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Pack and Vehicle Level Impacts of High C-Rate Cells for Fast Charging

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Abstract—The adoption of EVs as a mainstream option for vehicle buyers is underway globally [1]. One challenge facing customers is the tradeoff in utility with respect to internal combustion-engine (ICE) vehicles in terms of driving range. Typical EVs [2] may have a maximum range of 300 mi under favorable driving conditions, requiring the customer to stop and charge for longer trips. A 15 to 30-minute charging event might result in a range gain of around 200-mile whereas an ICE-equipped vehicle can typically refill to maximum range with a 5-minute fueling station stop. Advances in battery cell performance are an essential part of reducing the time to charge and increasing the range gain with each charge. Charging time is a particular challenge for large vehicle electrification, where lower vehicle energy efficiency results in larger energy requirements to achieve the same range gains. In this study, we examine the impact of an advanced battery cell chemistry on vehicle battery pack design and charging performance. An optimized battery pack design is developed using this cell; with a +8C average charge rate, the pack can theoretically accept a charge equivalent to 150 miles of energy in less than 5 minutes. However, there are pack volume and mass penalties relative to the baseline battery pack, and reduced overall range due to lower cell energy density.

Keywords-electric vehicle charging; battery pack design; electric vehicle range; charging time

I. INTRODUCTION

Developing new battery technology for electric vehicles (EVs) encompasses a wide range of activities, each critical to enhancing performance, safety, cost-efficiency, and sustainability. Usually when analyzing the battery technology for EVs, three levels of evaluation are considered, cell level, pack level and vehicle level. At the cell level, the focus is primarily on the materials and chemistry of the battery cells. Key aspects include chemistry, energy density, cycle life, thermal management, and degradation. At the pack level, multiple cells are combined and managed to work as a single unit. Key considerations include configuration, battery management system, cooling systems, and safety mechanisms. Finally, at the vehicle level, the integration of the battery pack into the vehicle is assessed. This includes energy efficiency, regenerative braking, total vehicle dynamics, charging system and overall performance. Each level of analysis is crucial for developing EVs that are efficient, safe, and reliable. Companies often invest heavily in research and development at all three levels as well as the tools and methods for analysis to push the boundaries of what their EVs can achieve. For a long time, the Combined Charging System (CCS) was prominent in the EV charging landscape. It was highly regarded for its adaptability, making it suitable for a range of vehicles. However, as the electric heavy-duty vehicles sector grew, CCS's constraints started to surface [3]. To satisfy the market demand of charging heavy-duty vehicles within a reasonable time, a new solution for high-power charging is needed. Also, batteries with larger capacities need to be taken into consideration [4-5]. To charge those large capacity batteries in comparable times as available today or even faster, the charging power needs to be increased. Besides the charging voltage, the charging current also needs to be increased to boost the charging power. The Megawatt Charging System (MCS) was designed for the industry to create a common solution for charging the heavy duty EVs within a reasonable time [6].

In this study we evaluate cells with repeatable fast charge C-rate to meet light and medium duty vehicle (MDV) application requirements. Figure 1 shows the average fast charge C-rate and estimated charge time to deliver battery energy equivalent to 150 miles of range for selected applications. Depending on the vehicle's energy consumption (Wh/mi), the energy equivalent to 150 mi of range will vary; coupled with the allowable charging rate for the cells used in the pack, the total time for charging that energy is determined. The first bar in the chart show potential targets (charge time, charge power) for an MDV option. Key performance constraints are maximum cell DCFC C-rate and the vehicle thermal system's capability to reject heat generated during charging. Other bars show some typical light-duty (LDV) EV vehicle charging capabilities as publicly reported. The LDVs require up to 2C average charge rates while the MD application requires a ~3C average charging rate for charging an equivalent of 150mi energy in 10 minutes. We can see that, to meet the MD requirement, an ideal cell should at least meet the 3C charging capability.

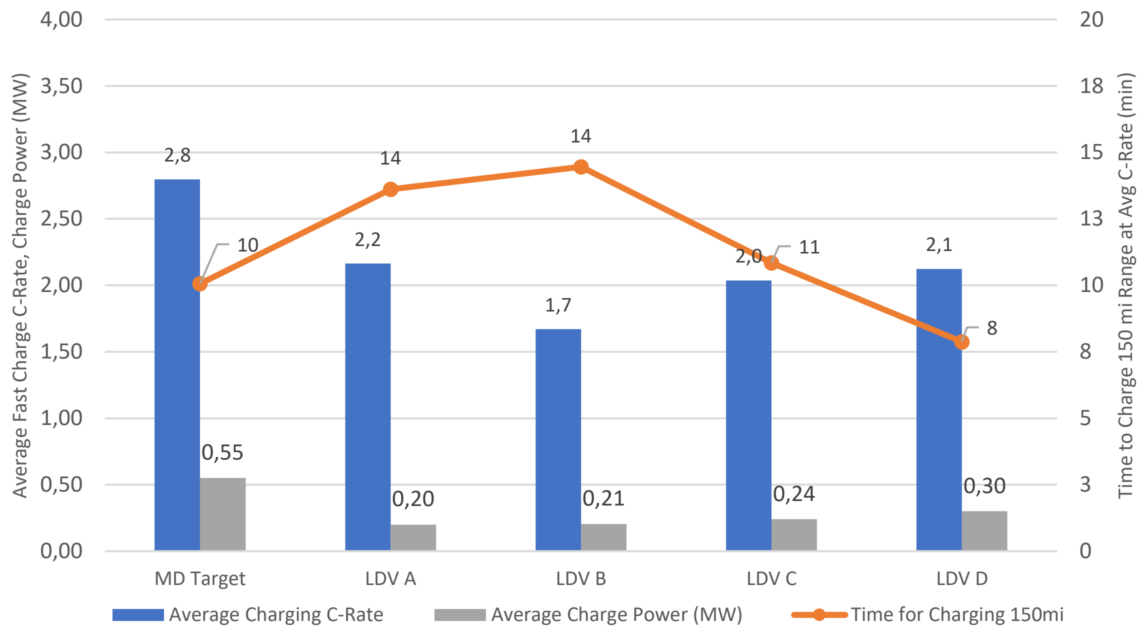

Figure 1 Average fast charge C-rate & estimated 150 mi charge time in various applications.

Cell characteristics (energy density, charging performance) for a high-C-rate fast charge cell, which we denote as 'cell A' were evaluated by GM's R&D battery research team. Using internally developed proprietary battery cell-to-pack synthesis tools, we modeled the candidate cells as scaled-up designs, with the resulting battery modules and packs based on the pack-level power and energy requirements. Design constraints include cell dimensional limits, cathode loading & pack dimensional limits. It is then possible to compare the performance of the candidate cell battery pack with a baseline battery pack considering energy density, volume, mass, and charging speed. The key challenge is balancing the cell design for best energy, fast-charge capability, and pack volume and mass increase.

II. Methodology for Pack Level and Vehicle Level Analysis

Battery pack design tools are in a rapid state of development both internally at automakers and commercially. Our internally developed R&D tool is intended to provide early battery pack architectural design guidance for GM engineers, allowing them to quickly explore the architecture of various batteries for a variety of applications, providing optimal design solutions at cell level, module level and pack level. The optimization objective can be selected between minimizing the pack mass or cost. This tool allows us to adjust cell design, module design and pack design given pack requirement such as energy and power.

The pack design space includes pack dimensions, the number of cells connected in parallel in each cell group (Np), and the total number of cell groups connected in series in a pack (Ns), which are determined by the cell capacity and power requirement.

The module design space includes cell arrangement orientation, numbers of cells per module, and module series count (i.e., the number of cell groups connected in series in each module). Figure 2 shows four typical battery pack designs using different cell formats. Case 1 represents a pouch-cell pack design. Packs using cylindrical cell and prismatic can cell are typically represented by Cases 2-4. The modules per row represent the number of modules in the cross-car direction. The modules per column represent the maximum number of modules in the longitudinal, wheel-base direction.

	Case 1	Case 2	Case 3	Case 4
Cell Orientation	2	1	1	2
Modules in Cross Car Dir	2	2	1	<= 10 (maximum)
Modules in Wheel-base dir	<= 10 (max)	<= 10 (max)	<= 10 (max)	1
Module to Module Clearance (mm)	20	20	3	3
Cross-beam width (mm)	30	30	0 (no cross-beam)	0

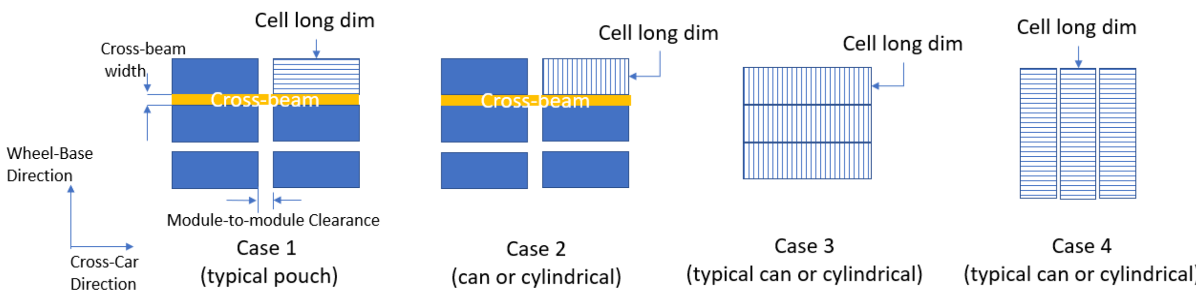

Figure 3 Pack Design Tool Cell and Pack Orientation Examples

The cell design space includes electrode chemistry, cell format, cell dimensions, and cathode loadings. There are three options of cell formats: cylindrical, pouch and prismatic can. The pack design tool uses an internally developed cell material model to output cell design parameters (e.g. energy density, power estimate) for a specific cell. The inputs include the negative and positive electrode properties for a specific chemistry. The pack design tool will output possible battery pack designs based on the constraints provided. In this study, we use this tool to build packs composed of the baseline cell and proposed new high C-rate cell A. We found that with cell A's lower energy density relative to the baseline cell, there is module volume growth compared to the baseline battery pack to

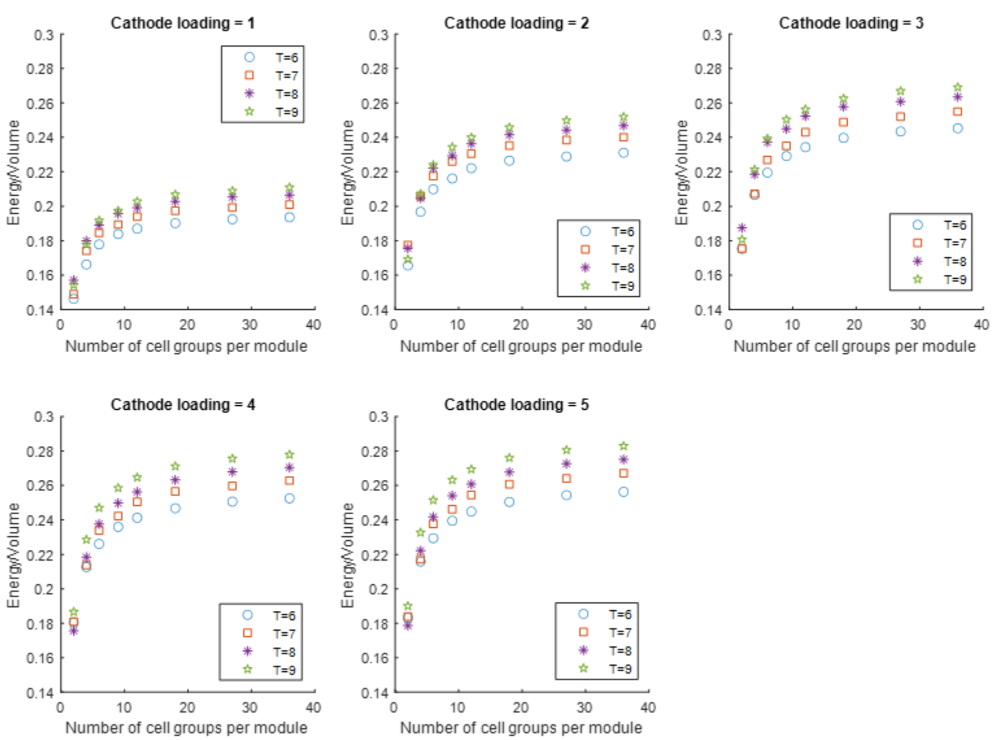

Figure 2 Pack-segmentation Trade-off to mitigate effect of lower Wh/L

meet the pack power and energy requirement. This module volume growth is a negative aspect of cell A, which motivates us to determine the minimum space required to maintain baseline battery pack energy.

Using the pack design tool, we varied the battery pack-segmentation (number of cells in series and parallel connections) to find different pack arrangements that would reduce the total module volume. The outcome is shown in Figure 3, where the x-axis represents the number of cell groups arranged per module (module series count) and the y-axis is the ratio of energy to module volume. The parameter T is the cell thickness (6 to 9 mm). It is found that as we increase the number of cells or cell groups in one module, the energy/volume ratio of the overall pack increases. However, the effectiveness of this strategy is limited because, as the module series count becomes larger, the energy/volume ratio increases more slowly.

III. Pack-level analysis

Using a baseline cell with typical performance (< 2.0C sustained DCFC charge rate) and cell A we designed a battery pack for a small SUV. The small SUV has a nominal pack energy of 70kWh. Due to space limitations, we will not cover the results for cell A in a medium duty context in this paper. It is sufficient to say that cell A would not meet the medium duty requirement due to the very large pack required (more than 2X the LDV case).

1) Pack level analysis for Small SUV

For the small SUV case design, the energy requirement of the battery pack is 70kwh, and the power requirement is 170KW. This battery pack needs to fit within specified rectangular dimensional constraints with allowed pack volume less than 300L. Optimizing for minimum pack mass with dimensional constraints we developed several virtual pack designs built with the baseline cell and selected the one with the minimal pack mass. The results for Cell A are shown in Fig. 4. From the relative differences, we can see that cell A has significantly higher relative pack mass, lower cell energy density and lower cell specific energy (Wh/kg). However, it does meet the overall pack energy requirement while providing significantly higher fast charge capability. Figure 5 shows relative pack dimensions for the packs using baseline cell and cell A. The lower energy density cell results in wider pack in the vehicle cross-car (Y) dimension than is desirable which would force change to the vehicle or a lower energy pack (about 17% lower).

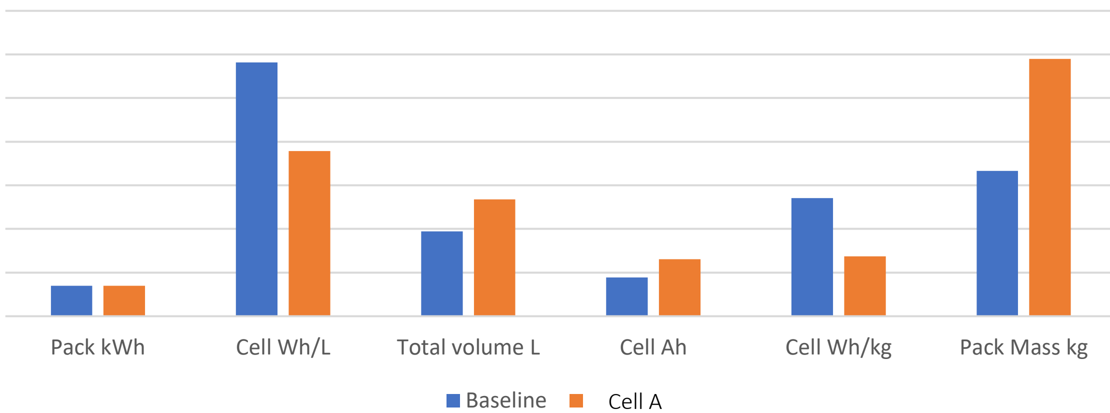

Figure 4 Relative volume, mass & energy impact of fast-charge cell A relative to baseline

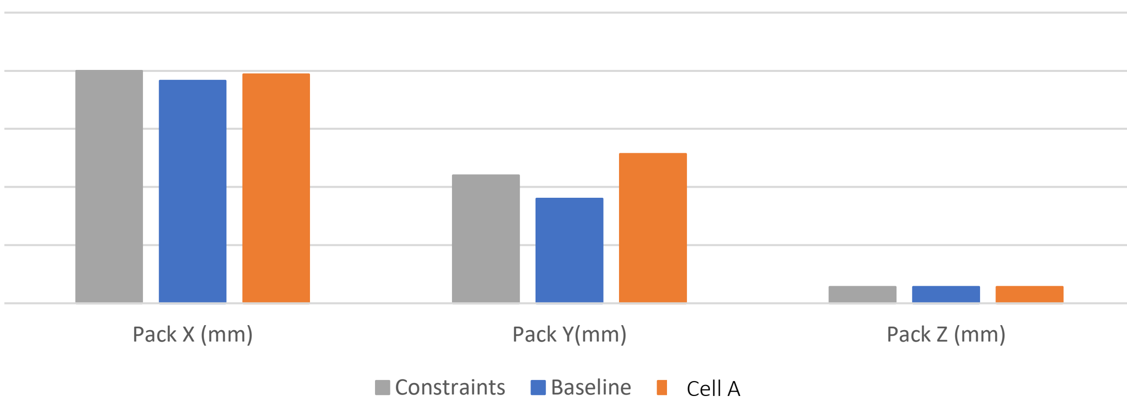

Figure 5 Relative dimensional comparison between pack using cell A and pack with baseline cell

2) Vehicle level analysis for Small SUV

In this section, the pack performance at the vehicle level is evaluated. In particular, the EV range and charging speed are calculated. For this 72S3P battery pack composed of the baseline cell, its pack capacity, Q_{pack}, is:

$$Q_{pack} = Q_{cell} \cdot N_p = 266.34Ah \qquad (1)$$

where Q_{cell} is the calculated cell capacity and Np is the number of cells connected in parallel in a cell group. The battery pack voltage is:

$$V_{pack} = V_{cell} \cdot N_s = 262.8V \qquad (2)$$

where V_{cell} is the cell nominal voltage and N_s is the number of cell groups connected in series. The battery pack total energy E is:

$$E = Q_{pack} \cdot V_{pack}/1000 = 70kWh \qquad (3)$$

The estimated usable battery energy (E_{ube}) is:

$$E_{ube} = E \cdot \mu = 67.2kWh \qquad (4)$$

The variable μ represents the usable fraction of the total battery energy. An example value of 0.96 is used here but it can vary with the specific cell, pack and vehicle application.

The vehicle range is:

$$Range_{ev} = \frac{E_{ube}}{C_{ac} \cdot \eta} = 252mi \qquad (5)$$

where C_{ac} is the energy consumption, which is the adjusted AC Wh/mile and η is the wall-to-battery charging efficiency. Here it is 0.89 based on the typical EPA vehicle certification test data [7]. The adjusted DC energy consumption is:

$$C_{dc} = C_{ac} \cdot \eta \cdot 100 = 267Wh/mi \qquad (6)$$

The energy to drive 150mi is:

$$E_{150mi} = C_{dc} * \frac{150}{1000} = 40.1kWh \qquad (7)$$

The charge current flow through each battery cell is:

$$I_{cell} = C_{rate} * Q_{cell} = 148.4A \qquad (8)$$

where C_{rate} is the long-duration charging C-rate of the baseline cell. The charge current for the battery pack is:

$$I_{pack} = I_{cell} * N_p = 445A \qquad (9)$$

The pack charge power is:

$$P_{charge} = I_{pack} * V_{pack} = 117kW \qquad (10)$$

The time to charge the 150mi energy is:

$$t = \frac{E_{150mi}}{P_{charge}} * 60 = 20.5min \qquad (11)$$

From the above calculation we evaluate that for the SUV case the pack built by the baseline cell takes 20.5 minutes to charge 60% of usable energy (150 miles).

Since the vehicle and pack energy are unchanged, values for (1)-(7) for the pack based on cell A are the same. With the higher C_{rate}, (8)-(11) are revised as follows:

$$I_{cell} = C_{rate} * Q_{cell} = 4.0 * 130.8 = 523.2A \qquad (12)$$

The long-term C_{rate} capability for cell A is > 8 but we use 4 here in consideration of the likely charging currents available from a typical DCFC charger. The charge current for the whole battery pack is:

$$I_{pack} = I_{cell} * N_p = 1046.3A \quad (13)$$

The pack charge power is:

$$P_{charge} = I_{pack} * V_{pack} = 280kW \quad (14)$$

The time to charge the 150-mile energy is:

$$t = \frac{E_{150mi}}{P_{charge}} * 60 = 8.6min \quad (15)$$

From the above calculation, the pack built with cell A can charge 62% of usable energy (150 miles) within 8.6 minutes at a 4C charging rate, which is much faster than the pack built with the baseline cell, which takes 20.5 minutes to charge 150 miles of energy due to the limitation of the charging C-rate.

IV. DISCUSSION

Due to the charging C-rate limitation of the baseline cell, the pack built with the baseline cell takes more than 20 minutes to charge the energy required for 150 miles for the small SUV EV. Cell A, with its fast-charging capability, can charge 150 miles of energy within 8.6 minutes. However, we found there would be a 37% increase in module volume and a 77% increase in mass compared to baseline battery pack due to cell A’s lower energy density. This would likely result in a 17% smaller pack if the vehicle space constraint is non-negotiable, which it often is. With double the C rate for charging, it remains to be seen if offering a shorter overall range would be an acceptable tradeoff for quicker charging stops. It is notable that a repeatable +8C charge rate is feasible with this cell. However, such high current has implications for the heat generation in the cell and the ability of the vehicle to reject that level of heat while at standstill during a charging event. Ongoing work includes optimizing the thermal system design to allow EVs to take advantage of this cell capability.

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