"I'm convinced that the country that leads in clean energy is also going to be the country that leads in the global economy. And I want America to be that nation."
– President Barack Obama, March 2, 2010

Optimal Control of Lithium-ion Battery Energy Storage Systems

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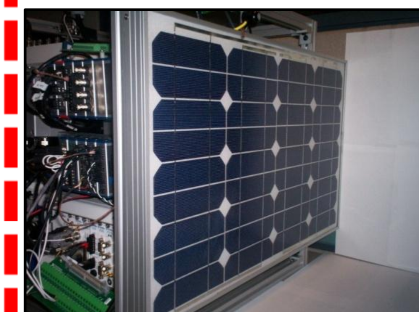
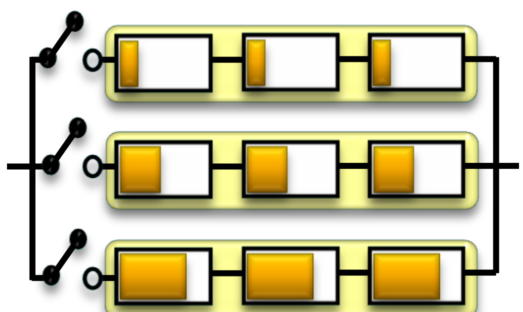
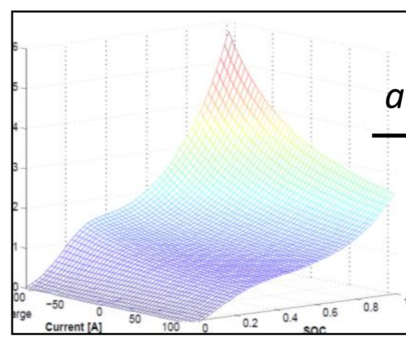
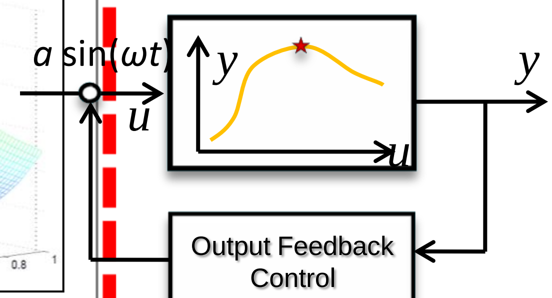
Department of Mechanical Engineering
University of Michigan, Ann Arbor, USA

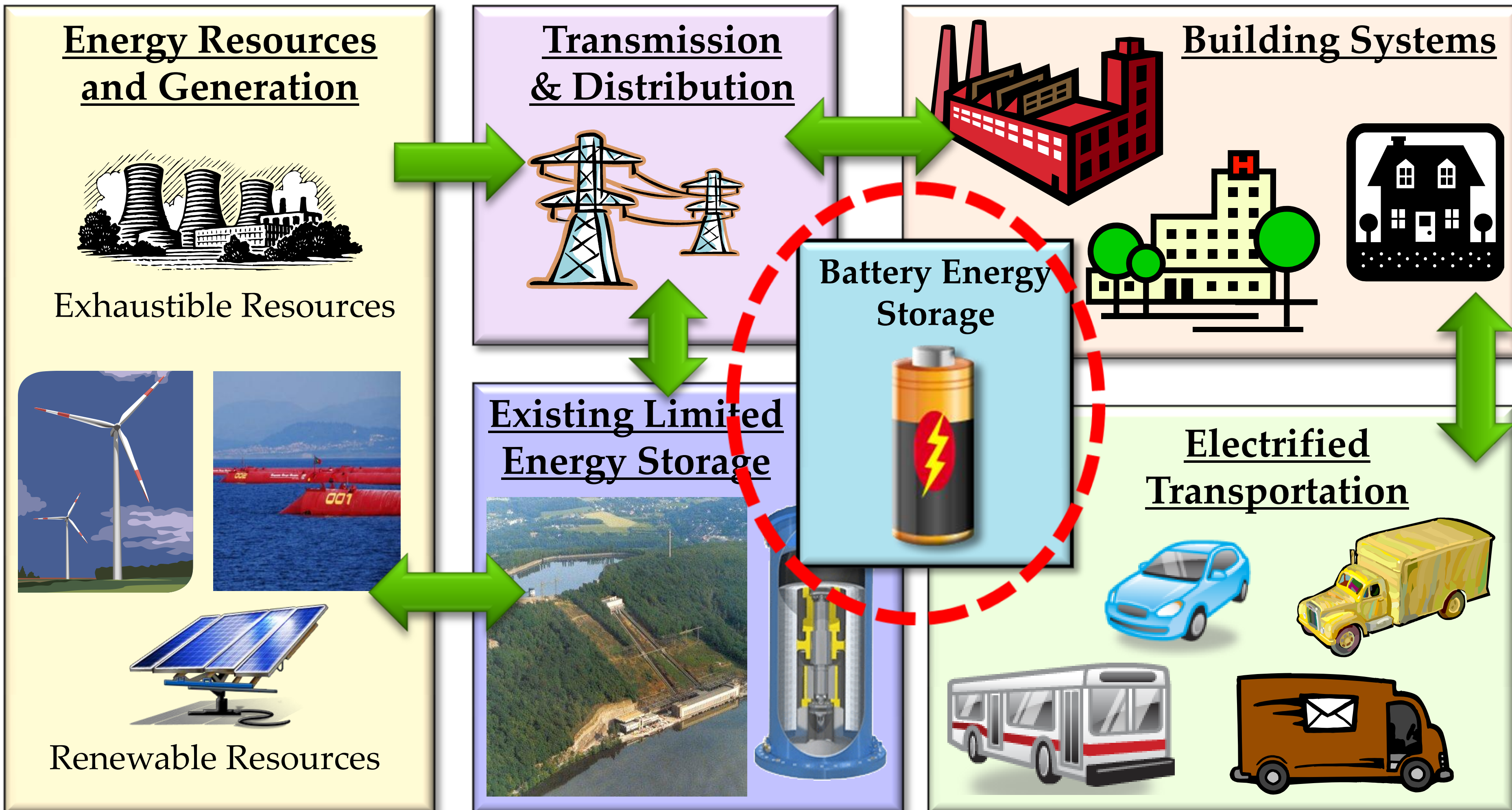
A Seminar Presentation at:

California Institute of Technology
Mechanical Engineering
Tuesday January 11, 2011

Overview of Research Contributions

APPLICATION / THEORY	Li-ion Batteries	Power Management	Photovoltaic and Fuel Cells
Theoretical Modeling & Identification		 $\begin{bmatrix} I_e & 0 & 0 & R+S \\ 0 & I_{M/G1} & 0 & -S \\ 0 & 0 & I'_{M/G2} & -R \\ -(R+S) & S & R & 0 \end{bmatrix} \begin{bmatrix} \dot{\omega}_e \\ \dot{\omega}_{M/G1} \\ \dot{\omega}_{M/G2} \\ F \end{bmatrix} = \begin{bmatrix} T_e \\ T_{M/G1} \\ T'_{M/G2} \\ 0 \end{bmatrix}$	
Optimal Control & Estimation			

Vision of Future Energy Infrastructure



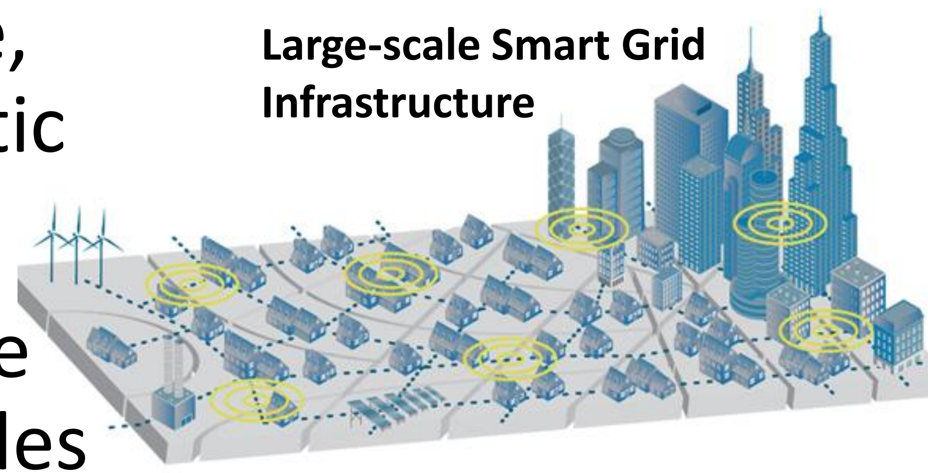
Technical Challenges

- Degradation not well understood -> overdesigned batteries

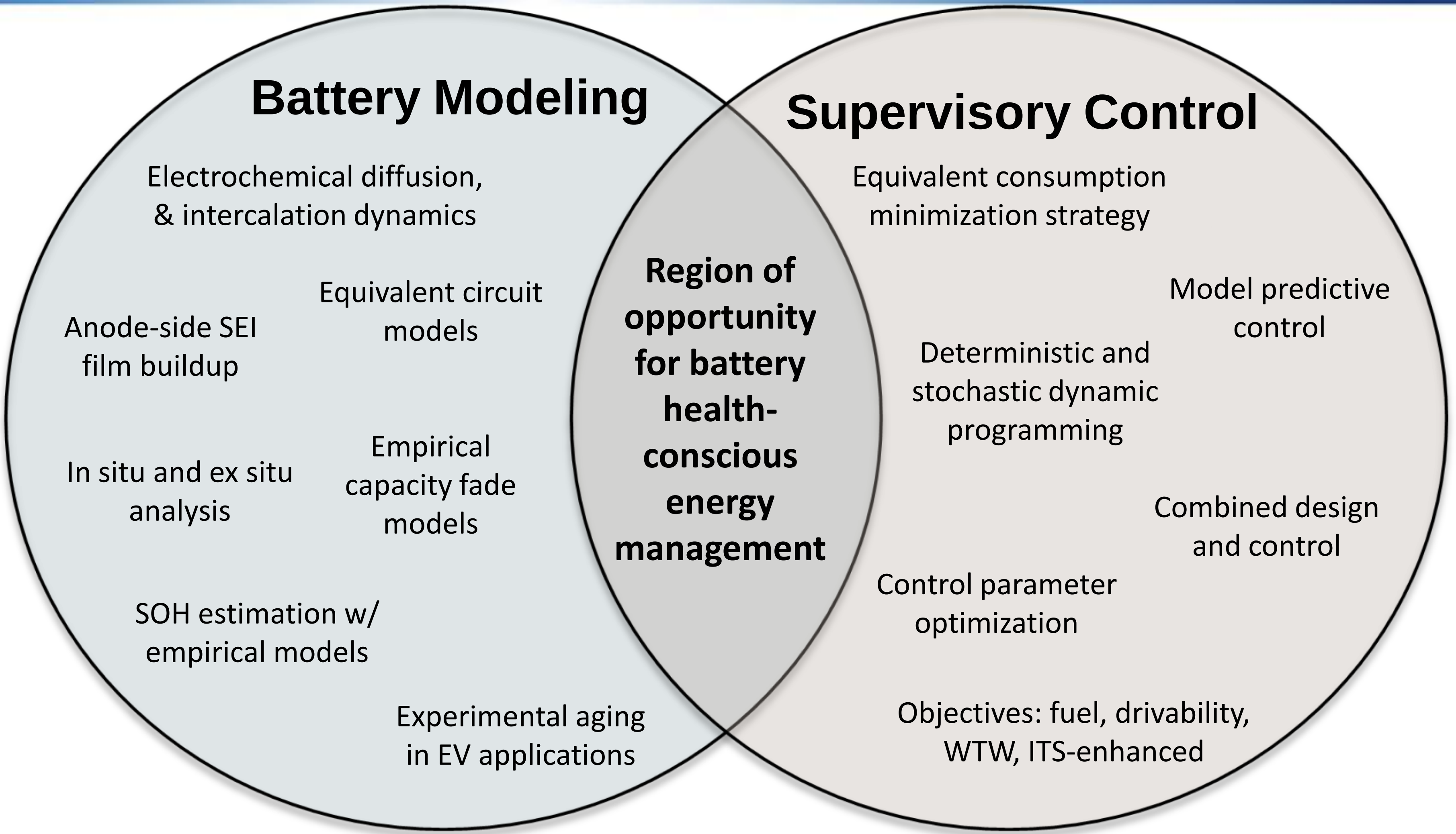
- Power management problem is multiobjective, constrained, and stochastic

- Smart Grid energy storage management at large scales

Chevrolet Volt Battery (16 kWh)



Literature Review



Key Research Topics

Electrochemical Battery Modeling

- Mathematical modeling based on first principles
- Experimental identification

Advanced Battery Pack Management

- The charge ***un***-equalization concept
- Modeling, optimal control, and analysis

PHEV Power Management

- PHEV powertrain and daily drive cycle modeling
- Stochastic optimal control
- Tradeoff analysis

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- **Mathematical modeling based on first principles**
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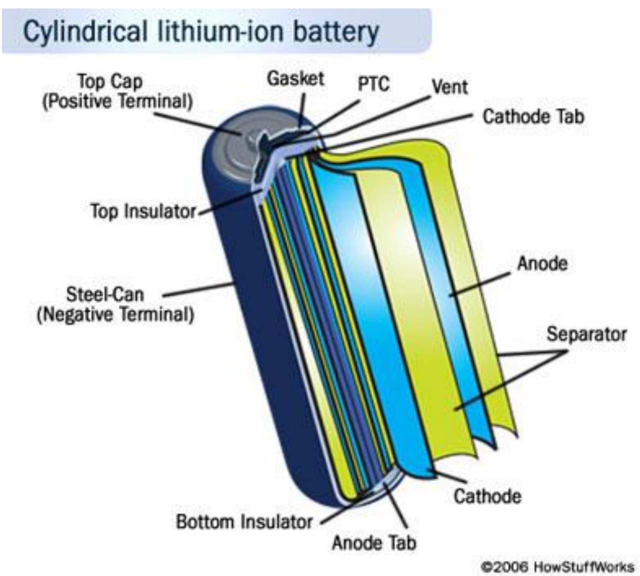
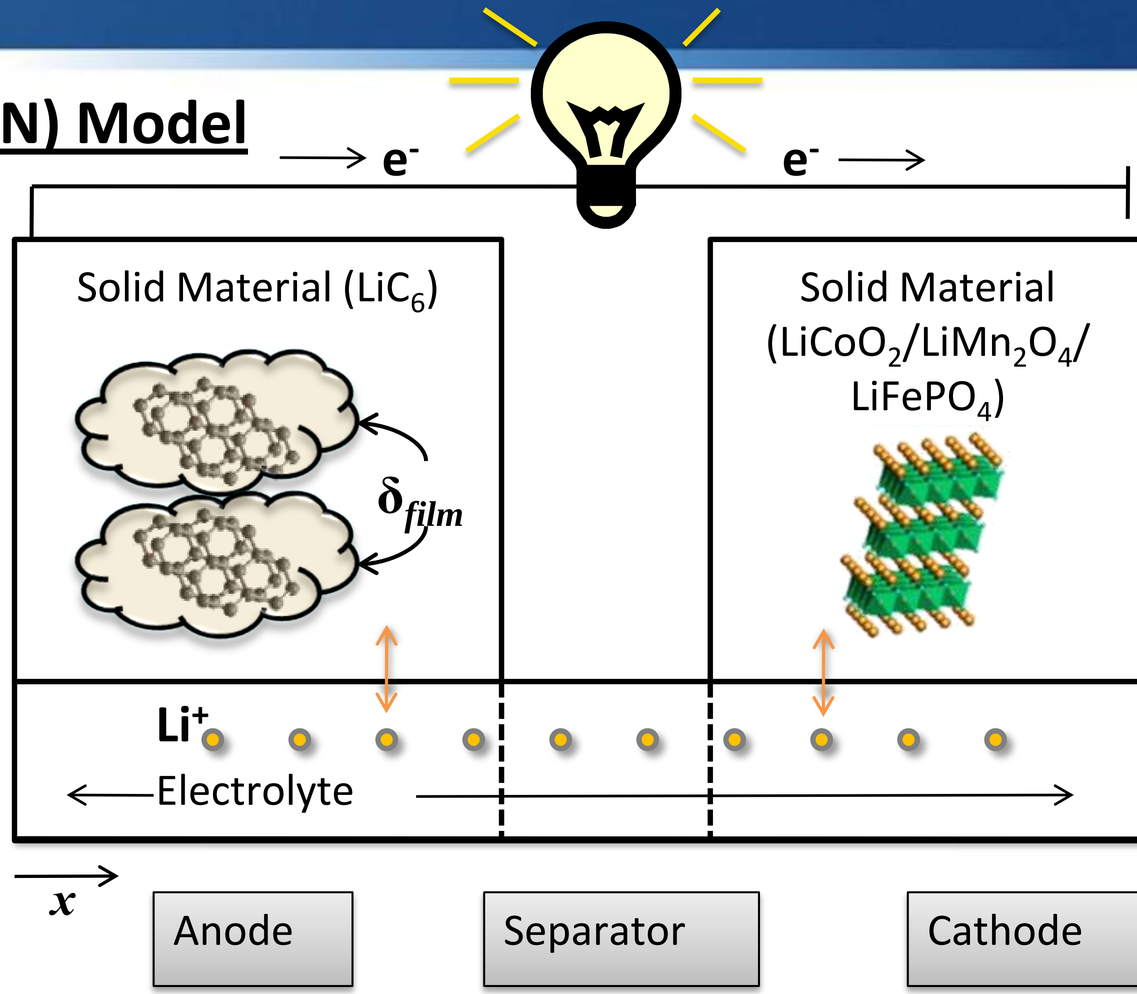
Electrochemical Li-ion Battery Modeling

Doyle-Fuller-Newman (DFN) Model





Diffusion, reaction, intercalation: Doyle, Fuller, Newman, 1993 and 1994

Anode-side SEI film buildup model: Ramadass *et al.*, 2004

Electrochemical Battery Model Eqns

A partial differential algebraic equation system (PDAE)

PDE's

$$\frac{\partial c_{1,j}(r,t)}{\partial t} = \frac{D_{1,j}}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial c_{1,j}}{\partial r}\right)$$

Spherical diffusion

$$\varepsilon_{2,j}\frac{\partial c_{2,j}(x,t)}{\partial t} = \nabla \cdot \left(D_2^{eff} \nabla c_{2,j}\right) + \frac{1-t^+}{F} J_j$$

Linear diffusion

$$\frac{\partial \delta_{film}(x,t)}{\partial t} = -\frac{M_P}{a_n \rho_P F} J_{sd}$$

Resistive film growth

AE's

$$0 = \nabla \cdot \left(\sigma_j^{eff} \nabla \phi_{1,j}(x,t)\right) - J_j$$

$$0 = \nabla \cdot \left(\kappa^{eff} \nabla \phi_{2,j}(x,t)\right) + \nabla \cdot \left(\kappa \nabla \ln c_{2,j}\right) - J_j$$

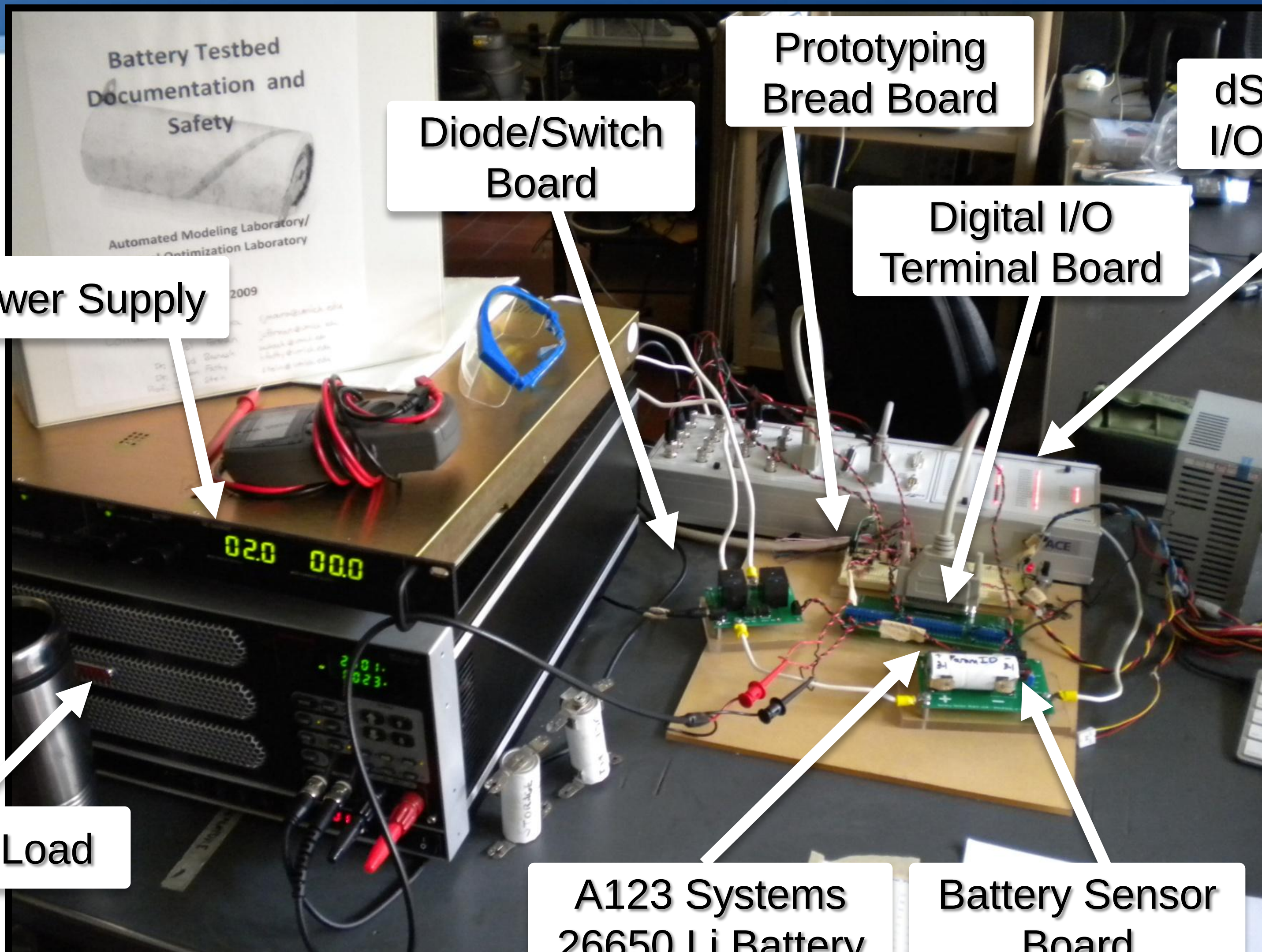
Ohm's Law

$$0 = a_j i_{0,j} \sinh\left[\frac{\alpha_{a,j} F}{RT}\left(\phi_{1,j} - \phi_{2,j} - U_{ref,j} - \frac{J_j}{a_n} R_{film}\right)\right] - J_j(x,t)$$

$$0 = -i_{0,sd} a_n \exp\left[-\frac{\alpha_n F}{RT}\left(\phi_{1,j} - \phi_{2,j} - U_{ref,sd} - \frac{J_j}{a_n} \cdot R_{film}\right)\right] - J_{sd}(x,t)$$

Butler-Volmer Kinetics

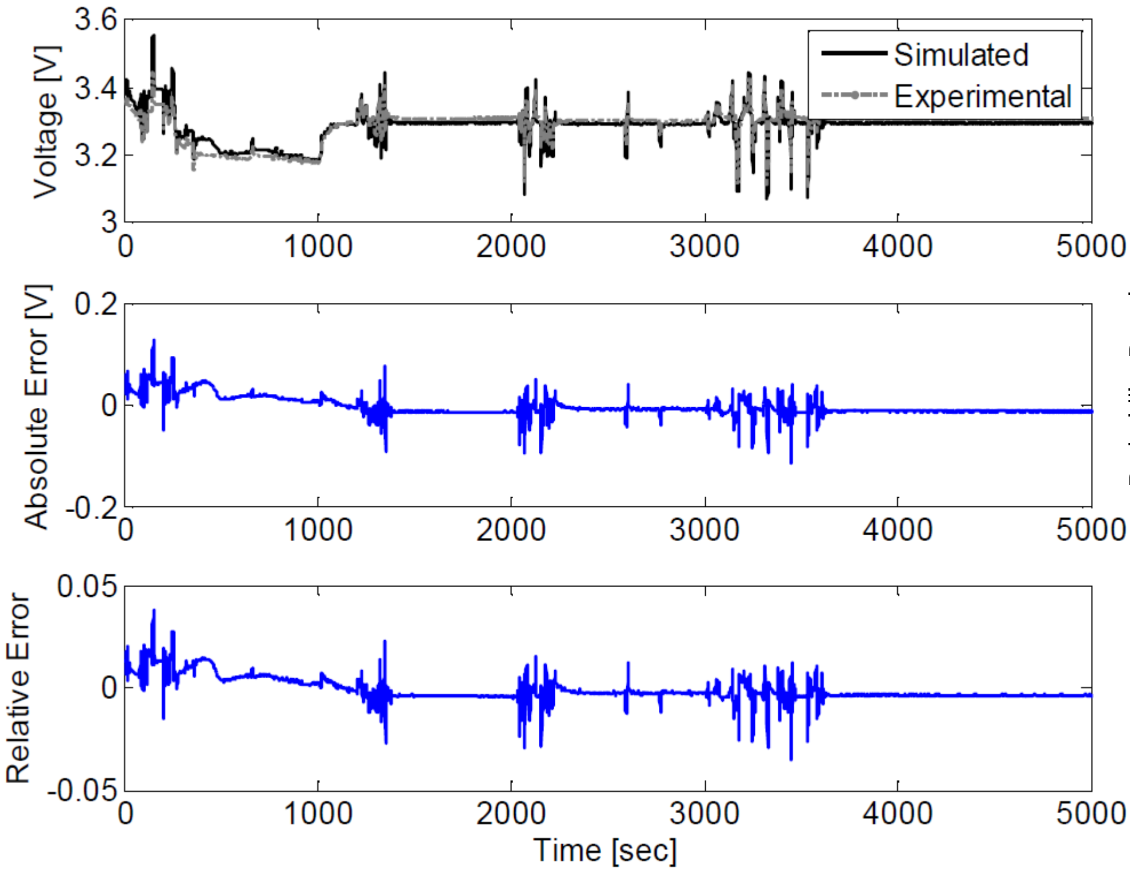
Battery-in-the-loop Hardware



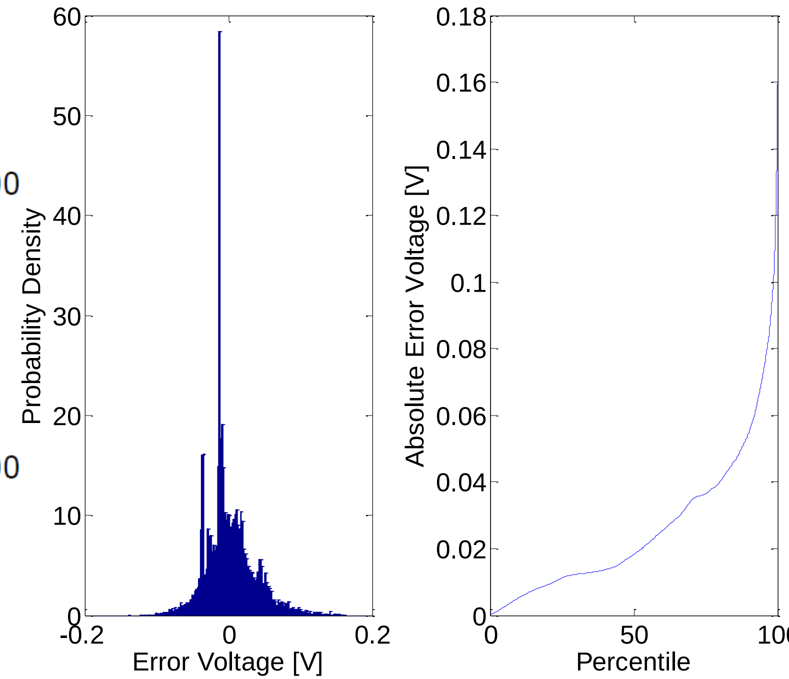
Parameter Identification Results

collaborative effort with Joel Forman, Ph.D. Candidate @ U-M

Time Responses of Experimental Validation Data vs. Identified Model for Naturalistic Drive Cycle



Statistical Analysis of Voltage Error



Publications

- J. C. Forman, **S. J. Moura**, J. L. Stein, H. K. Fathy "Parameter Identification of the Doyle-Fuller-Newman Model Based on Experimental Cycling of a Li-ion $LiFePO_4$ Battery Using a Genetic Algorithm," Submitted to 2011 American Control Conference, San Francisco, CA, 2011.

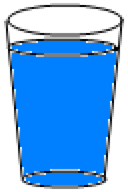
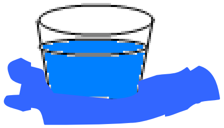
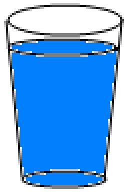
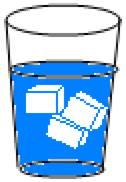
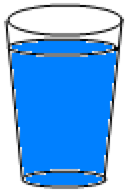
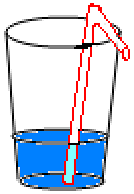
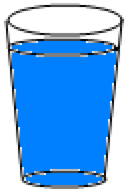
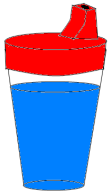
Causes of Battery Degradation

Causes of Battery Degradation

- Particle fracture
- Phase changes
- Active material consumption
- Solid electrolyte film (SEI) growth
- …

System-Level Relations to Aging

- SOC level
- Charge/discharge rates
- Temperature
- Time or cycles

The Cup Analogy	New	Aged
Particle Fracture		
Phase Changes		
Consumption of Active material		
SEI film growth		

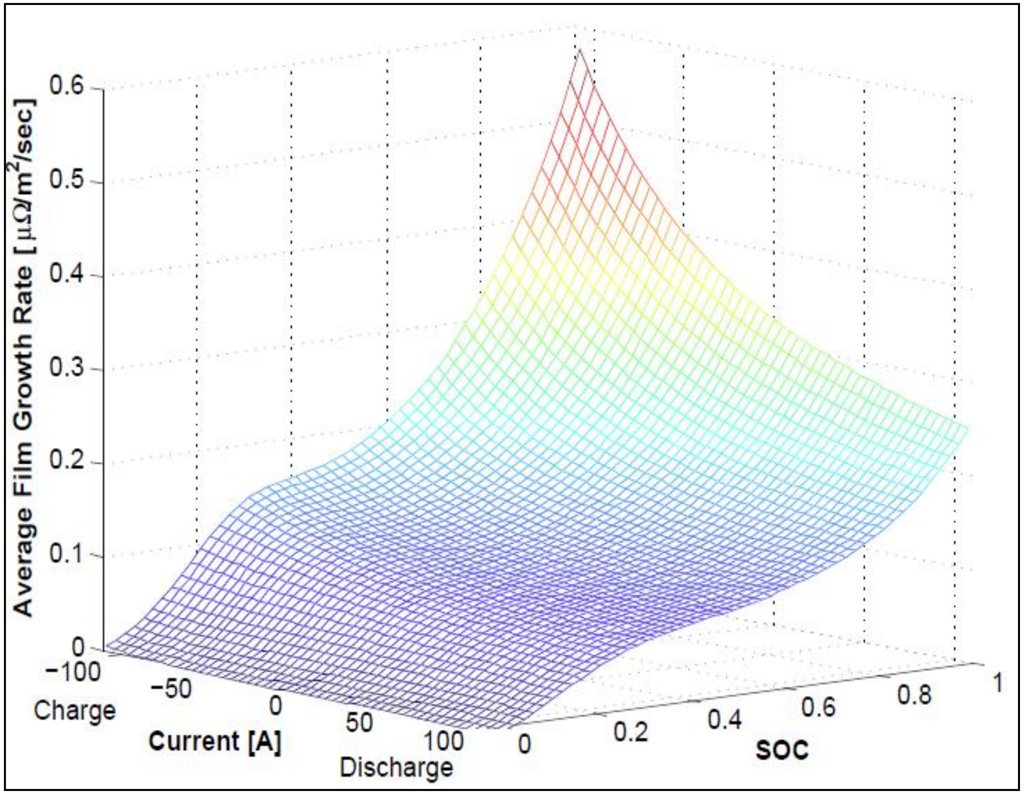
Anode-Side SEI Film Buildup

Ramadass et al, 2004

$$S + Li^{+} + e^{-} \rightarrow P$$

$$R_{film}(x,t) = R_{SEI} + \frac{\delta_{film}(x,t)}{\kappa_P}$$

$$\frac{\partial \delta_{film}(x,t)}{\partial t} = -\frac{M_P}{a_n \rho_P F} J_{sd}$$



Key Research Topics

Electrochemical Battery Modeling

- Mathematical modeling based on first principles
- Experimental identification

Advanced Battery Pack Management

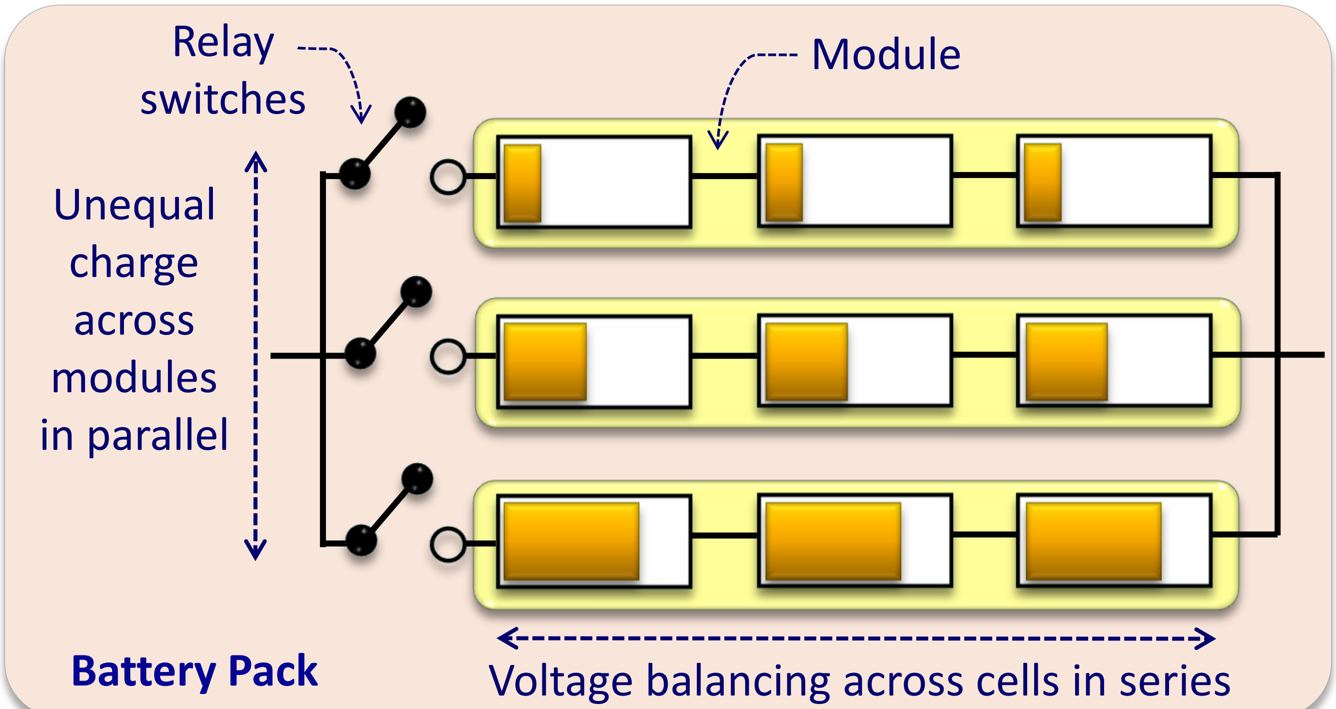
- **The charge *un*-equalization concept**
- **Modeling, optimal control, and analysis**

PHEV Power Management

- PHEV powertrain and daily drive cycle modeling
- Stochastic optimal control
- Tradeoff analysis

Unbalanced Charge Management

Objective: Explore unequal but controlled charge levels in battery packs for enhancing health



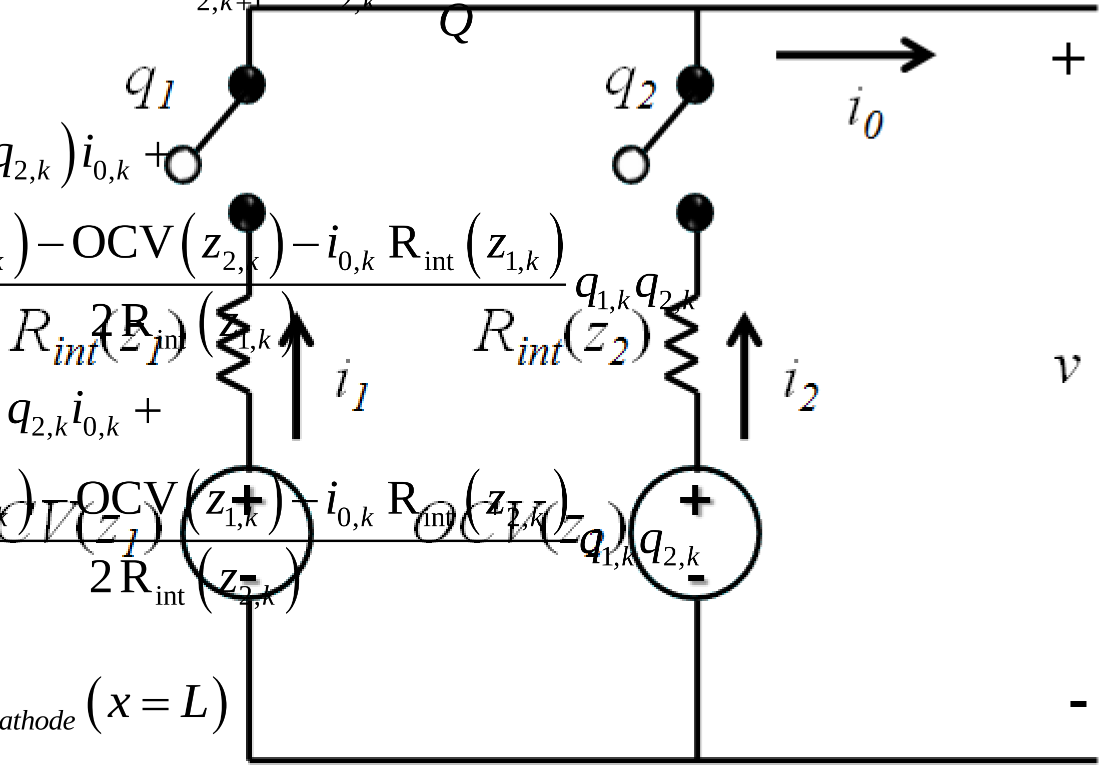
Theoretical Approach: Optimal control and reduced order models

Battery Pack Model

$$z_{1,k+1} = z_{1,k} - \frac{i_{1,k}}{Q}\Delta T \qquad z_{2,k+1} = z_{2,k} - \frac{i_{2,k}}{Q}\Delta T$$

$$i_{1,k+1} = q_{1,k}\left(1-q_{2,k}\right)i_{0,k} + \frac{\mathrm{OCV}\left(z_{1,k}\right)-\mathrm{OCV}\left(z_{2,k}\right)-i_{0,k}\,\mathrm{R}_{\mathrm{int}}\left(z_{1,k}\right)}{2\,\mathrm{R}_{\mathrm{int}}\left(z_{1,k}\right)}q_{1,k}q_{2,k}$$

$$i_{2,k+1} = \left(1-q_{1,k}\right)q_{2,k}i_{0,k} + \frac{\mathrm{OCV}\left(z_{2,k}\right)-\mathrm{OCV}\left(z_{1,k}\right)-i_{0,k}\,\mathrm{R}_{\mathrm{int}}\left(z_{2,k}\right)}{2\,\mathrm{R}_{\mathrm{int}}\left(z_{2,k}\right)}q_{1,k}q_{2,k}$$



$$\mathrm{OCV}\left(z\right) = \Delta\phi_{cathode}\left(x=L\right)$$

$$\mathrm{R}_{\mathrm{int}}\left(z\right) = \frac{\Delta\phi_{cathode}\left(x=L\right)-\mathrm{OCV}\left(z\right)}{i_{app}}$$

Problem Formulation

Minimize total spatially-averaged film growth over the charge cycle

$$\min_{q_1,q_2} J = \sum_{k=1}^{N} \left[\dot{\bar{\delta}}_{film}\left(z_{1,k}, i_{1,k}\right) + \dot{\bar{\delta}}_{film}\left(z_{2,k}, i_{2,k}\right) + g_z\left(z_k\right) \right] + \alpha_N \left\| z_N - 0.95 \right\|_2^2$$

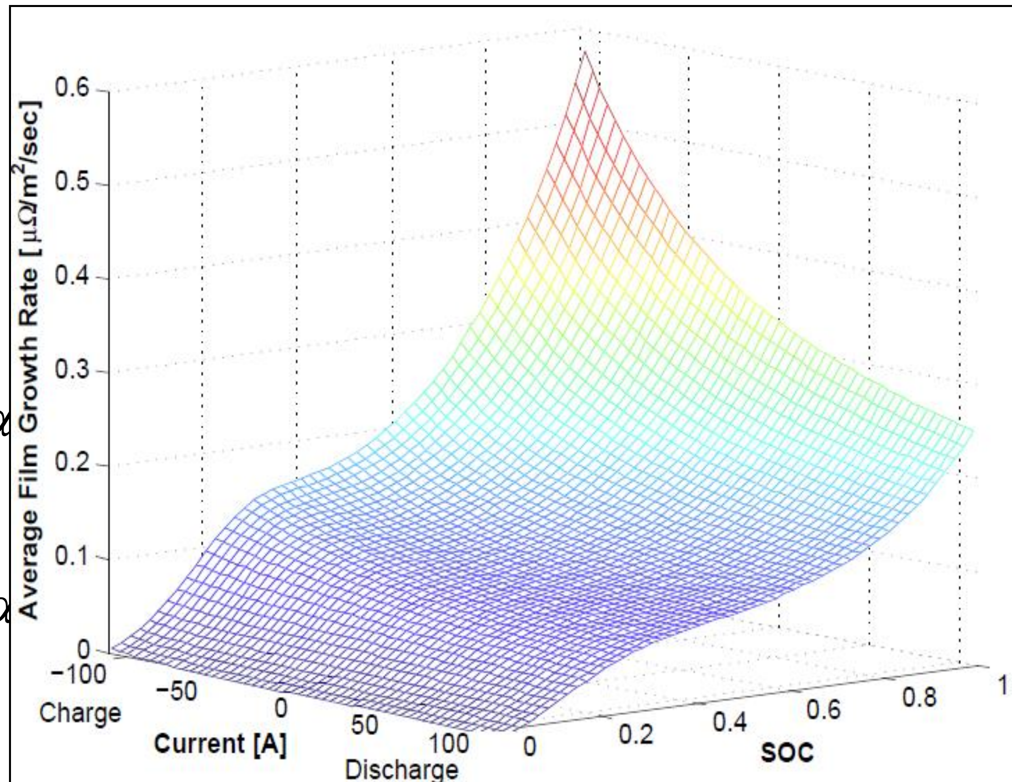
subject to $z_{k+1} =$

$i_k =$

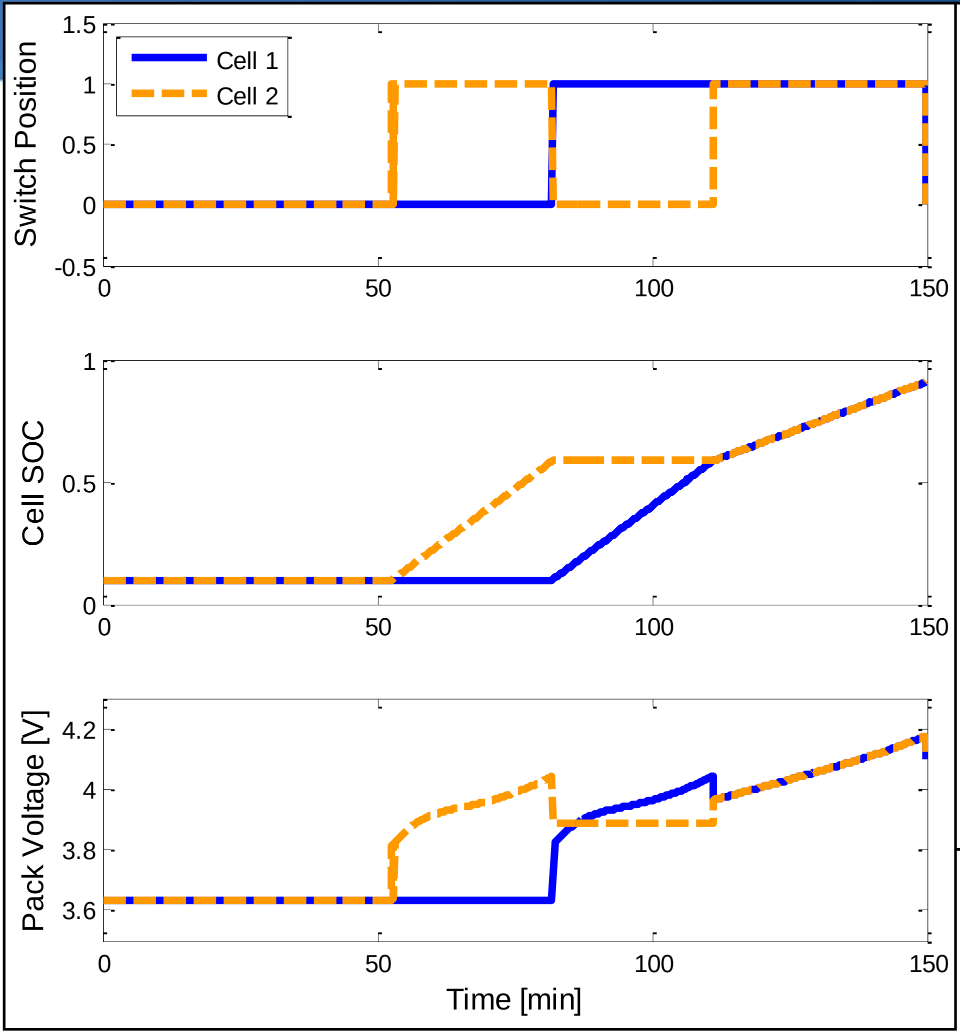
$z_1 =$

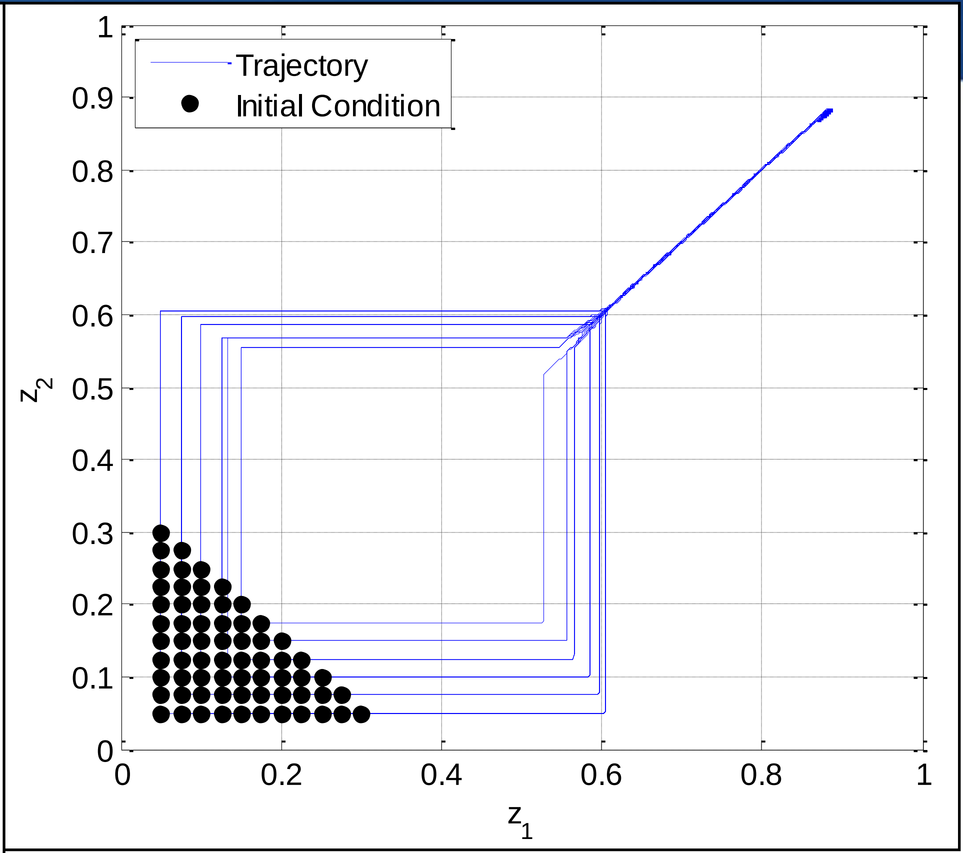
where $g_z\left(z_k\right) = \alpha$ straints

$+\alpha$ constraints

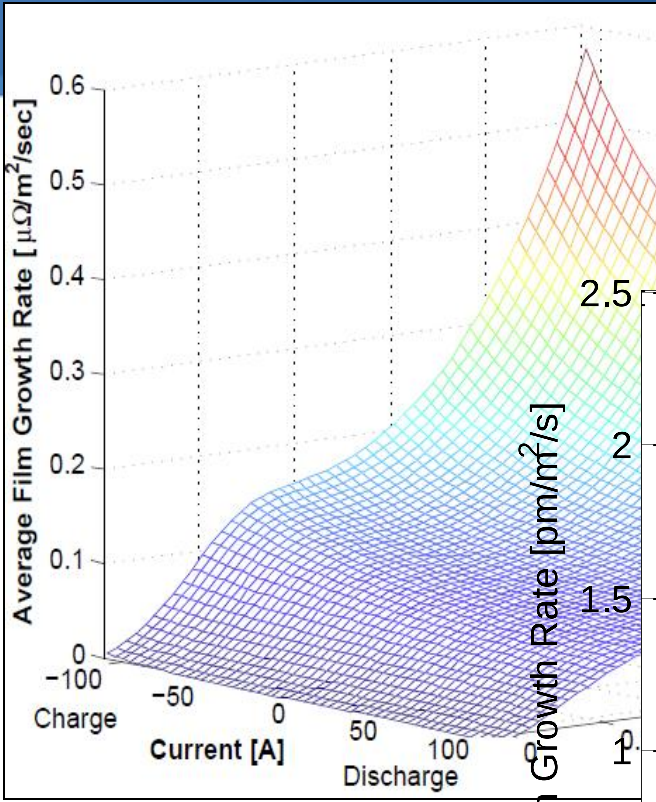


Solution Analysis: Optimal Trajectories

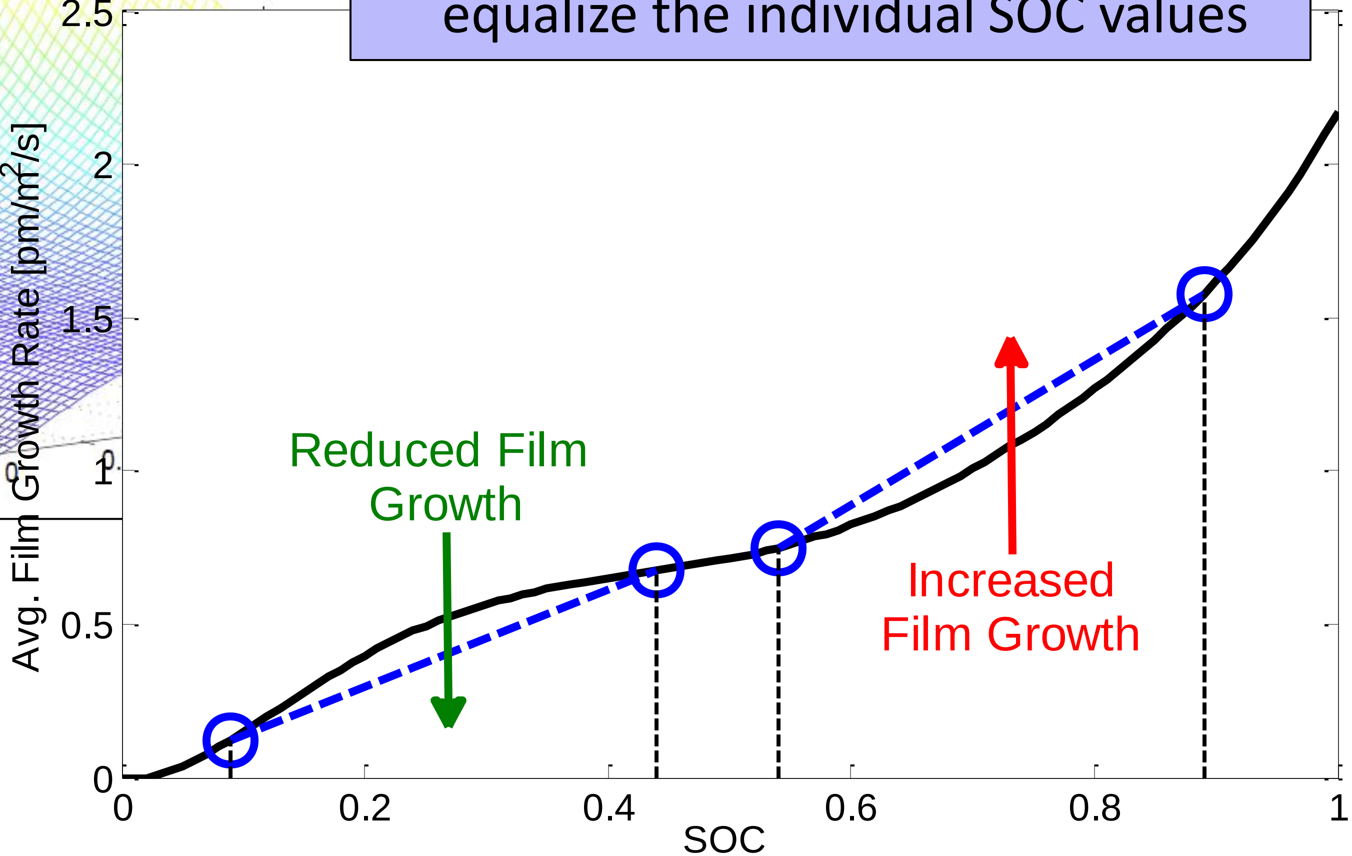




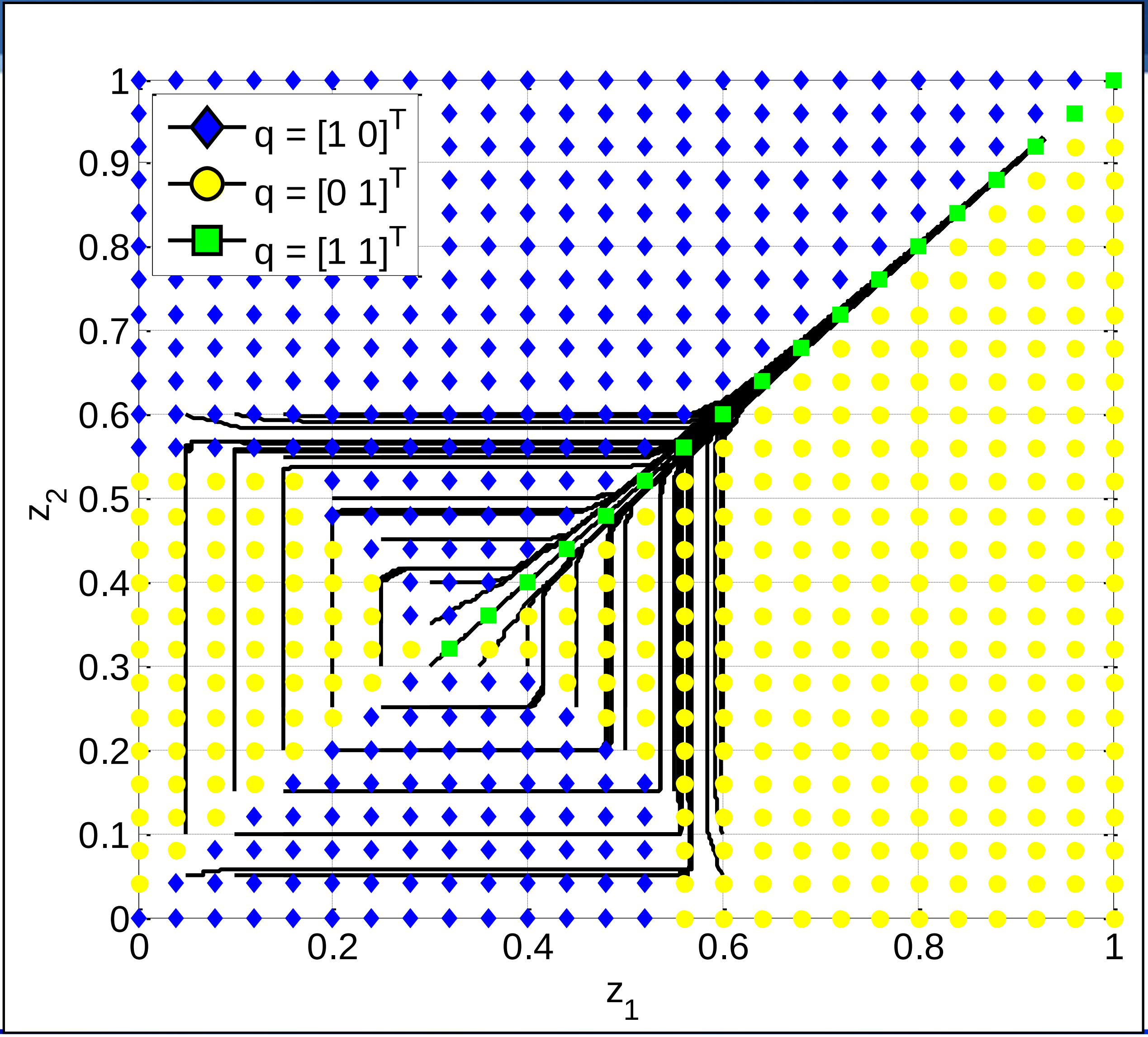
Solution Analysis: Convexity



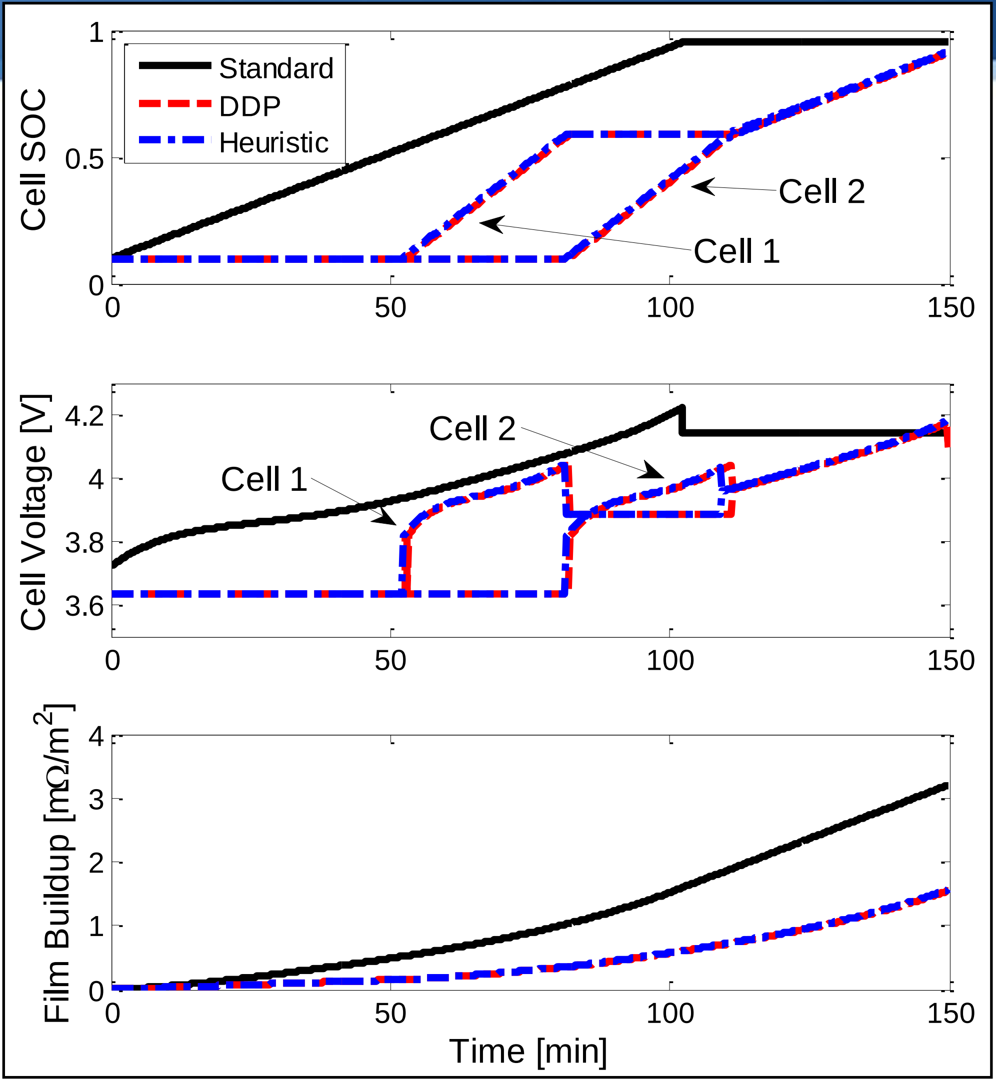
1. In the concave region of $\dot{\bar{\delta}}_{film}$, drive the individual SOC values apart
2. In the convex region of $\dot{\bar{\delta}}_{film}$, equalize the individual SOC values



Solution Analysis: Heuristic Control

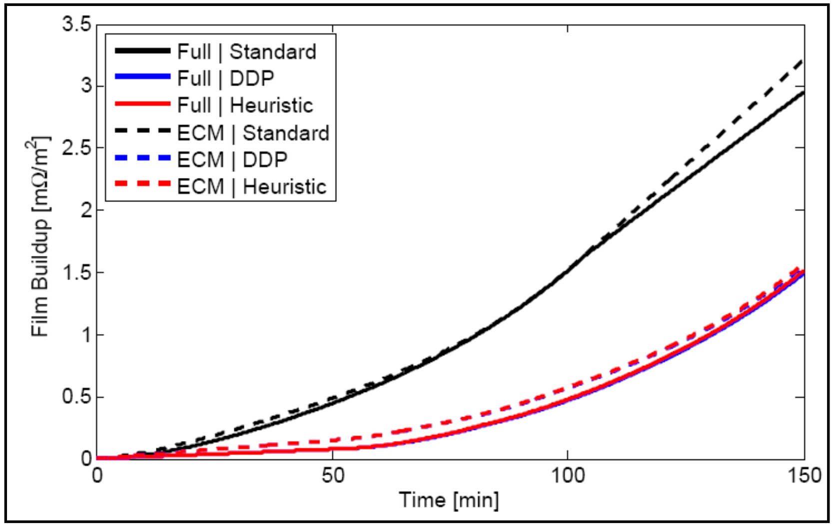


Simulation Results: Controller Comparison



Control Scheme	Resistance of Total Film Buildup	Reduction in Film Buildup
Standard	3.20 mΩ/m²	0%
DDP	1.55 mΩ/m²	51.8%
Heuristic	1.56 mΩ/m²	51.2%

Validation on Full Electrochemical Model



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PHEV Power Management

- **PHEV powertrain and daily drive cycle modeling**
- **Stochastic optimal control**
- **Tradeoff analysis**

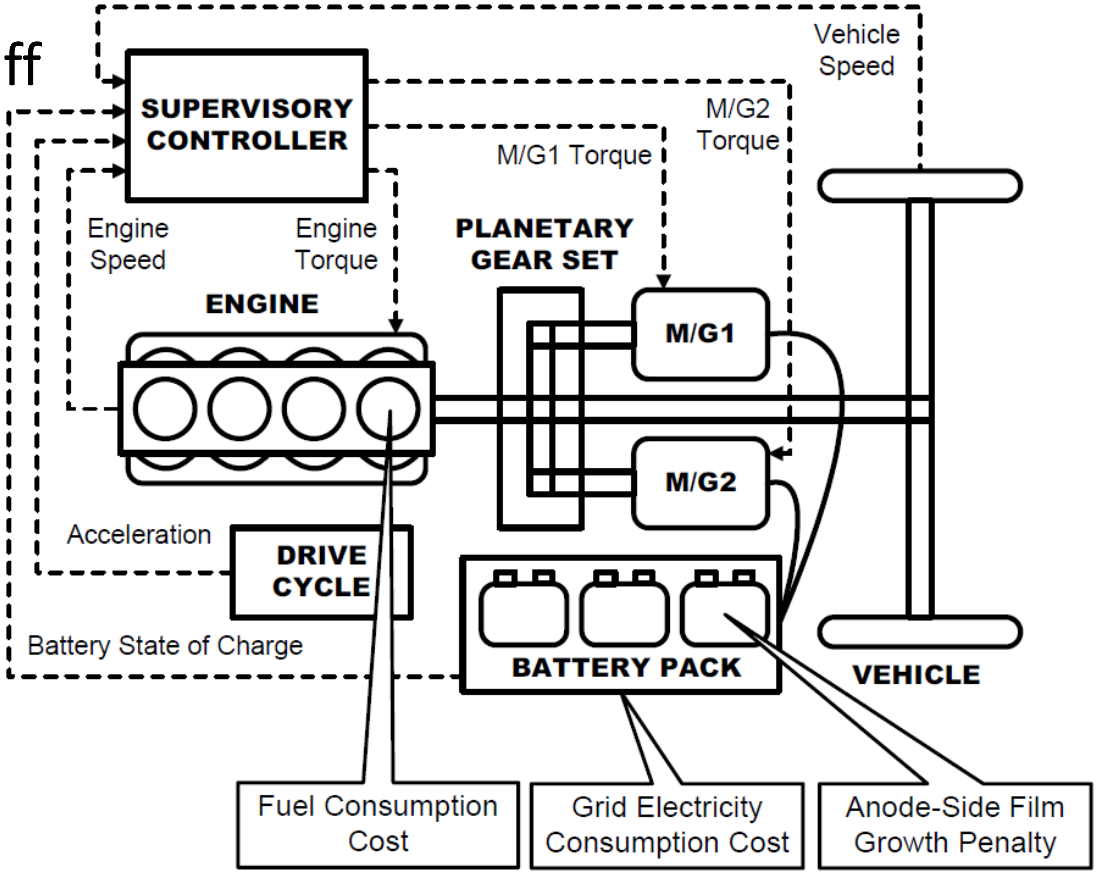
Research Objective

Design supervisory control algorithms that optimally balance battery health degradation and energy consumption cost in PHEVs

J. Voelcker, "Plugging Away in a Prius," *IEEE Spectrum*, vol. 45, pp. 30-48, 2008.

Power-Split PHEV Model

- Control Inputs
  - Engine Torque w/ Eng. Off
  - M/G1 Torque
- State Variables
  - Engine speed
  - Vehicle speed
  - Battery SOC
  - Vehicle acceleration (Markov chain)



Markov chain model of Drive Cycles

Drive cycle dynamics

Normal state transition dynamics

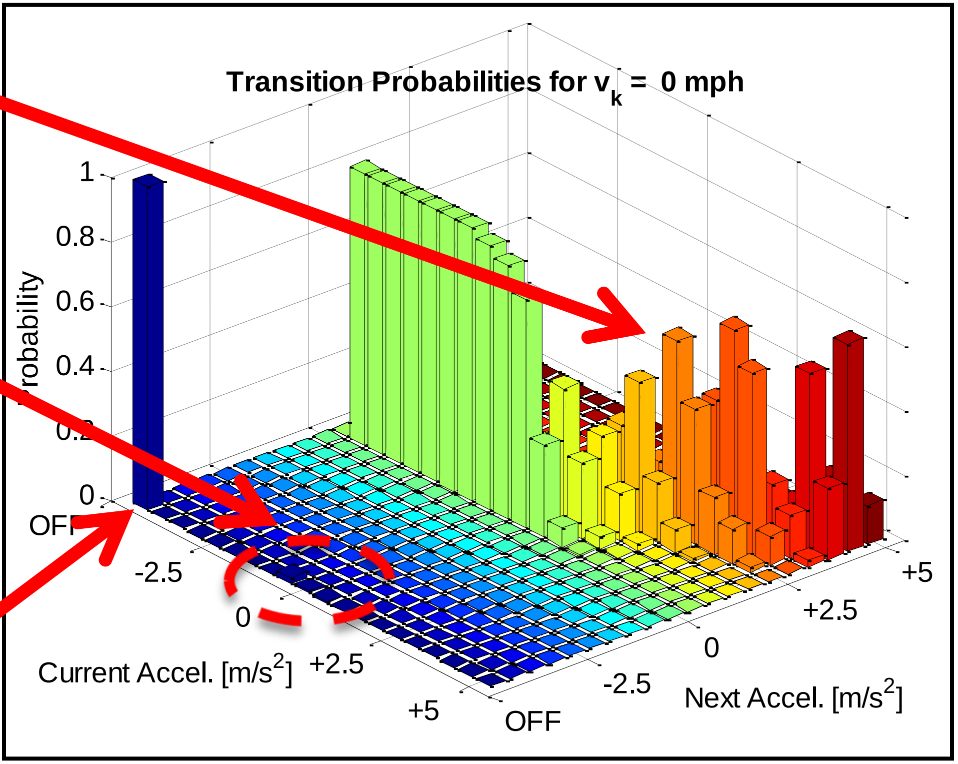
$$p_{ijm} = \Pr(a_{k+1} = j \mid a_k = i, v_k = m)$$

Transition to "vehicle off" denoted $a_{k+1} = t$

$$p_{itm} = \Pr(a_{k+1} = t \mid a_k = i, v_k = 0)$$

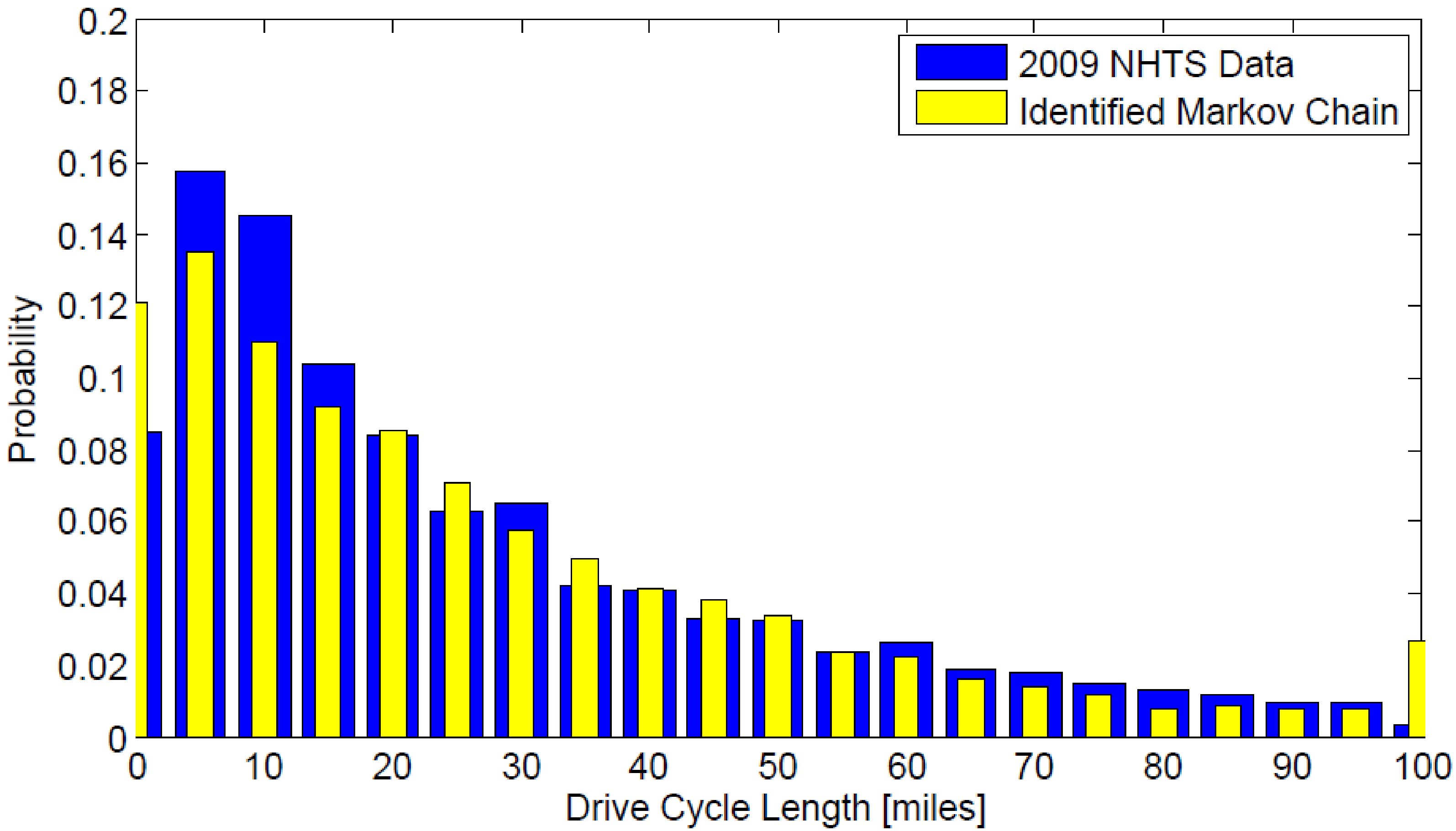
Absorbing state "vehicle off"

$$1 = \Pr(a_{k+1} = t \mid a_k = t, v_k = 0)$$



Markov chain model of Drive Cycles

Daily Trip Length Distribution



Optimal Control Problem Formulation

Multiobjective Shortest-Path Stochastic Dynamic Program

Cost Functional:

$$J^g = \lim_{N \to \infty} \mathrm{E}\left[\sum_{k=0}^{N} c\left(x_k, u_k\right) \right]$$

Constraints:

$$x_{k+1} = f\left(x_k, u_k, w_k\right)$$

$$x \in X$$

$$u \in U\left(x\right)$$

Objective:

$$g^* = \arg\inf_{g \in G} J^g$$

Combine two objectives into a single linear-weighted objective:

$$c\left(x_k, u_k\right) = \alpha \cdot c_{energy}\left(x_k, u_k\right) + \left(1 - \alpha\right) \cdot c_{film}\left(x_k, u_k\right)$$

where

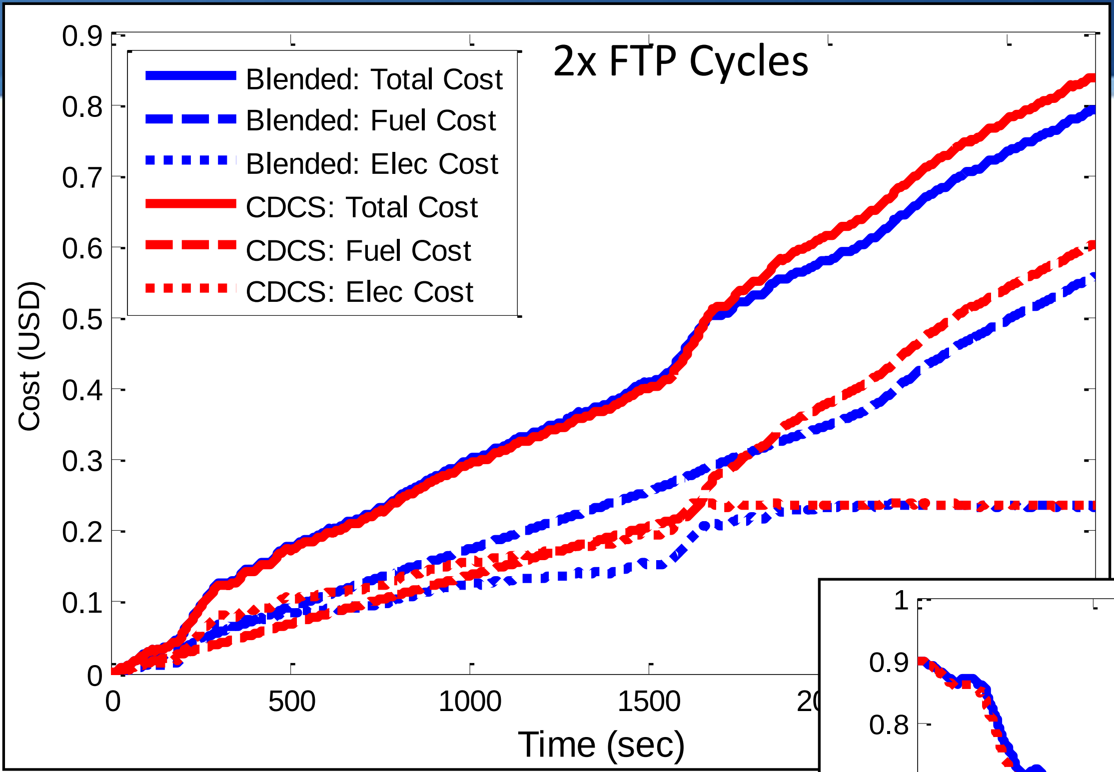
$$c_{energy}\left(x_k, u_k\right) = \beta \alpha_{fuel} W_{fuel} + \alpha_{fuel} \frac{-V_{oc} Q_{batt} \dot{SOC}}{\eta_{grid}}$$

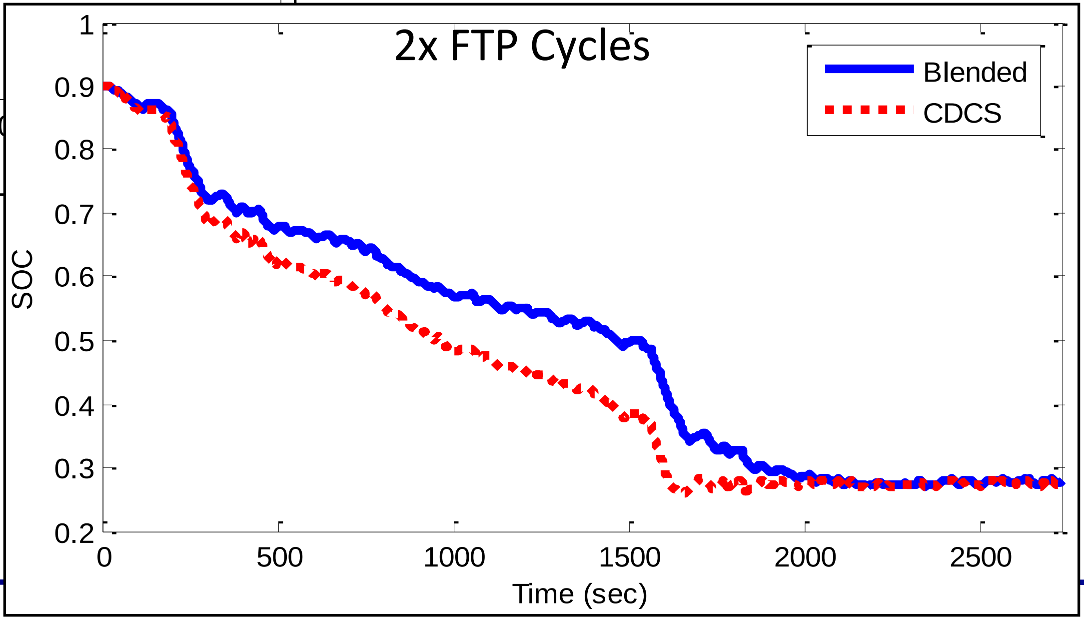
$$c_{film}\left(x_k, u_k\right) = \dot{\delta}_{film}\left(I, SOC\right)$$

$$\beta = \frac{\text{Price of Gasoline per MJ}}{\text{Price of Grid Electricity per MJ}}$$

Remark: Normalize individual objectives by scaling the range of their natural values to [0,1].

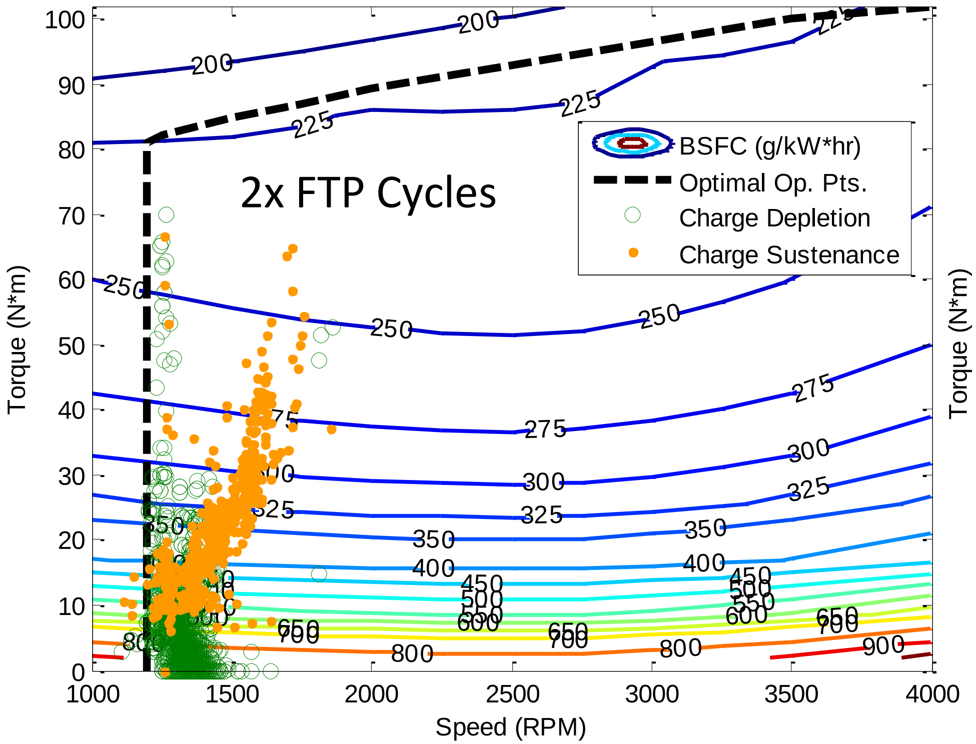
Power Management Results w/o Aging



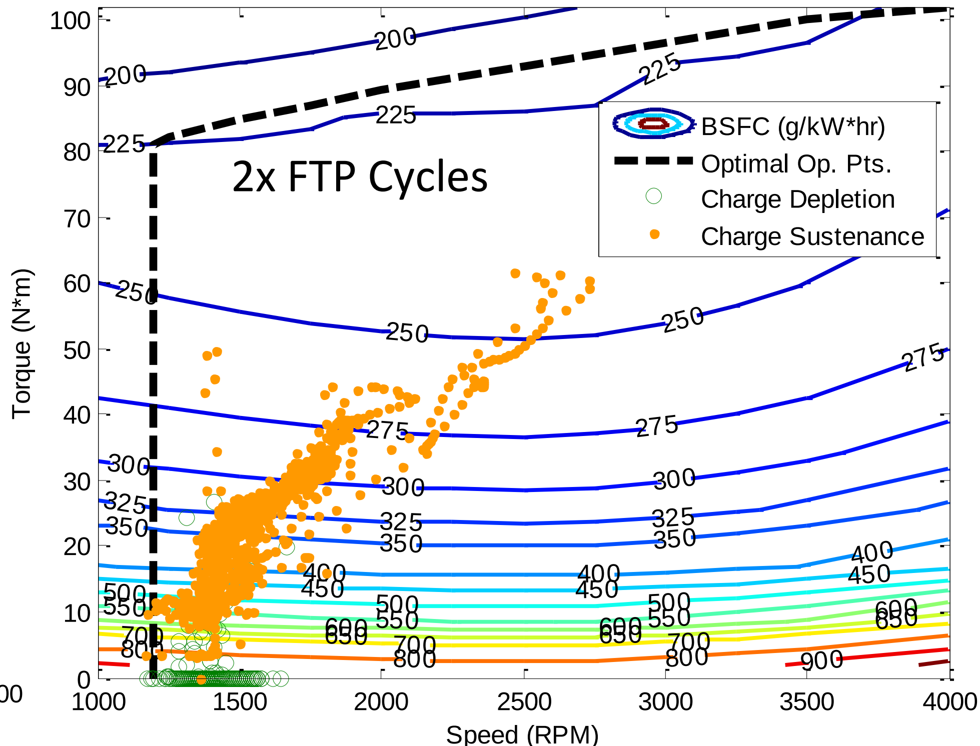


Engine Operating Point Analysis

Optimal Blending

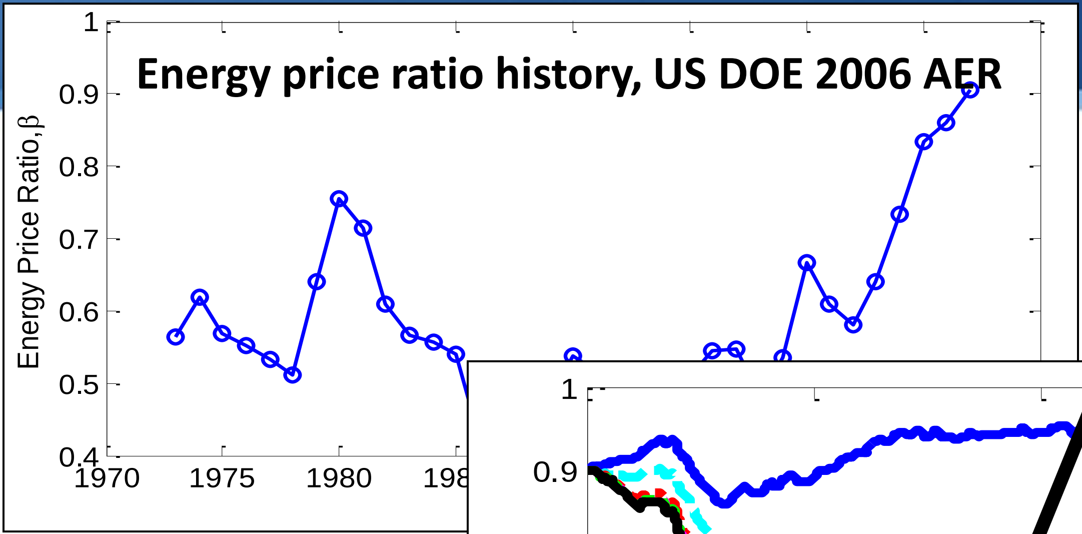


Charge Depletion, Charge Sustenance



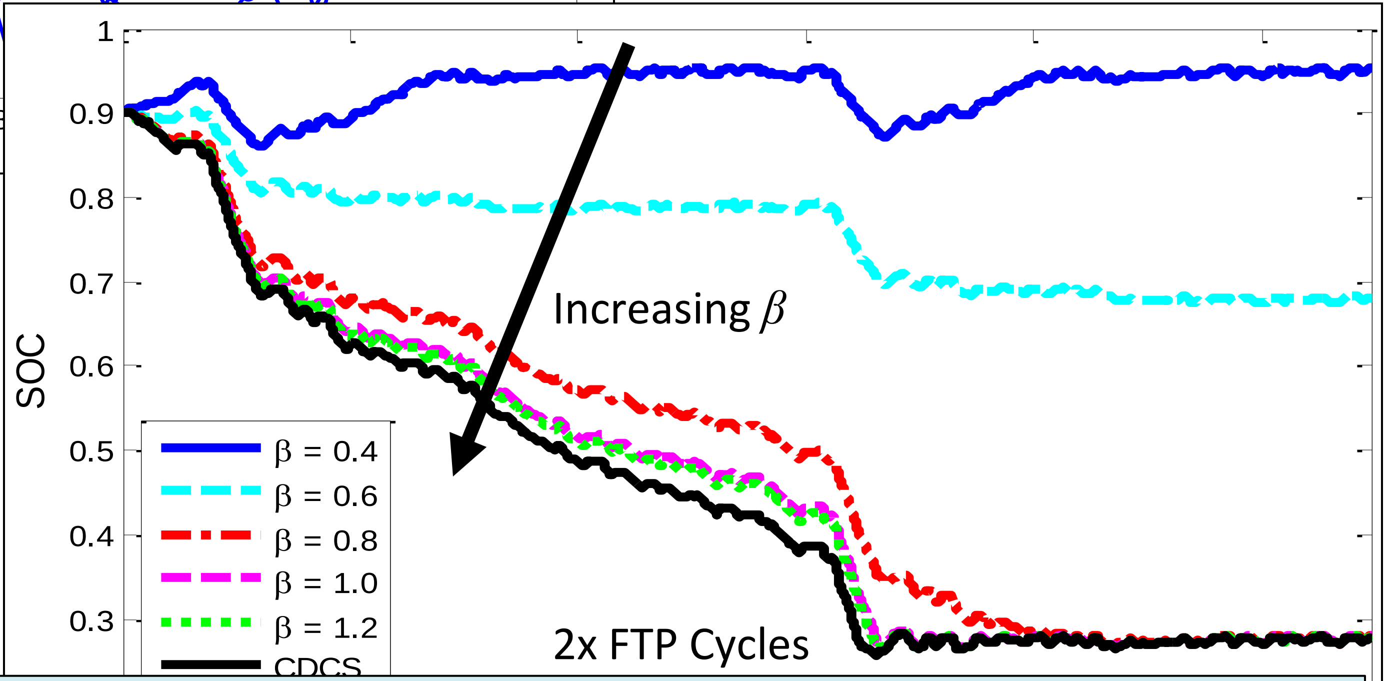
- Blended operates at higher engine efficiency during charge depletion
- Excess power goes to battery charge regeneration

Energy Price Ratio Analysis



$$\beta = \frac{\text{Price of Gasoline per MJ}}{\text{Price of Grid Electricity per MJ}}$$

$\beta = 0.8$ \$2.64 per gallon fuel & \$0.09 per kWh electricity (Year 2006)

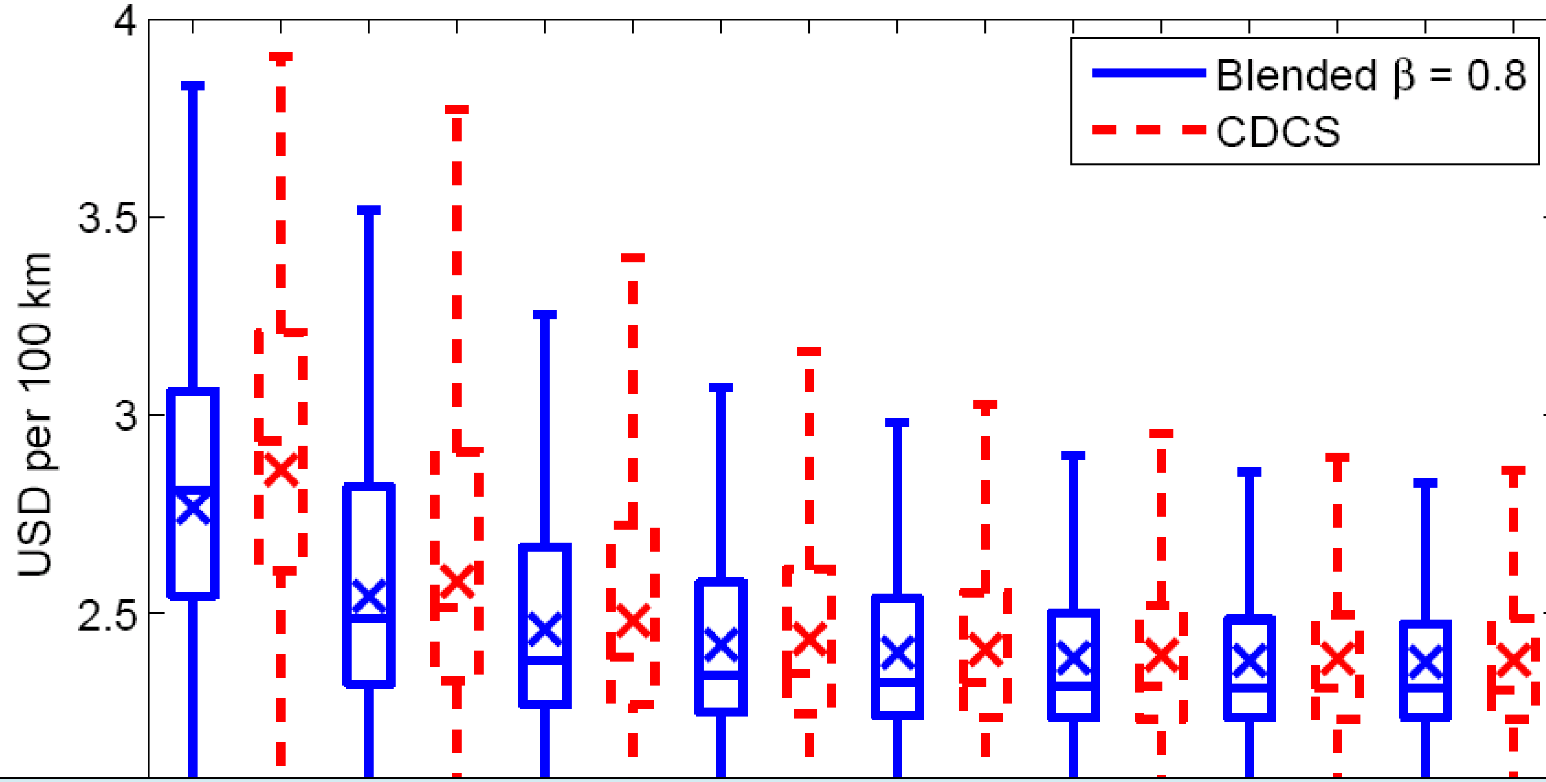


Publications

- **S. J. Moura**, H. K. Fathy, D. S. Callaway, and J. L. Stein, "A Stochastic Optimal Control Approach for Power Management in Plug-In Hybrid Electric Vehicles," *IEEE Transactions on Control Systems Technology*, vPP, n 99, 2010.
- **S. J. Moura**, H. K. Fathy, D. S. Callaway, and J. L. Stein, "A Stochastic Optimal Control Approach for Power Management in Plug-In Hybrid Electric Vehicles," *Proceedings of the 2008 ASME Dynamic Systems and Control Conference*, p 1357-1366, Ann Arbor, MI, 2008.

Sensitivity Analysis of Battery Size

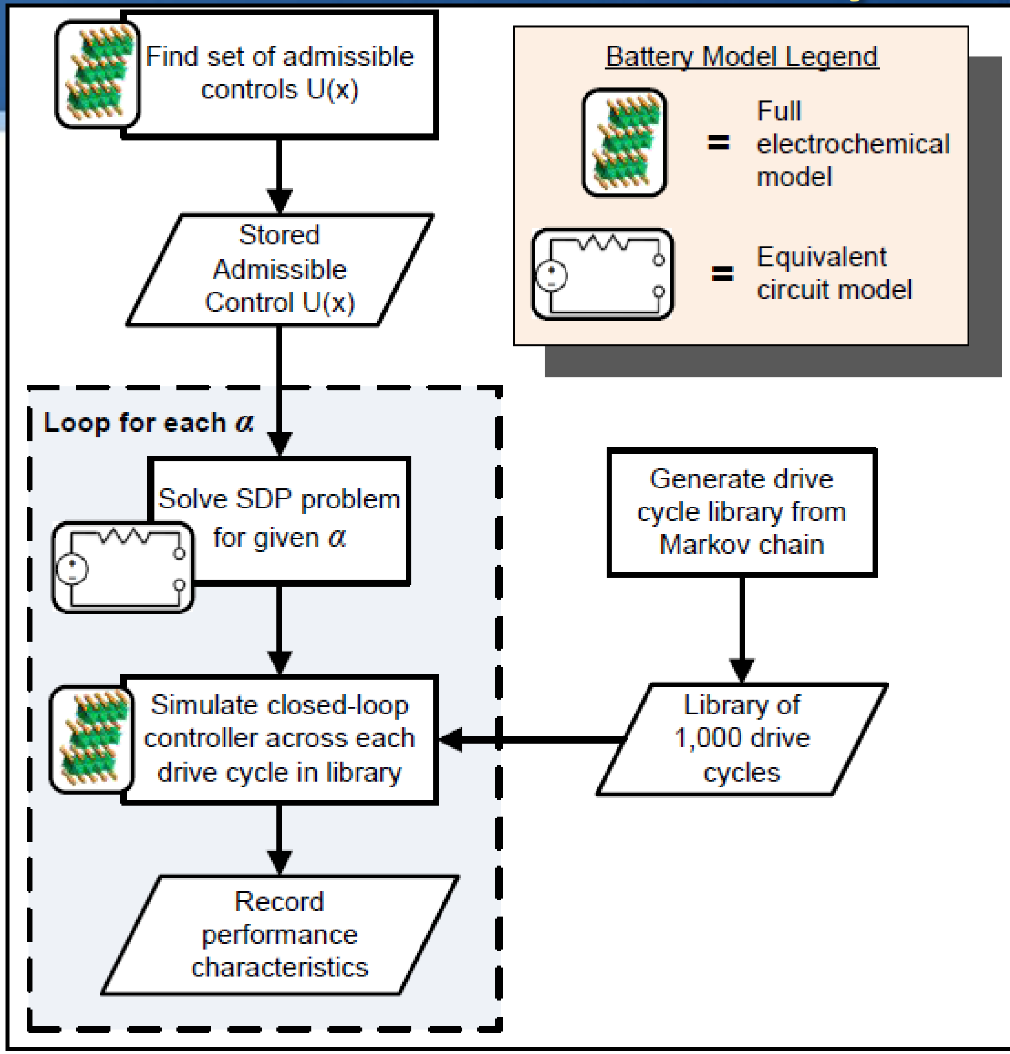
How sensitive is Blending vs. CDCS to battery size?



Publications

- **S. J. Moura**, D. S. Callaway, H. K. Fathy, and J. L. Stein, "Tradeoffs between Battery Energy Capacity and Stochastic Optimal Power Management in Plug-in Hybrid Electric Vehicles," *Journal of Power Sources*, v 195, n 9, p 2979-2988, May 2010.
- **S. J. Moura,** D. S. Callaway, H. K. Fathy, and J. L. Stein, "Impact of Battery Sizing on Stochastic Optimal Power Management in Plug-in Hybrid Electric Vehicles," *Proceedings of the 2008 IEEE International Conference on Vehicular Electronics and Safety*, p 96-102, Columbus, OH, 2008. **(Invited Paper)**

Battery-Health Conscious Analysis Procedure

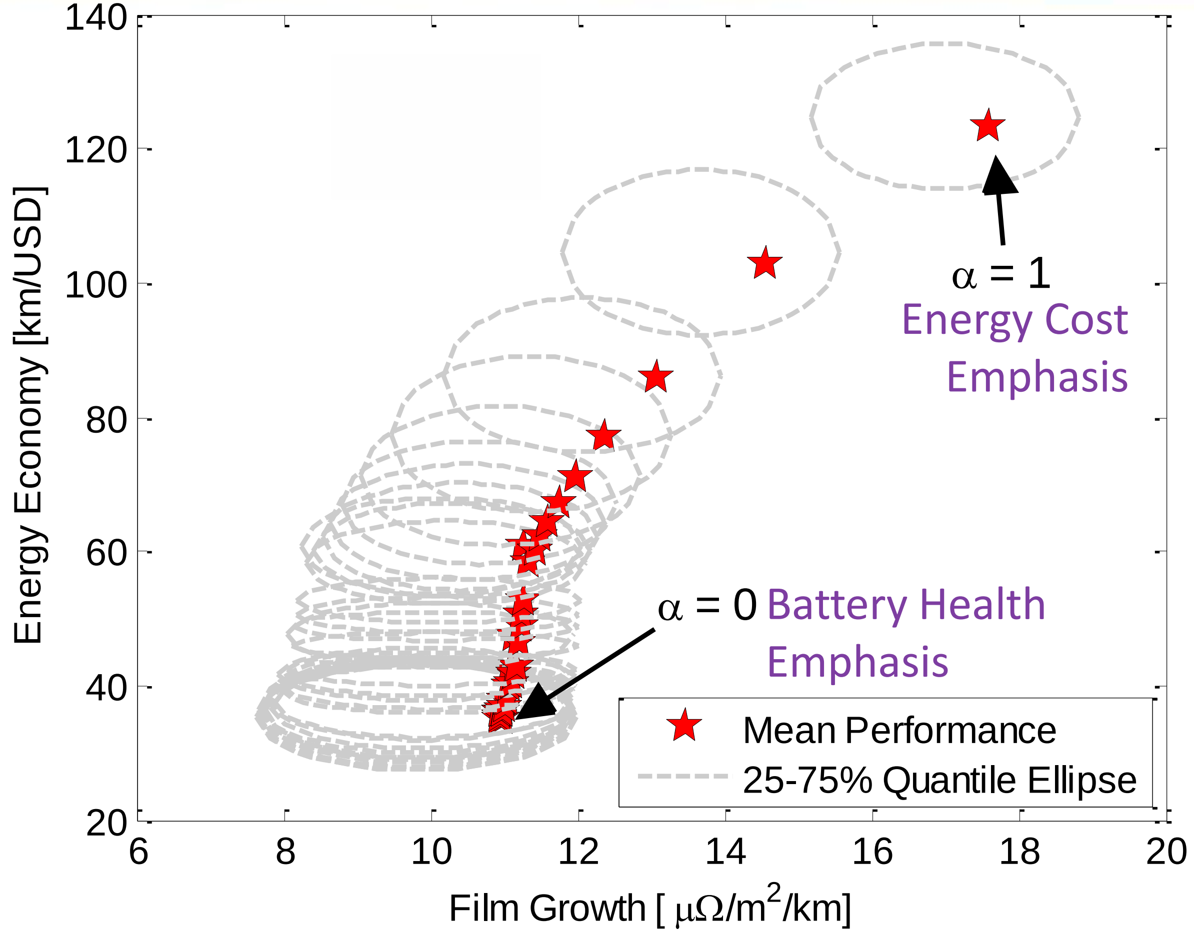


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{film}(x_k, u_k)$$

Remark: This study leveraged parallel computing resources at the University of Michigan Center for Advanced Computing to perform 32 SDP optimizations and 32,000 drive cycle simulations.

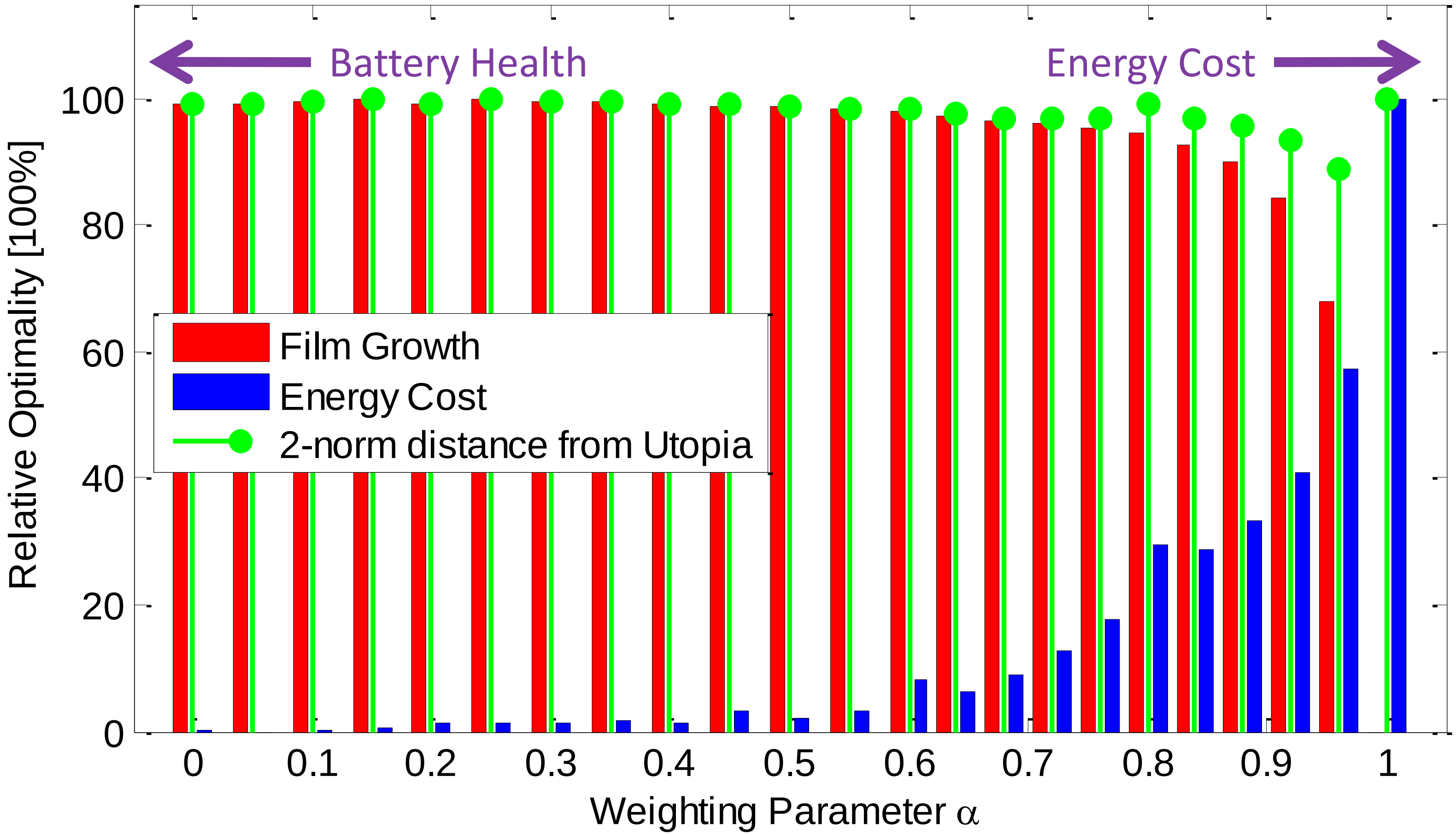
Pareto* Set of Optimal Solutions

*convex subset



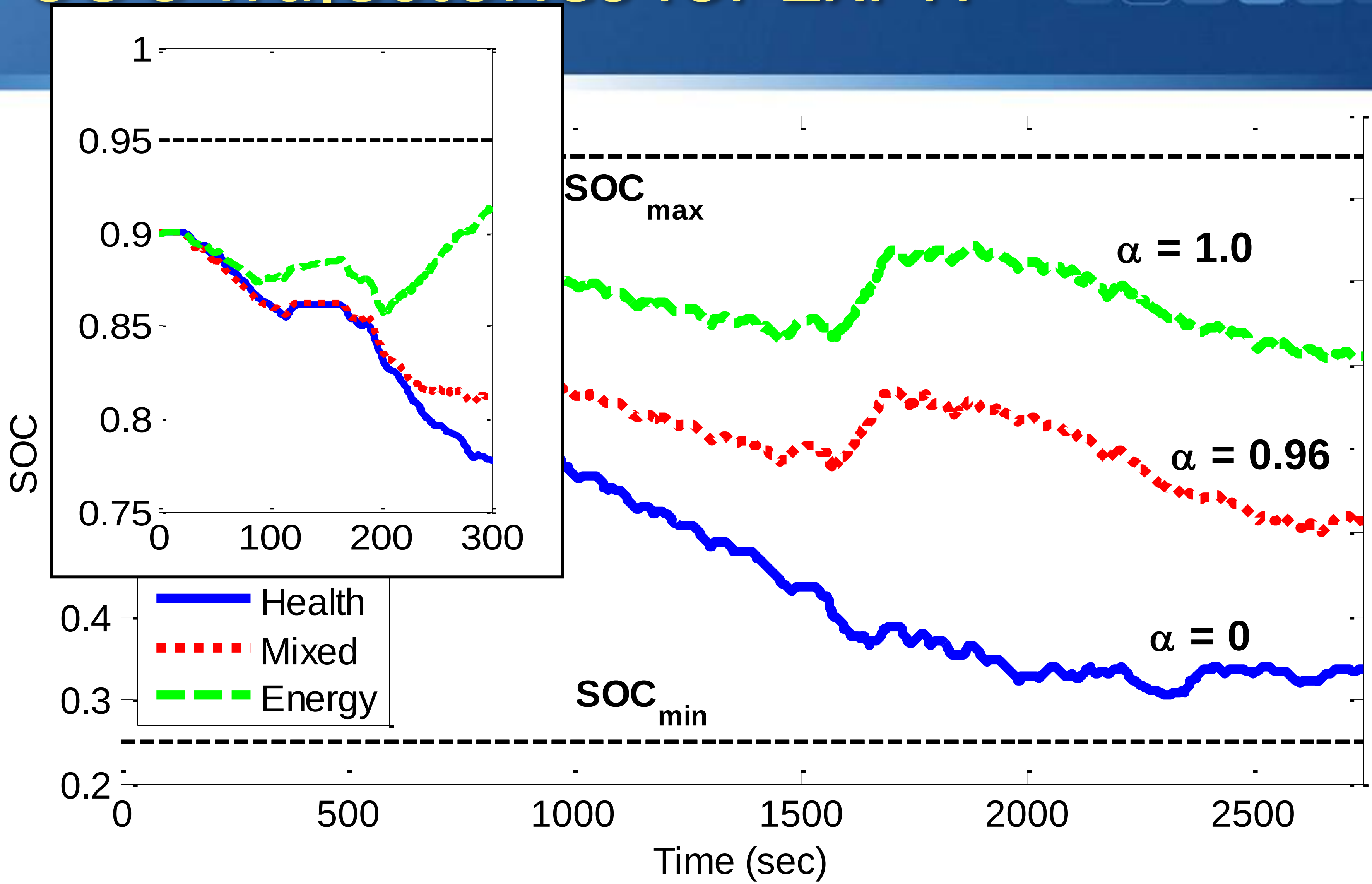
$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{film}(x_k, u_k)$$

Relative Optimality Analysis

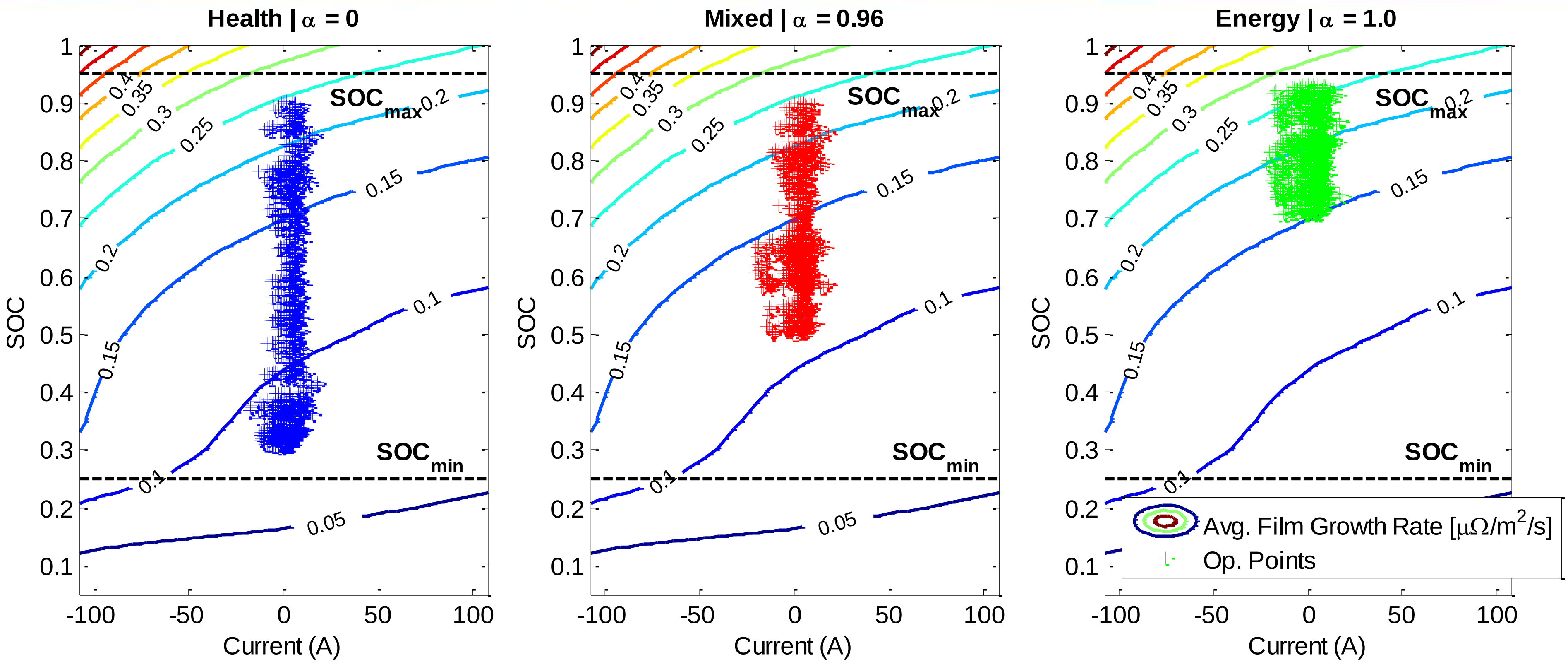


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{film}(x_k, u_k)$$

SOC Trajectories for 2xFTP



Film Growth Map Operating Points



Aggressively deplete battery charge to reduce film growth

(1) Aggressively deplete charge to escape fast film growth region
(2) Ration charge to reduce CS mode

Conservatively ration charge to reduce charge sustenance

Publications

- **S. J. Moura**, J. L. Stein, and H. K. Fathy, "Battery Health-Conscious Power Management for Plug-in Hybrid Electric Vehicles via Stochastic Control," *Proceedings of the 2010 ASME Dynamic Systems and Control Conference*, Cambridge, MA, 2010.

Ongoing / Future Work Topic:

Optimal Power Management in Vehicle-to-Grid Infrastructures

Collaborative work with Dr. Saeid Bashash (U-Michigan) and Professor Hosam Fathy (Penn State Univ.)

Research Objective

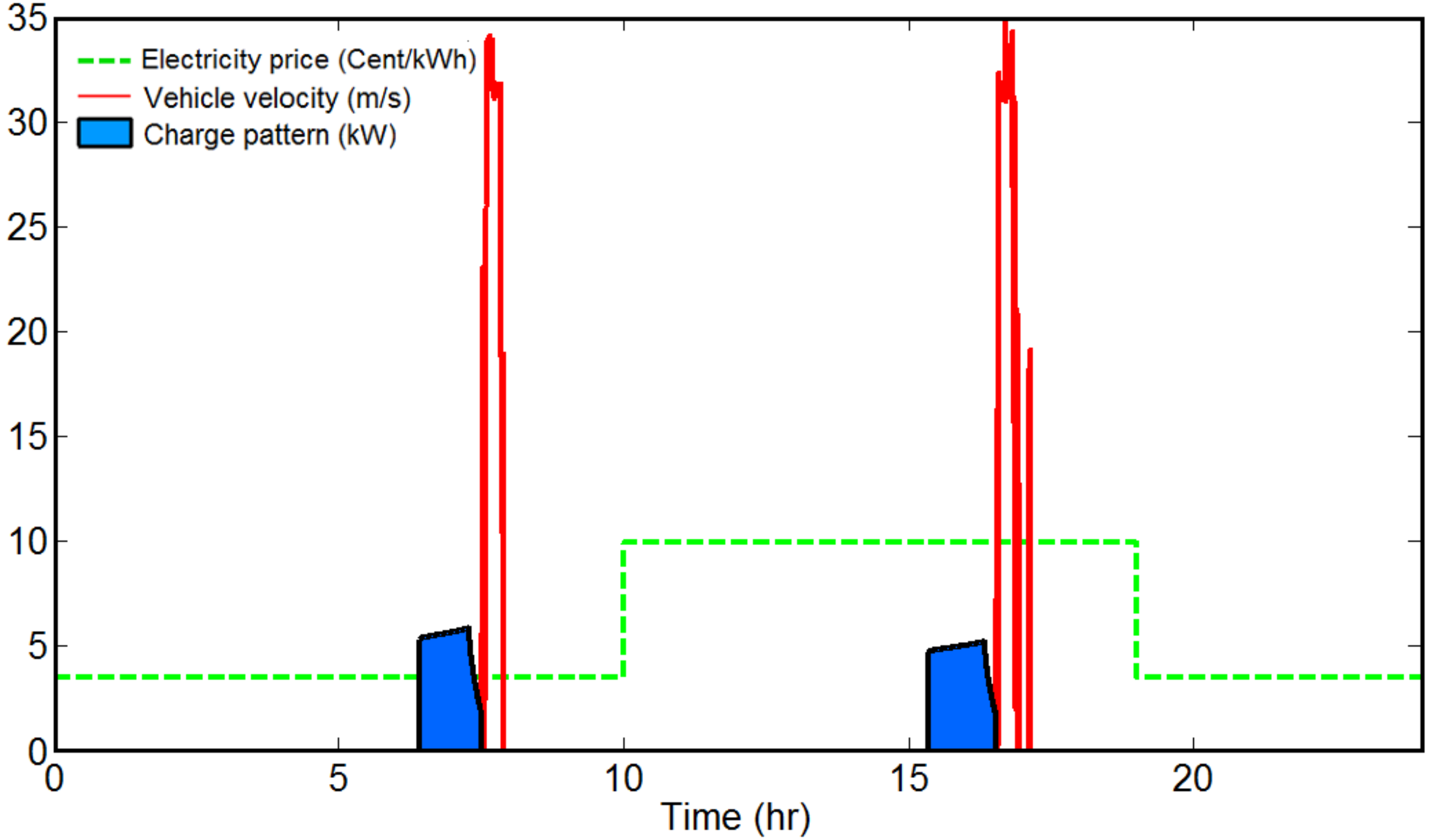
When is the optimal time to charge PHEVs to maximize consumer benefits? Specifically w.r.t. battery health & energy consumption cost.

J. Voelcker, "Plugging Away in a Prius," *IEEE Spectrum*, vol. 45, pp. 30-48, 2008.

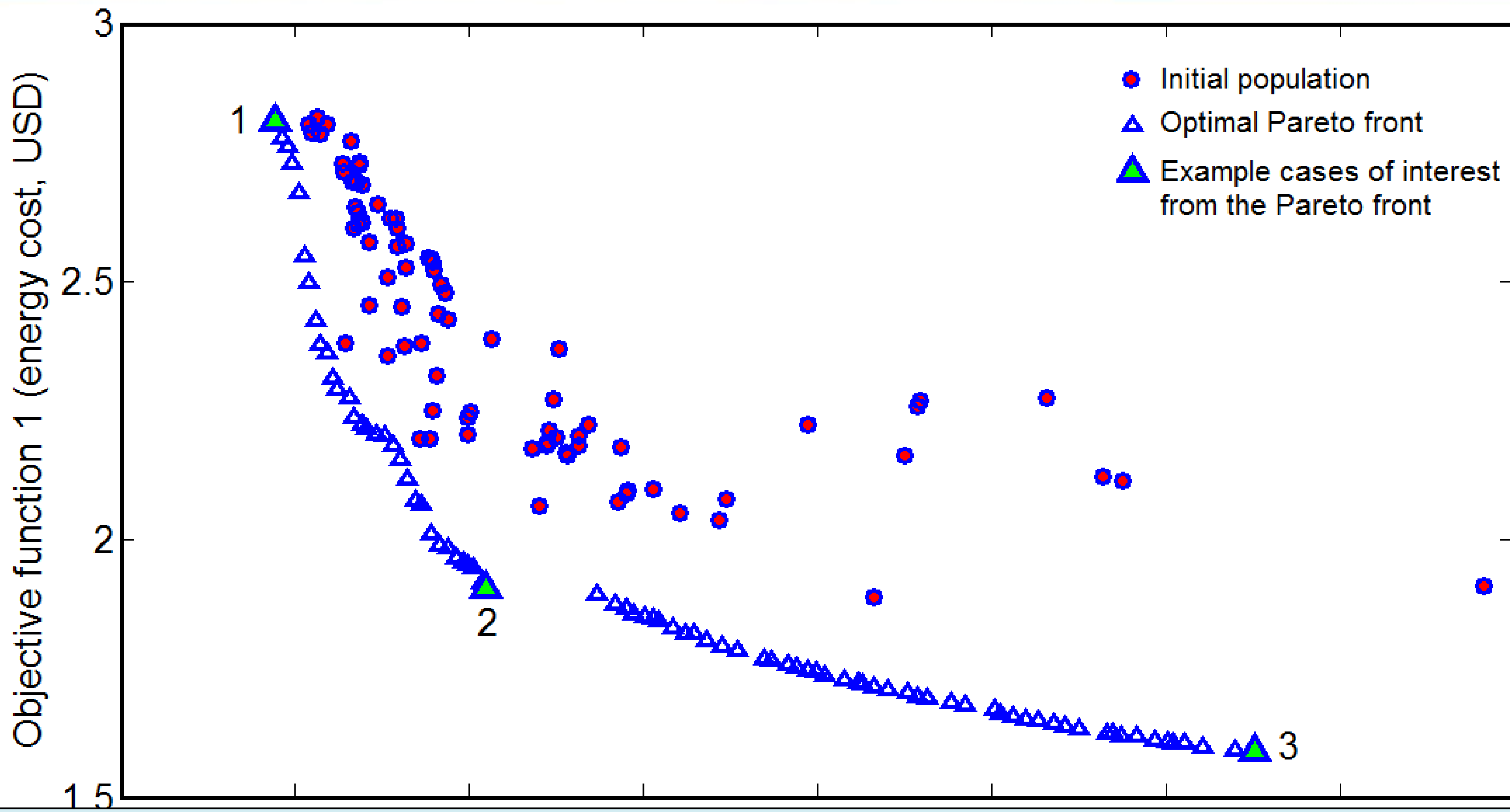
Procrastinate charging!
Do it immediately before you drive!

Objectives: fuel, electric energy cost, and battery health

Design variables: when, how long, at what rate to charge



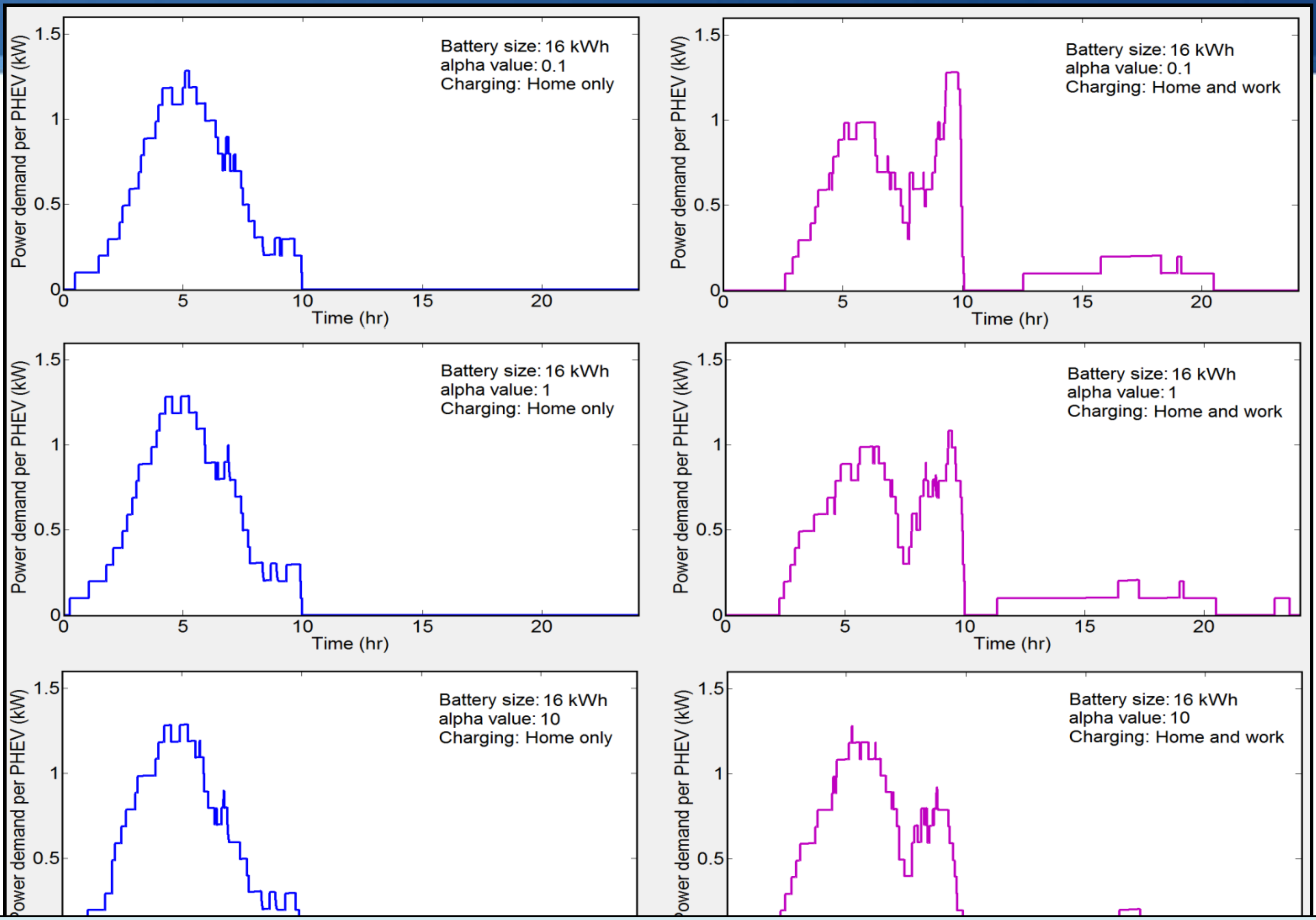
Multiobjective Optimization:
Energy Cost vs. Battery Resistive Film Growth



Publications

- S. Bashash, **S. J. Moura**, J. C. Forman, and H. K. Fathy, "Plug-in hybrid electric vehicle charge pattern optimization for energy cost and battery longevity," *Journal of Power Sources*, In Press, July 2010.
- S. Bashash, **S. J. Moura**, H. K. Fathy "Charge Trajectory Optimization of Plug-in Hybrid Electric Vehicles for Energy Cost Reduction and Battery Life Enhancement," *Proceedings of the 2010 American Control Conference*, Baltimore, MD, 2010.

PHEV Load Demand on Grid



Publications

- S. Bashash, **S. J. Moura**, H. K. Fathy, "Battery Health-Conscious Plug-in Hybrid Electric Vehicle Grid Load Prediction," *in review*.
- S. Bashash, **S. J. Moura**, H. K. Fathy "Battery Health-conscious Plug-in Hybrid Electric Vehicle Power Demand Prediction," *Proceedings of the 2010 ASME Dynamic Systems and Control Conference*, Cambridge, MA, 2010.

Ongoing / Future Work Topic:

Optimal Boundary Control and Estimation of Distributed Parameter Systems

Ongoing / Future Work:
Optimal Control & Estimation of Distributed Param. Systems

Develop practical extensions of LQR and optimal estimation results for distributed parameter systems

Relevant applications:

- Advanced batteries and fuel cells
- Thermal/fluid energy systems
- Stochastic distributions of PEV's and grid loads
- …

Publications

- **S. J. Moura** and H. K. Fathy "Optimal Boundary Control & Estimation of Diffusion-Reaction PDEs," Submitted to the *2011 American Control Conference*, San Francisco, CA, 2011

LQR Problem Formulation

Linear parabolic diffusion-reaction system

$$
\begin{aligned}
\text{Dynamics:} \quad u_t(x,t) &= u_{xx}(x,t) + cu(x,t) \\
\text{Boundary conditions:} \quad u_x(0,t) &= 0 \quad u(1,t) = U(t) \\
\text{Initial condition:} \quad u(x,0) &= u_0(x)
\end{aligned}
$$

$$
\text{Minimize:} \quad J = \frac{1}{2}\int_0^T \left[\langle u(x), Q(u(x))\rangle + RU^2(t)\right] dt + \frac{1}{2}\langle u(x,T), P_f(u(x,T))\rangle
$$

Derivation of optimal state-feedback:

- Weak-variation necessary conditions
- Linear operator theory

LQR Results: A partial differential Riccati equation

State-feedback

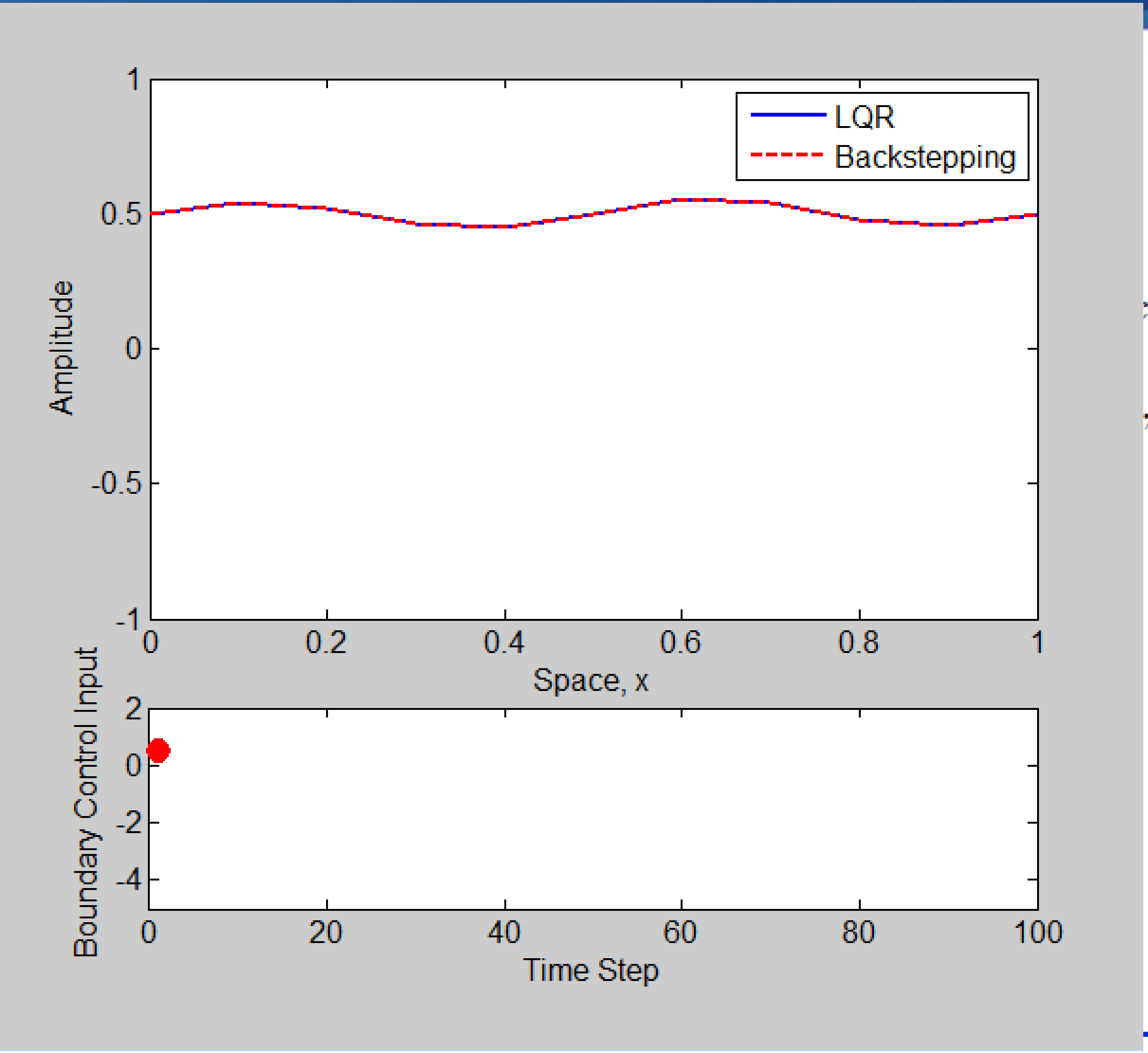
Riccati

$(1, y)$

Boundary Condit

$, t) = 0$

Final condi



Optimal Estimator Problem Formulation

Linear parabolic diffusion-reaction system

Dynamics: $u_t(x,t) = u_{xx}(x,t) + cu(x,t) + w(x,t)$

Boundary conditions: $u_x(0,t) = 0 \quad u(1,t) = U(t)$

Initial condition: $u(x,0) = u_0(x)$

Measurement: $y(t) = u(0,t) + v(t)$

Observer

Dynamics: $\hat{u}_t(x,t) = \hat{u}_{xx}(x,t) + c\hat{u}(x,t) + L^t(y(t) - \hat{u}(0,t))$

Boundary conditions: $\hat{u}_x(0,t) = L_0^t(y(t) - \hat{u}(0,t)) \qquad \hat{u}(1,t) = U(t)$

Initial condition: $\hat{u}(x,0) = \hat{u}_0(x)$

Estimation Results: A dual Riccati PDE

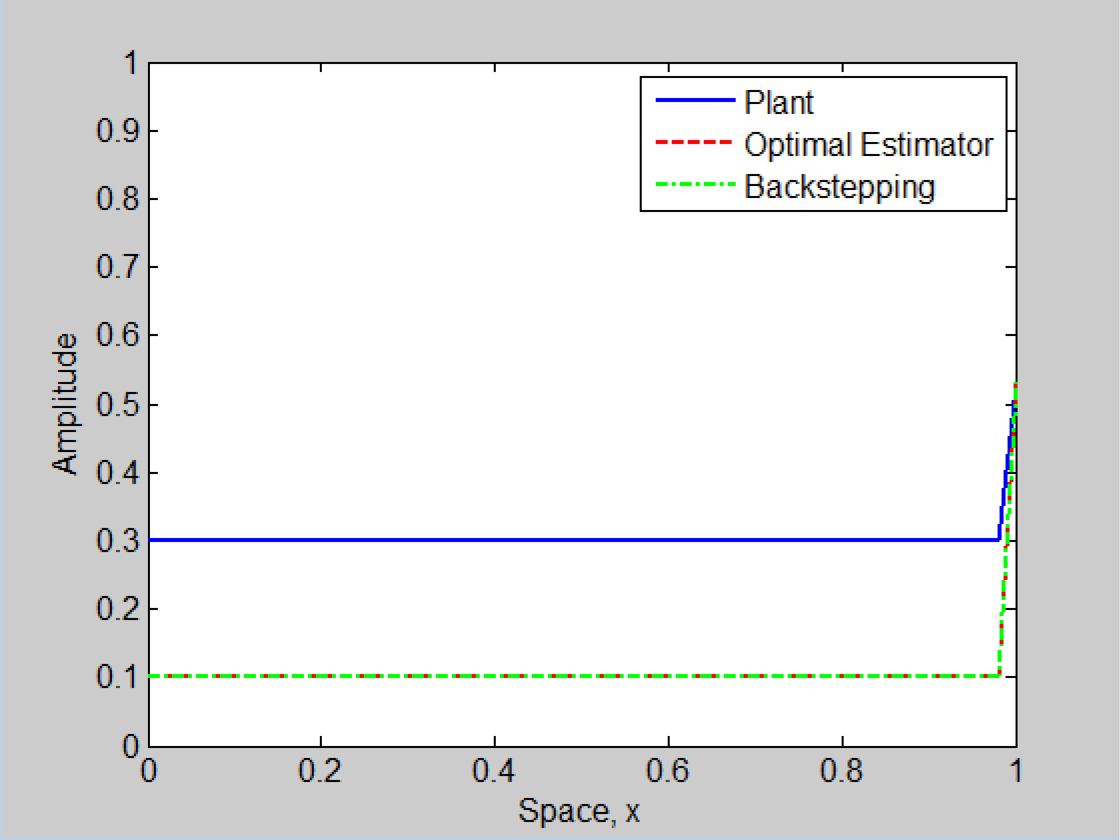
Output injection gain: $L^t = \frac{1}{V} S(x,t) \qquad L_0^t = -\frac{1}{V} S(0,t)$

Dual Riccati P

$+ W(x,0)$

Boundary Conditi

Initial condit



Future Research Directions

- Task #1: Advanced Battery Modeling for Control Apps.
  - DOE Office of EERE and ARPA-E
  - Ford Motor Company Univ. Research Program
- Task #2: Boundary Control and Estimation of Distributed Parameter Systems
  - NSF EPAS and CS programs
  - Bosch LLC & NSF GOALI
- Task #3: Distributed Control of PHEV Storage, Load Demand, and Renewable Generation
  - Resnick Institute, NSF EFRI, NSF MURI, California Energy Commission, electric utilities (EPRI & SCE), etc.

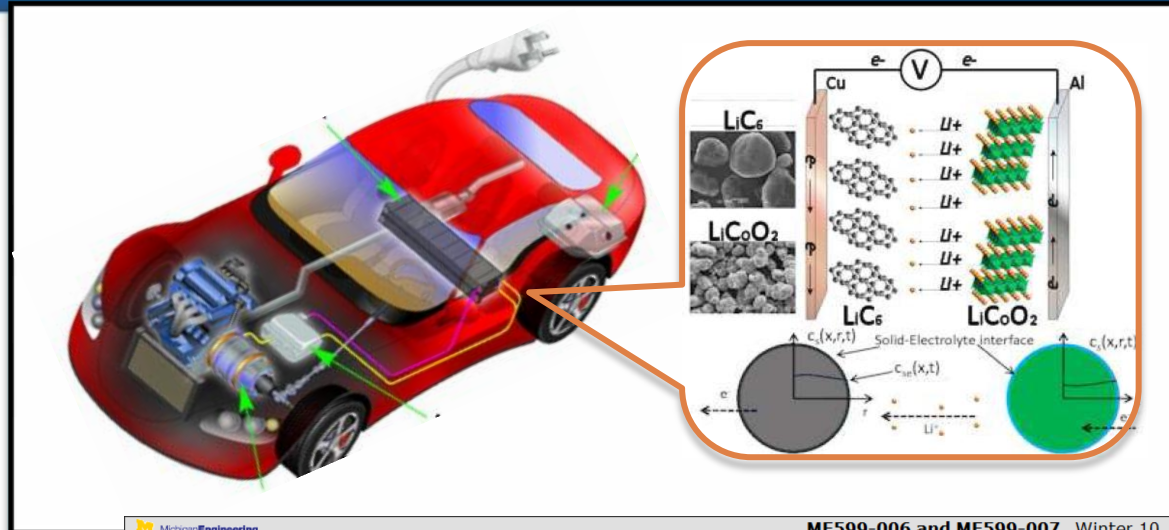
Battery Systems and Control Course:

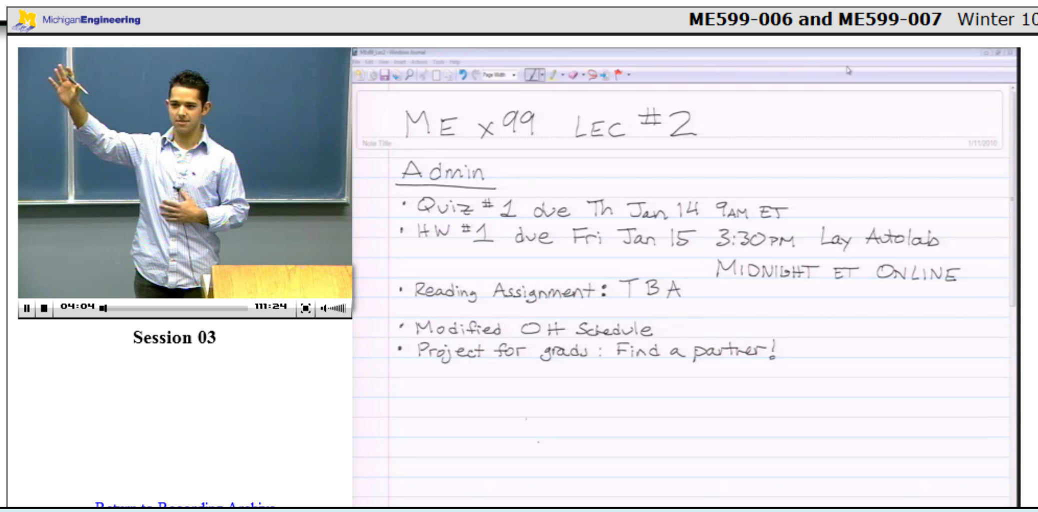
Funded by DOE-ARRA Advanced Electric Drive Vehicle Education Program

<u>**Student Enrollment**</u>

- **W'10:** 59 / 5 distance
- **W'11:** 55 / 24 distance
  - **Undergrads**
  - **Graduates**
  - **Professionals**
    - **General Motors (Volt battery engineers!)**
    - **Roush**
    - **US Army TARDEC**

- **ME**
- **ChemE**
- **Energy Systems**
- **Physics**
- **EE**
- **CS**
- **MatSci**
- **Math**





<u>Publications</u>

- **S. J. Moura**, J. B. Siegel, D. J. Siegel, H. K. Fathy, A. G. Stefanopoulou "Education on Vehicle Electrification: Battery Systems, Fuel Cells, and Hydrogen," *Proceedings of the 2010 IEEE Vehicle Power and Propulsion Conference*, Lille, France, 2010. **(Invited Paper)**.

Seminar Summary

- Battery Modeling and Experimentation
  - Modeling battery electrochemical dynamics from first principles
  - Battery-in-the-loop tester for parameter ID and control design
- Advanced Battery Pack Management Systems
  - Charge ***un***equalization
  - Relationship between SOH convexity properties and charge management
- Power Management in Plug-in Hybrid Electric Vehicles
  - Stochastic drive cycle modeling
  - Multi-objective, constrained
  - Fundamental tradeoffs between energy consumption and battery health

Thank you for your attention!

Questions?

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sjmoura@umich.edu, http://www.umich.edu/~sjmoura