



Evaluating Plug-In Series Hybrid Designs for Postal Delivery Vehicles

By Robert Myers, University of Michigan — Dearborn

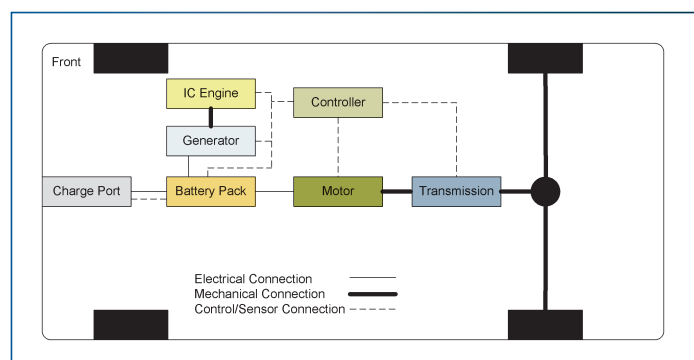
The College of Engineering and Computer Science at the University of Michigan – Dearborn is helping to meet the growing need for more fuel-efficient vehicles with an interdisciplinary program leading to a master’s degree in Automotive Systems Engineering. As part of this program, Robert Myers and John Longnecker, with faculty advisor Dr. Chris Mi, conducted a study to determine the feasibility of using plug-in series hybrid technology to extend the range of electric vehicles used by the United States Postal Service (USPS). In this article, Myers describes how he and Longnecker modeled and simulated the vehicle, its powertrain, and its control systems with physical modeling tools from The MathWorks—an approach that enabled them to focus on crucial design tradeoffs without becoming mired in low-level mathematical equations, and without building costly prototypes.

Why Electric?

Electric vehicle technology is especially well suited for delivery vehicles because postal vehicles use minimal energy when idle and can recapture kinetic energy from frequent braking. Unlike passenger vehicles, delivery vehicles do not need a publicly available charging infrastructure because they return to a central depot where they can be recharged overnight. And whereas passenger vehicles cover trips that may be beyond the range of an EV, postal vehicles have defined routes and travel a set distance each day.

In a study that concluded in 2001, USPS explored the possibility of using electric vehicle (EV) technology for postal carrier route vehicles. The study found that while electric vehicles generally had enough range to complete their appointed rounds, they sometimes exhausted their batteries and had to be towed back to the depot.

Figure 1. Series hybrid vehicle schematic.



In these cases, the ability to recharge batteries on the go with an onboard generator could have made the difference between successful completion of the route and a call for a tow truck.

To investigate this option, I began a research project with John Longnecker and our advisor, Dr. Chris Mi, Assistant Professor of Engineering at the University of Michigan – Dearborn. Our goal was to model a plug-in hybrid USPS delivery vehicle, and through simulation, validate its performance by comparing it to earlier electric-only delivery vehicles and USPS specifications for range, acceleration, and gradeability (the vehicle’s ability to maintain speed while traveling uphill).

The Plug-in Hybrid Architecture

A plug-in hybrid (Figure 1) uses an off-board system to recharge batteries. It also includes a generator powered by a small ICE to extend the vehicle’s range. In a series hybrid, the internal combustion engine (ICE) is used solely to charge batteries. This arrangement differs from the parallel hybrid configuration used in most passenger hybrid vehicles today, in which the engine powers the vehicle with assistance from the electric motor.

We based our carrier route model on the Utilmaster Flexible Fuel Vehicle (FFV), one of two vehicles that the USPS commonly uses for urban and suburban delivery routes. We replaced the FFV's engine with a DC motor powered by lithium ion batteries. A small displacement diesel engine powers an onboard generator to recharge the batteries en route.

Selecting the Battery Pack

A successful design must carefully balance the performance of a battery pack against its weight and cost. While a larger battery pack extends the vehicle's range, the added weight affects gradeability and reduces the vehicle's available payload. USPS specifications require the vehicle to carry a minimum payload of 454 kg. Because one of our design goals was to maintain the same gross vehicle weight as the original FFV (2313 kg), we had to strictly limit the weight of all hybrid-specific subsystems, including the battery pack.

Batteries have a much lower specific energy than gasoline or diesel fuel. One kilogram of gasoline can produce 12,000 watt-hours, while a one-kg lead acid battery produces only 35 watt-hours. Nickel metal hydride and lithium ion batteries offer higher specific energy, but at increased cost. Because the average life of the vehicle far exceeds that of the batteries, the batteries will probably be replaced several times over the vehicle's lifetime. As a result, operating costs are also an important design consideration.

Spanning Engineering Domains

To meet the stringent and at times competing performance objectives for a USPS delivery vehicle, we needed to build and validate a vehicle model that spanned control and electrical systems, powertrain, physical design, and other engineering domains. Further, we needed to conduct multiple design iterations and trade-off studies, optimizing the design until all specifications were met or exceeded.

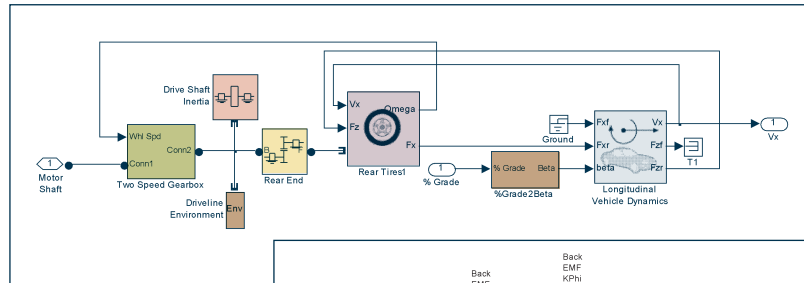


Figure 2. Simulink® vehicle model.

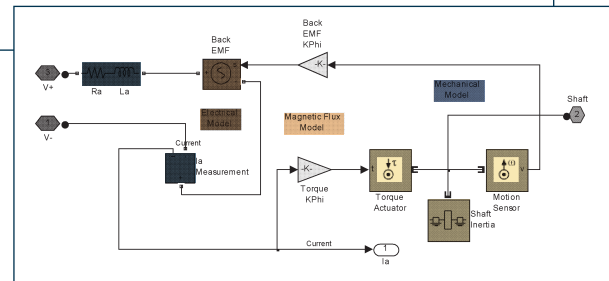


Figure 3. Simulink DC motor model.

A principal goal of our research was to go beyond merely assessing the EPA mileage estimates for a plug-in hybrid. Some simulators can provide miles-per-gallon (mpg) estimates over a defined route, but we wanted to fully evaluate the dynamic performance of the vehicle over specific carrier route drive cycles. As a result, we needed to build a comprehensive model of the vehicle and all its subsystems from the ground up.

We selected MathWorks tools for Model-Based Design for the research because they enabled us to span all the engineering disciplines involved. In addition, by using the predefined components within Simulink®, SimPowerSystems and SimDriveline, we would spend less time creating model components and deriving mathematical equations. We were already familiar with MathWorks tools, having used them in our coursework to develop a Simulink model of a Hall effect sensor for a wiper motor.

Modeling the Vehicle

We began by building a physical model of the vehicle (Figure 2). We used the Longitudinal Vehicle Dynamics block in SimDriveline to evaluate the response of the vehicle to torque applied by the driveline. After setting up vehicle-specific parameters in that block and modeling the tire – road interaction, we could easily plot vehicle speed as a function of grade and torque.

With the physical model complete, we modeled the motor and motor controller (Figure 3). We added a brushless DC permanent magnet motor to the Simulink model together with a basic motor controller based on the Four-Quadrant Chopper DC Drive block from SimPowerSystems.

The four-quadrant chopper uses a proportional integral (PI) controller to regulate both forward and backward speeds (Figure 4).

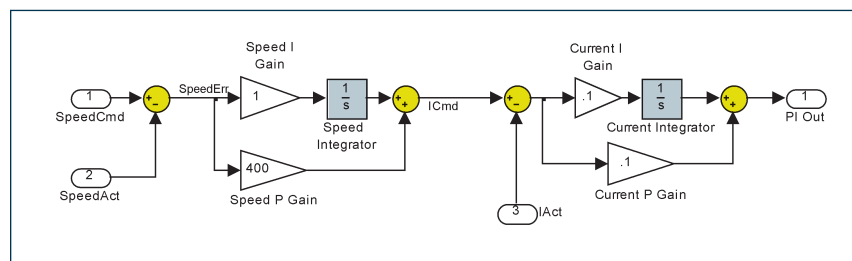


Figure 4. Simulink PI controller model.

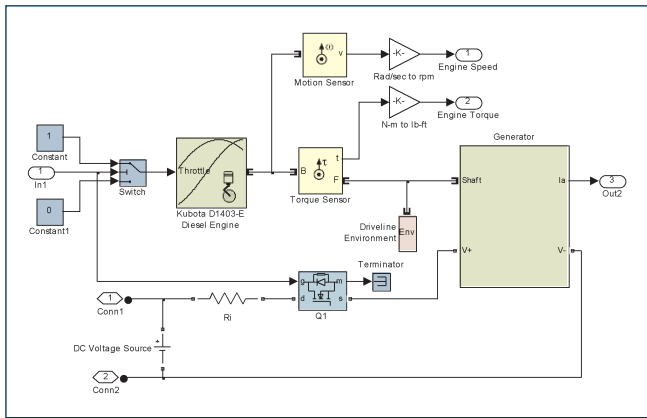


Figure 5. Simulink generator model.

Next, we modeled the battery, the generator, and the engine (Figure 5). Once again, we saved time by using predefined blocks from the SimDriveline vehicle components library. For example, to modeling the ICE we simply dropped the diesel engine block from the library into our model and specified the torque-speed curve for our Kubota D1403-E three-cylinder diesel engine.

The Simulink environment facilitated collaboration throughout the project. While John worked on the battery and generator models, I worked on other

components. Integrating our work was a straightforward matter of ensuring that we had properly developed the agreed-upon interfaces.

Simulating Real-World Drive Schedules

Once we had a complete model of the plug-in hybrid vehicle, we could evaluate vehicle performance across all three dimensions

specified by the USFS: gradeability, acceleration, and range (Figure 6).

We exercised the model using a range of drive cycles, including the EPA urban cycle, the EPA highway cycle, and drive cycles developed specifically for postal vehicles with frequent short hops and significant idle time (Figure 7).

Initial simulations revealed two design areas that needed improvement. First, while the vehicle met range requirements and easily exceeded acceleration specifications, it struggled to maintain speed on some of the steeper grades (Figure 8). Refining the transmission model using SimDriveline building blocks quickly addressed the problem.

Second, the drive schedules with steep grades tended to reduce battery charge to unacceptable levels. Some initial simulations showed the battery charge at just 1% when the vehicle returned to the depot. To keep a reasonable minimum

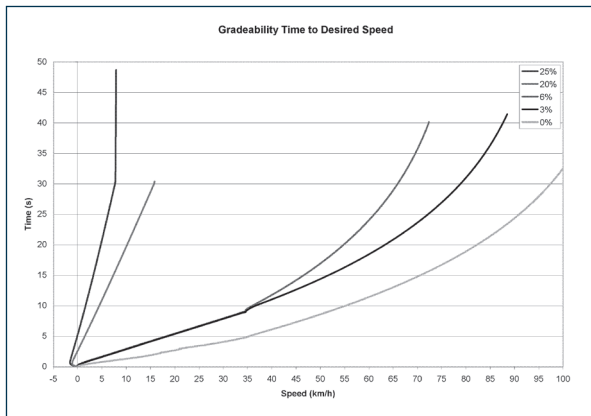


Figure 6. Gradeability performance tests.

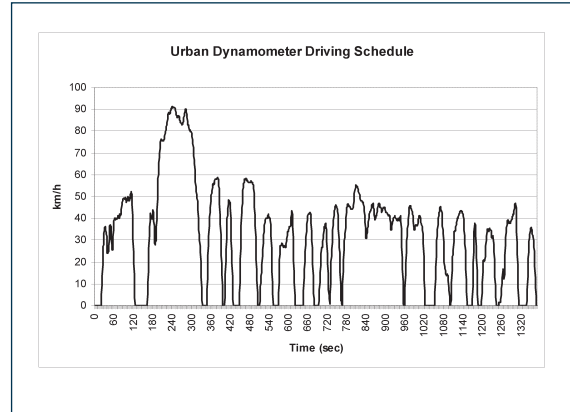


Figure 7. Speed profile for federal urban dynamometer driving schedule.

% Grade	Speed	Ending SoC	Generator Run Time	Fuel Used	Distance	Time to Speed
0%	100 km/hr	50.7%	41.9 s	0.021 gal	4.01 km	32.5 s
3%	88.5 km/hr	37.3%	152.8 s	0.077 gal	3.67 km	41.4 s
6%	72.4 km/hr	1.2%	155.3 s	0.079 gal	2.93 km	40.2 s
20%	16 km/hr	36.0%	149.7 s	0.076 gal	0.59 km	30.4 s
25%	8 km/hr	5.5%	149.8 s	0.076 gal	0.29 km	48.7 s

Figure 8. Gradeability time to desired speed.

Assistant Professor Dr. Chris Mi teaches several courses in power electronics, industrial controls, and electric and hybrid vehicle technology. Dr. Mi served as faculty advisor on the plug-in hybrid research project.

At the University of Michigan – Dearborn, we strive to stay on the leading edge of vehicle technology. Robert and John's research exemplifies that effort.

We use MATLAB® and Simulink in the classroom because students take almost no time at all to learn them. They are among the best tools available for building models

and exploring the underlying physics and differential equations. In my Hybrid Electrical Vehicle class, we also use Advisor, a Simulink-based tool for vehicle simulation.

Of course, Robert and John needed more advanced functionality to build a complete system model with detailed component-level models of the motor, power electronics, and more. When running acceleration tests and fuel economy tests, they needed a simulation environment that could perform simulations spanning minutes, not just low-level simulations of milliseconds.

In this very successful research effort Simulink, SimDriveline, and SimPowerSystems played a vital role. Robert and John learned a lot through doing this work. They gained experience in building models in Simulink, and the approach they used gave them an in-depth understanding of hybrid EV technology. At this point, we don't know if the vehicle they designed will be put into production, but the models that Robert and John built will be invaluable tools for other engineers, who can use them to find out how a production vehicle would perform before actually building one.

charge, we increased the size of the battery pack slightly until the charge remained within acceptable tolerances throughout simulation. Having the complete vehicle model in Simulink enabled us to quickly implement and test these types of improvements.

Reducing Emissions, Increasing Efficiency

Using Simulink, we simulated the plug-in electric hybrid and calculated fuel consumption over two commonly measured cycles: the federal urban drive schedule and the federal highway drive schedule. For comparison, the EPA mileage estimates for a USPS FFV are 15 mpg in the city and 19 mpg on the highway. Even taking into account the fuel equivalent of the electricity needed to charge our vehicle to full capacity, our design achieved higher fuel economy in simulations, with 24.9 mpg in the city and 28.5 mpg on the highway.

On identical drive schedules, the simulated hybrid used less than half the fuel consumed by its internal combustion engine counterpart, a saving that would greatly reduce exhaust emissions.

When the costs of charging the hybrid each night are included in the calculations, its fuel costs are still 25% less than

the ICE vehicle on the urban drive schedule, and 8% less on the highway schedule.

Looking Ahead

Clearly, there are many opportunities for further research in this area. One possibility to consider is a four-wheel-drive, parallel hybrid configuration with the electric motor driving the front wheels and an ICE driving the rear wheels. This configuration would make it easier to take advantage of regenerative braking to recharge the battery, and would provide four-wheel-drive benefits under adverse surface conditions. A benefit of using MathWorks tools for our research is the reusability of our models. Should we pursue such enhancements in the future, we would leverage our current work and hit the ground running.

We are presenting our findings at the SAE World Congress, where we hope to spur industry interest in the plug-in series hybrid for delivery vehicles. ■

For More Information

- College of Engineering and Computer Science, University of Michigan – Dearborn
www.engin.umd.umich.edu
- MathWorks Automotive Conference
www.mathworks.com/industries/automotive/mac2007

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