Optimal Control of Lithium-ion Battery Energy Storage Systems

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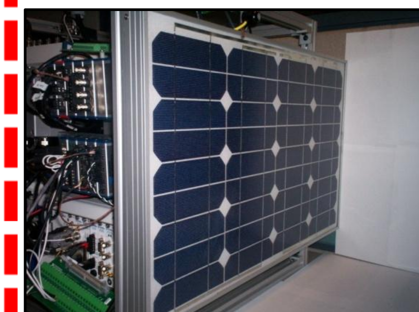
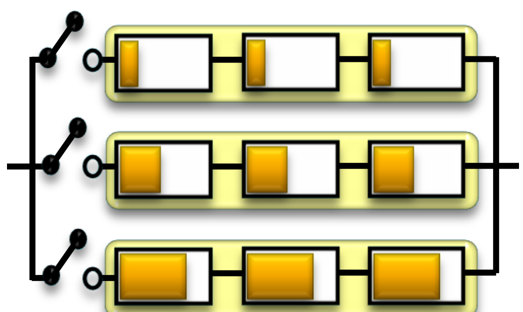
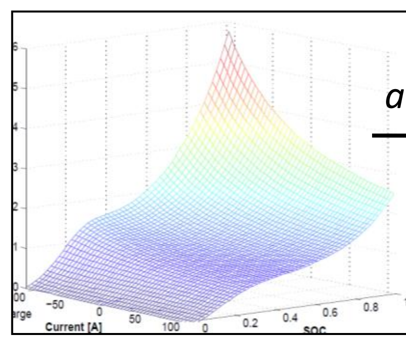
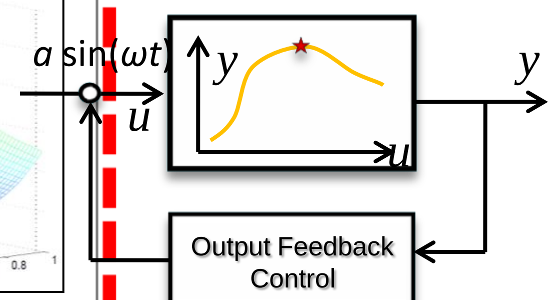
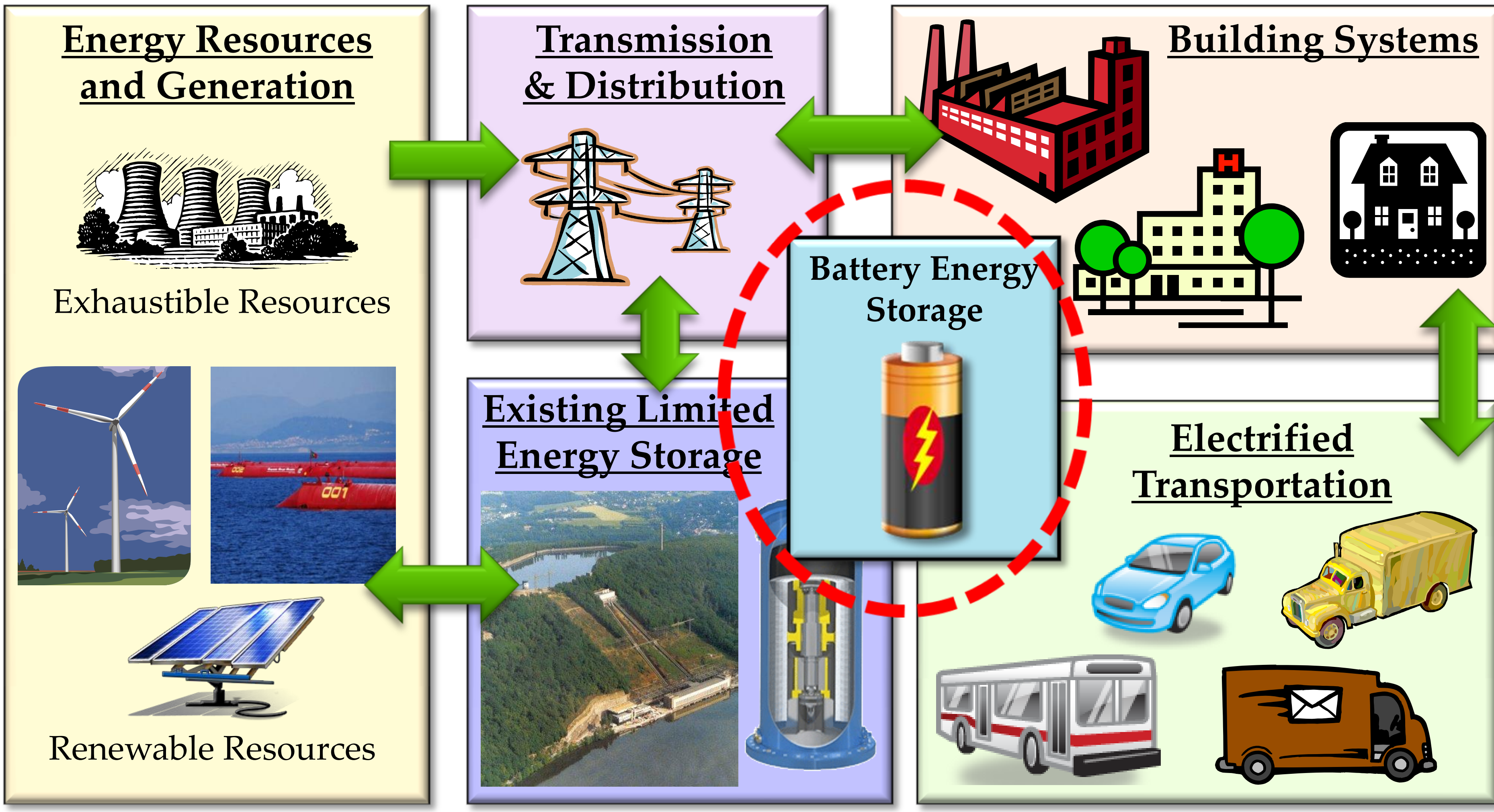
Ford Motor Company
Friday December 3, 2010

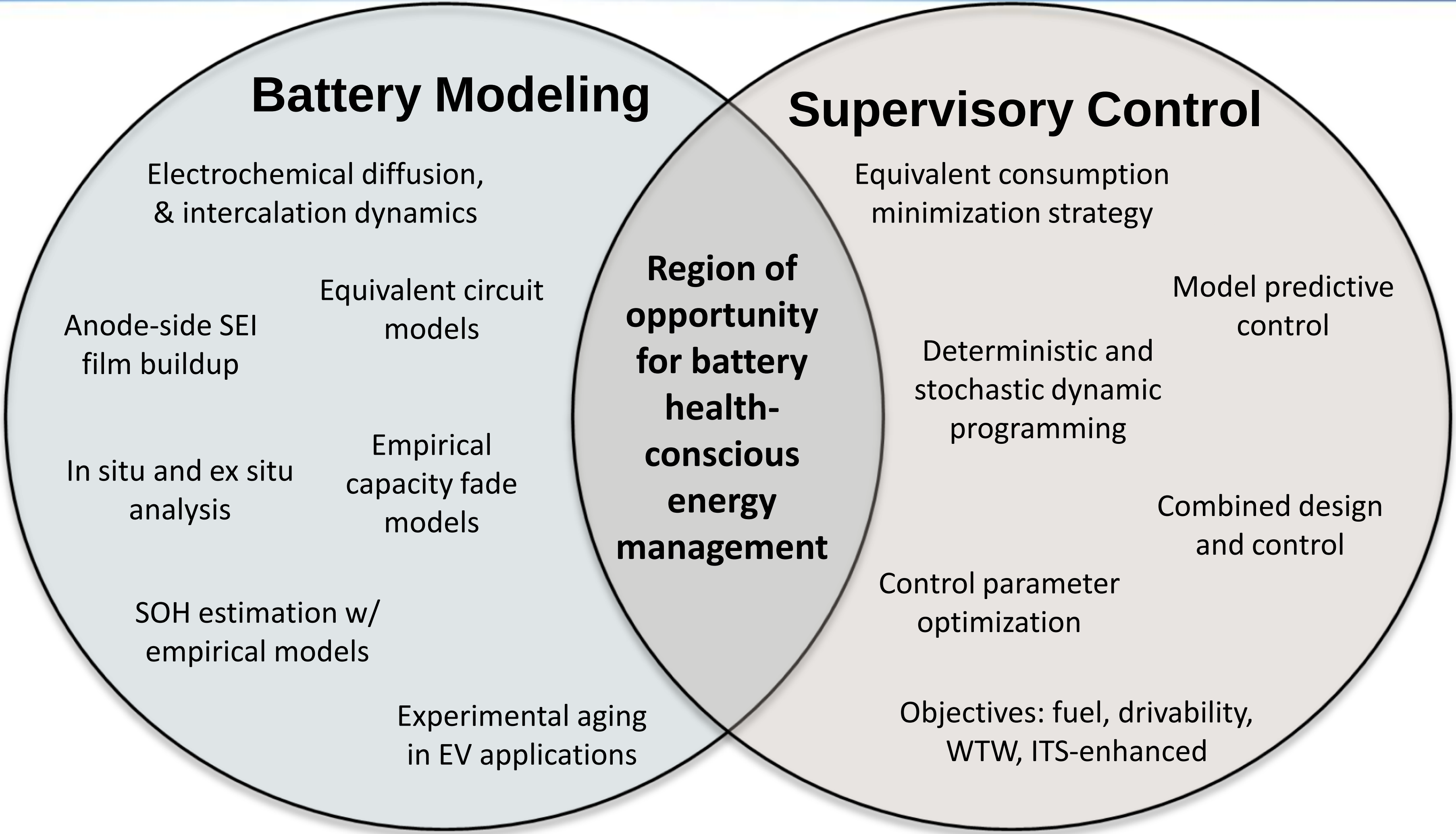
Overview of Research Contributions

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



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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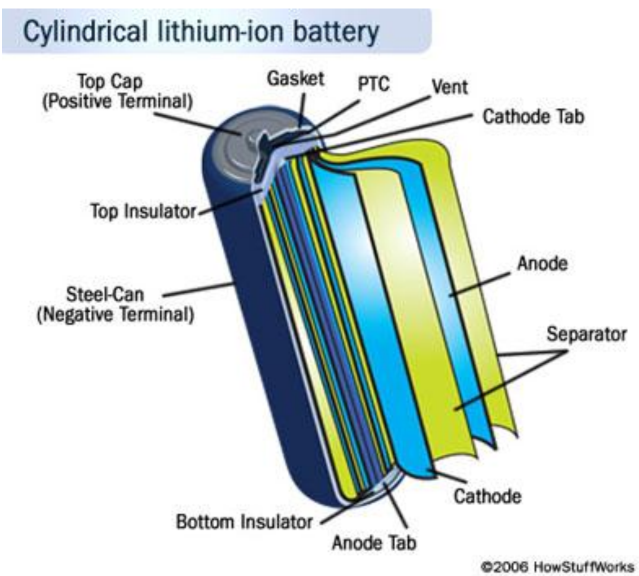
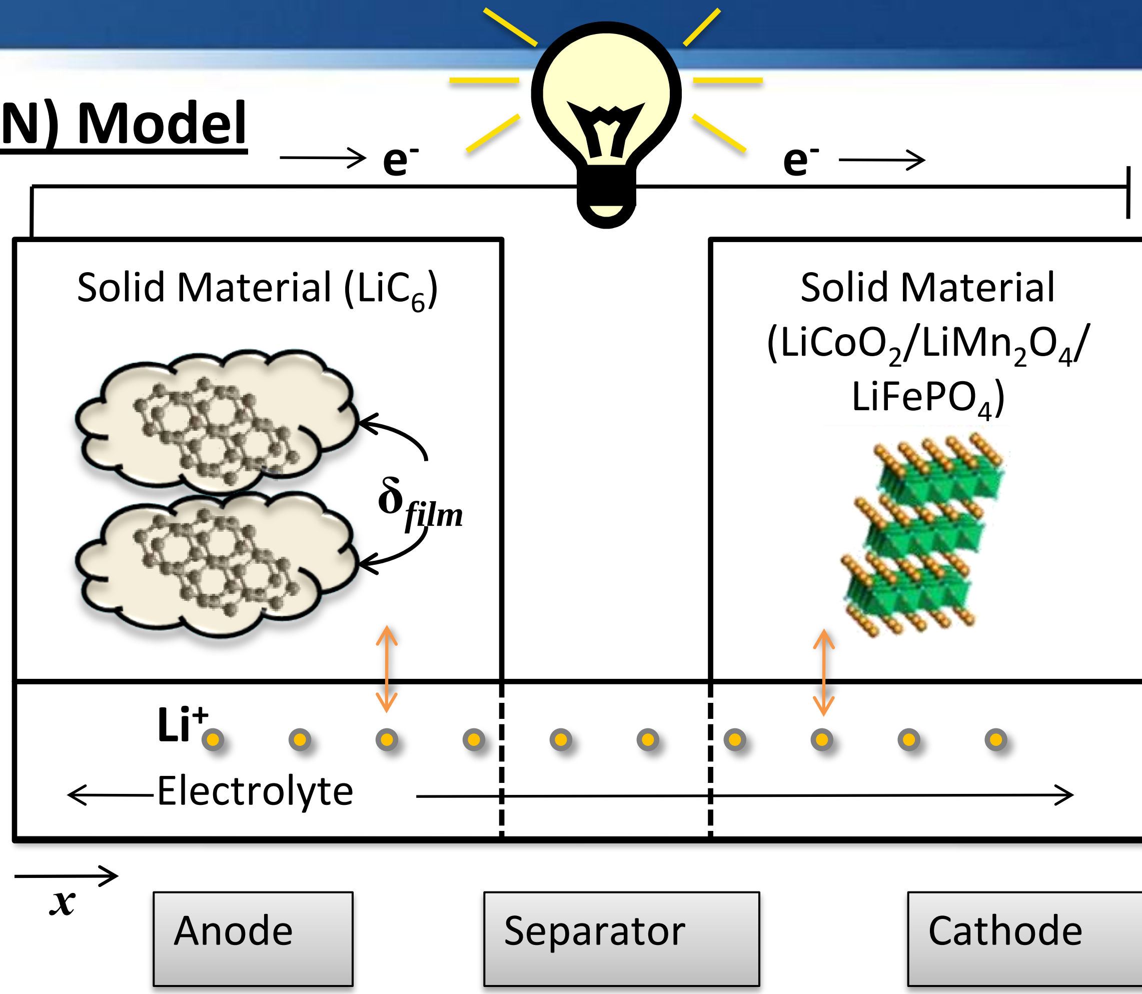
Electrochemical Li-ion Battery Modeling

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

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

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

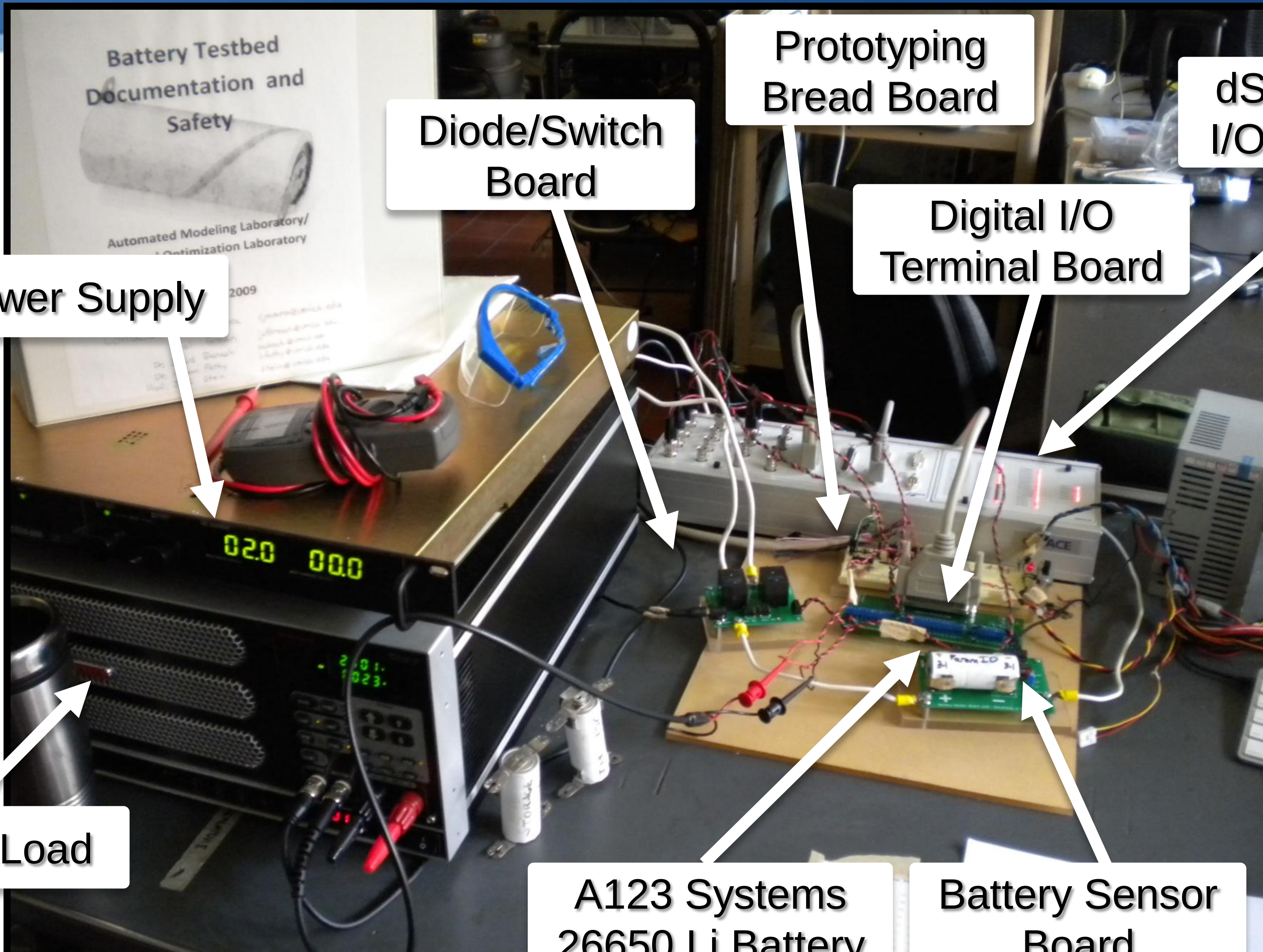
Ohm's Law

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

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

Butler-Volmer Kinetics

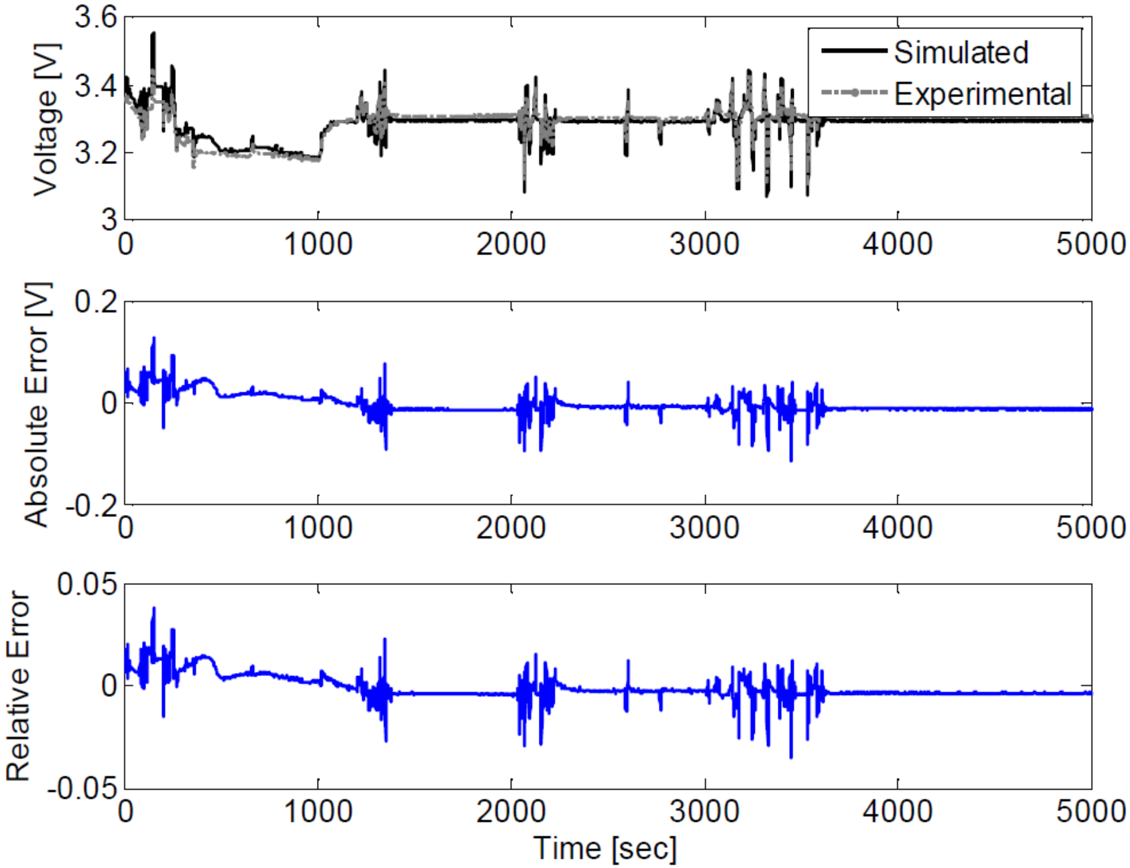
Battery-in-the-loop Hardware



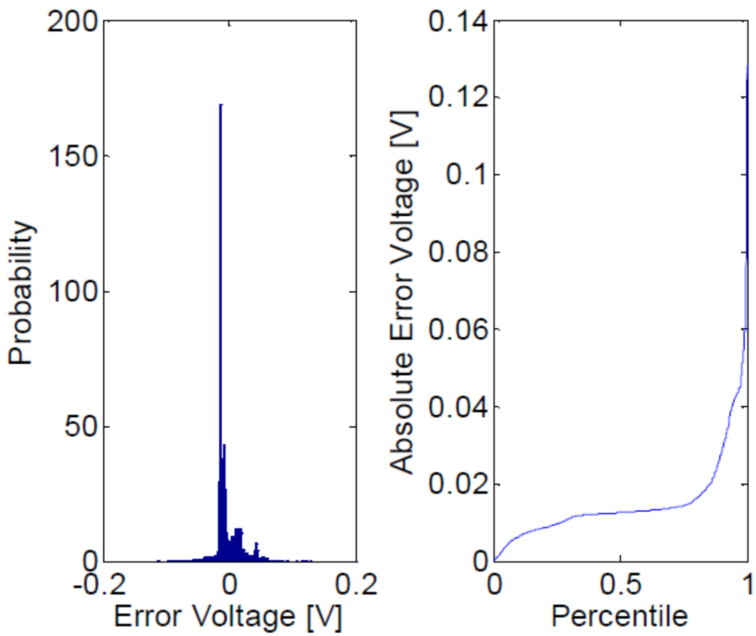
Parameter Identification Results

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.

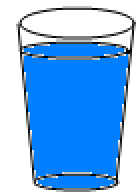
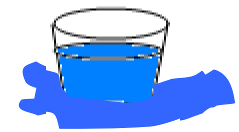
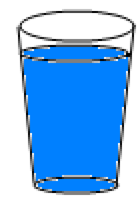
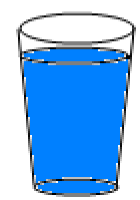
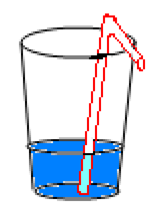
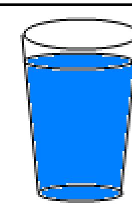
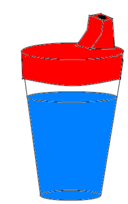
Causes of Battery Degradation

<u>Causes of Battery Degradation</u>

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

<u>System-Level Relations to Aging</u>

- 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		

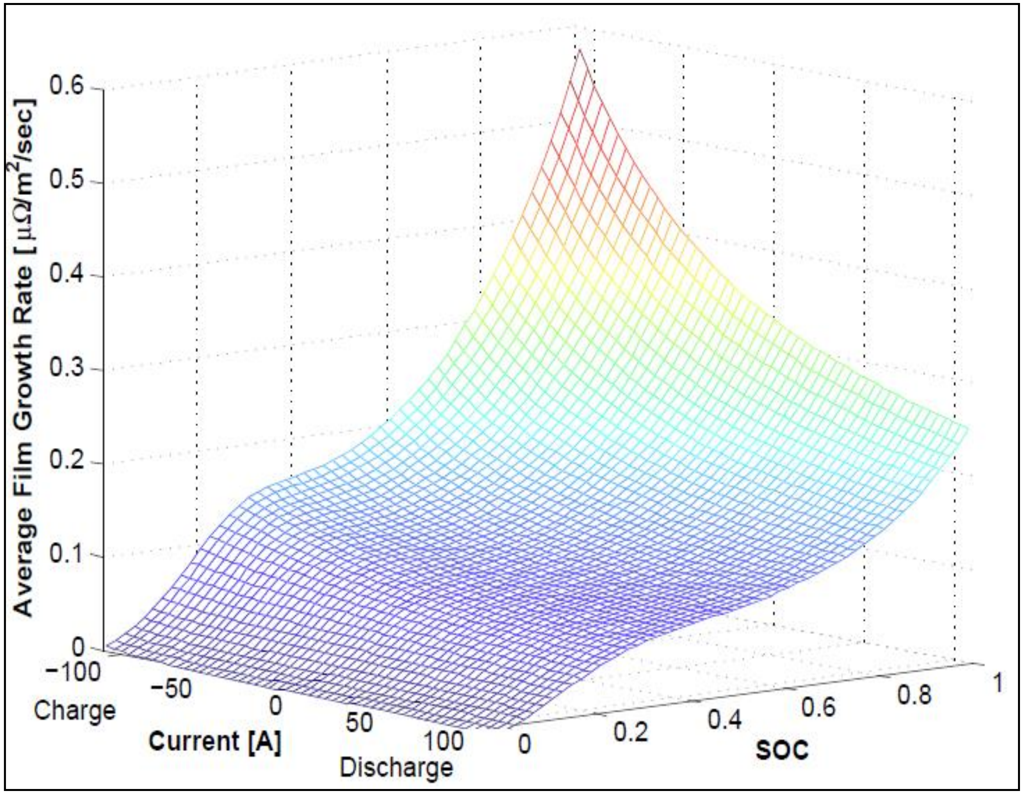
Anode-Side SEI Film Buildup

Ramadass et al, 2004

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

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

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



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Advanced Battery Pack Management

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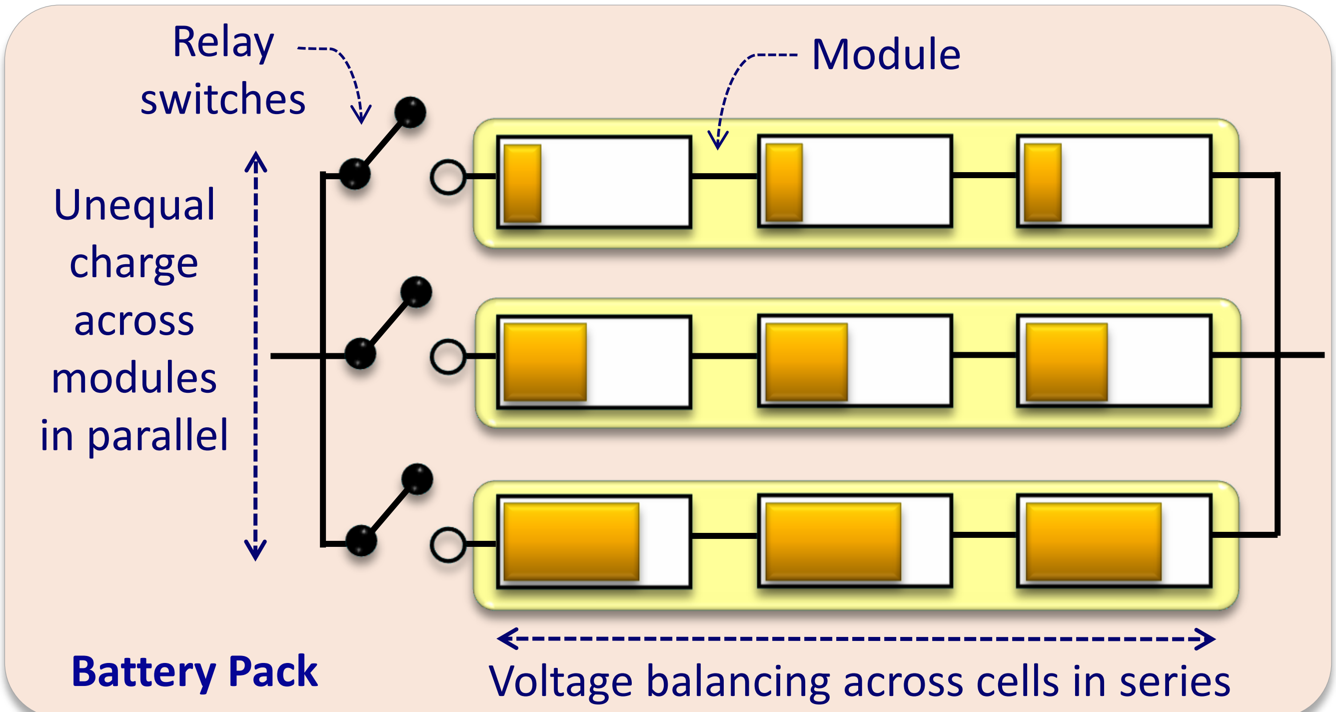
Unbalanced Charge Management

<u>Objective</u>: Explore unequal but controlled charge levels in battery packs for enhancing health



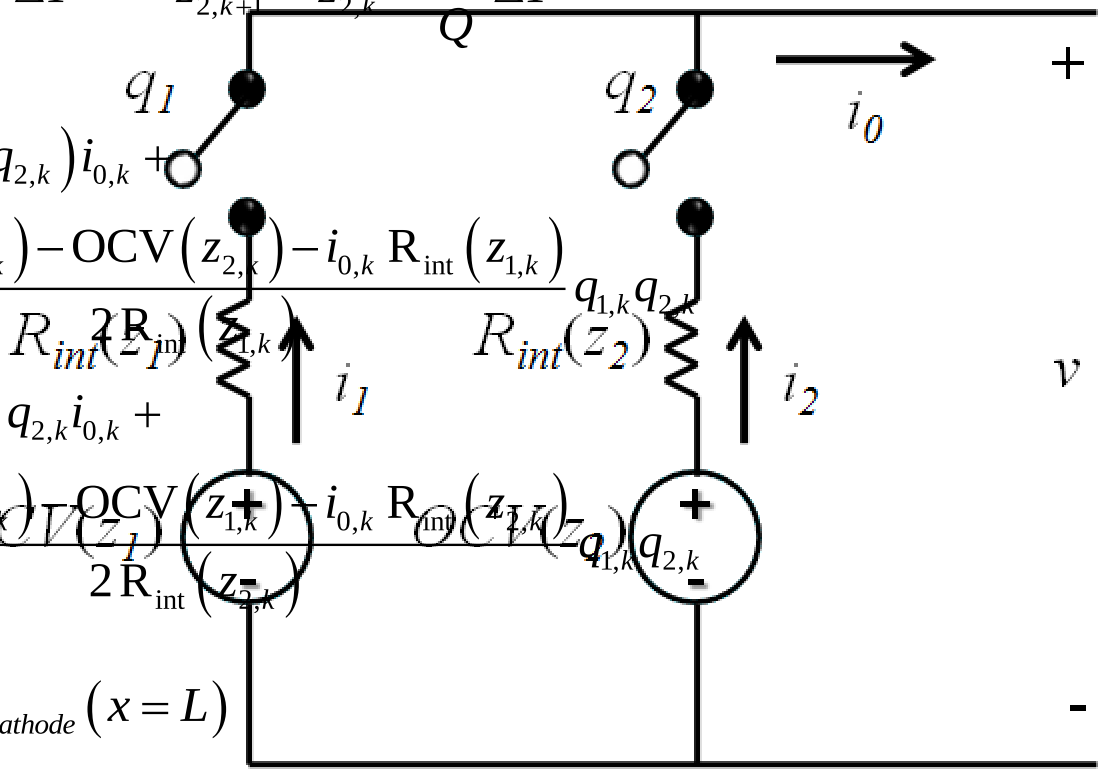
<u>Theoretical Approach:</u> Optimal control and reduced order models

Battery Pack Model

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

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

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



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

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

Problem Formulation

Minimize total spatially-averaged film growth over the charge cycle

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

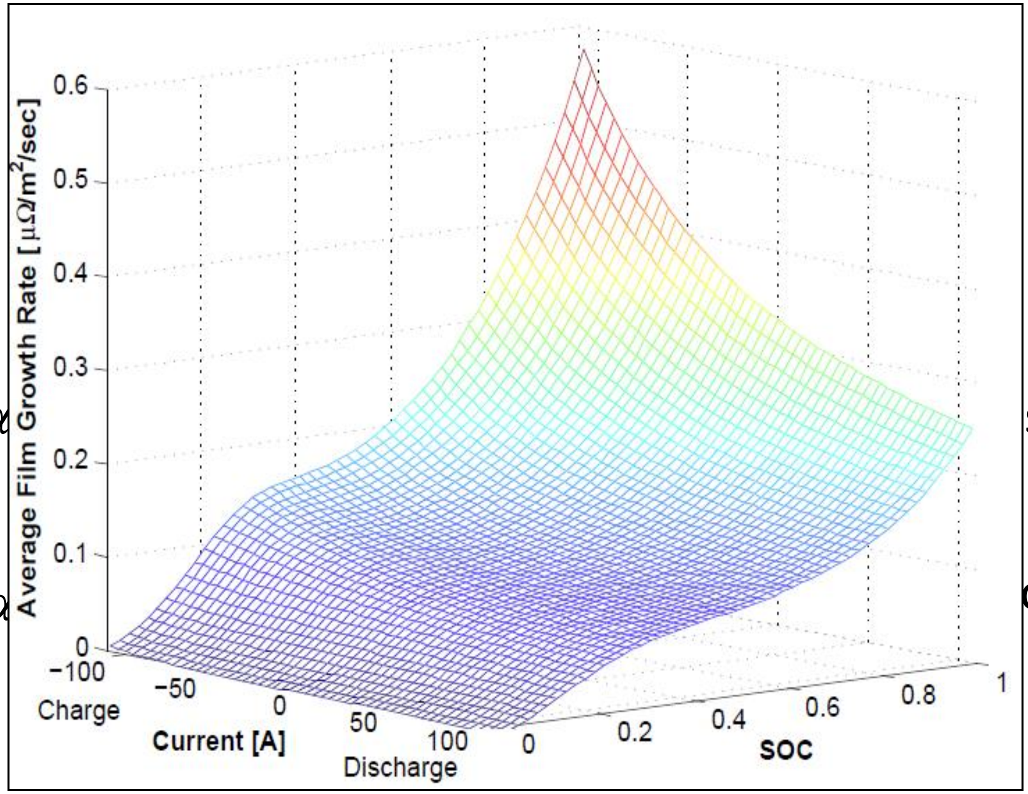
subject to $\quad z_{k+1} =$

$i_k =$

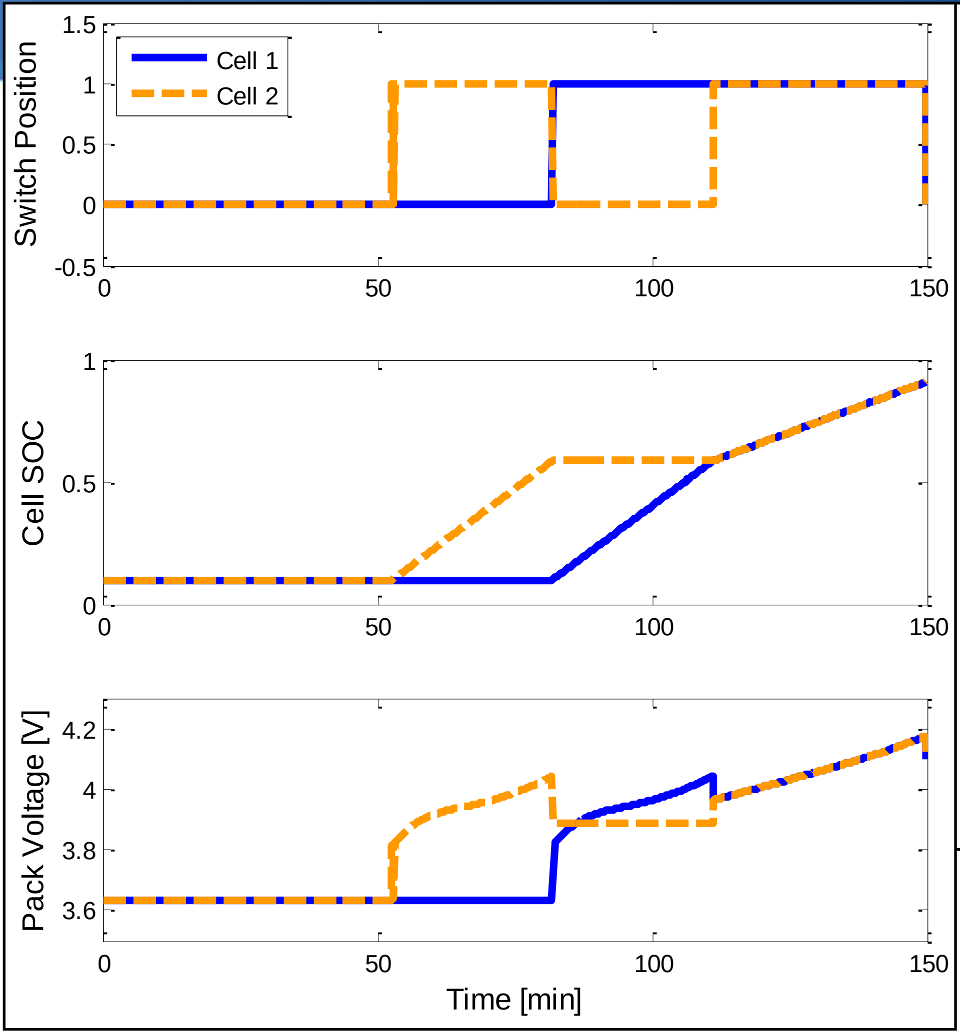
$z_1 =$

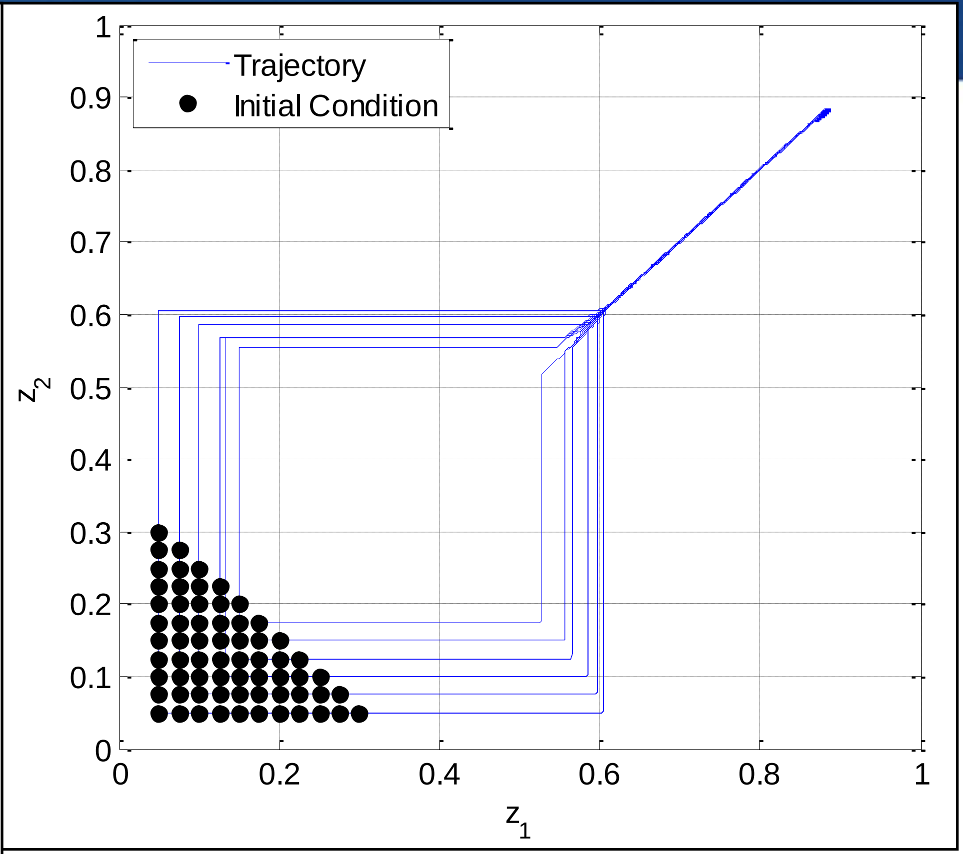
where $\quad g_z\left(z_k\right) = \alpha$ straints

$+\alpha$ constraints



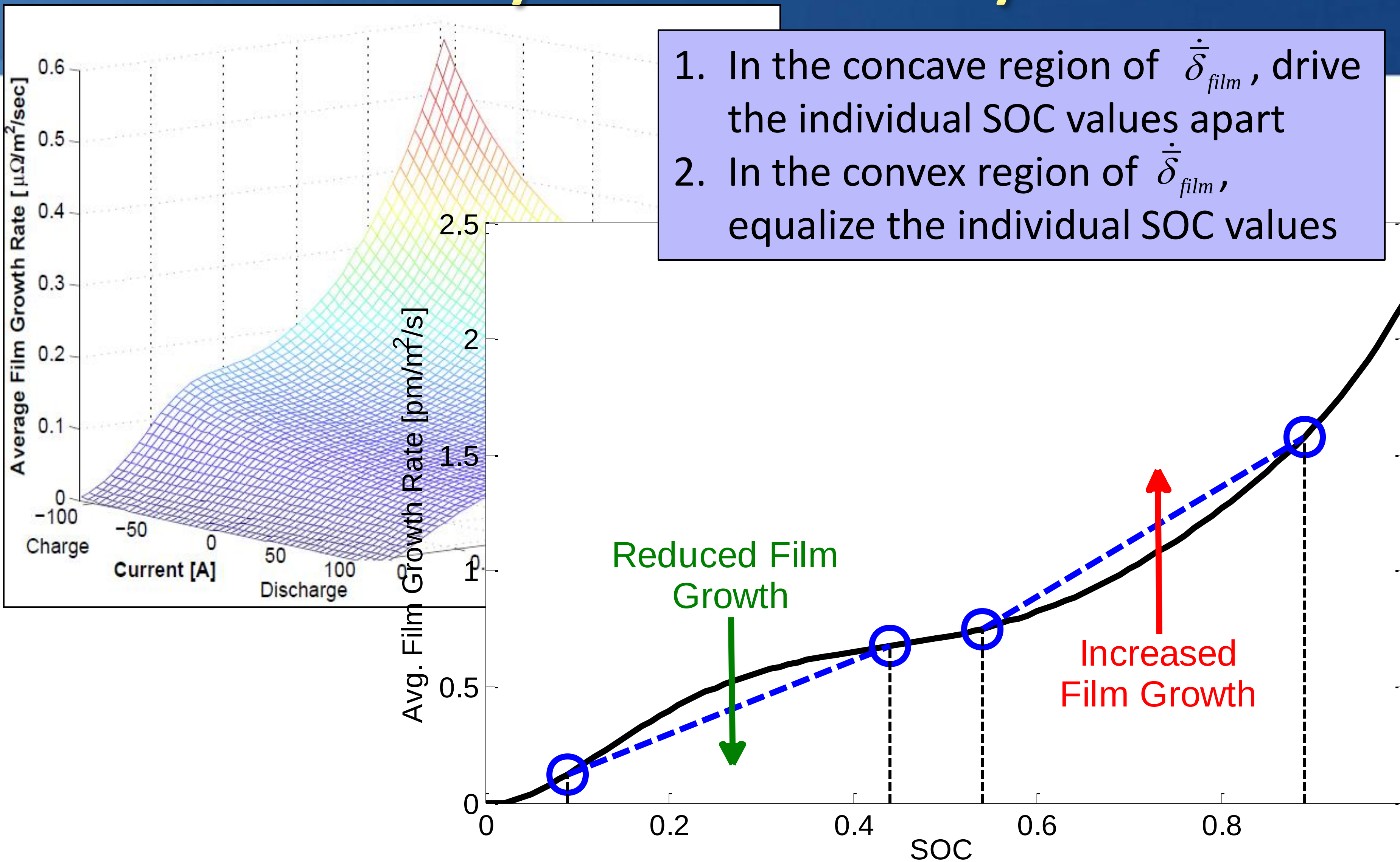
Solution Analysis: Optimal Trajectories



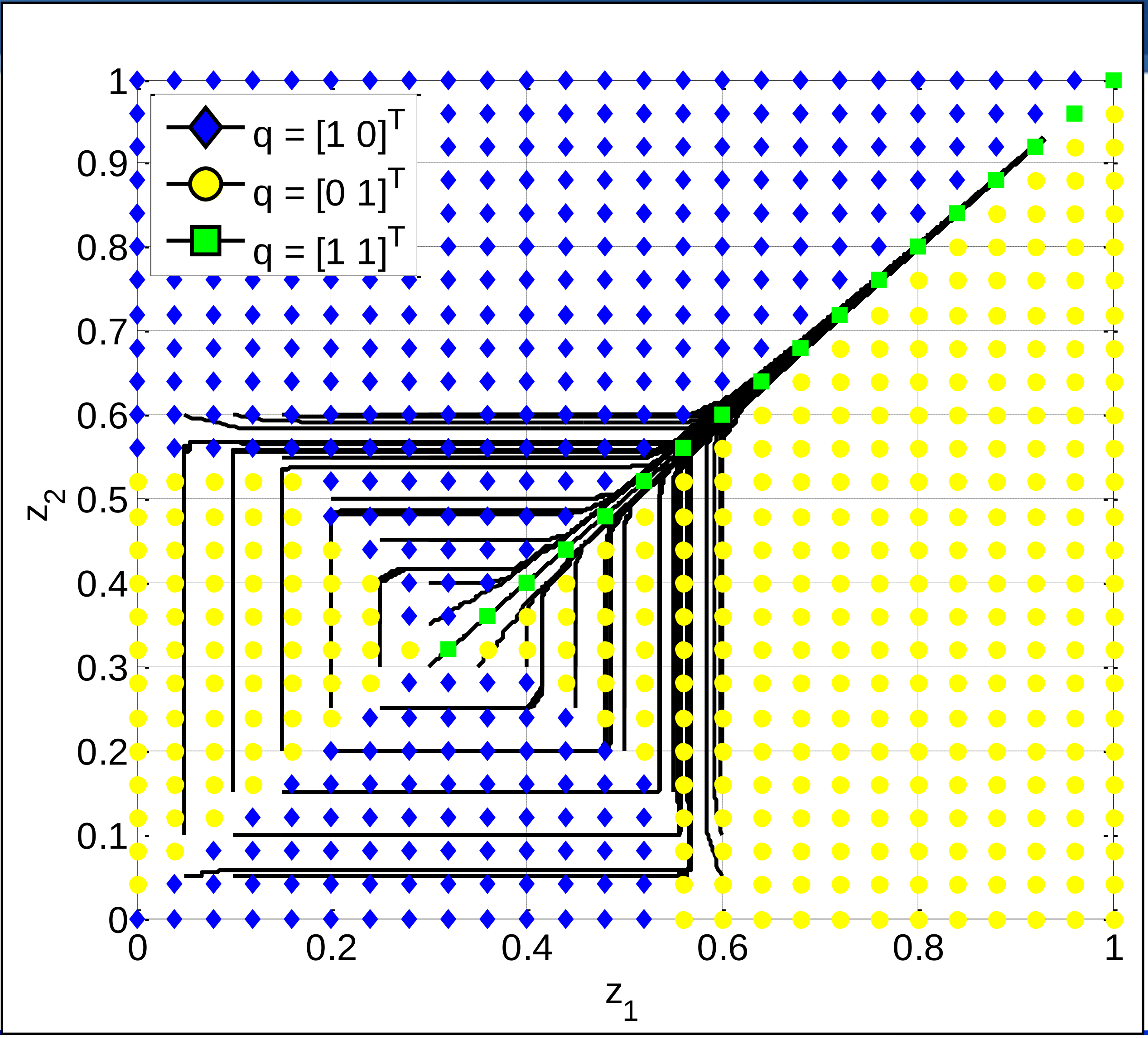


Solution Analysis: Convexity

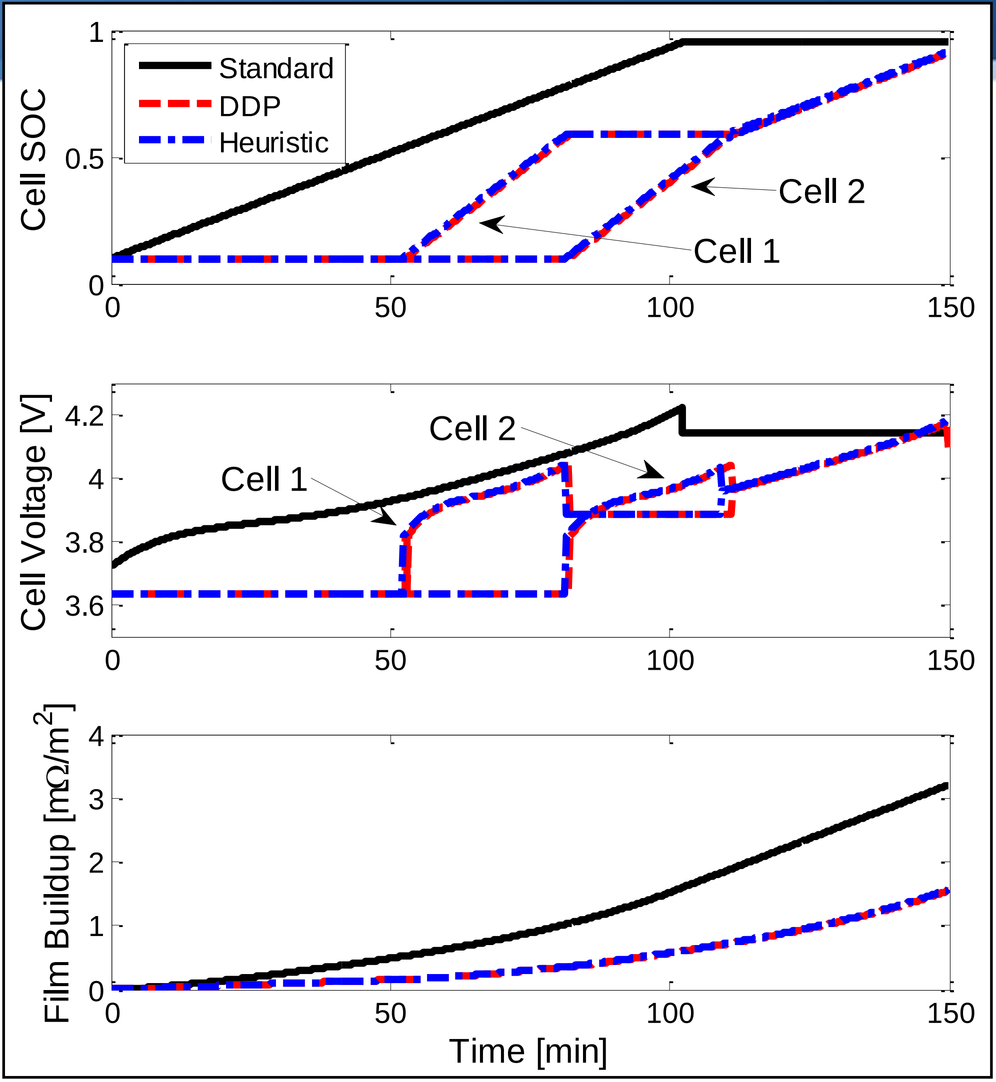
1. In the concave region of $\bar{\dot{\delta}}_{film}$, drive the individual SOC values apart
2. In the convex region of $\bar{\dot{\delta}}_{film}$, equalize the individual SOC values



Solution Analysis: Heuristic Control

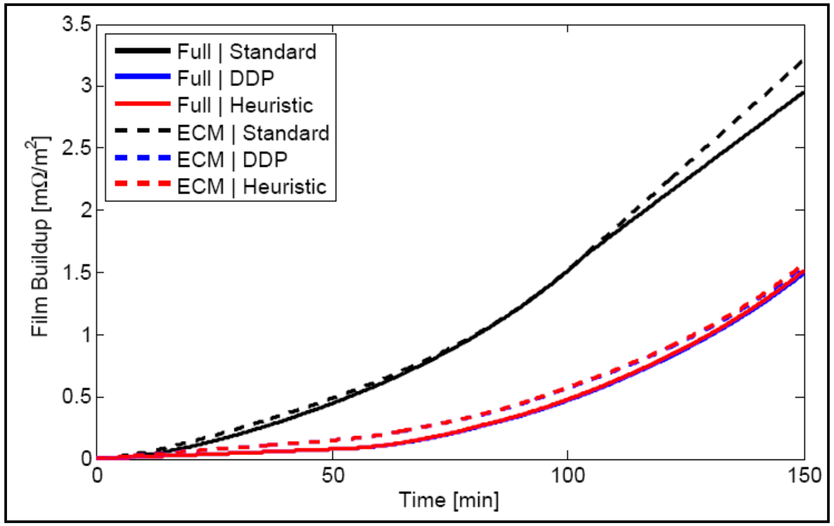


Simulation Results: Controller Comparison



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**

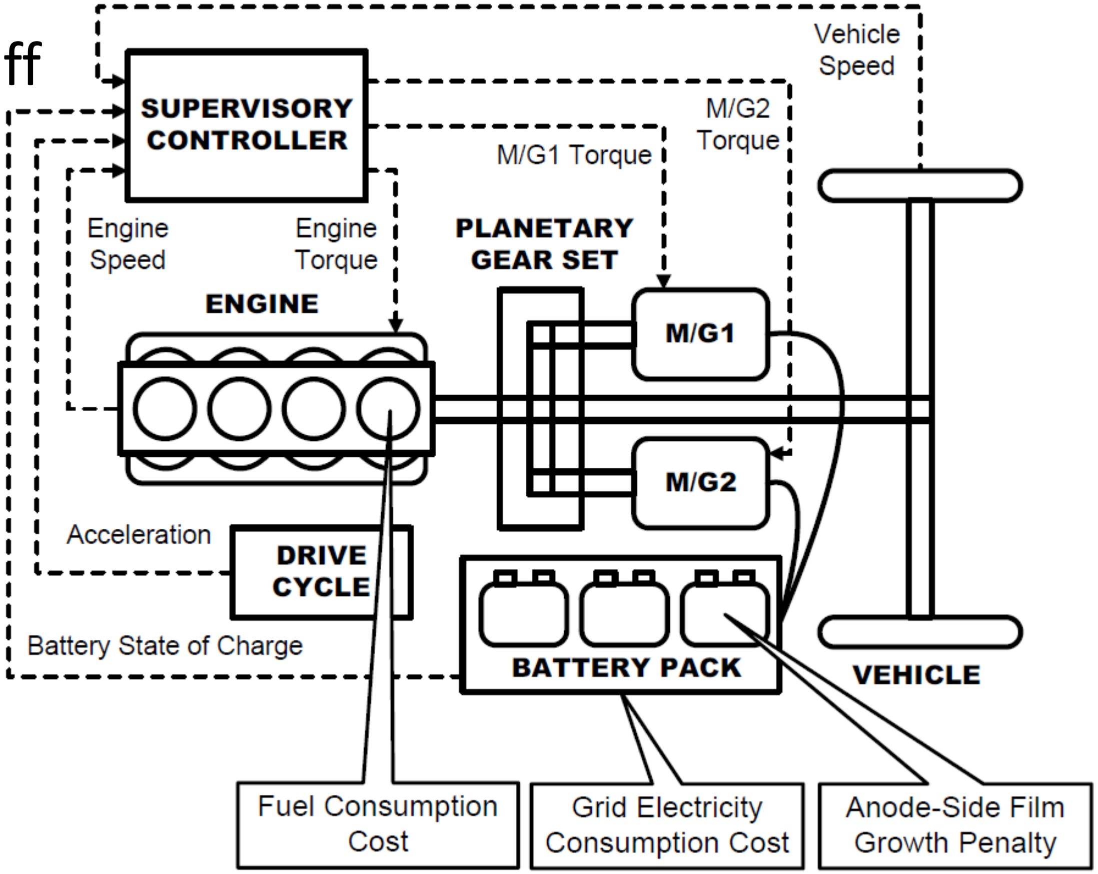
Research Objective

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

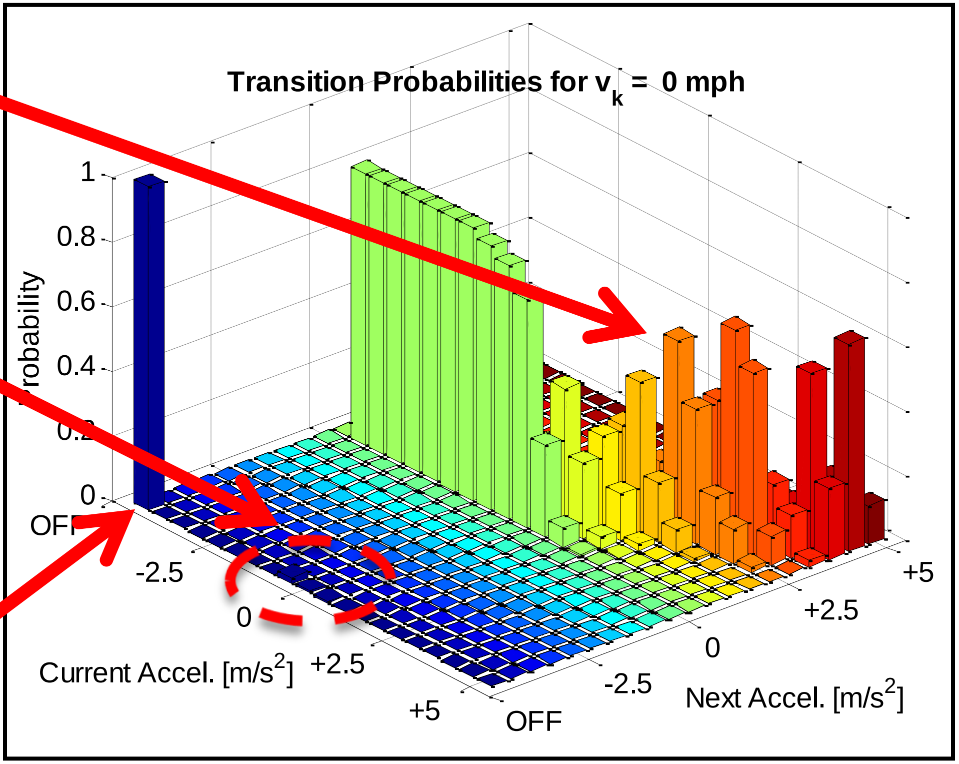
$$p_{ijm} = \Pr(a_{k+1} = j \mid a_k = i, v_k = m)$$

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

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

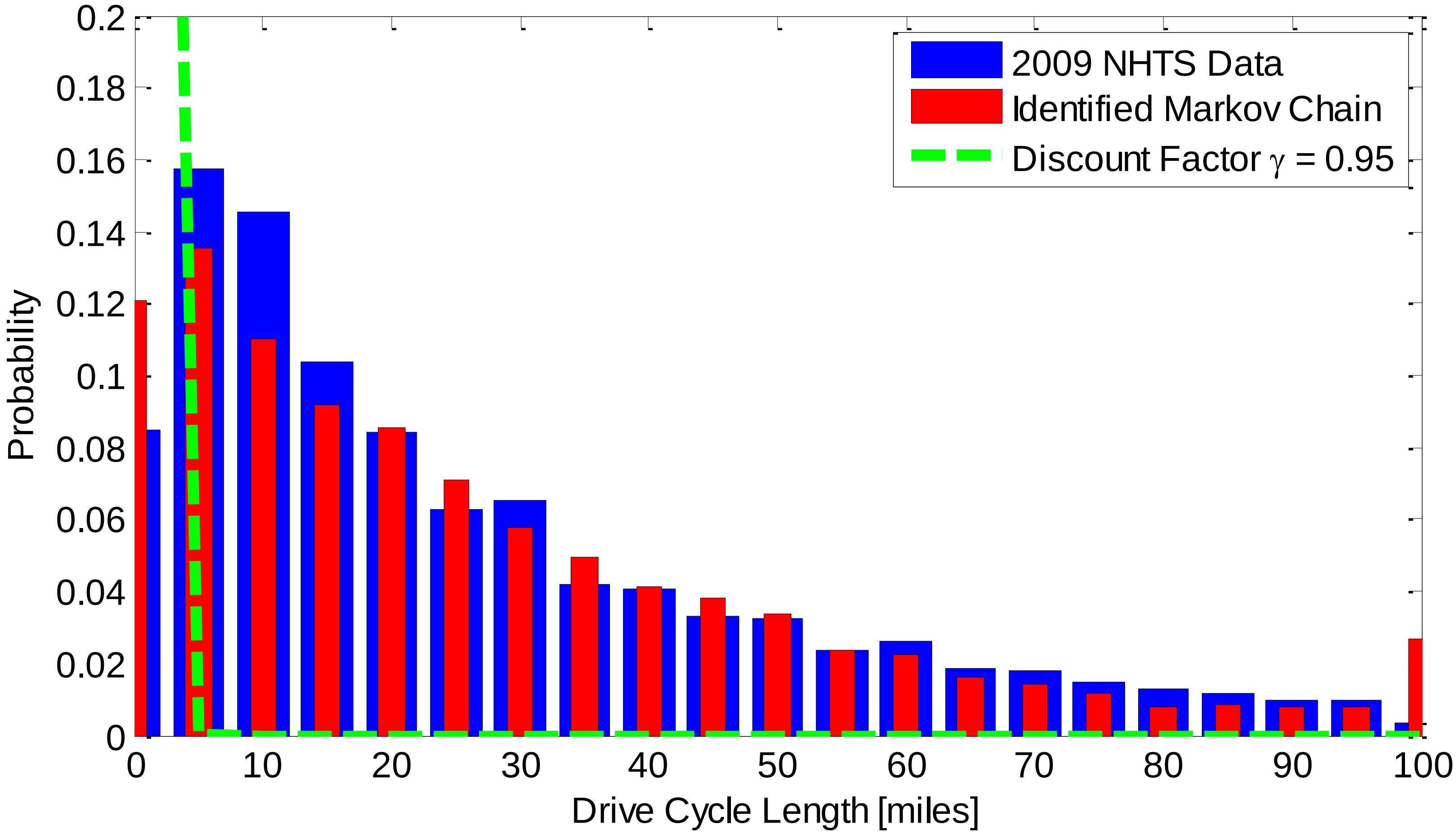
Absorbing state "vehicle off"

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



Markov chain model of Drive Cycles

Daily Trip Length Distribution



Optimal Control Problem Formulation

Multiobjective Shortest-Path Stochastic Dynamic Program

Cost Functional:

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

Constraints:

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

$$x \in X$$

$$u \in U(x)$$

Objective:

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

Combine two objectives into a single linear-weighted objective:

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

where

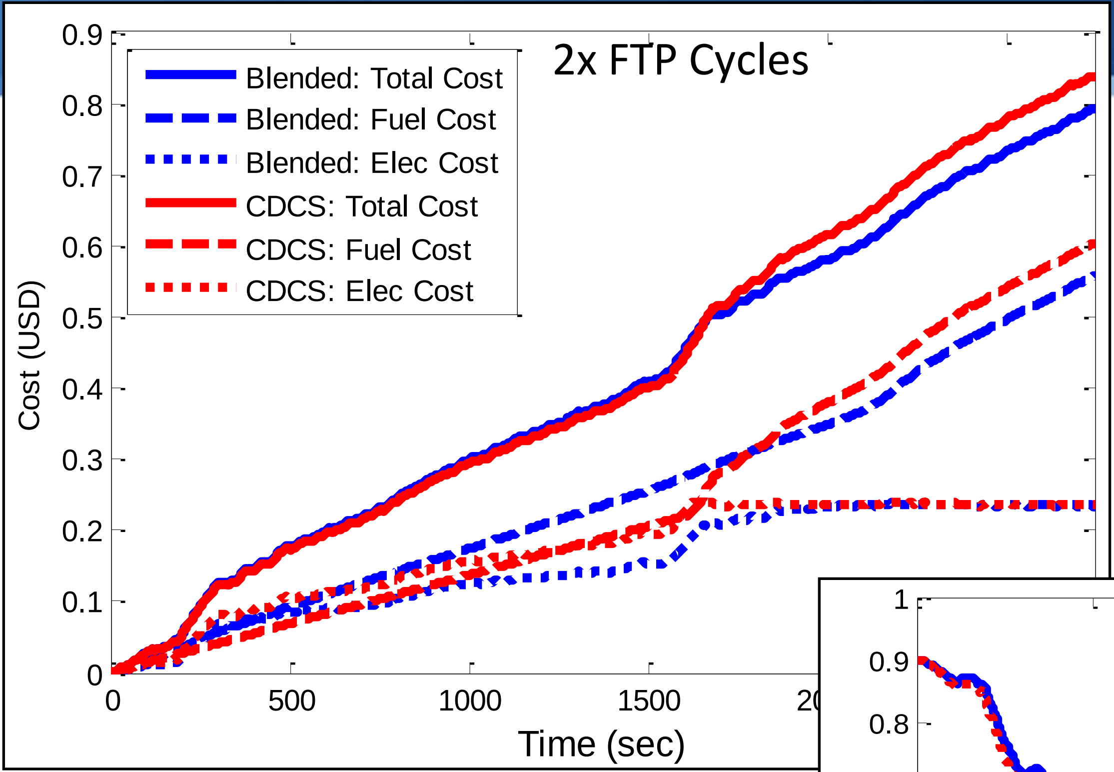
$$c_{energy}(x_k, u_k) = \beta \alpha_{fuel} W_{fuel} + \alpha_{fuel} \frac{-V_{oc} Q_{batt} \dot{SOC}}{\eta_{grid}}$$

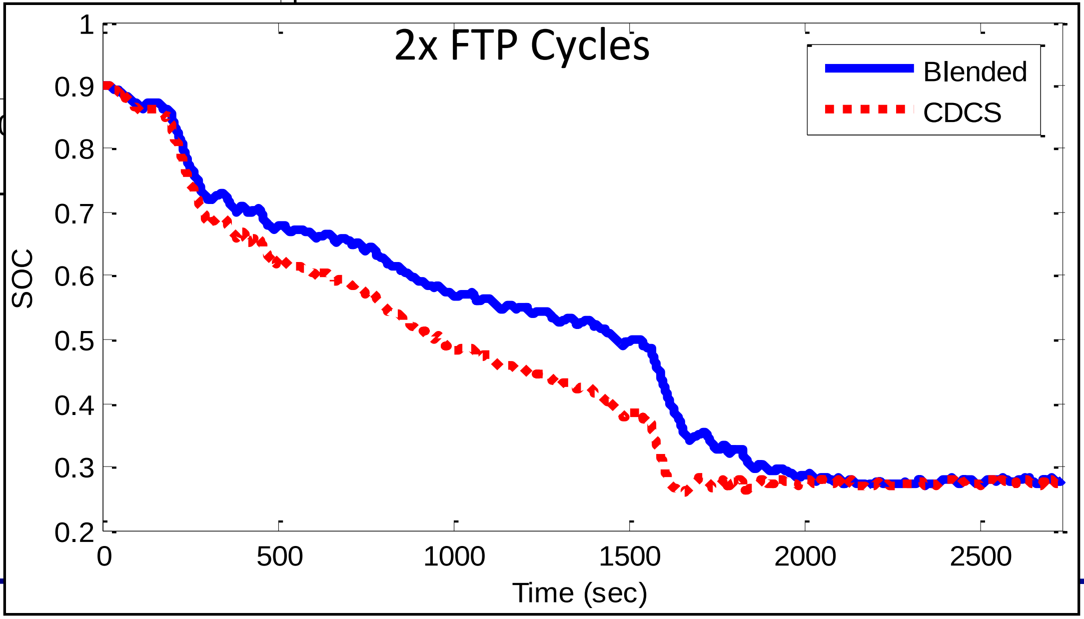
$$c_{film}(x_k, u_k) = \dot{\delta}_{film}(I, SOC)$$

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

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

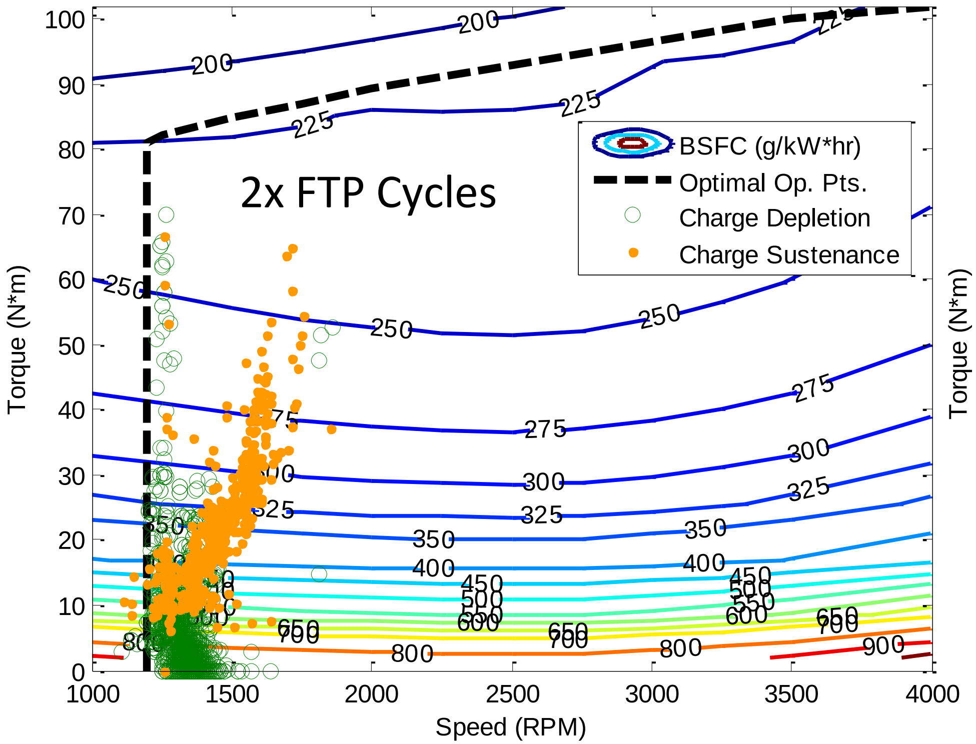
Power Management Results w/o Aging



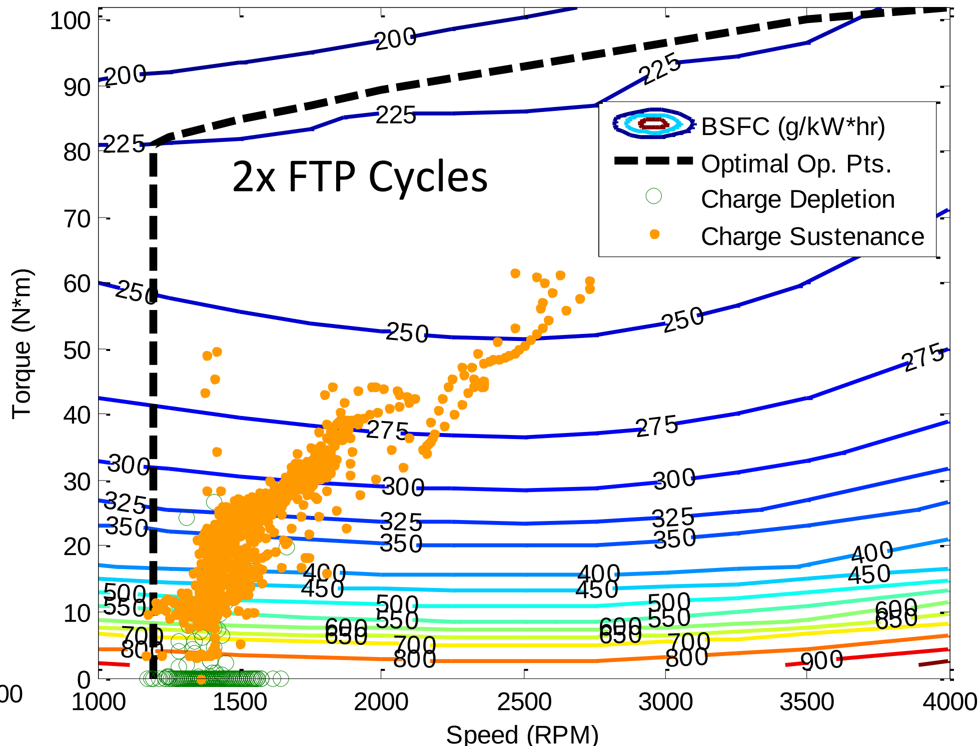


Engine Operating Point Analysis

Optimal Blending

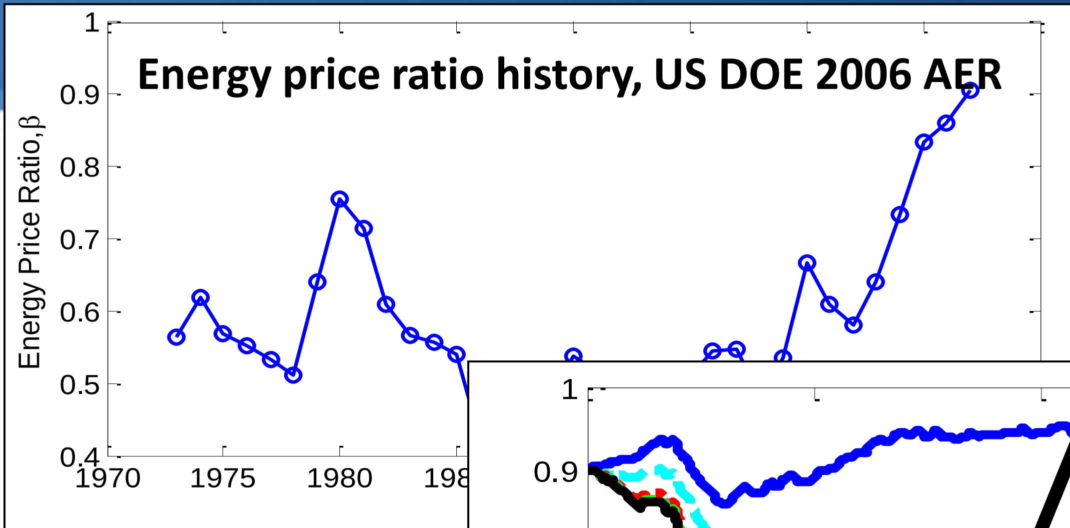


Charge Depletion, Charge Sustenance



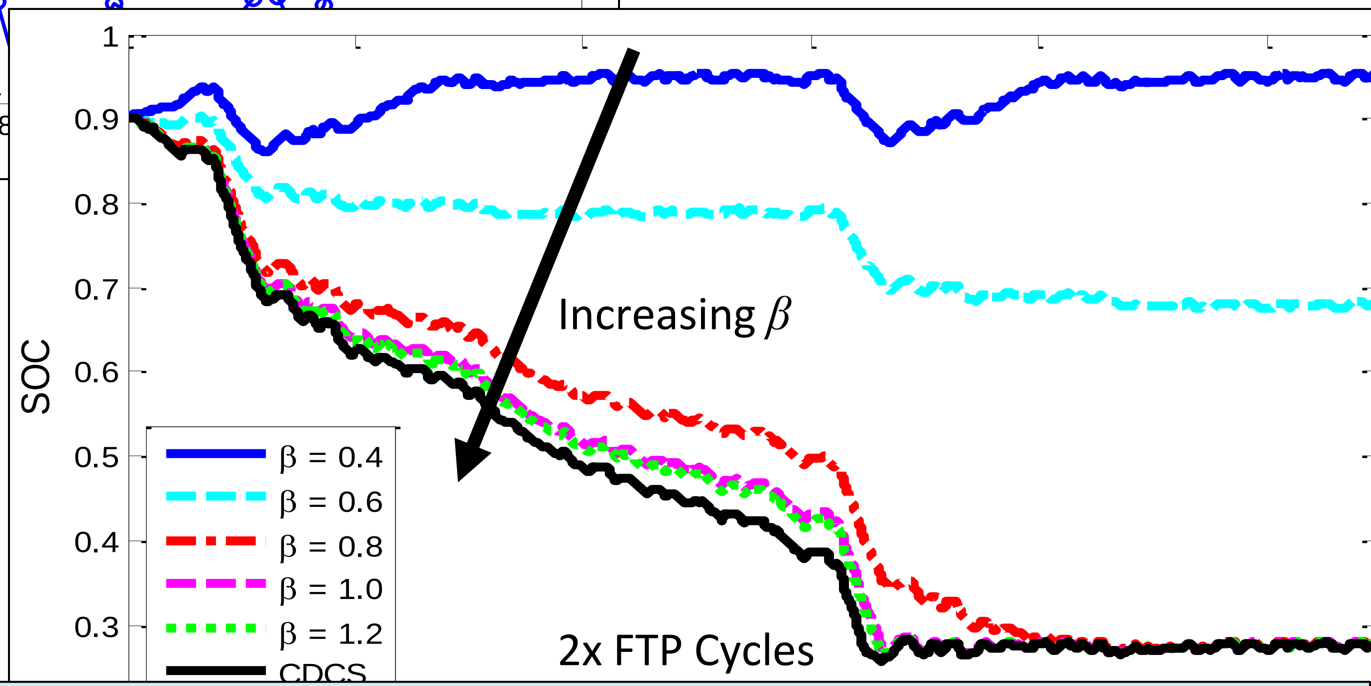
- Blended operates at higher engine efficiency during charge depletion
- Excess power goes to battery charge regeneration

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)

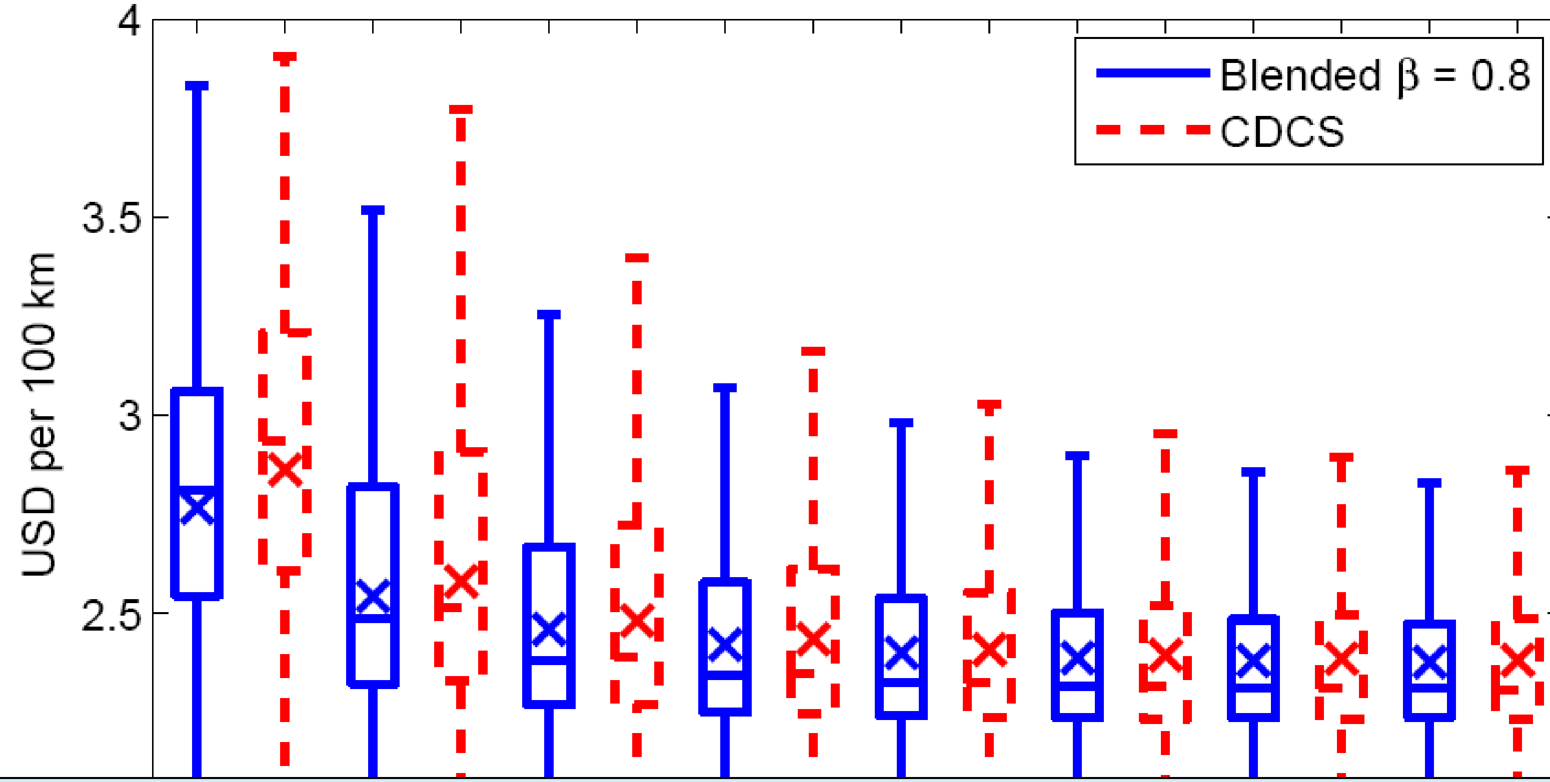


Publications

- **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

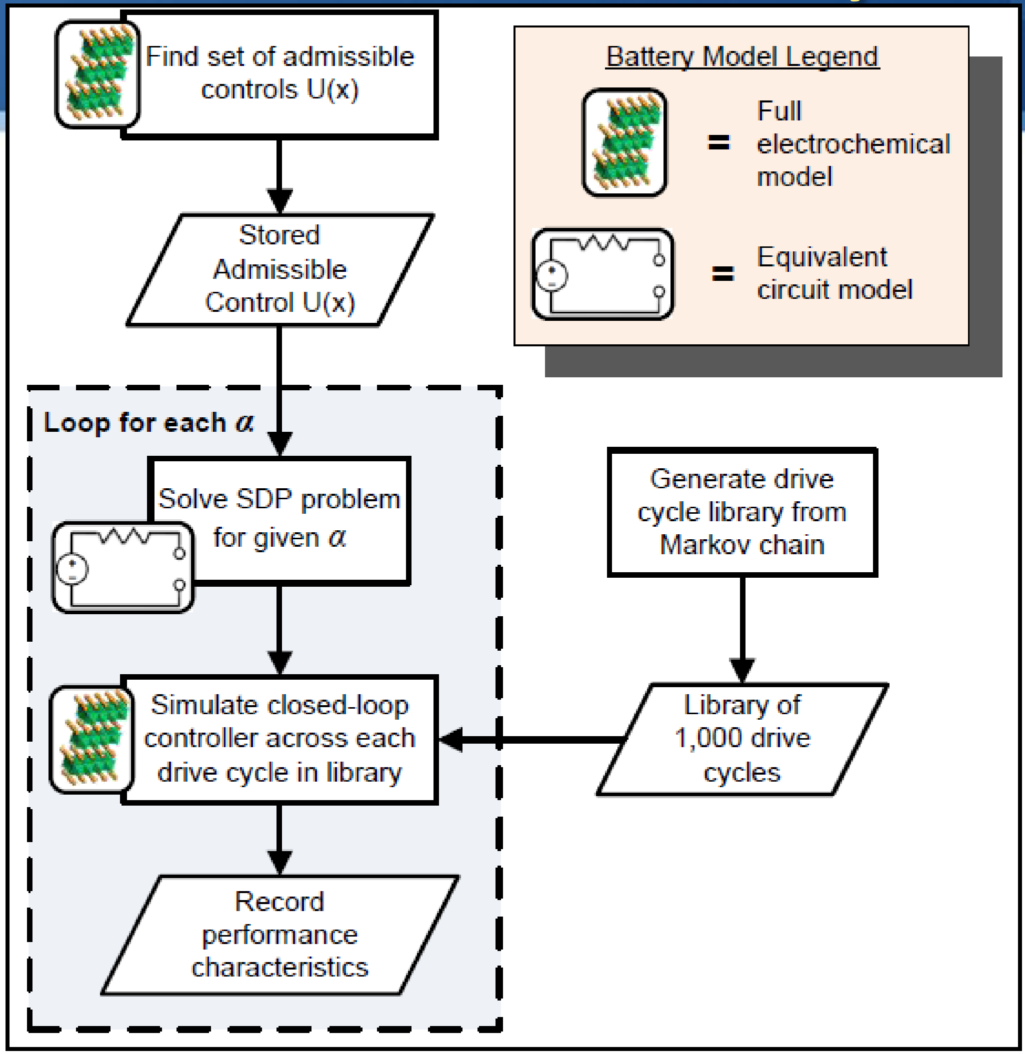
How sensitive is Blending vs. CDCS to battery size?



<u>Publications</u>

- **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

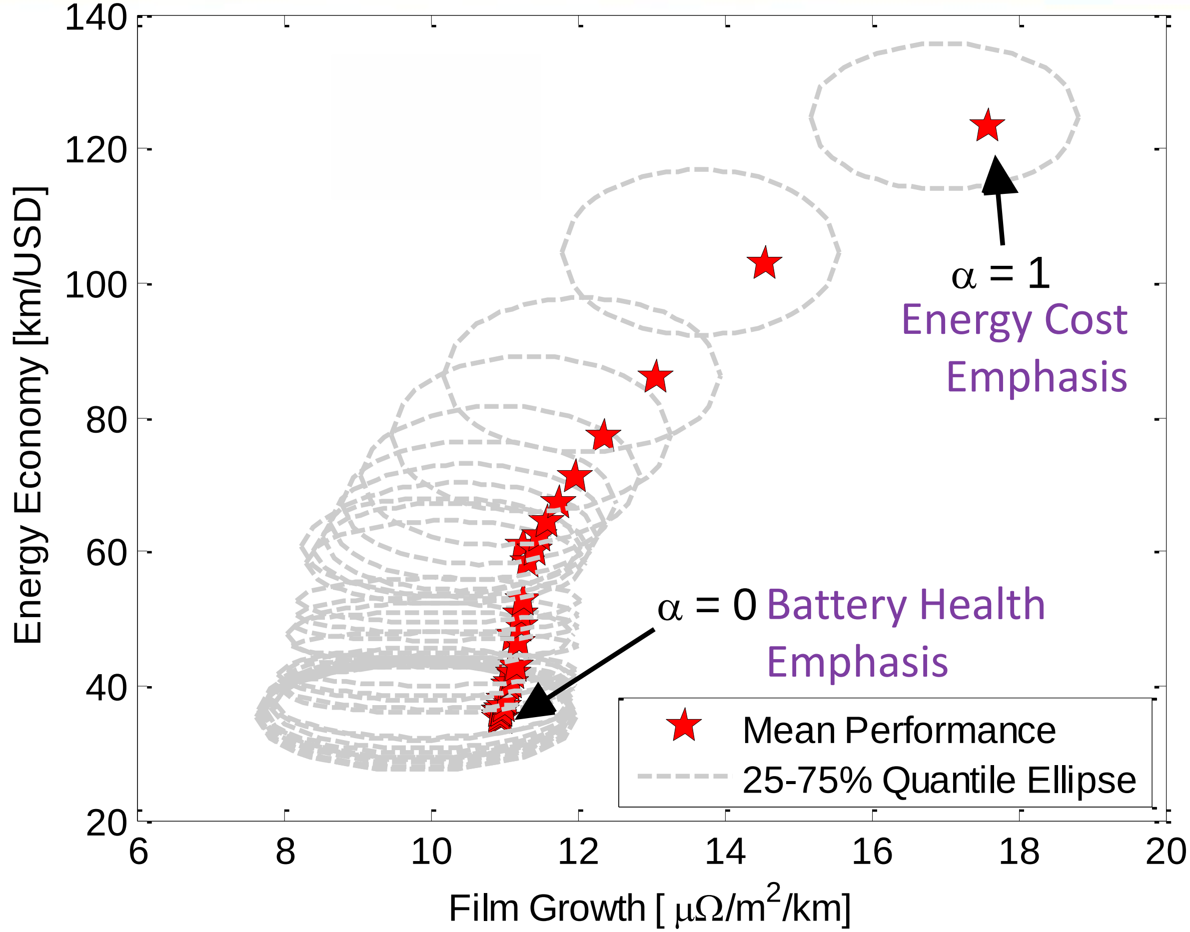


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1 - \alpha) \cdot c_{film}(x_k, u_k)$$

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.

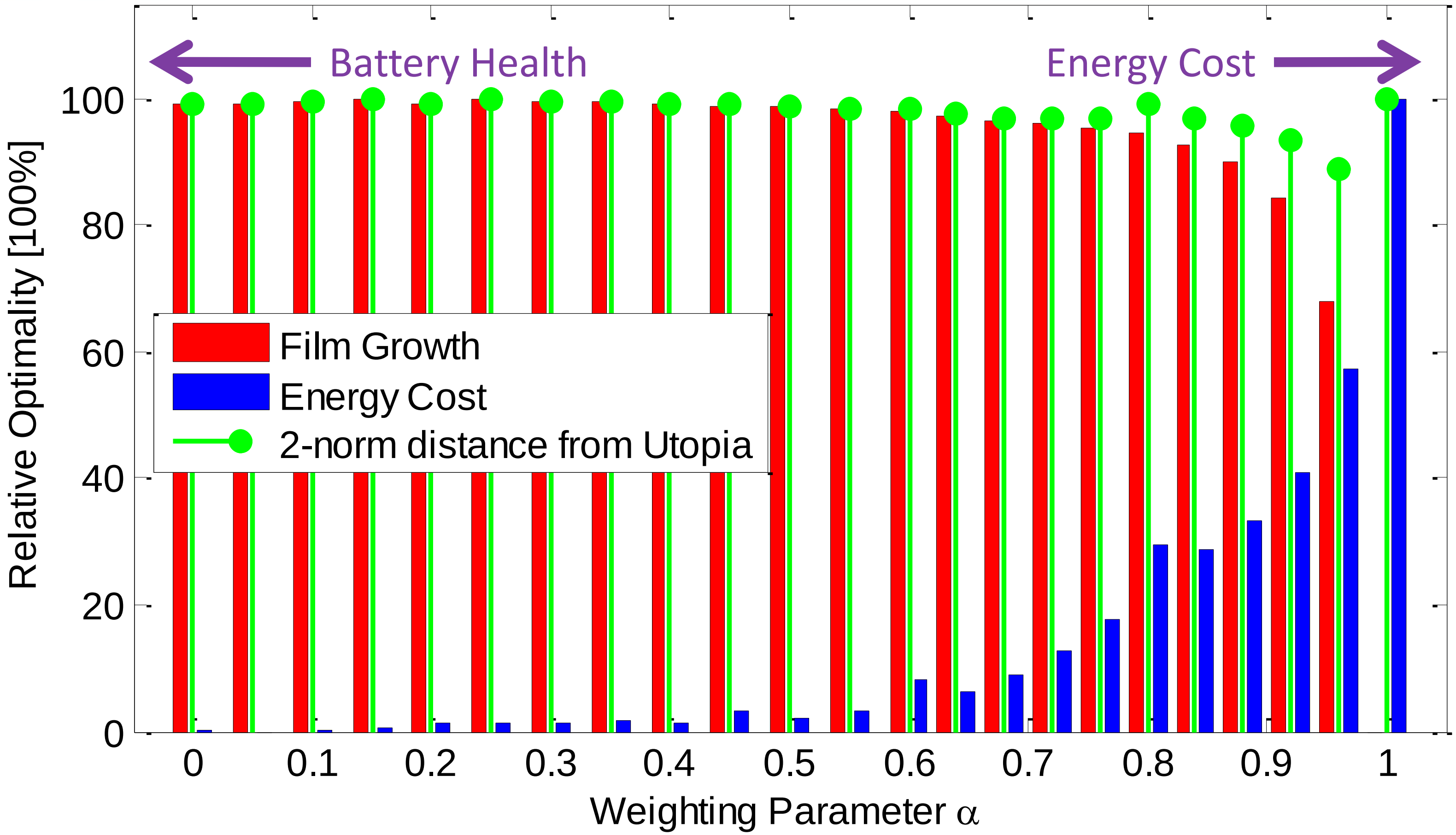
Pareto* Set of Optimal Solutions

*convex subset



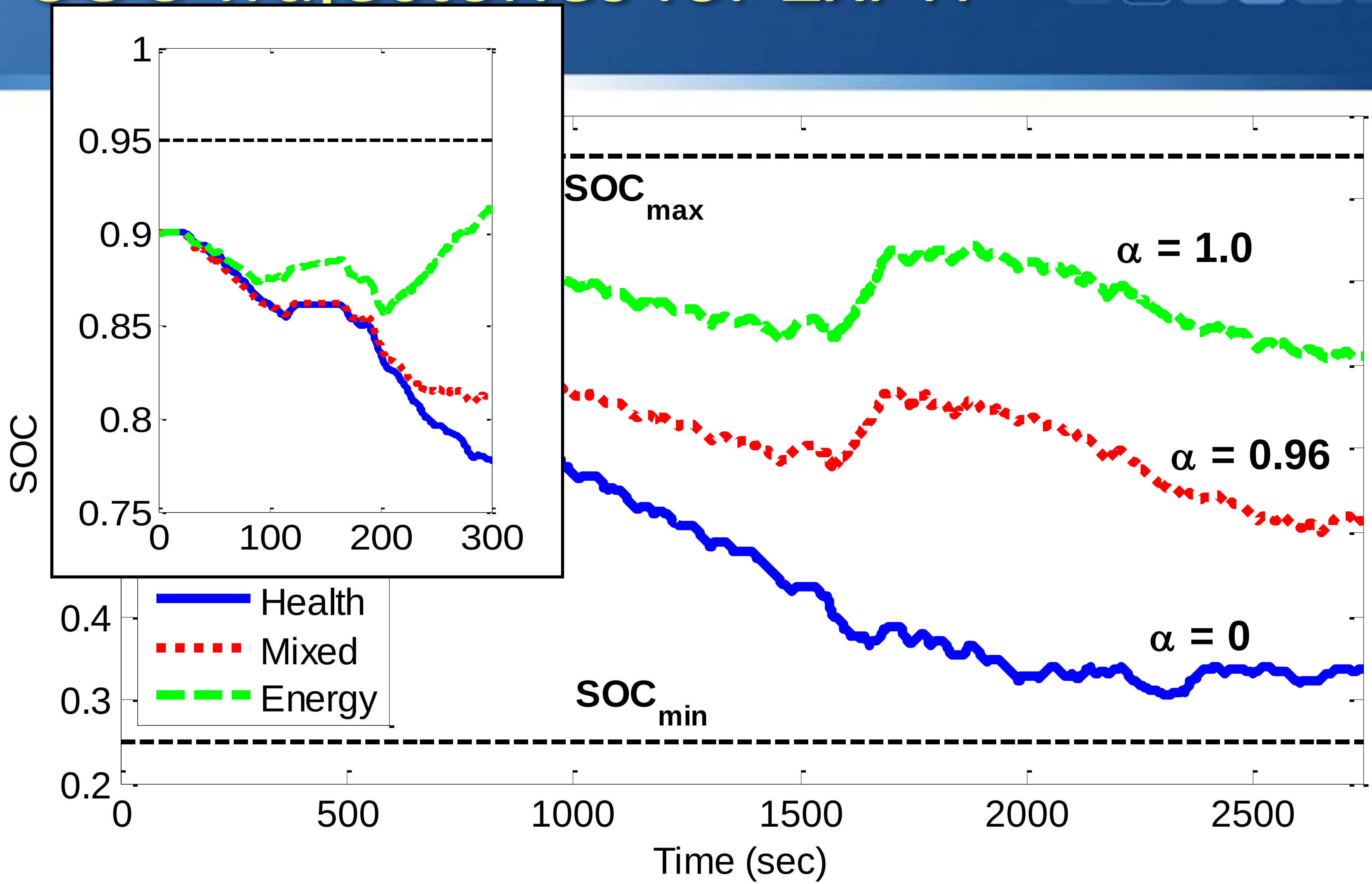
$$c\left(x_k,u_k\right)=\alpha\cdot c_{energy}\left(x_k,u_k\right)+\left(1-\alpha\right)\cdot c_{film}\left(x_k,u_k\right)$$

Relative Optimality Analysis

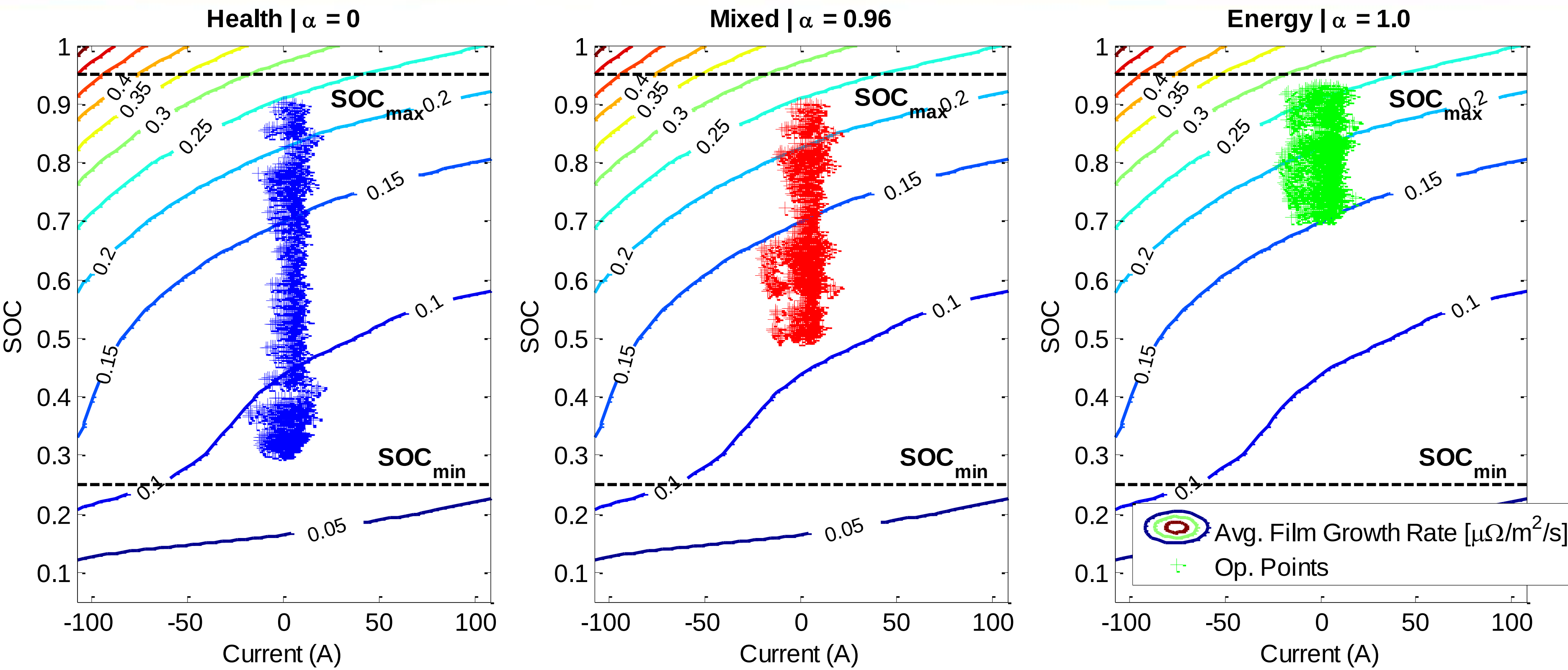


$$c\left(x_k, u_k\right) = \alpha \cdot c_{energy}\left(x_k, u_k\right) + \left(1-\alpha\right) \cdot c_{film}\left(x_k, u_k\right)$$

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:
Optimal Control & Estimation of Distributed Param. Systems

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

Relevant applications for Ford Motor Company:

- Advanced batteries and fuel cells
- Intelligent building 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

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

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

Derivation of optimal state-feedback:

- Weak-variation necessary conditions
- Linear operator theory

LQR Results: A partial differential Riccati equation

State-feedback

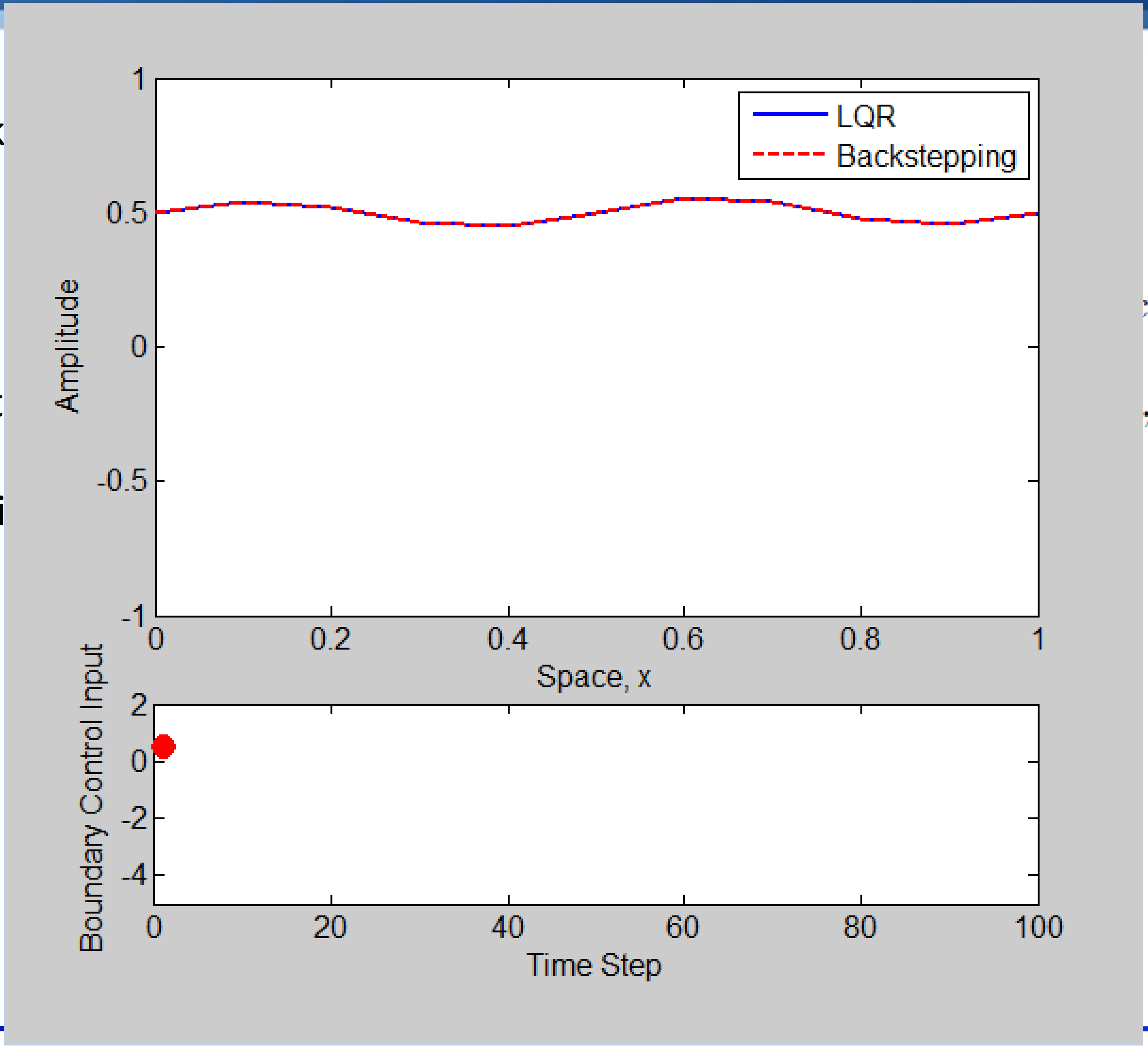
Riccati

$(1, y)$

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

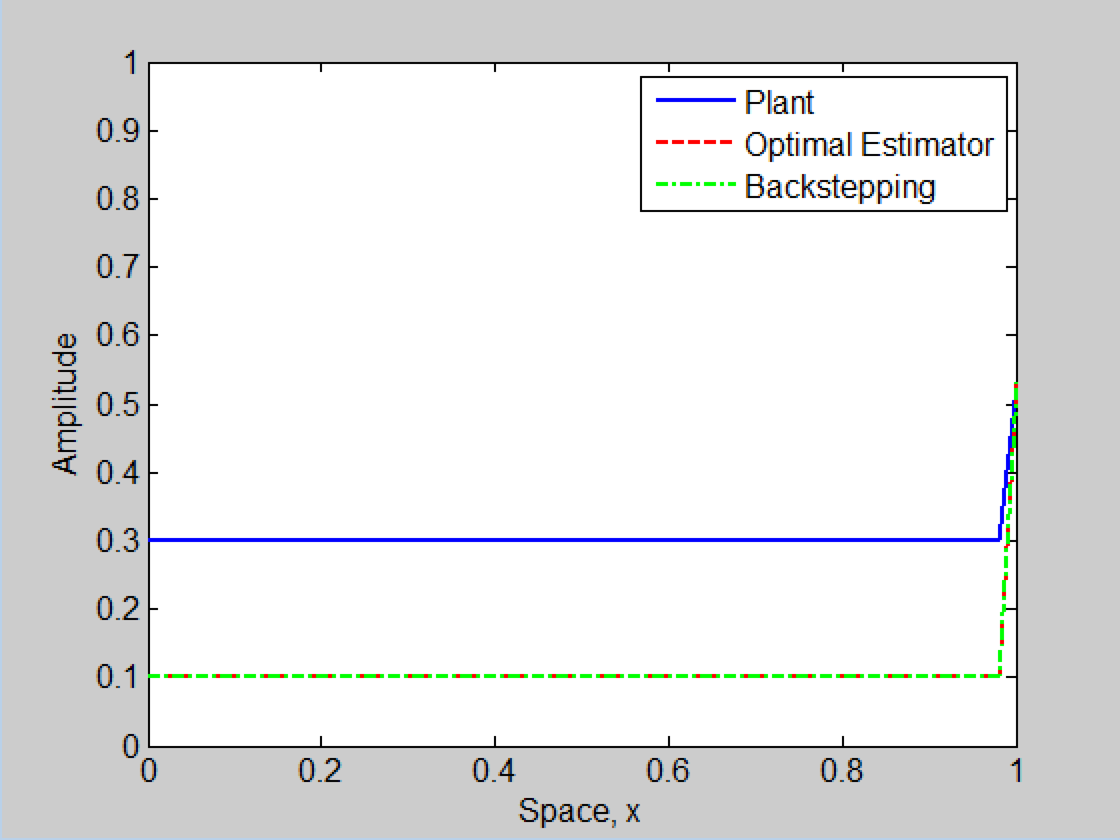
Estimation Results: A dual Riccati PDE

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

Dual Riccati P

Boundary Conditi

Initial condit



$+ W(x,0)$

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

Teaching Experience:

Battery Systems and Control Course

- **Winter 2010 Enrollment:** 59 (including 5 distance learning students)
- **Teaching Winter 2011**

Professional engineers (e.g. GM, US Army)

Graduate Students

Undergraduates

ME **ChemE** **ESE** **EECS** **CSE** **MatSci**

Publications

- **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)**.

Publications

Peer-Reviewed Journals (Accepted)

1. 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*, v PP, n 99, p 1-11, March 2010.
2. 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," *Journal of Power Sources*, v 195, n 9, p 2979-2988, May 2010.
3. 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*, v 196, n 1, p 541-549, January 2011.
4. S. J. Moura, J. C. Forman, S. Bashash, J. L. Stein, and H. K. Fathy, "Optimal Control of Film Growth in Lithium-Ion Battery Packs via Relay Switches," *accepted to IEEE Transactions on Industrial Electronics* in September 2010.

Peer-Reviewed Journals (Submitted or In Preparation)

5. S. Bashash, S. J. Moura, and H. K. Fathy, "Battery Health-Conscious Plug-in Hybrid Electric Vehicle Grid Load Prediction," (in review).
6. S. J. Moura and Y. A. Chang, "Lyapunov-Based Switched Extremum Seeking for Maximum Power Point Tracking in Photovoltaic Systems," (in preparation).
7. S. J. Moura, J. L. Stein, and H. K. Fathy, "Battery Health-Based Power Management for Plug-in Hybrid Vehicles via Trip Length Aware Stochastic Control," (in preperation).
8. S. J. Moura, J. B. Siegel, H. K. Fathy, A. G. Stefanopoulou, "Education on Vehicle Electrification: Battery Systems and Control," (in preparation).
9. J. C. Forman, S. J. Moura, J. L. Stein, H. K. Fathy, "Parameter Identification of the Doyle-Fuller-Newman Model for a $LiFePO_4$ Battery with Fisher Information-Based Identifiability Analysis," (in preparation).
10. S. J. Moura, J. L. Stein, and H. K. Fathy, "Optimal Boundary Control and Estimation of Diffusion-Reaction PDEs," (in preparation).

Conferences Proceedings (Accepted)

1. S. J. Moura, H. K. Fathy, D. S. Callaway, 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*, Ann Arbor, MI, 2008.
2. 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*, pp. 96-102, Columbus, OH, 2008. (Invited Paper)
3. Y. A. Chang, S. J. Moura, "Real-Time Air-Flow Control in Fuel Cell Systems: An Extremum Seeking Approach," *Proc. of the 2009 American Control Conference*, St. Louis, MO, 2009.
4. S. J. Moura, J. C. Forman, J. L Stein, H. K. Fathy, "Control of Film Growth in Lithium Ion Battery Packs via Switches," *Proceedings of the 2009 ASME Dynamic Systems and Control Conference*, Hollywood, CA, 2009. **Best Student Paper Finalist**
5. S. J. Moura, Y. A. Chang "Asymptotic Convergence through Lyapunov-Based Switching in Extremum Seeking with Application to Photovoltaic Systems," *Proceedings of the 2010 American Control Conference*, Baltimore, MD, 2010.
6. 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.
7. 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.
8. S. J. Moura, J. L. Stein, 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.
9. 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.

Conferences Proceedings (Submitted)

10. S. J. Moura, H. K. Fathy, "Optimal Boundary Control & Estimation of Diffusion-Reaction PDEs," Submitted to the *2011 American Control Conf.*, San Francisco, CA, 2011.
11. J. C. Forman, S. J. Moura, J. L. Stein, H. K. Fathy, "Genetic Parameter Identification of the Doyle-Fuller-Newman Model From Experimental Cycling of a Li-ion $LiFePO_4$ Battery," Submitted to the *2011 American Control Conference*, San Francisco, CA, 2011.

Relevant Honors

- National Science Foundation (NSF) Graduate Research Fellowship
- University of Michigan Rackham Merit Fellowship (RMF)
- Distinguished Leadership Award, College of Engineering, University of Michigan
- Best Student Paper Finalist at the 2009 ASME Dynamic Systems and Control Conference, Hollywood, CA USA
- 1st Place Technical Paper Competition, 2008 Society of Hispanic Professional Engineers Conference, Phoenix, AZ

Thank you for your attention!

Questions?

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