EVS26
Los Angeles, California, May 6-9, 2012

Impact of US06 Drive Cycle on EcoCAR 2 Plug-in Hybrid Electric Vehicle Architecture Design and Component Sizing

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Abstract

The Hybrid Electric Vehicle Team of Virginia Tech (HEVT) is participating in the 2012 - 2014 *EcoCAR 2: Plugging in to the Future* Advanced Vehicle Technology Competition series organized by Argonne National Lab (ANL), and sponsored by General Motors Corporation (GM) and the U.S. Department of Energy (DOE). The goals of the competition are to reduce well-to-wheel (WTW) petroleum energy consumption, WTW greenhouse gas and criteria emissions while maintaining vehicle performance, consumer acceptability and safety. Following the EcoCAR 2 Vehicle Development Process (VDP), HEVT will design, build, and refine an advanced technology vehicle over the course of the three year competition using a 2013 Chevrolet Malibu donated by GM as a base vehicle. The team considered 3 candidate powertrain architectures and selected a series-parallel EREV with P2 and P4 motors. While EcoCAR 1 is very similar to EcoCAR 2, one major difference is the evaluation method for emissions and energy consumption. EcoCAR 1 used the CAFE method (55% UDDS, 45% HwFET), where EcoCAR 2 uses a 4-cycle method that includes the more aggressive US06 cycle which features higher vehicle speeds and accelerations. For the described series-parallel EREV, the EV range was reduced by 24% between EcoCAR 1 CAFE and EcoCAR2 4-cycle methods. For this vehicle, the result is a difference of 14 miles in EV range. For a BEV designed for 200+ mile range, the range reduction would be more than 50 miles, necessitating an additional 10 kWh or more of battery energy. Thus, the new EcoCAR 2 4-cycle energy consumption evaluation method increases the powertrain power and energy design requirements, but offers a more realistic representation of real world driver behavior.

Keywords: PHEV, EREV (extended range electric vehicle), modelling, energy consumption, range, design

1 Introduction

EcoCAR 2: Plugging In to the Future [1] is a three year Advanced Vehicle Technology Competition series organized by Argonne National Lab (ANL), and sponsored by General Motors and the U.S. Department of Energy. University teams are challenged to design and build a midsize sedan powertrain to improve fuel economy, reduce petroleum energy use and well-to-wheel greenhouse gas and criteria emissions, while maintaining safety, performance, and consumer appeal. The Hybrid Electric Vehicle Team of Virginia Tech (HEVT) [2] is participating in EcoCAR 2. The competition follows the EcoCAR 2 Vehicle Design Process which is: design in year one, build in year two, and then refine in year three. There are 15 teams in the competition across the United States and Canada. Each team is tasked with re-engineering a 2013 Chevrolet Malibu to achieve the goals by various means. In the first year of the competition, each team must first select their competition fuel and powertrain architecture, develop component integration schemes, and develop safety-critical vehicle supervisory control code among other important and detailed tasks. HEVT has established team goals that meet or exceed the competition requirements for EcoCAR 2 in the powertrain architecture design of a plug-in extended-range hybrid electric vehicle (EREV).

In the previous EcoCAR competition [3], the energy consumption and emissions were evaluated using a series of on-road tests that closely approximated the 55% City - 45% Highway weighting of the standard UDDS and HwFET dynamometer drive cycles used for Corporate Average Fuel Economy (CAFE) rating of production vehicles. The on-road testing also includes a direct approximation of utility factor weighting used to evaluate charge depleting plug-in hybrid electric vehicles [4,5,9].

2 EcoCAR 2 Competition

HEVT must conform to all design and safety rules prescribed by the EcoCAR 2 rules. Per competition rules, the vehicle must have a minimum total range of 200 miles and cannot exceed a maximum curb weight of 2078 kg. The stock vehicle has a Gross Vehicle Weight Rating (GVWR) of 2260 kg, so a maximum curb weight of 2078 kg allows for only two passengers (91 kg each). There are also considerations for passenger space and cargo capacity. Stiff penalties are imposed for reducing the passenger capacity by removing seats or for reducing cargo capacity by raising the floor of the trunk. These penalties were kept in mind when possible packaging options for candidate architectures were considered. In addition to rigid constraints, there are also various scored categories in the competition including: acceleration, braking, lateral handling, drive quality, consumer acceptability as well as emissions and energy consumption. This means that performance and handling must be balanced against vehicle emissions and energy consumption, but also consumer appeal. Hence, the vehicle must still be designed with the consumer in mind. There are minimum thresholds and target values for several of these metrics set forth by competition rules; Table 2 summarizes some of these targets and requirements [1].

3 Vehicle Glider Properties

The vehicle platform that will be donated to each team will be a 2013 Chevrolet Malibu midsize sedan. Table 1 below details some of the vehicle properties of the expected donated vehicles.

Table 1: Vehicle Glider Properties

Specification	Value
Conventional Curb Mass	1560 kg
Conventional Test Mass	1700 kg
Gross Vehicle Weight Rating	2260 kg
Wheel Radius	0.324 m
Coefficient of Rolling Resistance	0.01
Drag Coefficient	0.33
Frontal Area	2.3 m^2

4 Design Goals

In addition to these EcoCAR 2 targets and requirements, HEVT has also established its own unique team goals. Reducing petroleum energy use is directly tied to fuel consumption and fuel consumption is often a trade-off with tailpipe emissions. Because of this trade-off, simultaneously reducing both tailpipe emissions and fuel consumption and, by extension, petroleum energy use can be difficult. For balance of trade reasons, the team has chosen to focus specifically on reducing the petroleum energy consumption of the vehicle.

Consumer acceptability is represented in a significant portion of competition points, so the team purposefully includes consumer features in the vehicle design. One such consumer feature is a pure Electric Vehicle (EV) mode, where the vehicle has near full performance as an EV. The presence of a fully capable EV mode coupled with a significant EV range also greatly displaces well-to-wheels (WTW) petroleum energy and marginally reduces WTW GHG and criteria emissions. Additionally, the team set the goal to retain the full passenger capacity of the vehicle. Table 3 summarizes the additional design goals set forth by the team.

Table 2: EcoCAR 2 Competition Design Targets and Requirements

Specification	Competition Design Target	Competition Requirement
Acceleration 0–60 mph	9.5 sec	11.5 sec
Acceleration 50–70 mph	8.0 sec	10.0 sec
Braking 60–0 mph	143. ft (43.7 m)	180. ft (54.8 m)
Highway Gradeability @ 20 min	3.5% @ 60 mph	3.5% @ 60 mph
Cargo Capacity	16. ft^3	7. ft^3
Passenger Capacity	>= 4	2
Mass	< 2260 kg	< 2260 kg
Starting Time	< 2 sec	< 15 sec
Ground Clearance	155 mm	> 127 mm
Vehicle Range	322 km (200 mi)	322 km (200 mi)

Table 3: HEVT Team Goals

Goal	Description
Petroleum Energy Consumption	Reduce petroleum consumption by > 80 %
All-Electric Range	> 56 km (35 mi) range as a pure all-electric vehicle
Passenger Capacity	Retain stock 5 passenger capacity

5 Powertrain Architecture Selection

As a part of the EcoCAR 2 VDP, the team modelled and compared 3 powertrain architectures: a BEV, a series EREV and a series-parallel EREV.

The first architecture considered was a Battery Electric Vehicle (BEV). This design would offer great potential for petroleum energy displacement and would also provide the driver with an appealing all electric mode. However, to meet the competition range requirements, the Rechargeable Energy Storage System (RESS) would have to be very large and certain consumer features, such as cargo space and passenger mass capacity, would necessarily be sacrificed in order to package the components for this architecture in the vehicle.

A series EREV architecture solves many of the challenges presented by a BEV without losing much of the appeal. An EV mode is retained for a limited range which is designed to optimize the utility of the battery pack based on American daily driving habits. This limited range reduces the size of the RESS and eases packaging, thus making it easier to retain consumer features. The competition range requirement can be met with a combination of electric range and fuel range. A pure series EREV is well suited for optimizing the efficiency of charge sustaining (CS) during city driving situations. While control of an engine-generator pair can be challenging, there are known solutions. One drawback of series mode is limited efficiency on the highway. Another is performance: the vehicle pays the mass penalty for carrying an engine and generator motor, but those components cannot directly assist the traction motor for acceleration performance or gradeability requirements. The generator must be sized for continuous power requirements for top speed or grade.

A solution to these drawbacks is adding a path for the engine to transmit torque directly to the wheels. This path could be selectively clutched in or out and the vehicle has the capability to switch between the series mode and the parallel mode – hence it is a series-parallel architecture. Figure 1 illustrates the implementation of the P2- P4 (motor positions) series-parallel powertrain.

The P4 motor or Rear Traction Motor (RTM) is the primary drive motor and is the sole form of propulsion in Charge Depleting (CD) mode. The architecture will leverage the neutral gear in the transmission to decouple the engine and P2 generator from the wheels to enable series operation during CS mode. This mode would be used at lower speeds or during periods of low road load. To couple engine torque directly to the wheels, the transmission would be engaged, most likely in 5^{th} or 6^{th} gear for efficiency. Because it is an automatic transmission, multiple gears could be used for performance and also to meet gradeability requirements. If the engine and gearing can meet gradeability in parallel mode without any power from the P2 or P4 motors, then the P2 generator can be downsized. Table 4 summarizes the components and parameters for the series-parallel design [6].

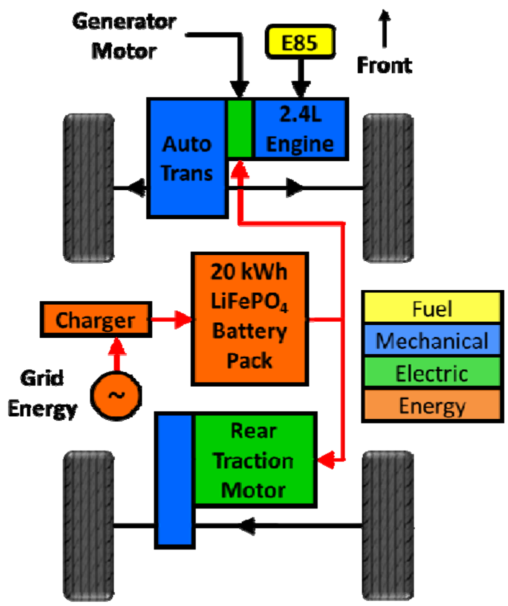

Figure 1: Series Parallel EREV Architecture

6 EcoCAR Drive Cycles

In the first EcoCAR competition (EC1) [3], energy consumption and emissions (E&EC) tests were evaluated using a series of on-road tests that closely approximated the 55% City - 45% Highway weighting of the standard UDDS and HwFET dynamometer drive cycles (Figure 2) used in calculating the Corporate Average Fuel Economy (CAFE) rating of production vehicles. The on-road testing also includes a direct approximation of utility factor weighting used to evaluate charge depleting plug-in hybrid electric vehicles [4,5,9]. This approach resulted in very mild vehicle powertrain loads.

EcoCAR 2 (EC2), however, adds US06 City and Highway drive cycles (Figure 3) and has a reformatted city-highway weighting to determine range and utility factor. The addition of these cycles helps to more closely emulate real-world driving, much like the revised EPA fuel economy label [7]. EC2 '4-cycle' weighting, however, does not test for cold weather and hot/air conditioning effects specifically. Thus, the EC2 approach falls just short of true 5-cycle testing. The US06 drive schedule aggressive accelerations and higher speeds make these cycles more demanding, and just like for certification testing, some trace misses are permitted.

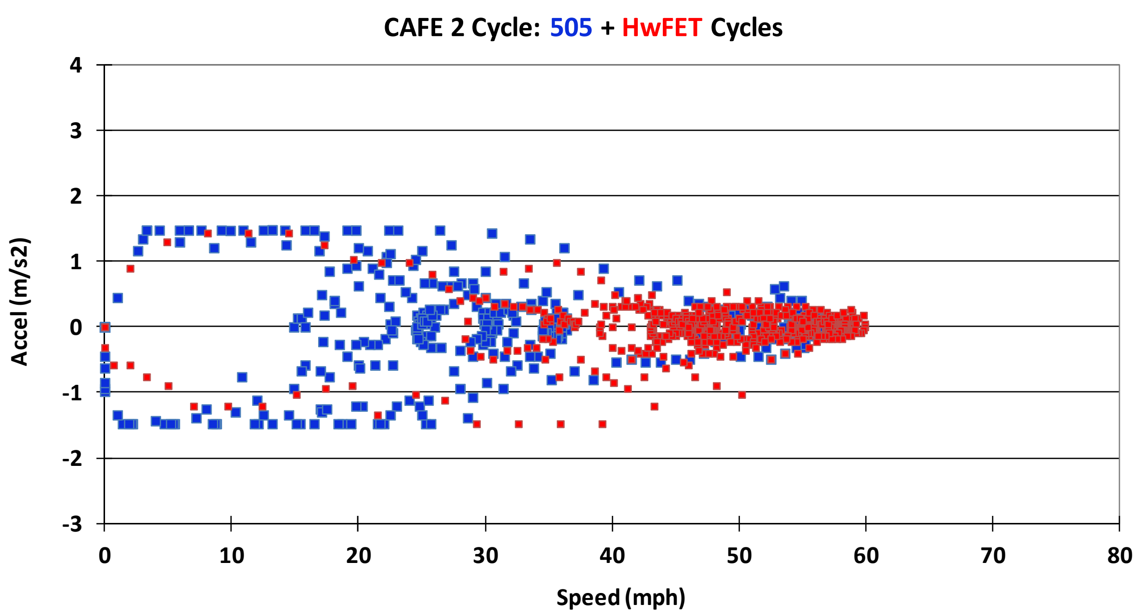

Figure 2: Acceleration vs. Speed for CAFE 2-Cycle combination

Table 4: E85 Series Parallel EREV Component Parameter

Vehicle Parameters	
Vehicle Test Mass	2050 kg
A123 Energy Storage System	
Energy capacity	18.9 kWh
Usable energy capacity	16. kWh
Total mass with mount structure	240 kg
P4 Drive motor	
Peak power	125 kW
Continuous torque	45 kW
Peak torque	300 Nm
Gear reduction	7.17:1
Top speed	85 mph
P2 Generator Motor	
Peak power	45 kW
Continuous power	25 kW
Peak torque	140 Nm
E85 Engine	
Peak power	131 kW
Peak torque	230 Nm
Displacement	2.4 L
Transmission	Auto 6-speed

Table 5 shows a summary of how the different drive cycles compare to each other. Statistics such as idle time, average speed, average running speed and some acceleration statistics are included. These statistics show that the US06 cycles have much wider range of acceleration demands and require a much higher average acceleration. These drive cycle properties require increased power capability of the vehicle to meet these schedules with minimum trace misses.

To determine power and energy requirements from these drive cycles, a two parameter road load model (Table 1) that scales rolling resistance with mass for the vehicle platform is used. The realistic target test mass for the vehicle design is 2050 kg, a significant 350 kg increase above the base vehicle to account for the addition of a large plug-in battery and traction motor, plus other HEV systems. The electric motor size and gearing are determined to meet an acceleration time of less than 11.5 seconds. Gearing for 85 mph (137 kph) top speed with max motor speed of 8000 rpm = 94 rpm/mph and with a tire rolling radius of 0.324 m requires an overall gear reduction of 7.1 Higher desired top speeds can be achieved with lower gearing, but more motor torque would be required to meet low speed accelerations. In order to meet the minimum acceleration time of 11.5 s, the minimum motor required needs to provide 97 kW and just over 300 Nm torque, assuming a generic torque-speed curve. A UQM PowerPhase 125 kW motor gives a 0-60 mph (97 kph) time of 10.6 sec and 4.9 sec 50-70 mph for the Malibu properties listed previously in Table 1.

7 Effect of Drive Cycles on Component Sizing

To size the motor for CD mode in the E&EC events of EC1, peak power and torque only needed to meet UDDS and HwFET requirements. Table 6 below shows peak motor torque and power as well

Table 5: Summary of Drive Cycle Properties

Cycle	Distance (mi)	Time (s)	Idle Time (s)	Weight (%)	Max Speed (mph)	Avg Speed (mph)	Avg Run Speed (mph)	Peak Accel (m/s^2)	Peak Neg Accel (m/s^2)	Average Accel (m/s^2)
UDDS	7.45	1369	241	55%	56.7	19.6	23.8	1.48	-1.48	0.51
HwFET	10.26	765	4	45%	59.9	48.3	48.5	1.43	-1.48	0.19
EC1 CAFE weighting:				**100%**	**59.9**	**26.7**	**30.9**	**1.48**	**-1.48**	
505	3.59	505	94	67%	56.7	25.6	31.5	1.48	-1.48	0.54
US06 C	1.77	231	27	33%	70.7	27.6	31.3	3.76	-3.00	1.29
EC2 City weighting:				**43%**	**70.7**	**26.2**	**31.4**	**3.76**	**-3.00**	
HwFET	10.26	765	4	22%	59.9	48.3	48.5	1.43	-1.48	0.19
US06 H	6.24	365	8	78%	80.3	61.5	62.9	3.08	-3.08	0.34
EC2 Hwy weighting:				**57%**	**80.3**	**58.0**	**59.0**	**3.08**	**-3.08**	
EC2 4 cycle City - Hwy weighting:				**100%**	**80.3**	**38.1**	**42.8**	**3.76**	**-3.08**	

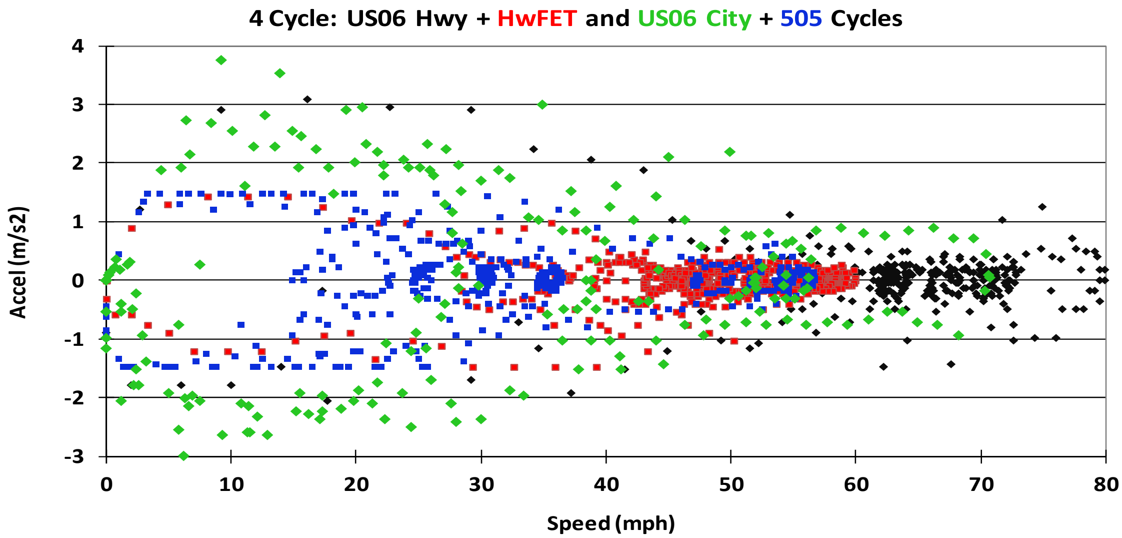

Figure 3: Acceleration vs. Speed for 4-Cycle combination

as battery current and power required meet the actual drive cycles for both EcoCAR competitions. Note that these requirements can be relaxed slightly if some trace miss is allowed. This table shows that peak power and torque are relatively low for the UDDS and HWFET. However, with a motor sized for these conditions, the vehicle would not meet the minimum acceleration requirement and would be sluggish, lacking in performance. With a 55 kW, 175 Nm motor, the vehicle (gearing for 85 mph top speed) would only achieve a 0-60 mph time of 22 sec, and a 50-70 time of 14 sec. Gearing the vehicle for lower top speed could improve the 0-60 some, but not significantly due to the constant power region of the electric motor. Motor and battery requirements to meet US06 drive cycle, on the other hand, require much higher values of peak motor power and torque and peak battery power, as seen in Table 6.

A motor sized to meet the minimum acceleration requirement of 11.5 sec paired with a battery capable of 100 kW and 300 A can meet all but a few (less than 10 sec) of the peak operating points in the US06 cycles seen in Figure 3. Hence, the drive cycle is now effectively an equivalent driving force behind vehicle acceleration performance. Considering that the US06 cycle is a more aggressive cycle and more representative of actual driver habits, this also illustrates the minimum performance expectations of consumers.

The Li-Ion Battery chosen has a nominal capacity of 18.9 kWh and a useable capacity of 16 kWh using an aggressive 85% delta State of Charge (SOC) swing to maximize the CD range.

Table 7 below details the net road load energy loss, battery energy consumed, and range for the same vehicle parameters and components using both the

Table 6: Torque and Power Requirements for Drive Cycles

Cycle	**Peak Motor Torque (Nm)**	**Peak Motor Power (kW)**	**Avg. Battery Current (A rms)**	**Peak Battery Current (A rms)**	**Peak Battery Power (kW)**
EC1					
UDDS	168	49.0	36	163	53.4
HwFET	161	40.3	50	132	43.6
Max:	**168**	**49**	**50**	**163**	**53.4**
EC2					
505	168	49.0	46	163	53.4
US06C	405	117	110	409	127
HwFET	161	40.3	50	132	43.6
US06H	335	120	106	417	129
Max:	**405**	**120**	**110**	**417**	**129**

EC1 CAFE weighting as well as the EC2 4-cycle weighting. This table shows that the new 4-cycle weighting increases the road load by 32% and battery energy consumption by 31% per mile. Using the battery energy consumption and the energy capacity of the battery, the range can be determined. The range for the new weighting is only 76% of the range calculated using the CAFE weighting which reduces the Utility Factor by 11%.

Table 7: Road Load, Battery Energy Consumption, and Range for 2 Drive Cycle Weightings

Cycle	Net Road Load (Wh/mi)	Battery Energy (DC Wh/mi)	Range (mi)	Utility Factor
UDDS	135	265	61	0.748
HwFET	195	277	58	0.734
EC1 CAFE	162	270	59	0.738
505	158	280	57	0.728
US06 C	180	460	35	0.573
HwFET	195	277	58	0.734
US06H	266	390	41	0.625
EC2 4-Cycle	214	354	45	0.655

The effect of the new 4-cycle is even more meaningful when considering a BEV. As an example, consider a BEV with a 250 mile range. This vehicle would have easily fulfilled the range requirement under the EC1, but very likely will fail to meet the range requirement under the EC2 4-cycle weighting. Inversely, a BEV with a 200 mile range under the EC1 CAFE weighting would need to add 10 kWh or more of battery capacity to meet range under the EC2 weighting. Thus, the more realistic 4-cycle weighting underscores the real range challenges that BEVs face in the consumer market today.

8 Conclusions

HEVT is a part of the 2012-2014 EcoCAR 2 challenge and is designing a vehicle powertrain that will reduce petroleum energy consumption and greenhouse gas and criteria emissions. The vehicle must be designed within the confines of the EcoCAR 2 rules and will be evaluated on several metrics including: acceleration, braking, lateral handling, drive quality, consumer acceptability as well as emissions and energy consumption. As part of the vehicle development process for the competition, the team considered 3 candidate architectures and selected a series-parallel EREV with P2 and P4 motors.

While EcoCAR 1 is very similar to EcoCAR 2 in purpose, structure and organization, one major difference is the evaluation method for emissions and energy consumption. EcoCAR 1 used the CAFE method (55% UDDS, 45% HwFET) traditionally used by the EPA for fuel economy labelling. EcoCAR 2 uses a 4-cycle method that approximates the newer EPA 5-cycle method. The 4-cycle method includes the more aggressive US06 cycle which features higher vehicle speeds and accelerations and is more representative of actual driving habits.

This shift from CAFE to 4-cycle has big implications for vehicle powertrain architecture design and component sizing and selection. The 4-cycle method is much more aggressive and necessitates a larger drive motor and battery to meet the accelerations of the US06 drive cycle. The effect of this change on EV range is especially important. For the described series-parallel EREV, the EV range was reduced by 24% between EC1 CAFE and EC2 4-cycle methods. For this vehicle, the result is a loss of 14 miles of EV range. For a BEV designed for 200+ mile range, the range reduction could be more than 50 miles, necessitating an additional 10 kWh of battery capacity. Thus, the new EcoCAR 2 4-cycle energy consumption evaluation method increases the powertrain design requirements, but offers a more realistic representation of real world driver behavior.

HEVT will continue to develop the series-parallel EREV architecture over the remainder of year 1. Upon the delivery of the GM-donated 2013 Chevy Malibu, the team will implement these designs during year 2 then refine the powertrain integration and control during year 3.

Acknowledgments

The contributions of the research, modeling, and results from HEVT are gratefully acknowledged. We would like to thank General Motors, the U.S. Department of Energy, Argonne National Laboratories, and the rest of the sponsors of the EcoCAR 2 competition. Finally we would like to thank all the team members of the 2011-2012 Hybrid Electric Vehicle Team and local sponsors.

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