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Results of 2011 EcoCAR Plug-in Hybrid Electric Vehicle On-Road Testing

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Abstract

EcoCAR: The NeXt Challenge 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 crossover SUV powertrain to improve fuel economy, reduce petroleum energy use and well-to-wheel greenhouse gas emissions, while maintaining safety, performance, and consumer appeal. Many of the 16 teams selected a plug-in hybrid electric vehicle (PHEV) powertrain design in 2009 Year One, and built a vehicle for the 2010 Year Two competition held in Yuma, AZ. The third and final 2011 Year 3 competition was held in Milford, MI where the vehicles were subjected to a series of on-road tests to measure emissions and energy consumption, acceleration and braking performance, handling, and static and dynamic consumer acceptability. The competition requires participating teams to re-engineer a stock crossover utility vehicle donated by GM. The result of this design process was an Extended Range Electric Vehicle (EREV) which uses grid electric energy and E85 fuel for propulsion. The vehicle achieved an SAE J1711 utility factor corrected fuel consumption of 2.9 L(ge)/100 km (82 mpgge) with an all-electric range of 87 km (54 miles). Using corn-based E85 fuel, the well-to-wheels petroleum energy use (WTW PEU) and greenhouse gas emissions (GHG) were reduced by 91 % and 18 % respectively when compared to the stock 4-cylinder, gasoline-fueled vehicle. This paper will give a brief overview of some of the supervisory control strategy employed and detail the on-road vehicle testing performed during the Year 3 EcoCAR 2011 competition that was held at GM's proving grounds in Milford, MI. Data from this testing will show the effectiveness of the control strategy in reducing emissions and energy consumption compared to the stock vehicle.

Keywords: Hybrid, PHEV, EcoCAR, Electric Vehicle, energy consumption, control strategy

1 Introduction

This paper includes an in-depth review of the vehicle powertrain architecture, as well as the supporting design work used to develop the architecture, including fuel selection and component sizing. The vehicle was tested in year 2 of EcoCAR. The components used, as well as the limitations created by those components are discussed in brief, and test results from the year 2 EcoCAR competition were used as a baseline for refinement for year 3. Next, year 3 refinements are detailed. These refinements include powertrain component changes and integration refinements as well as controller hardware changes and control system refinements. Finally, test results and subsequent vehicle refinements are described. This includes results from dynamometer testing at EPA's National Fuel and Emissions Lab in Ann Arbor, MI, on-road testing around Blacksburg, VA, and closed course testing at GM's Milford Proving Grounds in Milford, MI.

2 Team Goals

The main goals of the EcoCAR Challenge are to reduce petroleum energy consumption and greenhouse gas emissions while maintaining consumer acceptability, performance, and safety. Stemming from these goals, EcoCAR supplied the

Hybrid Electric Vehicle Team (HEVT) with minimum requirements for vehicle efficiency, utility and performance. In addition to these requirements, HEVT also established its own set of goals for petroleum energy consumption, all-electric range, and passenger space, which are shown in Table 1.

Table 1: HEVT 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
Towing Speed and Grade for 20 minute test	> 90 kph and 3.5% grade

The benefits of an all-electric mode are clear: better overall vehicle efficiency, a substantial reduction in petroleum energy use, and a small reduction in WTW GHG emissions. Thus, the goal of a large all-electric mode is implicitly linked to the goal of reducing petroleum energy consumption; a large all-electric range will inevitably lead to reduced petroleum energy usage. The drawback with electric vehicles, however, is range. To extend the range of the vehicle without the need for an excessively large battery pack, an additional energy source is required. Following the stated goals, HEVT reached the logical conclusion to design an EREV. Note that for the competition, the vehicle must be able to tow a mass of 680 kg (1500 lb) for an extended time and that HEVT could not depend on having a charged hybrid battery pack at the beginning of the test to meet the this requirement. The vehicle must depend on the engine in a worst case situation to carry the load completely, eliminating the possibility of large engine downsizing. These goals were then used to constrain and direct the architecture and component selection process to ensure that HEVT created a vehicle that meets the competition requirements while safely completing all events.

3 Vehicle Modeling and Fuel Selection

The first step in designing the hybrid architecture is the selection of an energy source for the vehicle. This selection is based on basic models constructed with Powertrain Systems Analysis Toolkit (PSAT), developed by ANL [1]. These models calculate the energy usage of the stock vehicle and compare the effects of various fuel sources on the energy used by the vehicle. In short, the models predict the overall vehicle efficiency specific to a given fuel, and then quantify the amount of petroleum energy that is expended by the vehicle for the given fuel. Similarly, vehicle GHG emissions for a given fuel are also quantified based on fuel-specific vehicle energy consumption. To consider the total life cycle of the fuel, the analysis is performed on a well-to-wheels basis. To consider the upstream well-to-pump (WTP) factors for GHG and criteria emissions as well as petroleum energy use, ANL's GREET model [2] is used to calculate total WTP energy, GHG emissions and criteria emissions released for the fuel. EcoCAR teams are given WTP numbers specific to North America for different candidate fuels: gasoline (E10), ethanol (E85), biodiesel (B20), electricity and hydrogen (H2) [3]. The last factor that affects the selection of fuel is the practicality of the components that would be used to convert fuel to kinetic energy.

Considering the factors outlined above with team goals in mind, HEVT selected electricity and E85 as its competition fuels [4]. With the combination of grid electricity and E85, HEVT predicts a 90 % reduction in petroleum energy use and a 20 % reduction in WTW GHG emissions compared to the stock vehicle. This GHG number will improve as the US energy grid becomes more renewable and cellulosic E85 becomes available. For a more detailed discussion on the fuel selection for the HEVT vehicle VT_{REX}, see [4].

4 Component Sizing and Selection

The next step in the vehicle design process for HEVT is the selection and sizing of the components, which is constrained by the fuels selected in the previous section. To meet the goal of a large electric-only range, HEVT chose to design and build a 20 kWh energy storage system (ESS) with materials and modules donated by

A123 Systems. This was the larger of two Lithium Iron Phosphate battery packs offered by A123 to the teams in the EcoCAR Challenge. The pack has a nominal voltage of 360 V and is rated at a peak discharge rate of 600 A and a peak charging rate of 300 A. The main traction motor used on the vehicle is a UQM 125 kW liquid-cooled permanent magnet motor, which is paired with a BorgWarner 3103 single speed transmission with a gear reduction of 7.17:1. The motor has a top powered speed of 8,000 RPM, which gives a top vehicle speed of 89 mph. The ESS is charged using an on-board Brusa 3.3 kW charger that can operate on either 120 or 240 V AC grid power. A complete recharge of 93 % State of Charge (SOC) swing (100% - 7%) will take 6 hours from a 240 V 20 A household circuit. Figure 1 shows a high-level schematic of the components used in the vehicle.

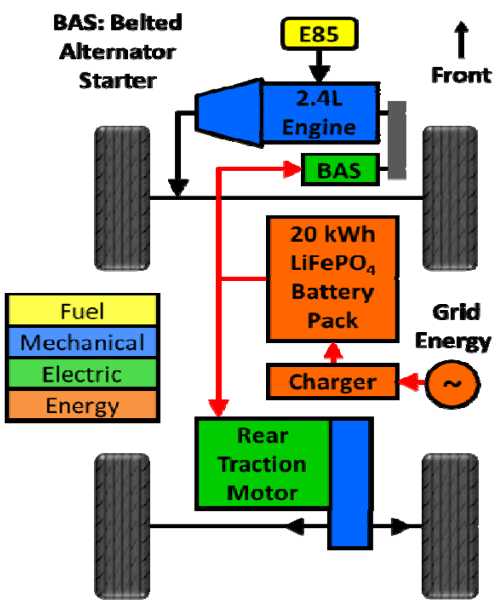

Figure 1: Energy flow diagram of the VT_{REX}

The stock engine is replaced with a GM 2009 LE9 (4-cylinder 2.4 L) FlexFuel engine. This FlexFuel engine enables the use of E85, which was chosen to meet the goal of reducing petroleum energy consumption. The engine will act as the primary source of propulsion in charge sustaining (CS) mode. Belted to the engine is a custom Kollmorgen 8 kW (peak) liquid-cooled AC induction motor that serves as a belted alternator starter (BAS). This motor replaces the alternator and starter and improves vehicle efficiency by enabling engine idle start/stop, as well as engine load leveling which increases the average operating efficiency of the engine. The engine is coupled with the GM ME7 4T45 4-speed automatic transmission from GM's BAS hybrid system. The transmission has an auxiliary fluid pump that keeps transmission lines pressurized while the engine is off to allow smooth, quick takeoff as soon as the engine is restarted. Since the BAS provides load leveling which increases the operating efficiency of the engine, and the rear traction motor (RTM) provides electric launch, the efficiency benefits offered by adopting a 6-speed transmission were not as significant. Thus the team instead chose the 4-speed transmission to ease the integration challenges and reduce weight. Table 2 shows an overview of the components on board the VT_{REX}.

Table 2: VT_{REX} Component Specifications

Components	Size	Type
Engine	130 kW peak	GM LE9 2.4 L ECOTEC VVT DOHC 16V I4 FlexFuel SI
Transmission	-	ME7 4T45 hybrid 4-speed automatic FWD
BAS	8 kW peak	Kollmorgen custom AC induction motor
RTM	125 kW peak	UQM liquid cooled permanent magnet motor
RTM Transaxle	-	BorgWarner 3103, gear reduction: 7.17:1
ESS	360 V	A123 Systems custom built prismatic pack, 18.7 kWh useable
12 V Supply	1 kW cont.	Delphi DC/DC Converter, from 360 V to 13.8 V
A/C System	10 kW	High voltage electric drive, high efficiency, variable speed
ESS Charger	3.3 kW cont.	Brusa 120/240 V 50/60 Hz AC, integrated on-board
Supervisory Controller	-	NI CompactRIO with field programmable gate array (FPGA)

Since there are large amounts of time when the vehicle operates with the engine off, an electric high voltage air conditioning (A/C) compressor is installed on the vehicle to keep consumers comfortable regardless of propulsion mode. A Delphi DC/DC converter provides power for the 12V system directly from the high voltage A123 battery pack. As expected, this converter is a necessity for charge depleting (CD) mode, but it is also necessary for CS mode because there is not a traditional 13.8 V alternator on the vehicle.

5 Vehicle Technical Specifications

With component architecture and components selected, HEVT developed a set of vehicle technical specifications. These specifications were developed using PSAT and are based on vehicle characteristics including predicted final weight and component characteristics. The purpose of these specifications is to provide a set of quantifiable goals that can be validated through testing. As part of the EcoCAR competition, HEVT is judged not only on overall performance but additionally on how closely the vehicle met the VTS. The key vehicle technical specifications can be seen in Table 3. As the vehicle design evolves, the VTS is updated to reflect the proposed final design, but the final VTS is locked in well before the final EcoCAR competition where vehicle testing occurs. Table 3 represents the final VTS that was locked in before year 3 competition. The calculated combined fleet utility factor (UF) is 0.69 (69% of travel distance as EV) based on the proposed SAE J1711 standard, which leads to a predicted UF weighted fuel consumption of 2.7 l(ge)/100 km (88 mpgge). This figure is a substantial improvement over the stock vehicle and greatly exceeds the competition requirement of 7.4 l(ge)/100 km (32 mpgge). With the 20 kWh operating in an SOC window of 100% to 7%, the team predicts a CD range of 50 miles, which exceeds HEVT's goal of a 35 mile electric vehicle (EV) range. The CD range specification has a large impact on UF weighted fuel consumption because of the utility factor - the larger the EV range, the greater the utility factor. Since the vehicle operates much more efficiently as an EV in CD mode, a larger UF will decrease UF weighted fuel consumption. On-road testing has been performed to validate these specifications, and the results are presented later in the paper.

6 Control Strategy Overview

The VT_{REX} is first and foremost an electric vehicle. It will operate in Electric Vehicle (EV) or Charge Depleting (CD) mode for as long as battery SOC allows and then switch to Charge Sustaining (CS) mode. In CS mode, the engine, rather than the motor, becomes the main source of propulsion and the BAS motor is now utilized for engine start/stop. This section will outline the control strategy used in the VT_{REX} to transition into CS mode, split torque among the 3 powertrain components, and to reduce fuel used while idling. For a more thorough discussion of the operating strategy of the VT_{REX}, see [5], [6], [7].

6.1 Charge Depleting Mode

CD mode is very straightforward from a control strategy standpoint. There is only one energy source (ESS) and one power source (RTM). The vehicle begins operation charged to 100% SOC and will exit CD mode at 7% SOC, which is also the lower SOC target. The vehicle will enter engine warm-up mode (discussed in section 6.4) before reaching 7% SOC, but will still deplete charge during engine warm-up mode.

6.2 Charge Sustaining Mode

In CS mode, all net energy used to propel the vehicle comes from the fuel tank. The ESS and electric motors are still used, but the net energy out of the ESS is by definition very close to zero. CS mode seeks to maintain the charge of the battery within a 2% window. Hence, the control strategy will allow the ESS to go as low as 6% and as high as 8%. This is a very tight window, but the ESS is rather large. A 2% SOC swing is about 400 Wh, which is enough of an energy buffer to allow for the capture of energy through regenerative (or regen) braking or engine load levelling and the expenditure of energy through electric assist with the RTM.

6.3 Torque Split Strategy

In CS mode, the engine is the main source of propulsion, but the RTM is also available to be used. This presents the opportunity to divide torque between the engine and the motor. The engine is primarily responsible for meeting the driver demand, but the RTM is used to improve fuel economy and reduce emissions. One way this is done is by using the RTM to keep the engine out of undesirable operation zones. Immediately after a cold start, for instance, the engine torque is

Table 3: Vehicle Technical Specifications

Specifications	Metrics	EcoCAR Vehicle Information		Architectures Goals
	M: Measured T: Tested I: Inspected	Stock Vue XE	EcoCAR Requirements	HEVT SPA
Acceleration IVM-60 mph	M,T	10.6 s	≤ 14 s	7.3 s
Acceleration 50-70 mph	M,T	7.2 s	≤ 10 s	4.0 s
Towed mass	M	680 kg (1500 lb)	≥ 680 kg ≥ (1500 lb)	≥ 680 kg ≥ (1500 lb)
Towing Grade	T	-	≥ 3.5 %	6%
Towing Duration	M	-	20 min	> 20 min
Towing Speed	M	-	≥ 72 kph ≥ (45 mph)	≥ 89 kph ≥ (55 mph)
Cargo Capacity	I	.83 m^3 29.3 ft^3	0.24 m^3 8.48 ft^3	0.61 m^3 21.7 ft^3
Passenger Capacity	I	5	≥ 4	4 (mass limited)
Braking 60-0 mph	M,T	38 - 43 m (123-140 ft)	< 51.8 m < (170 ft)	< 45 m < (147 ft)
Curb Weight	M	1758 kg (3875 lb)	≤ 2318 kg ≤ (5110 lb)	2123 kg (4680 lb)
Starting Time	M	≤ 2 s	≤ 15 s	< 15 s
Ground Clearance	M	198 mm (7.8 in)	≥178 mm ≥ (7 in)	≥178 mm ≥ (7 in)
Range	M,T	> 580 km ≥ (360 mi)	≥ 320 km ≥ (200 mi)	≥ 340 km ≥ (215 mi)

limited to allow the engine and catalytic converter to heat up while keeping emissions low. This will be discussed more in the following section. The RTM is used in this case to make up the rest of the driver demand. Once the engine has warmed up, a minimum torque limit is imposed on the engine. If the driver demand is less than this limit, the engine operates at the lower limit while the RTM is commanded negative torque to achieve the driver demand while storing the extra energy in the battery pack.

Another way efficiency is improved is by avoiding fast transients on the engine. Sharp increases in driver demand are met immediately by the RTM while engine torque is slowly ramped up. This ramp prevents fuel enrichment that is often used to quickly increase engine output which results in lower efficiency and higher emissions. Figure 2 shows actual data illustrating the torque split strategy in action [7].

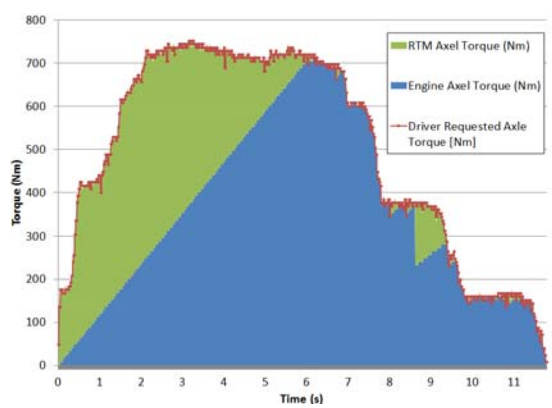

Figure 2: Example of data from an actual drive showing engine torque being ramped

6.4 Engine Warm-Up Mode

In the first phase of engine operation, before the catalyst has reached light-off temperature, a considerable portion of the engine-out emissions pass through the catalyst and out of the tailpipe.

Under normal operation, the first engine start for the vehicle will occur during the transition from CD to CS mode and will be a true cold start. The warm-up phase is triggered before full charge sustaining operation is allowed, in order to warm up the catalyst before commanding large torque requests to the engine. The VT_{REX} is capable of limiting commanded engine torque during the warm-up phase due to the torque-split operating strategy, and the powerful main electric traction motor.

Since the engine is being severely limited during this warm-up period, the vehicle is not capable of truly sustaining charge in the ESS and the driver risks pushing the vehicle to a critically low SOC during warm-up mode. To work around this, a buffer is put in place to enter warm-up mode before reaching the target SOC for CS mode. Additionally, the buffer is flexible to give the vehicle a chance to perform the first BAS start (a cold start) while the vehicle is at rest. The size of this buffer was tested and finally changed to be a range of 5-10 % SOC. This range means that the engine will start the first time the vehicle comes to a stop after dropping below 17% SOC (the CS target SOC is 7%) but will start the engine regardless of speed if the SOC reaches 12%. For a detailed discussion of the engine warm-up strategy used, see [5], [6].

6.5 Engine Idle Start/Stop Strategy

The VT_{REX} has a 8 kW BAS motor that enables engine idle start/stop, which improves fuel economy by eliminating idle fuel use. To compound the effectiveness of this strategy, engine idle start/stop mode is followed by electric launch mode in which the RTM is the sole source of propulsion. The engine does not restart until the vehicle speed reaches a certain threshold or the battery SOC drops too low. The minimum speed threshold was put in place to eliminate engine use at low speeds and inefficient operation. The transmission shifts out of first gear before 30 mph, so the exit criteria was set at 30 mph. Thus, the engine will shut off when the vehicle comes to a stop and will not restart until the vehicle reaches 30 mph or the SOC drops to the lower SOC limit.

7 Year 3 Competition Testing and Results

EcoCAR year 3 competition was held at GM's Milford Proving Grounds in Milford, MI. Each EcoCAR school was required to run various dynamic testing events to evaluate the various metrics of vehicle performance. While results from all dynamic events will be presented, this paper will focus on the results of the Emissions and Energy Consumption (E&EC) event, and specifically the last leg of the event, known as schedule C.

7.1 E&EC Drive Cycle and Description

The drive cycle used for the E&EC event in year 3 of EcoCAR is a blend of city and highway driving elements. As shown in Figure 3, the city portion consists of lower speed driving with more stops and starts, while the highway portion consists of only a few stops and higher speed driving. The cycle is designed to mimic the UDDS and HWFET cycles with the constraint that it must be driven on-road on the circle track at GM's Milford Proving Grounds. Table 4 summarizes some key characteristics of the drive cycle.

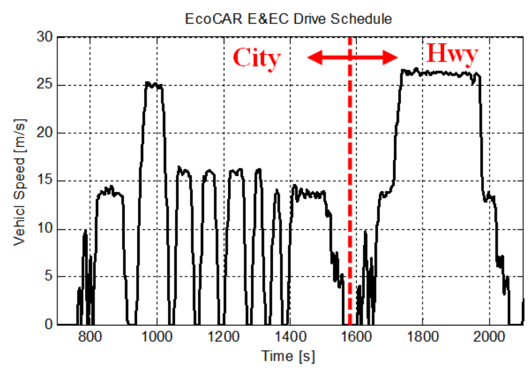

Figure 3: E&EC drive schedule.

There are three parts to the E&EC event: schedules A, B & C. The only difference between the schedules is the length: Schedule A is 33 km (20 mi), schedule B is 66 km (41 mi) and schedule C is 167 km (104 mi). The drive cycle shown in Figure 3 is repeated in each portion of the event and the number of cycle repetitions depends on the designed distance of the particular E&EC schedule. The repetition of the cycles is designed to mimic CAFE weighting of 55% city and 45% highway driving.

Table 4: Specifications of the E&EC drive schedule

Cycle	**Dist.** mi	**Time** s	**Avg. Speed** mph	**Idle Time** s	**Avg. Running Speed** mph	**Max. Speed** mph	**Peak Accel.** m/s^2	**Peak Negative Accel.** m/s^2	**Average Accel.** m/s^2
UDDS	7.45	1369	19.59	241	23.78	56.7	1.48	-1.48	0.51
HwFET	10.26	765	48.27	4	48.52	59.9	1.43	-1.48	0.19
EC1 CAFE weighting			26.74		30.86	55% UDDS + 45% HwFET			

Teams start each of the 3 portions of the E&EC event with a full battery charge and a full tank of fuel. The fuel tank is weighed before and after driving each schedule, and the battery is recharged at the end of each schedule. Thus, the battery and fuel energy for a particular schedule is determined. After all three schedules are completed, the total battery energy from each of the three legs is summed to find the UF weighted electric energy consumption, and total fuel use is summed for UF weighted fuel consumption. The distances of the three schedules (approximately 20, 40 and 100 miles) are designed to mimic the SAE J1711 standard for evaluating the UF weighted fuel economy of a PHEV. For a more detailed explanation of the design of the on-road utility factor approximation, see [8].

7.2 Overall Behavior

To get a high-level picture of the behavior of the VT_{REX} during the E&EC event, Figure 4 shows the energy consumption of the vehicle over the duration of schedule C of the event. Wheel energy is the integrated road load of the vehicle. Motor energy is on the mechanical side of the motor and is calculated by integrating motor torque and motor speed. Battery energy is calculated by integrating voltage and current at the battery terminals and necessarily does not account for internal losses due to battery resistance. Engine energy is calculated at the engine based on the engine controller estimated flow rate of fuel.

Because the event is performed on-road, there are 3 distinct stages. Stages 1 and 3 are the distance travelled to and from the circle track while stage 2 is the actual designed drive cycle. During stage 1, the engine is turned on (regardless of SOC or control strategy) to test the on-board emissions equipment. Essentially, the vehicle is forced into CS mode for stage 1. Because of this, the engine expends about 3 MJ of energy before reaching the circle track. Once on the circle track operating normally, the vehicle begins operation in CD mode with the battery (green line) supplying all propulsive energy and the RTM supplying all propulsive power. As expected, the battery energy

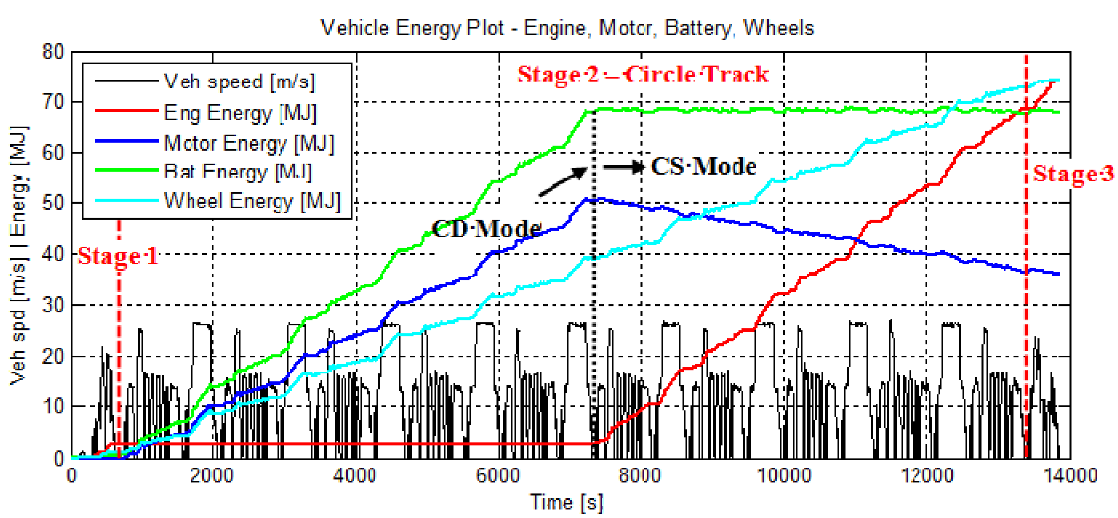

Figure 4: Overall energy consumption of the VT_{REX} during schedule C of the E&EC event

line is steeper than the motor energy line, which is steeper than the wheel energy line. This illustrates the effect of component efficiencies as energy is lost in the powertrain.

When the vehicle transitions to CS mode, a distinct change in behavior is observed. Most obviously, the engine turns on and starts expending fuel energy. It is interesting to note that the slope of the engine energy line is steeper than the motor energy line, which illustrates the efficiency advantage of an electric drivetrain over a conventional drivetrain. The battery energy plateaus, showing that the vehicle is truly sustaining the charge of the pack. The motor energy, however, begins to slope downward, showing that the net flow of energy through the motor is into the battery. This is due to the fact that the RTM is still doing regen braking and is now also putting additional load on the engine via the torque-split strategy previously described. The motor is still used to propel the vehicle for brief periods during electric launch mode, but the energy flowing out of the motor is minimal compared to CD mode. Hence, the RTM is acting more like a generator than a motor during CS mode.

Note that the sum of the net battery energy (68.5 MJ) and engine fuel energy (74.1 MJ) equals the total energy expended by the vehicle (142.6 MJ) over schedule C of the E&EC event. Using the total wheel energy (74.4 MJ), the net powertrain efficiency of the of the VT_{REX} over schedule C is about 52%. Bear in mind, this is not the overall UF weighting powertrain efficiency because the calculation does account for energy expended during schedules A or B. This number is, of course, dependent on the distance of the schedule and ultimately illustrates the effect of the utility factor weighting used to evaluate PHEVs. If the schedule were shorter, less engine energy would have been used and the more efficient electric drivetrain would have counted for more of the total energy expended by the vehicle and the vehicle powertrain would appear more efficient.

7.3 Engine Warm-up Mode, Engine Idle Start/Stop and Torque Split Strategy

Figure 5 shows power traces of the engine, motor and battery during the first 6 hills of the first and second full E&EC drive cycles performed while in CS mode. The first 6 hills of the first drive cycle (top graph) illustrate the effect of the warm-up

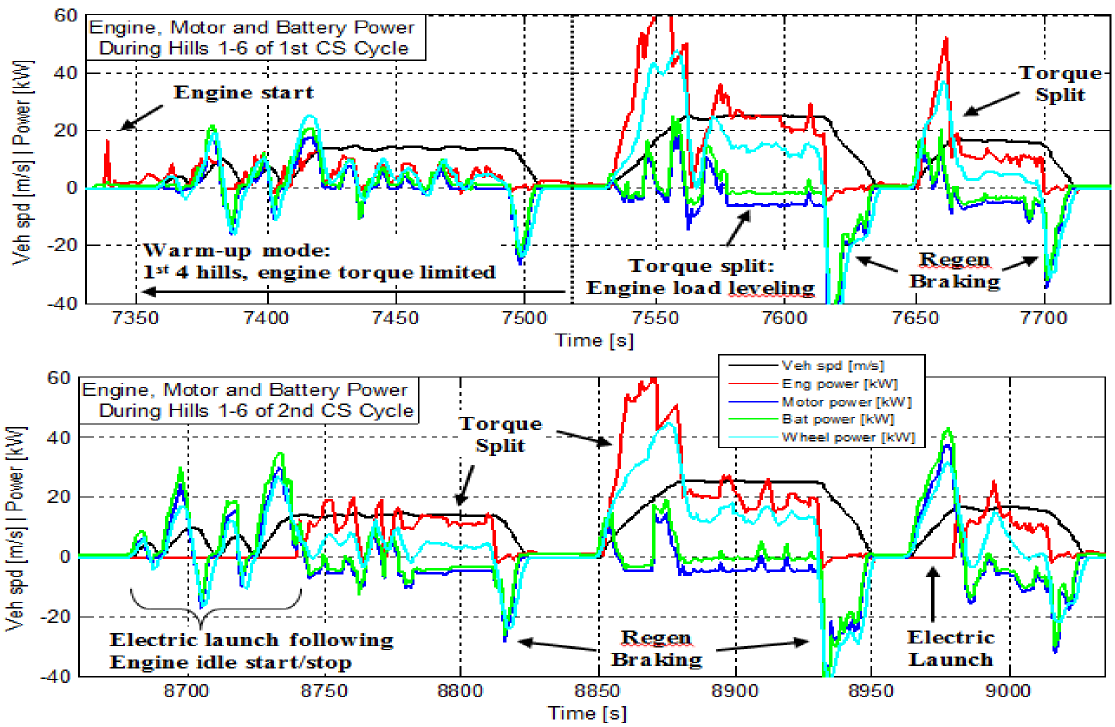

Figure 5: 1st 6 hills of the 1st and 2nd full cycles performed in CS mode.

mode previously described. It is clear from comparing the top trace (1st CS cycle) to the bottom trace (2nd CS cycle) that the engine output is limited during the first few hills of the cycle. It is also evident that the RTM is supplying a significant portion of the tractive power during this period. Bear in mind that the engine was operating for a brief time on the drive from the garage to the circle track. This gave the engine and catalyst some amount of a 'head start' on heating up, so the first engine start was not a true cold start. This paper does not address the emissions results of these tests – for this analysis see reference [6].

While the vehicle is in engine warm-up mode, it will not shut off the engine at idle in order to heat up the catalyst as fast as possible, and avoid multiple engine starts before the catalyst reaches light-off temperature. Thus, engine idle start/stop mode is disabled while the engine and catalyst are warming up. Hence, it is not until the 2nd CS cycle that the vehicle begins performing engine idle start/stop. It is not possible to determine from the plots if the engine is running during vehicle idle. However, an engine idle start/stop event is always followed by an electric launch, so it is evident that multiple engine idle start/stops occurred during the 2nd CS cycle.

These two plots also illustrate the effects of the torque split strategy previously described. At various instances in the drive trace, it is clear that the tractive power (labelled as wheel power) is satisfied by a combination of the motor and the engine. In some instances, like the acceleration at the beginning of a hill, the RTM supplies positive power to assist the engine. As previously mentioned, this allows the engine to come up to the requested torque gradually which avoids fuel enrichment, improving fuel economy and emissions. In other instances, the RTM supplies negative power which artificially loads the engine. In these instances, the engine power is clearly greater than tractive power. This strategy keeps the engine above a minimum torque threshold which constrains the engine to a relatively efficient operating region. The energy stored during these load levelling events is later used to perform electric launch or to assist the engine.

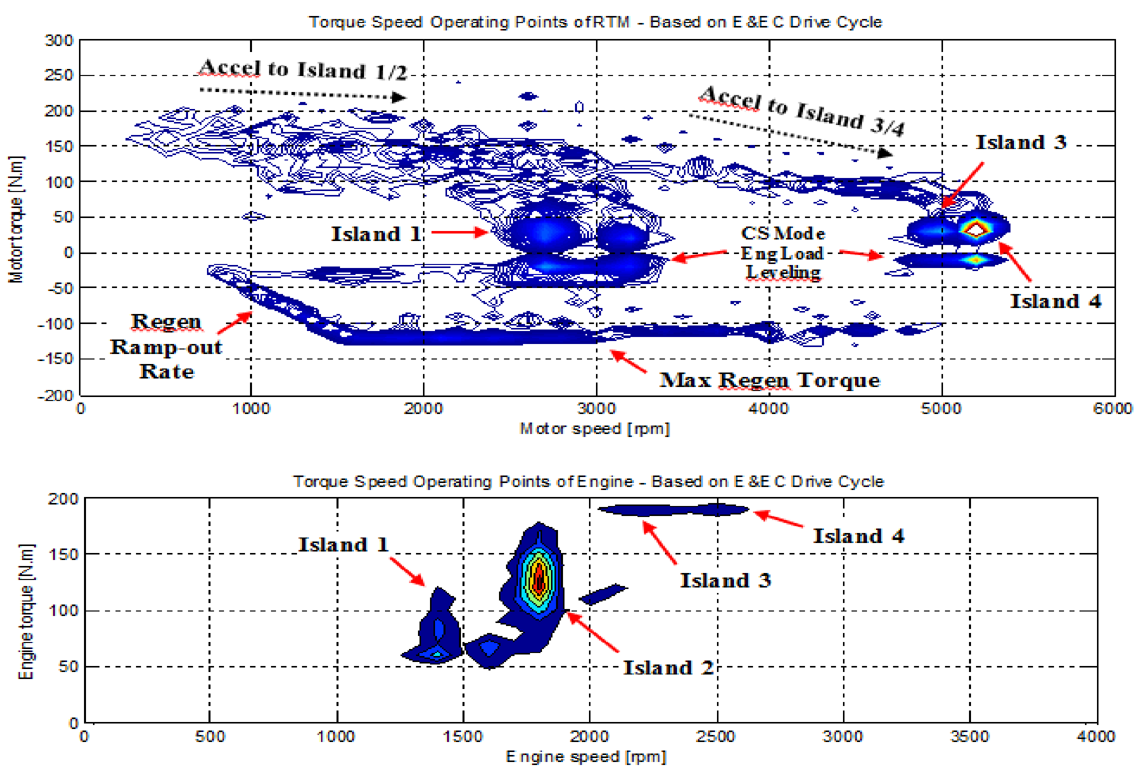

Figure 6: Engine and RTM operating points over schedule C of the E&EC event.

7.4 Engine and Motor Operating Regions

Figure 6 illustrates the engine and motor operating regions for schedule C of the E&EC event. These plots are useful for gaining insight into the behavior of the motor and the engine based on the designed control strategy over the E&EC drive cycle. Examining the first plot, there are clearly four 'islands' where the motor operated for extended periods of time. These four islands correspond to the hills of the E&EC drive cycle: the hills of the drive cycle plateau at either 30, 35, 55, or 60 mph. In the positive torque quadrant, there is also some operation at speeds leading up to these islands. These regions are from the accelerations at the beginning of the hills.

In the negative torque quadrant, these four islands are mirrored across the torque axis. This means that the RTM spent a significant amount of time at those same speeds applying negative torque. This, of course, occurred while engine load levelling, as shown in Figure 5. A lower operating envelope can also be seen around -120 Nm – this is the maximum torque allowed for regen braking. Because the RTM is on the rear axle, this maximum torque limit was established due to vehicle stability concerns. The regen brake strategy also ramps out regen braking as the vehicle comes to a stop, beginning to derate the maximum regen torque at about 1500 rpm (16 mph) and cutting out regen braking altogether at about 800 rpm (9 mph).

Engine operating points are much more constrained than those of the motor. The same four islands from steady-speed operation are present and prominent. Unlike the motor, however, there is little time spent outside these islands which is a symptom of the torque split strategy as well as the presence of electric launch. Low-speed operation was avoided with electric launch and engine transients were avoided by using the motor to supply the necessary transient torque while allowing the engine to ramp in torque more gradually. As a result, the majority of engine operation was spent between 1500 and 2000 rpm and above 100 Nm of torque, which is an efficient area of operation for the LE9 engine.

7.5 Overall Year 3 Competition Testing Results

Each EcoCAR school was required to run various dynamic testing events to evaluate the vehicle acceleration, braking, lateral handling, drive quality, towing capability, emissions, and energy consumption. The VT_{REX} completed all events and scored exceptionally in most of them. The results from year 3 competition are summarized in Table 5 alongside the final VTS predictions. Some competition elements not listed in this table include AVL drive quality and dynamic consumer acceptability, which are objective and subjective (respectively) measures of linear drive quality. The team placed first in both events with scores of 45 out of 45 for AVL drive quality and 46 out of 50 for dynamic consumer acceptability.

Table 5: Year 3 Competition Results

HEVT VTS	Stock Vue XE	Y3 Actual
EV Range	---	54
Fuel Economy: CAFE Unadjusted, Combined, UF weighted	28 mpgge	82 mpgge
	8.3 l(ge)/100km	2.9 l(ge)/100km
CS Fuel Economy	28 mpgge	25 mpgge
	8.3 l(ge)/100km	9.4 l(ge)/100km
0-60 mph Acceleration	10.6 s	6.7 s
50-70 mph Acceleration	7.2 s	3.12 s
60-0 mph Braking	38-43 m	40 m
Curb Weight	1758 kg	2123 kg
Total Range	>306 mi	205 mi

8 Conclusions

The VT_{REX} completed and performed well in all dynamic and static events at the year 3 EcoCAR competition, placing 1^{st} overall. The vehicle recorded an EV range of 54 miles and a UF weighted fuel economy of 2.9 l(ge)/100km (82 mpgge). Compared to the stock vehicle, the VT_{REX} achieved a 91% reduction in WTW UF weighted petroleum energy reduction and an 18% reduction in WTW UF weighted greenhouse gas emissions. The vehicle met the HEVT goals of 80% petroleum energy reduction and a 35 mile EV range, and met or exceeded most of the vehicle technical specifications. These achievements were largely the result of a carefully conceived and well-refined supervisory control strategy that balanced the priorities of reducing both emissions and fuel consumption.

The EcoCAR challenge has ended and Virginia Tech is now a part of EcoCAR 2: Plugging In to the Future. The key goals and objectives are the same, but the vehicle is now a 2013 Chevy Malibu. HEVT hopes to replicate the success experienced in EcoCAR and is excited to continue pushing the envelope of sustainable transportation.

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