Evaluation of the Effects of Thermal Management on Battery Life in Plug-in Hybrid Electric Vehicles

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Abstract

We develop a simulation model that aims to evaluate the effect of thermal management on battery life. The model consists of two sub-models: a thermal model and a battery degradation model. The temperature rise in the battery is calculated using the thermal model, and a temperature profile is obtained under pre-defined driving, charging and stand-by scenarios. The temperature profile and the energy requirement required to achieve a driving profile act as inputs to the degradation sub-model, which is used to predict the battery life. The degradation model is derived from models and test data available in literature, and the model is constructed for air-cooled cylindrical $LiFePO_4$ cells based on the Hymotion Prius-conversion configuration. Preliminary results suggest that peak temperatures have the greatest impact on degradation: Thermal management increases life substantially in climates with high peak temperatures (Pheonix) and for more aggressive driving cycles (US06), while thermal management has less influence in climates with lower peak temperatures (Miami) and with gentle driving cycles (UDDS). Use of cabin air vs. outside air for thermal management has minor impact on battery life for the control strategy used, but thermostat control settings are important for lowering peak temperatures and extending battery life.

Introduction[1]

Plug-in hybrid electric vehicles (PHEVs) have the potential to reduce operating cost, greenhouse gas (GHG) emissions, and petroleum consumption in the transportation sector. One of the most important factors affecting the commercialization of PHEVs is the battery cost, which should be reduced for PHEVs to be cost competitive with other vehicles [2-5]. While reducing the cost, other requirements should also be satisfied such as power, energy, weight, size, and life. Often, improving one of these factors causes an adverse effect in others.

If the battery reaches end of life (EOL) before vehicle life, there would be need for battery replacement, which raises the costs for the consumer substantially since the battery is the most expensive part of the vehicle for many electrified vehicles. Although different design choices can lead to different battery EOL criteria [6], EOL is typically defined as the time when 20% capacity loss or 30% internal resistance growth is reached. According to the goals set by US Advanced Battery Consortium (USABC), a PHEV battery is targeted to have 15 years of calendar life and 300,000 cycles of cycle life[2] [7]. To achieve these goals, it is necessary to improve battery life by managing the stress factors that affect battery life.

One of these stress factors that strongly affects degradation rate is temperature. The relationship between degradation and temperature can be formulated by an Arrhenius type behavior where degradation rate increases exponentially with temperature[3] [8-10]. However, the exact relation depends on the specific electrochemistry and design of the battery. Therefore, there is no single life model that models all different chemistries. Degradation data obtained so far is experimental data from the literature. These data are obtained mostly by performing experiments on cells rather than whole battery packs, and they show a wide variety depending on the cell electrochemistry, capacity and power characteristics. Two chemistries that have been extensively tested in the public literature are $LiNi_xCo_yAl_{(1-x-y)}O_2$ (NCA) and $LiFePO_4$ (LFP) chemistries.

Hall et al. [11] tested NCA cells used in satellite applications and found that the main degradation mechanism is the lithium loss due to the formation of a layer between cathode and electrolyte called solid electrolyte interface (SEI). In the same study, it was also shown that during storage impedance growth has a $t^{1/2}$ dependence, where t represents time, and during cycling a component linear with time is added to this behavior. The same type of storage behavior of impedance growth in this chemistry was also reported by Thomas et al. [9] in which the temperature dependence of impedance growth rate was modeled using an Arrhenius type of equation. The Gen 2

[1] Portions of this paper were adapted from [1] with permission.

[2] Calendar life is the battery life at storage, and cycle life is the number of discharge and charge cycles the battery can survive before it reaches end of its life.

[3] Arrhenius equation formulates the relation between the rate of a chemical reaction and temperature

Performance Evaluation Final Report [12] by Advanced Technology Development Program showed that the capacity loss in this chemistry depends not only on temperature but also on SOC exponentially.

The $LiFePO_4$ chemistry is promising due to its safety and longer life characteristics [13-15]. Liu et al. [16] showed that, similar to the NCA chemistry, the main mechanism of degradation in $LiFePO_4$ batteries is active lithium loss during the formation of the SEI layer. They also showed that there is not an appreciable impedance growth in this chemistry. Peterson et al. [17] tested $LiFePO_4$ chemistry cells manufactured by A123 Systems at a single ambient temperature and reported that degradation rate is not dependent upon the depth of discharge (DOD). Wang et al. [10] performed similar tests at various temperatures and showed that capacity loss can be related to temperature and charge (*Ah*) processed. They modeled the temperature dependence with an Arrhenius type of equation and dependence on Ah-processed by an $Ah^{0.552}$ behavior. Li et al. [18] tested and evaluated the degradation in cells by considering the effects of coupling between stress factors. They analyzed the effects of temperature, charge/discharge rate, end of charge voltage and end of discharge voltage, and they showed that there is a coupling effect between each of these factors. Coupling is related to stress levels, and there exists a critical stress level at which coupling can be neglected. Finally, A123 Systems provides specifications for capacity loss with cycling and storage at different temperatures for their $LiFePO_4$ chemistry ANR26650M1 cells [19, 20].

Thermal management techniques can be classified depending on the purpose (cooling only versus heating and cooling), depending on the source (passive if ambient or cabin air is used without additional pre-conditioning, active if a dedicated heating/cooling device is built-in the system to pre-condition the air before entering into the pack) and depending on the cooling medium (air versus liquid) [21]. Ma *et al*. [22] calculated temperature increase in a PHEV battery pack using a finite element thermal model. Kim and Paseran [23] compared alternative thermal management techniques in maintaining battery temperature within predefined limits and concluded that it is possible to obtain a better heat removal rate by using liquid cooling, but its disadvantages, like increased cost and complexity, as well as maintenance requirements need to be considered before selecting a liquid cooling system.

To the authors' knowledge, the studies that combine battery degradation and thermal management to study the effects of thermal management on battery life are rare. Gross and Clark [24] aimed to analyze the effect of thermal management on battery life in a battery electric vehicle (BEV). They used a generic formulation for degradation which they assumed to be applicable to all battery chemistries. Experimentally driven estimates for heat transfer rates were used to calculate the change in battery temperature, and passive and active cooling of batteries were compared. They found that active cooling improves battery life by 4.4% to 6.5%, where values vary depending on the region.

In this study, we aim to analyze the effects of thermal management on battery life using an integrated thermal management and battery degradation simulation for an air cooled PHEV battery pack of cylindrical $LiFePO_4$/graphite cells. The main question being addressed is: "How much improvement can be obtained in battery life with simple air cooling?". A daily driving and storage scenario is posed and applied under different weather conditions in two cities, Miami and Phoenix .We analyze the effects of different parameters on this improvement by simulating various driving and cooling cases. The model used in this study was first introduced in [1].

Modeling

1. Thermal Management Model

In this study, a battery pack with the specifications of a A123 Systems Hymotion Li-ion battery pack is modeled. The pack consists of 14 modules, connected in series. Each module has 44 cylindrical cells, and the cells are connected with a 4 parallel by 11 series configuration [22]. The pack is cooled by a fan drawing air to the battery as shown in Figure 1. The flow of air is divided in parallel so that same amount of air passes through each module in the pack [22]. Therefore, it is enough to model and simulate one single module to obtain the temperature profile of the whole pack.

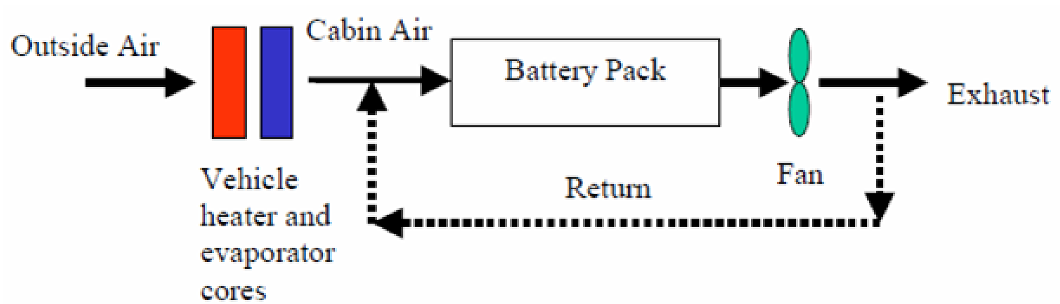

Figure 1. Air cooling thermal management system [21]

The rate of heat generated inside a single module can be shown as:

$$\dot{Q}^{\mathrm{GEN}} = NI^2R \qquad (1)$$

In this equation I represent the current drawn from each cell and R is the internal resistance of the cell. Internal resistance is a function of temperature and state-of-charge (SOC). N is the total number of cells inside a single module.

When the fan is on, the forced air flow over the cells removes some of the heat generated. The overall heat transfer coefficient h is calculated by:

$$h = N_{\mathrm{Nu}}k/D \qquad (2)$$

where N_{Nu} is the Nusselt number, k is thermal conductivity of air and D is the cell diameter. The cell configuration inside the pack is neither fully aligned nor fully staggered. However, it has mostly a staggered arrangement and therefore in this study the correlation in Equation 3 by Zhukauskas [25] for "flow across staggered bank of tubes" is used to estimate the Nusselt number. The assumed pack configuration is shown in Figure 2.

$$N_{\mathrm{Nu}} = CN_{\mathrm{Re,max}}^{m}N_{\mathrm{Pr}}^{0.36}\left(N_{\mathrm{Pr}}/N_{\mathrm{Pr,s}}\right)^{1/4} \qquad (3)$$

$N_{\mathrm{Re,max}}$ is the Reynolds number calculated at maximum air velocity, C and m are constants obtained empirically and tabulated for $N_{\mathrm{Re,max}}$, and N_{Pr} is the Prandtl number. $N_{\mathrm{Re,max}}$ and N_{Pr} are calculated at the film temperature, T_f, which is defined as:

$$T_f \equiv (T_{\mathrm{s}} + T_{\mathrm{i}})/2 \qquad (4)$$

where T_{s} is the cell surface temperature and T_{i} is inlet air temperature (which is equal to the cabin air temperature). $N_{\mathrm{Pr,s}}$ is calculated at T_{s}.

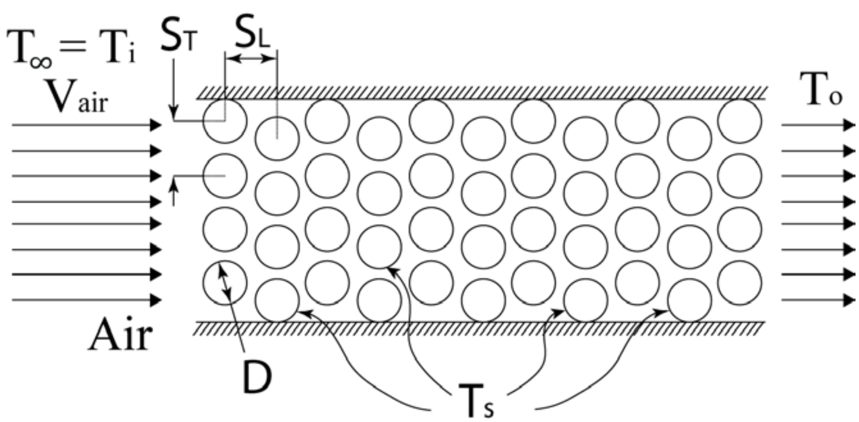

Figure 2. Staggered cell arrangement inside a module (Used with permission [1])

Once h is calculated, the rate of heat transfer from the battery can be computed as:

$$\dot{Q}^{\mathrm{TR}} = Nh\pi D\Delta T_{lm}L \qquad (5)$$

L is the length of a cell and ΔT_{lm} is the log mean temperature difference defined as:

$$\Delta T_{lm} = \frac{(T_s - T_i) - (T_s - T_o)}{\ln\left(\frac{T_s - T_i}{T_s - T_o}\right)} \qquad (6)$$

T_o is the temperature of air leaving the battery, and can be calculated by using the relation given in Equation 7, which can be obtained by equating the heat transferred from the cell surfaces to air (Equation 5) to the heat carried away by air ($m_{air}c_{air}\Delta T_{air}$):

$$\left(\frac{T_s - T_o}{T_s - T_i}\right) = exp\left(-\frac{\pi DNh}{\rho_{air} V_{air} N_T S_T c_{air}}\right) \quad (7)$$

where, N_T is the number of cells in transverse direction, S_T is the transverse pitch shown in Figure 2, V_{air} is the air speed, ρ_{air} is air density and c_{air} is air constant specific heat.

For the no-thermal-management case and for the times when the fan is turned off the generated heat will be removed by natural convection and conduction. However, for simulation purposes it is assumed that the heat removed in these cases is negligible compared to the heat generated. In addition, it is assumed that battery temperature drops to the ambient temperature immediately after the vehicle comes to rest.

After rates of heat generation and heat transfer are calculated, the rate of change of T at each time step can be computed as:

$$\dot{T} = (\dot{Q}^{\text{GEN}} - \dot{Q}^{\text{TR}})/(m \cdot c_p) \qquad (8)$$

where m is the module mass and c_p is the module thermal capacity.

2. Battery Life Model

In this study, the focus is on $LiFePO_4$ chemistry. The main reasons of this choice are: (1) the cells used in the actual Hymotion battery pack are of this chemistry, (2) this chemistry is extensively studied in public literature [10, 16-18], and (3) this chemistry has negligible impedance growth [16,17], therefore the battery life model can be simplified by considering only capacity loss criteria.

Although it has not been proved yet, cycling and storage capacity loss mechanisms are usually assumed to be decoupled [8]. In this study, we follow the same assumption and calculate the cycling and storage fade separately, summing them up to find the total fade.

Both cycling and storage capacity fade are modeled using manufacturer data. A123 Systems provides constant charge/discharge capacity loss versus number of cycles for their $LiFePO_4$/graphite based ANR26650M1 cells [19]. The curves are given for three different temperatures. However, since the data are given for constant charge/discharge, they are converted to a measure that can be applicable to real driving conditions, where discharge behavior is dynamic and involves changing duty cycles. Therefore, in this study, the number of cycles given in the specifications is converted to Ah-processed (I^{PR}), which can be considered as the integral of the absolute value of current over time. The model is constructed using an Arrhenius type of relation for temperature and a power function relation for Ah-processed $(I^{\text{PR}})^{z}$. It has been shown that z has a value near 0.5 [10]. Using a least-squares fit the model given in Equation 9 is obtained:

$$C^{\text{CYC}} = A \cdot \exp\left(-B/\left(R_{\text{gas}} \cdot T\right)\right) (I^{\text{PR}})^{0.55} \quad (9)$$

where $A = 1.1443 \times 10^6$ and $B = 4.257 \times 10^4$.

Similarly, to obtain a capacity loss model for storage fade, the manufacturer's data, which give the capacity loss with time at various temperature values, are used [20]. In the given data, the percent capacity loss was observed to vary linearly with the logarithm of time in days. Therefore, the model form given in Equation 10 is used to estimate the storage fade. The constant parameters given in the formula are again obtained using least squares regression.

$$\begin{cases} C^{\text{STO}} = (0.23T - 67)\log10(t) - (0.3T - 88.95), T \leq 45°\text{C} \\ C^{\text{STO}} = (0.23T - 67)\log10(t) - (0.013T + 2.36), T > 45°\text{C} \end{cases} \qquad (10)$$

Data and fits for both cycling and capacity fades are given in Figures 3 and 4.

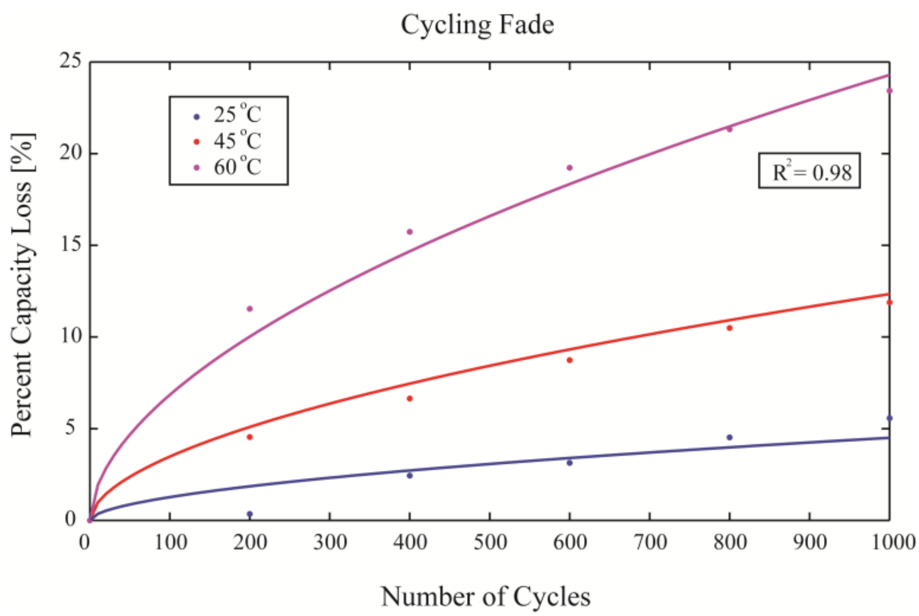

Figure 3 – Capacity fade with cycling-Data and fit (Used with permission [24])

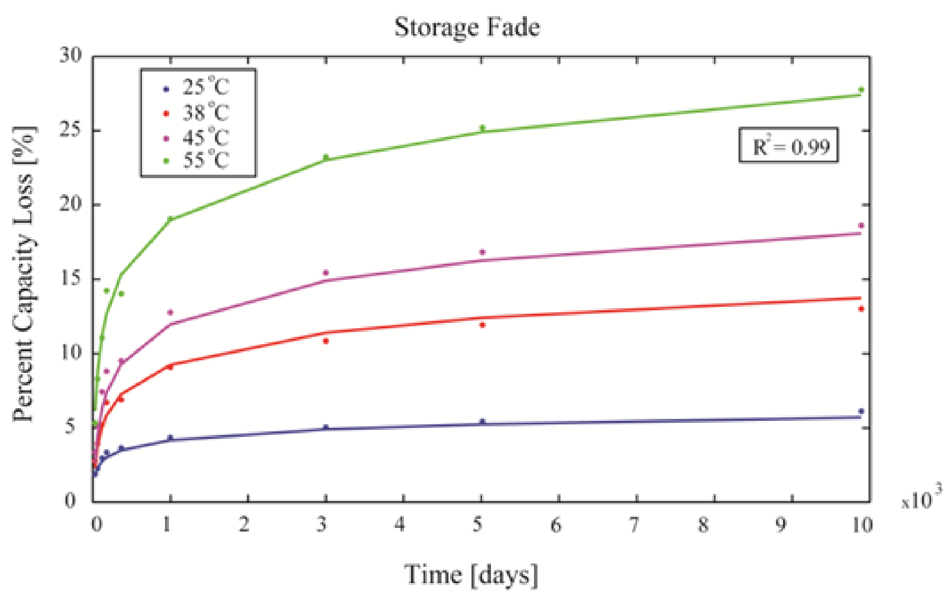

Figure 4 – Capacity Fade at Storage-Data and Fit (Used with permission [24]**)**

Simulations

1. Procedure

Using the thermal and life models, daily simulations for a vehicle use and storage profiles are performed. These simulations are summarized in Figure 5. Battery life is calculated by computing capacity loss in two parts: cycling capacity loss, which corresponds to the loss during driving and charging, and storage capacity loss.

To calculate cycling degradation, driving and charging power demand at each time step are given as inputs to the thermal model. The thermal model calculates the rate of change of battery temperature by computing heat generated inside and heat transferred from the battery for two separate cases: (1) the battery is being cooled by an air cooling thermal management system, and (2) there is no thermal management system to cool the battery. In these calculations, the initial battery temperature is assumed to be equal to ambient temperature. The net heat transfer is used to calculate the change in battery temperature. Temperature is an input to the cycle life model, which computes capacity loss at each time step using temperature, time and current drawn from the battery as inputs. Battery current is obtained based on the driving and charging profile. The cycling life model also takes the previous capacity loss history into account during calculations. The set of calculations performed at each time step are given in Equations 11 and 12.

$$T_t = T_{t-1} + \dot{T}_{t-1}\left(\dot{Q}_{t-1}^{\mathrm{TR}}, \dot{Q}_{t-1}^{\mathrm{GEN}}\right) \cdot \Delta t \qquad (11)$$

$$\begin{cases} \dot{Q}_{t-1}^{\mathrm{TR}} = \dot{Q}_{t-1}^{\mathrm{TR}}(T_\infty, V_{\mathrm{air}}, \rho_{\mathrm{air}}, c_{\mathrm{air}}, A_{\mathrm{cell}}) \\ \dot{Q}_{t-1}^{\mathrm{GEN}} = \dot{Q}_{t-1}^{\mathrm{GEN}}(I_{t-1}, R_{t-1}) \end{cases}$$

$$C_t^{\mathrm{CYC}} = C_{t-1}^{\mathrm{CYC}} + \Delta C_{t-1}^{\mathrm{CYC}}\left(C_{t-1}^{\mathrm{CYC}}, I_{t-1}, T_{t-1}, \Delta t\right) \qquad (12)$$

In these equations, subscript t refers to time step t. T is the battery temperature, $\dot{T}$ is the change in battery temperature which is assumed to be constant over Δt, $\dot{Q}^{\mathrm{GEN}}$ is rate of the heat generated in the battery, $\dot{Q}^{\mathrm{TR}}$ is the rate of heat removed from the battery, T_∞ is the cabin air temperature entering into pack, V_{air}, ρ_{air} and c_{air} are air speed, density and constant specific heat respectively, A_{cell} is the heat transfer area of a cell, C^{CYC} is percent cycling capacity loss, I is the current drawn from the battery, and R is internal resistance.

Daily storage fade (capacity loss when the battery is at rest) is evaluated using the calendar life model, assuming that the battery is at ambient temperature when it is at rest. The total capacity fade at the end of the day is the sum of cycling and capacity fade. Simulations corresponding to duration of one week are performed at each seasonal ambient temperature. It was observed from one week simulations that capacity fade is not constant on daily basis, but there is a power function relationship between the number of days and capacity loss, where the power is equal to ½. Using this fact, capacity fade profile during the simulated one week period is extrapolated to estimate fade during the remainder of the season. Battery life is defined as the number of years passed until a total capacity loss of 20% reached. The evaluated system and the calculations performed at each block of the simulation are detailed in the following sections.

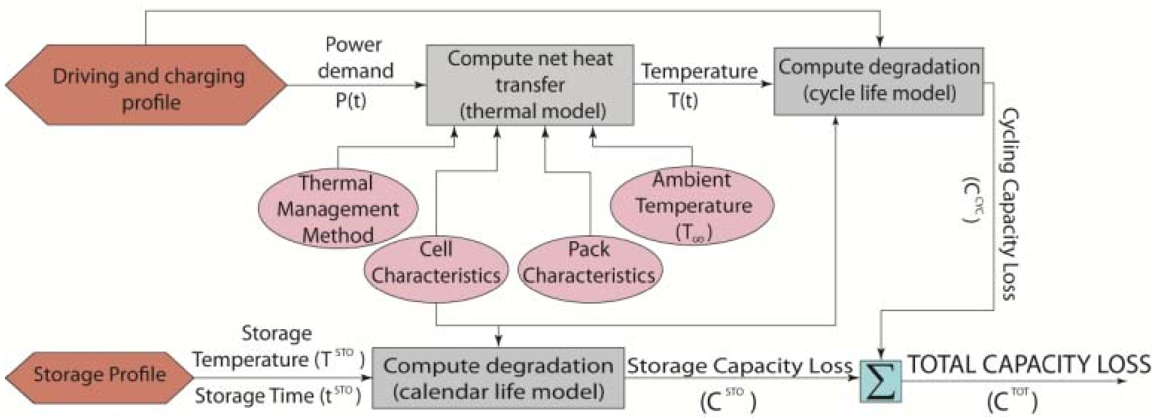

Figure 5 - Schematic view of simulations to calculate battery life (Used with permission [1]**)**

2. Daily Usage Profile

In this study, the simulated vehicle is assumed to have the specifications of a PHEV conversion of a 2004 Toyota Prius, which is assumed to make a 14.9 mile trip per day. Each trip is followed by a constant current charging period. After charging, the vehicle is at rest until the next trip the next day. This daily profile is simulated for two different cities: Miami and Phoenix. Seasonal average temperatures of each city are used as daily ambient temperature. The average temperatures used in simulations are given in Table 1.

Table 1. Seasonal Average Temperatures in Simulated Cities [^{o}C] (Used with permission [1])

	Winter	Spring	Summer	Fall
Miami	22	26	27.5	25
Phoenix	15	26	33	17

3. Cases Tested

Using the simulation procedure and daily usage profile described above, various case studies were performed to see the sensitivity of the results to different parameters in the model.

To see the effect of driving cycle on battery life and on the benefits of thermal management, two different driving cycles were tested: the Urban Dynamometer Driving Schedule (UDDS) and the US06 cycle [26]. These driving cycles were shown to provide a reasonable lower and upper bound in terms of the fuel consumption compared to GPS data collected in southeast Michigan [27]. These two driving cycles were selected for simulations based on this fact, considering that energy limits demanded from the battery will also reflect to the battery life. The dynamic power profile needed to achieve the 14.9 miles trip with given driving cycles is obtained by calculating the traction and resistance forces, as described in Peterson, 2010 [17].

The fan can draw ambient or cabin air to cool the battery. Both of these options might have advantages or disadvantages relative to one another. For example, using ambient air may not be a very efficient way of cooling in hot days. Using conditioned cabin air will provide better efficiency for the thermal management system (although not necessarily for the overall vehicle system). However, there is a possibility that the cabin is initially hotter than ambient air due to the vehicle's greenhouse effect when sitting in the sun or that the driver never conditions the cabin. Therefore, two different cases were compared for both driving cycles. In the first case, it is assumed that the fan draws cabin air and the driver always keeps the cabin air at 24^{o}C; therefore the temperature of the air entering to the battery is always 24^{o}C. In the second case, it is assumed that the fan uses ambient air, where the air inlet temperature is equal to the season's average ambient temperature. In the base case simulations, the Hymotion pack fan is assumed to have the same on-off control strategy as the Prius HEV: the fan is not turned on until the battery temperature reaches 35^{o}C and then it turns off again if the battery temperature falls to 33^{o}C [28]. Various fan on-off temperatures were also tested in Miami, and battery life was obtained for each set of on-off temperatures.

Results and Discussion

1. Climate and Driving Cycles Comparison

Figures 6 gives the comparison of battery life in Miami and Phoenix for two different driving cycles. The results presented in Figure 6 show the case when there is an air cooling thermal management system issued in the vehicle with the default fan on-off control strategy described in the previous section. Figure 7 makes the same comparison for the case when there is no battery thermal management system in the vehicle at all.

For the thermal management case, it can be observed that battery life differs slightly for both cities. The effect of driving cycle on battery life is significant in both cases but particularly substantial when thermal management is absent. Results show that, when there is no thermal management issued, driving the same distance with the US06 cycle decreases the battery life by ~60 % in Miami and by ~54 % in Phoenix, compared to driving that distance under the UDDS cycle. Two conclusions can be drawn from these results: (1) the driving cycle has a significant effect on battery life, and (2) this effect can be successively reduced by using thermal management.

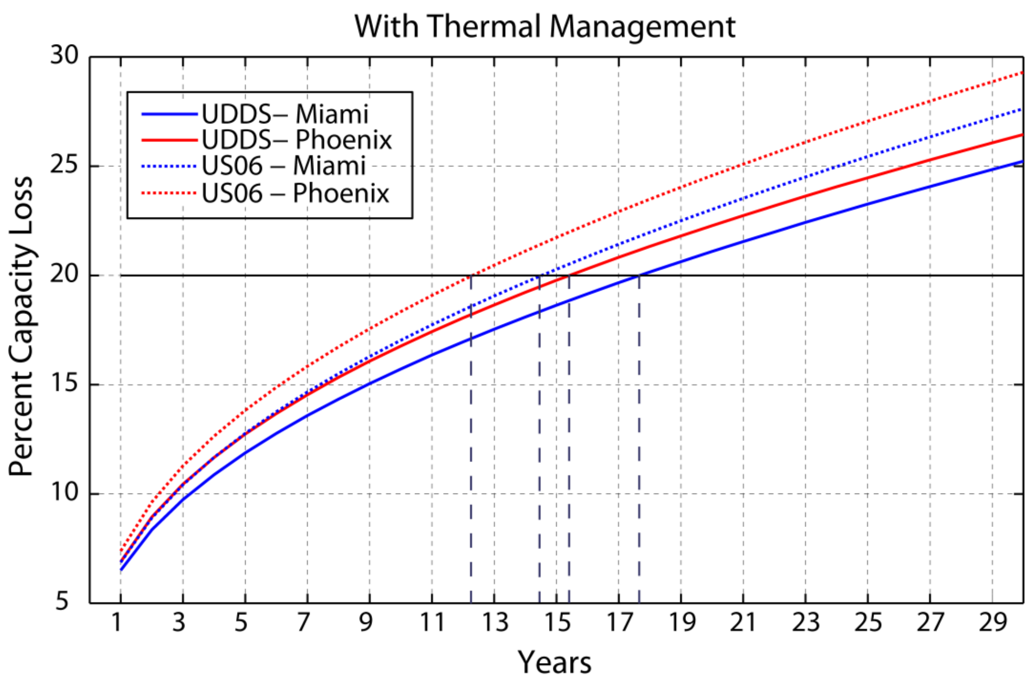

Figure 6. Capacity fade comparison for driving with UDDS and US06- with thermal management

The results also designate that when there is no thermal management to cool the battery, battery life in Phoenix is ~3 years shorter than the battery life in Miami, despite the fact that average seasonal temperatures in Phoenix are lower than or equal to the corresponding temperatures in Miami except during the summer season. This shows the importance of high peak temperatures on battery life, even if they are observed only in one fourth of the year. The effect of this high temperature season could be reduced by cooling the battery with air in Phoenix, where air cooling provides an estimated battery life improvement of 23%. However, in Miami the improvement in battery life is only 5%, corresponding to 1 year of additional battery life. This shows that the life improvement that can be obtained with a specific type of thermal management system, and/or the decision to upgrade a thermal management system depends on the region where the vehicle is being used. The results also indicate that battery thermal management is most critical for peak temperatures.

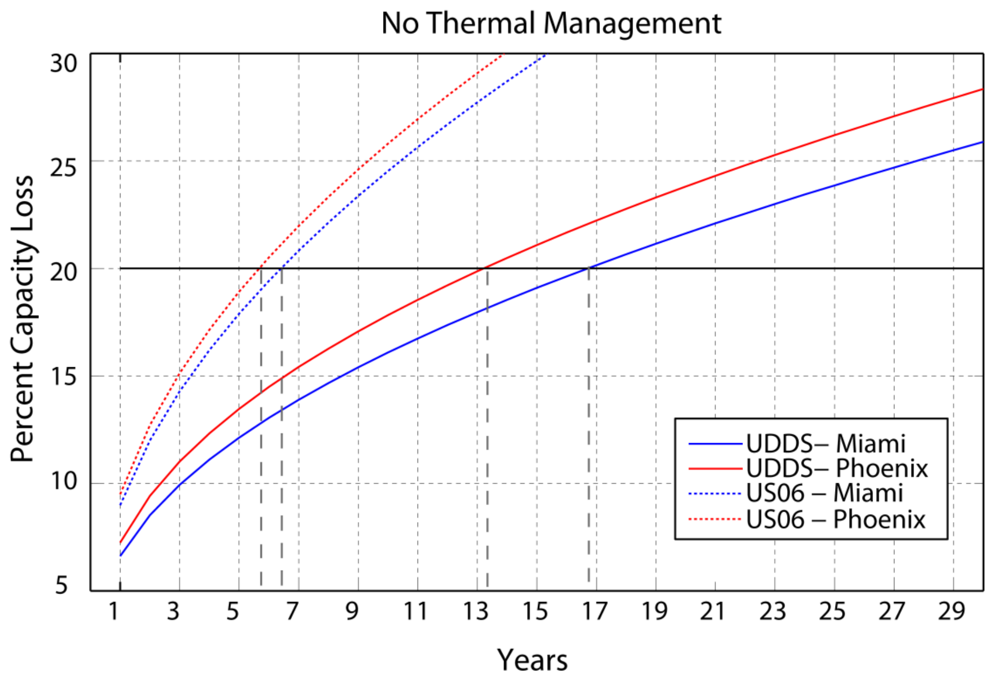

Figure 7. Capacity fade comparison for driving with UDDS and US06- no thermal management

2. Ambient Air Cooling / Cabin Air Cooling Comparison

Figures 8 and 9 show that battery life increases slightly when ambient air is used instead of cabin to cool the battery. The fan control strategy used in these comparisons is the default on-off control strategy described above, which turns on when the battery reaches 35°C.When ambient air is used, the fan is able to keep the battery temperature below 35°C, even using the air when its temperature is 33°C in Phoenix. The amount of time that takes the fan to cool the battery back to 33°C increases slightly; however, its effect on battery life is almost negligible. If alternative thermal control strategies that work to maintain lower battery temperatures were used, then the source of inlet air may be more significant in determining degradation rate.

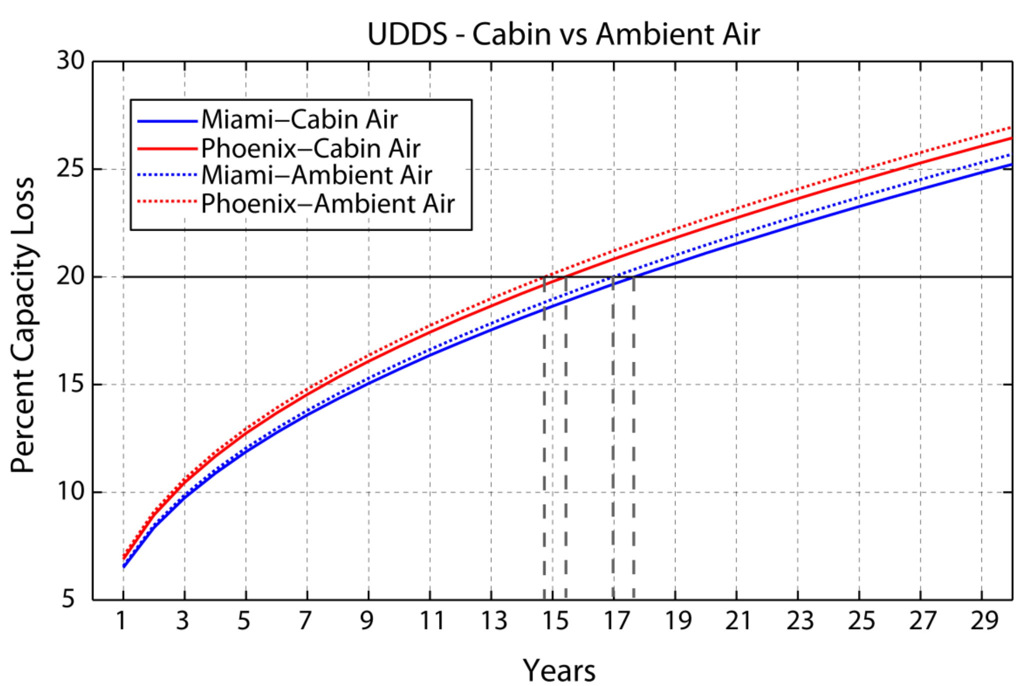

Figure 8. Cooling medium comparison for driving with UDDS- Cabin air vs ambient air

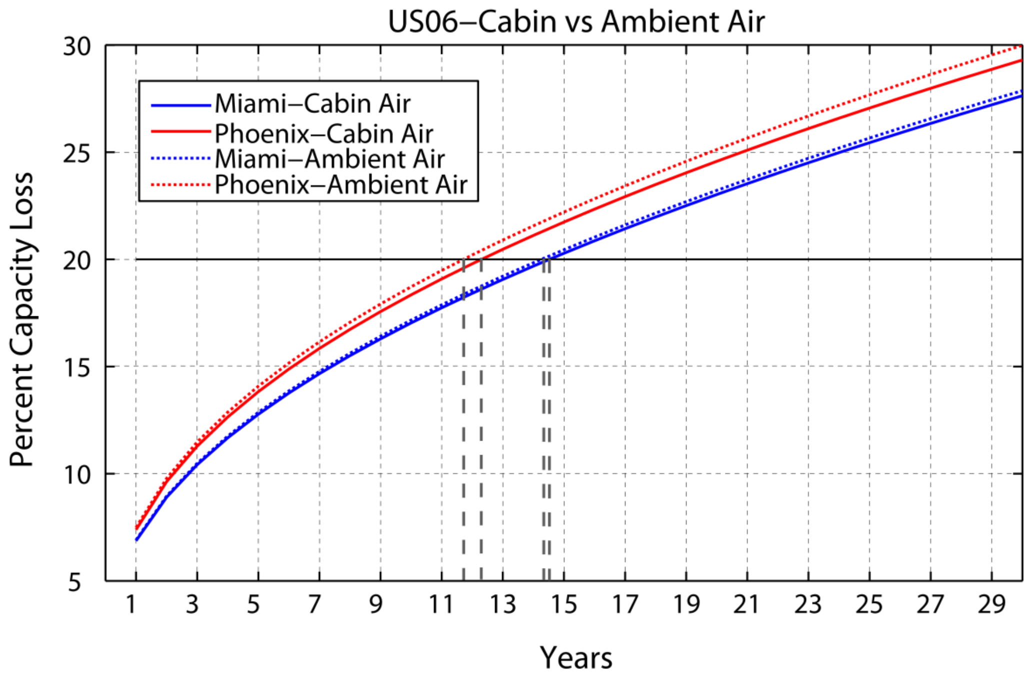

Figure 9. Cooling medium comparison for driving with US06- Cabin air vs ambient air

3. Fan On-Off Temperature

In all simulations described so far, a default fan on-off control strategy was used. To understand the effect of thermal control variables, various on-off control strategies were simulated for UDDS driving cycle. The cases tested are given in Table 2. Note that, case 0 (zero) refers to the case when there is no battery thermal management system issued in the vehicle.

Table 2. Fan on-off temperatures tested

Cases	ON Temp [^{o}C]	OFF Temp [^{o}C]
0	-	-
1	35	33
2	35	30
3	35	28
4	30	28
5	30	25
6	33	28
7	33	25
8	35	25

Battery capacity fade versus time in Miami for all fan on-off temperatures are given in Figure 10. The results indicate that given the same driving conditions the battery life can be increased significantly just by altering the fan on-off control strategy. However, further analysis is required to see the system level indications of choosing different control strategies. Also, it can be seen both on and off temperature settings are important for determining life.

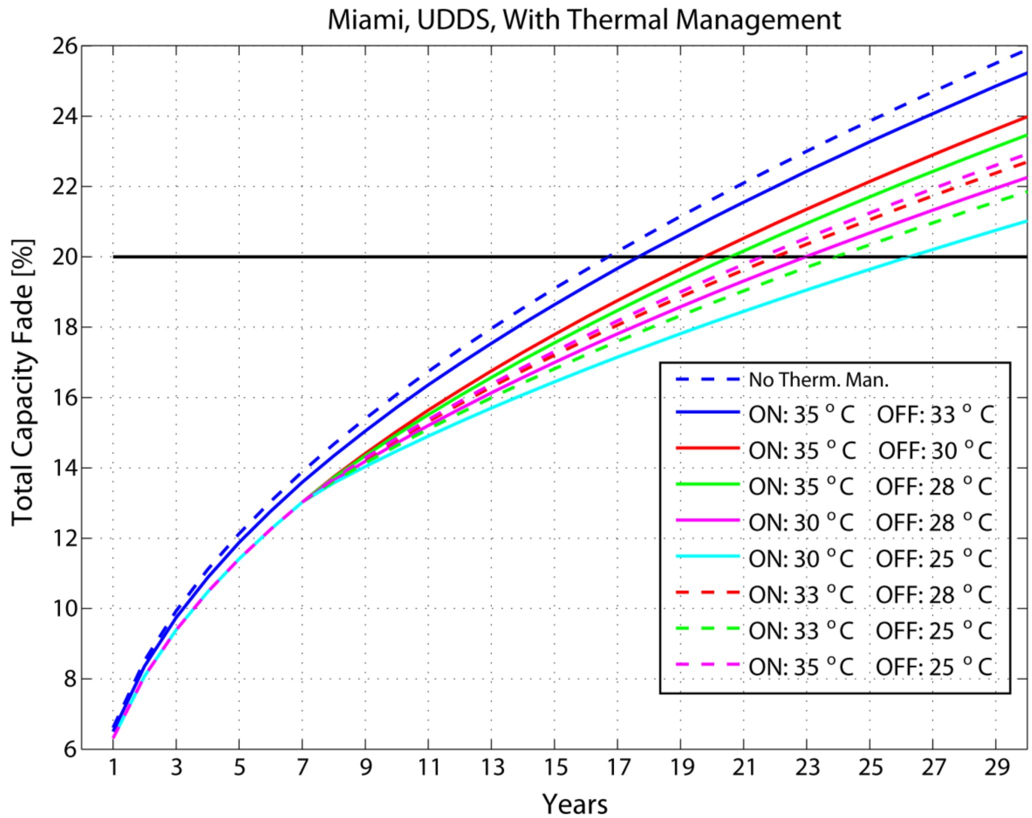

Figure 10. Capacity fade in Miami with UDDS- Comparison of fan on-off temperatures

Assumptions/Model Limitations

This paper presents the preliminary results of an ongoing study evaluating the effect of thermal management on battery life. In its current form the model has several limitations that should be considered when interpreting results.

The battery life models used in this study are derived using data for a limited range of temperatures, and trends are extrapolated for lower temperatures. When storage life models are extrapolated to temperatures lower than 15^{o}C, counterintuitive trends are observed. We selected cities to avoid temperatures below 15^{o}C; however, because degradation rates are primarily driven by peak temperatures, errors in degradation rates at low temperatures may be less critical. To the authors' knowledge, a more comprehensive battery life model is currently not available in public literature.

In thermal management, providing a uniform temperature distribution across cells in the battery pack is a design criterion. In this study, it was assumed that the system satisfies this criterion by maintaining a negligible temperature variance across the pack. However, since temperature variance will cause some cells degrade faster than others, it is still necessary to check the validity of this assumption with more detailed simulation. In addition, natural convection and pack conduction, ignored in this study, is important when there is no forced air flow over the cells over long periods. Moreover, the assumption that battery temperature reaches ambient immediately when the vehicle is at rest underestimates storage fade. By ignoring the time taken for the battery to cool down when at rest, we also underestimate the benefit of thermal management over no thermal management. Therefore, it is necessary in future work to assess the actual temperature profile of the battery at rest and use that profile in storage fade calculations. In addition, changing air flow rate may affect results significantly.

Besides model limitations, the design of the simulations can also affect results. In this study, although reasonable bounds on driving cycle conditions were selected for simulations, the driving profile created differs from real driving conditions both in driving style, average driving distance, and variation in driving distance over time. Since it was shown in the results section that driving cycle has a significant effect on battery life, using real world driving profiles, in which daily driving distances and speeds vary every day, is expected to decrease the battery life. Therefore, real-world driving profiles should be simulated to obtain more realistic battery life results. In addition, in the simulations described above, seasonal average temperatures are used. However, since results significantly depend on peak temperatures, higher resolution temperature data, such as hourly or daily temperature averages should be used in simulations. In future work, we intend to analyze sensitivity of results to these variables and conditions and address the model limitations described above.

Summary and Conclusions

We apply a joint thermal and degradation model of an air-cooled cylindrical $LiFePO_4$/graphite PHEV battery pack to study the effect of thermal management on battery life under several climate, drive cycle, fan control, and air source scenarios. Preliminary results suggest that thermal management increases life by 5% to 53%, depending on the scenario. Variation in driving conditions from the UDDS cycle to the US06 cycle has a dramatic effect on battery life if there is no thermal management, reducing life by about 60%. With air cooling, US06 decreases life by only 20%. Thus, driving conditions are important for battery longevity, and thermal management mitigates the effects of aggressive driving. Climate also affects battery life: batteries have a 20% shorter life in Pheonix than in Miami (reduced to 11% with thermal management) due to higher summer peak temperatures in Pheonix even though Miami has higher average temperatures. Use of ambient inlet air vs. pre-conditioned cabin air for battery cooling has a minor effect on degradation for the base control strategy. However, variation in control parameters (fan on-off temperatures) can increase battery life by 53% or more.

Future work will address the identified model limitations to improve accuracy of estimates and comparisons.

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