

Depth of Discharge Affects Cycling Aging but May Not Affect Real-World Lifetime in Powered Wheelchair Batteries

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ABSTRACT

Powered wheelchairs are essential to many, and lithium-ion batteries are commonly used in powered wheelchairs. This means long-lasting batteries are important for powered wheelchair users to reduce costs and increase sustainability. This study investigates how depth of discharge affects the cycle life of lithium-ion batteries, and what charging strategy maximizes useful battery lifetime for powered wheelchair users under realistic daily usage patterns. Cycling data was obtained from Sandia National Labs and accessed through the Battery Archive database. Full, moderate, and shallow depth of discharge conditions were studied, with temperature and charge rates being held constant. Deeper discharge demonstrated faster fade rates, with shallower depth of discharge surviving many more cycles than deeper depth of discharge. There was a statistically significant difference found between the moderate and shallow discharge fade rates. The full discharge condition had only one cell and demonstrated a pattern of faster fade rate, but this could not be confirmed because only one cell was analyzed. Applying these results to powered wheelchair usage profiles to obtain predicted battery lifetimes from cycling alone demonstrated that the predicted battery lifetimes greatly exceeded what typical usage length would look like. This suggested that calendar aging is a likely competing limitation on battery life compared to depth of discharge, but this comparison was not analyzed directly and future work is needed to confirm this conclusion. Thus, while shallower depth of discharge provides the longest battery life, the practical benefits appear to be limited. Managing factors like storage temperature and state of charge may be more beneficial to extending powered wheelchair battery life.

INTRODUCTION

In the United States, approximately 30% of the 2.7 million wheelchair users rely on powered wheelchairs (Kairy et al., 2014). These people rely on powered wheelchairs to go about their daily lives, and battery life of these wheelchairs is essential to uphold their quality of life. It is important to have long-lasting batteries because replacement costs can be high and place unnecessary burdens on the users, and unexpected failure of a battery disrupts the daily lives of wheelchair users. Powered wheelchair users

depend on the batteries daily. Therefore, increasing battery lifespan of powered wheelchairs is significant because it can reduce costs, improve quality of life, and uphold the independence and mobility of the wheelchair users.

One of the most prominent factors impacting battery aging is depth-of-discharge. Depth of discharge is the percentage of the battery's capacity that has been used. Previous studies have shown that deeper discharge shortens cycle life of lithium ion batteries by increasing the degradation within the battery (de Vries et al., 2015). The effect of depth of discharge on lithium-ion batteries has been studied in multiple applications such as electric vehicles and grid storage, but has been relatively unexplored for assistive devices such as powered wheelchairs. Additionally, while the effect depth of discharge has on lithium-ion batteries has been understood, this effect has not been quantified. Understanding this gap can help identify charging strategies that increase battery life and quality, improving the quality of life for the millions of powered wheelchair users.

This paper quantifies the effect depth of discharge has on battery cycling aging by using real data, translating it to wheelchair users, and testing whether it actually matters for real-world battery life. This paper's research question is: How does depth of discharge affect the cycle life of lithium-ion batteries, and what charging strategy maximizes useful battery lifetime for powered wheelchair users under realistic daily usage patterns?

METHODS

The battery cycling data was obtained from Sandia National Labs and accessed through the Battery Archive database. Lithium iron phosphate 18650 battery cells with 1.1 Ah nominal capacity were used. These types of batteries are increasingly used in modern powered mobility devices. Seven cells across three state of charge conditions were analyzed, which corresponded to three depth-of-discharge conditions: full 0-100% state of charge (100% depth of discharge), moderate 20-80% state of charge (60% depth of discharge), and shallow 40-60% state of charge (20% depth of discharge). These are referred to as full, moderate, and shallow depth of discharge in the rest of the paper. There was one full cell, four moderate cells, and two shallow cells. Specifically, the filenames for the Battery Archive cells were SNL_18650_LFP_25C_0-100_0.5-0.5C_a for full, SNL_18650_LFP_25C_20-80_0.5-0.5C_a, _b, _c, and _d for moderate, and SNL_18650_LFP_25C_40-60_0.5-0.5C_a and _b for shallow. All cells were 25°C and matched 0.5C charge and discharge rates. Temperature and rate were held constant to ensure that depth of discharge was the sole independent variable.

Before analysis, the data needed to be cleaned up. The raw data mixed everyday partial cycles with periodic full-capacity reference cycles which had a discharge capacity between 0.85 and 1.2 Ah. Only the reference cycles were kept because these are the consistent measurements of true battery health. They measure full capacity consistently and are thus the only fair way to compare aging.

Battery health was measured using state of health (SOH). Each cell's baseline capacity was set as the median of its first five reference cycles, then SOH was expressed as a percentage of that baseline. A small number of non-physical readings were removed as measurement artifacts based on two rules. Reference cycles with a state of health above 101% were removed. Additionally, any point deviating sharply by more than 2 percentage points from a computed centered rolling median of state of health with a 5 cycle window was removed.

Equivalent full cycles (EFC) is a way to compare cells by total energy delivered expressed in units of 'full batteries' rather than raw cycle count. This was computed with this equation: $EFC = \text{Cumulative Discharge Capacity (Ah)} \div \text{Nominal Capacity (Ah)}$. EFC was used because a shallow cycle does less work than a full one, so counting raw cycles can be misleading. Comparing by energy delivered (EFC) is the fair comparison.

To find the fade-rate, a straight line was fitted to SOH versus EFC for each condition. Then, the slope was used as the fade rate, which is the percent capacity lost per 1000 EFC. SOH decreases as EFC increases, so the regression slope is negative for every condition. However, to better understand the differences in rates of decline, all of the fade rates are reported as the magnitude of the regression slopes, which is why all fade rates are shown as positive. Because cells were tested over different EFC ranges, all three conditions were fit over the same EFC window of 0 to 1735 EFC, set by the cell with the shortest life: SNL_18650_LFP_25C_40-60_0.5-0.5C_a, which reached a maximum of 1735 EFC. This was done so the fade rates were directly comparable rather than distorted by differing test lengths. This created a pooled fade rate made by fitting one line through all reference cycles from all cells in one condition combined. This fade rate is stated as the headline fade rate for each condition. This value is used in all lifetime calculations. For a check on uncertainty, a fade rate was fit for each cell in the same window, instead of pooling cells together. These individual fade rates cannot be used as the headline fade rate because the pooled fit is not the average of the fits per cell, but a fit that allows the spread from cells within each condition to be quantified. The mean and standard deviation of individual cell slopes were calculated for the moderate and shallow conditions, and Welch's t-test was used to determine whether the two conditions' individual cell fade rates differed. Because the full discharge condition had one cell, there was no variance that could be estimated between individual cells. This means that a statistical comparison involving this condition was not possible, so its fade rate is shown as a pooled estimate with a single cell with no uncertainty measure. Analysis was done in Python using pandas, NumPy, and Matplotlib.

For wheelchair usage profiles, light, average, and heavy users were defined with daily driving distances drawn from three published powered-wheelchair studies. A study analyzing a group of 2615 Permobil powered wheelchairs and a group of 3058 Permobil powered wheelchairs over an entire year found the mean distance driven daily was 1365m (Zhu et al. 2025). Cooper et al. (2002) tracked two different powered wheelchair using groups for 5 days: one group in the communities of Pittsburgh and the other at the National Veterans Wheelchair Games in San Antonio. With a total of seventeen participants in the study, the Pittsburgh group drove about 1667m/day and the San Antonio group drove about 3433 m/day. Finally, Cooper et al. (2008) studied 9 children using powered wheelchairs over 5 days and found their

average daily driving distance was about 1752 m/day, with a standard deviation of about 835. The average usage profile was set at 1400m/day to roughly match the mean from Zhu et al. (2025) because this study had the largest sample size. The heavy usage profile was set at 3400 m/day to match the most active group in the Cooper et al. (2002) study. The light usage profile was set at 1000 m/day. While this is less than the means in the three studies, it was chosen to be representative of a user that uses a wheelchair less than typical averages. This number does fall within the standard deviation seen in Cooper et al. (2008), but this number should still be treated as an assumption. A representative range of about 15km per full charge was assumed. The manufacturer whose wheelchairs were studied in Zhu et al. (2025), Permobil, published usage-distance data as manufacturer rated ranges of a maximum of about 21 to 32 km (Permobil, n.d.). However, manufacturer range is measured under ideal conditions and is not consistent with realistic driving conditions. Because of this, real driving ranges are usually under the manufacturer ranges so 15km was estimated to be the range driven as a pure assumption. Daily driving distance was converted to equivalent full cycles per day by dividing distance by range per charge, then multiplied by annual use-days which was approximately 300 from literature (Zhu et al., 2025). Two equations were used to calculate the values shown in Table 1:

$$EFC/day = Distance (m \text{ per day}) \div Range (m \text{ per charge})$$

$$\text{and } EFC/year = EFC/day \times Days/year (days/year).$$

For example, the average user traveled 1400 meters per day, so the calculations were $1400m/day \div 15000 m/charge \times 300 days \approx 28 EFC/year$. This gave EFC per year for each user profile. Table 1 demonstrates the driving distance for each user profile, then the calculations for EFC/day and EFC/year. Light usage results in the least EFC/year, while heavy usage results in the highest EFC/year. As daily driving distance increases, EFC/year increases.

Table 1. Wheelchair usage profiles

Profile	Distance (m/day)	EFC/day	EFC/year
Light	1000	0.07	20
Average	1400	0.09	28
Heavy	3400	0.23	68

RESULTS

For full depth-of-discharge, the rate of capacity loss per 1000 EFC was 3.51%, using a pooled fit across all of the reference cycles in the common window for n=1 cell. This value is also the individual cell fade rate slope because only one cell was in this condition. For moderate depth-of-discharge, the rate of

capacity loss per 1000 EFC was 3.34%, using a pooled fit with $n=4$ cells. For shallow depth-of-discharge, the rate of capacity loss per 1000 EFC was 2.88%, using a pooled fit with $n=2$ cells. To determine whether these pooled fade rates demonstrated real depth-of-discharge effects on batteries instead of cell variation, a fade rate was fit separately to each individual cell. The moderate cells had fade rates of 3.42%, 3.34%, 3.26%, and 3.19% per 1000 EFC. The standard deviation was 0.10 and standard error was 0.05, using the mean of 3.30%. The shallow cells had fade rates of 2.91% and 2.87% per 1000 EFC. Using the mean of 2.89%, the standard deviation was 0.03 and the standard error was 0.02. Using a Welch's t-test comparing the cell slopes of the moderate and shallow conditions demonstrated the difference to be statistically significant, with a t value of -7.90 and a p value of 0.002. This supported a real difference between the two depth-of-discharge conditions. The full discharge condition has only one cell, so no cell variance estimation or statistical test comparison could be done with it. The pooled fade rate of 3.51% does fall outside the range of all fade rates of the moderate cells, which is consistent with a conclusion of a faster fade rate at deeper discharge, but this conclusion cannot be reached because it is unknown if that cell was simply unusually fast rather than deeper discharge truly fading faster. The difference between moderate and shallow discharge conditions is statistically supported evidence supporting the conclusion that depth of discharge affects fade rate, but any comparison with the full discharge condition is purely descriptive evidence rather than an indication of any causation.

Figure 1. Battery state of health versus cycle number for three depth-of-discharge conditions. Rate at which state of health decreases per cycle increases as depth of discharge decreases.

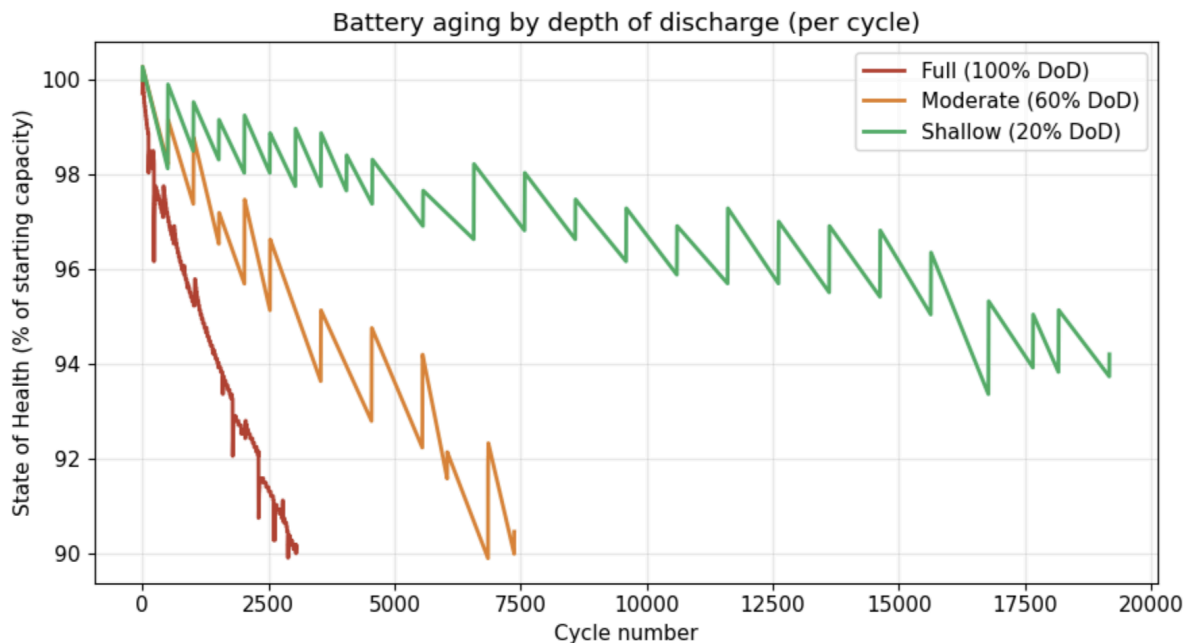


Figure 2. State of health versus equivalent full cycles, with fitted trend lines, compared over a common energy window. Deeper discharge shows a faster fade rate per unit of energy delivered.

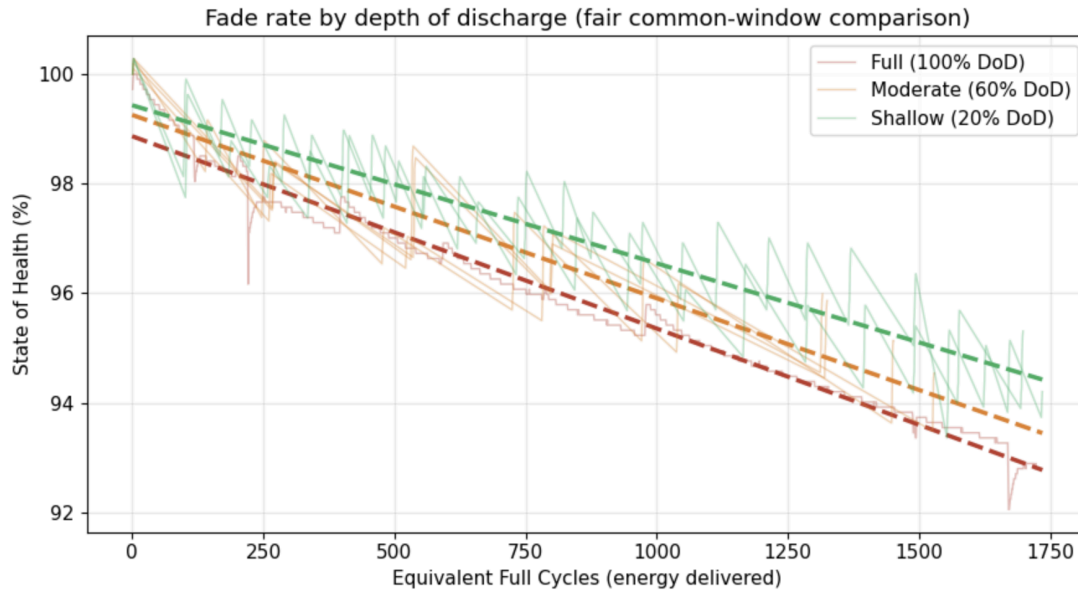


Figure 1 demonstrates that full depth-of-discharge conditions survive the least amount of cycles in the tested range. As depth-of-discharge decreases, the battery life in cycles increases. Figure 2 demonstrates that batteries with greater depth-of-discharge wear down faster over time than batteries with shallower depth-of-discharge. As depth-of-discharge decreases, the fade rate of the battery decreases.

The industry standard for battery end-of-life threshold is 80% capacity. The energy delivered before end-of-life was found by dividing the 20% capacity loss by each fade rate:
 $EFC = 20\% \div \text{Fade Rate (\% per 1000 EFC)} \times 1000 \text{ EFC}.$

$$\text{Full: } 20\% \div 3.51\% \times 1000 \text{ EFC} \approx 5,700 \text{ EFC}.$$

$$\text{Moderate: } 20\% \div 3.34\% \times 1000 \text{ EFC} \approx 6,000 \text{ EFC}.$$

$$\text{Shallow: } 20\% \div 2.88\% \times 1000 \text{ EFC} \approx 6,900 \text{ EFC}.$$

Using this capacity, full depth of discharge reaches 5700 EFC, moderate depth of discharge reaches 6000 EFC, and shallow depth of discharge reaches 6900 EFC. Combining this with the three usage profiles gives the predicted battery life for each user type and charging style. Finding the end-of-life- values requires extrapolating the fitted linear fade rate significantly beyond the range it is measured over. None of the cells tested were cycled to reach the end-of-life threshold of 80%. The farthest tested cell for each condition was only 2791 EFC for full, 3650 EFC for moderate, and 2012 EFC for shallow. The highest capacity loss for any cell was observed to be about 10%. Thus, the projects extrapolate about 1.6 to 3.5 times beyond the farthest tested cell for each condition. In the tested range, the fade rates were not perfectly linear. The full cell and all moderate cells demonstrated a slower fade rate in the second half of the range compared to the first. The shallow cells both demonstrated a faster fade rate in the second half

of the range. The linear fade-rate assumption is approximate over the tested data itself, so extrapolating this significantly adds uncertainty to the results. The predicted lifetime values were found by this equation: $Lifetime (years) = EFC_{EndofLife} (EFC) \div EFC/year (EFC \text{ per year})$. For example, to find the expected lifetime for a light user with shallow depth-of-discharge, these calculations are used: $6900 EFC \div 20 EFC/year \approx 345 \text{ years}$. The results of all of these combinations are shown in Table 2. It is seen that shallow depth-of-discharge yields the highest battery lifetimes compared to moderate and full. The values range from 84 years with a heavy user and full discharge, to 345 years with a light user and shallow discharge. These are the predicted years of use before the battery degrades to 80% from cycling alone.

Table 2. Predicted battery lifetime in years (cycling only, to 80% capacity), under assumption that fitted fade rate remains linear beyond the tested range and over the extrapolated range

User	Full	Moderate	Shallow
Light	285	300	345
Average	204	214	246
Heavy	84	88	101

EFC/year and the lifetime in years were calculated using 10km and 20km per charge to test the sensitivity of the lifetime year projects to the assumed 15km range, with all other assumptions held constant. At the 10km range, the calculated lifetime predictions ranged from 56 years for a heavy user with full discharge to 231 years for a light user with shallow discharge. At the 20km range, the calculated lifetime predictions ranged from 112 years for a heavy user with full discharge to 462 years for a light user with shallow discharge. Because the 15km range estimates fall within these ranges of numbers, the conclusion that comes from the paper is not highly sensitive to the 15km range value assumed. Even with a heavy user, full discharge, and a 10km range, the predicted lifetime is still a significant amount of years and indicative of the same general conclusion that comes from using the 15km range.

DISCUSSION

The results imply that depth of discharge does affect cycling aging and deeper discharge wears batteries faster. Shallower depth-of-discharge will likely result in longer battery lifespans for any usage profile. However, translating the fade rates into lifetimes represented in years requires extrapolating the fitted trend 1.6 to 3.5 times beyond the farthest range any cell was tested, because no cell reached the 80% end-of-life capacity. This extrapolation itself assumes the fade rate is linear over the tested range, but the range is not able to be proven to be fully linear itself. The predicted cycling lifetimes are still extremely long, ranging over 100 years for most users. If the linear fade rate assumption is true, it would indicate that under realistic wheelchair usage, cycling is not what limits battery life, because essentially all users

are not using wheelchairs for that significant amount of time, and batteries will realistically tend to wear down many years before those predicted lifetimes. However, given the significant extrapolation done, this conclusion is unable to be confirmed.

At average use, the extrapolated projection suggests the battery reaches end-of-life from cycling alone in roughly 200 years. Studies show lithium-ion batteries lose less than about 1% of capacity per year at room temperature from calendar aging, which reaches the 20% end-of-life threshold in roughly 20 years (Ali et al., 2023). However, this literature shows that the rate strongly depends on cell chemistry, state of charge, temperature, and storage conditions. These factors were not matched to the cells analyzed in this study. This estimate from literature is an order-of-magnitude faster than the extrapolated cycling fade rate, which makes calendar aging a realistic competing limitation on real-world battery lifetime rather than depth of discharge. However, because calendar aging was not analyzed with the same cells and conditions as this study, calendar aging cannot be directly compared to depth-of-discharge and concluded to be a faster factor for wearing the batteries in this study. Published work shows calendar aging is generally driven by storage temperature and state of charge, not depth of discharge, and controlling both of these factors is essential to extending lithium-ion battery life (Yang et al., 2025). If calendar aging limited battery aging for powered wheelchairs more significantly than depth-of-discharge did, more useful advice could be for a user to avoid storing the battery fully in a hot place, rather than to focus on how deeply they discharge it.

Under the specific LFP cycling conditions and usage assumptions analyzed, depth-of-discharge differences appear small relative to the modeled time scale. Wheelchair users could possibly benefit from focusing on not storing the battery in a hot place in a fully-charged storage state. The findings of this study are strongest for powered wheelchairs that use modern lithium-ion batteries, since these were the specific batteries studied. Additionally, shallower depth-of-discharge strategies improved projected battery lifetime for all simulated usage patterns. The proportional benefit is similar across usage patterns, and even heavy users' projected cycling lifetime far exceeds realistic battery life.

Limitations

The cycling cells and cited calendar-aging studies are not the exact same battery under the same conditions, so the side-by-side comparison is order-of-magnitude, not exact. The data does not measure calendar aging directly; the calendar aging information was brought in from published work. The published work brought in about calendar aging tested different cells and conditions than the ones analyzed in this study. The calendar aging literature also shows that the fade rate depends strongly on chemistry, state of charge, temperature, and storage conditions, which were not matched between the cycling cells in this study and the cells in the calendar-aging literature. Thus, the comparison between degradation due to cycling and due to calendar aging should be treated as an order-of-magnitude comparison that is a possible competing limitation to battery life rather than depth-of-discharge. Lithium-ion batteries were studied, but many real wheelchairs use lead-acid batteries, which age much faster. This is one reason why real batteries are replaced every 1 to 3 years, much sooner than the 20 year

calendar-aging estimate for lithium-ion. The data was at a constant 25°C with clean charging patterns, however real-world temperature swings and irregular charging could change how depth of discharge affects the aging of the battery. The full-discharge condition used one cell, moderate used four, and shallow used two, so some conditions are better supported than others. The data does not represent each discharge condition equally.

Additionally, the lifetime predictions seen in Table 2 rely on extrapolations that extend the fade rates 1.6 to 3.5 times beyond the farthest EFC range any cell reached. The fade rates themselves were shown to not be completely linear, adding more uncertainty to this extrapolation. This extrapolation is the step that connects the cycling data to real world battery lifetime predictions for powered wheelchairs, so these year estimates are order-of-magnitude rather than concrete lifetimes in years.

The 15km range assumption was drawn from Permobil's published usage-distance data for lithium ion batteries, and the Zhu et al. (2025) study data was drawn from Permobil wheelchair users. However, Permobil powered wheelchairs typically use lead-acid batteries rather than lithium, which was the battery type of the data analyzed. This means that the 15km assumption could possibly not represent a typical user studied in Zhu et al. (2025) if they were using lead acid instead of lithium ion batteries, since the study does not make it clear which battery is being used. Also, the three studies cited to define the wheelchair usage profiles greatly vary in sample size, with Zhu et al. (2025) sampling thousands of wheelchairs while the other studies only use 9 and 17 participants. Additionally, Cooper et al. (2002) sampled a group of attendees of a wheelchair sporting competition which could not be representative of what a realistic powered wheelchair user's daily usage would look like. Cooper et al. (2008) studied children only, which could limit its applicability to adult powered wheelchair users, which are much more plentiful. The sources used to generate the light, average, and heavy usage profiles are composed of vastly different sample sizes and circumstances in which the powered wheelchairs were used, so these should simply be treated as benchmarks rather than actual representative sampling of the broader powered wheelchair-using population.

Future Work

Future studies would test calendar aging with the same cell chemistry and the same cells analyzed in this study to have matched calendar-aging and cycling-aging data that could be combined into a single model that predicts which factor dominates and when. This would also be analyzed across multiple storage conditions, temperatures, and states of charge, because the calendar-aging literature cited these as conditions that calendar aging fade rates depend on strongly. Multiple battery chemistries including lead-acid would be tested with a range of temperatures to make the data more representative. Finally, the data would be validated against real wheelchair battery replacement data. This future work would provide better comprehensive advice for powered wheelchair users to optimize the methods in which they charge and store their batteries so they can have greater battery life for their wheelchairs.

CONCLUSION

This paper studied the research question of how depth of discharge affects the cycle life of lithium-ion batteries, and what charging strategy maximizes useful battery lifetime for powered wheelchair users under realistic daily usage patterns. It was found that deeper discharge wears the batteries faster, but depth of discharge does not appear to realistically limit cycle life in the specific cycling conditions studied. At realistic usage the cycling lifetime is so long that cycling is likely not the practical limit in this study. Calendar aging could be a possible alternative limit to battery life rather than depth of discharge, so it is important for future studies to directly measure how calendar aging affects battery lifetime for powered wheelchair users. Charging depth appears to offer limited real-world benefit for typical users, but storage temperature and state of charge could matter more. Confirming this comparison requires analyzing data from battery cycling that extends much closer to the end-of-life-threshold.

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