Optimal Control of Lithium-ion Battery Energy Storage Systems

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Syracuse University
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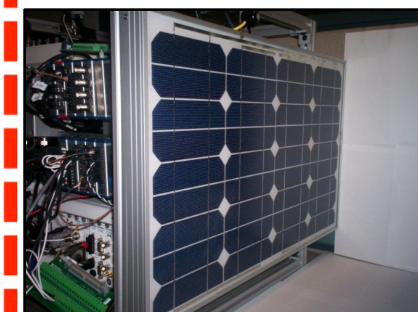
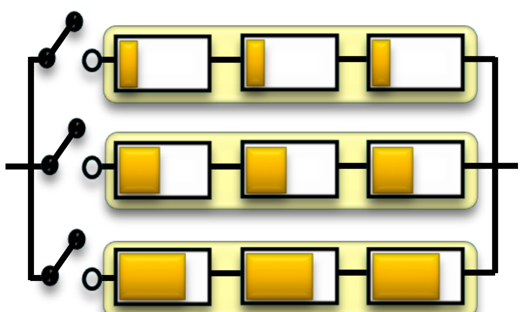
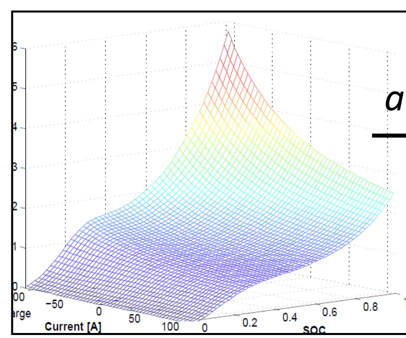
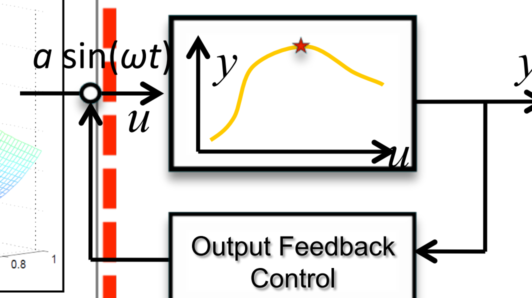
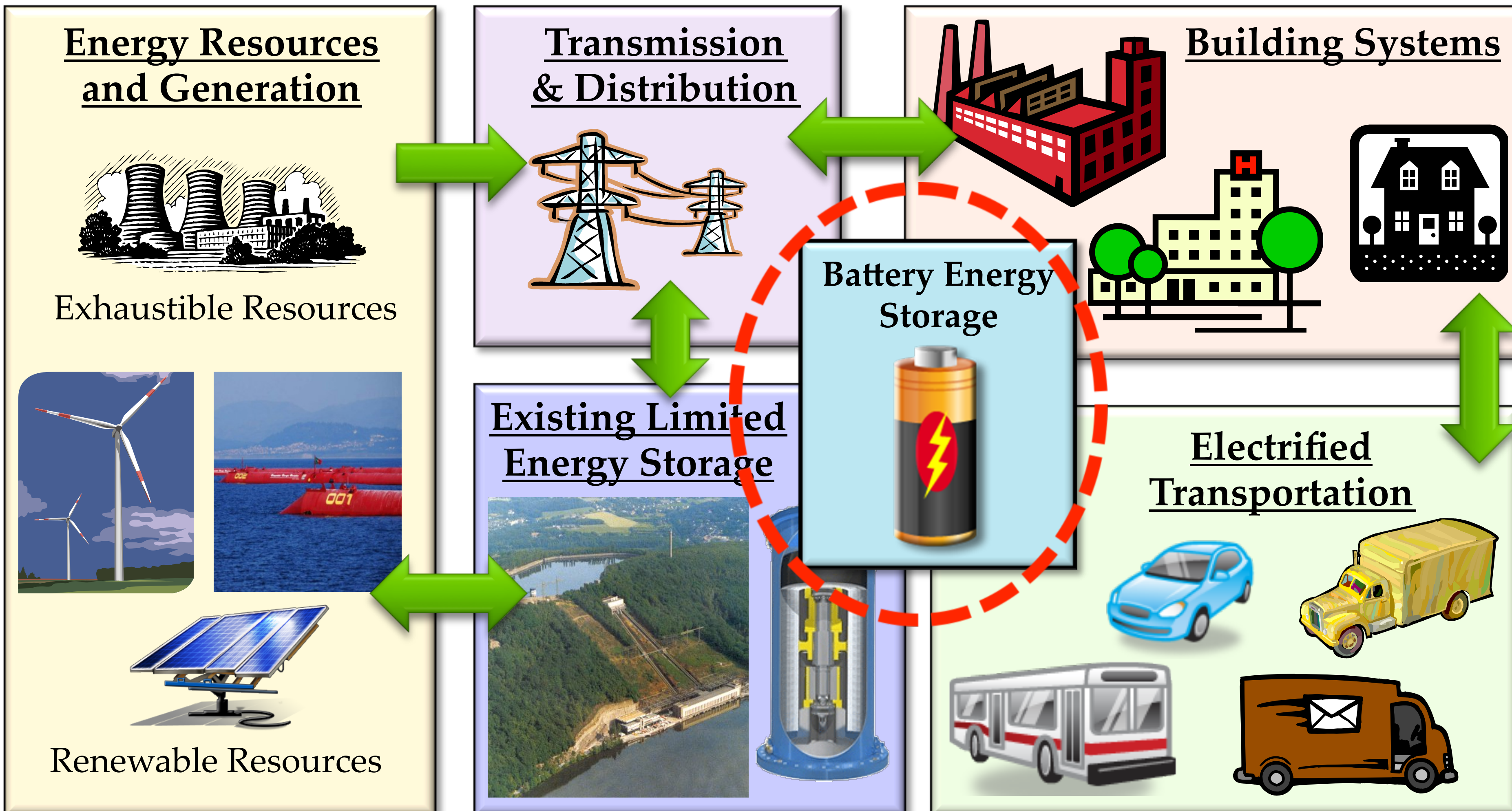
Overview of Research Contributions

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

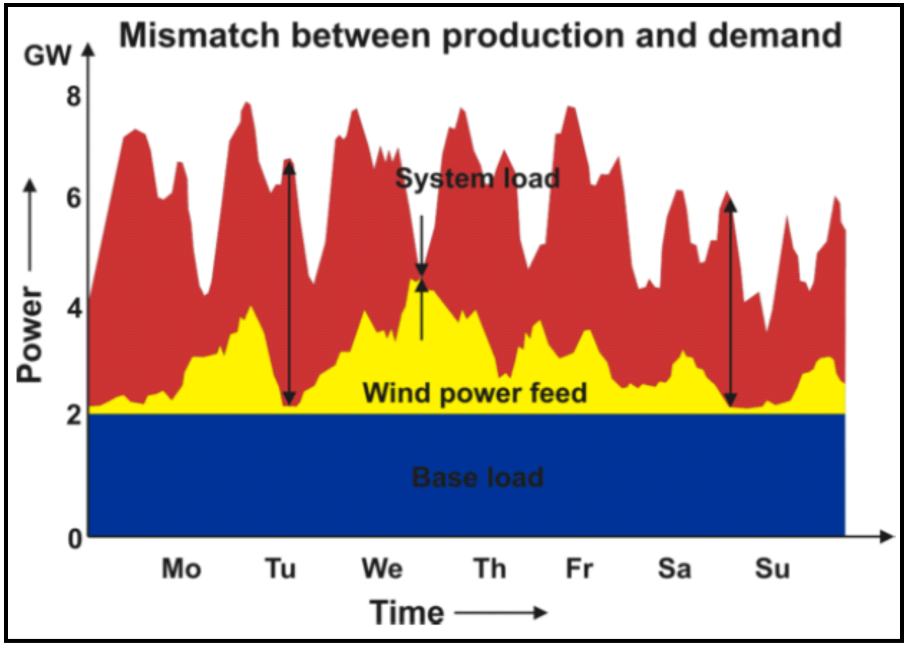


Technical Challenges

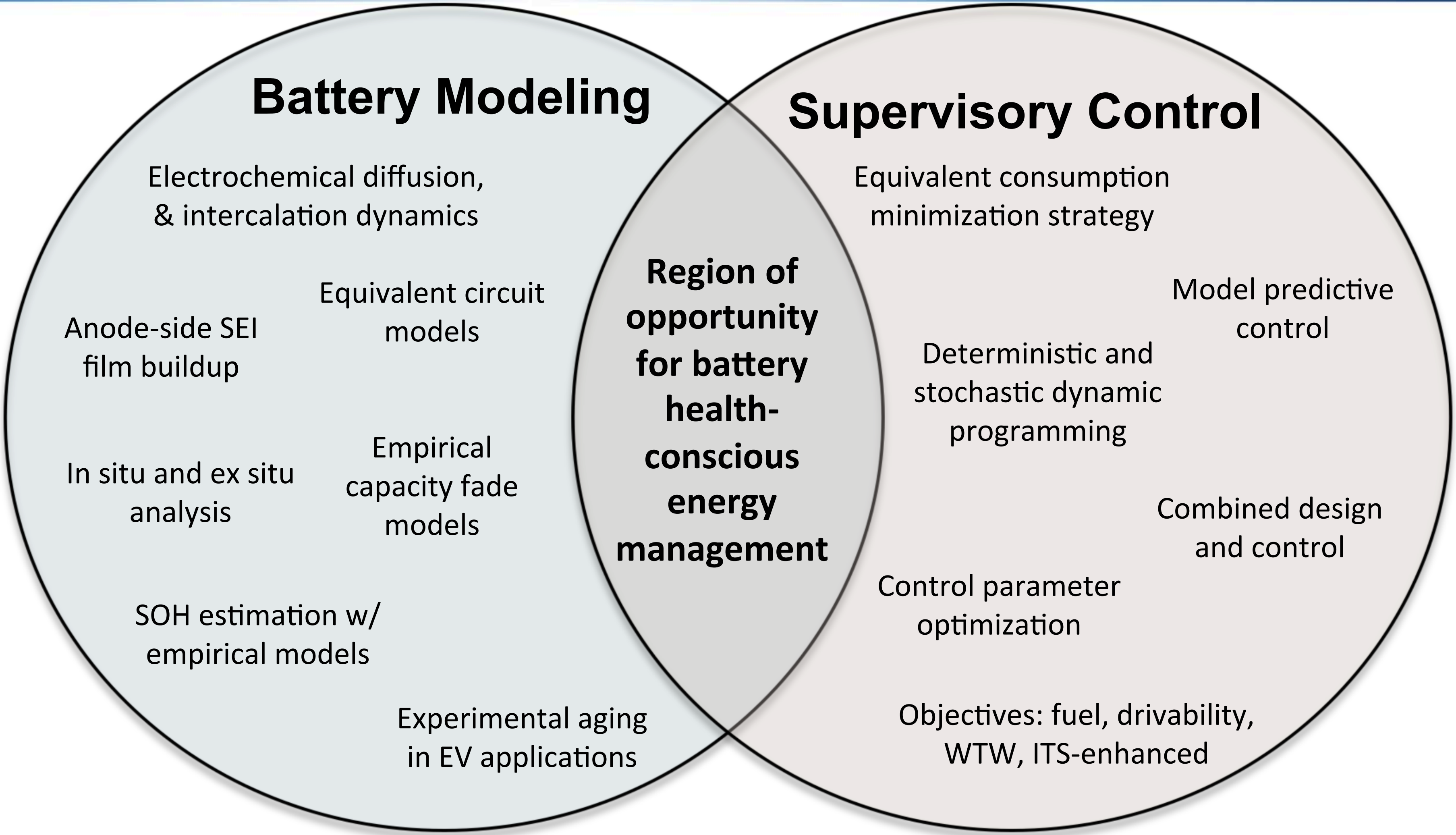
Oversized battery packs → $$$

Plug-in Vehicle	Projected MSRP
Tesla Roadster	$109,000
Fisker Automotive	$89,000
Chevy Volt	$41,000
Nissan Leaf	$33,000
Toyota Prius PHEV	$30,000

Significant penetration of renewable energy → high capacity energy storage



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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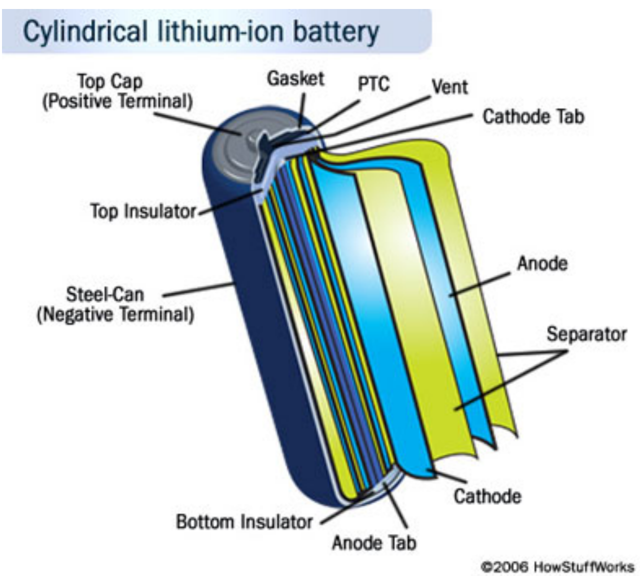
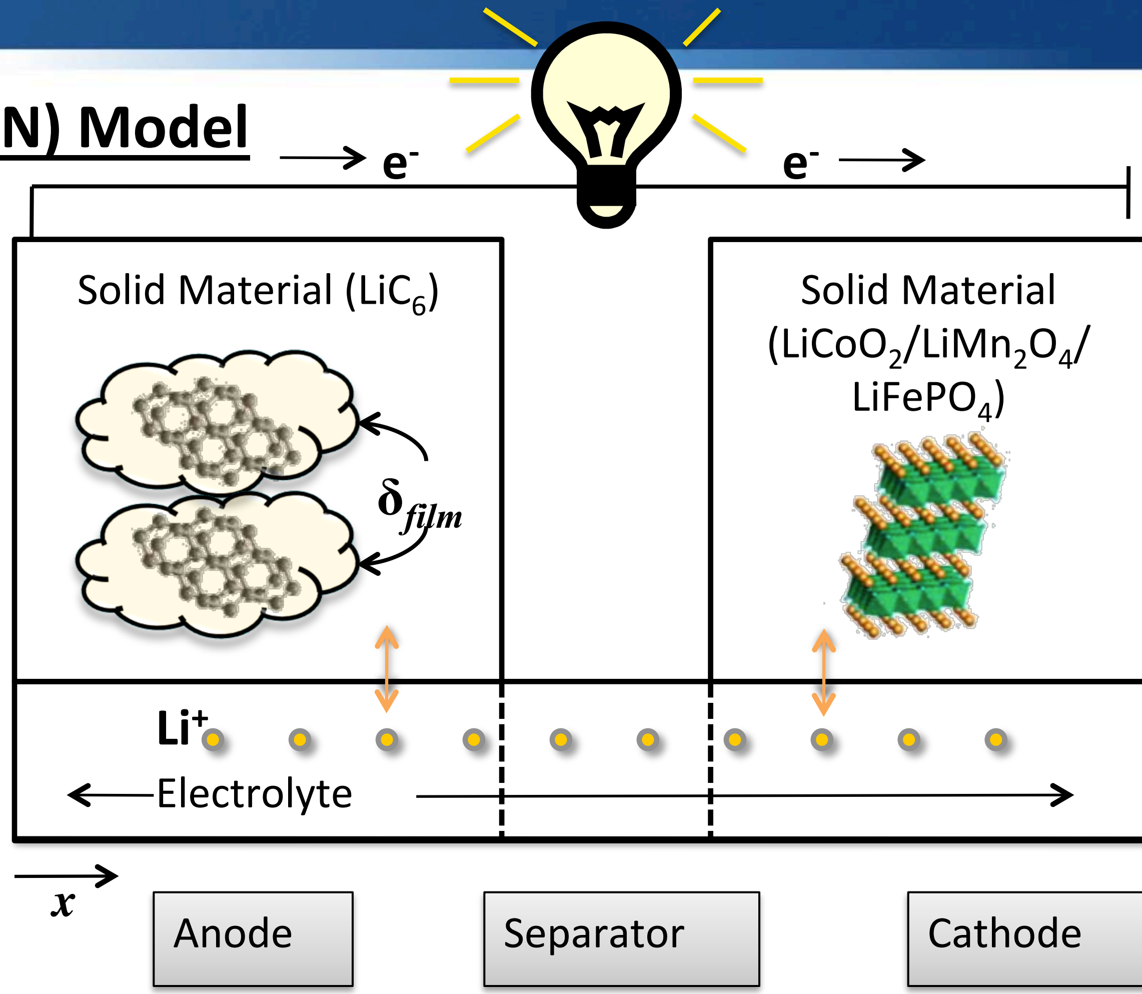
Electrochemical Li-ion Battery Modeling

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

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

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

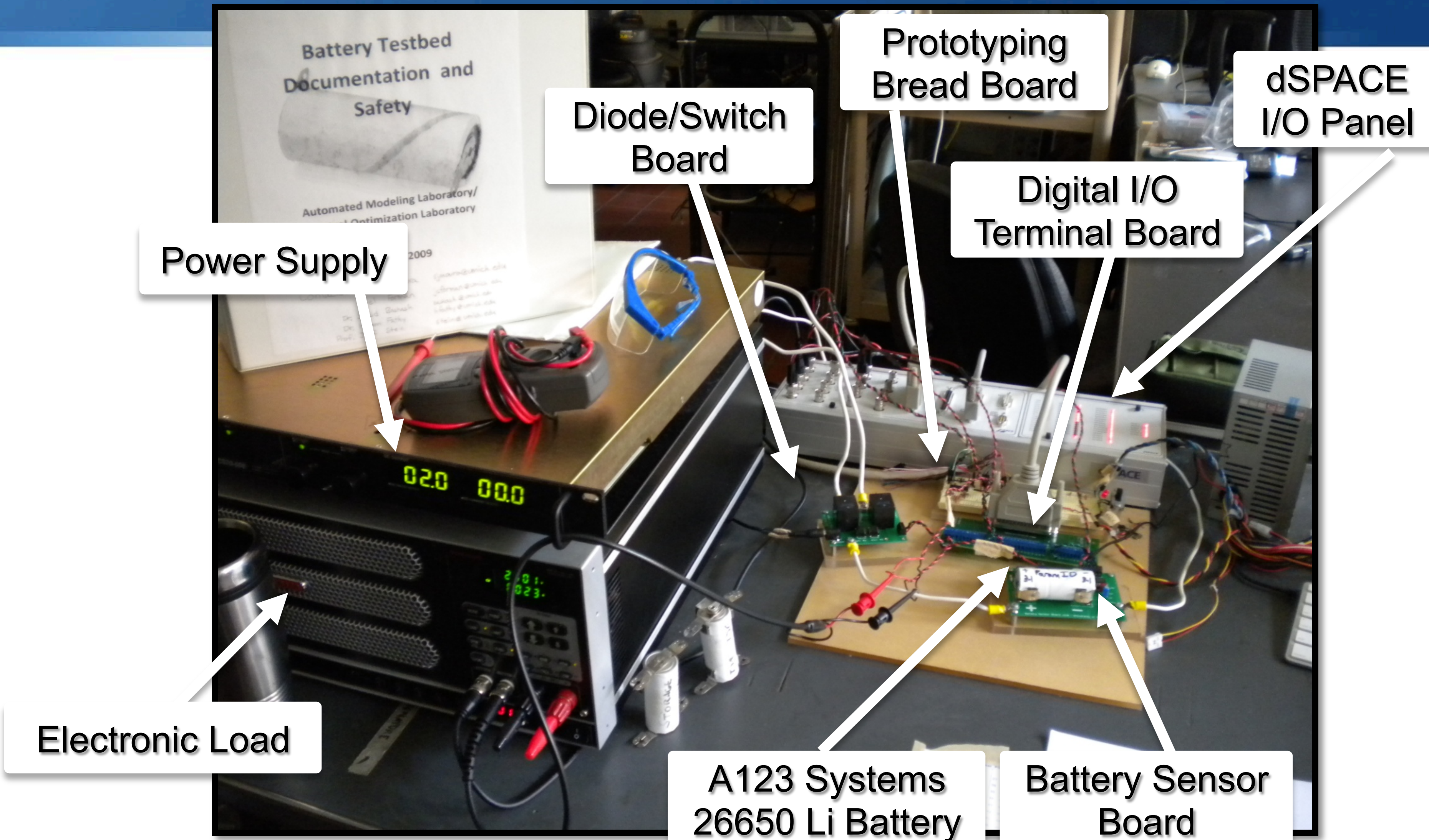
Ohm's Law

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

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

Butler-Volmer Kinetics

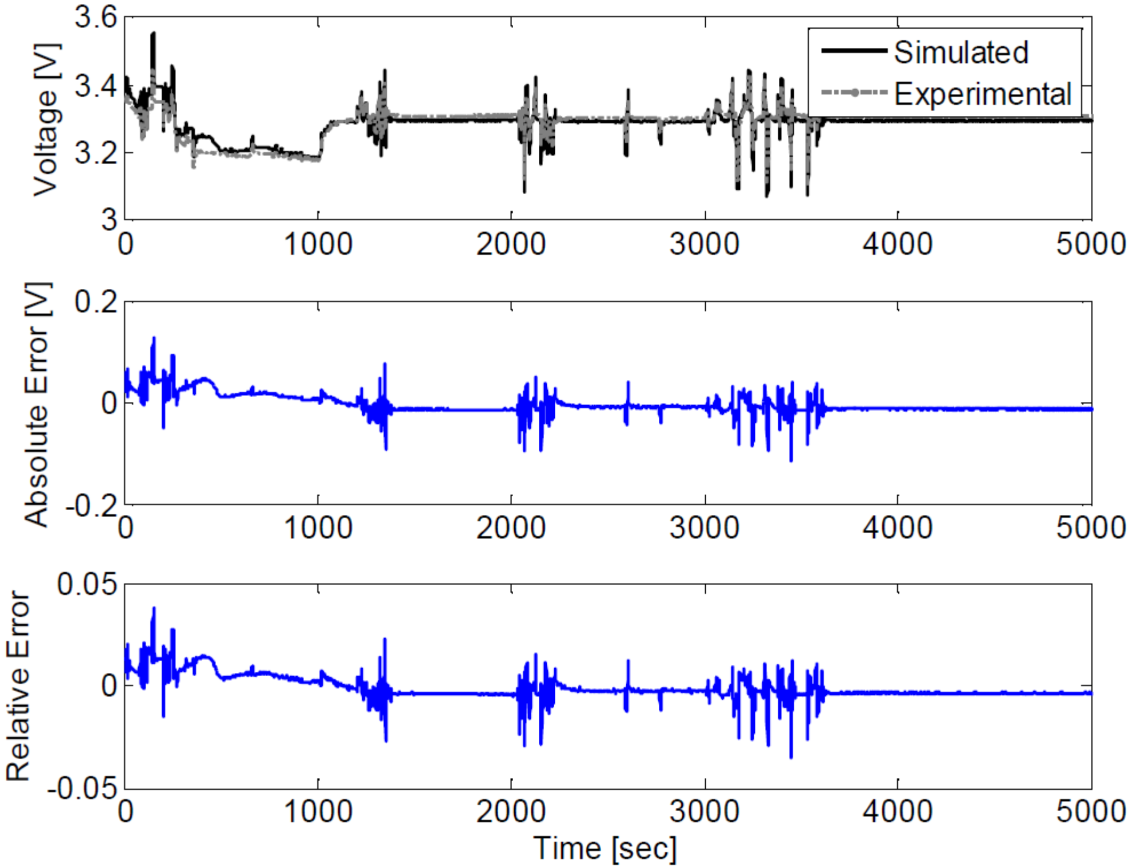
Battery-in-the-loop Hardware



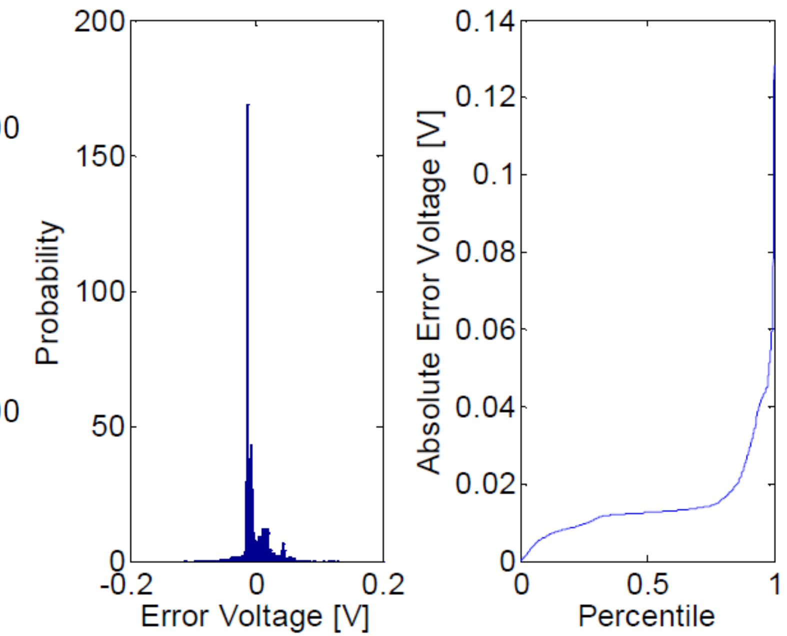
Parameter Identification Results

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.

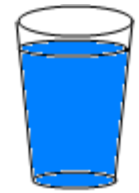
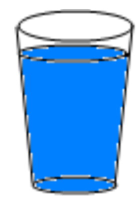
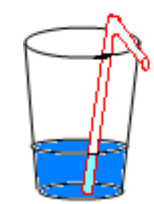
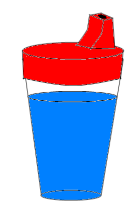
Causes of Battery Degradation

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		

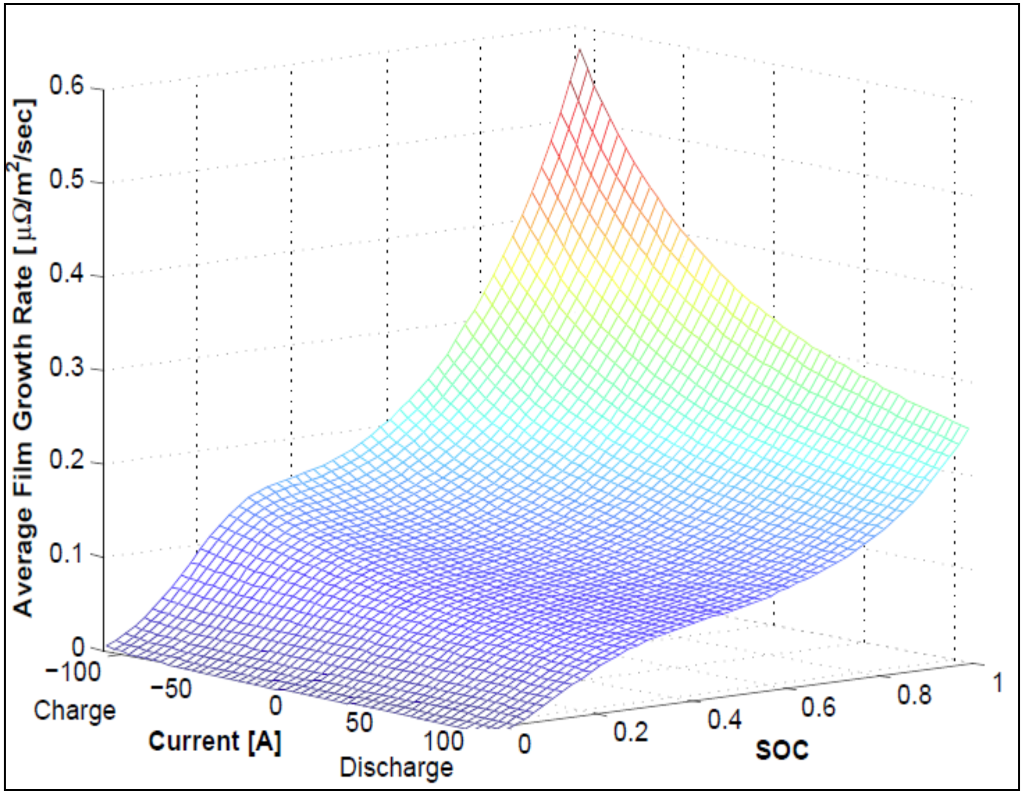
Anode-Side SEI Film Buildup

Ramadass et al, 2004

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

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

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



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Advanced Battery Pack Management

- **The charge *un*-equalization concept**
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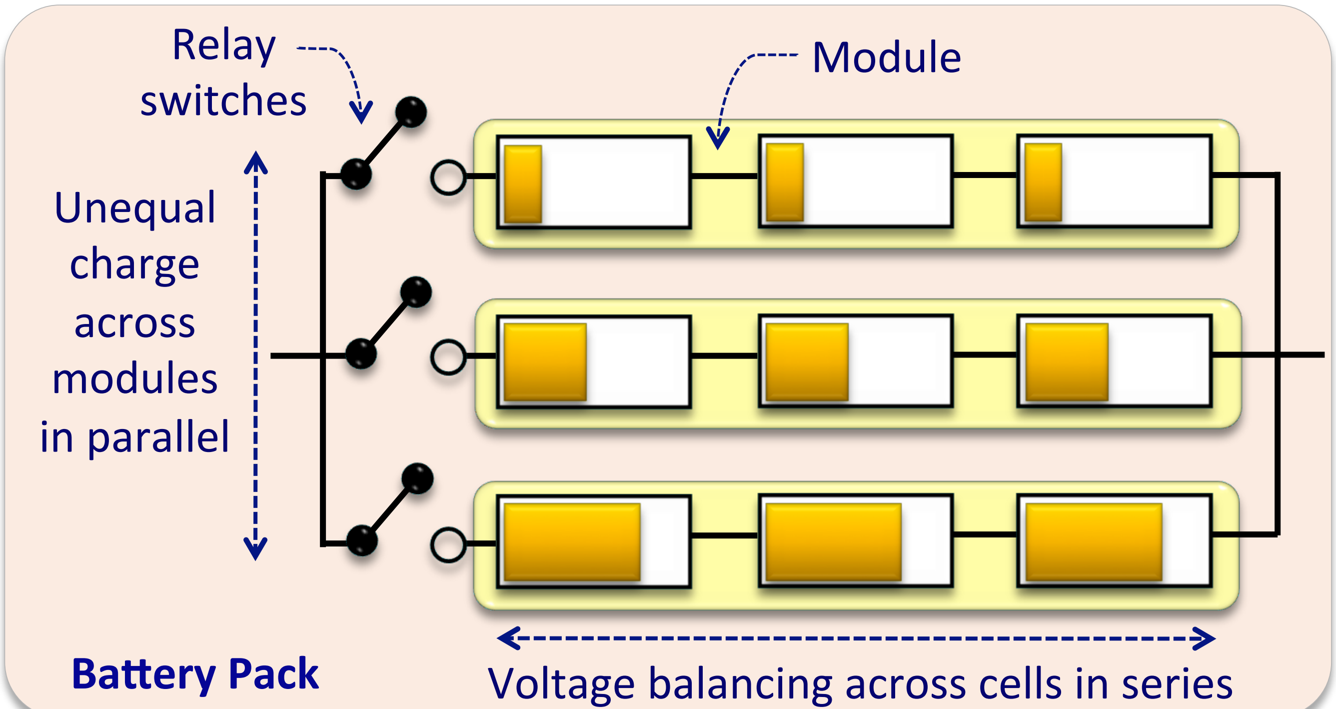
Unbalanced Charge Management

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



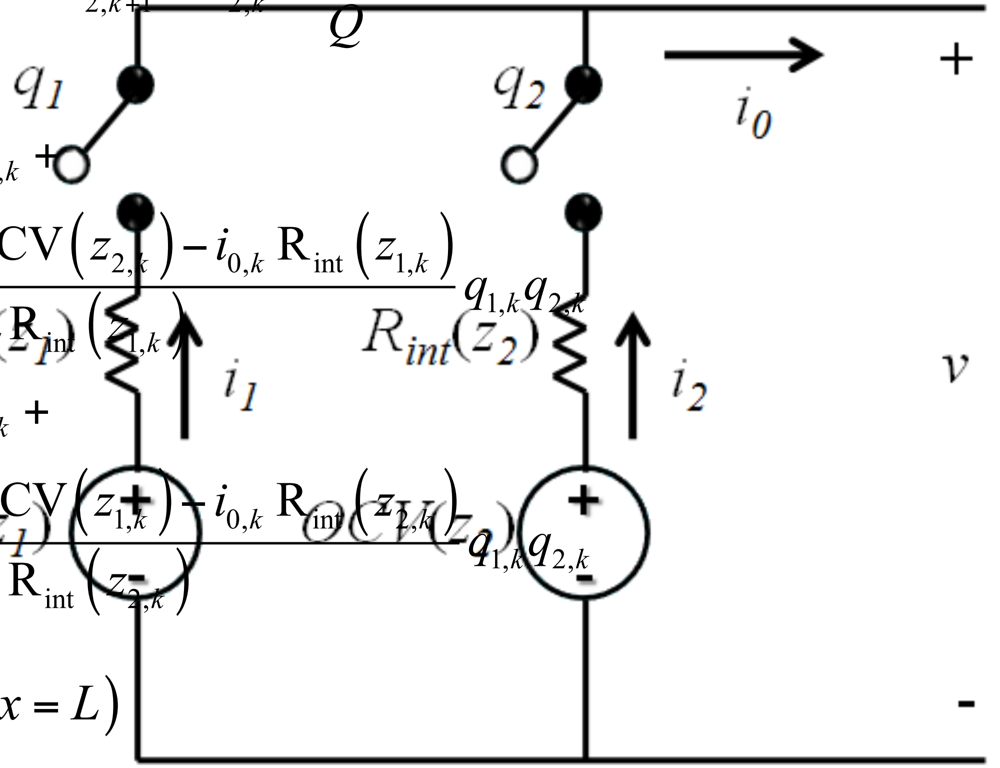
Theoretical Approach: Optimal control and reduced order models

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

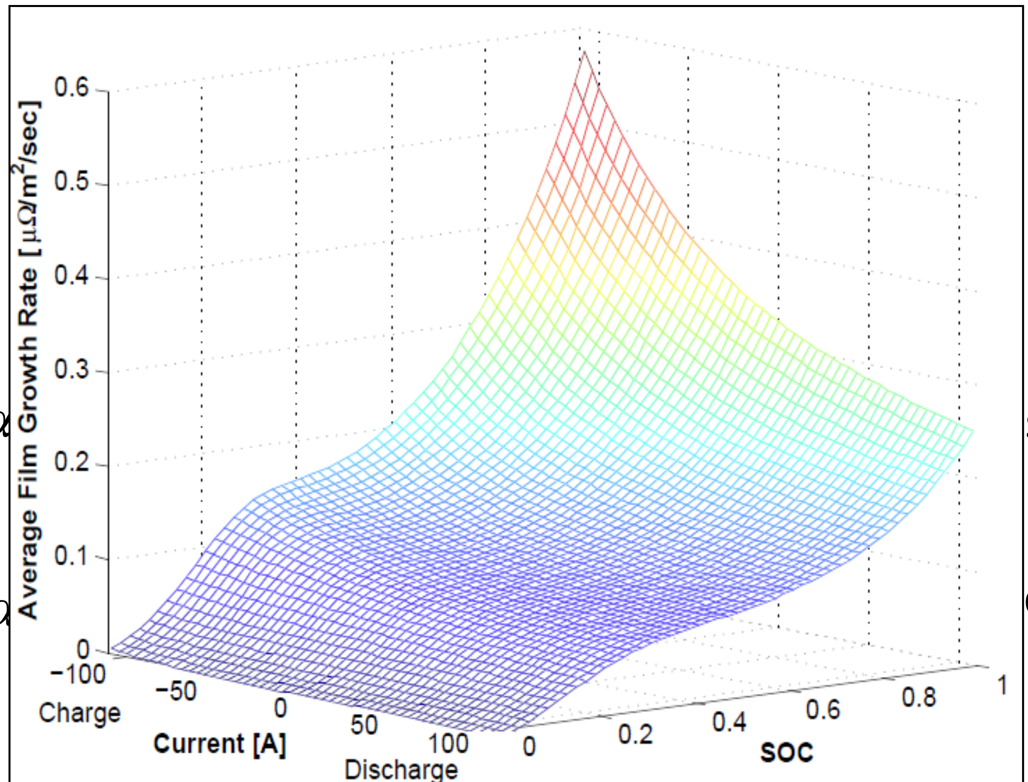
Minimize total spatially-averaged film growth over the charge cycle

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

subject to $z_{k+1} =$

$i_k =$

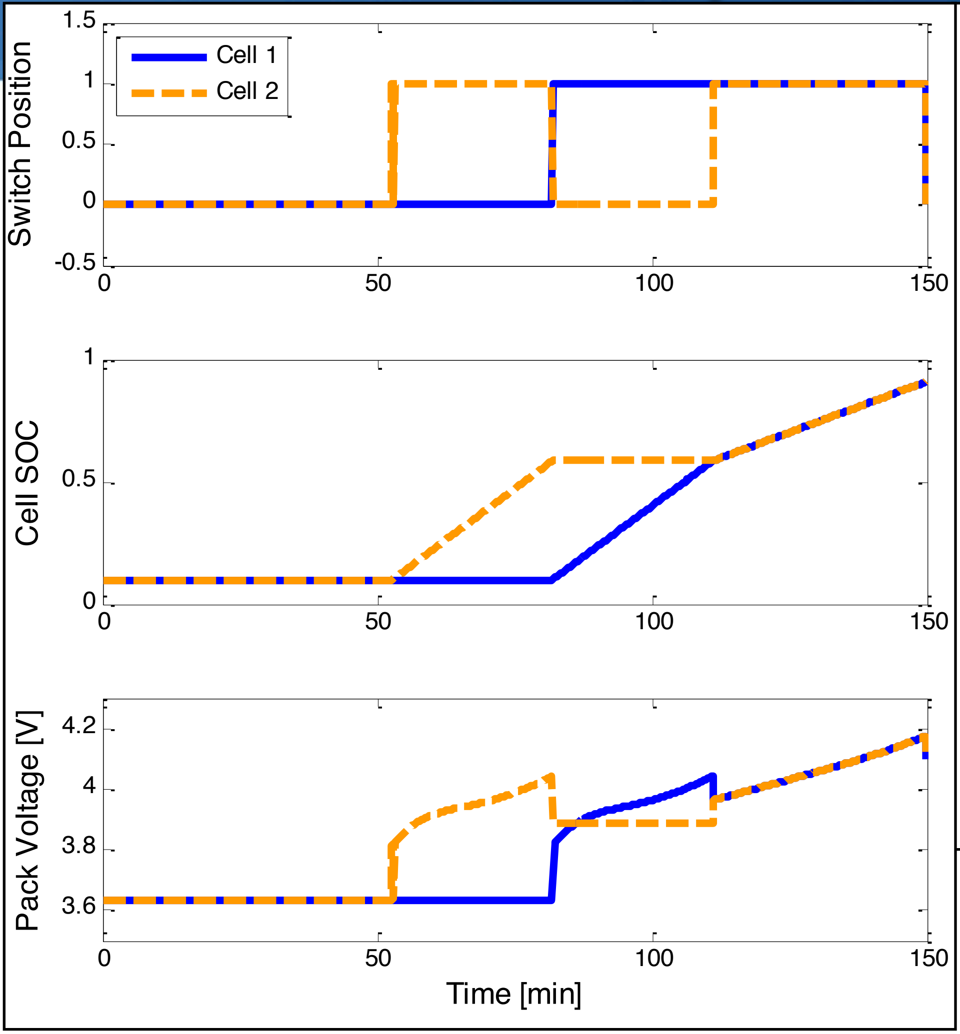
$z_1 =$

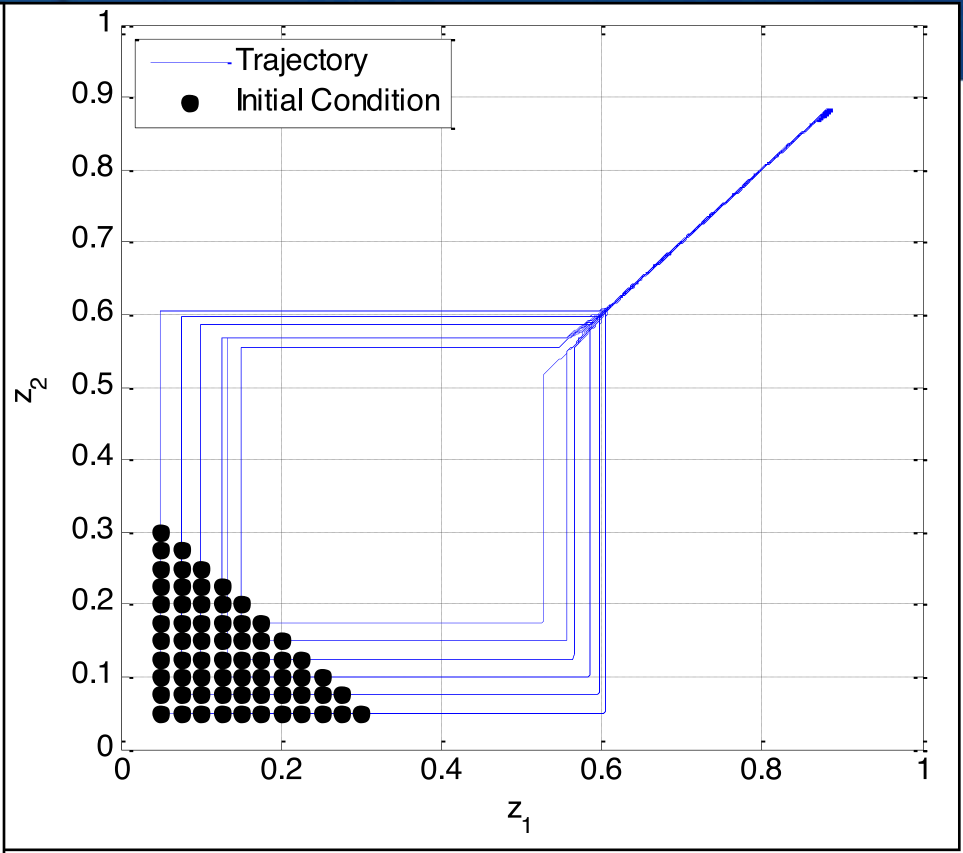


where $g_z\left(z_k\right) = \alpha$ … straints

$+\alpha$ … constraints

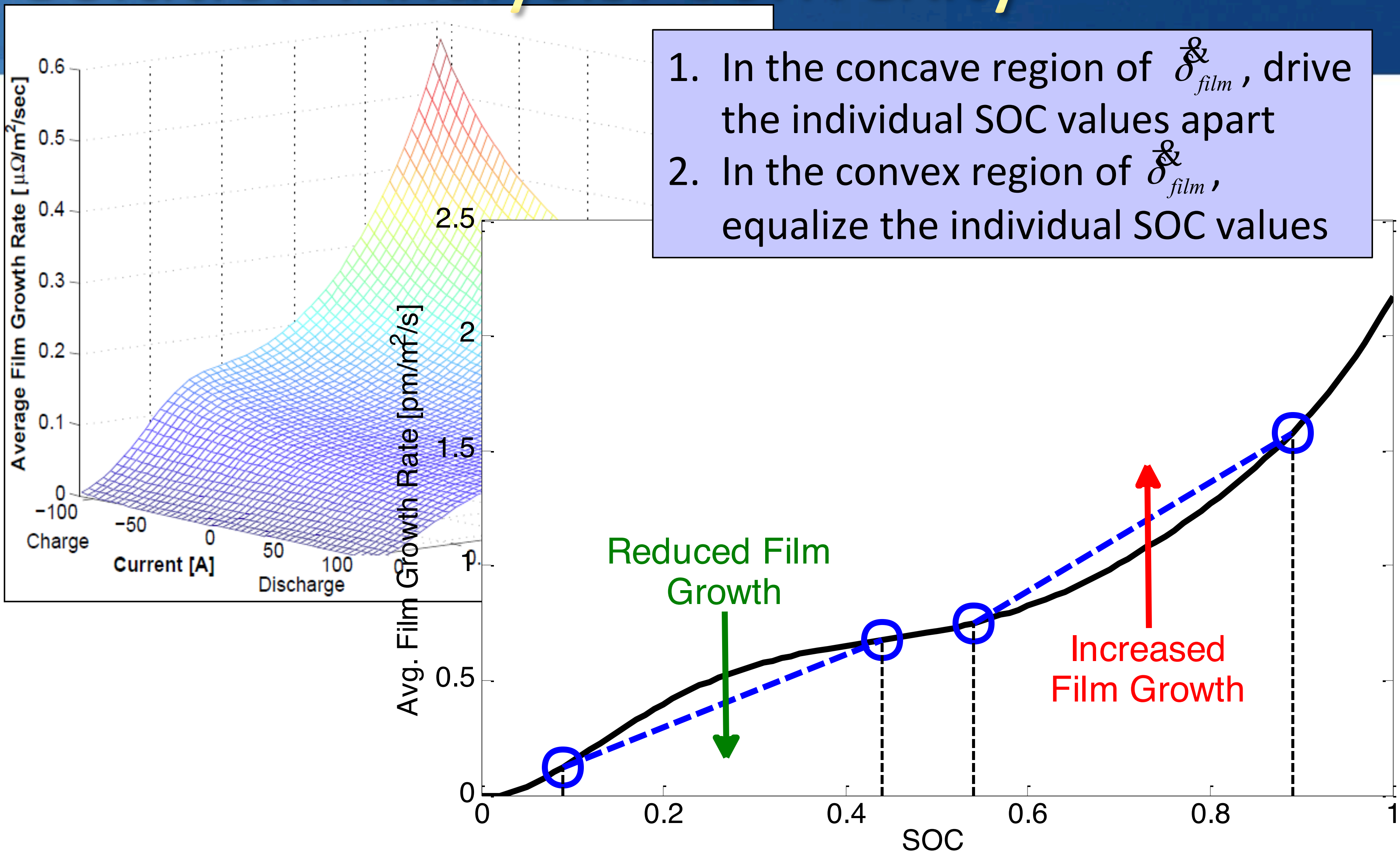
Solution Analysis: Optimal



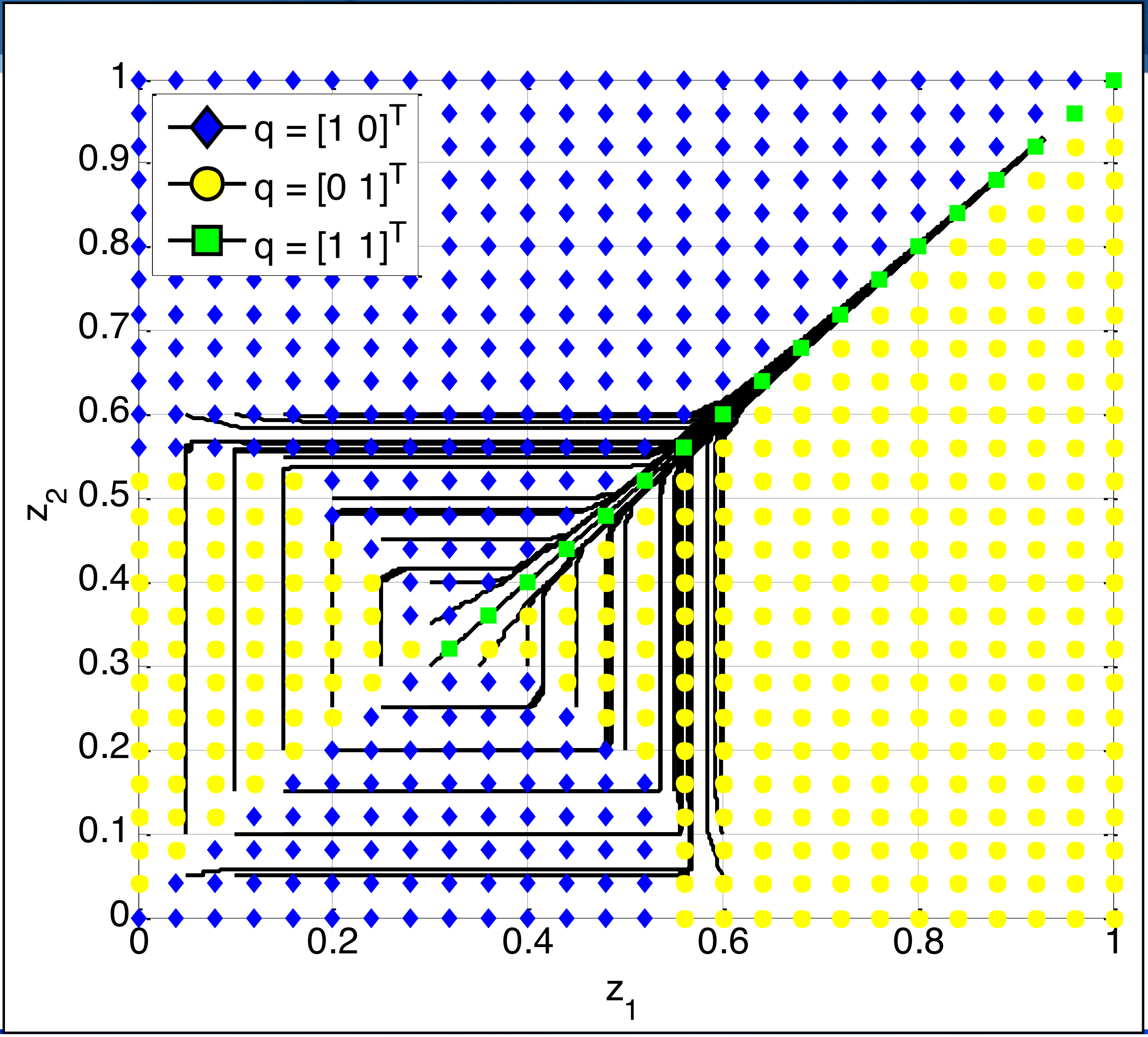


Solution Analysis: Convexity

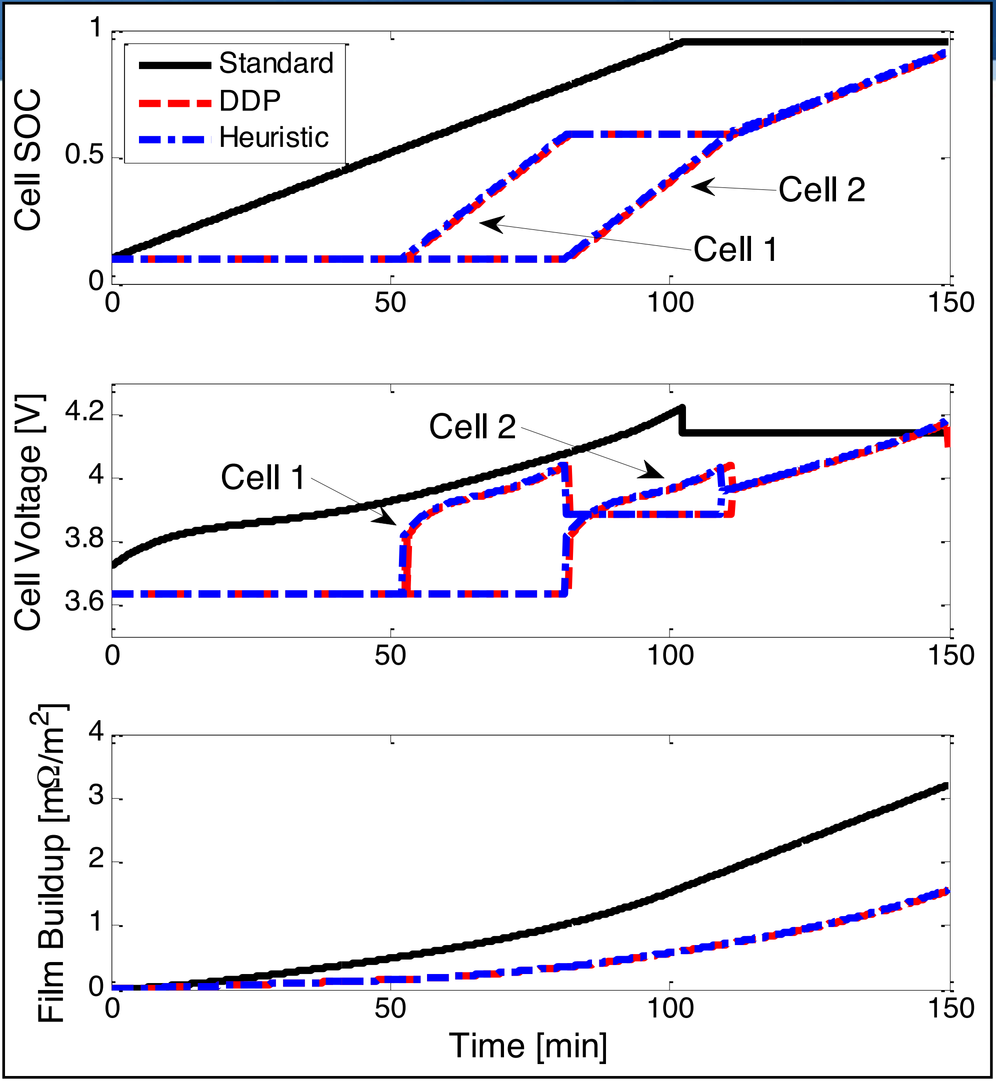
1. In the concave region of $\dot{\delta}_{film}$, drive the individual SOC values apart
2. In the convex region of $\dot{\delta}_{film}$, equalize the individual SOC values



Solution Analysis: Heuristic Control

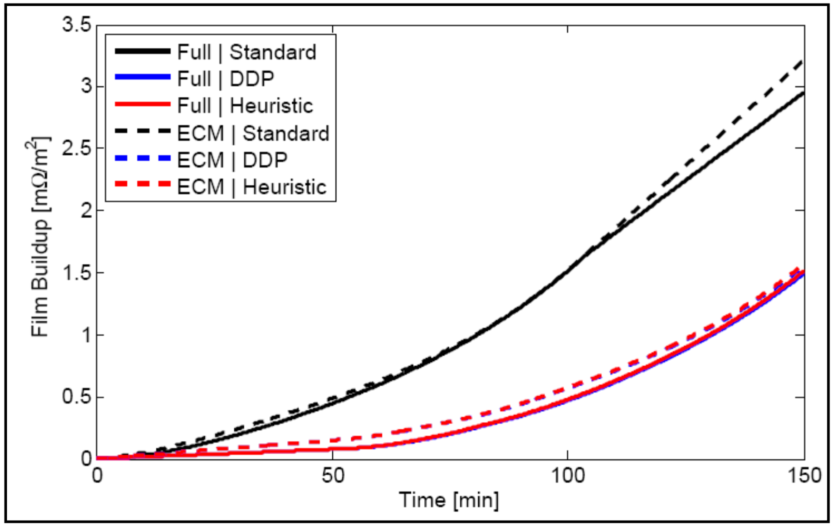


Simulation Results: Controller Comparison



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**

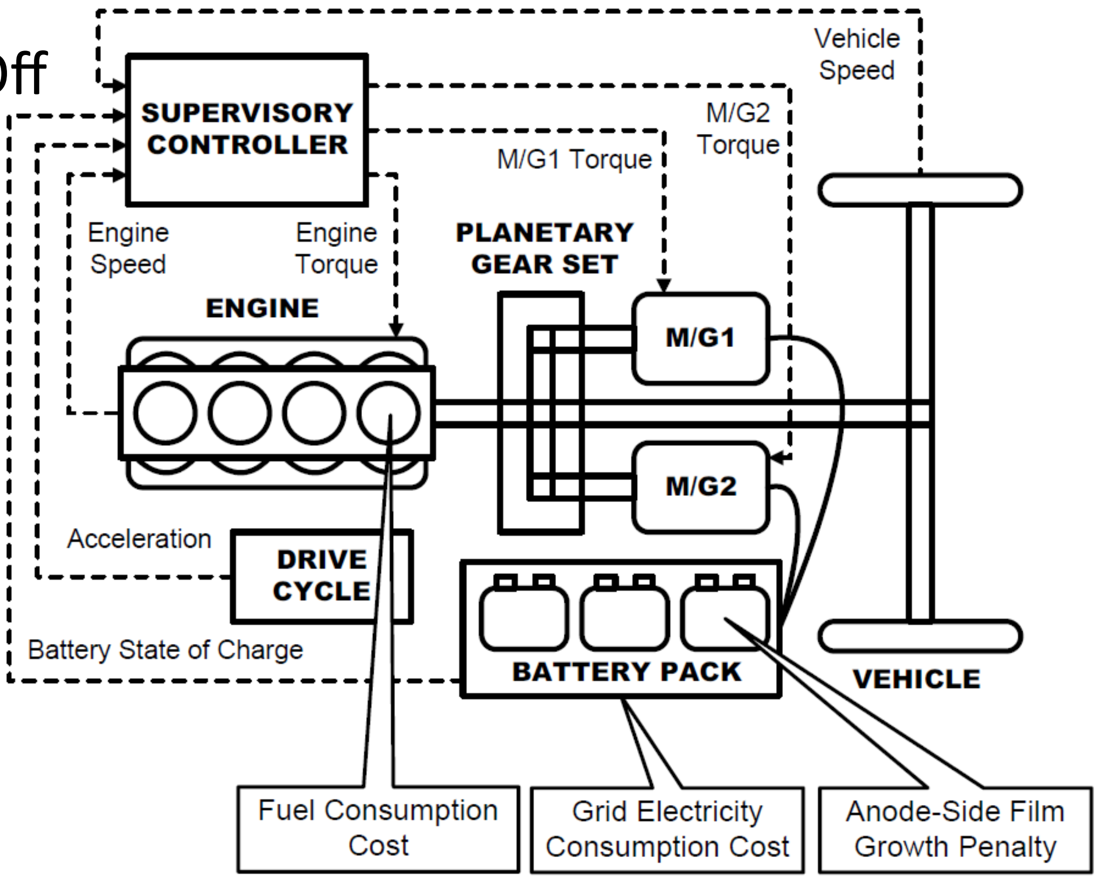
Research Objective

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

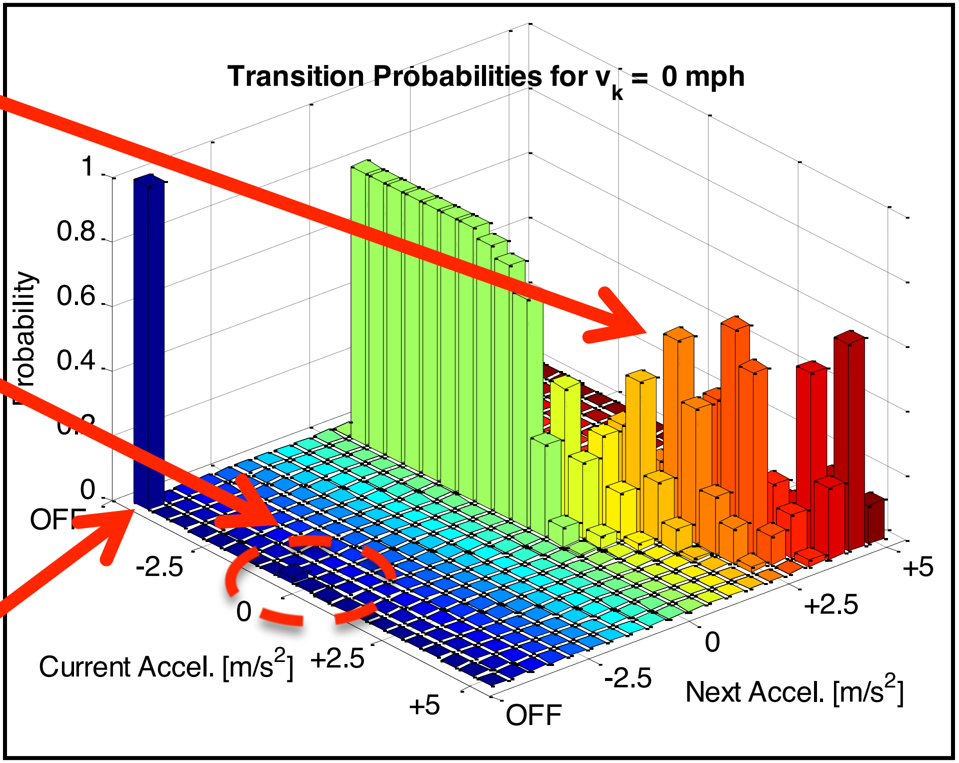
$$p_{ijm} = \Pr(a_{k+1} = j \mid a_k = i, v_k = m)$$

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

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

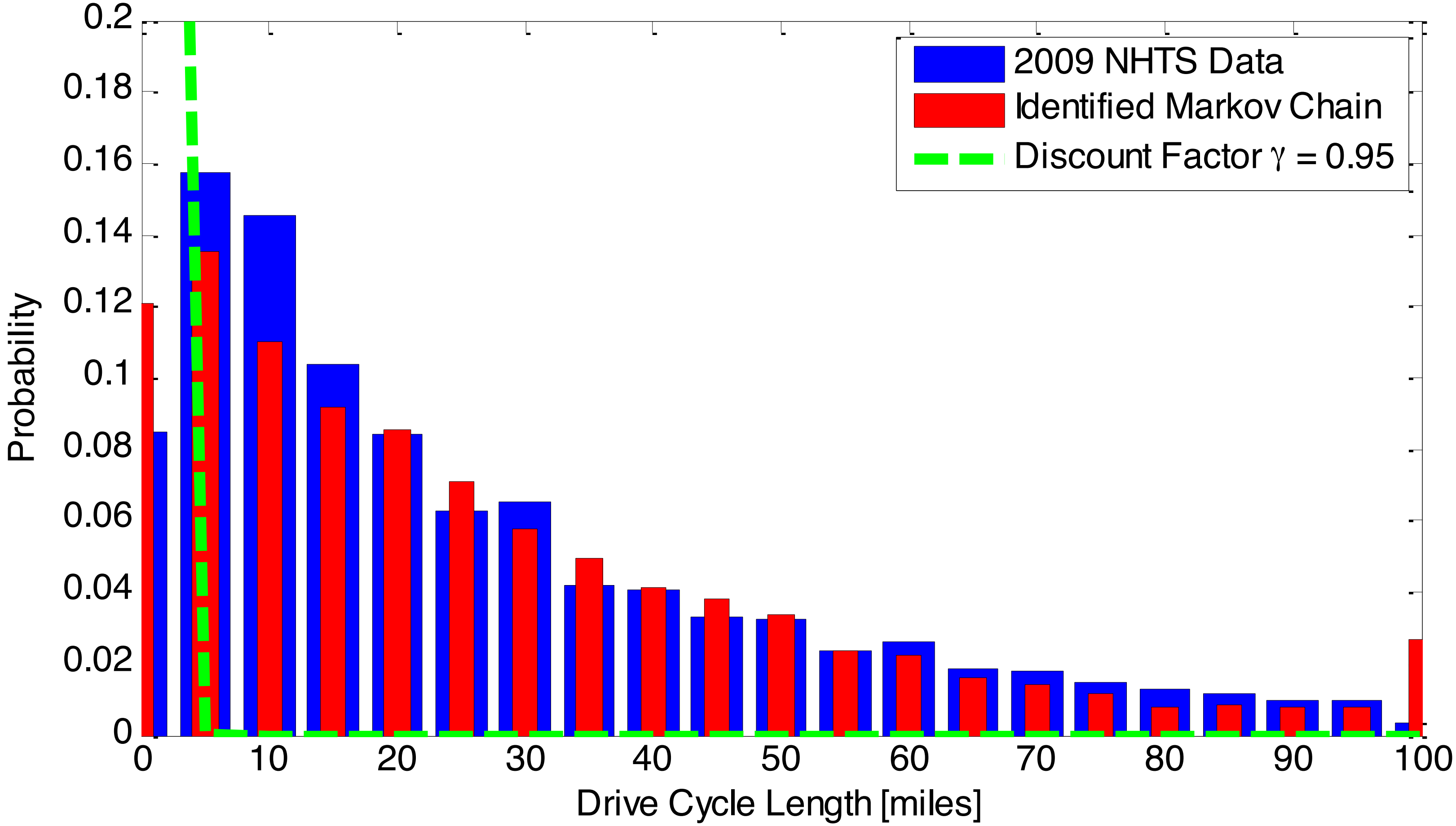
Absorbing state "vehicle off"

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



Markov chain model of Drive Cycles

Daily Trip Length Distribution



Optimal Control Problem Formulation

Multiobjective Shortest-Path Stochastic Dynamic Program

Cost Functional:

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

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

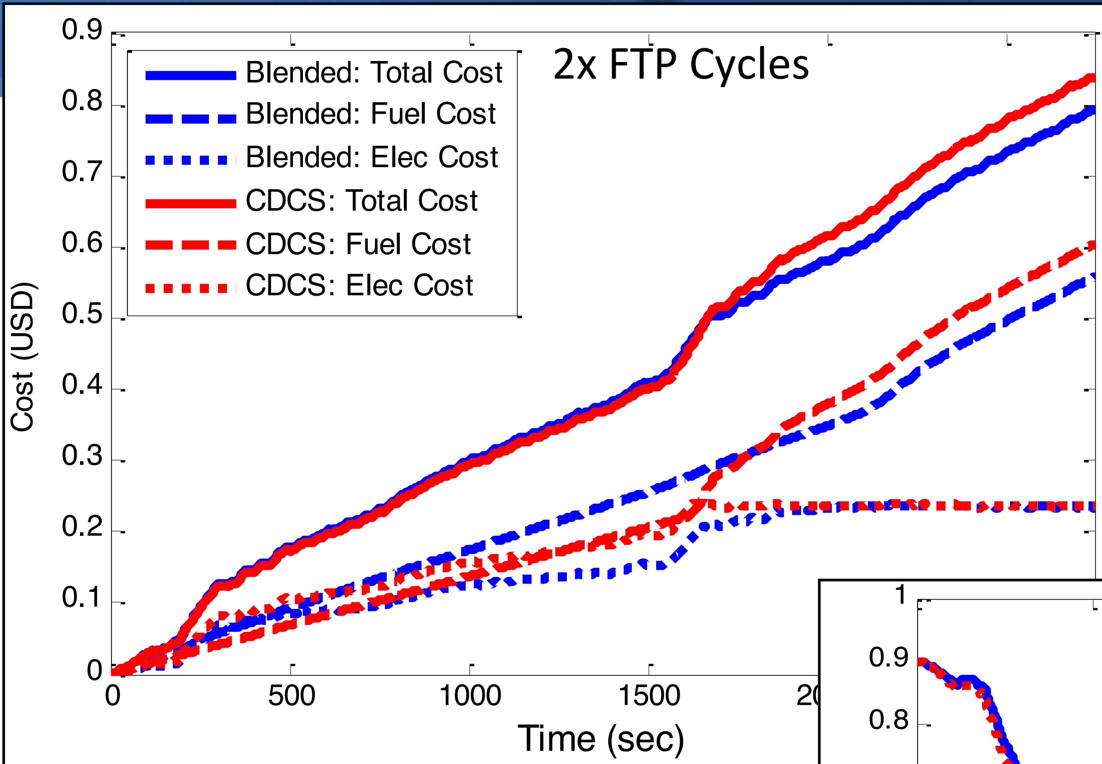
$$c_{energy}\left(x_k, u_k\right) = \beta \alpha_{fuel} W_{fuel} + \alpha_{fuel} \frac{-V_{oc} Q_{batt} \dot{SOC}}{\eta_{grid}}$$

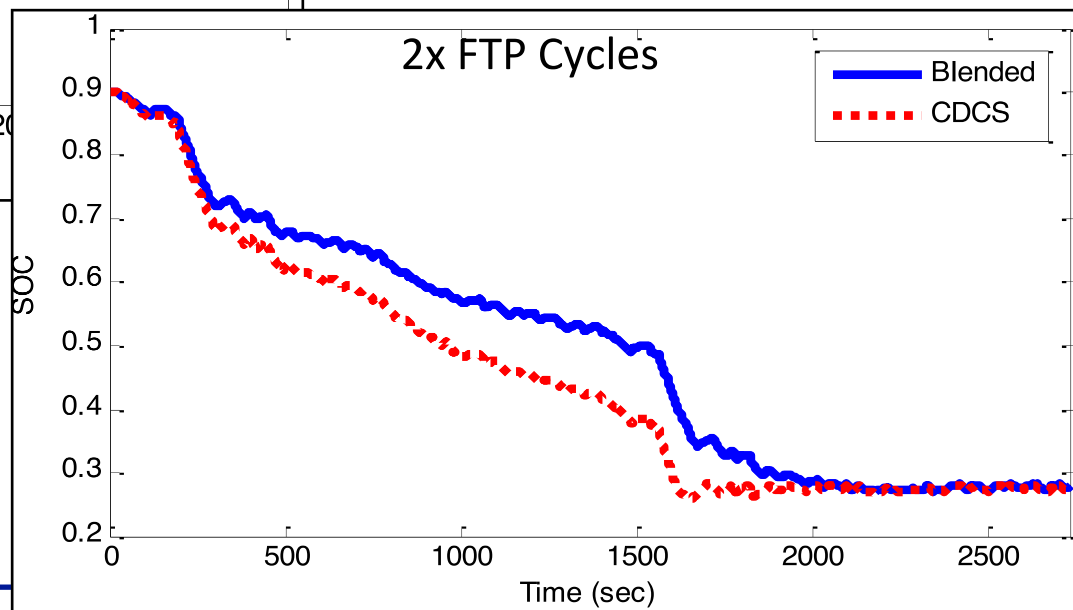
$$c_{film}\left(x_k, u_k\right) = \dot{\delta}_{film}\left(I, SOC\right)$$

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

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

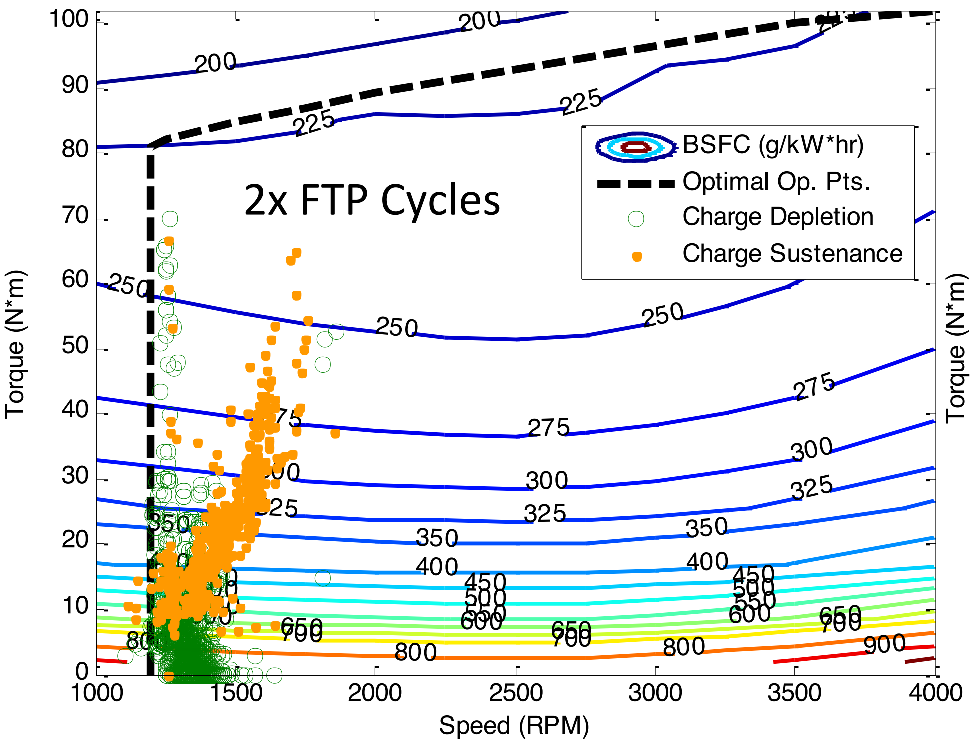
Power Management Results w/o Aging



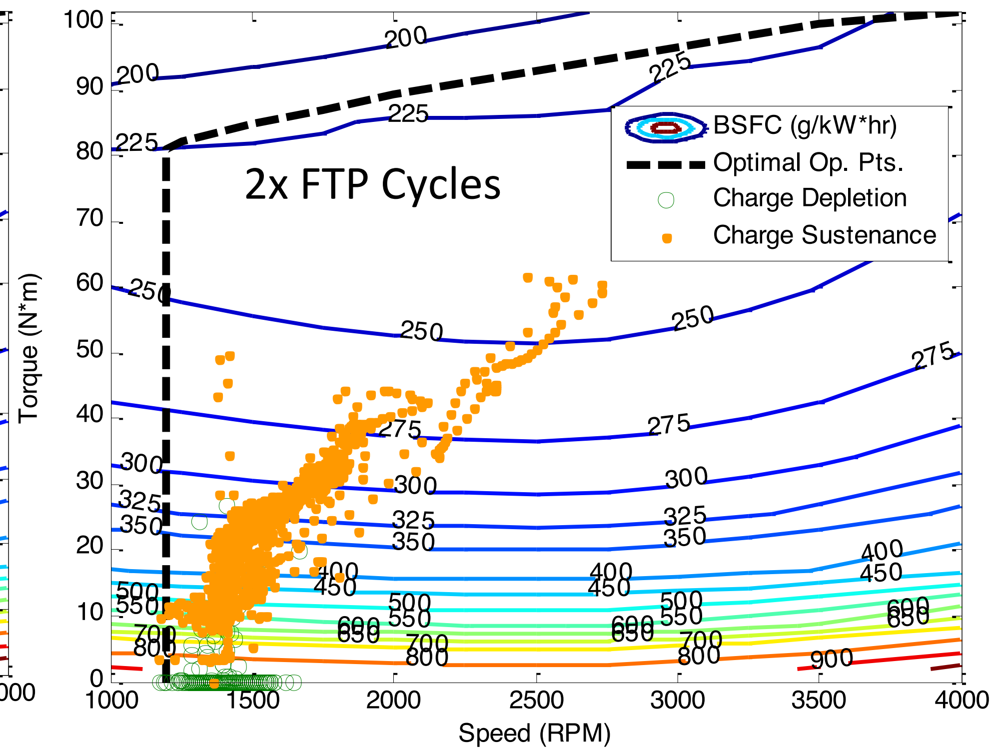


Engine Operating Point Analysis

Optimal Blending

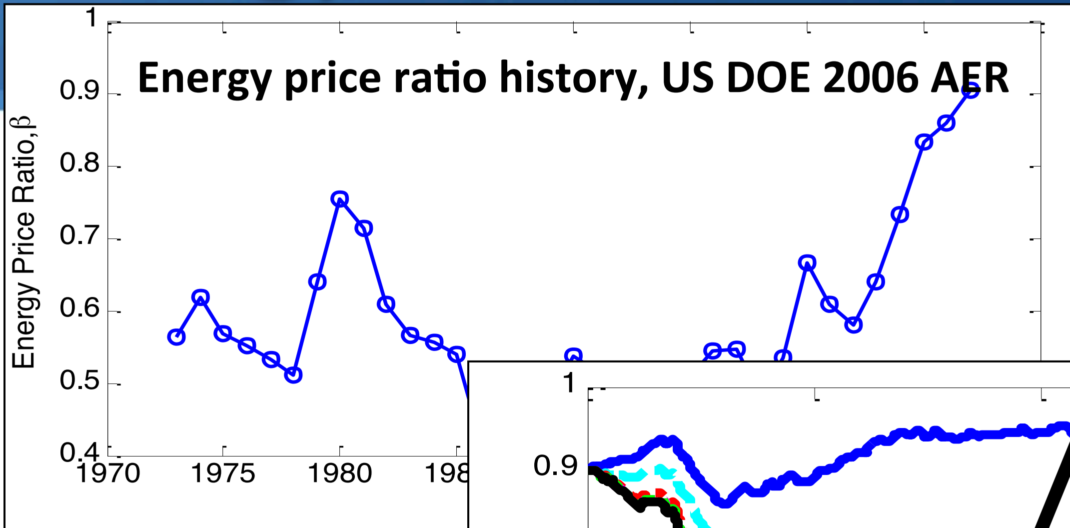


Charge Depletion, Charge Sustenance



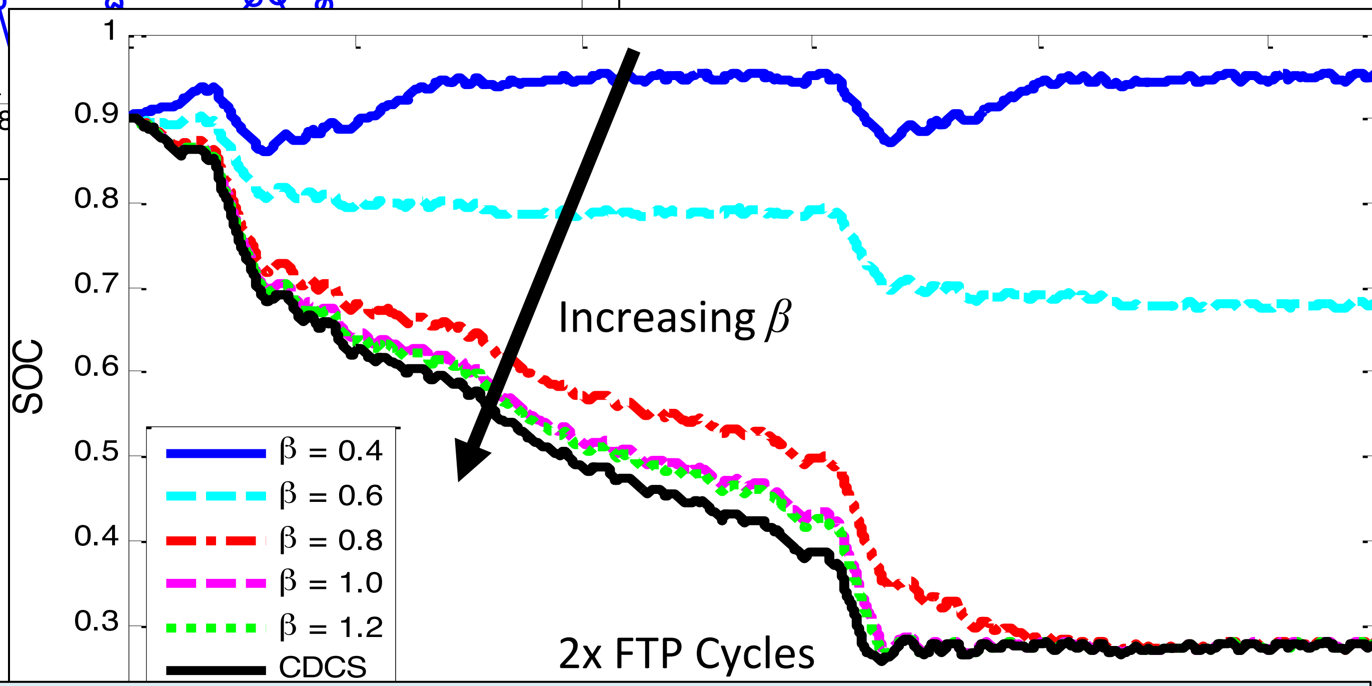
- Blended operates at higher engine efficiency during charge depletion
- Excess power goes to battery charge regeneration

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)

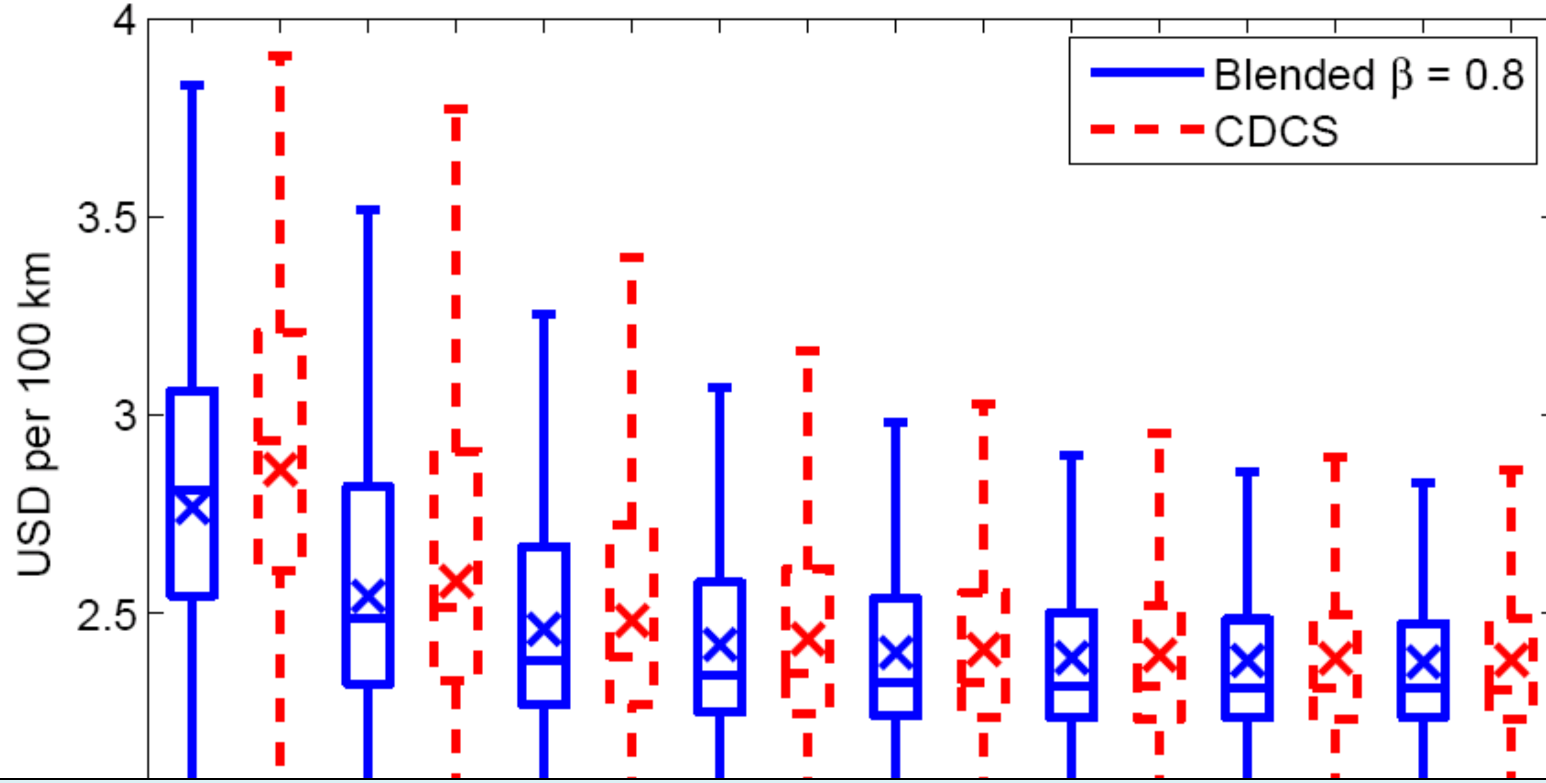


Publications

- **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

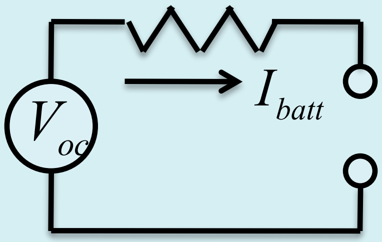
- **S. J. Moura**, D. S. Callaway, H. K. Fathy, and J. L. Stein, "Tradeoffs between Battery Energy Capacity and Stochastic Optimal Power Management in Plug-in Hybrid Electric Vehicles," *Journal of Power Sources*, v 195, n 9, p 2979-2988, May 2010.
- **S. J. Moura,** D. S. Callaway, H. K. Fathy, and 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)**

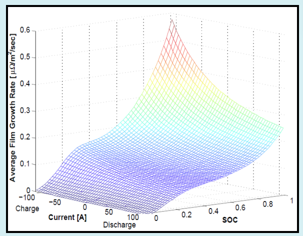
Battery-Health Conscious Analysis Procedure

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

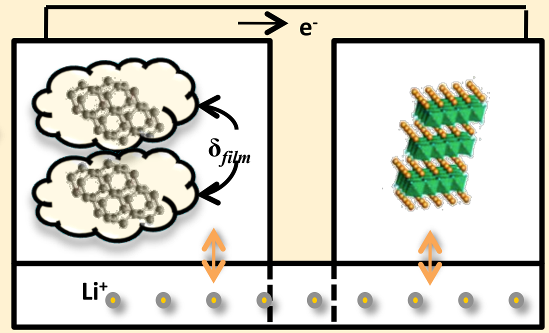
Stochastic DP

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

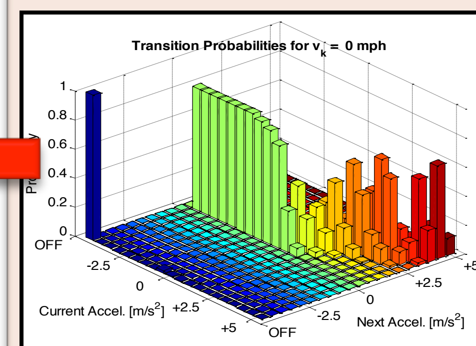




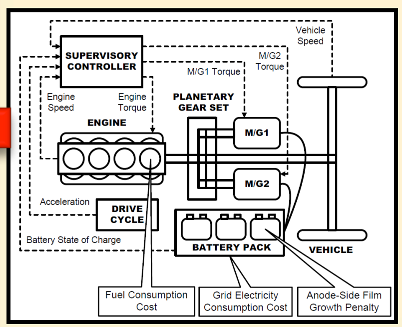
Constraint satisfaction

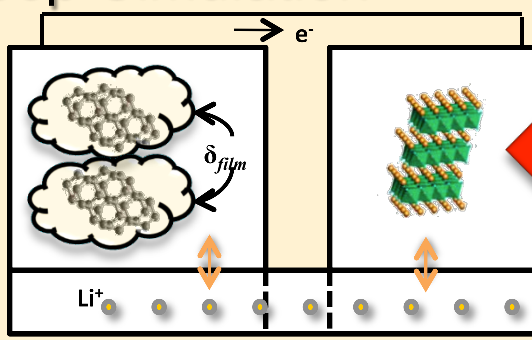


Drive Cycle Library



Closed-loop Simulation



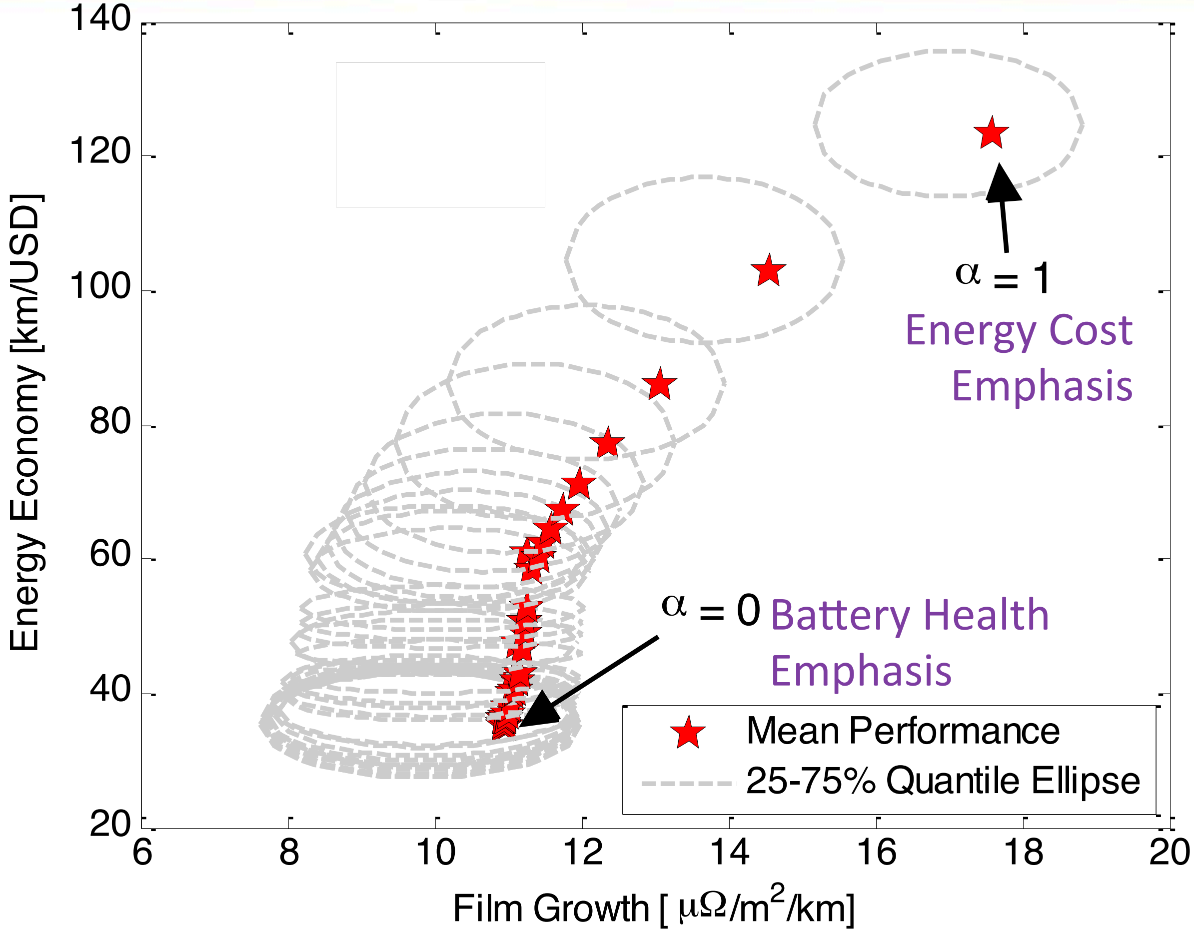


Final Results

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.

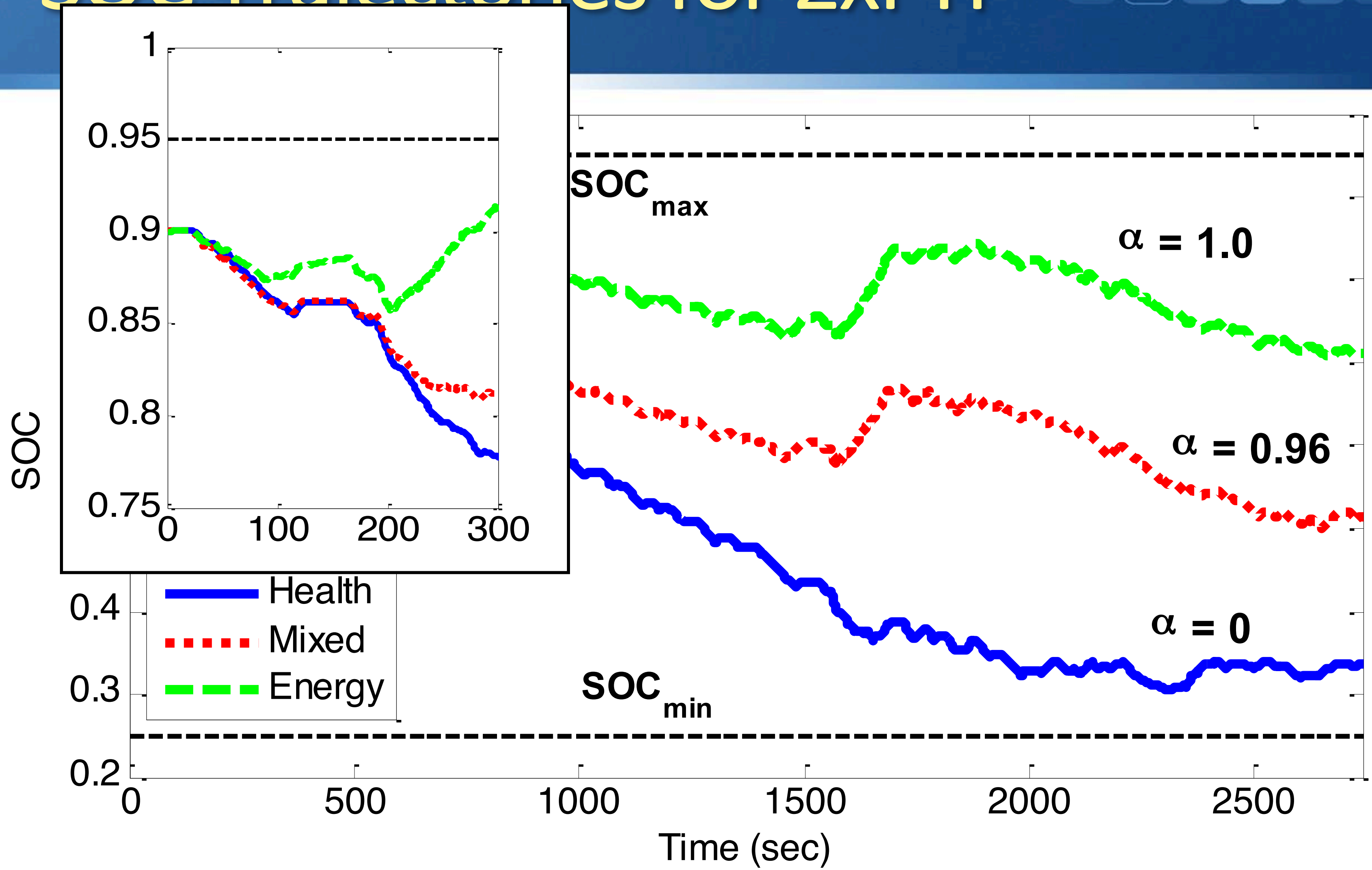
Pareto* Set of Optimal Solutions

*convex subset

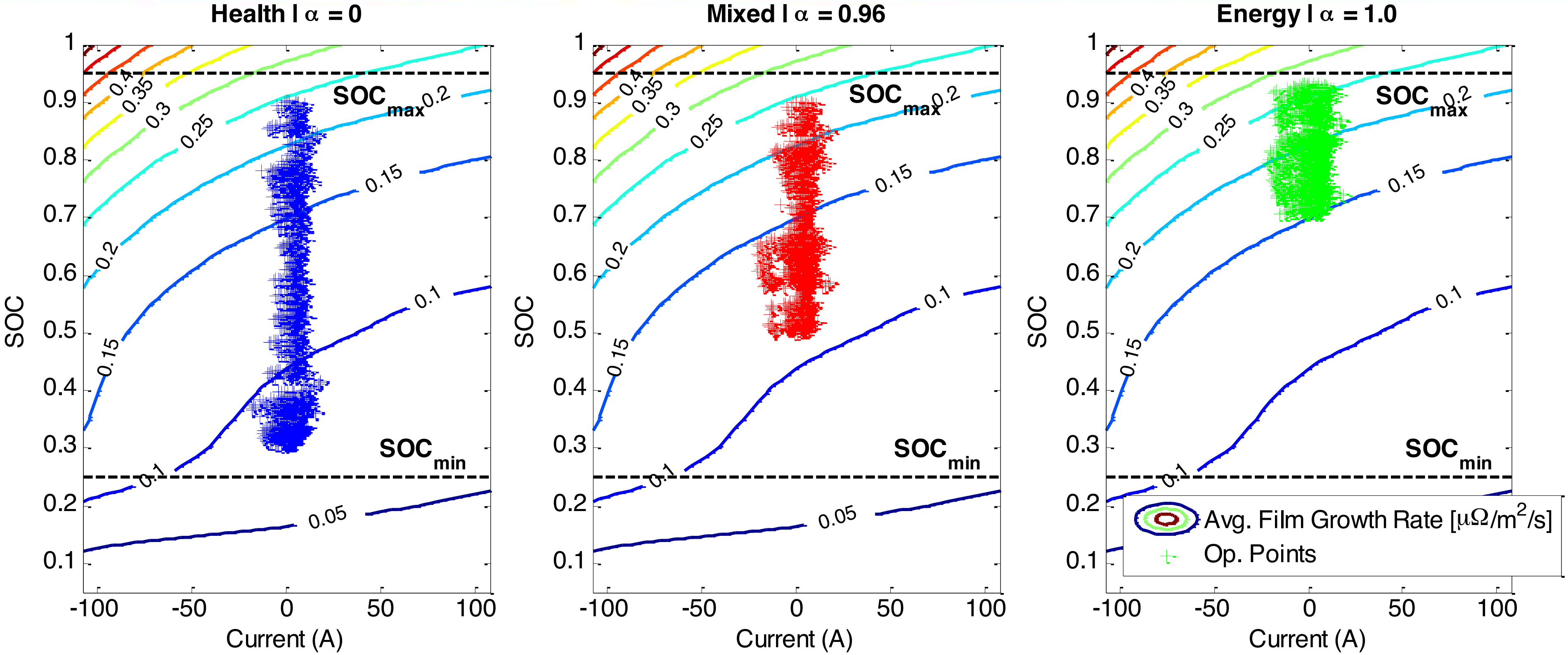


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{film}(x_k, u_k)$$

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

Applications that complement existing SU research:

- 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

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

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

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

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

Derivation of optimal state-feedback:

- Weak-variation necessary conditions
- Linear operator theory

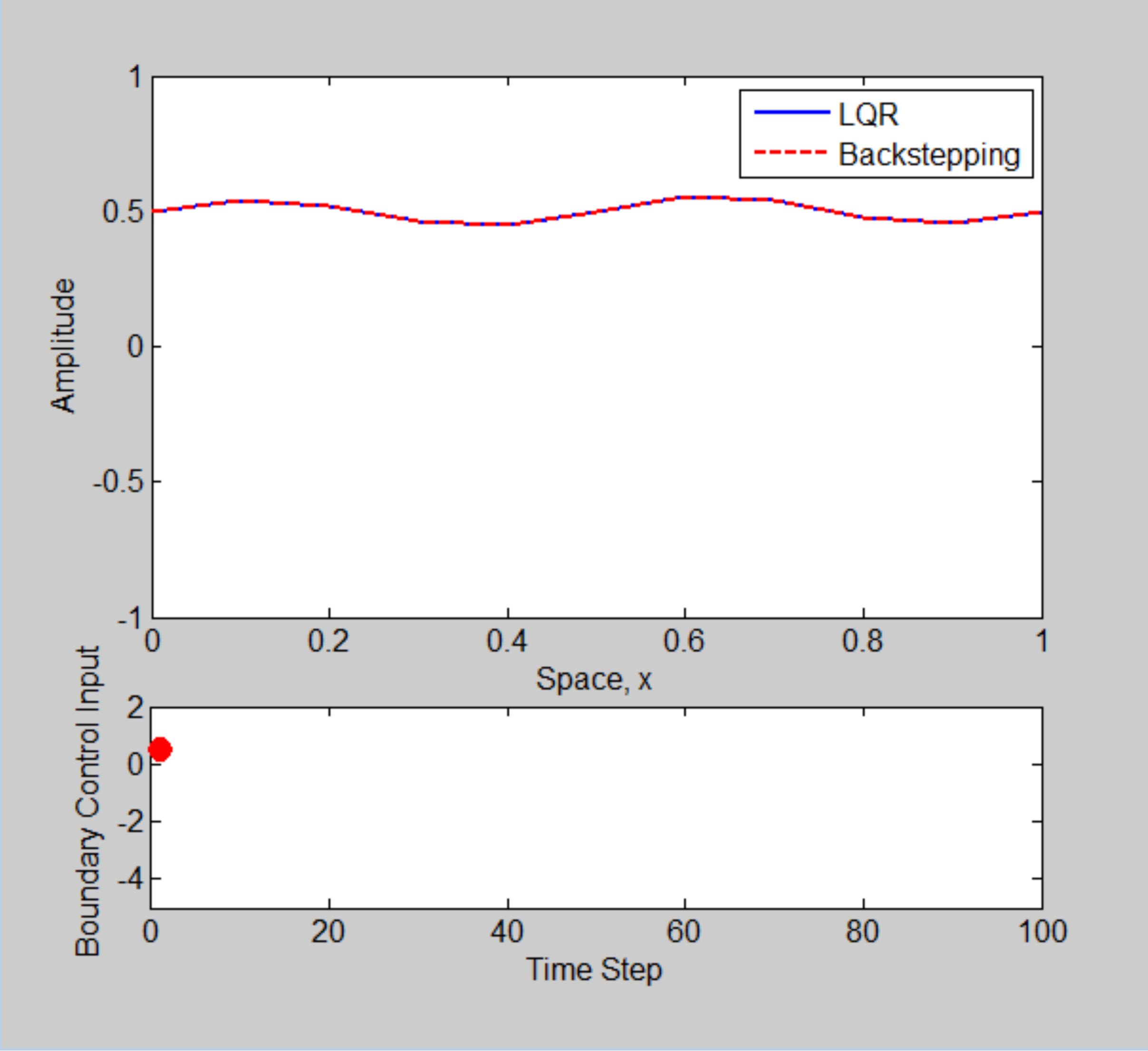
LQR Results: A partial differential Riccati equation

State-feedback

Riccati $\cdot(1, y)$

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: $$u_x(0,t) = 0 \qquad u(1,t) = U(t)$$

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

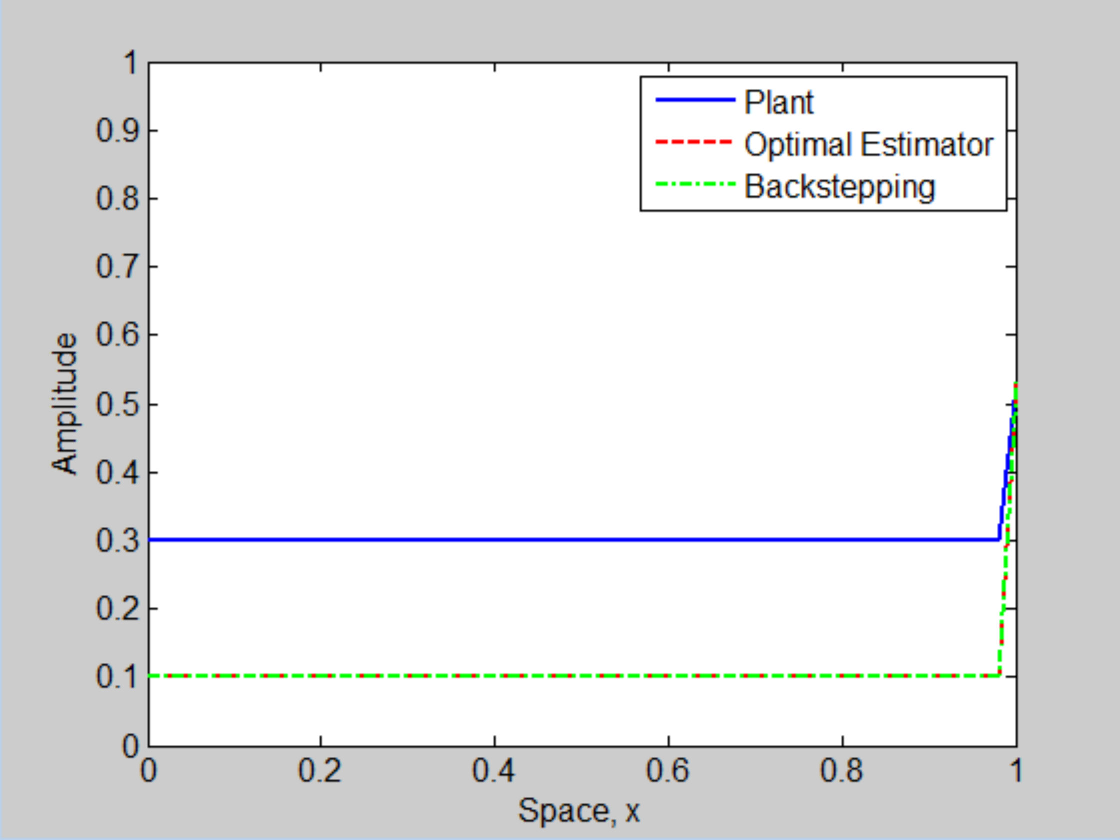
Output injection gain: $L^t = \frac{1}{V} S(x,t) \qquad L_0^t = -\frac{1}{V} S(0,t)$

Dual Riccati P

$+ W(x,0)$

Boundary Conditi

Initial condit

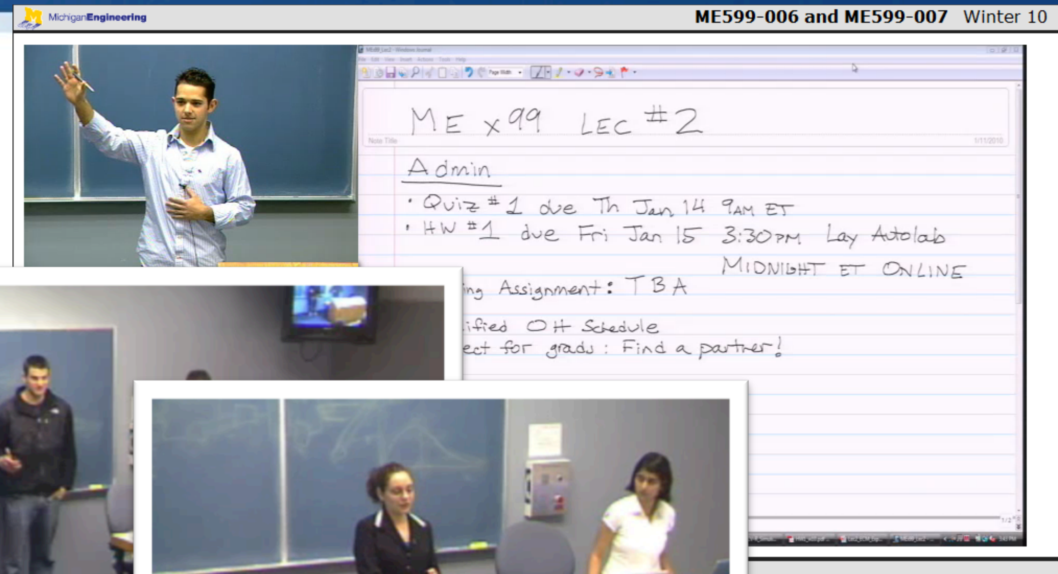


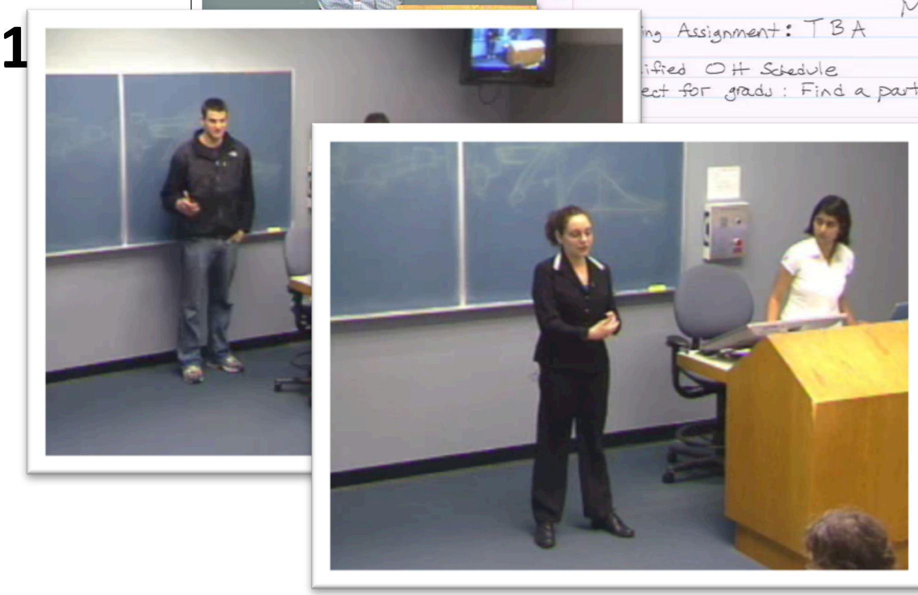
Seminar Summary

- 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)**.

Potential Funding Sources
(in addition to NSF CAREER, NSF GRFP, DoD NDSEG, etc.)

- Task #1: Advanced Battery Modeling for Control Apps.
  - DOE Office of Energy Efficiency & Renewable Energy
  - DOE Advanced Research Projects Agency – Energy
- Task #2: Boundary Control and Estimation of Distributed Parameter Systems
  - NSF Energy, Power, and Adaptive Systems program
  - NSF Control Systems program
- Task #3: Optimal Power Management of Sustainable Energy Systems
  - NSF Emerging Frontiers in Research and Innovation (EFRI)
  - DoD Multidisciplinary University Research Initiative (MURI)
  - Transportation industry, energy planning agencies (NYSERDA)

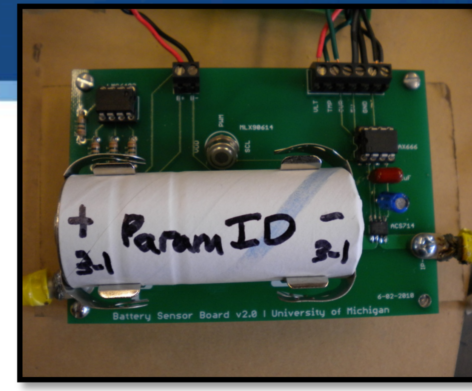
Thank you for your attention!

Questions?

Scott Moura – Ph.D. Candidate, University of Michigan
sjmoura@umich.edu, http://www.umich.edu/~sjmoura

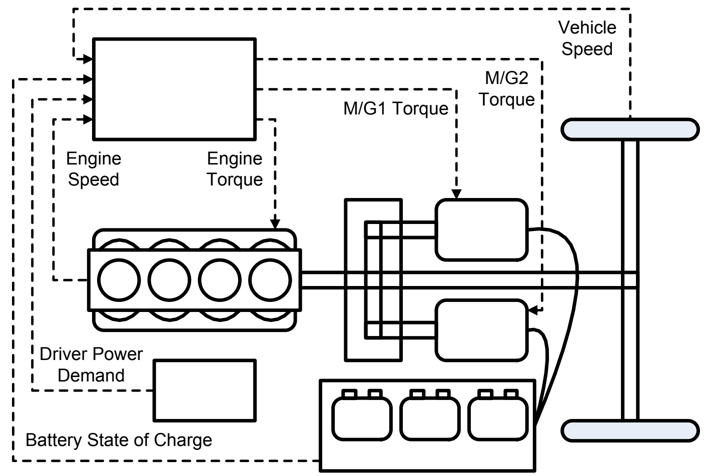
Appendix Slides

Research Challenges



Battery Level:

- Electrochemical battery modeling, identification, estimation, and control

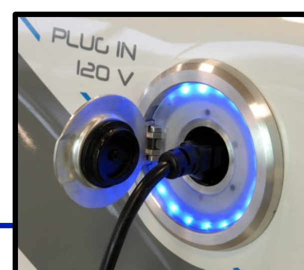


Vehicle Level:

- Power management at the supervisory control level

Vehicle-to-Grid Level:

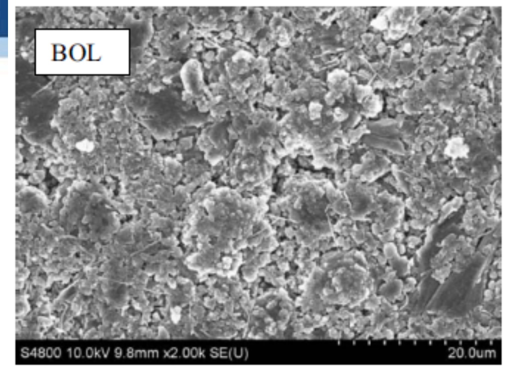
- Optimal grid-to-vehicle charging for consumer benefits



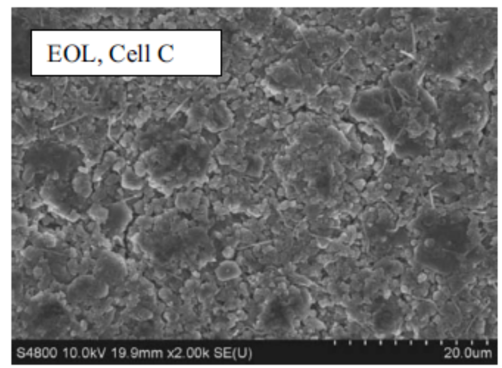
Experimental Aging of $LiFePO_4$ cells

Liu, Wang, Verbrugge, *et al.*, J. ECS, 2010

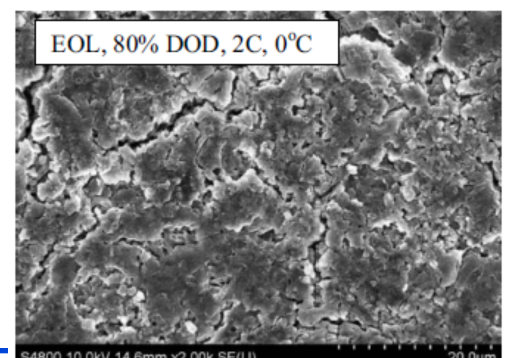
Delamination of negative electrode near the current collector



Beginning of life



End of life
50% DOD
6C
45°C



End of life
80% DOD
2C
0°C

Film Growth Model Analysis

Question: When does film growth rate increase with SOC?

Proposition: Consider a rested Li-ion battery cell, with constant concentration and potential distributions, zero applied current, and hence zero intercalation current $J_1 = 0$. Then the rate of SEI film growth increases with cell SOC,

$$\frac{\partial \dot{\delta}_{film}}{\partial \theta_a} > 0 \qquad\qquad 0 \leq \theta_a \leq 1$$

θ_a : bulk SOC of the anode = cell SOC by definition.

Requires anode equilibrium potential to be decreasing with SOC

$$\frac{\partial U_{ref,a}}{\partial \theta_a} < 0$$

Thermodynamic electrochemical property of lithiated carbon electrodes

Film Growth Model Analysis

Proof:

Write Butler-Volmer equation for the anode as:

$$J_1 = a_0 i_{0,a} \sinh\left[\frac{\alpha_a F}{RT}\left(\phi_{1,a} - \phi_{2,a} - U_{ref,a} - \frac{R_{film}}{a_n} J_1\right)\right]$$

If J_1 =0 above [steady-state assumption], then the following holds true:

$$\phi_{1,a} - \phi_{2,a} = U_{ref,a}\left(\theta_a\right) \qquad (*)$$

The simplifying condition allows us to express $\dot{\delta}_{film}$ as an explicit function of θ_a

One-sided Butler-Volmer reaction + film growth:

$$\dot{\delta}_{film} = C_1 C_2 \exp\left(-C_3 \eta_s\right)$$

Side reaction overpotential + (*)

$$\begin{aligned}\eta_s &= \phi_{1,a} - \phi_{2,a} - U_{ref,s} \\ &= U_{ref,a}\left(\theta_a\right) - U_{ref,s}\end{aligned}$$

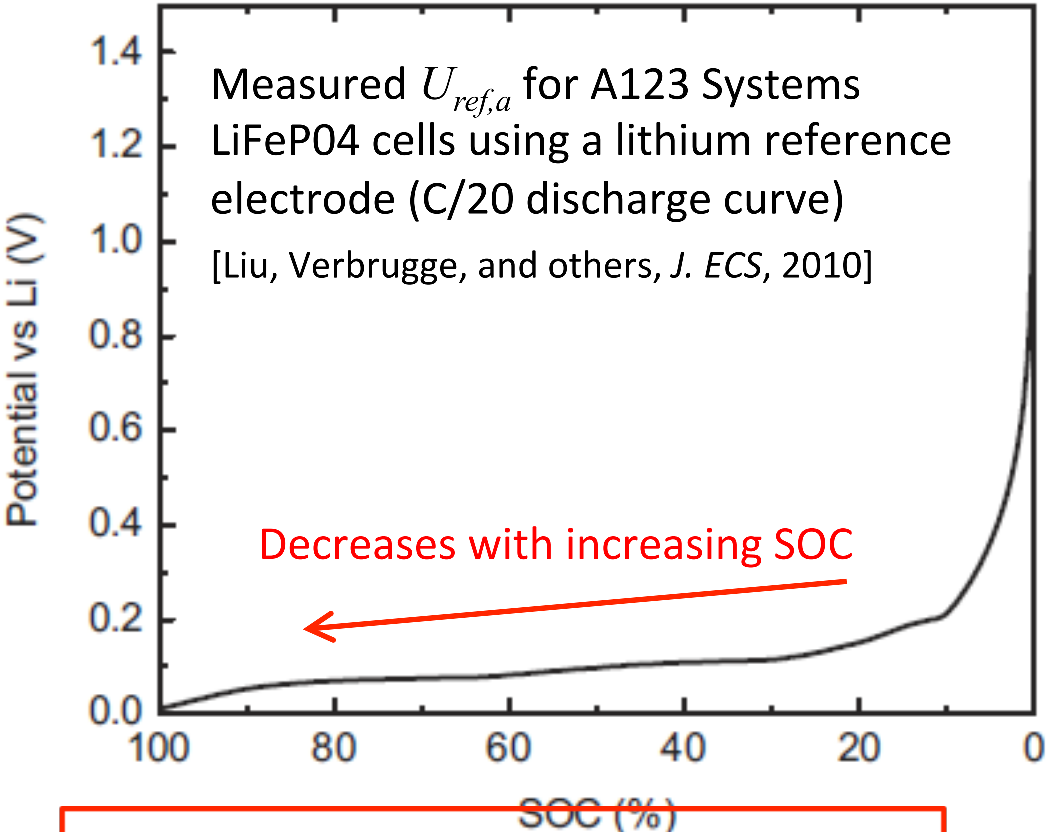
Substitute η_s into one-sided BV eqn.

$$\dot{\delta}_{film} = C_1 C_2 \exp\left[-C_3\left(U_{ref,a}\left(\theta_a\right) - U_{ref,s}\right)\right]$$

Differentiate w.r.t. θ_a : $\frac{\partial}{\partial \theta_a}\dot{\delta}_{film} =$

$$\underbrace{\left\{-C_1 C_2 C_3 \exp\left[-C_3\left(U_{ref,a}\left(\theta_a\right) - U_{ref,s}\right)\right]\right\}}_{\textbf{Negative}} \underbrace{\left[\frac{dU_{ref,a}}{d\theta_a}\right]}_{\textbf{???}}$$

Anode Equilibrium Potential



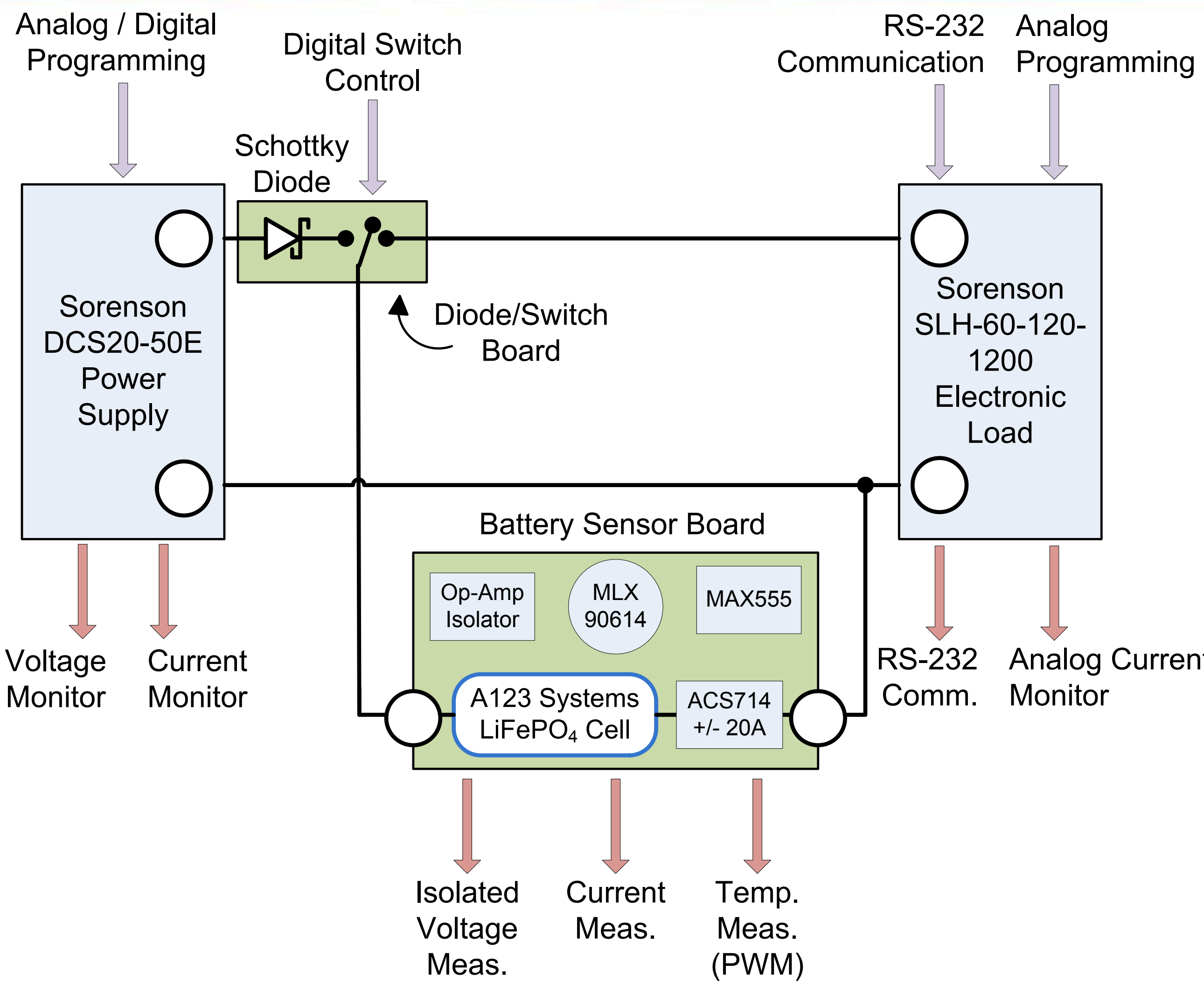
$$\frac{dU_{ref,a}}{d\theta_a} < 0 \quad \Longrightarrow \quad \frac{\partial}{\partial \theta_a} \dot{\delta}_{film} > 0$$

Equilibrium Potential:
"Electrochemical barrier I need to overcome through overpotentials to drive lithium ions *OUT* of the anode."

Generality:

- Fundamental thermodynamic property
- General to all cells with lithiated carbon electrodes
- Proof requires steady-state, zero current assumption, but one may be able to relax those assumptions

Schematic of BIL Experiment



Dynamic Programming Problem

Let $V_k(z_k)$ represent the minimum total film growth from discrete time k to the end of the time horizon, given that the cell SOC in the present time step k is given by the vector z_k.

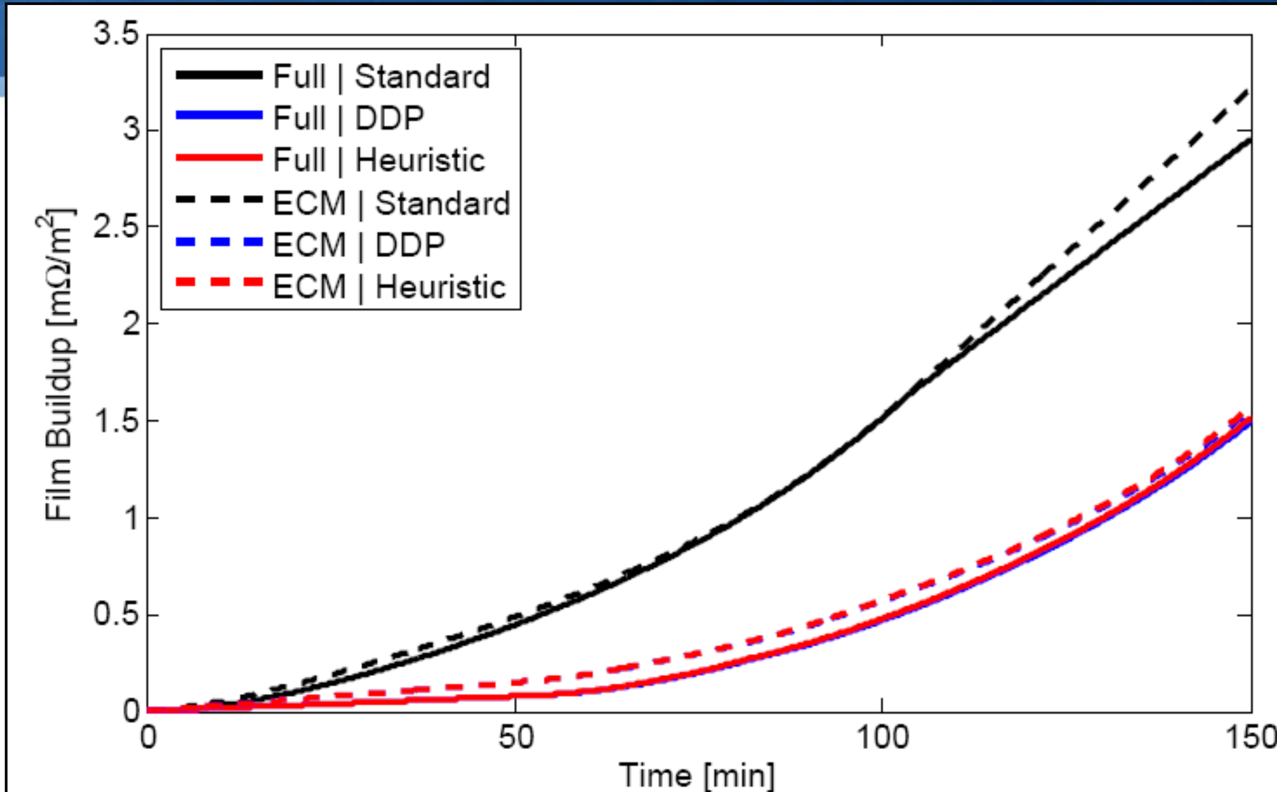
Optimality Equation

$$V_k\left(z_k\right) = \min_{q_1, q_2}\left\{\dot{\delta}_{film}\left(z_{1,k}, i_{1,k}\right) + \dot{\delta}_{film}\left(z_{2,k}, i_{2,k}\right) + g_z\left(z_k\right) + V_{k+1}\left(z_{k+1}\right)\right\}$$

Boundary Condition

$$V_N\left(z_{N-1}\right) = \min_{q_1, q_2}\left\{\alpha_N \left\| z_N - 0.95 \right\|_2^2\right\}$$

Validation on Full Electrochem. Model



Control Scheme	Resistance of Total Film Buildup	Reduction in Film Buildup	Resistance of Total Film Buildup	Reduction in Film Buildup	ECM vs. Full Error
Standard	3.20 mΩ/m^2	0%	2.95 mΩ/m^2	0%	8.47%
DDP	1.55 mΩ/m^2	51.8%	1.49 mΩ/m^2	49.5%	4.03%
Heuristic	1.56 mΩ/m^2	51.2%	1.51 mΩ/m^2	48.7%	3.31%

Summary of Charge Unbalancing

- Key Results: Film growth can be reduced by
  - Allowing unequal SOC values during charging
  - Delaying charging until immediately before discharge
- Film growth rate approximated by a static map that depends on cell SOC and applied current
- Use relay switches originally designed for thermal runaway for active film growth control
- Pose an optimal control problem for minimizing film growth
- Optimal trajectories can be closely approximated using a heuristic static state-feedback controller

Publications

- **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," *IEEE Transactions on Industrial Electronics*, vPP, n 99, 2010.
- **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*, p 139-147, Hollywood, CA, 2009. **Best Student Paper Finalist.**

Literature Review

Electrochemical Li-ion Battery Modeling

- Electrochemical systems (Newman, 1991)
- Lithium diffusion, intercalation kinetics (Doyle, Fuller, Newman, 1993 & 1994)
- Model Parameter ID (Schmidt et al., 2010; Speltino et. al. 2010; **Forman et al., ACC11**)
- Li-ion battery degradation review (Aurbach et al., 2000)
- Capacity fade via anode-side film formation (Ramadass et al., 2004)

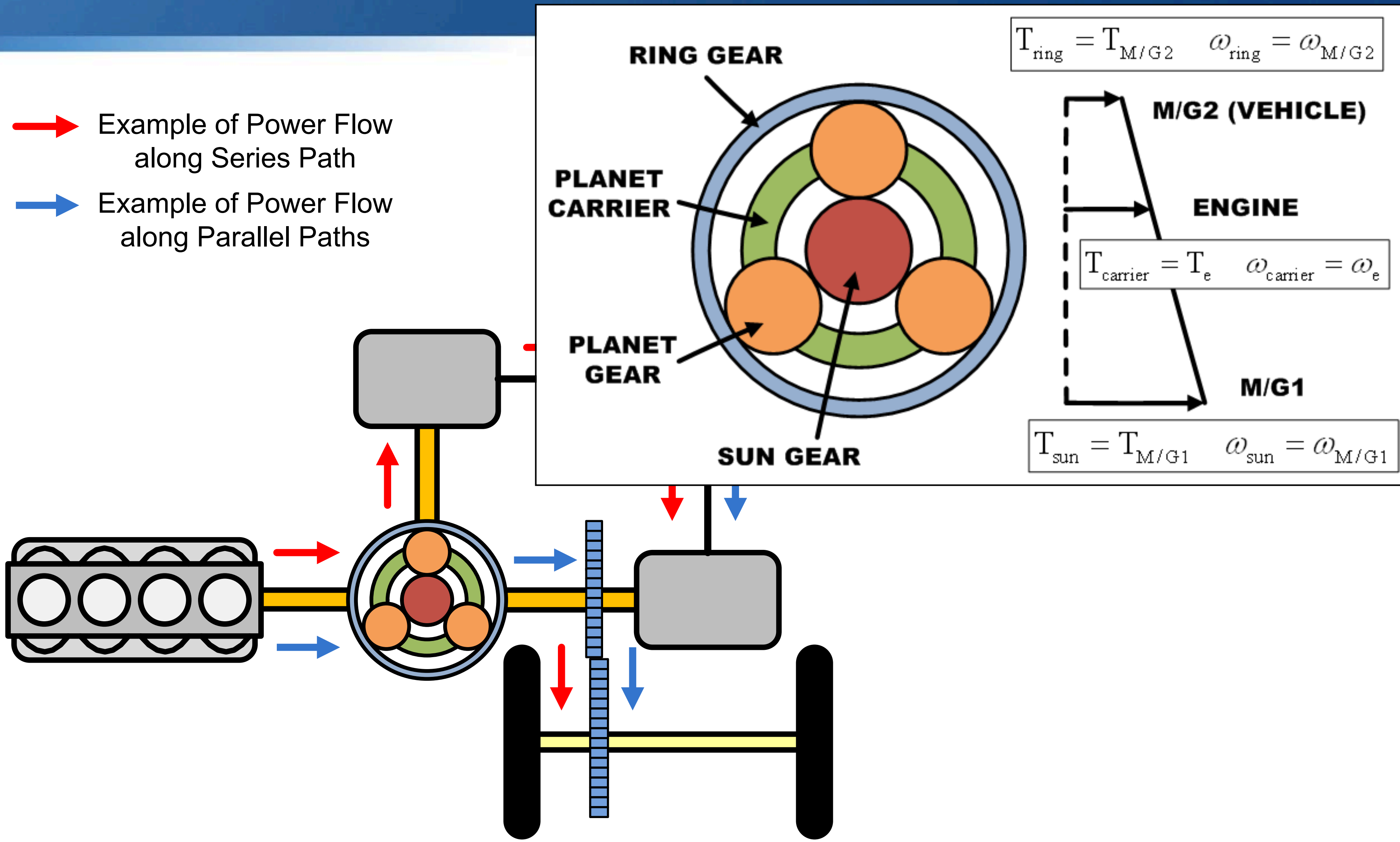
HEV Power Management

- ECMS (Musardo et al., 2005)
- Model Predictive Control (Vahidi et al., 2006)
- Deterministic DP (Gong et al., 2008; O'Keefe, 2006)
- Stochastic DP (Lin 2004; Johannesson et al., 2007; Tate et al., 2008; **Moura et al., 2010**)
- Design & control (Sharer et al., 2008; Gao et al., 2010)
- Emissions (Kum et al., 2008), Drivability (Opila et al., 2010), WTW (Stockar et al., 2010), Traffic/Trip Preview (Gong et al, 2008; Zhang et al., 2009)

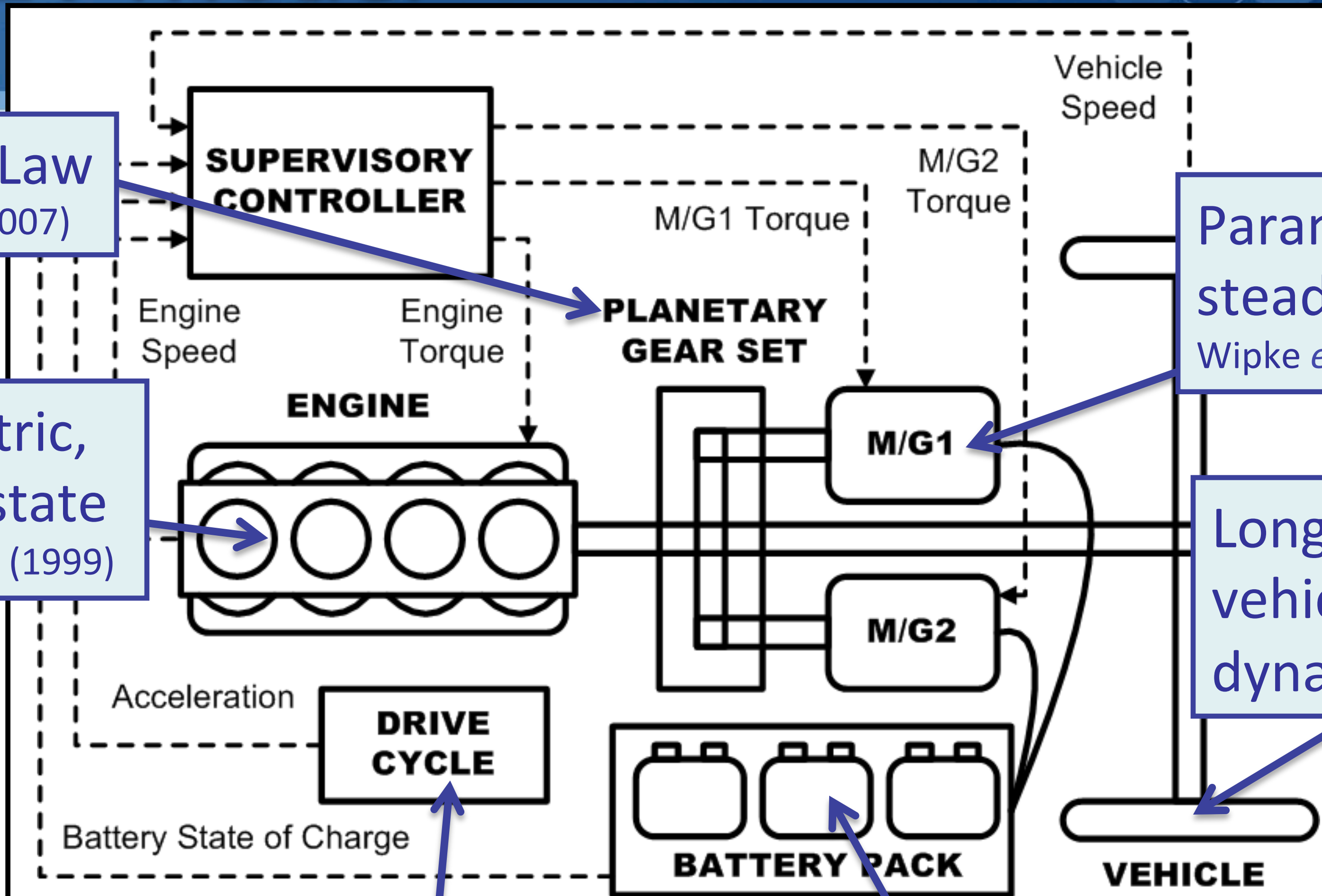
Battery Health-Conscious PHEV Power Management

- Depth of discharge control (Amiri et al., 2009; Shidore et al., 2009)
- Power electronics (Amjadi et al, 2010)
- Temperature management (Mi et al, 2007)
- **Electrochemical phenomena?**

Single Mode Power-Split Configuration



PHEV Model



Euler's Law
Liu *et al.* (2007)

Parametric, steady-state
Wipke *et al.* (1999)

Parametric, steady-state
Wipke *et al.* (1999)

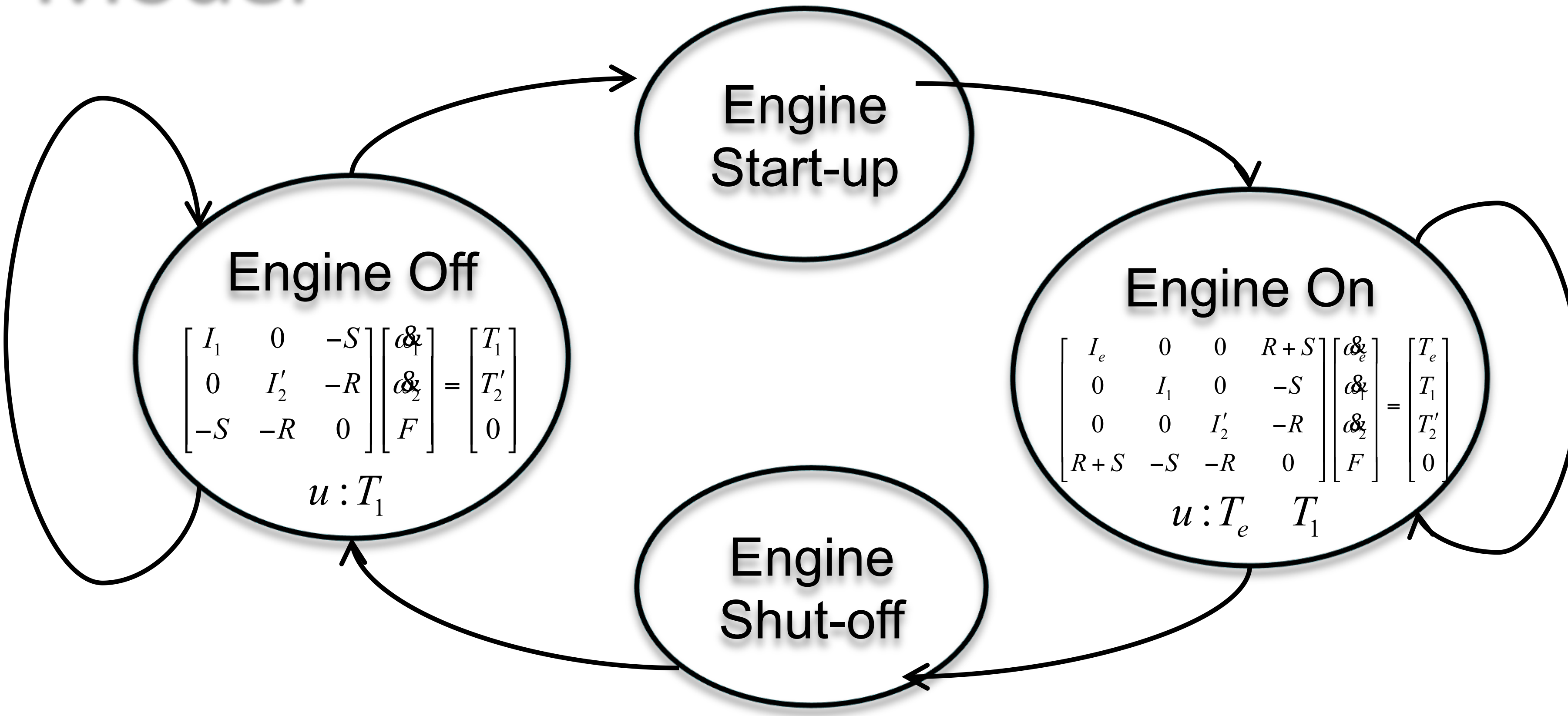
Longitudinal vehicle dynamics

Markov Chain Model
Lin *et al.* (2004)

Equivalent Circuit
Liu *et al.* (2004), Wipke *et al.* (1999)

$$x = \left[\omega_e \quad v \quad SOC \quad a\right]^T \qquad u = \left[T_e \quad T_{M/G1} \quad T_{M/G2}\right]^T$$

Hybrid Engine-On/Engine-Off Model

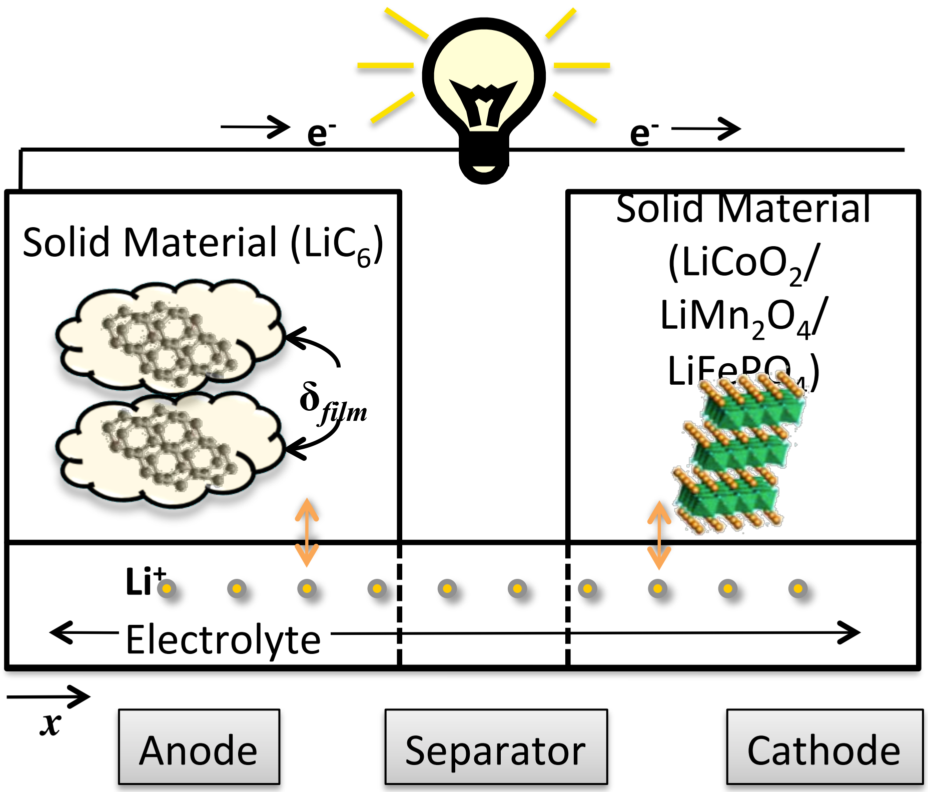


Li-ion Battery Modeling

Full Electrochemical Model

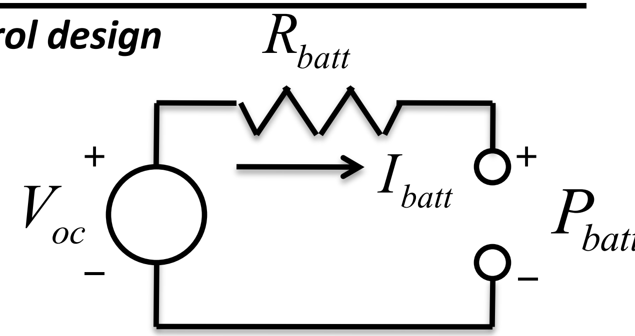
Use for defining admissible controls and states

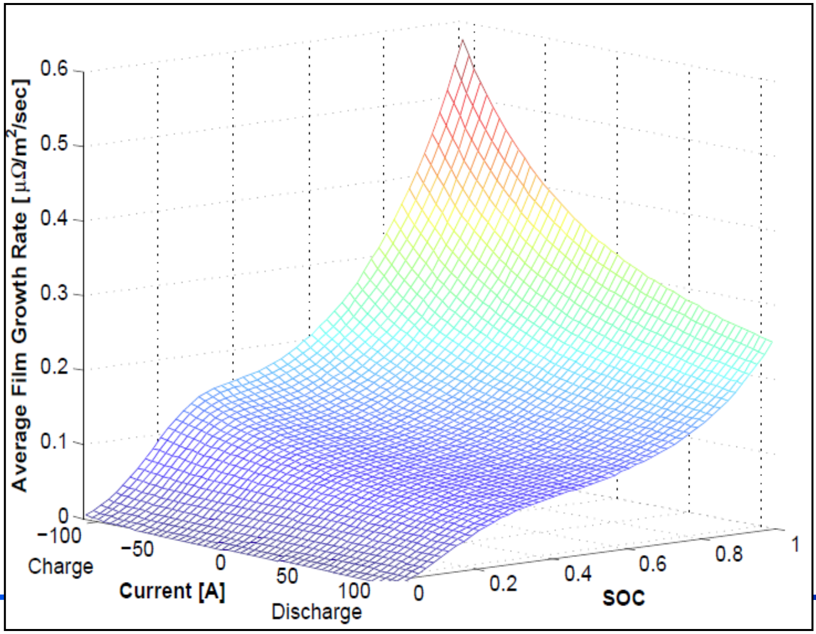
Use for simulating PHEV with final control design



ID'ed Equivalent Circuit Model

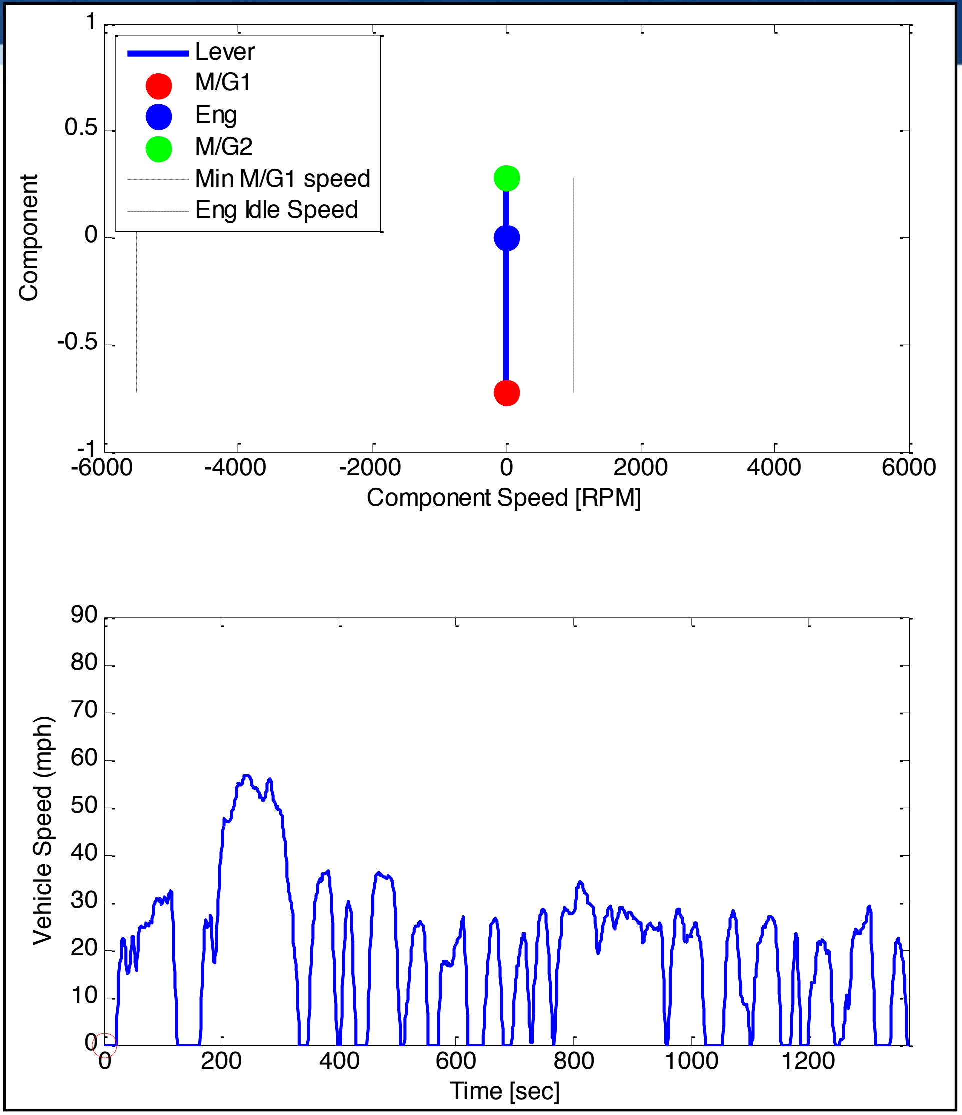
Use for control design





PHEV State/Control Constraints

- Engine Speed Constraints
  - Min, Max, Idle Speed
- Engine Torque Constraints
  - Min, Max (fcn. of eng. speed)
- M/G1 Speed Constraints
  - Min, Max
- M/G2 Speed Constraints
  - Min, Max
- Battery Voltage Constraints
  - Min, Max
    Max regeneration through braking, M/G torques



Numerical Computation

Question: How do you enforce the constraints???

Modified Policy Iteration:

Step 1: Policy Evaluation

$$J^g(i) = c(i, g(i)) + \sum_{i \in S} p(j \mid i) J\left(f(i, g(i))\right) \quad \forall i \in S$$

Step 2: Policy Improvement

$$g(i) = \arg\min_{u \in U(i)} \left\{ c(i,u) + \sum_{i \in S} p(j \mid i) J\left(f(i,u)\right) \right\} \quad \forall i \in S$$

Question: How do you generate $U(i)$? Do it offline!

1. For each state x, compute $x_{k+1} = f(x,u)$ for all controls u
2. Determine if x_{k+1} is feasible. If so, place corresponding u into set U(x)
3. Repeat for every single state x

Huge computational savings!

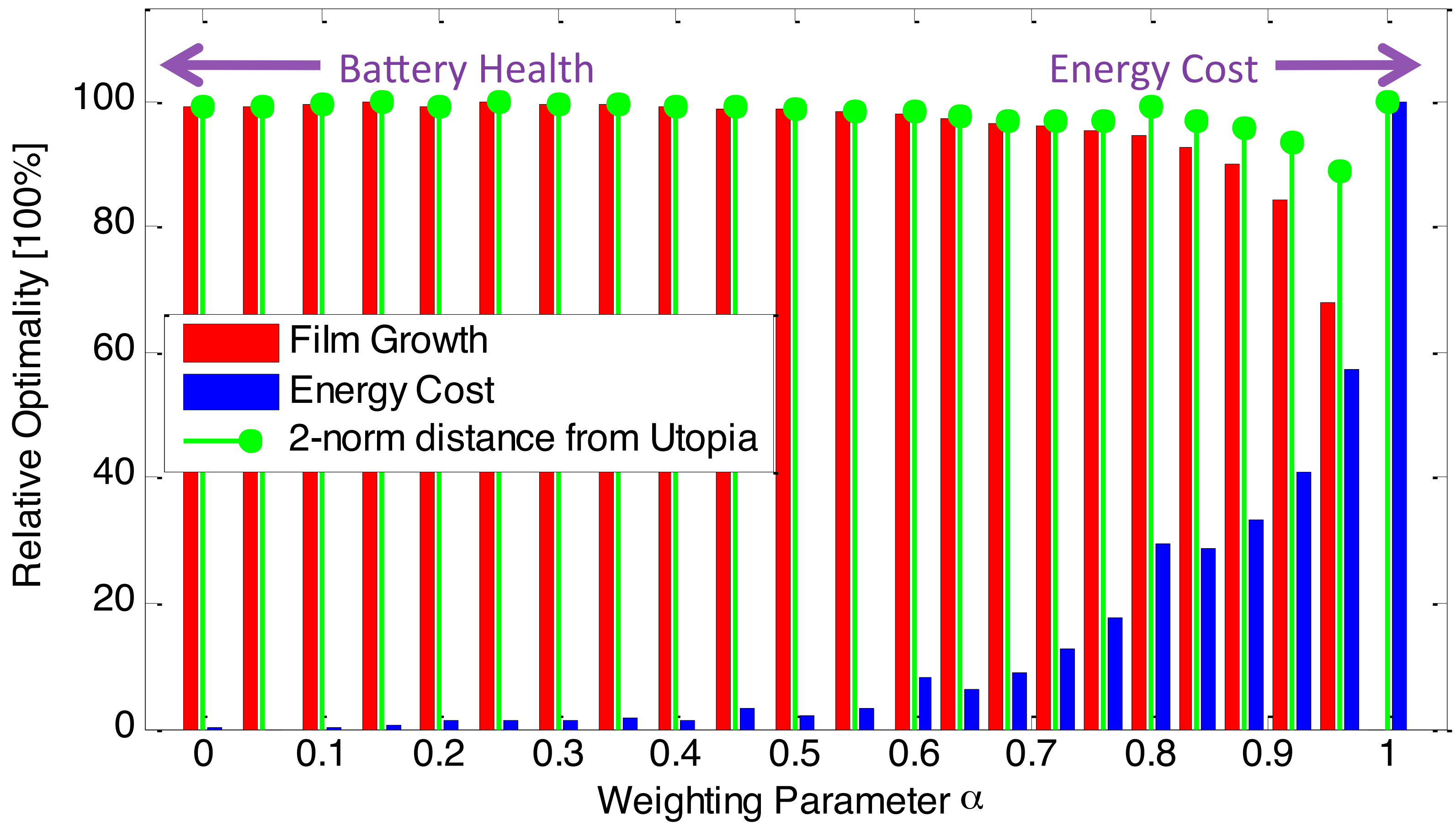
Center for Advanced Computing (CAC)

- Over 3,500 64-bit AMD Opteron nodes
- Free for students and faculty
- Easily accessible via FTP and SSH
- Computational Resource Options
  - Normal Queue, guaranteed completion
  - Private notes, immediate execution, but preem tive

Code program in Matlab → FTP files to CAC → Compile into executable → Write script to execute code (parallel jobs) → E-mails you when jobs are complete

In this study: 32 SDP optimizations and 32,000 drive cycle simulations

Relative Optimality Analysis



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

Summary

- PHEV Battery Health/Energy Model Development
  - Dynamic PHEV Power-split powertrain model
  - Stochastic drive cycle/trip length model
  - Anode-side film growth model
- Stochastic Control Problem Formulation
  - Multiobjective, Constrained
  - Battery health & energy consumption cost
- Main Results
  - Performance distributions across 1,000 drive cycles
  - Health map properties → battery charge rationing

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

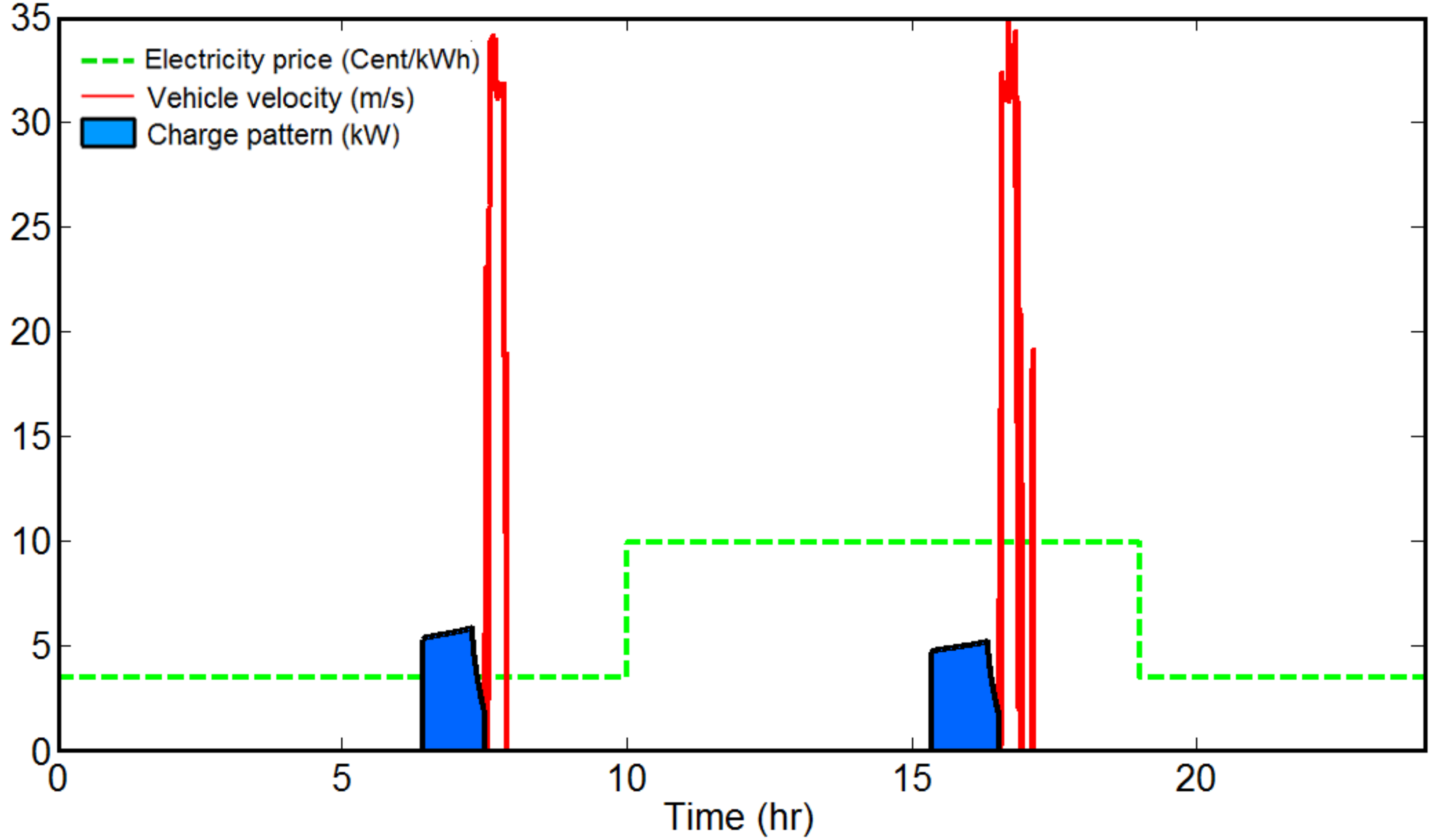
When is the optimal time to charge PHEVs to maximize consumer benefits? Specifically w.r.t. battery health & energy consumption cost.

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

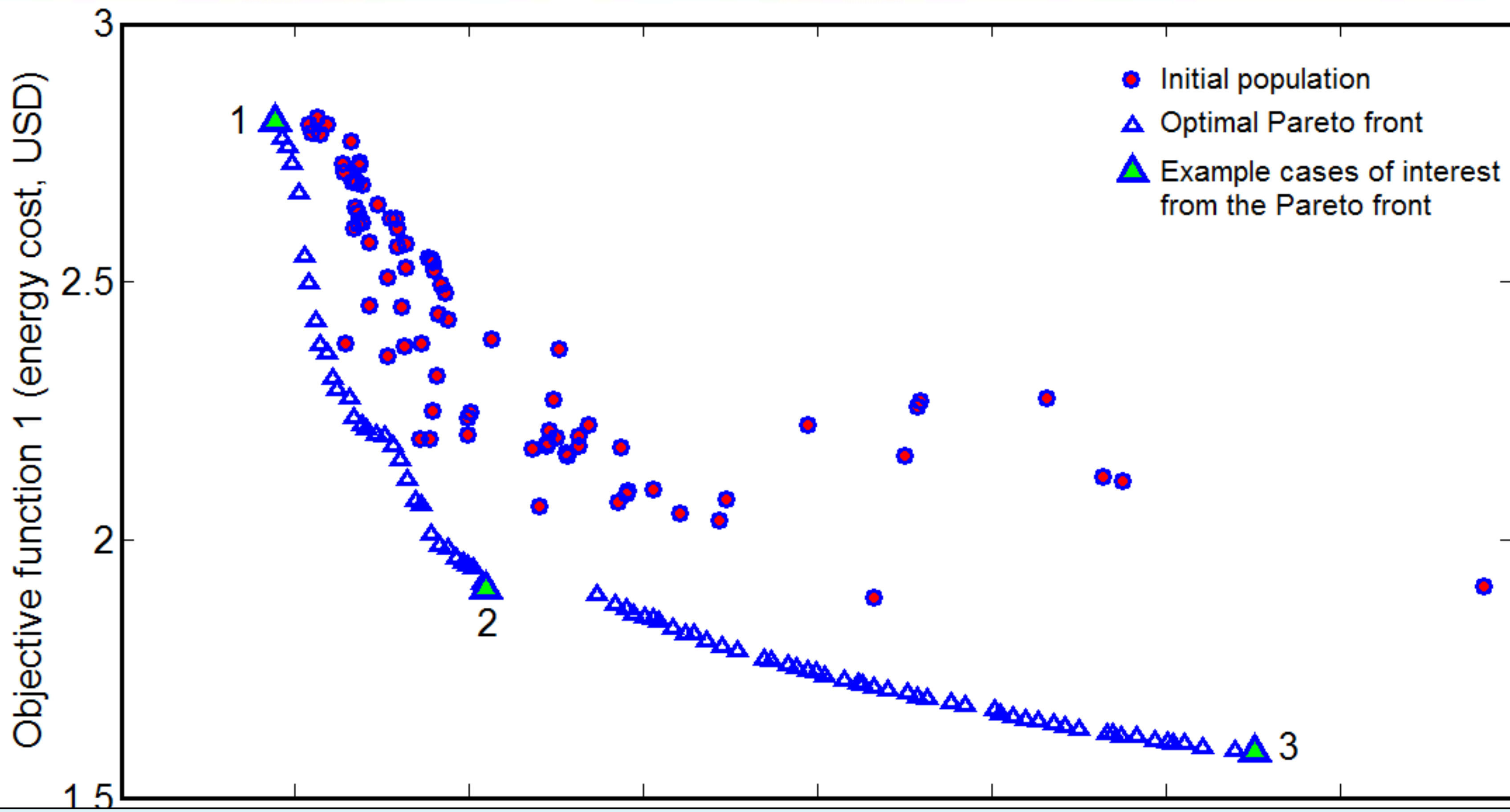
Procrastinate charging!
Do it immediately before you drive!

Objectives: fuel, electric energy cost, and battery health

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



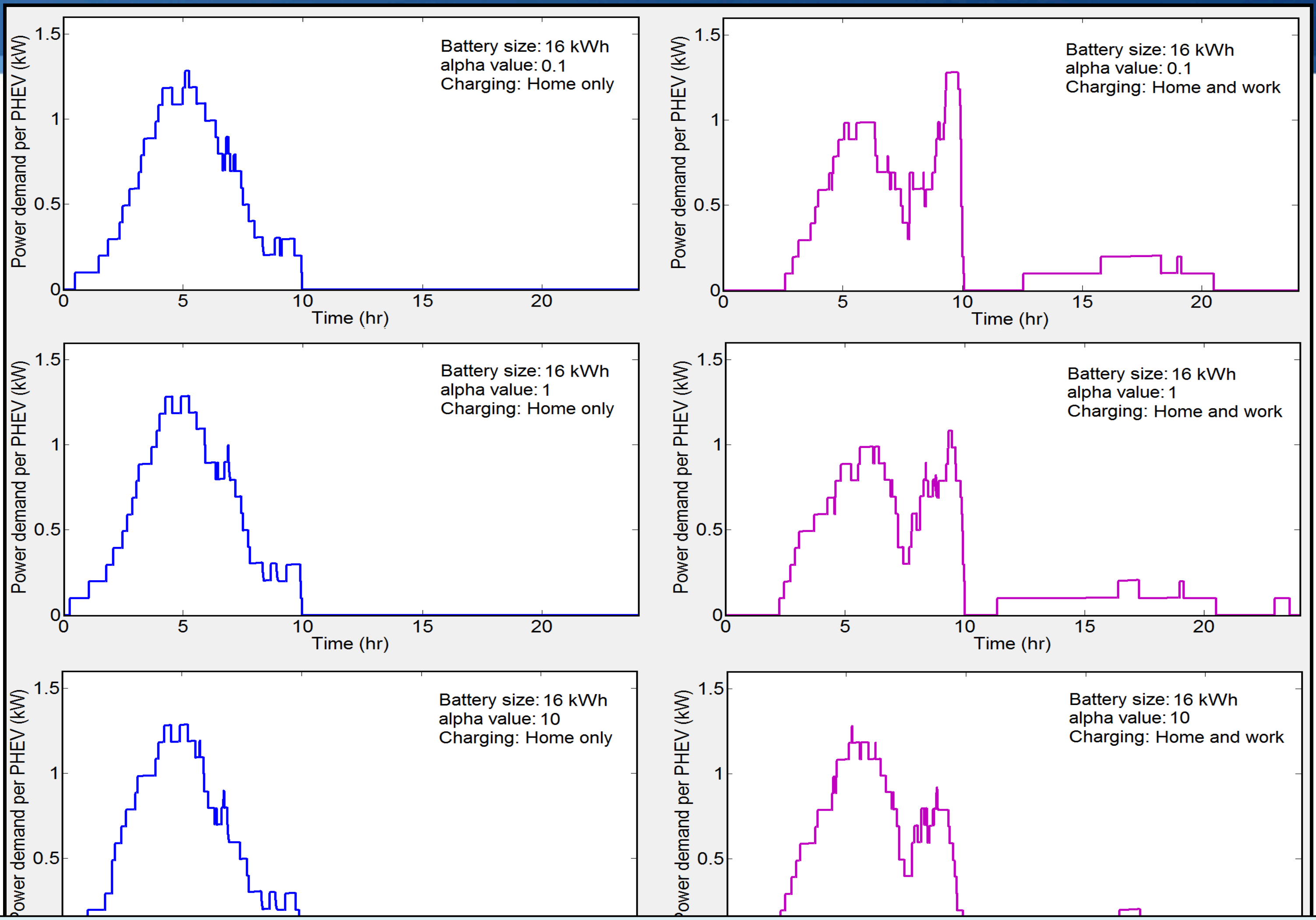
Multiobjective Optimization:
Energy Cost vs. Battery Resistive Film Growth



<u>Publications</u>

- 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

Research Objective

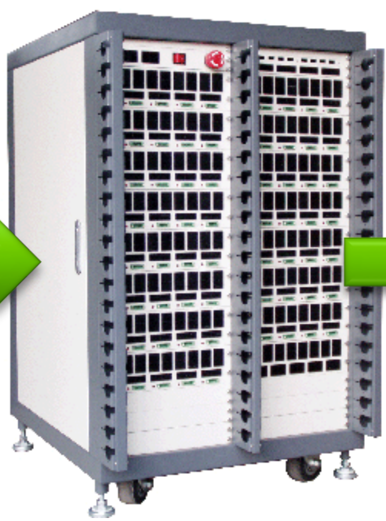
Develop practical extensions of LQR and optimal estimation results for distributed parameter systems

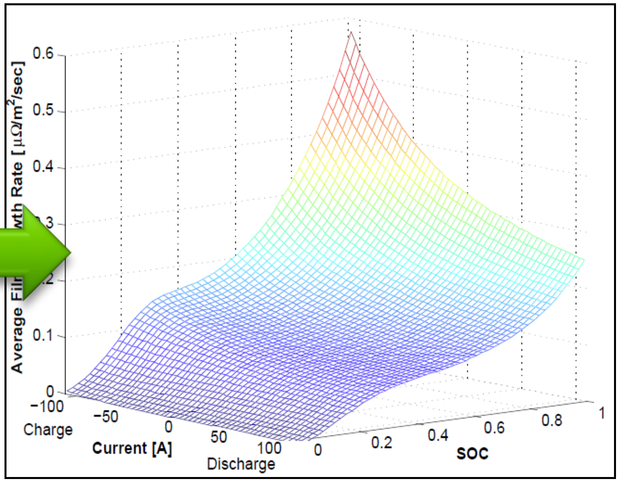
- Boundary control & estimation in advanced batteries and fuel cells
- Distributed control & estimation in intelligent building systems
- Control & estimation in stochastic distributions of PEV's and grid loads / generators

Ongoing / Future Work:
Data-driven Health Degradation Modeling of Li-ion Batteries

Collaborative work with Joel Forman, Prof. Jeff Stein, Prof. Huei Peng (U-Michigan) and Professor Hosam Fathy (Penn State Univ.)

Develop data-driven models of health degradation in $LiFePO_4$ batteries through intelligently designed multi-channel cycling.





Ongoing / Future Work:
Extremum Seeking Methods in Photovoltaics and Fuel Cells

Collaborative work with Andy Chang (National Instruments)

Develop real-time control systems that adaptively identify the optimum operating point.

- Lyapunov-based extremum seeking algorithms
- Air flow control in PEM fuel cells
- Maximum power point tracking in photovoltaics

Publications

- **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.
- Y. A. Chang, **S. J. Moura**, "Air-Flow Control in Fuel Cell Systems: An Extremum Seeking Approach," *Proceedings of the 2009 American Control Conference*, pp 1052-1059, St. Louis, MO, 2009.

Ongoing / Future Work:
Optimal Power Management in Vehicle to Grid Infrastructures

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

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

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.
- 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.

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