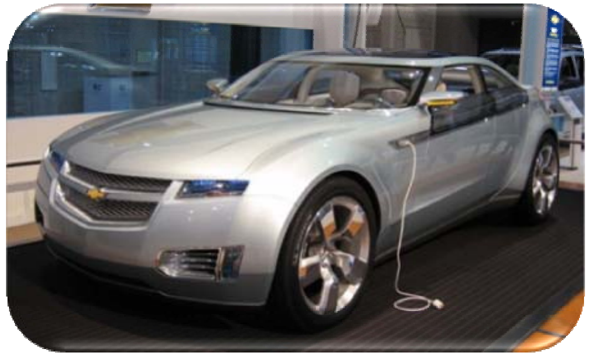
The low cost of electricity (especially at off-peak hours) decreases the cost per gallon of gasoline equivalent.

Vehicle-to-Grid (V2G)

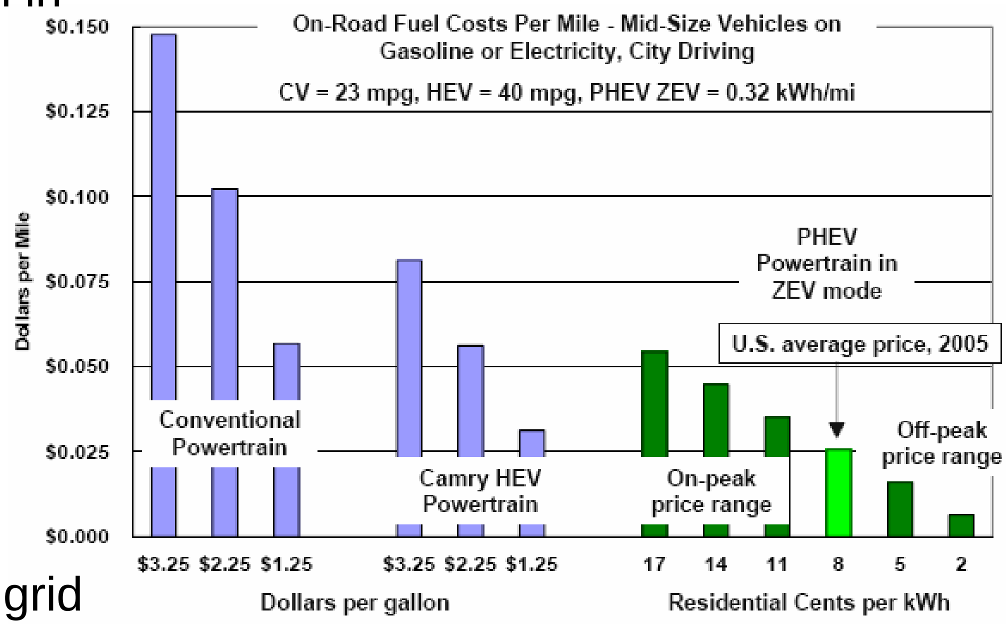
Recharge battery during off-peak hours

Excess battery capacity to load balance grid

Electrical capacitance for intermittent renewable energy



Chevrolet Volt Concept Car at 2007 NAIAS



Source: Santini *et al,* "Energy and Petroluem Attribues of Plug-in Hybrids," Sept 2007.

Problem Statement

Research Question

What is the optimal power management strategy to minimize fuel consumption and emissions?

Literature Review

Current PHEV power management strategies adopt the conventional hybrid methodology: charge depletion & sustenance. Can improved performance be achieved with “blending”?

Problem Statement

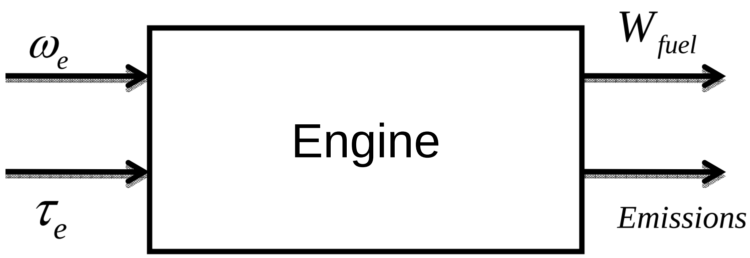
Develop a control-oriented model of sufficient fidelity and minimal complexity for power management control synthesis

Outline

- Why Plug-in?
- Engine, Battery, Electric Machine Models
- Vehicle Dynamics & Power-Split Device Models
- Rule-Based Power Management Strategy
- Dynamic Simulation & Analysis
- Summary & Future Work

Engine

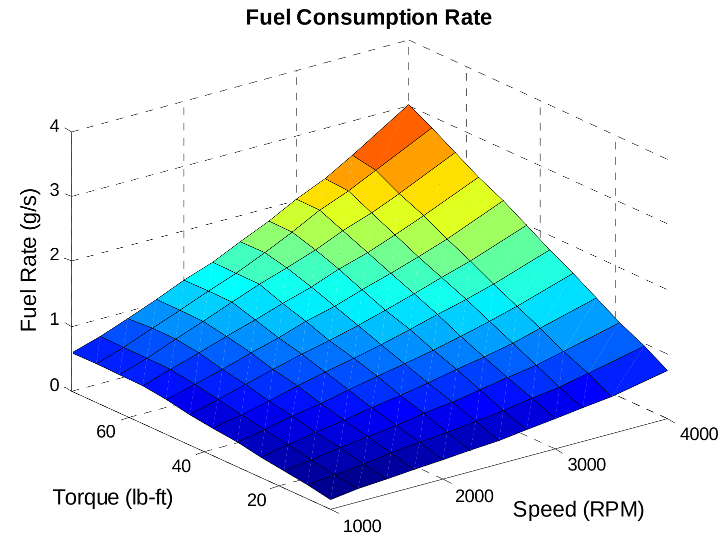
Engine Model Adapted from ADVISOR 2004

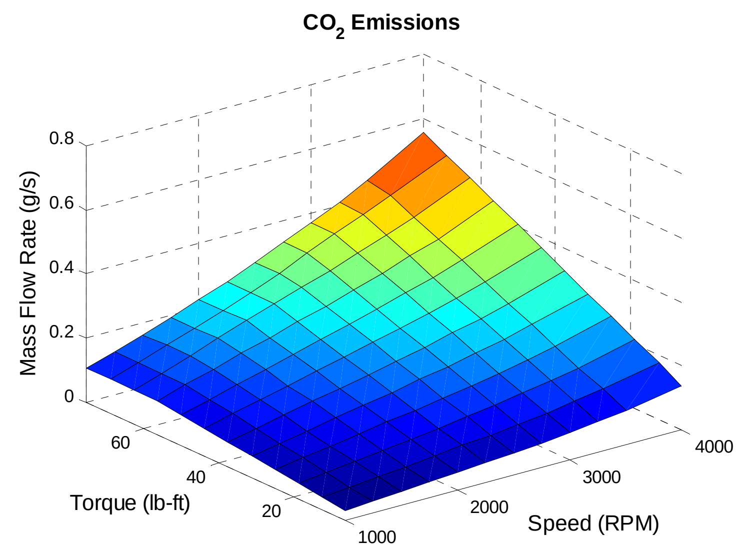


Experimental maps and regression models

$$W_{fuel} = f_{fuel}(\omega_e, \tau_e, T_e)$$
$$W_{HC} = f_{HC}(\omega_e, \tau_e, T_e)$$
$$W_{CO} = f_{CO}(\omega_e, \tau_e, T_e)$$
$$W_{NO_x} = f_{NO_x}(\omega_e, \tau_e, T_e)$$
$$W_{PM} = f_{PM}(\omega_e, \tau_e, T_e)$$

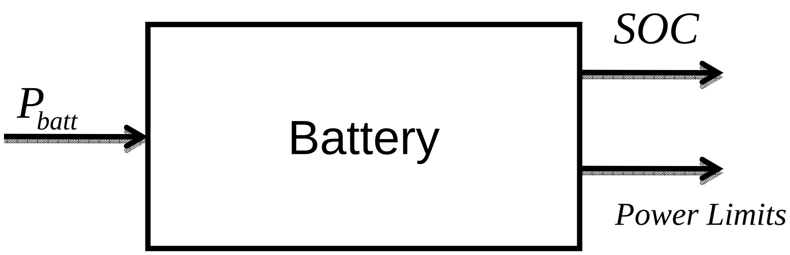
NOTE: The model contains NO dynamics (i.e. manifold filling, induction to power delays, boost lag, etc.)





Battery

Equivalent Resistance model of NiMH Battery



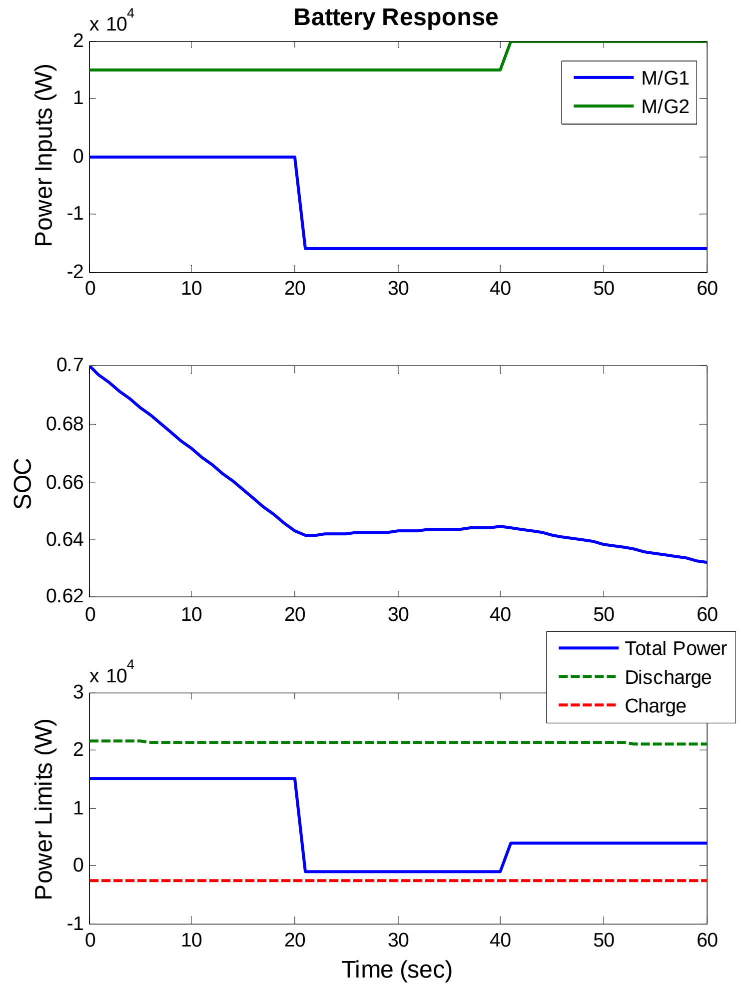
$$S\dot{O}C = -\frac{I_{batt}}{Q_{batt}}$$

$$P_{batt} = V_{oc} I_{batt} - I_{batt}^2 R_{batt} \qquad P_{batt} = P_{m/g1} + P_{m/g2}$$

$$V_{oc} = f\left(SOC\right) \qquad R_{batt} = g\left(SOC\right)$$

$$S\dot{O}C = -\frac{V_{oc} - \sqrt{V_{oc}^2 - 4 P_{batt} R_{batt}}}{2 R_{batt} Q_{batt}}$$

First order nonlinear ordinary differential equation

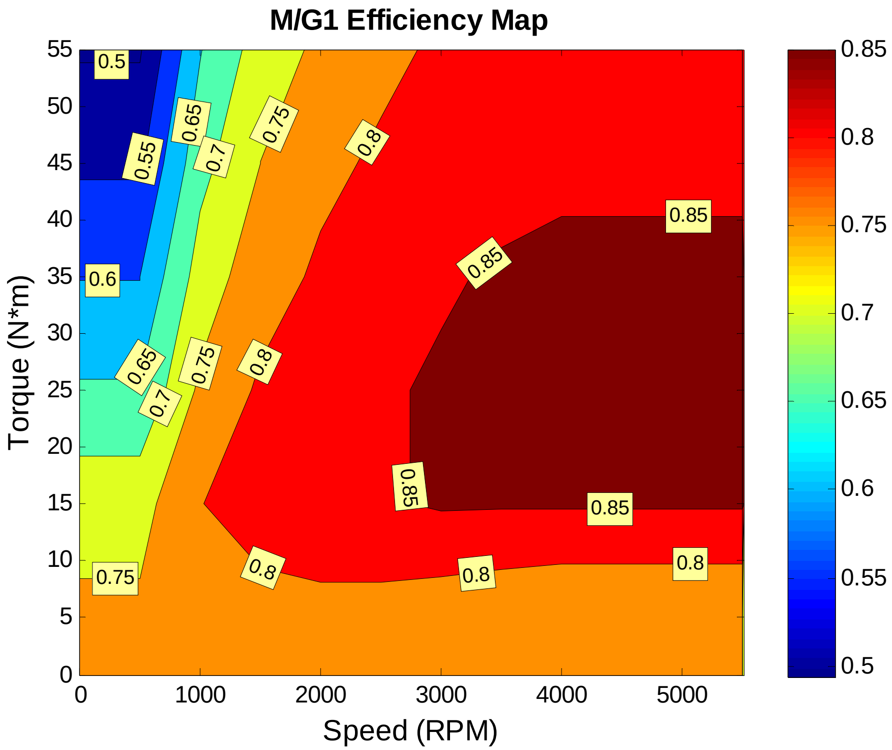


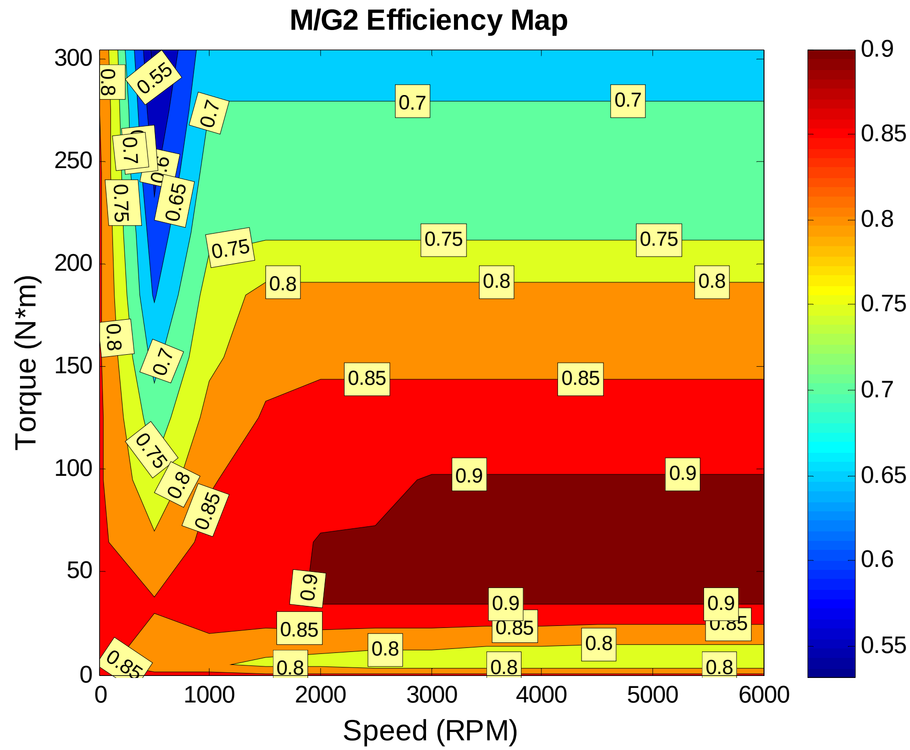
Electric Machines

Assume the electric machine time constant is faster than other system dynamics

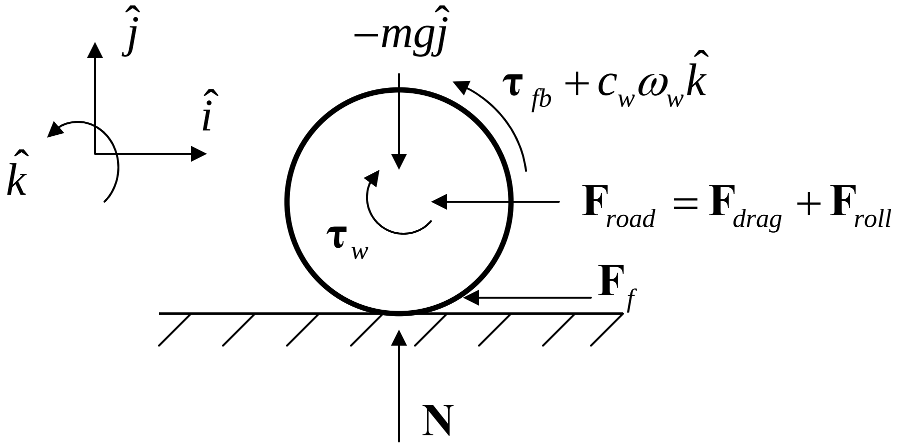
Modeled by efficiency tables, given in ADVISOR 2004

$$\eta_{m/g1} = f_1\left(\omega_{m/g1}, \tau_{m/g1}\right) \qquad \eta_{m/g2} = f_2\left(\omega_{m/g2}, \tau_{m/g2}\right)$$





Vehicle Dynamics



- Model the vehicle as a point mass
- Assume no slip

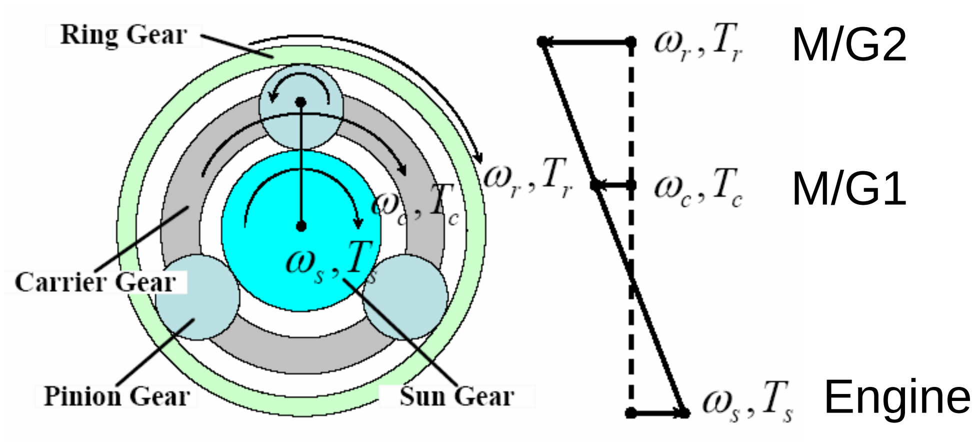
Rolling Friction $F_{roll} = \mu_{roll} mg$

Viscous Air Drag $F_{drag} = \frac{1}{2}\rho A C_d \|v_x\|^2 = \frac{1}{2}\rho A C_d \|R_{tire}\omega_w\|^2$

Euler's Equation about the contact point in the k-direction

$$-J\dot{\omega}_w = -\tau_w + \mu_{roll} mg R_{tire} + \frac{1}{2}\rho A C_d \|R_{tire}\omega_w\|^2 R_{tire} + T_{fb} + C_w \omega_w$$

Power-Split Device



$$\omega_e S + \omega_r R = \omega_c \left(R + S \right)$$

$$\left(I_{M/G1} + I_s \right) \dot{\omega}_{M/G1} = \tau_{M/G1} + FS$$

$$\left(I_e + I_c \right) \dot{\omega}_e = \tau_e - \left(R + S \right) F$$

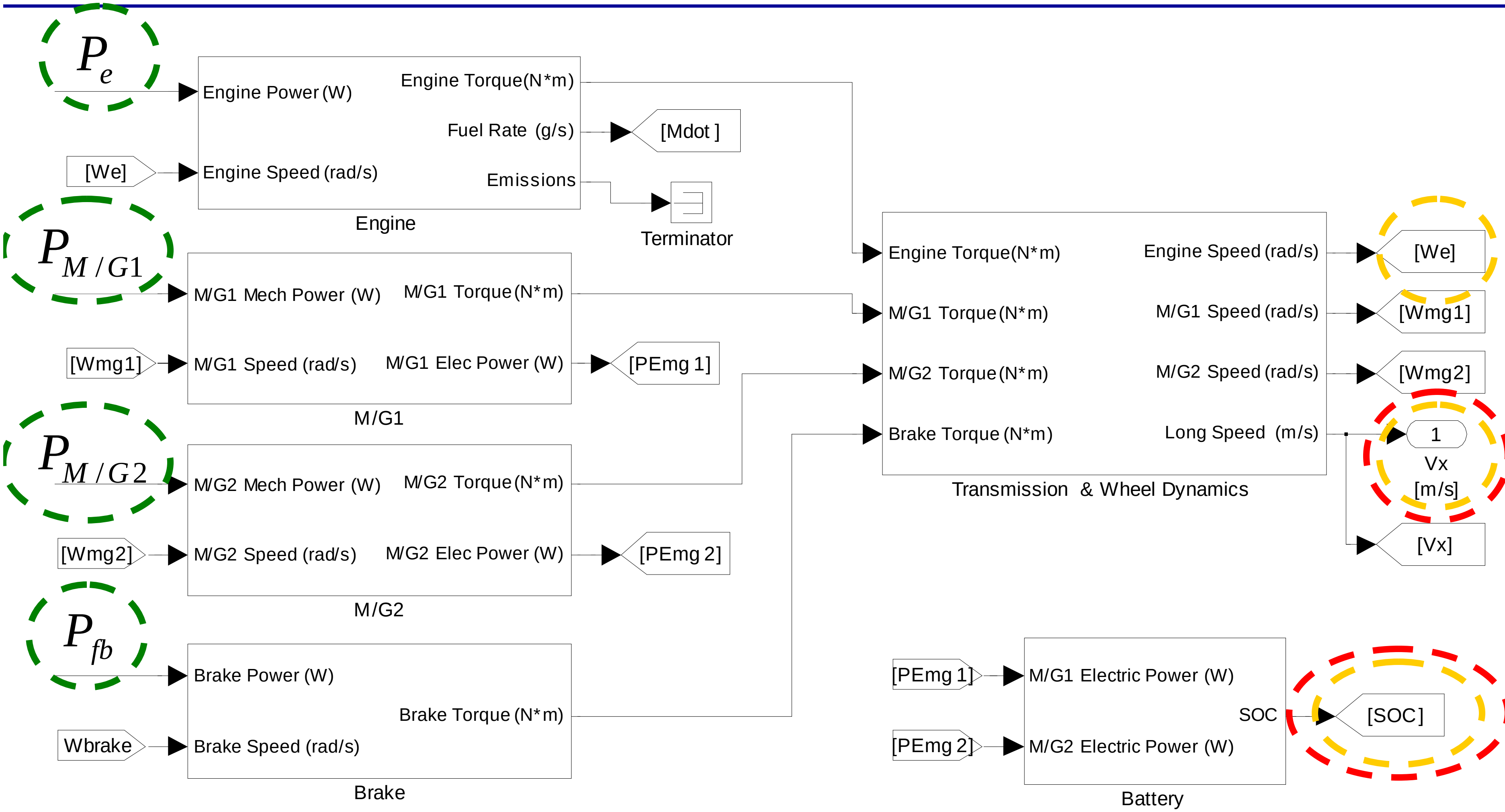
$$\left(I_{M/G2} + I_r \right) \dot{\omega}_r = \tau_{M/G2} + FR - \tau_r$$

$$\frac{\omega_r}{\omega_w} = K = \frac{\tau_w}{\tau_r} \quad \Rightarrow \quad \left(I_{M/G2} + I_r \right) \dot{\omega}_r = \tau_{M/G2} + FR - \frac{F_{road}}{K} R_{tire} - \frac{\tau_{fb}}{K} - \frac{C_w \omega_r}{K}$$

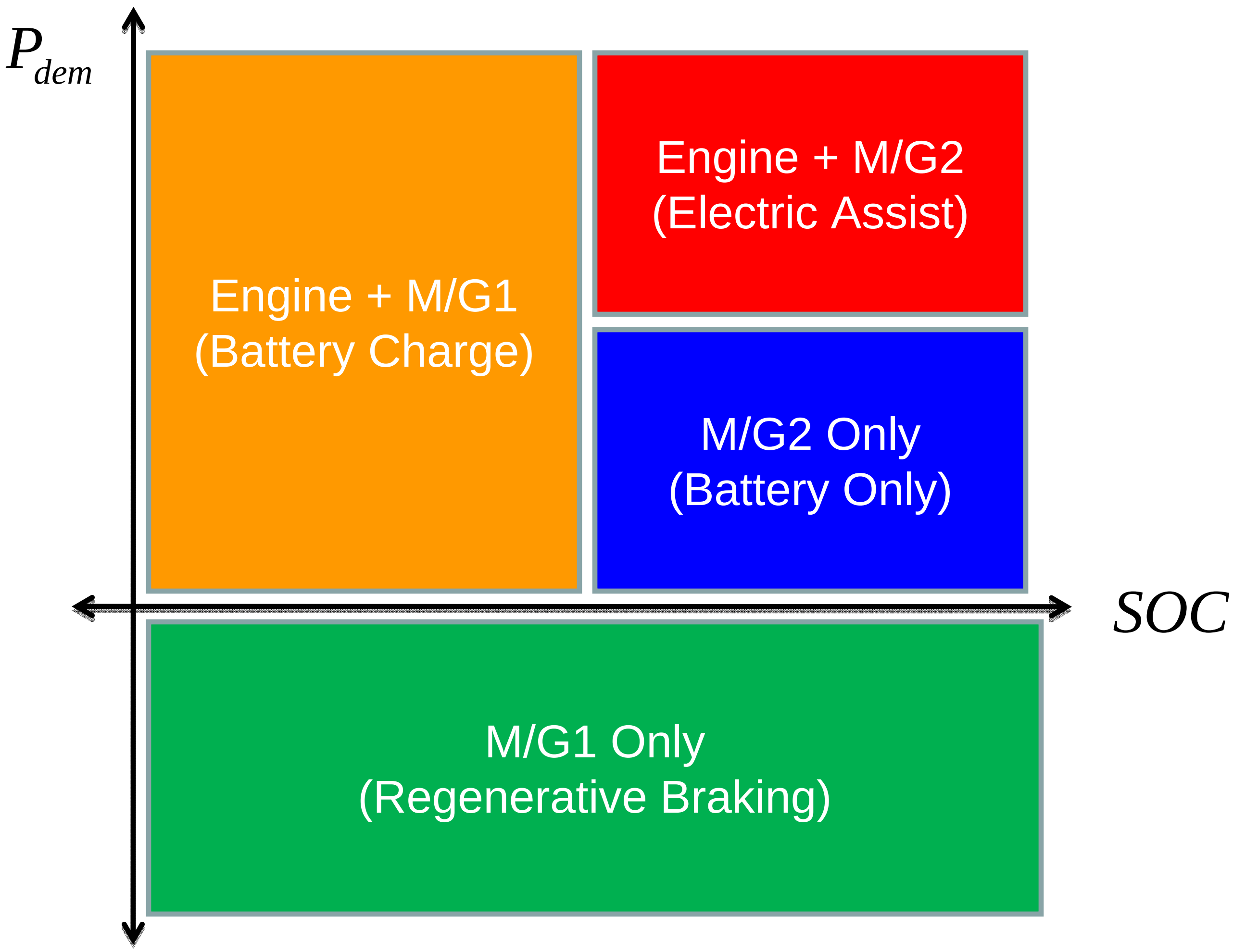
$$\begin{bmatrix} I_s + I_{M/G1} & 0 & 0 & -S \\ 0 & I_e + I_c & 0 & R+S \\ 0 & 0 & I_{M/G2} + I_r + \frac{J}{K^2} & -R \\ S & -\left(R+S\right) & R & 0 \end{bmatrix} \begin{bmatrix} \dot{\omega}_{M/G1} \\ \dot{\omega}_e \\ \dot{\omega}_r \\ F \end{bmatrix} = \begin{bmatrix} \tau_{M/G1} \\ \tau_e \\ \tau_{M/G2} - \frac{F_{road} R_{tire} - T_{fb} - C_w \omega_r}{K} \\ 0 \end{bmatrix}$$

Adapted from Liu *et al* [3]

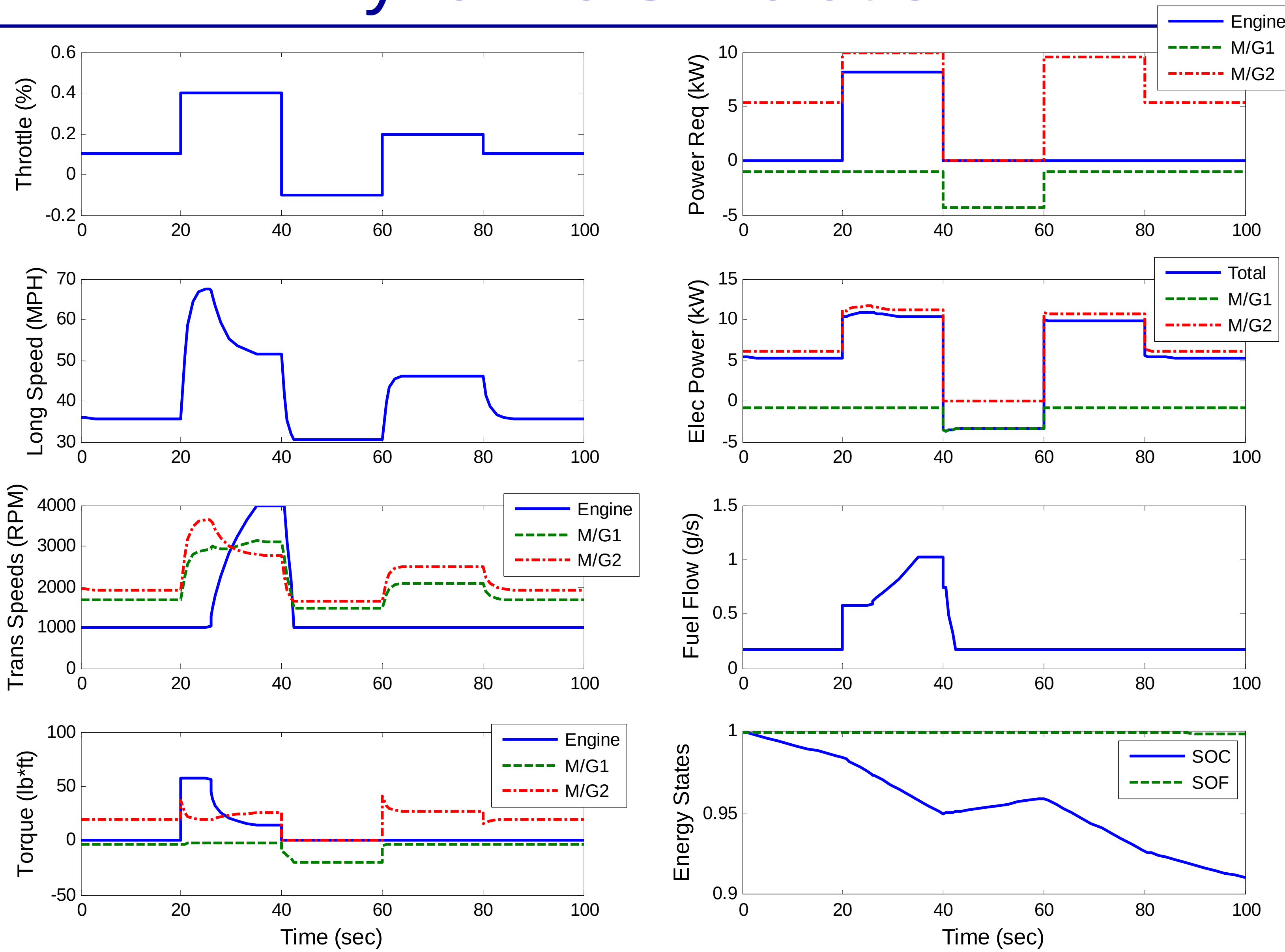
System Level Block Diagram



Rule-Based Power Management



Dynamic Simulation



Summary & Future Work

Summary

Developed:

1. Dynamic powertrain models for higher fidelity simulations
2. Rule-based power management strategy
3. Dynamic simulation analysis to verify model operation

Future Work

- Incorporate a stochastic driver model
- Apply stochastic dynamic programming to find the optimal "blended-mode" operation
- Utilize optimal design techniques to balance performance and battery size (i.e. cost)

Key References

[1] Kliesch, J. and Langer, T. "Plug-In Hybrids: an Environmental and Economic Performance Outlook" American Council for an Energy-Efficient Economy, Sept 2006.

[2] O'Keefe, M. P., and Markel, T., 2006, "Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-In HEV," 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, (EVS-22), Anonymous Yokohama, Japan.

[3] Liu, J., Peng, H., and Filipi, Z., 2005, "Modeling and analysis of the Toyota hybrid system," 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Anonymous IEEE, Monterey, CA, USA, **OL. 1,** pp. 134-9.

[4] Liu, J., and Peng, H., 2006, "Control optimization for a power-split hybrid vehicle," 2006 American Control Conference, Anonymous IEEE, Minneapolis, MN, USA, pp. 6.

QUESTIONS?