

Design of a Series-Parallel Plug-in Hybrid Sedan through Modeling and Simulation

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ABSTRACT

EcoCAR 2: Plugging In to the Future is a three-year design competition co-sponsored by General Motors and the Department of Energy. Mississippi State University has designed a plug-in hybrid powertrain for a 2013 Chevrolet Malibu vehicle platform. This vehicle will be capable of 57 miles all-electric range and utility-factor corrected fuel economy of greater than 80 miles per gallon gasoline equivalent (mpgge). All modifications are designed without sacrificing any of the vehicle's utility or performance. Advanced modeling, simulation, and Hardware-in-the-Loop (HIL) simulation capabilities are being used for rapid control prototyping and vehicle design to ensure success in the following years of the competition.

CITATION: Doude, M., Molen, G., Brown, W., Hoop, J. et al., "Design of a Series-Parallel Plug-in Hybrid Sedan through Modeling and Simulation," *SAE Int. J. Alt. Power.* 1(2):2012, doi:10.4271/2012-01-1768.

INTRODUCTION

EcoCAR 2: Plugging Into the Future is a three-year collegiate student engineering competition that focuses on vehicle integration of advanced propulsion technologies. The competition challenges 15 universities across North America to explore vehicle solutions that minimize energy consumption and reduce greenhouse gas emissions, while retaining the vehicle's performance and consumer appeal. Using a real-world engineering process mirroring GM's Global Vehicle Development Process (GVDP), teams will integrate their advanced technology solutions into a 2013 Chevrolet Malibu. The first year of the competition includes a heavy emphasis on modeling and simulation. The following years will then focus on implementation and refinement of the vehicle technologies. At the conclusion of each year, teams will compete in events designed to evaluate each team's progress, and an overall winner for that year will be selected.

Mississippi State University (MSU) enters the EcoCAR 2 competition as a seven-year veteran of the Advanced Vehicle Technology Competitions (AVTC) which are developed by the U.S. Department of Energy. The team, working out of MSU's Center for Advanced Vehicular Systems (CAVS), is seeking to bring into EcoCAR 2 the success they enjoyed in Challenge X and EcoCAR, having won first place three of the last five years. The team is entirely student-led and currently

consists of over 80 students from a wide range of majors, both engineering and non-engineering.

USE OF ECOCAR 2 VEHICLE DESIGN PROCESS

The EcoCAR 2 Vehicle Development Process (VDP) is modeled after GM's GVDP. A VDP contains a predefined set of activities linked in time to achieve a desired result [1]. The intent of the GVDP is to streamline and organize a very complex problem into a repeatable and measurable process [2]. The GVDP includes specific points in the process, called milestones, where the design process and status are evaluated. Three primary milestones, called Milestone Gate Reviews, are Vehicle Program Initiation (VPI), Verified Data Release (VDR), and Vehicle Testing Complete (VTC). In the EcoCAR 2 VDP, these Milestone Gate Reviews correspond to the Year 1, 2, and 3 competitions. The Year 2 and 3 competitions also involve dynamic vehicle reviews, which in the GVDP are called Milestone Buy-off Rides. The Buy-off Rides are designed to test the vehicle at different phases of readiness, including 65%, 99%, and 100% production-ready.

The EcoCAR 2 VDP includes many of the elements of the GVDP, but is modified and scaled down to represent what is primarily a powertrain design project. The EcoCAR 2 VDP divides the design process into three separate tracks: mechanical, controls, and electrical. Each track has its own development timeline such that all tracks align at the end of each year for EcoCAR 2 competitions. The MSU EcoCAR 2

team is similarly divided into four primary groups: Outreach/Business, Controls, Electrical, and Mechanical. Some groups also have sub-teams in charge of more specific areas such as hardware-in-the-loop (HIL) modeling, tailpipe emissions, and passenger infotainment software development. Each group has a leader who reports to the project's overall team leader. The team structure is arranged in a hierarchy such that individuals responsible for each task and deliverable have a clear path of responsibility. Group leaders are responsible for delegating tasks to team members and ensuring that work is completed on schedule. The team leader and group leaders meet once a week to update the status of all active tasks.

The work breakdown structure (WBS) of the project is managed by the team leader in cooperation with the group leaders. It is maintained and organized using the project planning software tool Microsoft Project. Project allows the allocation of resources as well as the arrangement of summary and terminal elements into a Gantt chart structure. This tool also allows the team to track dependencies and flag high-risk items. The team's project management plan is linked to the EcoCAR 2 VDP as a tool to accomplish successful completion of milestone events. It includes several universal milestones such as competition report deadlines. The WBS was developed based on these milestones as well as the overall competition goals. An example of an EcoCAR 2-mandated Year 1 milestone broken down into team-specific sub tasks is shown in Fig. 1.

far has been very successful in meeting Year 1 deadlines and goals. The team's engineering goals for Year 1 have either all been accomplished or are on track to be completed prior to Year 1 competition. The team's project organizational structure will be even more important during the second year of the project, where there are fewer competition-mandated deliverables before the Year 2 competition.

POWERTRAIN CONFIGURATION

Overall Team Strategy

In preparation of establishing vehicle design goals, the team conducted an analysis of the mid-size sedan market. Specifications for the 2013 Chevrolet Malibu Eco were compared to those of its top six best-selling competitors, based on the most recent data available. An excerpt including notable results is shown in Table 1.

Table 1. Mid-size sedan specifications

	2013 Chevrolet Malibu Eco	2013 Ford Fusion	2012 Toyota Camry	2012 Hyundai Sonata	2012 Nissan Altima	2012 Subaru Legacy	2012 Honda Accord
City MPG	25	23	25	24	23	19	23
Highway MPG	37	33	35	35	32	27	34
Cargo (ft ³)	14.3	20.1	15.4	16.4	15.3	14.7	14.7
Seating	5	5	5	5	5	5	5
0-60 (s)	8.7	7.0	8.7	8.2	7.5	8.4	7.8

The Malibu Eco already has best-in-class fuel economy, but at the expense of its cargo capacity, which is the smallest in the group. The stock Malibu's 0-60 mph acceleration is likewise tied for the slowest in this group. Each vehicle in the class has 5-passenger seating. These observations led the team to the conclusion that for its full-hybrid Malibu to remain a viable competitor in its class, the base vehicle's cargo room, passenger room, and acceleration performance could not be sacrificed to further improve fuel economy.

The team has also been collecting survey data from consumers in its region for the last five years. Through this market research the team has been building a profile of consumers' knowledge and priorities regarding vehicle purchases. Interesting results include that, even though our demographic is mostly rural, 77% of respondents reported driving 40 or fewer miles every day. Also, fuel economy was chosen as by far the most important factor when purchasing a car, followed by style and then space.

Based on the market analysis and research, the team was able to prioritize design goals. Following the consumer research, outstanding fuel economy was agreed to be the highest priority objective. Maintenance or improvement of acceleration, cargo and passenger room, and other consumer

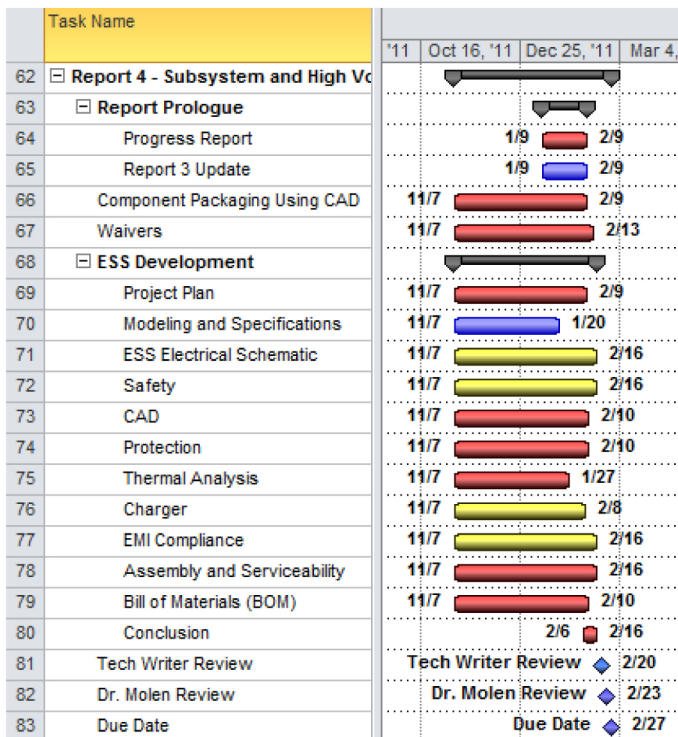


Figure 1. Gantt Chart

The team is currently nearing the end of Year 1. Several tasks are active in preparation for competition. The project so

acceptability metrics was also considered critical. Finally, the vehicle must be in compliance with competition-mandated emissions standards. The following overall design goal was set in order to drive the design process:

Build a vehicle that achieves outstanding fuel economy and meets emissions standards, while maintaining or improving all other stock consumer features.

This overarching goal does have difficult implications to the team. Initial modeling results showed that a plug-in hybrid with an all-electric range would be the only way to achieve the desired level of fuel economy. Preliminary packaging studies, as well as experience, indicated that packaging an electrical energy storage system (ESS) capable of providing significant all-electric range without reducing cargo room will be very difficult. The increased mass associated with the battery pack will also make maintaining the acceleration and handling performance difficult. The team was committed to this goal, however, and established its specific design metrics around this target.

Vehicle Technical Specifications (VTS)

VTS are a set of parameters that define critical vehicle requirements. These requirements drive the design process by guiding decision making and prioritizing aspects of vehicle performance. VTS can relate to any part of the vehicle design, but for EcoCAR 2 the team's VTS are related to powertrain characteristics and criteria relevant to competition-measured aspects.

Emissions and Energy Consumption

The EcoCAR 2 competition will use a combined four-cycle method for measuring fuel economy. Plug-in hybrid electric energy usage will be combined with fuel energy usage through the utility-factor correction method. This method uses National Household Travel Survey (NHTS) data to predict the distances traveled in both all-electric (charge depleting) and engine-on (charge sustaining) modes on a fleet basis. The energy usage values are then combined based on energy content of the medium and the result is converted to gasoline equivalent. This allows results from differently-fueled vehicles to be compared. Vehicle tailpipe emissions will be measured over the same four-cycle method. This will be done through the use of a portable 5-gas emissions analyzer.

The EcoCAR 2 competition also takes into account upstream usage factors for fuels. This takes the specific form of well-to-wheel greenhouse gas emissions (WTW GHG) and well-to-wheel petroleum energy usage (WTW PEU). Both of these factors are based on a complete life-cycle analysis of the chosen fuels. Since fuel production efficiencies and energy sources vary by region, a standard U.S. and Canadian energy mix is applied to all teams.

The MSU EcoCAR 2 Team formulated its emissions and energy consumption (E&EC) VTS on previous competition

results and preliminary modeling data, with the overall goal of maximizing on-road fuel economy and minimizing WTW GHG and WTW PEU. The team's E&EC VTS are shown in [Table 2](#).

Table 2. MSU EcoCAR 2 E&EC VTS

Metric	Production 2013 Malibu	MSU Design VTS
CD Range	N/A	64.4 km
CD Fuel Consumption	N/A	250 Wh/km
Charge-Sustaining Fuel Consumption	N/A	420 Wh/km
UF-Weighted Fuel Energy Consumption	787 Wh/km	161 Wh/km
UF-Weighted AC Electric Energy Consumption	N/A	154 Wh/km
UF-Weighted Total Energy Consumption	787 Wh/km	315 Wh/km
UF-Weighted WTW Petroleum Energy Use	774 Wh/km	150 Wh/km
UF-Weighted WTW GHG Emissions	253 g/km	204 g/km
Criteria Emissions	Tier 2 Bin 5	Tier 2 Bin 5

Performance

The EcoCAR 2 competition measures acceleration from 0-60 mph and 50-70 mph, braking from 60-0 mph, gradability, and handling performance over an autocross course. The team's objective when establishing VTS values for performance was to improve the vehicle's acceleration to best-in-class levels. The goal for braking was to maintain the stock vehicle's stopping distance, despite the increase in the vehicle's mass. There is no VTS directly linked to autocross performance; however, the acceleration and braking efforts will contribute to the vehicle's overall autocross abilities. VTS values for performance are shown in [Table 3](#).

Table 3. MSU EcoCAR 2 Performance VTS

Metric	Production 2013 Malibu	MSU Design VTS
Acceleration 0-60 mph	8.2 s	6.9 s
Acceleration 50-70 mph	8.0 s	4.0 s
Braking 60-0 mph	43.7 m	43.7 m
Gradability @ 20 min	10+% @ 60 mph	10+% @ 60 mph

Consumer Acceptability

The cargo capacity VTS was set to 0.467 m³, which would improve the vehicle to second in its class in cargo capacity. The passenger seating capacity VTS was kept at 5. Competition limits on fuel tank capacity reduce the overall range VTS, while the vehicle starting time is not reduced from the stock vehicle. Consumer acceptability VTS are shown in [Table 4](#). The complete compiled VTS may be found in the appendices to this document.

Table 4. MSU EcoCAR 2 Consumer Acceptability VTS

Metric	Production 2013 Malibu	MSU Design VTS
Cargo Capacity	0.405 m ³	0.467 m ³
Passenger Capacity	5	5
Starting Time	<2 s	<2 s
Range	736 km	322 km

Fuel Selection

The EcoCAR 2 competition allows the use of five fuels, as shown below in [Table 5](#).

Table 5. EcoCAR 2-allowed fuels

Biodiesel (B20)	20% methyl soy ester, 80% low-sulfur diesel (<15 ppm S)
Gasoline (E10)	90% gasoline, 10% ethanol
Ethanol (E85)	85% denatured ethanol, 15% gasoline
Gaseous hydrogen (H ₂)	(70 MPa, 10,000 psig)
Electricity	North American grid average

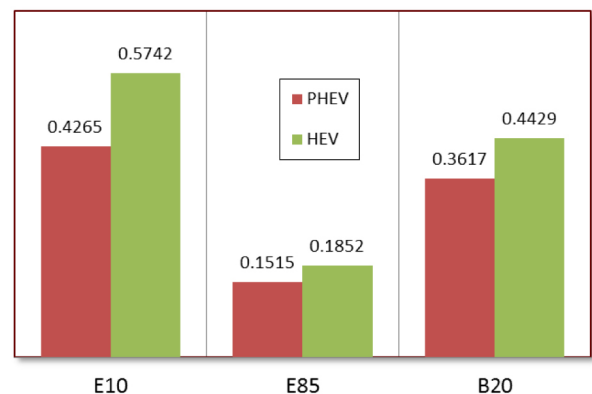
Each fuel has different characteristics regarding upstream factors, combustion efficiencies, and tailpipe emissions. Gaseous hydrogen, although it produces no tailpipe emissions, requires a larger volume for on-board storage. The extra hydrogen fuel storage requirement to meet the EcoCAR 2 minimum range VTS would not be compatible with the team's cargo and passenger volume VTS. Thus, hydrogen was deemed incompatible with the team's VTS and eliminated from consideration.

Grid-generated electricity produces no tailpipe emissions and is known to lead to energy consumptions much less than that of combustion engines when used on board a vehicle. Numerous technical papers, as well as the team's experience, show how plug-in hybrids can achieve lower overall UF-corrected energy consumption than their hybrid counterparts that do not connect to the grid. The team's modeling results confirmed this, leading to the selection of electricity as one of the fuels which would power the team's vehicle. By extrapolating the information used to reach the conclusion to use electricity as a fuel, one might conclude that the optimal design would be a battery-electric vehicle (BEV) running exclusively on electricity. While some day this might be true, currently the energy density by volume of the best automotive battery technology is still less than 10% that of conventional gasoline. This means that to reach the team's range VTS of 322 km using electricity alone would require the elimination of some cargo or passenger room, thus not meeting the team's VTS.

Table 6. Summary of Fuel Selection Factors

	E10	E85	B20
WTW PEU		+	
WTW GHG		+	+
Tailpipe Emissions		+	
On-board efficiency			+
Energy density			+
Team experience			+
Availability	+		

There are several factors that play into determining which liquid fuel to use. The three available fuels (E10, E85, and B20) were investigated using Argonne National Laboratory's Greenhouse Gas, Regulated Emissions and Energy Use in Transport (GREET) model. This tool allows the calculation of upstream emissions and energy usage, and when combined with modeled vehicle results, gives an overall WTW picture of fuel performance. The results comparing the three fuels are shown in [Figs. 2 and 3](#), below. E85 performs by far the best in the WTW PEU category; this is because it has the highest percentage of biofuel content. E85 and B20 perform very similarly in the WTW GHG category; both outperform E10. The relatively low energy density of E85 means that much more fuel must be carried on board to travel a given distance, even though the final results are normalized on an gasoline energy density equivalent basis. Nearly twice as much E85 is required to go the same distance as a gallon of B20. Both of MSU's previous competition vehicles have run on B20, giving it an advantage in team experience. Finally, while E10 is available universally, both E85 and B20 can be less common. A summary of these factors is shown in [Table 6](#).


Figure 2. WTW PEU Comparison for PHEV (kWh/km)

After extensive simulation and research, the team selected E85 as its liquid fuel source.

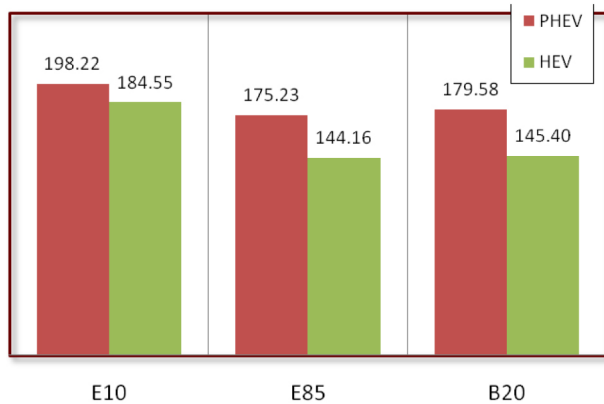


Figure 3. WTW GHG Comparison for PHEV (g/km)

Architecture Selection

The team used Argonne National Laboratory's Autonomie software tool to rapidly model different architectures and component combinations. This tool provided energy consumption, component efficiency, and acceleration data for the team's architecture simulations. Siemens NX was also used to analyze packaging options for different architectures. From this research, the team was able to narrow its focus to the three which offered the most promise to meet the team's VTS. These were the series hybrid, the parallel pre-transmission hybrid, and the belt-alternator-starter (BAS) hybrid. These three were then modeled in greater detail in order to make a final selection. Some of the results are shown in Table 7.

Table 7. Architecture Modeling Results

	Parallel	Series (E-REV)	BAS
UF-corrected fuel economy (mpgge)	81.4	75.6	39.1
WTW GHG (g/km)	179.4	194.4	411.9
WTW PEU (Wh/km)	38.8	44.6	171.3
Acceleration 0-60 (s)	7.2	9.1	9
Acceleration 50-70	3.9	7.3	7.1
Gradability (%)	19.5	6.59	16.48
Mass (kg)	1769	1782	1572
Controls*	4.4	9.8	7.4
Mechanical*	7.0	8.6	9.2
Electrical*	6.5	8.0	9.0
Reliability*	5.0	9.0	8.3
Marketability*	9.0	9.5	4.5
Component availability & support*	5.5	7.0	7.5
Team experience*	5.0	9.0	7.0

*1=more difficult/worse, 10=less difficult/better

Table 7 also shows a summary of some of the qualitative metrics assigned to each design. The team composed a feasibility matrix including each of these three designs. It evaluated, based on a defined scale, the relative difficulty or

complexity of specific vehicle integration topics, such as emissions control, electrical reliability, and ESS mechanical integration. In Table 7 these metrics are categorized and valued on a scale from 1 to 10, with 10 generally being the better value. The team also conducted a preliminary packaging study on each of these three architectures, using CAD.

Each of the three designs had a unique advantage. The BAS would be the easiest to integrate, but was limited in the improvements that could be realized. The Series (E-REV) design was familiar to the team, achieved good results, and was deemed only slightly more difficult to engineer than the BAS, but was lacking in some VTS metrics and was a high-risk choice from a packaging room standpoint. The Parallel offered the highest potential results across the board, but was also considered the most challenging to implement in almost every category. Ultimately, the team decided to apply its experience and efforts to use the most optimal design from an engineering standpoint: the parallel PHEV. By coupling the motor pre-transmission and using an overrunning clutch on the engine output, the vehicle will have the capability to perform in a series-parallel switching manner.

Final Component Selection

Once the final architecture was chosen, the team began confirming component selection. The original architecture modeling was performed using component models modified to represent actual components which were being provided by GM and other sponsors as well as some components which the team already owned. To validate these choices, the team performed some basic calculations.

Traction Motor

A modified version of the vehicle road load equation was used to calculate the minimum traction motor power required to achieve the team's acceleration and gradability VTS. These calculations are shown below in Table 8.

Table 8. Traction motor sizing calculations [4]

Equation and description	VTS	Power required
$P_t = \frac{\delta \cdot M_v}{2 \cdot t_a} \cdot (V_f^2 + V_b^2) + \frac{2}{3} \cdot M_v \cdot g \cdot f_r \cdot V_f + \frac{1}{5} \cdot \rho \cdot C_d \cdot A \cdot V_f^3$ Min. peak power from all motors to meet acceleration	0-60 mph 6.9 s	143 kW
Where P_t = tractive power, δ =mass factor, M_v = mass, t_a = accel. time, V_f = final velocity, V_b = vehicle velocity at base speed of motor, g = accel. due to gravity, f_r = rolling resistance, ρ = density of air, C_d = drag coeff., and A = frontal area		
$P_{tow} = \left[(F_0 + F_1 \cdot V_c) + (F_2 \cdot V_c^2) + (M_v + M_{tow}) \cdot g \cdot \sin(\alpha) \right] \cdot V$ Min. continuous power from all motors to meet gradability	20 min, 10% @ 60 mph	56.0 kW
Where P_{tow} = power, F_0 , F_1 , and F_2 = road load coeffs., V_c = cruising velocity, M_v = mass, M_{tow} = towing mass, g = accel. due to gravity, and α = grade		
$P_{gen} = \frac{V_c}{\eta_t \cdot \eta_m} \left(\text{mass} \cdot g \cdot f_r + \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V_c^2 \right)$ Min. continuous power to meet cruising speed	75 mph	26.3 kW
Where P_{gen} = generator power, V_c = cruising speed, η_t = transaxle efficiency, and η_m = motor efficiency		

The first equation listed gives the minimum power required to meet the team's acceleration VTS of 6.9 s. This is an approximate value and helps validate that the modeled traction motor is an appropriate choice. The other two equations estimate the traction motor's required continuous power capability to meet the vehicle's cruising and gradability requirements.

The traction motor used for modeling the series-parallel PHEV was a 145 kW PMDC motor manufactured by UQM Technologies (Table 9). This was used because the team has accurate models and data for this component, and also because the team already owns this component. Team experience, modeled results and power-based calculations confirm that this component will be an appropriate selection.

Table 9. UQM PowerPhase 145 Specifications

Peak power (10 s)	145 kW
Continuous power	85 kW
Maximum Torque	400 Nm
Maximum Speed	8000 rpm
Maximum Efficiency	94%

Engine

The characteristics used to determine engine selection were power output, brake specific fuel consumption, physical size, and availability of support. Since the vehicle must also be able to meet the gradability and cruising VTS in charge sustaining mode, the engine must be capable of at least producing the same 56.0 kW continuous power as the electric motor. During acceleration, the electric motor will be able to supplement the engine's power. Since the motor alone meets the acceleration VTS there is not a maximum power requirement for the engine. When researching available engines, the team put a heavy emphasis on the availability of support from the manufacturer. Most OEM automotive engines have some controls challenges when used in a different vehicle than that for which it was designed. As an example, the engine controller will require compatibility with the vehicle body controller. The team was not able to find another manufacturer which could match the same level of support in this area that GM has pledged; therefore, the engines considered were those which GM has agreed to supply and support. Of these, the four-cylinder turbocharged 1.4L Ecotec engine was chosen (Table 10). The primary reasons for this selection include:

- Packaging- this engine was the only one which fit along with the other hybrid components in the engine bay
- Power- with the smallest output power, this engine still had more power than was required

Table 10. 1.4L Ecotec Engine Specifications

Displacement	1.4L (4 cylinder)
Air induction	Turbocharged
Maximum power	103 kW
Maximum torque	200 Nm

Battery

A123 Systems is a major sponsor of the EcoCAR 2 competition and one of the main Li-ion battery suppliers in the U.S. for automotive applications. The team has found A123 to be very supportive of their products with which they have had exceptional results. Therefore, the team chose to select from one of the four module configurations offered by A123 (Table 11).

Table 11. A123 Pack Options

Configuration	Energy	Mass
6x 15s2p	10.8 kWh	86 kg
7x 15s2p	12.6 kWh	101 kg
6x 15s3p	16.2 kWh	130 kg
7x 15s3p	18.9 kWh	151 kg

The team simulated its series-parallel PHEV with each pack design and found that the one with the largest energy storage offered the best overall UF-corrected fuel economy. Since this selection was also the largest by volume, the team sought to determine if the pack could be packaged without reducing stock cargo or seating capacity of the vehicle. The solution was a novel, undermount "H" shaped pack which will occupy both the stock fuel tank as well as spare tire mounting areas. The team therefore chose the A123 LiFePO₄ 18.9 kWh pack.

CONTROL DEVELOPMENT PROCESS

The ultimate goal of the control system is to provide utility and safety to the consumer. A hybrid vehicle's control system is intrinsically more complex than that of a conventional vehicle, which has only one source of propulsion. The platform of the EcoCAR 2 competition presents additional challenges for the development of a control system because stock vehicle components are often utilized outside of their originally intended application. This challenge must be considered along with the characteristics of the proposed vehicle architecture when developing the control system.

The process of developing the vehicle controls requires extensive cooperation between the controls team members because of the complexity of the hybrid vehicle such as the addition of an alternate source of propulsion. The ultimate goal of this control system is to provide the consumer with a safe and useful vehicle that maintains drivability that is similar to a conventional automobile while being more eco-friendly.

Throughout the year, Mississippi State students implemented the industry-recognized "V-diagram", such as shown in Fig. 4, for the team's series-parallel hybrid vehicle control system development. The process began by defining control requirements, which were in turn considered while designing the hardware architecture for the system. After the selection of the vehicle and control system architecture, team