Battery Health Conscious Power Management in Plug-in Hybrid Electric Vehicles via Electrochemical Modeling & Stochastic Control

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Ph.D. Candidate
Department of Mechanical Engineering
University of Michigan, Ann Arbor, USA

A Seminar Presentation at:

Tesla Motors

Friday March 4, 2011

About me: Education & Work Experience

- Education
  - Ph.D. Mechanical Engineering (Apr 2011)
    University of Michigan, Ann Arbor
  - M.S.E. Mechanical Engineering, Ann Arbor (Dec 2008)
    University of Michigan, Ann Arbor
  - B.S. Mechanical Engineering (May 2006)
    University of California, Berkeley
- Work Experience
  - DaimlerChrysler Corporation (Electric Engineering)
  - Ford Motor Company (Manufacturing)
  - Southern California Edison (Staff Engineering)

Publications

Peer-Reviewed Journals (Accepted)

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.

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.

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.

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 (In Review or In Preparation)

S. Bashash, S. J. Moura, and H. K. Fathy, "On the Aggregated Grid Load Imposed by Battery Health-Conscious Charging of Plug-in Hybrid Electric Vehicles," (in review).

S. J. Moura, J. L. Stein, and H. K. Fathy, "Battery Health Conscious Power Management in Plug-in Hybrid Electric Vehicles via Electrochemical Modeling and Stochastic Control," (in review).

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 $LiFePO_4$ Battery and Fisher Information" (in preparation).

S. J. Moura and Y. A. Chang, "Lyapunov-Based Switched Extremum Seeking for Maximum Power Point Tracking in Photovoltaic Systems," (in preparation).

S. J. Moura, J. B. Siegel, H. K. Fathy, A. G. Stefanopoulou, "Education on Vehicle Electrification: Battery Systems and Control," (in preparation).

S. J. Moura, J. L. Stein, and H. K. Fathy, "Optimal Boundary Control and Estimation of Diffusion-Reaction PDEs," (in preparation).

Conferences Proceedings

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.

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)

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.

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**

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.

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. 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.

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.

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.

S. J. Moura, H. K. Fathy, "Optimal Boundary Control & Estimation of Diffusion-Reaction PDEs," *Proceedings of the 2011 American Control Conf.*, San Francisco, CA, 2011. **Best Student Paper Finalist**

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.

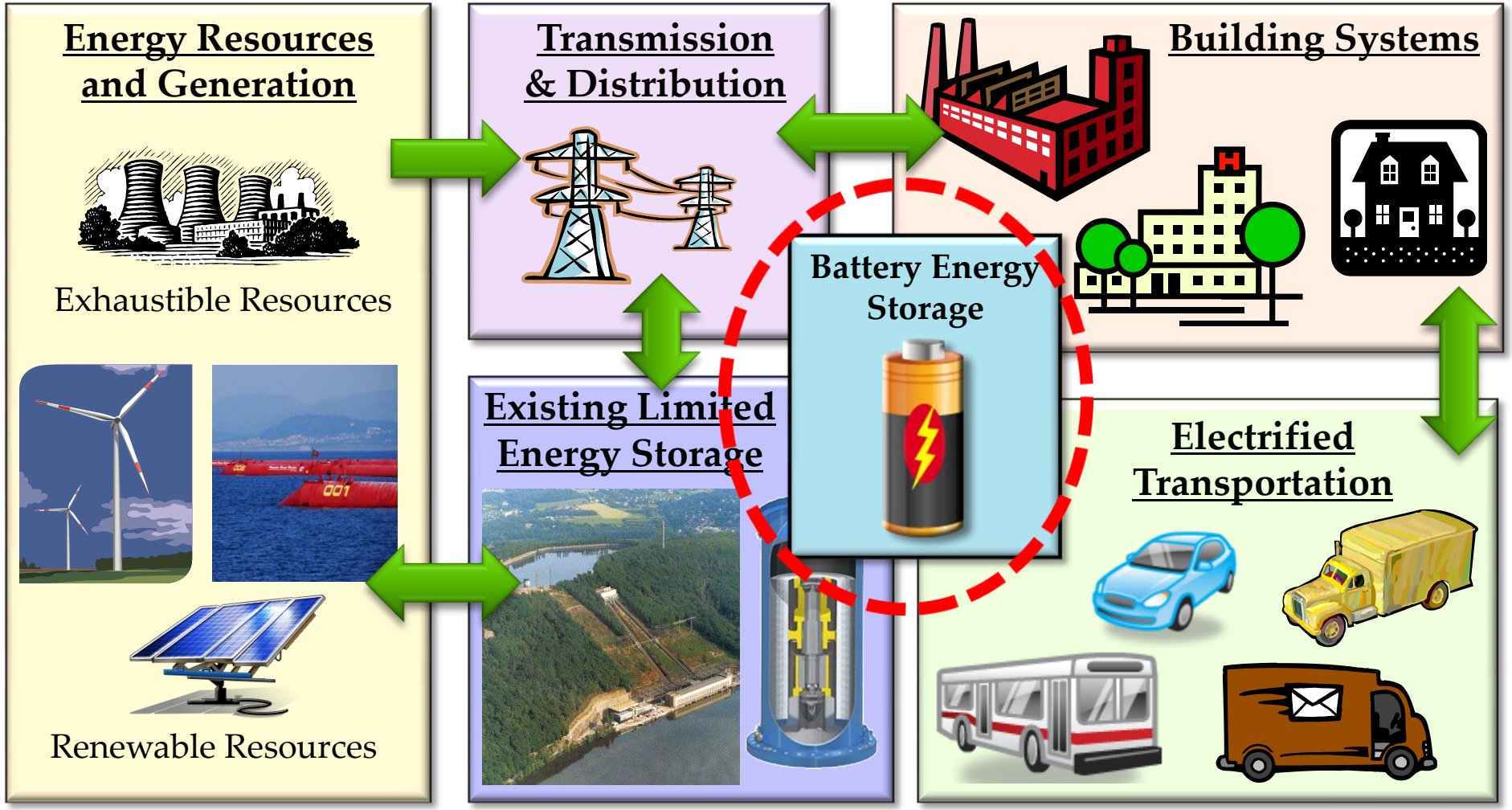
Relevant Honors

- 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
  - 2009 ASME Dynamic Systems and Control Conference
  - 2011 American Control Conference
- 1st Place Technical Paper Competition
  - 2008 Society of Hispanic Professional Engineers Conference

My Technical Interests

- Fundamental
  - Optimal control
  - Dynamic system modeling
  - Distributed parameter systems
- Applied
  - Sustainable & alternative energy storage/conversion systems
  - Advanced battery systems
  - Vehicle Electrification
  - Vehicle-to-grid applications

Vision of Future Energy Infrastructure



Key Research Topics

Electrochemical Battery Modeling

- Mathematical modeling based on first principles
- Experimental identification

PHEV Power Management

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

Key Research Topics

Electrochemical Battery Modeling

- **Mathematical modeling based on first principles**
- **Experimental identification**

PHEV Power Management

- PHEV powertrain and daily drive cycle modeling
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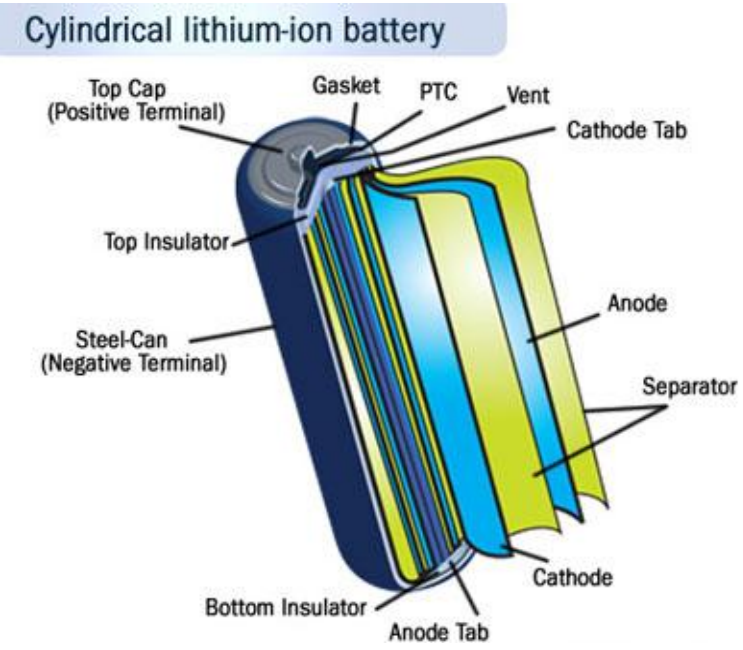
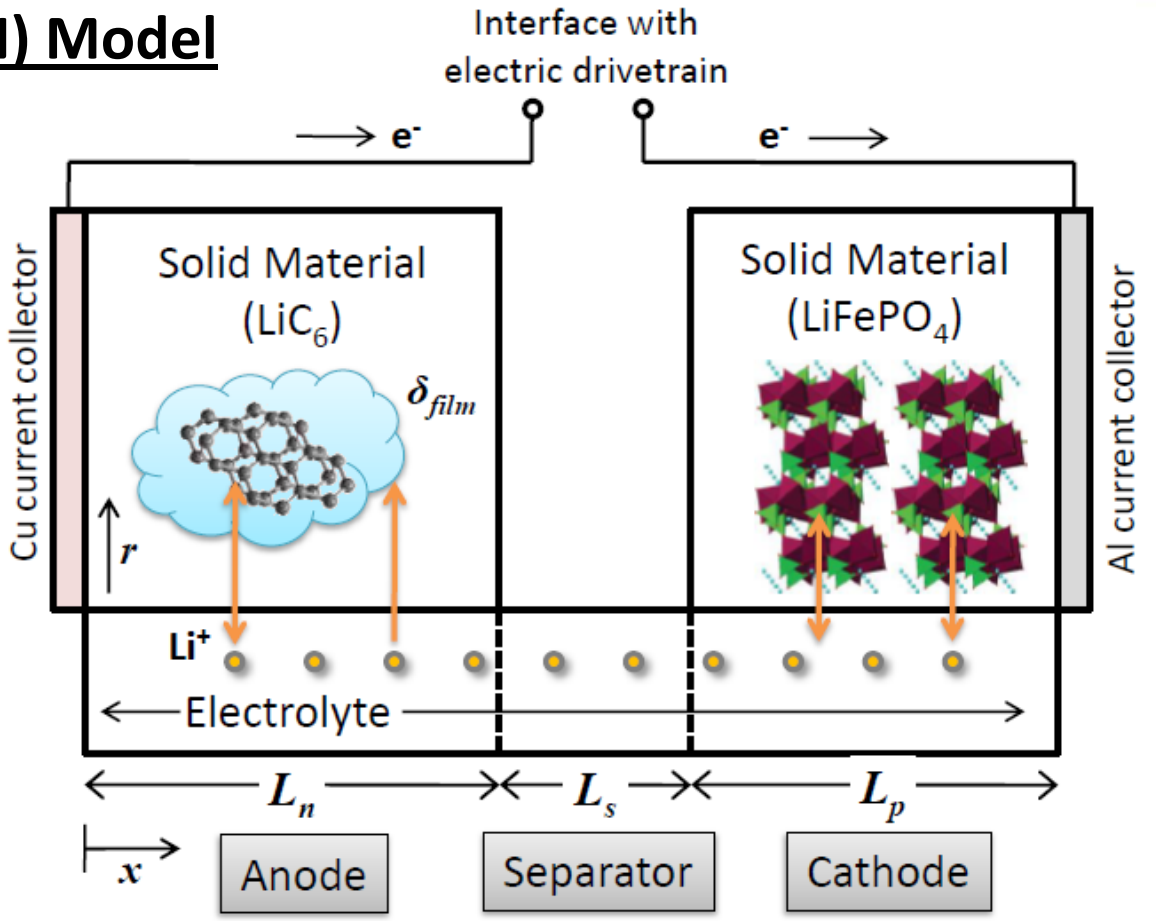
Electrochemical Li-ion Battery Modeling

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

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

Spherical diffusion

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

Linear diffusion

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

Resistive film growth

AE's

$$J_j(x,t) = \sigma_j^{eff}\frac{\partial^2 \phi_{1,j}}{\partial x^2}(x,t)$$

Ohm's Law

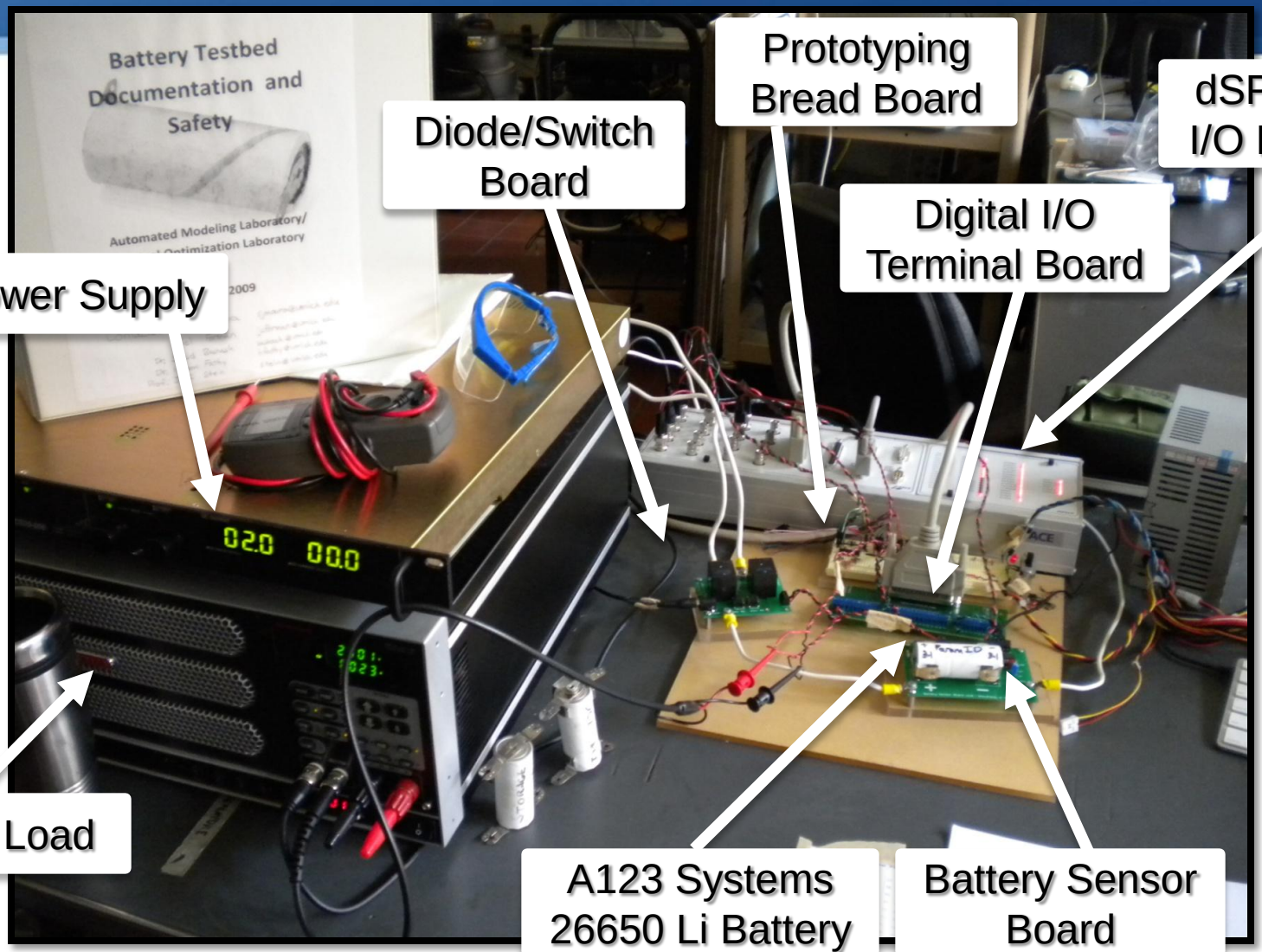
$$J_j(x,t) = \frac{\partial}{\partial x}\left(\kappa^{eff}\frac{\partial \phi_{2,j}}{\partial x}(x,t)\right) + \frac{\partial}{\partial x}\cdot\left(\kappa\frac{\partial \ln c_{2,j}}{\partial x}(x,t)\right)$$

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

Butler-Volmer Kinetics

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

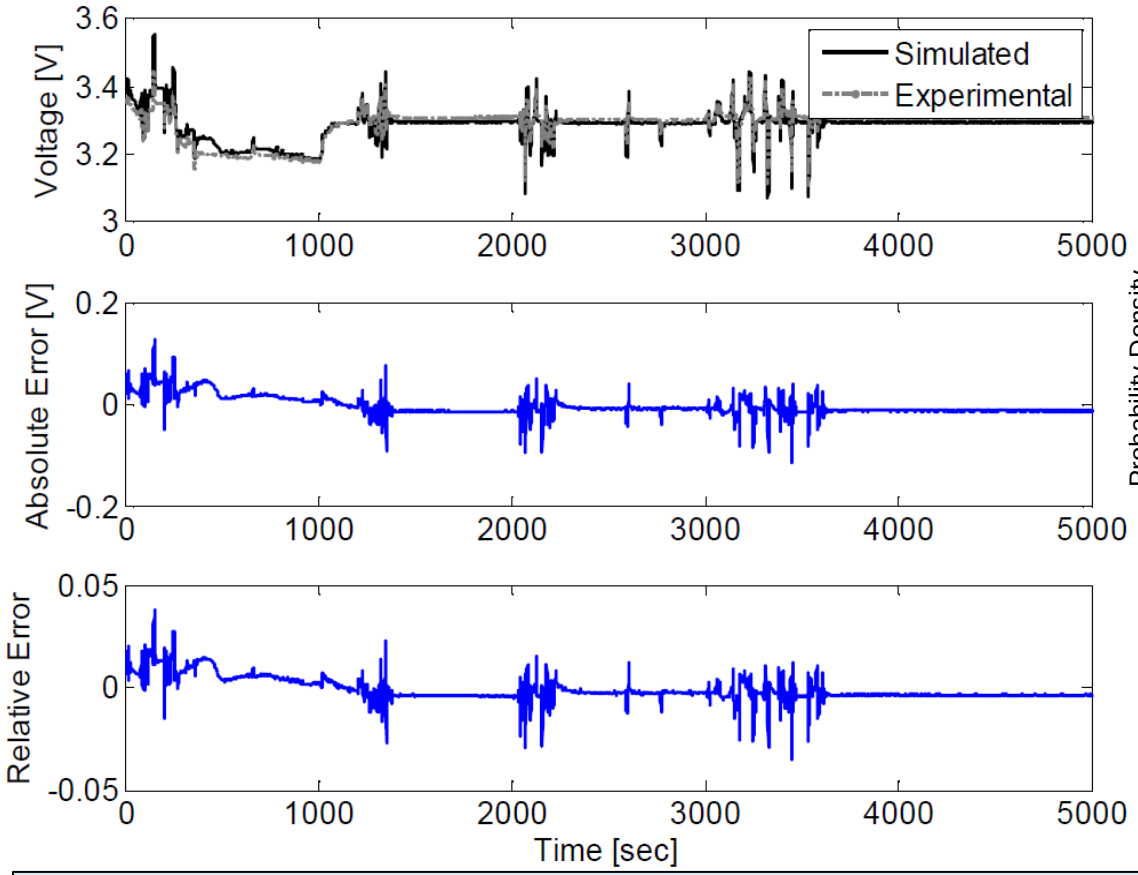
Battery-in-the-loop Hardware



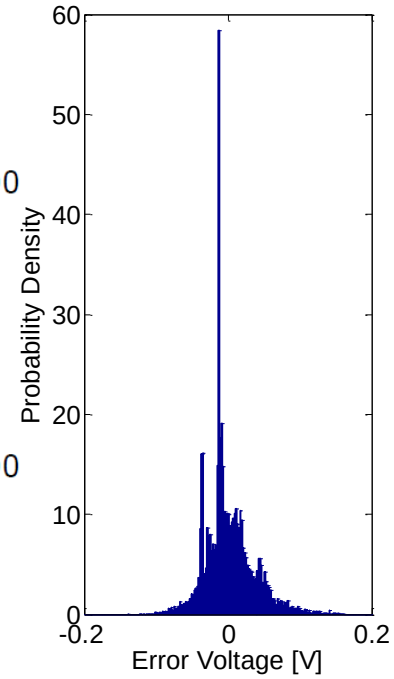
Parameter Identification Results

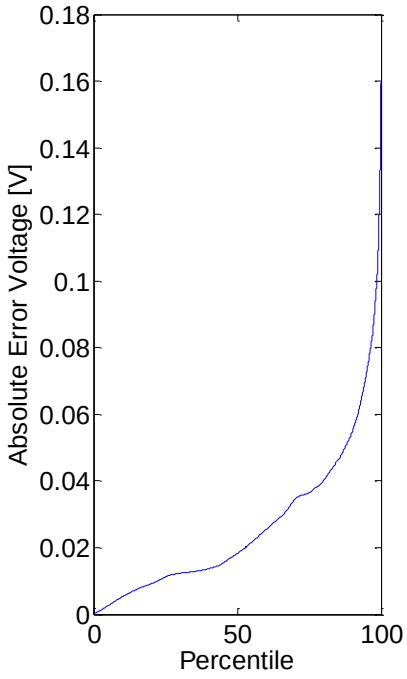
collaborative effort with Joel Forman, Ph.D. Candidate @ U-M

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.

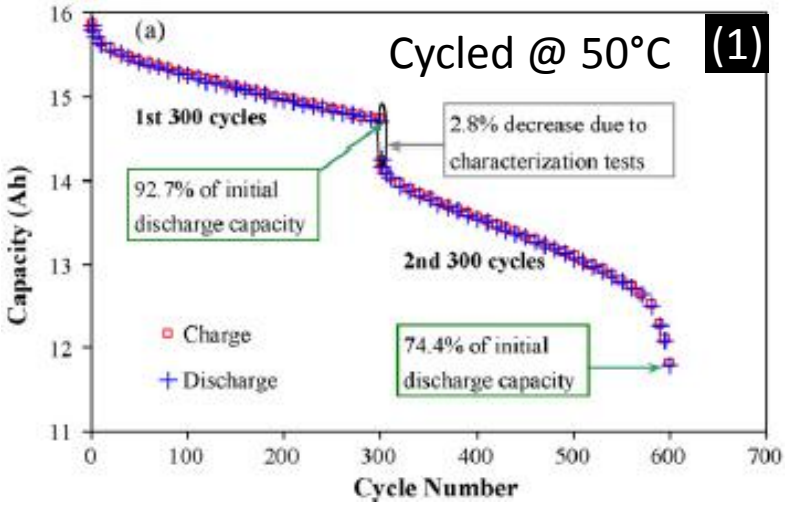
Capacity Fade in C-$LiFePO_4$ Cells

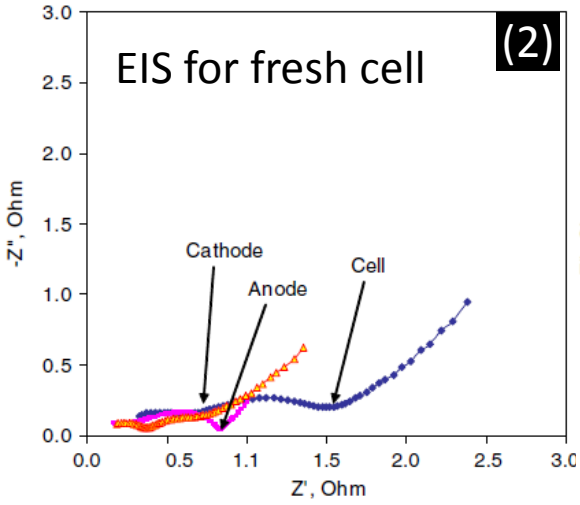
Cau

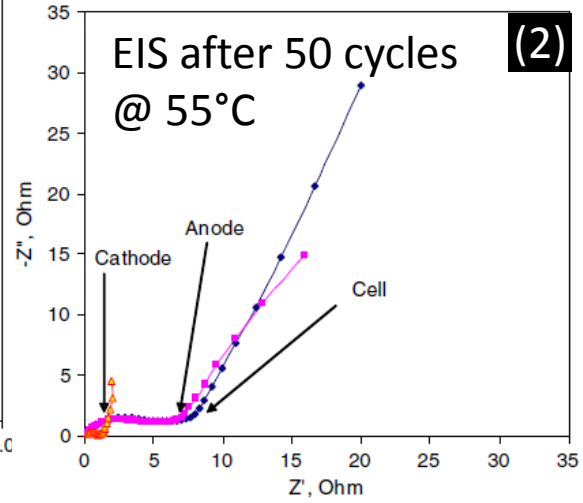
- S
- I
- A
- T

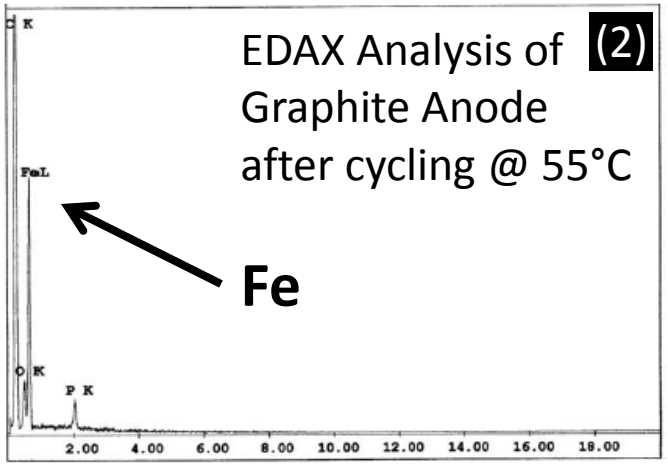
System-Level Relations to Aging

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









(1) Zhang, Wang Tang, *Journal of Power Sources*, 2011.
(2) Amine, Liu, Belharouak, *Electrochemistry Communications*, 2005

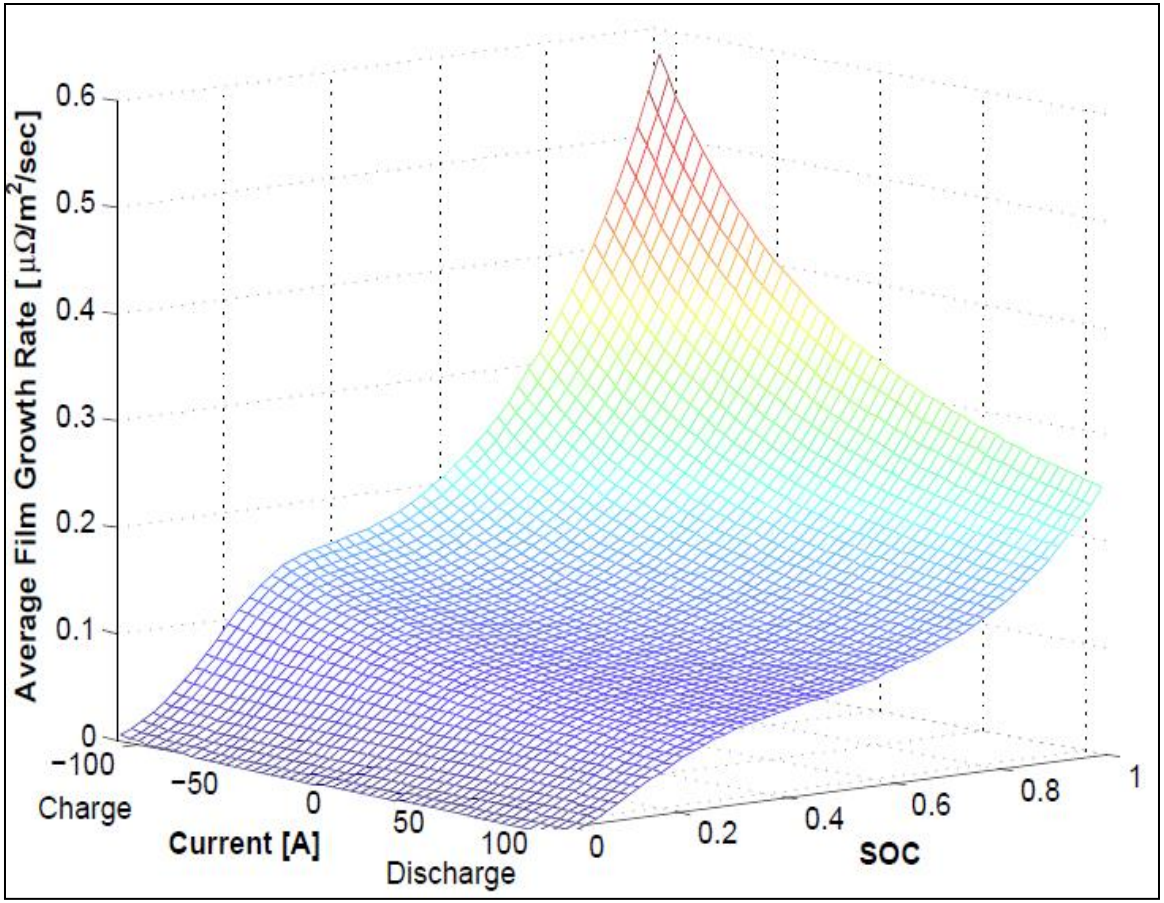
Anode-Side SEI Film Buildup

Ramadass et al, 2004

Hypothesize a solvent reduction reaction at the solid/electrolyte interface, which forms a resistive SEI layer.

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

Approximate this mechanism by instantaneous rate of film growth, for a fresh rested cell

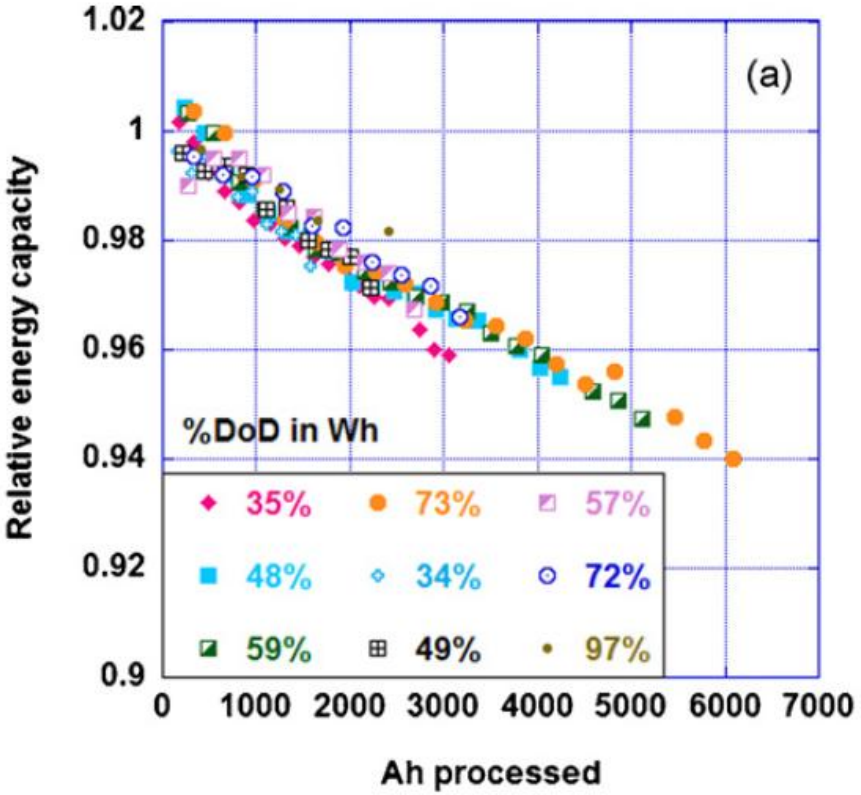


Ah Processed

Empirical model for C-LiFePO$_4$ cells

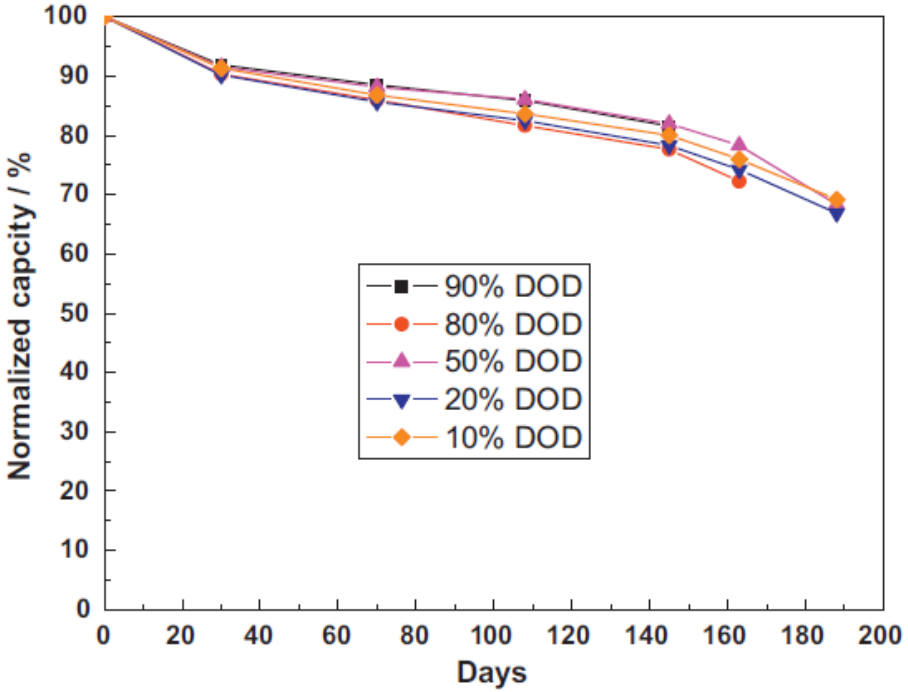
Key Idea: min total Ah-processed!

Scaled PHEV drive cycle load with C-rates ranging from -3C to +1C, Ambient Room Temp.



Peterson *et al., Journal of Power Sources,* 2010

Constant current cycles @ C/2, 60°C



Wang *et al., Journal of Power Sources,* 2011

Key Research Topics

Electrochemical Battery Modeling

- Mathematical modeling based on first principles
- Experimental identification

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

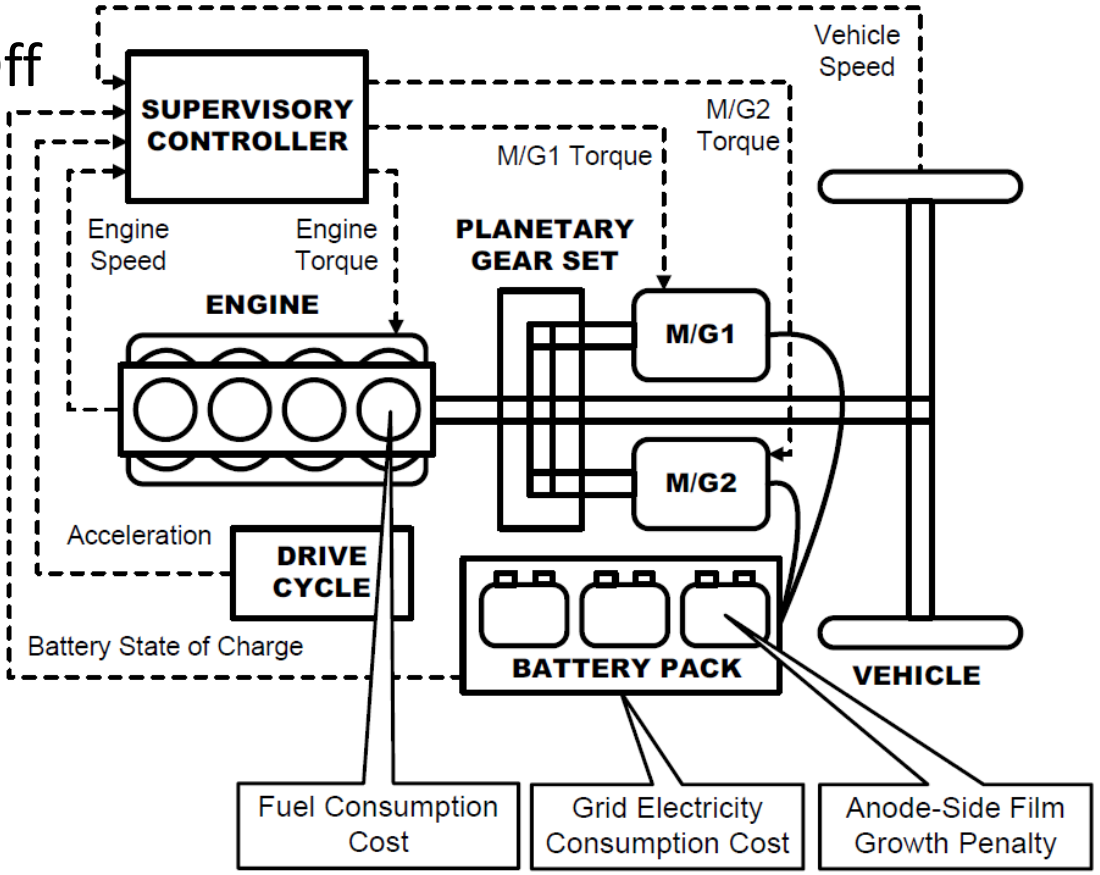
J. Voelcker, "Plugging Away in a Prius," *IEEE Spectrum*, vol. 45, pp. 30-48, 2008.

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.
- **S. J. Moura**, J. L. Stein, and H. K. Fathy, "Battery Health Conscious Power Management in Plug-in Hybrid Electric Vehicles via Electrochemical Modeling and Stochastic Control" *in review.*

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

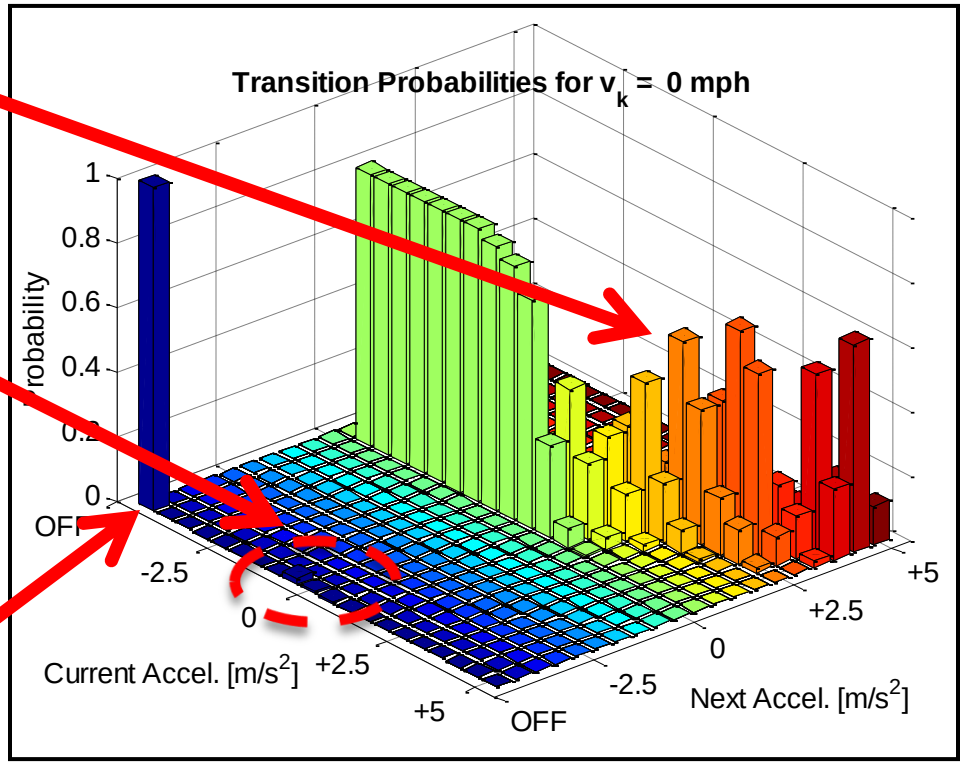
$$p_{ijm} = \Pr(a_{k+1} = j \mid a_k = i, v_k = m)$$

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

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

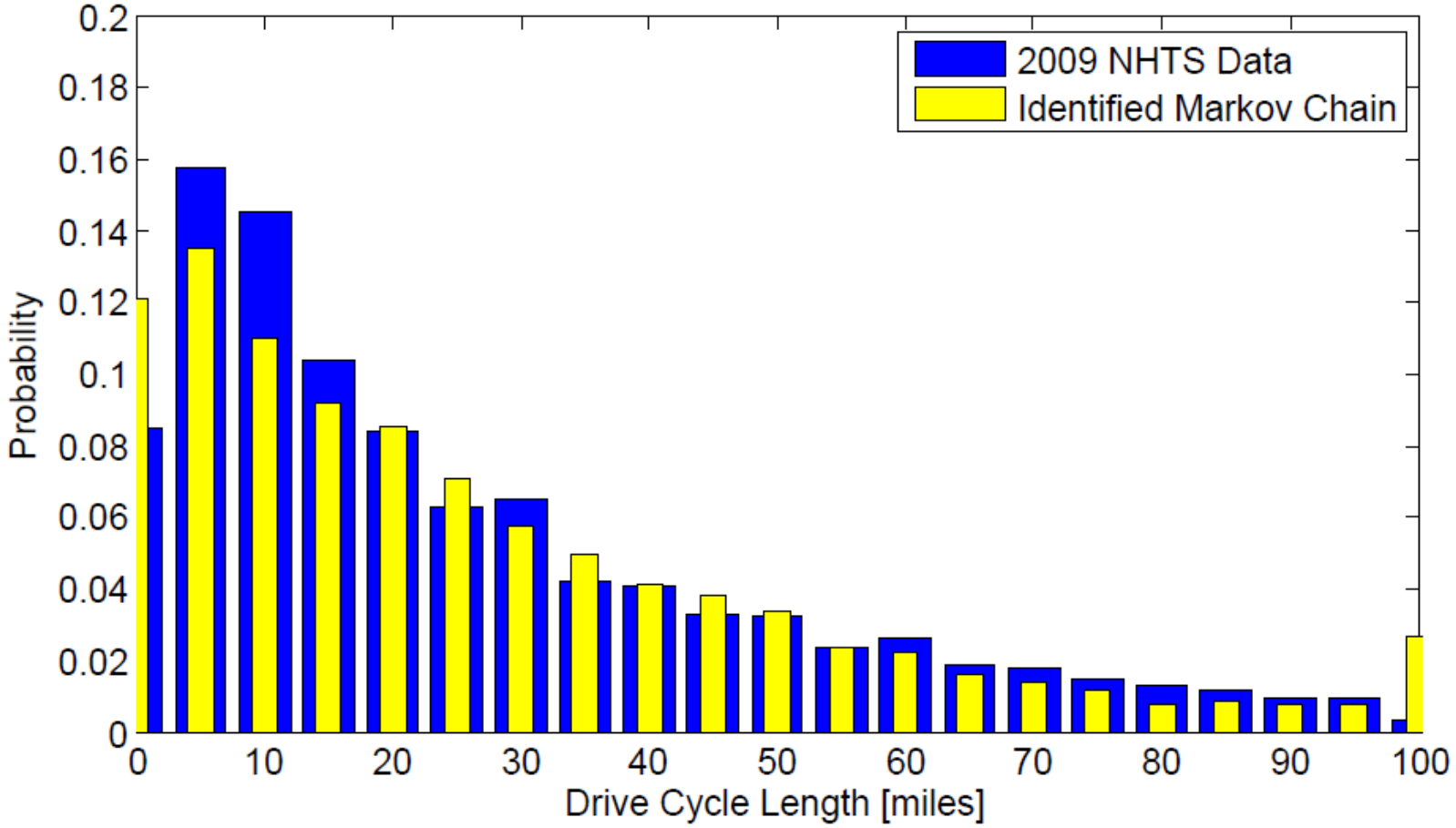
Absorbing state "vehicle off"

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



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:

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

where

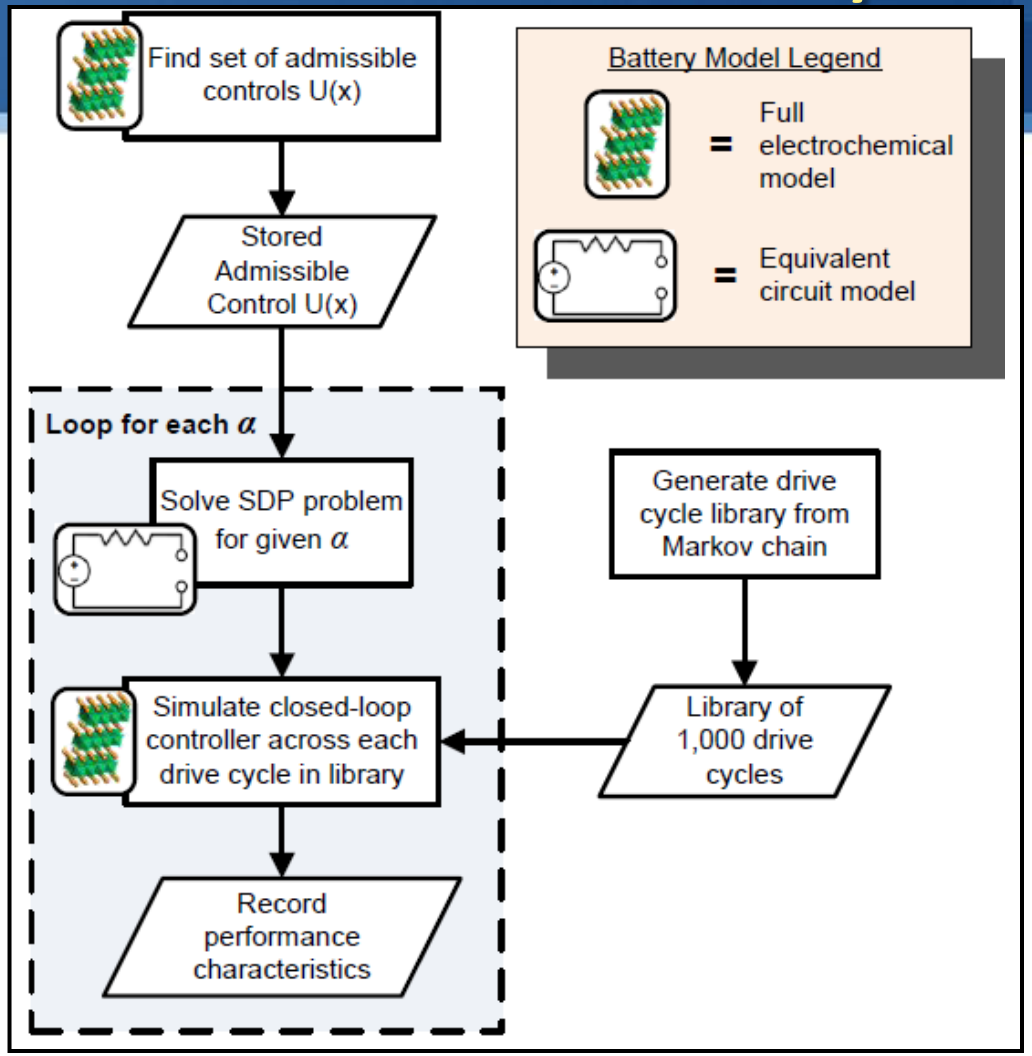
$$c_{energy}(x_k, u_k) = \beta\alpha_{fuel} W_{fuel} + \alpha_{fuel}\frac{-V_{oc} Q_{batt} \dot{SOC}}{\eta_{grid}}$$

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

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

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

Battery-Health Conscious Analysis Procedure

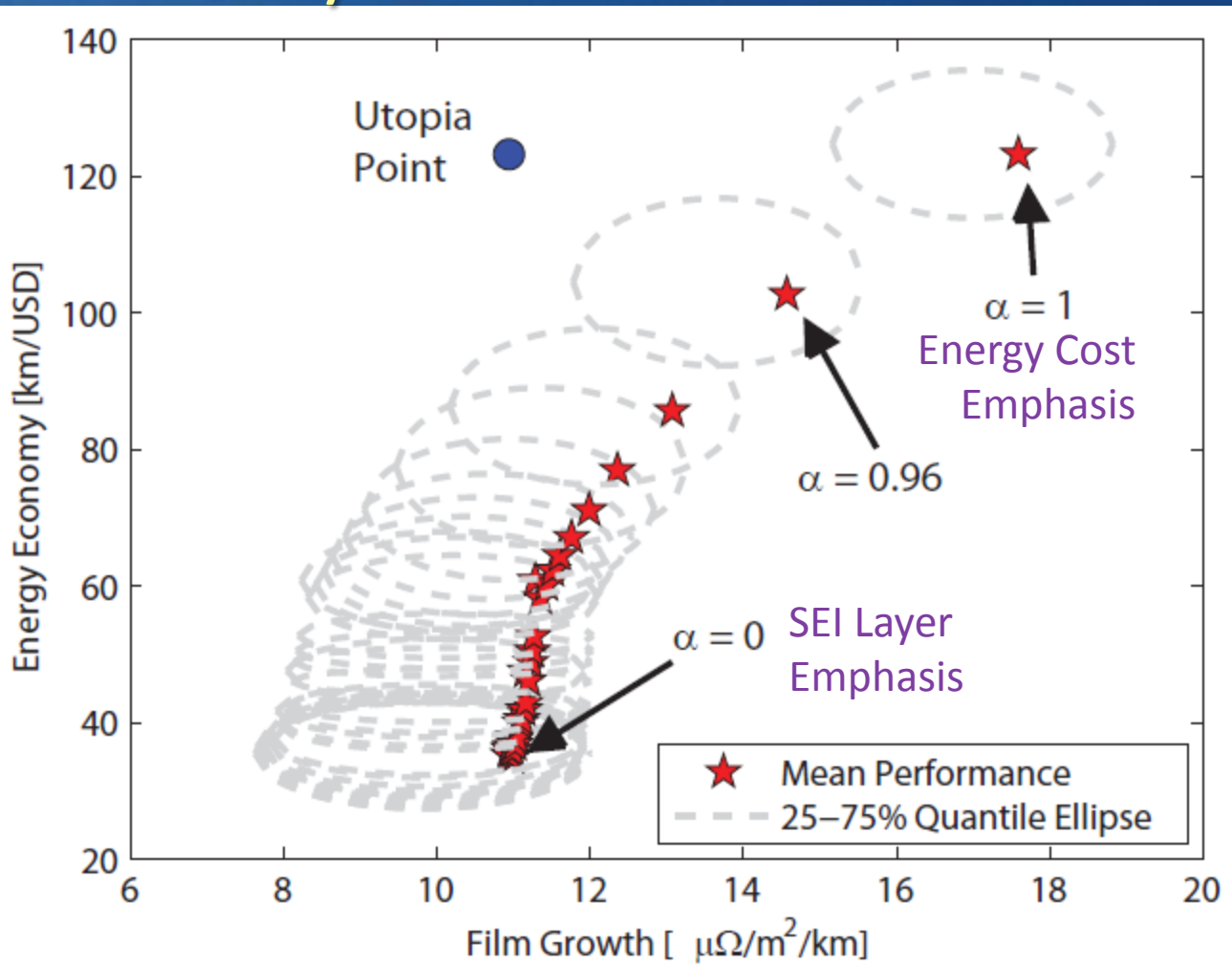


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{health}(x_k, u_k)$$

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.

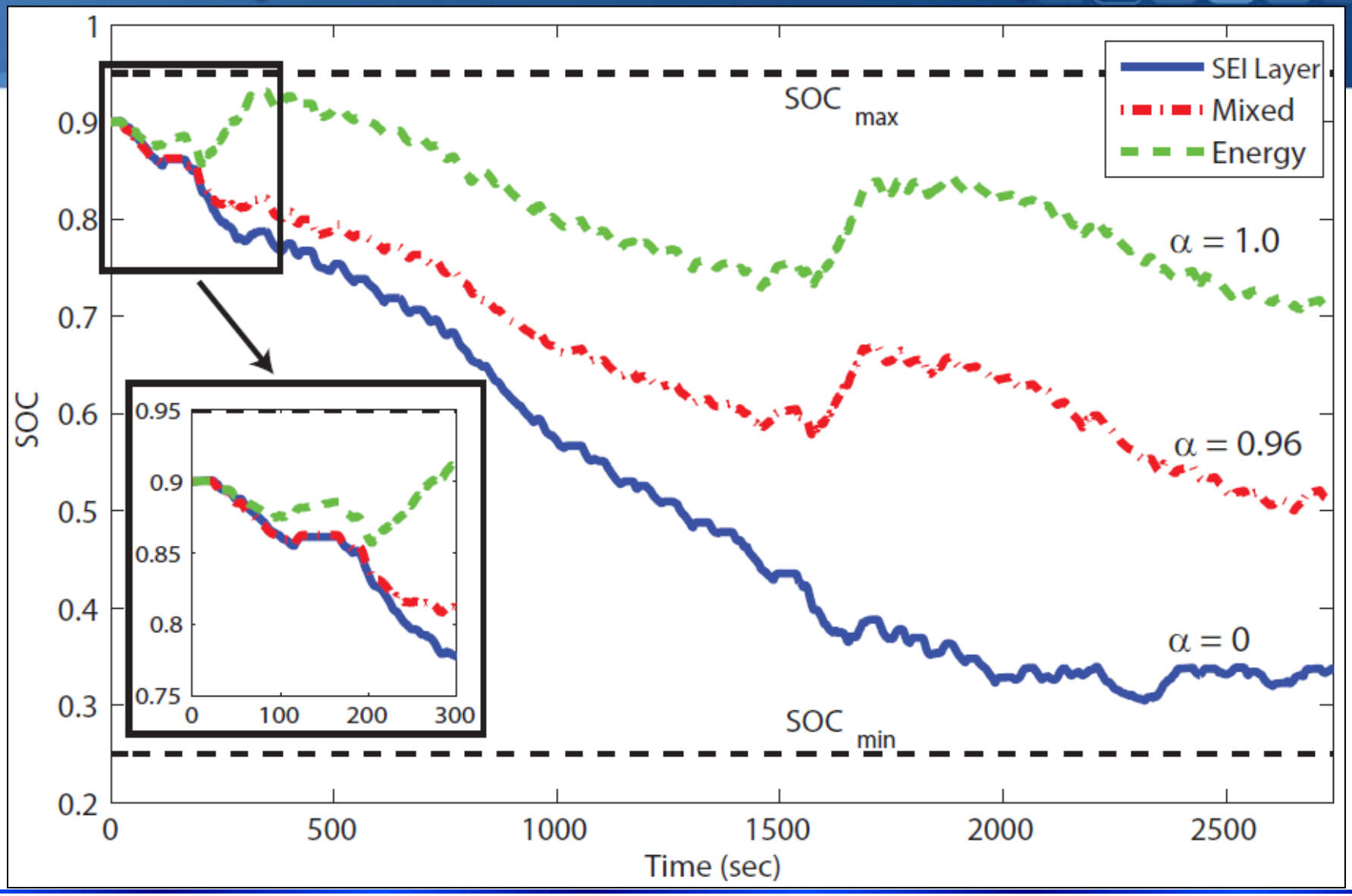
Pareto Set of Optimal Solutions

Anode-side SEI layer Growth

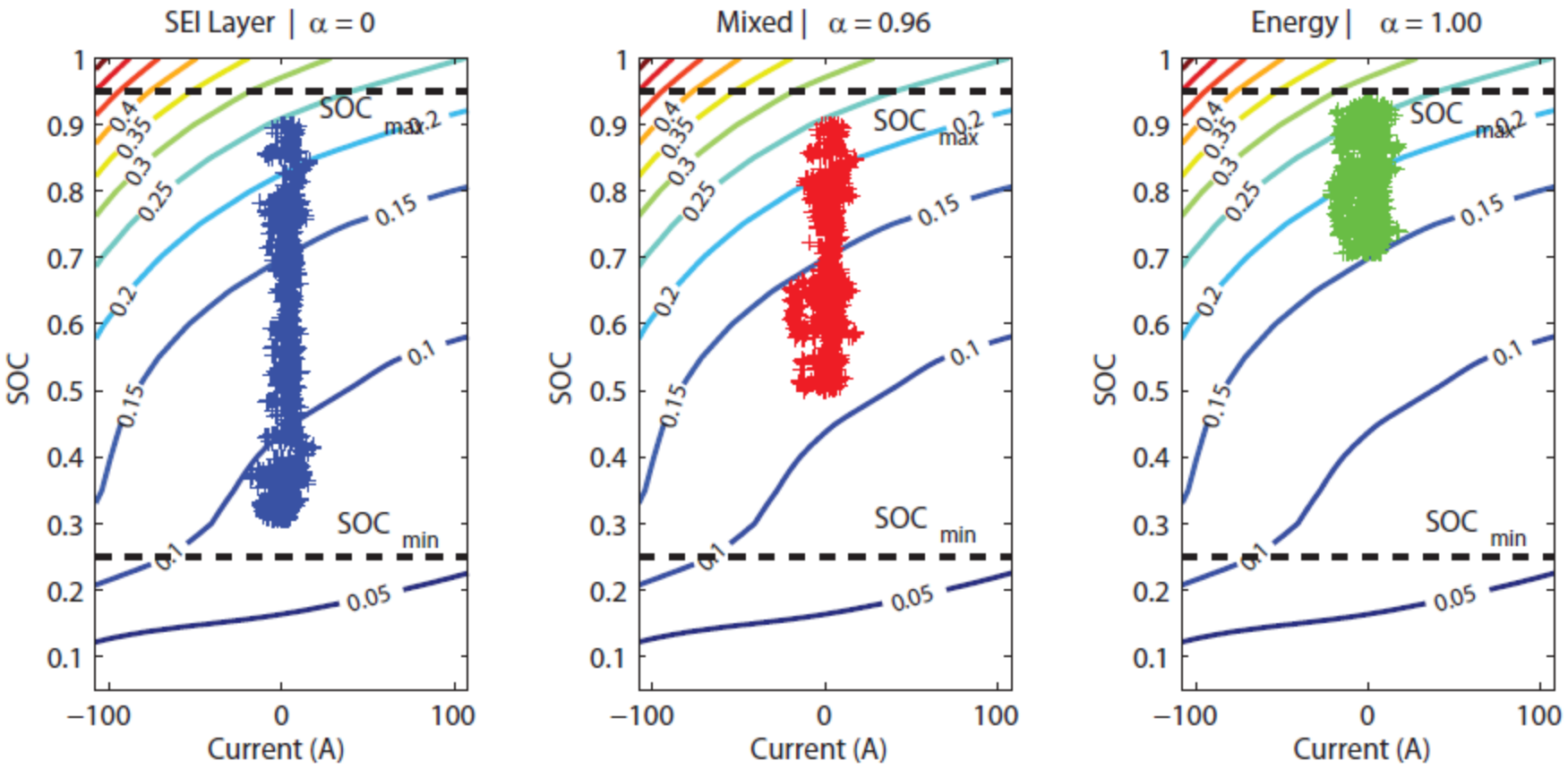


$$c(x_k,u_k)=\alpha\cdot c_{energy}(x_k,u_k)+(1-\alpha)\cdot c_{film}(x_k,u_k)$$

SOC Trajectories for Min SEI Layer



Film Growth Map Operating Points



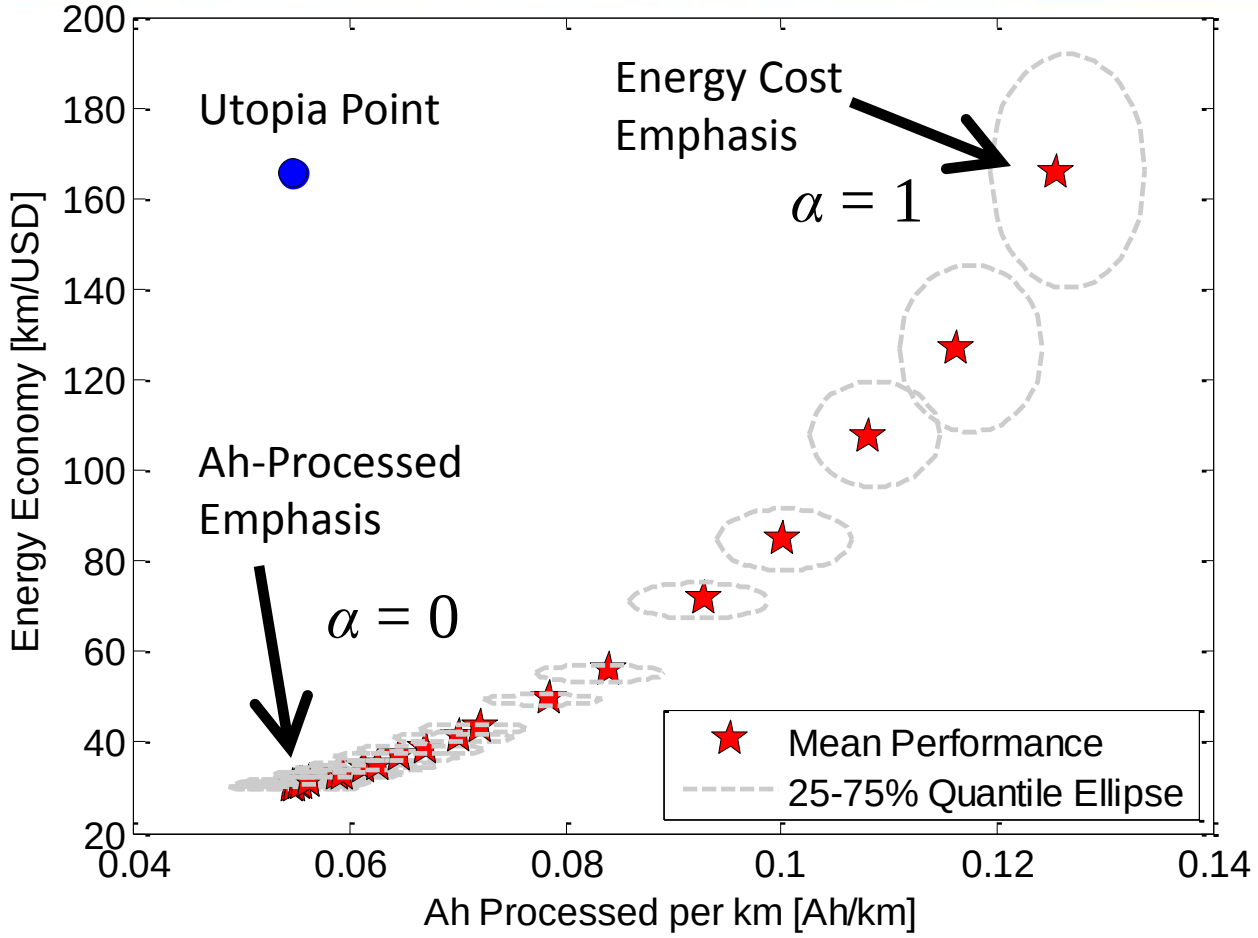
Aggressively deplete battery charge to reduce film growth

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

Conservatively ration charge to reduce charge sustenance

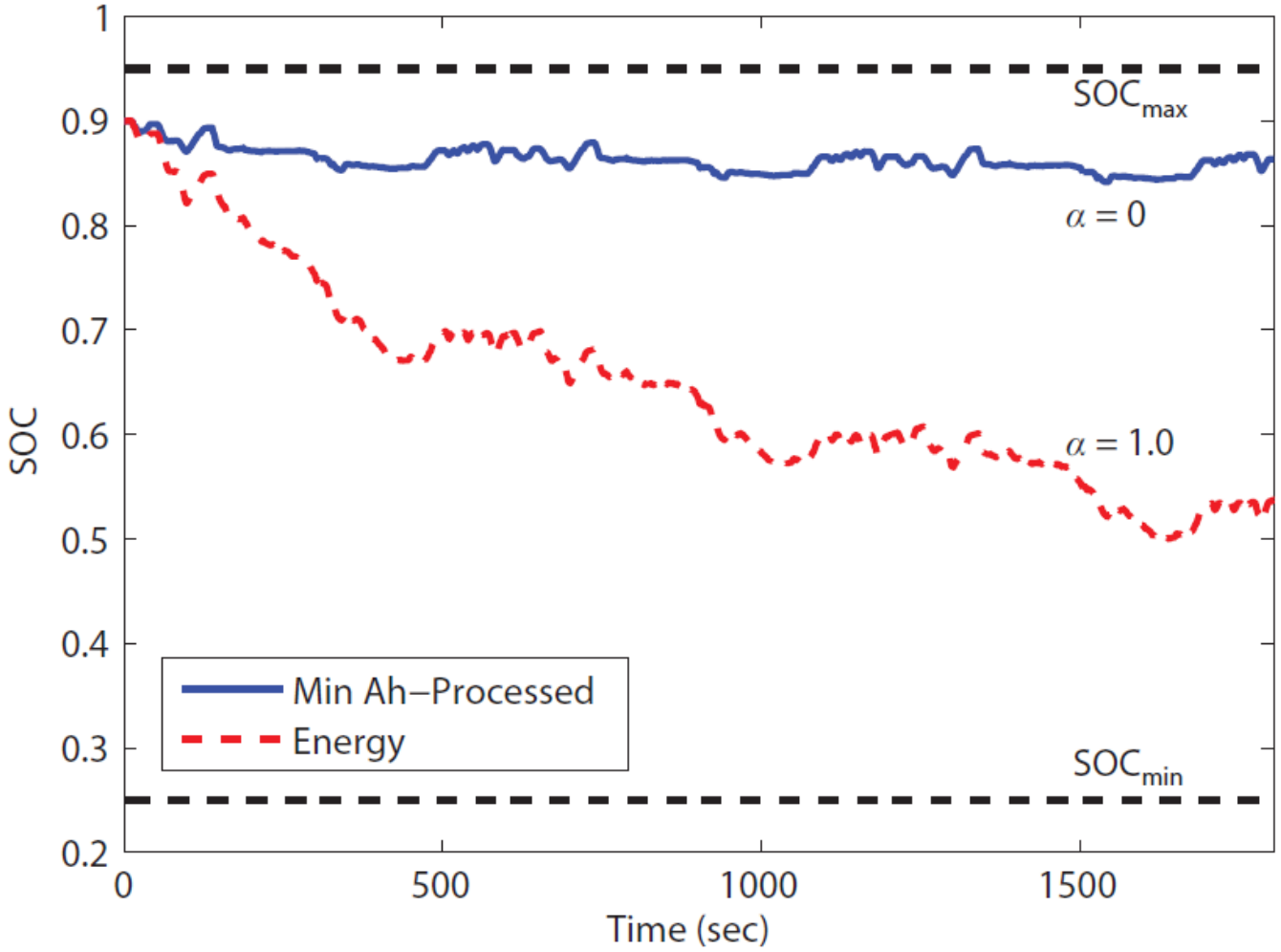
Pareto Set of Optimal Solutions

Ah Processed

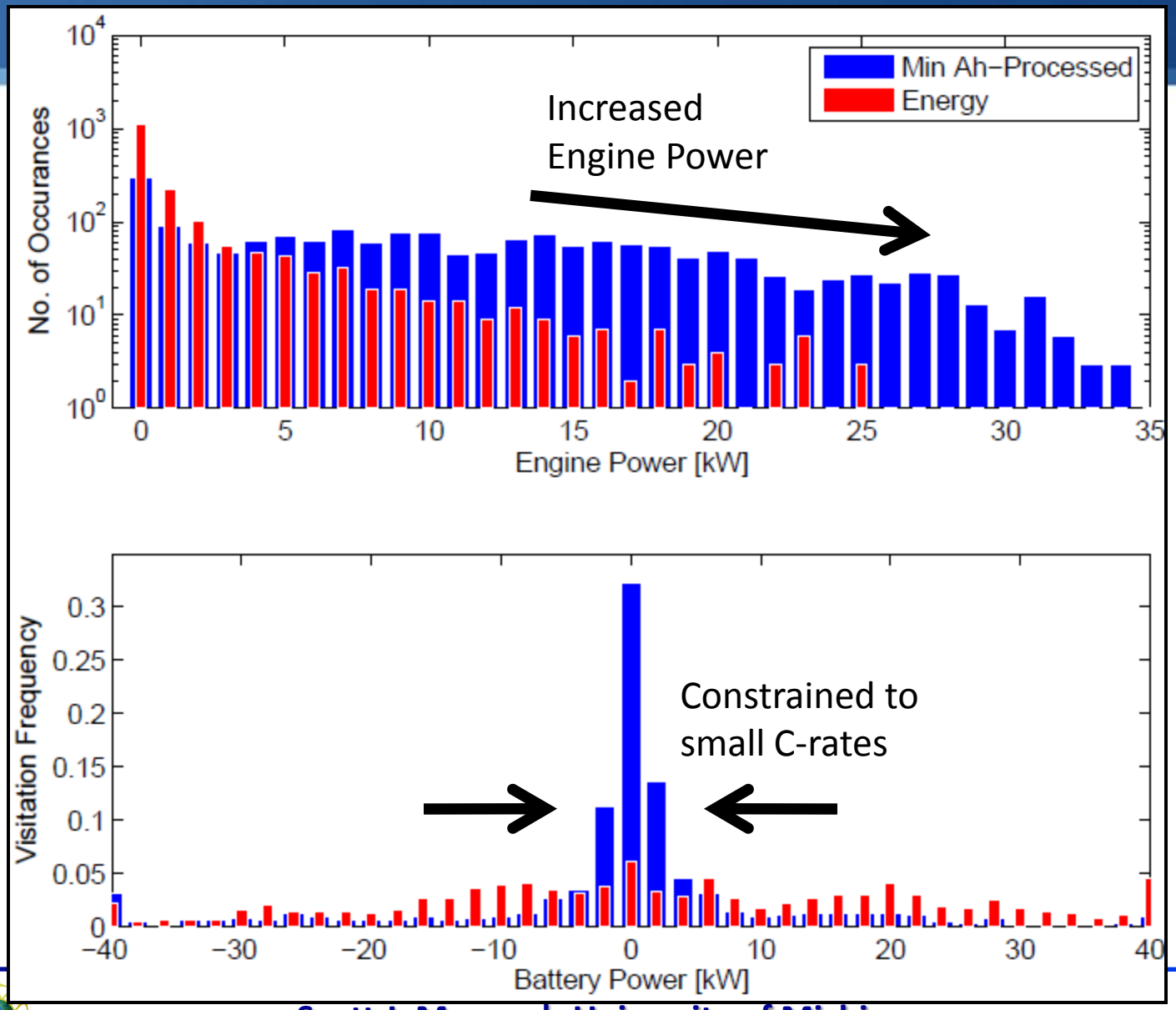


$$c(x_k, u_k) = \alpha \cdot c_{energy}(x_k, u_k) + (1-\alpha) \cdot c_{Ah}(x_k, u_k)$$

SOC Trajectories for Min Ah-Processed



Engine & Battery Power Distributions

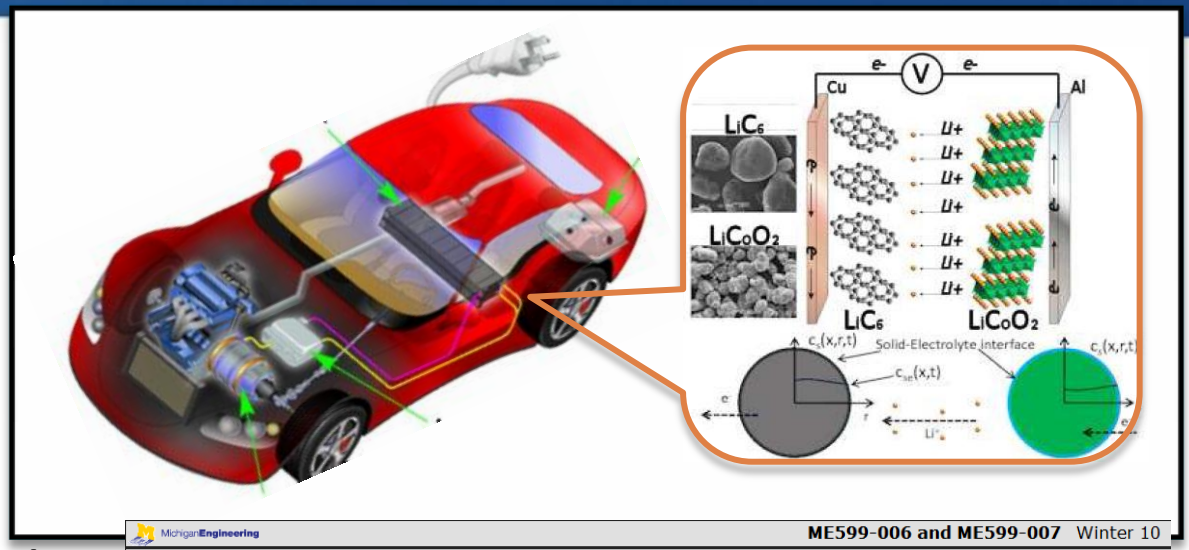


Seminar Summary

- Battery Modeling and Experimentation
  - Modeling battery electrochemical dynamics from first principles
  - Battery-in-the-loop tester for parameter ID and control design
- Power Management in Plug-in Hybrid Electric Vehicles
  - Stochastic drive cycle modeling
  - Multi-objective, constrained
  - Fundamental tradeoffs between energy consumption and battery health

Battery Systems and Control Course:

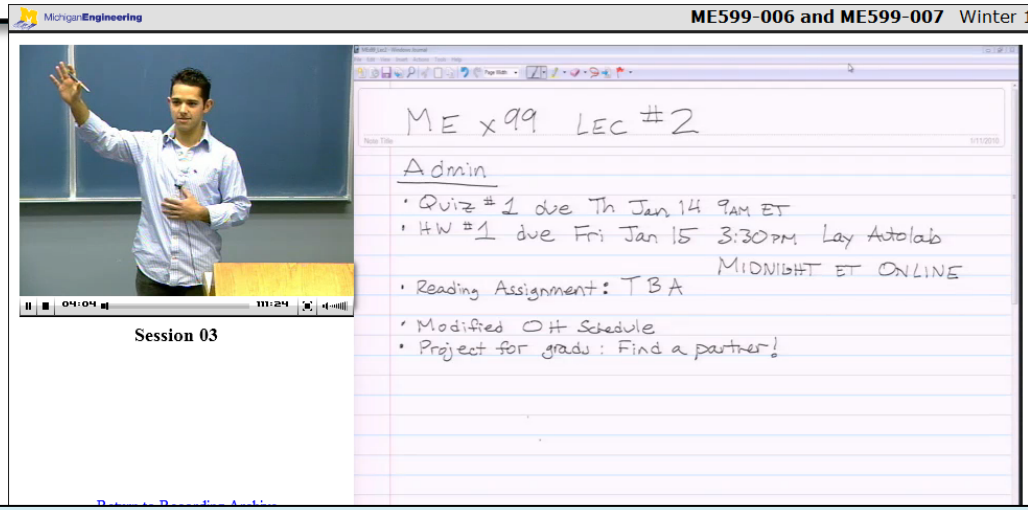
Funded by DOE-ARRA Advanced Electric Drive Vehicle Education Program



Student Enrollment

- **W'10:** 59 / 5 distance
- **W'11:** 43 / 25 distance
  - Undergrads
  - Graduates
  - Professionals
    - Tesla Motors (Jacob Oberlin and Mark Pokora)
    - General Motors (Volt battery engineers)
    - Roush, US Army TARDEC

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



Publications

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Thank you for your attention!

Questions?

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