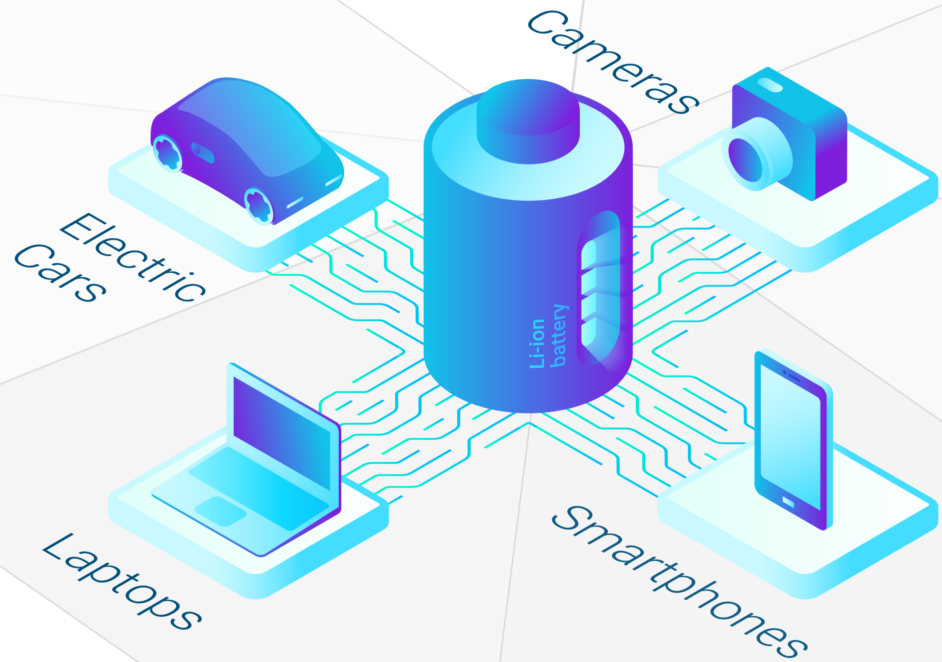

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Stories from Industry: Using Battery Models to Optimize Performance

Whether a company is looking to squeeze more power out of an electric vehicle, or hoping to improve the lifespan of a battery within our everyday devices, energy efficient design of battery powered systems is becoming increasingly necessary, and battery models are now an indispensable tool in optimizing these systems.

Battery systems have an impact on an overall system's uptime, lifespan, thermal stability and product safety, making battery performance a crucial aspect of a system's design. High-fidelity battery models, like those found in the MapleSim Battery Library, can assist in providing accurate estimates of realistic battery behavior and model-based techniques can give physics-based answers to important questions in the design process. With the MapleSim Battery Library, battery powered systems can be modeled far quicker than with traditional techniques, while still preserving accuracy for meaningful results.

This paper highlights three industry stories ranging from high-performance to high-efficiency applications. Each story helps outline the ways that battery models and a system-level modeling approach gives companies the ability to make better decisions during their design process.

Motorcycle Battery Model Gives Better Results by Incorporating Electrical and Thermal Characteristics

A leading motorcycle manufacturer wanted to include a realistic battery model in its MapleSim powertrain model. The challenge of this project was to create an electrical and thermal model of a lead-acid automotive battery. The behavior of lead-acid batteries is extremely nonlinear and depends on numerous factors, including the temperature, rate of charge or discharge, and the state of charge of the battery. Far from being a simple constant voltage source, a battery's voltage will change under these varying operating conditions, and therefore, an accurate battery model is critical for choosing a battery that meets the motorcycle design requirements.

The battery's state of charge can be thought of as a "gas tank" function that is one when the battery is full and zero when the battery is empty. When the state of charge is zero, the battery will not deliver any charge and must be recharged. As the battery recharges, the state of charge increases from zero to one. If the battery is recharged beyond its capacity, the excess energy is lost in the form of heat through various processes that are detrimental to the battery's longevity.

The open-circuit voltage is measured at the terminals of the battery when no load is attached. The open-circuit voltage is itself a function of the state of charge and battery temperature. The equivalent series resistance (ESR) of the battery is the apparent resistance internal to the battery and is a complicated function of the state of charge and rate of charge or discharge.

Typically, the manufacturer will provide a variety of charge/discharge curves and parameters that give information on the dynamic behavior of a battery. The challenge for engineers is to model the dynamic behavior of a battery and fit the manufacturer data to the chosen model. Many of the available models are circuit-based and rely on dynamic components like resistors and capacitors whose values change in response to the operating conditions. However, purely circuit-based implementations do not apply the thermal characteristics of the battery, and very few circuit simulators allow for dynamic components with such complicated governing equations. Consequently, existing models are inadequate predictors of battery behavior, and are therefore ill-suited for use in

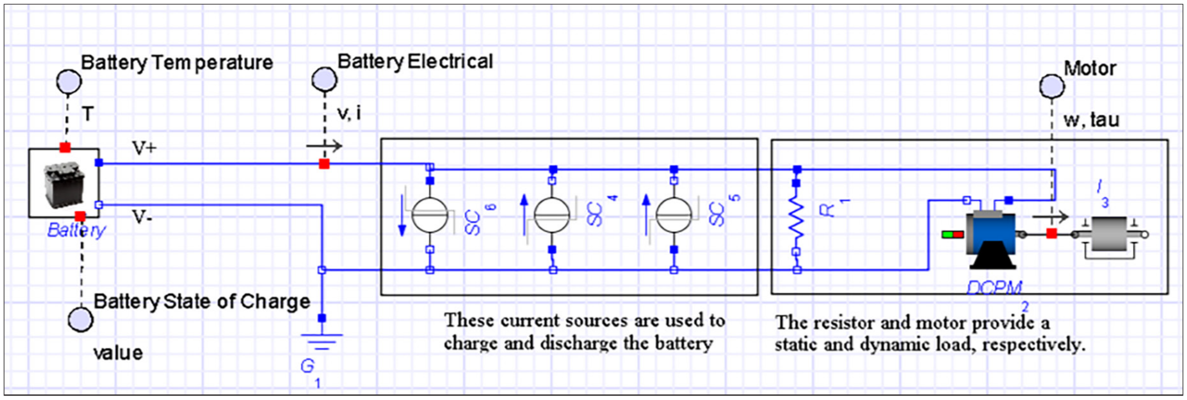


Figure 1. The battery model connected to a variety of loads.

engine models where heat loss must be considered and maximum energy efficiency is required.

The multiphysics and parametric nature of MapleSim makes it especially well-suited to implementing a realistic battery model, as shown in **Figure 1**. The model has positive and negative electrodes, a temperature port, and a state of charge port, and is also connected to a resistor and a motor to demonstrate that it can power both static and dynamic loads. Current sources are used to facilitate charging and discharging of the battery model.

The battery model was divided into a thermal component and an electrical component that were connected, as seen in **Figure 2**. The power losses in the electrical component are fed into the thermal component and cause a rise in temperature. The thermal component provides the operating temperature to the electrical component, which affects the performance of the battery.

The electrical model uses MapleSim custom components to directly specify the governing equations of the active circuit elements. Instead of a mess of functions blocks, the complicated governing equations are specified directly in a Maple worksheet. The net result is a clean and intuitive schematic that exposes the model to the user. The simulated dynamic response of the battery accurately matches the behavior of real batteries, as shown in the simulation results in **Figure 3**.

The MapleSim Battery Library allows a complex multi-domain analytical model of a lead-acid battery to be implemented in a straightforward way that provides realistic results. By connecting the battery model to a MapleSim powertrain model, a user can efficiently analyze options for components such as starters and alternators, and investigate the results under a variety of operating conditions.

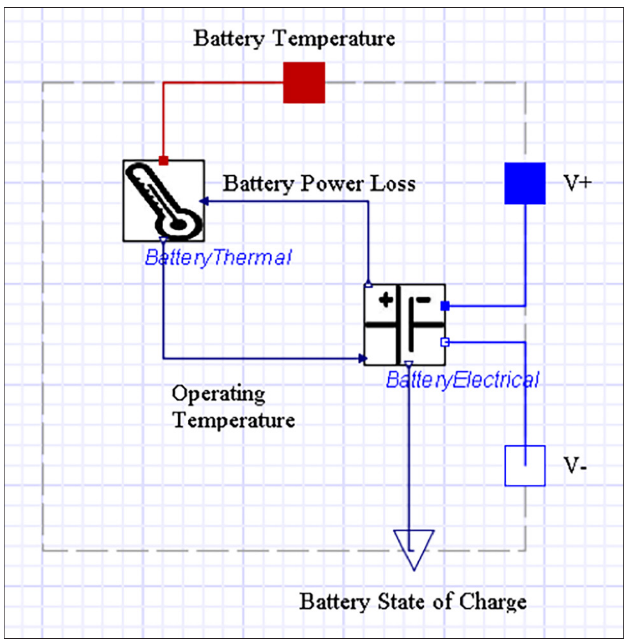


Figure 2. The thermal and electrical characteristics of the battery are easily separated and connected in MapleSim.

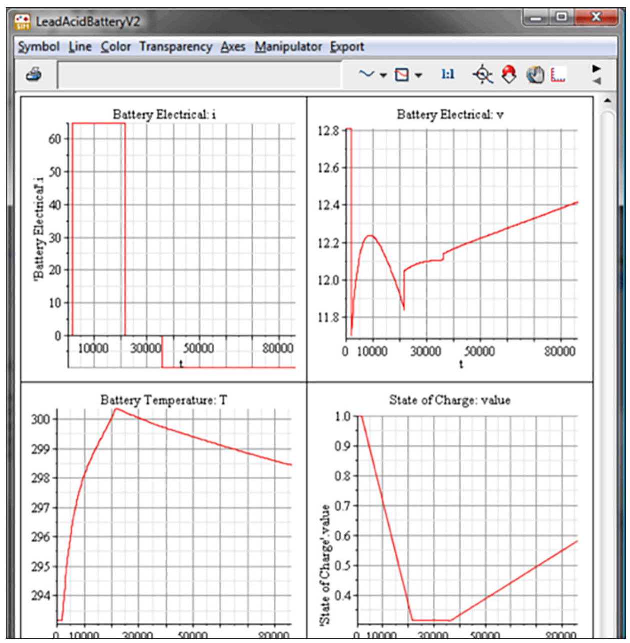


Figure 3. The output of a MapleSim simulation of the dynamic response of the battery model. The battery current is shown in the top left plot. First, 65 A is drawn from the battery, the battery rests, then is recharged with 10 A. The dynamic response of the voltage (top right), temperature (bottom left) and state of charge (bottom right) are shown.

High Fidelity, High Performance Battery Models Help Build Greener Cars

As the price of oil rises and environmental concerns become more important, automotive companies are putting greater effort into electric and hybrid-electric vehicles. There is an increased focus on developing high efficiency, cost-effective electric vehicles whose performance will be competitive with gas-powered cars. The automotive industry is turning more and more to virtual prototyping for vehicle development as a way to significantly reduce development times and costs, and so it is essential that they have computationally efficient, high-fidelity battery models as part of their electric vehicle development.

The development of such vehicles is a significantly more complex task than designing conventional cars because they incorporate many different engineering domains into a single system. At the same time, competitive pressures are forcing auto manufacturers to come up with new designs faster than ever before. The industry is turning to math-based physical modeling techniques which allow engineers to accurately describe the behavior of the components that comprise the system and the physical constraints on the system. These model equations are then used to develop, test, and refine designs very quickly, and without the expense and time required to build physical prototypes.

One of the most important components of a hybrid-electric or fully electric vehicle is the battery itself. Having a good virtual model of the battery is essential so that both battery behavior and the physical interaction of the battery with all the other components are properly reflected in the model.

Because the battery plays such a vital role in the vehicle, capturing these interactions is essential to designing an efficient, effective electric vehicle. Dr. Dao and Mr. Seaman worked alongside Dr. McPhee, the NSERC/Toyota/Maplesoft Industrial Research Chair for Mathematics-based Modeling and Design, to develop high-fidelity models of hybrid-electric and electric vehicles, including the batteries.

Battery Electric Vehicle (BEV) Model

Using MapleSim, a math-based model of a complete battery pack was implemented along with a simple power controller, motor/generator, terrain, and drive-cycle models. The resulting differential equations were simplified symbolically and then simulated numerically. A variety of driving conditions were also simulated, such as hard and gentle acceleration and driving up and down hills. The results were physically consistent and clearly demonstrated the tight coupling between the battery and the movement of the vehicle. This model will form the basis for a more comprehensive vehicle model, which will include a more sophisticated power controller and more complex motor, terrain, and drive-cycle models.

Hybrid-Electric Vehicle (HEV) Model

MapleSim was used to develop a multi-domain model of a series HEV, including an automatically generated optimized set of governing equations. The HEV model consists of a mean-value internal combustion engine (ICE), DC motors driven by a chemistry-based NiMH battery pack, and a multibody vehicle model. Simulations were used to demonstrate the performance of the developed HEV system. Simulation results showed that the model is viable and, as a result of MapleSim's lossless symbolic techniques for automatically producing an optimal set of equations, the number of governing equations was significantly reduced, resulting in a computationally efficient system. This HEV model can be used for design, control, and prediction of vehicle handling performance under different driving scenarios. The model can also be used for sensitivity analysis, model reduction, and real-time applications such as hardware-in-the-loop (HIL) simulations.

Figure 4 shows a power-split hybrid-electric vehicle model in MapleSim. This complex system includes a 70-cell lithium-ion battery pack, a mean-value internal combustion engine, electrical motors and generators, a power-controller,

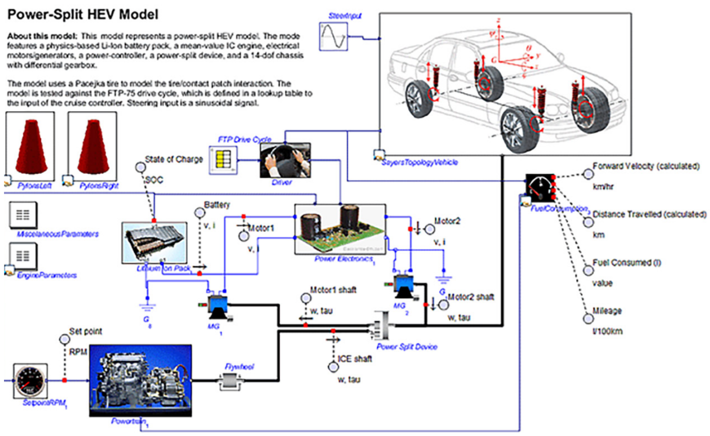


Figure 4. Power-split hybrid-electric vehicle model.

a power-split device, and a 14 degree-of-freedom chassis with a differential gear box. The MapleSim model simulates very rapidly, thanks to the highly efficient battery model and high performance, high-fidelity simulations that the symbolic technology behind MapleSim provides.

"With the use of MapleSim, the development time of these models is significantly reduced, and the system representations are much closer to the physics of the actual systems," said Dr. John McPhee. "We firmly believe that a math-based approach is the best and quite possibly the only feasible approach for tackling the design problems associated with complex systems such as electric and hybrid-electric vehicles."

Taking the Lead in Formula E: High-Performance Racing with System-Level Modeling

Competitive racing pushes the limits of driver skill and modern feats of engineering, all while adhering to tight regulations to keep a spirit of fair competition. In 2014, Beijing hosted the inaugural championship race for the newly-conceived, all-electric class of Formula E. Since the beginning, these vehicles have been tightly standardized, only allowing individual teams to customize certain aspects of their car. To this day, the battery must remain the same in every vehicle, so new ways to push performance are needed.

Recognizing these limitations, a leading Formula E team approached Maplesoft to develop dynamic models of their car, hoping to find new ways to tweak their systems for optimal performance. By modeling the dynamics of the car, they would be better able to develop customized racing strategies for different tracks, weather conditions, and pit stops, ensuring they were using their battery power for peak performance in each case. A lithium-ion battery can be modeled in MapleSim with high precision, and the Formula E team used the battery model to understand the actual performance of their batteries under a wide range of scenarios.

Using MapleSim, engineers were able to capture the dynamics of each system in one multi-domain environment, connecting the battery model with other vehicle components. A key step in the process of creating the functional model is to correlate the model's parameters with test data. This step was crucial in order to ensure that the model would provide accurate data across the range of operating conditions. These optimizing strategies also included design tweaks to the vehicle itself, and real-time simulations that could update the team with information as variables change during the race - features not commonly available without a system-level modeling tool.

With only a few years of racing under their belt, the Formula E class has made huge strides in all-electric racing. Using only a battery to power their high-performance cars, it's more important than ever for teams to fully understand their car's behavior for race day, and get the most out of their battery. By using MapleSim, the Formula E team can bring a new level of optimization to their engineers, and, as with other leading-edge industries, these are developments we can hope to see in the near future for our own cars, moving us even closer to efficient, powerful electric vehicles for all.

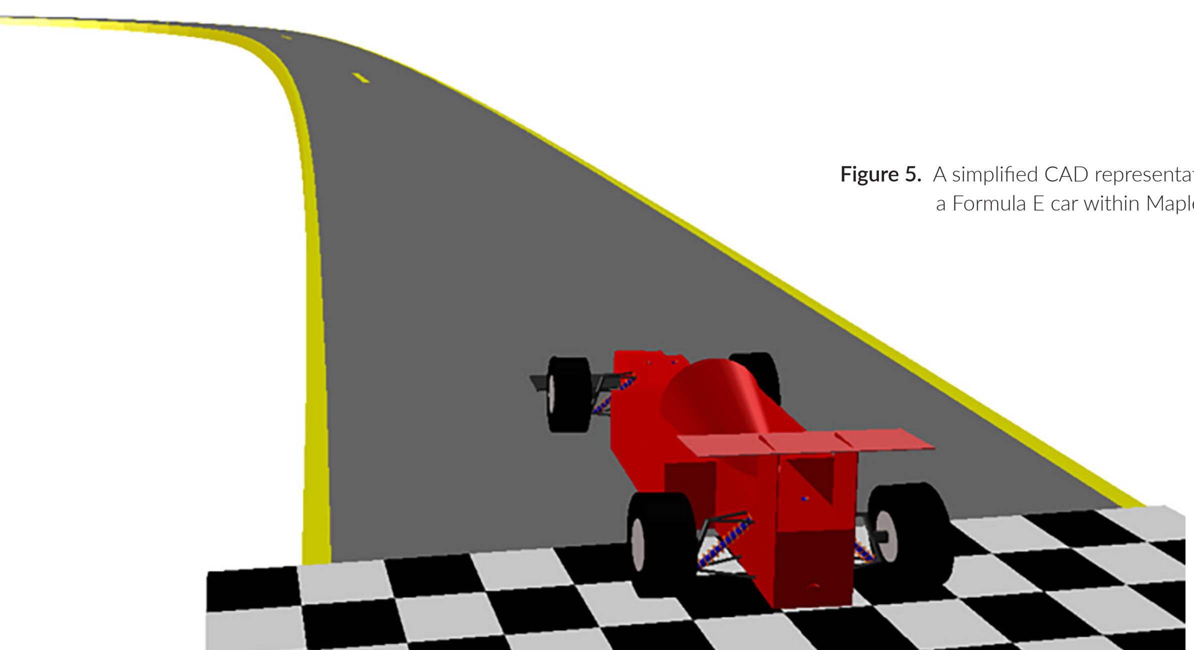
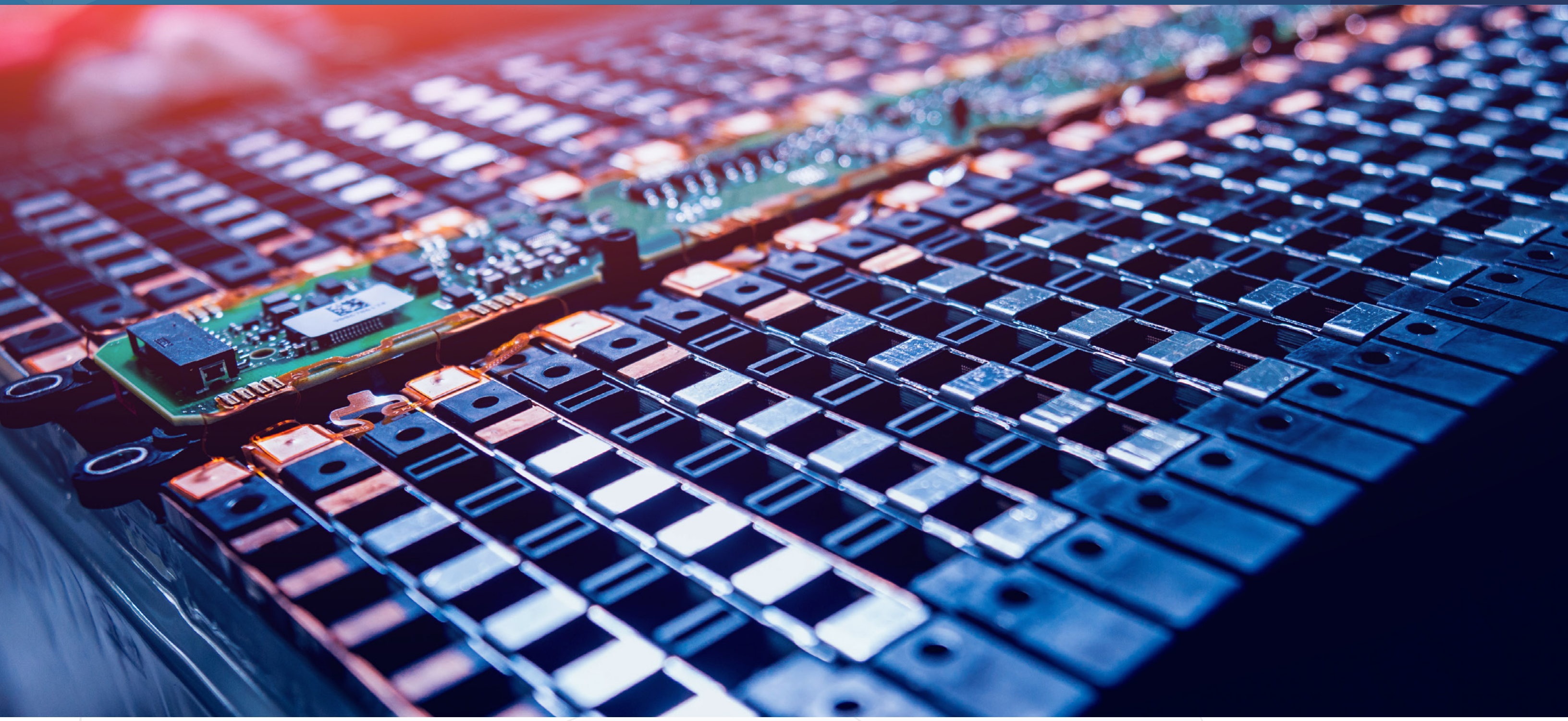


Figure 5. A simplified CAD representation of a Formula E car within MapleSim.



Conclusion

As manufacturers face the challenges of delivering products that are economically attractive while fulfilling their environmental and legal demands placed on them, complex mathematical models of the products are becoming increasingly important – and increasingly complex! The flexibility of component-based modeling has allowed for the development of highly accurate and customizable battery models.

These battery models, available in the MapleSim Battery Library, can be incorporated into larger system models, allowing for the development of the complete system by integrating the various subsystems into one environment. These subsystems can come from various engineering domains, such as mechanical, electrical, chemical, and thermal. A schematic approach is used to define the model – components can easily be connected together and the environment takes care of the math and calculations. Once a model has been created, the system equations and parameters are available for analysis and optimization, enabling higher performance, while reducing development costs.

The ways in which these system-level battery models might be used can vary dramatically. What is common among them, however, is a shared focus on developing the best techniques to improve our battery-powered systems. The inefficiencies of past vehicles, batteries, or power systems are continuing to be understood by engineers as the result of design processes that need improvement. By adopting a system-level modeling approach to managing battery powered systems, companies are able to easily perform optimizations, trade-off analyses, and ultimately bring more powerful and efficient products to market.

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