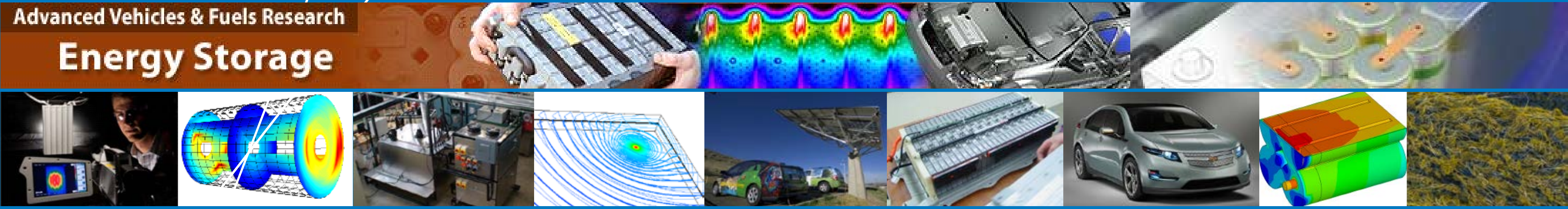
Comparison of Battery Life Across Real-World Automotive Drive-Cycles



7th Lithium Battery Power Conference

Las Vegas, NV

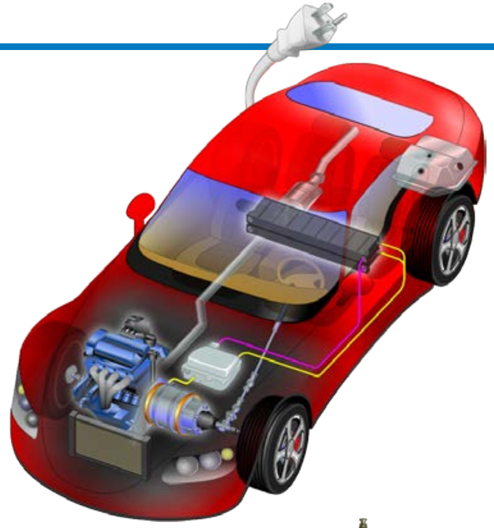
Kandler Smith, Matthew Earleywine,
Eric Wood, Ahmad Pesaran

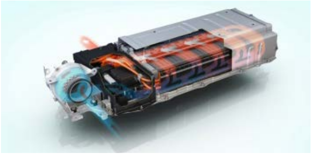
November 7-8, 2011

NREL/PR-5400-53470

Motivation

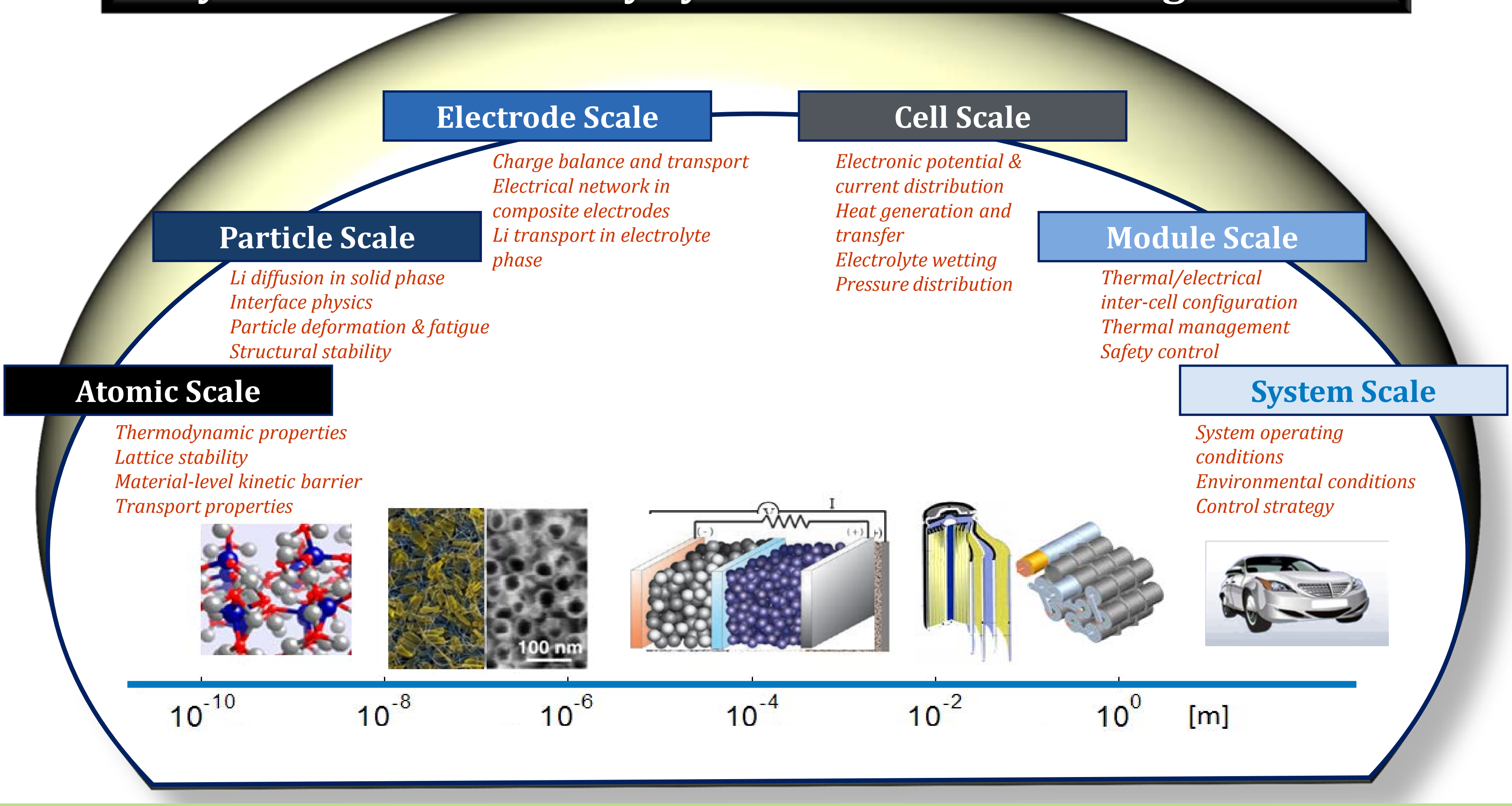
- **Overcome barriers to clean, efficient transportation**
  - Electric-drive vehicles
- **Maximize life, minimize cost of electric drive vehicle batteries (alt: maximize income)**
- **Quantify systems-level tradeoffs for plug-in hybrid vehicle (PHEV) batteries**
  - 3000-5000 deep cycles
  - 10-15 year calendar life at 35°C
  - $300/kWh at pack level
    (2014 target ~ 70% reduction)





DOE's Computer-Aided Engineering of Batteries (CAEBAT) Program Integrating Battery R&D Models

Physics of Li-Ion Battery Systems in Different Length Scales



Atomic Scale

Thermodynamic properties
Lattice stability
Material-level kinetic barrier
Transport properties

Particle Scale

Li diffusion in solid phase
Interface physics
Particle deformation & fatigue
Structural stability

Electrode Scale

Charge balance and transport
Electrical network in composite electrodes
Li transport in electrolyte phase

Cell Scale

Electronic potential & current distribution
Heat generation and transfer
Electrolyte wetting
Pressure distribution

Module Scale

Thermal/electrical inter-cell configuration
Thermal management
Safety control

System Scale

System operating conditions
Environmental conditions
Control strategy

Challenge: How to perform life-predictive analysis for "what-if" scenarios untested in the laboratory (V2G, charging behavior, swapping, 2nd use, …)

Factors in Vehicle Battery Aging

Cell Design

- **Chemical**
- **Electrochemical**
- **Electrical**
- **Manuf. uniformity**
  - defects

Environment

- **Thermal**
  - geography
  - thermal management system ($)
  - heat generation
- **Humidity**
- **Vibration**

Duty Cycle

- **System design**
  - vehicle
  - excess power & energy @ BOL ($)
  - system controls
- **Driver**
  - annual mileage
  - trips/day
  - aggressiveness
  - charging behavior
    - charges/day
    - fast charge

Factors in Vehicle Battery Aging

Cell Design

- **Chemical**
- **Electrochemical**
- **Electrical**
- **~~Manuf. uniformity~~**
  - ~~defects~~

~~(Not considered)~~

Environment

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  - geography
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- **~~Humidity~~**
- **~~Vibration~~**

Duty Cycle

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  - excess power & energy @ BOL ($)
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- **Driver**
  - annual mileage
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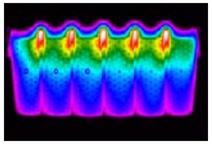
  - aggressiveness
  - charging behavior
    - charges/day
    - ~~fast charge~~

Simulation Approach

Vehicle drive cycles

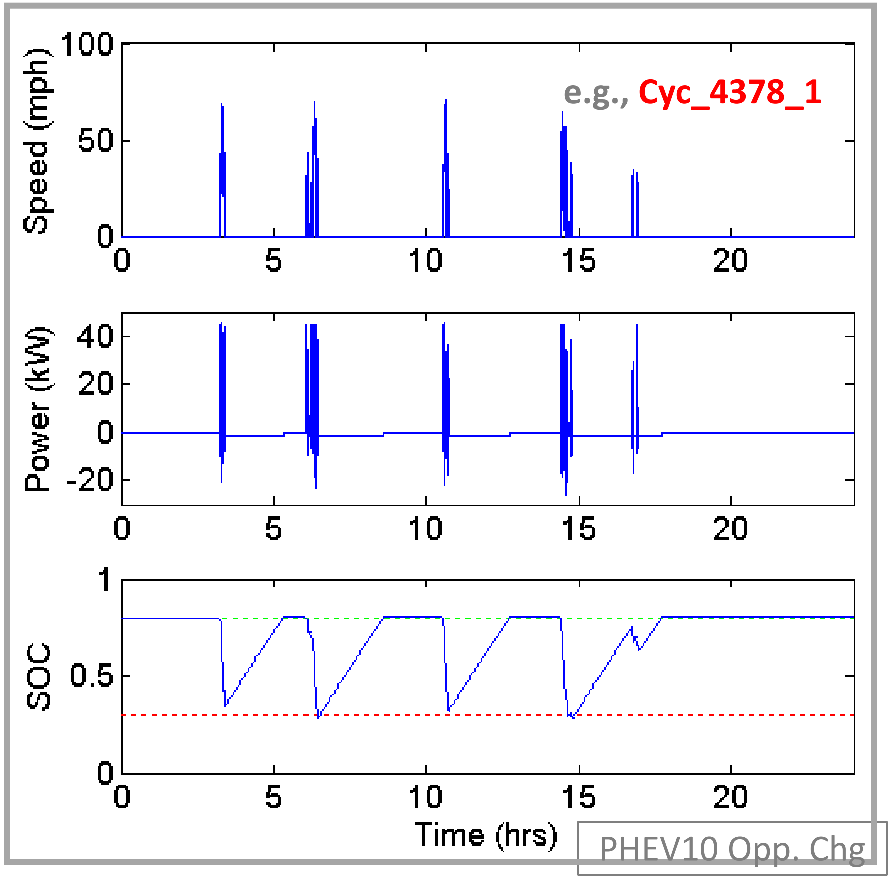
- 782 speed vs. time traces
- Charging assumptions

Vehicle Model



Battery power profile

- SOC(t), Heat gen(t), etc.



PHEV10 Opp. Chg

Simulation Approach

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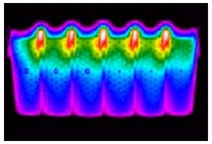
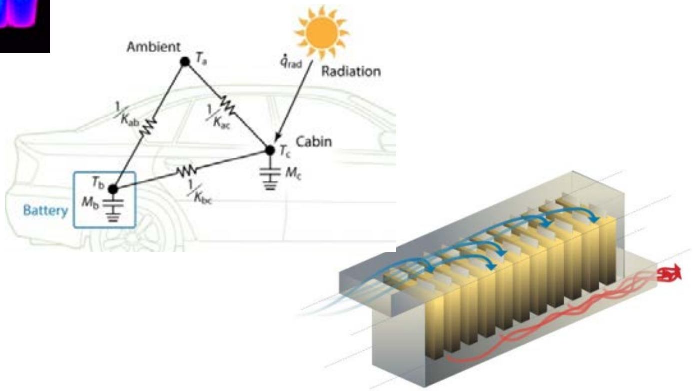
Battery Thermal Model

Battery stress statistics

- T(t), Voc(t), ΔDODi, Ni, …





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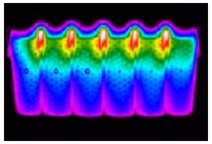
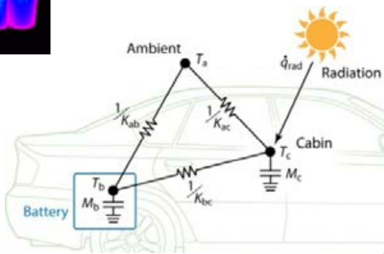
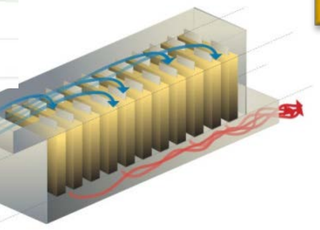
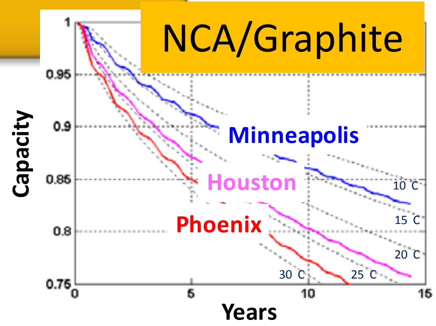
Battery Life Model

Life









Life Model Approach

Battery aging datasets fit with empirical, yet physically justifiable formulas

Calendar fade

- SEI growth (partially suppressed by cycling)
- Loss of cyclable lithium
- $a_1, d_1 = f(\Delta DOD, T, V_{oc})$

Cycling fade

- active material structure degradation and mechanical fracture
- $a_2, e_1 = f(\Delta DOD, T, V_{oc})$

Relative Resistance

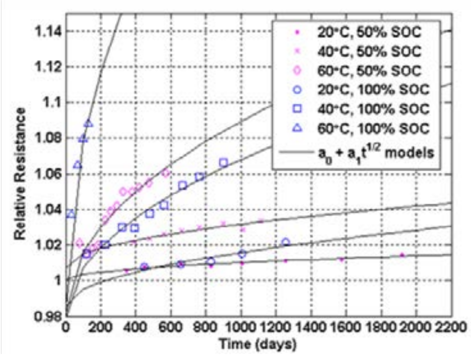
$$R = a_1 t^{1/2} + a_2 N$$

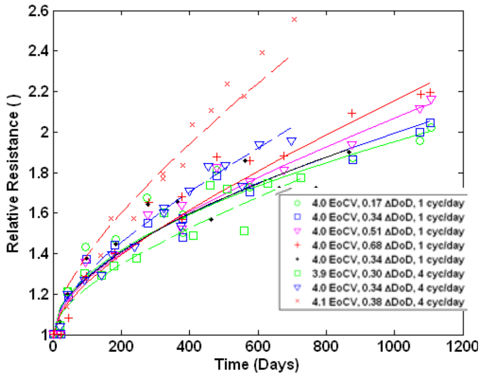
Relative Capacity

$$Q = \min(Q_{Li}, Q_{active})$$

$$Q_{Li} = d_0 + d_1 t^{1/2}$$

$$Q_{active} = e_0 + e_1 N$$





Enables life predictions for untested real-world scenarios

Acceleration Factors

- **Arrhenius Eqn.**

$$\theta_T = \exp\left[\frac{-E_a}{R}\left(\frac{1}{T(t)} - \frac{1}{T_{ref}}\right)\right]$$

- **Tafel Eqn.**

$$\theta_V = \exp\left[\frac{\alpha F}{R}\left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}}\right)\right]$$

- **Wöhler Eqn.**

$$\theta_{\Delta DoD} = \left(\frac{\Delta DoD}{\Delta DoD_{ref}}\right)^{\beta}$$

- **Describe a_1, a_2, b_1, c_1 as f(T,V_{oc},ΔDoD)**
- **Combined effects assumed multiplicative**

Acceleration Factors

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$$\theta_T = \exp\left[\frac{-E_a}{R}\left(\frac{1}{T(t)} - \frac{1}{T_{ref}}\right)\right]$$

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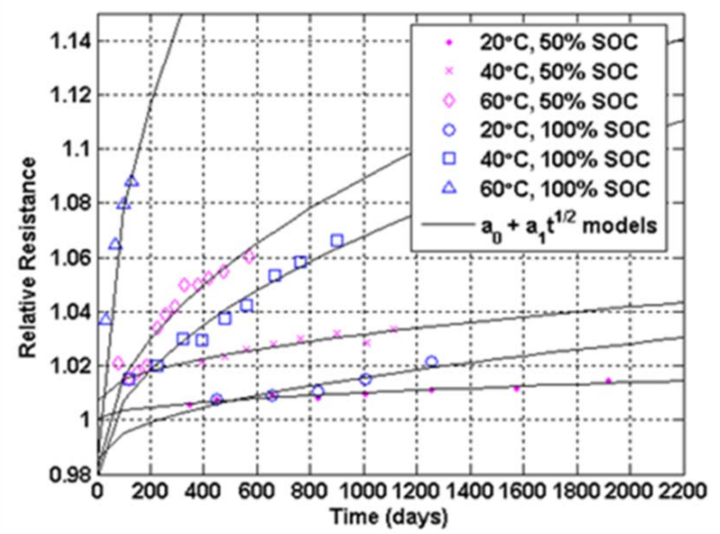
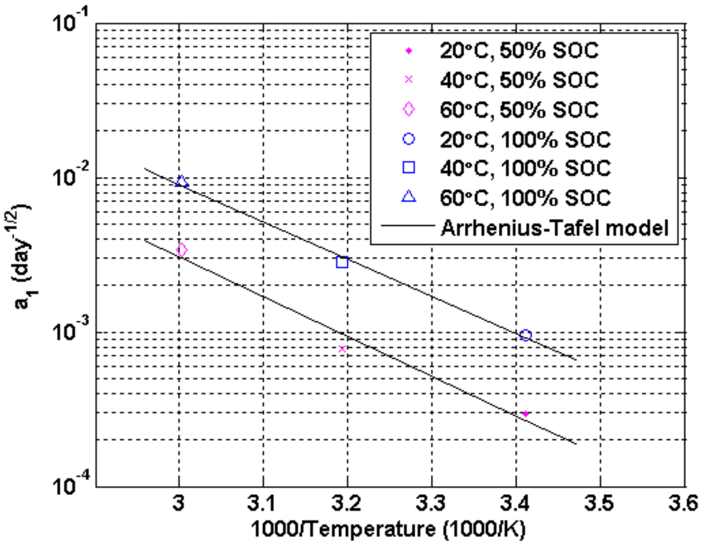
Resistance growth during storage

Data: Broussely, 2007





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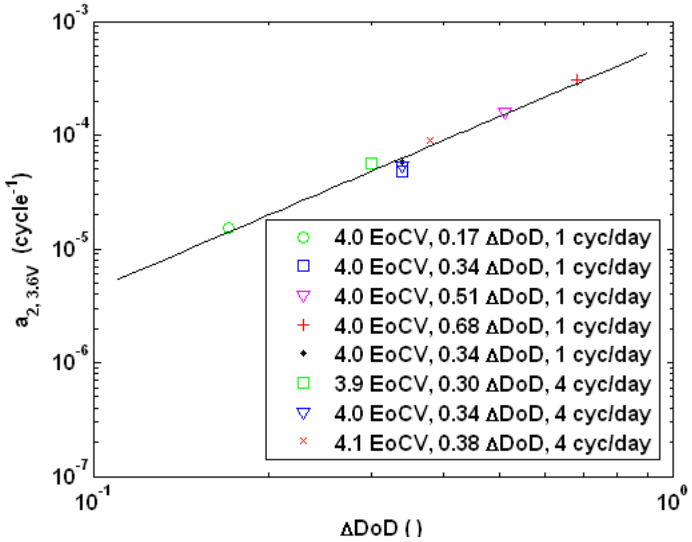
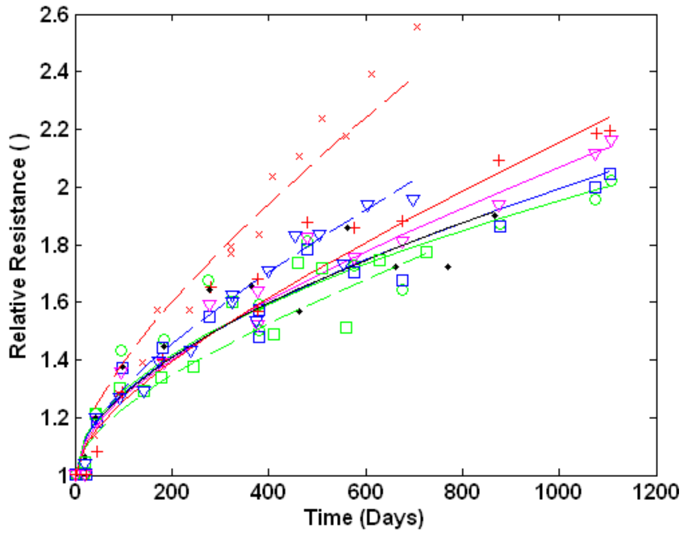
Resistance growth during cycling

Data: Hall, 2006





Acceleration Factors

Capacity fade during cycling

Data: Hall, 2006

- **Arrhenius Eqn.**

$$\theta_T = \exp\left[\frac{-E_a}{R}\left(\frac{1}{T(t)} - \frac{1}{T_{ref}}\right)\right]$$

- **Tafel Eqn.**

$$\theta_V = \exp\left[\frac{\alpha F}{R}\left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}}\right)\right]$$

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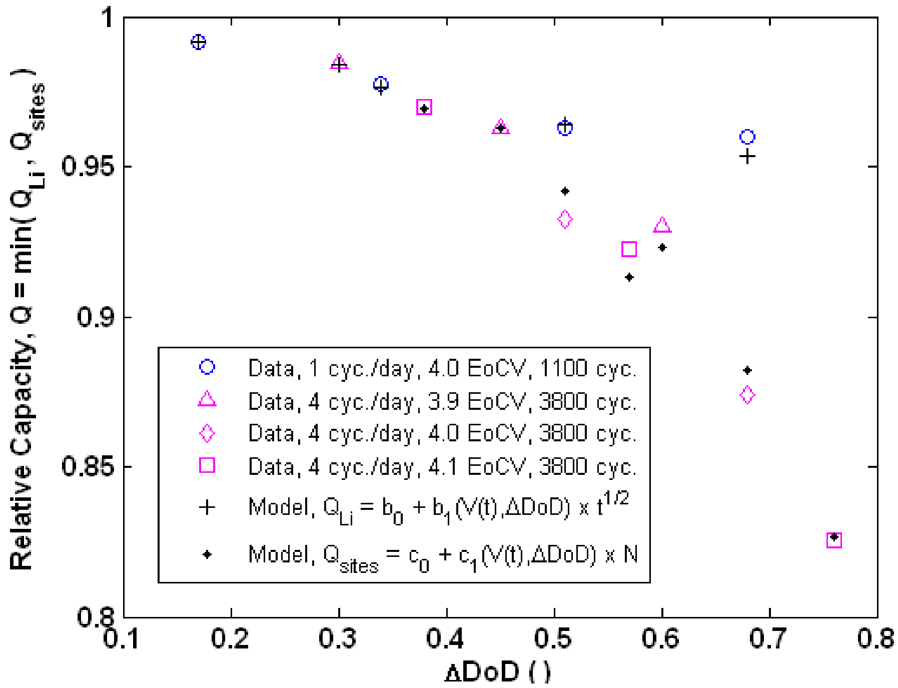


Vehicle & Battery Assumptions

		PHEV10	PHEV40
Vehicle	All-electric range, km	16.7	67
	Total vehicle mass, kg	1714	1830
	Electric motor power, kW	40	43
	IC engine power, kW	77	80
Battery Electrical[1]	Useable power, kW	44	48
	Useable energy, kWh	2.67	11.48
	Maximum SOC	80%	90%
	Minimum SOC at BOL	30%	30%
	Minimum SOC at EOL	13%	10%
	Excess energy at BOL	100%	67%
	Excess power at BOL, 10% SOC	43%	43%
Battery Thermal[2]	Heat transfer area - cells-to-coolant, m^2	1	3
	Heat transfer area - pack-to-ambient, m^2	1.2	2.9
	Heat transfer coeff. - pack-to-ambient, W/m^2K	2	2

PHEV10:
50% ΔDOD at BOL
80% SOC_{max}

PHEV40:
60% ΔDOD at BOL
90% SOC_{max}

1. EOL condition = 75% of BOL nameplate 1C capacity remaining
2. Heat generation rate at 2/3 of EOL resistance growth

Life Variability with Real-World Drive Cycles

- **Matrix of analytic scenarios**

Vehicles

- PHEV10 sedan
- PHEV40 sedan

Drive Cycles[1]

- 782 Real-World drive cycles from Texas Dept. of Transportation

Thermal Management[2]

- Fixed 28°C battery temperature*
- Limited cooling (forced ambient air)
- Aggressive cooling (20°C chilled liquid)

Charging Profiles[3]

- Nightly charge (baseline)
- Opportunity charge

---

1. Average daily driving distance of Texas dataset is 37.97 miles/day. This paper assumes 335 driving days and 30 rest days per year, scaling the Texas dataset to US-equivalent average mileage of 12,375 miles/year. 5th and 95th percentile daily driving distances from the Texas dataset are 99.13 and 4.87 miles/day, respectively.
2. A constant ambient temperature of 28°C was assumed for all thermal simulations, representative of typical worst-case hot climate in Phoenix, AZ. Under battery storage conditions, this effective ambient temperature causes similar battery degradation as would daily and annual temperature variations for a full year in Phoenix.
3. Charging at Level I rate of 1.5 kW.

Results

- Variability in PHEV battery life with real-world drive cycles

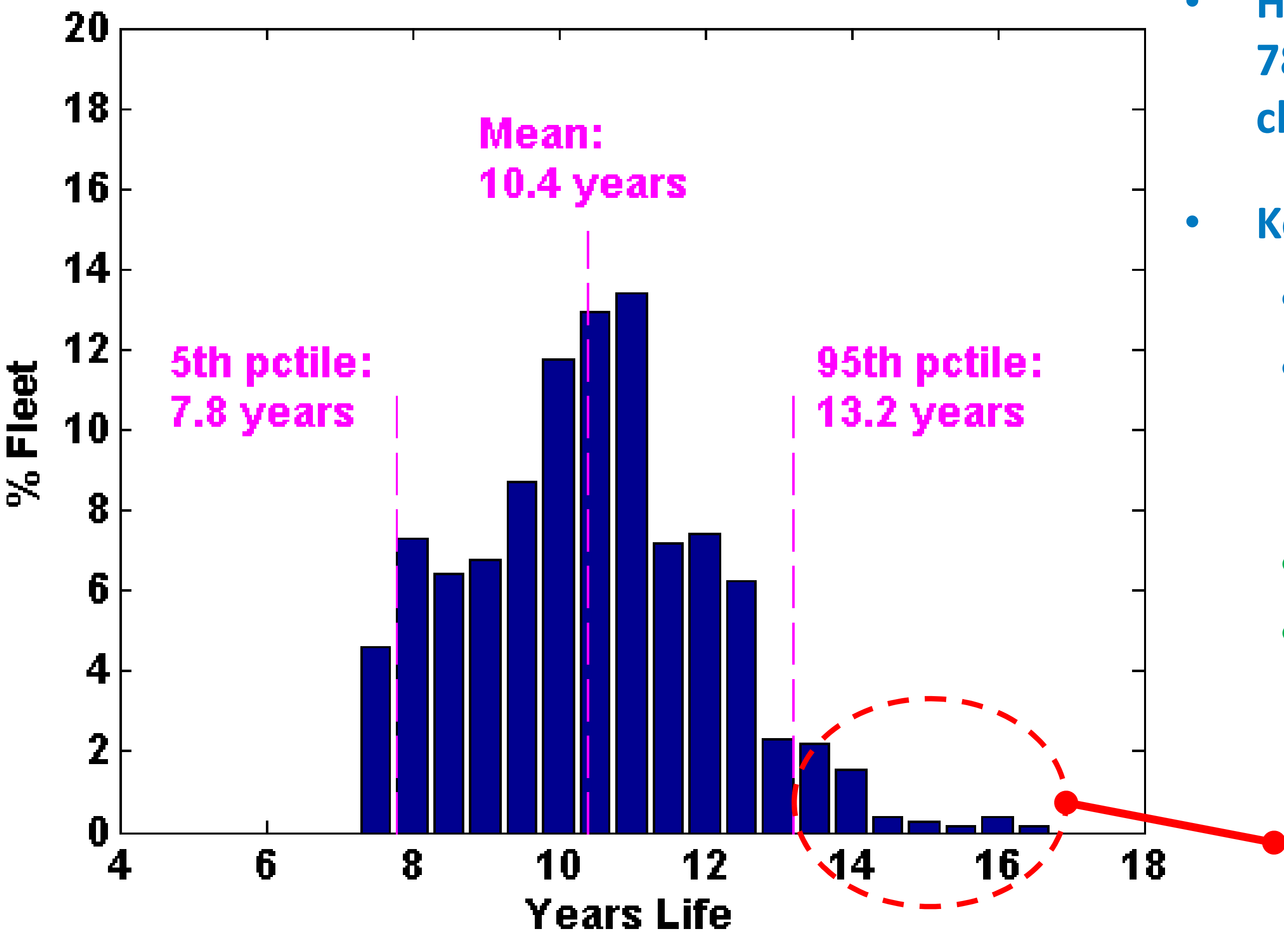
- Impact of thermal management

- Impact of opportunity versus nightly charging

Expected Life – PHEV10

Nightly Charge
Phoenix Climate
Constant 28°C

- **Different daily driving distances and battery charge/discharge histories result in a distribution of expected battery life outcomes**

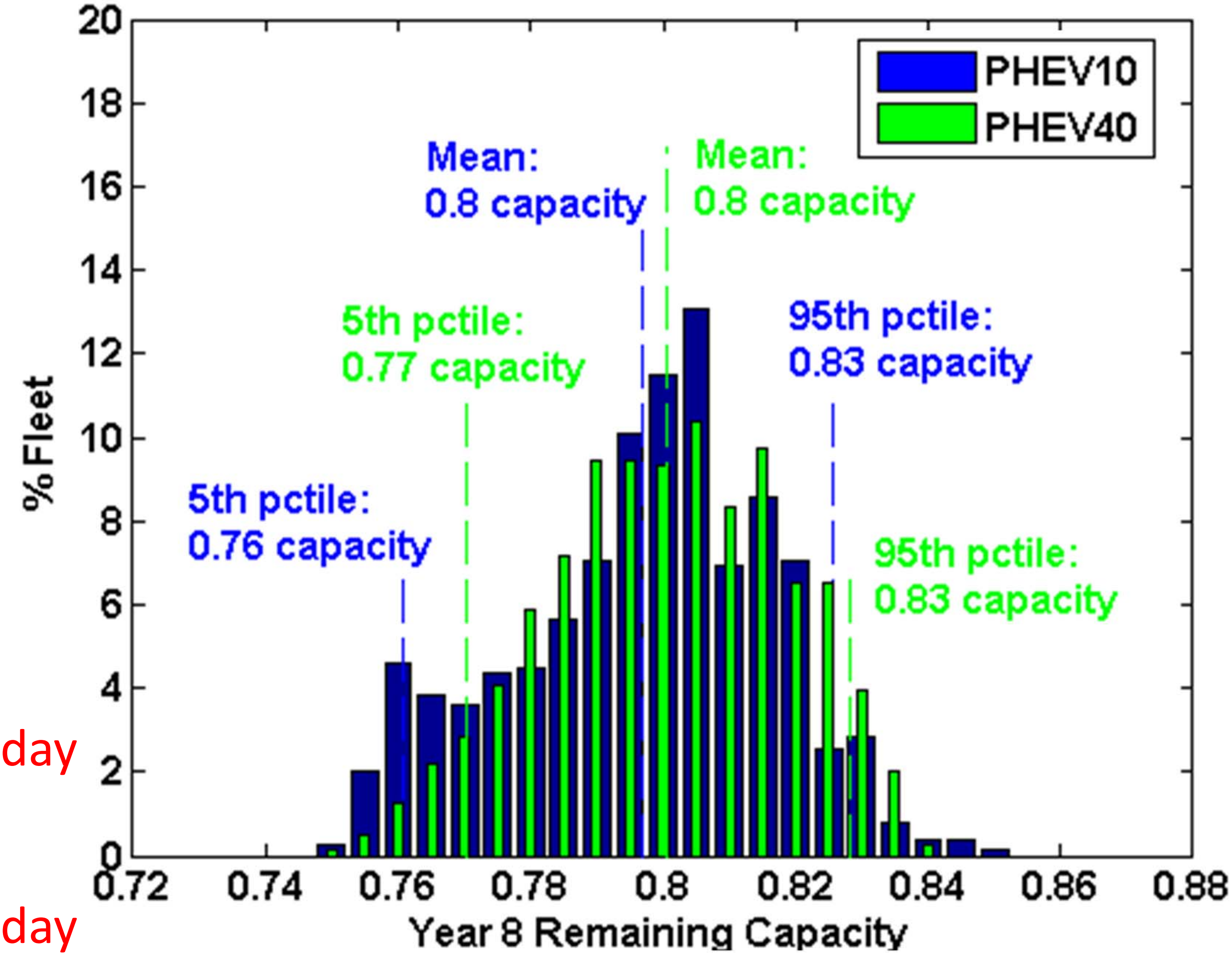


- **Here, life expectancy across 782 driving cycles in a hot climate is <u>7.8 to 13.2 years</u>**
- **Key assumptions:**
  - ○ Graphite/NCA chemistry
  - ○ End-of-life condition: 75% remaining capacity (of initial nameplate)
  - ○ 80% SOC_{max}
  - ○ 30% $SOC_{min\ @\ BOL}$

Opportunities for V2G, 2nd use?

Expected Life – PHEV10 vs. PHEV40

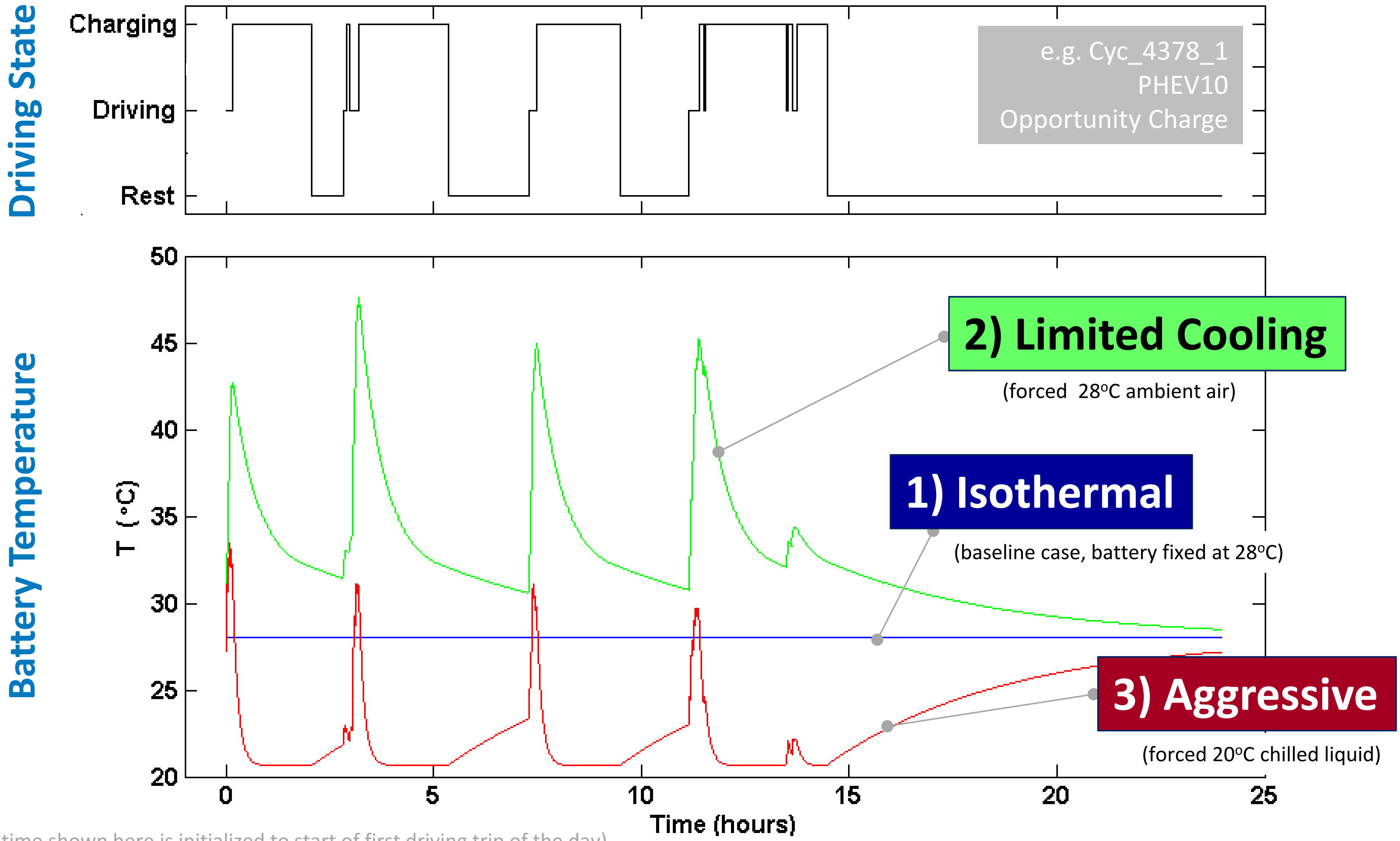
Nightly Charge
Phoenix Climate
Constant 28°C



86% of driving cycles > 10 mi/day

34% of driving cycles > 40 mi/day

Three battery thermal management scenarios illustrated for an example driving cycle



(time shown here is initialized to start of first driving trip of the day)

Expected Life – Thermal Management Impact

Nightly Charge
Phoenix Climate

Limited Cooling Scenario

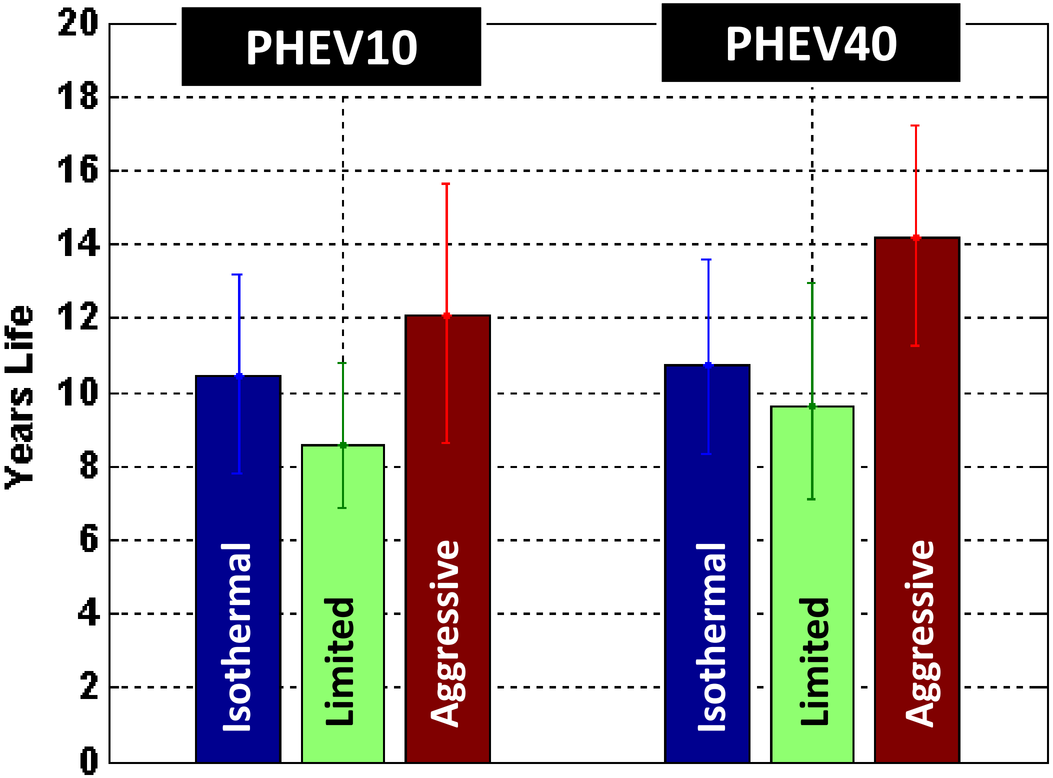
(T_{fluid}=28°C, h=15 W/m^{2}K)

- Excessive temperature rise shortens life by 1-2 years compared to baseline

Aggressive Cooling Scenario

(T_{fluid}=20°C, h=85 W/m^{2}K)

- Periodic drawdown of battery temperature to 20°C, possible during charging with chilled coolant, extends life by 1-3 years compared to baseline

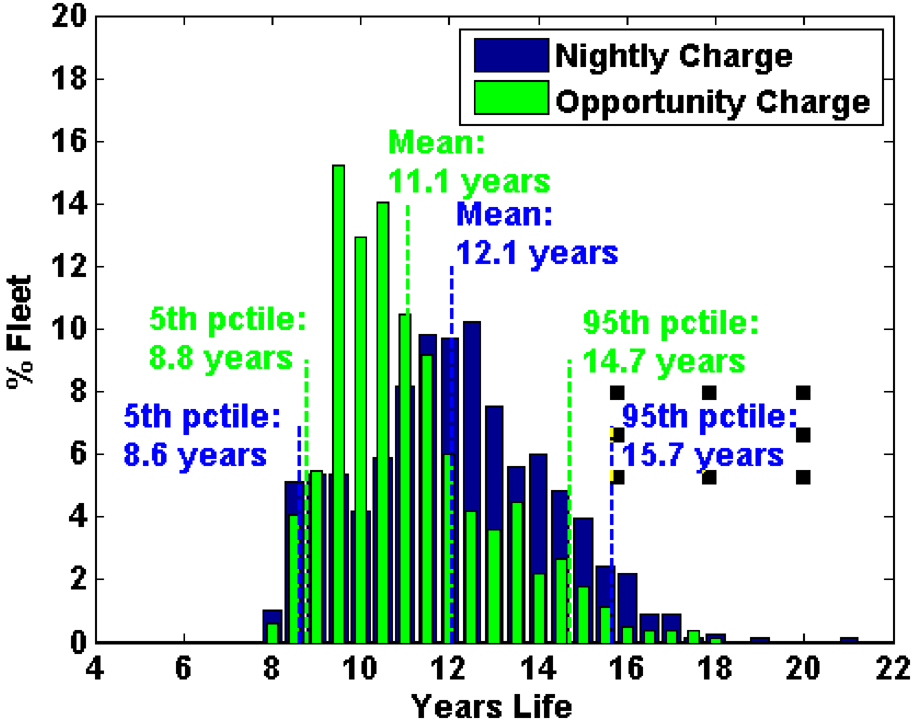


Error bars denote 5th and 95th percentile drive cycles

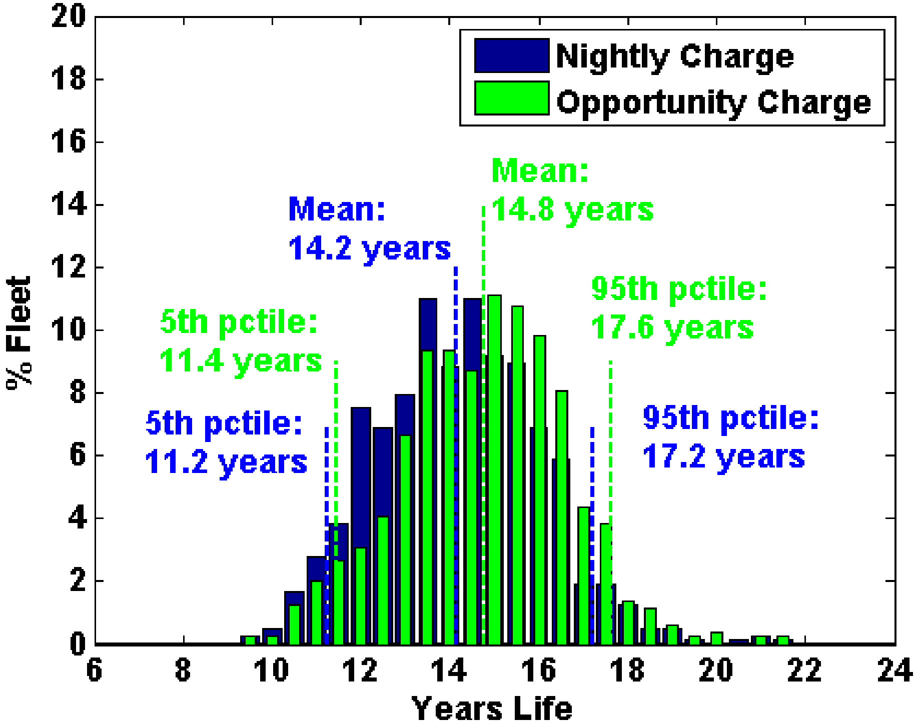
Impact of Opportunity Charging (Level 1)

Phoenix Climate
Aggressive Cooling

PHEV10



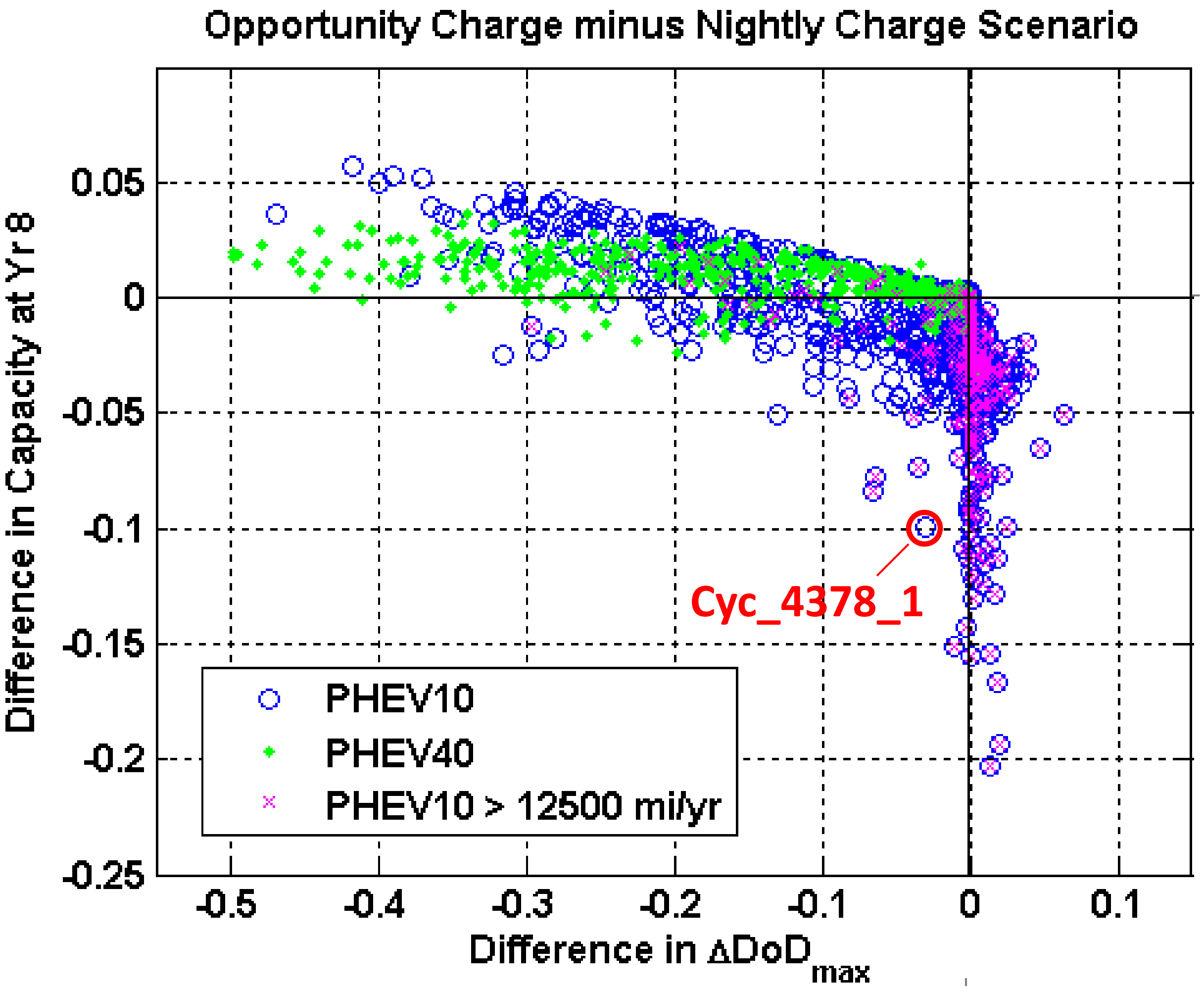
PHEV40



- PHEV10: Frequent charging can reduce average life by 1 year
- PHEV40: Frequent charging can extend average life by ½ year

Impact of Opportunity Charging (Level 1)

Phoenix Climate
Aggressive Cooling



↑ Longer life

Shorter life ↓

← Shallower cycling

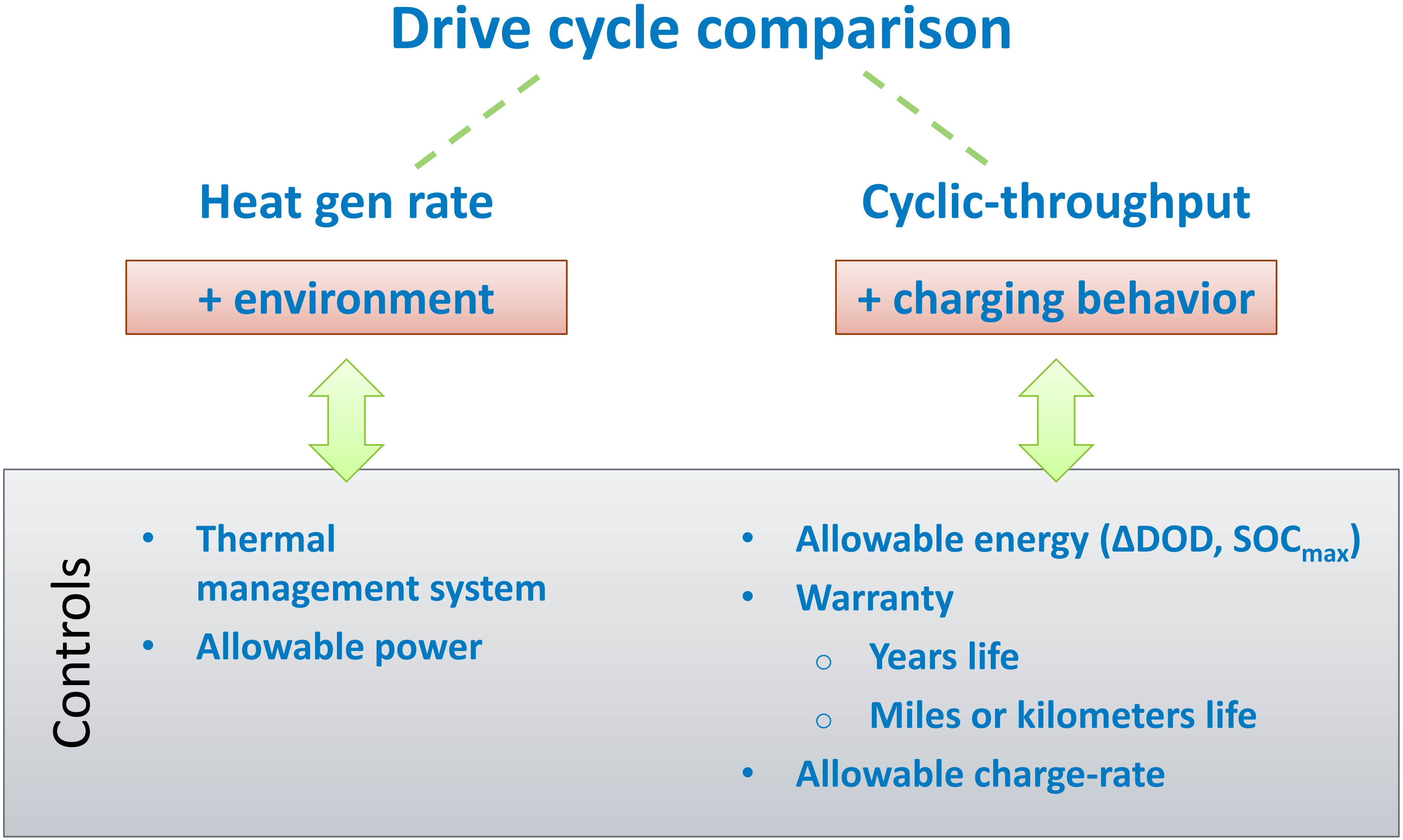
Deeper cycling →

PHEV40:
Longer life due to shallower CD cycles

PHEV10:
Generally shorter life due to many more CD cycles

- **Worst case mostly high mileage drivers**
- **Exception: Cycle 4378_1 with four daily trips of ~9 miles ea.**

Life-Extending Controls



Drive cycle comparison

Heat gen rate

+ environment

Cyclic-throughput

+ charging behavior

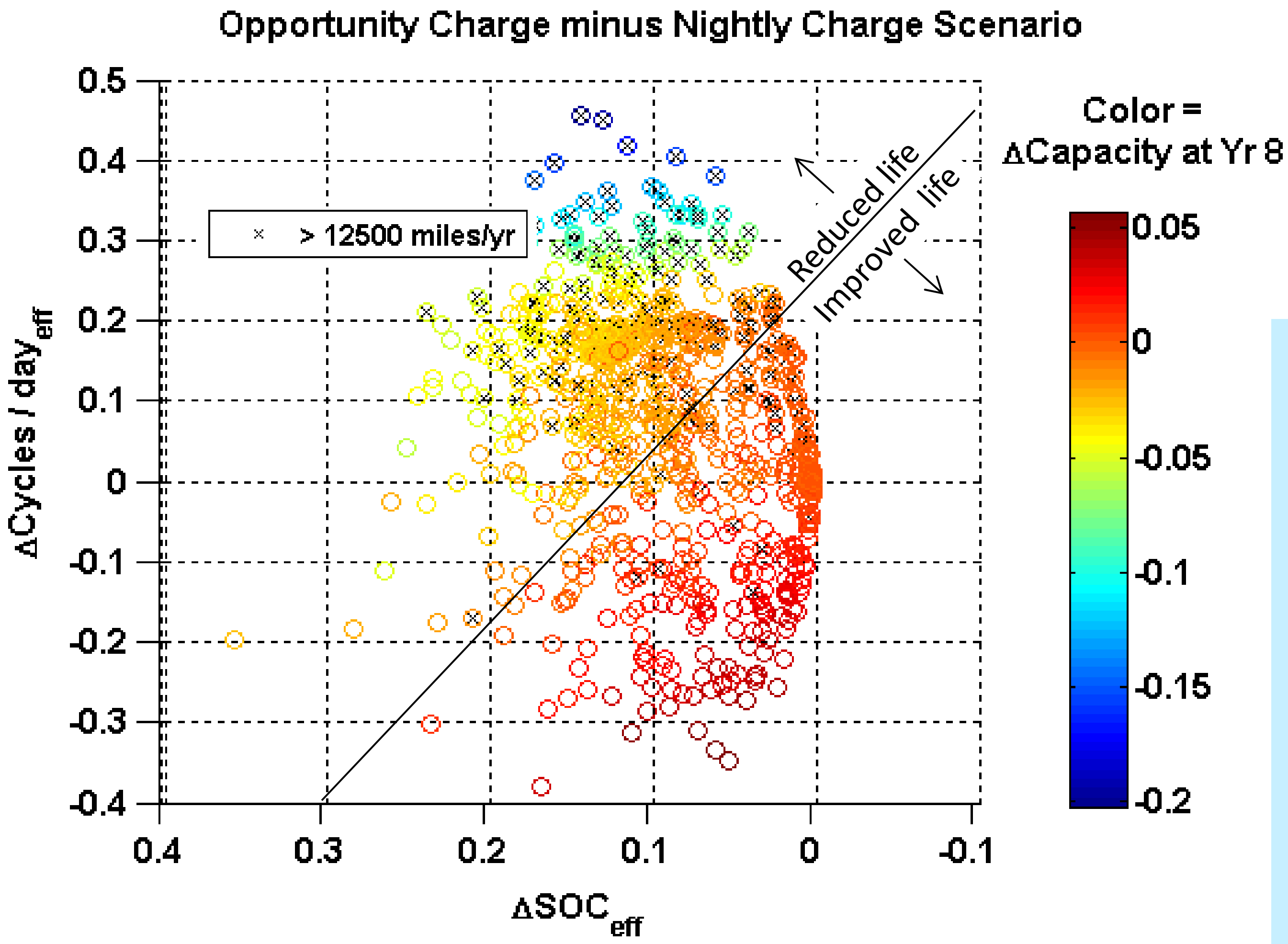
Controls

- Thermal management system
- Allowable power

- Allowable energy (ΔDOD, SOC_{max})
- Warranty
  - ○ Years life
  - ○ Miles or kilometers life
- Allowable charge-rate

Opportunity for Life-Controls – PHEV10

Phoenix Climate
Aggressive Cooling



Regain 1% capacity at year 8 (extend life by ~6 months) by:

- Reducing charge depletion available energy by 1.5%, or
- Reducing avg. SOC by 5%, or
- Lowering avg. T by 0.5°C

Conclusions

- **Electric-drive vehicle batteries designed to last 8 years under worst-case duty cycles and environments may last well beyond that for typical aging conditions**
  - Opportunities for vehicle-to-grid and 2nd use
- **Refrigeration-type cooling systems reduce excessive over-sizing of batteries specifically for hot climates**
- **Worst-case PHEV driving and charging patterns are those with high utilization of charge-depletion mode of operation**
  - Small PHEV10 battery life highly sensitive to frequent charging scenarios for moderate-to-high mileage drivers
  - However, electricity is less expensive than petroleum operation and can financially offset shorter battery life
  - Opportunities to improve life through design and controls

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