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# Challenge X Year 2: Spring Technical Report

**University of Tulsa Challenge X Team**
The University of Tulsa

## ABSTRACT

Using General Motors' Vehicle Development Process, the University of Tulsa's Challenge X team (TUCX) has designed, modeled, and implemented a novel vehicle architecture that will increase the fuel economy of a 2005 Chevrolet Equinox while simultaneously maintaining performance. All of the major new and modified components are installed in the vehicle, and the control system can operate all of them at a basic level. TUCX is now optimizing the control system for economy and user-friendliness via on-road testing.

## INTRODUCTION

The University of Tulsa is one of seventeen university teams in the Challenge X advanced vehicle design competition. The challenge of the event is to reduce the fuel consumption and lower the emissions of a crossover sport utility vehicle without compromising its performance or utility characteristics. The competition is managed by the Department of Energy's Center for Transportation Research at Argonne National Laboratory (ANL) in partnership with General Motors (GM) with the cooperation of many industrial sponsors. The target vehicle is the 2005 Chevrolet Equinox.

The three-year program follows a vehicle development process similar to that used in the automotive industry to develop new products. For the first year, the team's focus was on simulation and design studies with limited hardware testing. This optimized the design before investment in major hardware assembly and testing. This year is devoted to refining, installing, and testing the design innovations developed during the first year studies. The third year provides for refinement of the design and enabling all of the vehicle's original utility and functionality.

In this report, the Tulsa team will briefly describe their vehicle architecture, describe how the proposed design of the first year study is being integrated into the Equinox, and summarize the progress of implementation. The report will also analyze the control strategy and subsystem architecture models. Although much of the work has been completed, continuous improvement on the control systems will continue until the competition. Continued simulation studies of vehicle performance under selected control strategies are being used to project how well the actual vehicle will meet the team's vehicle technical specifications (VTS). Testing is underway for comparing actual vehicle performance to simulation results.

## OVERVIEW OF COMPONENT SELECTION AND HYBRID CONTROL

Previous TUCX reports described the decision to use a diesel-electric through-the-road parallel hybrid architecture with fuel cells providing additional power. A schematic of this architecture is shown in Figure 1. At the present time, the project-specific major components have been received through the sponsor donation program and have been integrated into the vehicle infrastructure, as well as locally-built support and infrastructure components.

### Internal Combustion Engine

TUCX selected and received a GM 1.9 l four-cylinder 150 hp (112 kW) CDTI (common rail direct injected turbocharged) diesel engine for the internal combustion engine (ICE). This state-of-the-art compression ignition engine was developed by the GM/Fiat partnership and is used in Opel Vectra passenger cars in Europe. It was made available through the GM Parts program. This engine drives the front axle, and, while it is not powerful enough to meet all of the VTS alone, it provides enough power to meet basic propulsion needs for cruising and towing. The TUCX strategy is to run the diesel engine only when it is most efficient, and to shut it off when it is not needed. The engine will run on a mixture of 80% petroleum-based diesel and 20% bio-diesel (B20), which is stored in the competition-mandated liquid fuel tank. This tank is mounted under the rear of the vehicle and can be easily removed for fueling or fuel measurement.

### Electric Motor

The electric motor driving the rear axle is a Ballard Integrated Power Train (IPT) induction motor provided through the Ballard component donation program. The IPT includes the electric motor, controller, gearing, and differential in one unit. It provides up to 2500 Nm of propulsion torque or 1250 Nm of braking torque at shaft speeds less than 300 rpm, and decreasing amounts of torque at progressively higher speeds up to 1200 rpm. The motor has a maximum short-term output power capability of 65 kW. The motor provides torque to the rear wheels when the diesel engine is disengaged, assists the engine during peak torque demands, and recaptures energy through regenerative braking. Regenerative braking (a negative torque demand) recaptures kinetic energy and stores it in the Energy Storage System (ESS) when braking by using the motor as a generator.

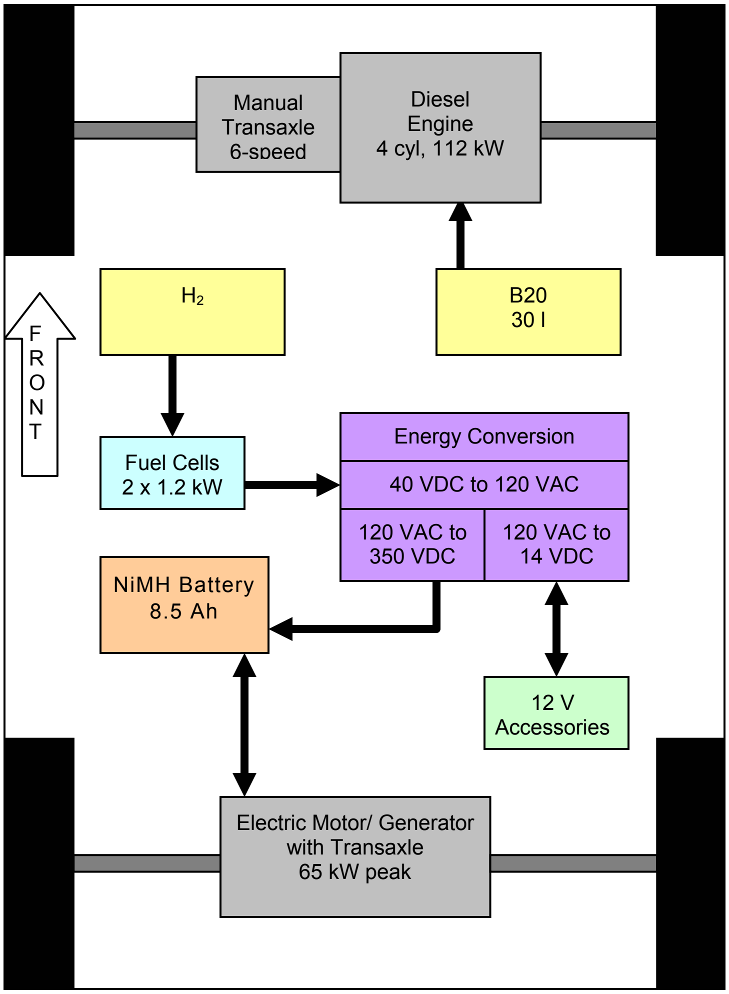

**Figure 1. Powertrain Architecture**

## Transmission

TUCX has chosen a manual transmission over a conventional automatic or continuously variable transmission for the diesel because of its higher efficiency and its ability to optimize the performance potential of the diesel engine using “driver-in-the-loop” control. The chosen six-speed F40 manual transmission is used in several vehicles including the Opel Vectra, and was acquired through the GM Parts program with the diesel engine.

The Ballard IPT includes its own gearing for wheel speeds up to 110 mph, so no external transmission is required for the rear axle.

With TUCX’s parallel through-the-road design, the vehicle will have all-wheel drive when both the diesel engine and the electric motor are running.

## Fuel Cells

Two 1.2 kW Ballard Nexa proton exchange membrane (PEM) fuel cells are installed for onboard electricity generation. These fuel cells were acquired through the Ballard component donation program. The output of the fuel cells charges the traction battery and powers 12 V accessories via the energy conversion subsystem.

A Quantum $H_2$ tank stores gaseous hydrogen for the fuel cells. This tank is plumbed to a WEH fill receptacle on the exterior of the vehicle for refueling.

The tank, fuel cells, and related plumbing are mounted in the rear cargo space, but are totally enclosed and vented only to the exterior of the vehicle. Gas sensors, both stand-alone and built into the fuel cells, monitor for hydrogen leaks.

## Energy Conversion

The output from each fuel cell, which ranges from about 30 to 40 V DC, is converted to 120 V AC with an Analytic Systems LVS 1000 inverter. Since the fuel cell is very sensitive to voltage ripple, a filter circuit is installed between the fuel cell and the inverter. This 120 V AC is then rectified and converted to 350 V DC to recharge the traction battery, using two Vicor 500 W DC-DC converters. The 120 V AC is also rectified and converted to 14 V DC to power 12 V nominal accessories with a Vicor DC-DC converter. Finally, the 120 V AC is also available directly to power standard appliances.

There are two identical halves to the system for a total of two filter circuits, two LVS 1000 inverters, four 500 W Vicor DC-DC converters with 350 V DC output, and two Vicor DC-DC converters with 14 V output. The total output power available is 2000 W.

## Electrical Energy Storage System (ESS)

The main ESS is the Cobasys NiMHax 288-60, which is a nickel metal hydride (NiMH) battery designed for use in small SUVs. It has a nominal voltage of 288 V at 35°C, a nominal capacity of 8.5 Ah and a maximum instantaneous power output of 60 kW. The battery supplies energy to the electric motor for propulsion and stores energy generated by regenerative braking and by the fuel cells. It was received through the Cobasys component donation program.

This battery was initially installed under the vehicle, between the frame rails and just ahead of the rear wheel wells. Since then, Cobasys supplied a replacement battery with enhanced safety features, which had a slightly larger housing that would not fit in the original location. The battery is now located in the floor of the vehicle just in front of the rear seat. This creates some issues with passenger comfort and seating, but this location does not require modifications that would affect the structural integrity of the vehicle. Special housings have been added to ensure passenger safety.

A conventional 12 V flooded lead-acid battery runs standard 12 V accessories, including the starter motor for the ICE. This battery is recharged by the ICE alternator and the 14 V output of the energy conversion subsystem.

Cooling Systems

The stock radiator, filled with standard non-Dexcool antifreeze and water, cools the diesel engine. The induction air is cooled after turbocharging by an intercooler located on top of the engine. A hood scoop forces ambient air through the intercooler.

The Ballard IPT and the Cobasys battery both require liquid cooling to ensure proper operation, but the required coolant temperatures are much lower than that of the diesel engine. The battery requires an even lower temperature than the IPT. Therefore, the IPT and the battery have independent cooling systems. Both systems use a 12 V electric water pump, an equal mixture of Dexcool antifreeze and water, and a liquid-to-air heat exchanger.

The cooling system for the Ballard IPT uses a 2.8 gallon per minute (GPM) Shur-Flo pump to move the coolant through the IPT and a 5-inch by 20-inch heat exchanger. This heat exchanger is mounted on the front side of the vehicle air conditioning condenser and is cooled by ambient air. HYSYS, a process simulator available through the Chemical Engineering department, verified the energy balances in this process, and sized the cooling components. With 1000 W of heat generated by the IPT and an inlet air temperature of 40°C, a HYSYS simulation shows an inlet coolant temperature of 52.1°C and an outlet coolant temperature of 53.7°C.

The Cobasys battery cooling system uses a 3.5 GPM Shur-Flo pump and a 5-inch by 7.5-inch heat exchanger. This heat exchanger is mounted in a steel housing in the interior of the vehicle and is cooled by the lower duct of the air conditioning system. With 500 W of heat generated by the battery and an inlet air temperature of 40°C, a HYSYS simulation shows an inlet coolant temperature of 36.9°C and an outlet coolant temperature of 37.3°C.

The stock Equinox air conditioning system is used to cool the interior of the vehicle. The compressor is mounted on the ICE and driven by a belt. This minimizes the use of stored electrical energy and eliminates the weight of an additional electric motor that would be needed to drive the compressor. For Year 3, TUCX is considering using the energy generated by the fuel cells to power an electric compressor in order to make the HVAC system fully hybrid.

Control System

The control and data acquisition system is implemented using National Instruments' LabVIEW software and compactRIO real-time controller. Both the hardware and software were donated by National Instruments. A block diagram of the system design is shown in Appendix A. Much of the communication between the new hybrid system components and the existing Equinox systems is by the high-speed CAN (Controller Area Network) protocol, but there is also a system of non-networked analog and digital I/O. The system can run completely autonomously, or a laptop can be connected for enhanced data display and data logging.

## OVERALL INTENDED COMPETITION DESIGN (VTS) AND VALIDATION OF RESULTS THAT SUBSTANTIATE THE DESIGN

TUCX has *not* changed its VTS since Report 5 from the first year of competition, although an incorrect table was published with the Fall 2005 report that reflected the most optimistic conditions. Continued modeling has reinforced the decision to remain with the original VTS. The VTS are critical to ensuring that the vehicle meets the requirements of the consumer. Choosing the VTS of the vehicle is challenging due to the delicate balance between performance, architecture and the selected components. As shown by modeling of different vehicle architectures and levels of hybridization (changing the percent of total vehicle power supplied by the electric motor), changing one component of the vehicle (such as the size of the engine) affects several technical specifications.

Changing engine size, for example, will change not only the 0-60 mph time, but also the vehicle weight, fuel economy, emissions level, and trailering capacity. When sizing of the electric motor and engine there are definite trade-offs. If the engine is too large, the fuel economy will be poor; if it is too small, the vehicle will weigh more (since the power densities of the electric motor and battery are less than that of the engine) and the engine may not be able to keep the battery at a desirable state of charge. This can lead the vehicle to becoming an essentially electric vehicle and requiring a recharge after a short driving range. The goal of the competition is a successful evaluation of these trade-offs to create the best possible overall vehicle.

**Table 1: Current TUCX VTS**

| Description | VTS |
|---|---|
| IVM 0-60 MPH | 8.5 s |
| 50-70 MPH | 5.5 s |

| | |
|---|---|
| Vehicle Mass | 4400 lbs |
| MPG Combined EPS | 32.0 mpgge |
| Emissions | Tier 2, Bin 5 |
| Highway range | 250 mi |
| Passenger Capacity | 5 Passengers |
| Trailering Capacity | 2500 lbs |
| Starting Time | < 5.0 s |

Acceleration Times

The majority of Tulsa's VTS were selected through simulations with PSAT. The basis for sizing the components was the condition that there would be enough power to meet the competition target VTS of a 9.0 second 0-60 mph acceleration. Simulations showed that an 8.9 second 0-60 time would require a peak power of 168 kW. Simulation of different hybridization factors showed about 40% hybridization would result in the best fuel economy. This meant that the engine would need to provide about 101 kW of peak power and the electric motor would need to provide about 67 kW. TUCX chose a 110 kW peak diesel engine and a 65 kW peak electric motor, for 175 kW of peak power. Because the peak power is slightly greater than required, this combination performed slightly better in the simulations than the 168 kW version, attaining a 0-60 time of 8.5 seconds. The vehicle also accelerated from 50 to 70 mph in 5.5 s, significantly faster than the stock 6.8 s.

Vehicle Mass

Vehicle mass is the most straightforward and easiest to predict of the vehicle technical specifications. The weight of the original vehicle and that of each component are known, so finding the total vehicle mass is just a matter of addition. The current estimated weight of the vehicle runs over our expected weight due to the modification of the chassis and/or suspension in order to package the new components. Table 2 shows the estimated weight of the vehicle based on the listed component changes.

**Table 2: Analysis of Vehicle Weight Changes**

| **Components** | **Weight Lost (lbs)** | **Weight Gained (lbs)** | **Total (lbs)** |
|---|---|---|---|
| **Stock Equinox** | | | **3830** |
| **3.4L Gasoline Engine** | 362.4 | | 3468 |
| **Automatic Transmission** | 190.9 | | 3277 |
| **Gasoline Tank + Fuel** | 124.2 | | 3153 |
| **Spare Tire** | 34.6 | | 3118 |
| **Stock Tires (4)** | 195.2 | | 2923 |
| **Rear Differential** | 30.0 | | 2893 |
| **Control System** | 13.7 | 15.0 | 2894 |
| **Nexa Fuel Cells (2)** | | 55.6 | 2950 |
| **Structural Modifications** | | 115.0 | 3065 |
| **Diesel Engine + Manual Transmission** | | 545.7 | 3610 |
| **Ballard IPT** | | 185.8 | 3796 |
| **NiMH Battery** | | 166.4 | 3963 |
| **$H_2$ Tank + Fuel** | | 50.0 | 4013 |
| **8 gal Diesel Tank + Fuel** | | 66.0 | 4079 |
| **Run Flat Tires (4)** | | 258.4 | 4337 |
| **IPT/Battery Cooling System** | | 50.0 | **4387** |

Fuel Efficiency

Currently, the combined fuel economy of the vehicle model is approximately 32 miles per gallon gasoline equivalent (mpgge) which meets the competition target of 32.0 mpgge.

It is also noteworthy that the vehicle model library in PSAT does not allow for a parallel through-the-road hybrid architecture that incorporates a fuel cell. For the sake of modeling, the fuel cells have been neglected because they will only produce 2.4 kW total compared to the 175 kW produced by the engine and electric motor. Having the fuel cells available to assist in maintaining a satisfactory state-of-charge (SOC) for the ESS during high accessory load conditions, such as a hot day at the GM Desert Proving Grounds, will improve the overall fuel economy.

*Maximizing Vehicle Fuel Economy*

To minimize fuel use, the diesel engine is shut down during idle conditions and when engine warm up is not needed. During this time, the battery pack and fuel cells supply power to electrical loads. A control strategy using "map referencing" for individual motor torques and efficiencies controls the selection of the current propulsion mode. Modes include electric motor only, electric motor and internal combustion engine, internal combustion engine only, internal combustion engine with electric power regeneration, and electric power regeneration. Mode selection is based on battery state of charge, accelerator pedal position, brake pedal position, and vehicle speed. During normal driving conditions, this selection process will provide dramatically improved fuel economy by maximizing drive train component efficiencies.

A number of other controls are designed to improve efficiency. Since the diesel engine operates at a much lower efficiency during warm-up than in drive cycles, its temperature will be continually monitored by the Hybrid Vehicle Control Unit (HVCU). When necessary, the diesel engine will start and idle for a period sufficient to return the engine to a suitable temperature.

The electric propulsion subsystem requires that the battery be maintained within a certain SOC range. The energy to charge the battery is supplied mainly by the diesel engine and additionally from the fuel cells. When the diesel engine is operating in a speed range that provides peak efficiency, the HVCU requests additional positive torque from the diesel and requests a similar negative torque from the electric motor/generator to charge the battery. Kinetic energy will also be recovered and stored in the battery by regenerative braking.

### *Minimizing Vehicle Emissions*

Minimizing emissions is accomplished through maximizing fuel economy and through component selection. The GM 1.9L diesel engine meets European Euro 4 emission standards, and therefore exceeds U.S. emissions standards. (See Table 3 below.) This engine is also equipped with an exhaust after-treatment system using a series of catalytic converters and particulate trap filters with after-burn regeneration cleansing to reduce emissions. This system is effective in meeting all emissions criteria except for particulate matter (PM) emissions. Maintaining proper operating temperature of the diesel engine during electric-only periods also minimizes emissions. The engine's excellent fuel economy also contributes to the improved emissions. Simply put, less fuel burned results in less exhaust and therefore lower CO and $NO_x$ emissions.

**Table 3: Comparison of EURO IV and U.S. Tier 2 Bin 5 Emissions Standards**

| Allowable g/mi | EURO IV | US T2B5 | Difference |
|---|---|---|---|
| CO | 0.81 | 4.2 | -3.4 |
| PM | 0.04 | 0.01 | +0.03 |
| NOx | 0.40 | 0.07 | +0.33 |
| NMOG | -- | 0.09 | -- |
| NOx + NMOG | -- | 0.16 | -- |

TUCX is researching additional alternatives for reducing the emissions from the diesel engine. TUCX is very interested in controlling diesel NOx emissions with urea injection methods and adding a particulate filter to reduce the PM emissions, but this approach has been postponed until Year 3 due to constraints of time and money.

### Highway Range

Based on in-house models of the vehicle, the highway range of 300 miles will be achievable with 8 gallons of diesel fuel and a full tank of hydrogen. For more information on fuel efficiency and control strategy modeling, please see the **PSAT Modeling** section below.

### Passenger Capacity

There is sufficient room to package many major components including the fuel cells, IPT and hydrogen tank in the cargo area behind the rear seat. It is expected that packaging of future components will not affect the seating capacity of the vehicle. Retaining the stock seats allows TUCX to meet the required capacity of 5 passengers.

### Trailering Capacity

Given the limited amount of electrical energy available and the sustained power needed to tow, the diesel engine will be responsible for the towing capability. Calculations (Appendix B) have shown that the engine with manual transmission will provide ample torque for the required towing, without using the electric motor. PSAT and in-house models were used to verify that the components selected would meet or exceed the TUCX VTS.

### Startup Time

To ensure a start-up time of fewer than 2 seconds, control system initialization begins when the doors are unlocked or opened or when the ignition key is turned ON. The electric motor propels the vehicle at first, giving the engine time to start and warm up. The control strategy maintains the ESS SOC to keep the electric motor available at startup.

### *PSAT Modeling*

The first step was to change the stock Equinox model included in PSAT to reflect the hybrid approach taken by the team. As of this writing, the University of Tulsa is still the only Challenge X team whose vehicle architecture is not included in any of the supplied PSAT models.

The base Equinox model is modified to include a 1.9L 150 HP (112 kW) CDTI diesel engine as the primary power source. The electric motor has a peak power output of 65 kW. The ICE and electric motor are used in a through-the-road parallel configuration. The ESS is a 288V, 8.5 Ah NiMH battery. TUCX's design also includes two 1.2 kW PEM fuel cells that provide additional traction battery charging and accessory power, but these were not included in the simulation.

Simulations were performed with six control strategies (A through F), two drive cycles (505 and US06), and a hybridization factor (HF) of 0.5. The control strategies are summarized in Appendix C and the drive cycle characteristics are given in Table 4. This report will focus on control strategy E, which uses basic braking, "Consumption" propulsion, and "Best Engine Curve" shifting.

**Table 4. Drive Cycle Characteristics**

| | |
|---|---|
| 505 | City cycle with in-town (25-35 mph) and highway (55 mph) sections. This cycle is the first 505 seconds (Phase I) of the EPA Federal Test Procedure (FTP 75/EPA III). The cycle simulates a 3.59 mile drive with an average speed of 25.6 mph and a top speed of 56.7 mph (5.78 km, 41.2 km/h, 91.2 km/h). [1] [5] |

| | |
|---|---|
| US06 | Aggressive, high speed and high acceleration driving with rapid speed fluctuations. The 600-second cycle simulates an 8.01 mile route with an average speed of 48.4 mph and a top speed of 80.3 mph (12.9 km, 77.2 km/h, 129 km/h). [1] [5] |

Fuel Economy vs. Hybridization Factor

As shown in the graph in Appendix D, control strategy E is the most fuel efficient control strategy combination. Therefore, the fuel economy of the hybrid vehicle was further studied for control strategy E and various hybridization factors, in order to select a HF where the vehicle will have equal performance but higher fuel economy compared to a conventional powertrain.

Figure 2 shows the trend of predicted fuel economy at different HFs, with various local maximums and minimums. The maximum at HF = 0.2 on the 505 cycle is not an optimum HF, because the engine is large when compared to the motor, and it operates with low efficiency since the optimum torque is above the operating point [4]. The maximum at HF = 0.9 on both cycles is also not optimum, because the engine is much smaller than the motor and does not operate efficiently due to high torque demand [4]. Also, since the vehicle mass increases with HF [2 – 4], the vehicle mass is very large at HF = 0.9. The maximum at HF = 0.6 on both cycles represents a good size balance between the engine and the motor, and a reasonable vehicle mass, and so this value was selected as the optimum HF for use with control strategy E.

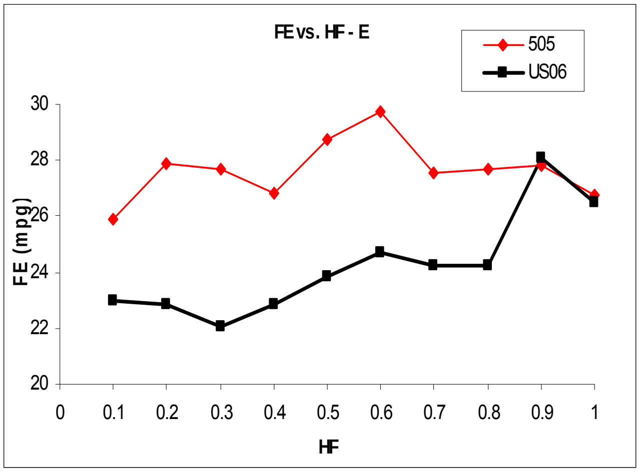

**Figure 2. Fuel economy at various hybridization factors on 505 and US06 drive cycles with control strategy E**

PSAT was used to model both the TUCX hybrid vehicle and the stock Equinox. Figure 3 shows the effect of performance models on propulsion and shifting for these vehicles, Figure 4 shows the effect of consumption models on propulsion and shifting for these vehicles. As can be seen in these graphs, optimal fuel economy in each case is obtained with a hybridization factor (HF) of approximately 0.6. A summary of valid simulation results based on the distance traveled specific to driving cycle is included in Appendix E. The target distance was specified to be ≥95% of the actual distance that the vehicle should cover for a particular driving cycle.

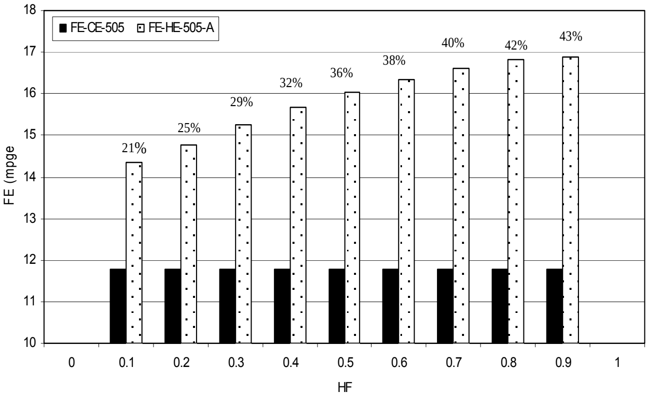

**Figure 3. Fuel economy of the conventional Equinox and Hybrid Equinox in 505 cycle with performance models of the propulsion and shifting strategies.**

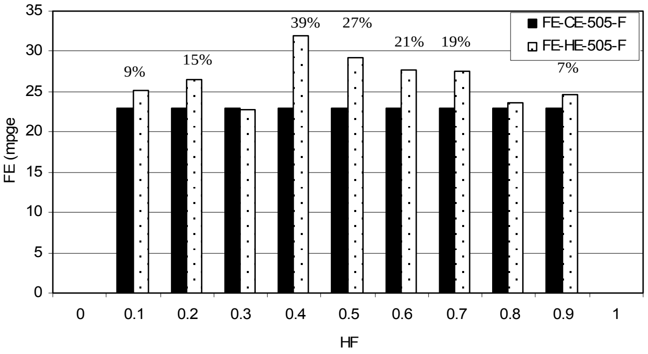

**Figure 4. Fuel economy of the conventional Equinox and Hybrid Equinox in 505 cycle with consumption models of the propulsion and shifting strategies.**

## POWERTRAIN CONTROL CAPABILITIES DESCRIBED AND COMPARED TO THE STOCK VEHICLE

This section compares the capabilities of the modified vehicle to the stock production Equinox. First, the highlights of the control system hardware architecture are described. Second, the control strategy goals are given. Third, the operational modes of the control strategy are explained. Finally, the unique features of the TUCX system are described.

Control System Architecture

The control system is designed so that the driver is presented with a traditional vehicle control interface: a steering wheel, an accelerator pedal, a brake pedal, a gearshift, a clutch pedal, and the instrument panel. The driver has no way to force the system into a particular mode of operation, except by his or her driving habits.

The control strategy is implemented by the Hybrid Vehicle Control Unit (HVCU), which is a National Instruments CompactRIO-9104 (cRIO) real-time controller running LabVIEW RT. The cRIO contains I/O modules for analog, digital, and CAN bus signals.

There are four high-speed CAN buses, one for each major component: Ballard IPT, Cobasys battery, diesel electronic control unit (ECU), and the stock Equinox CAN bus. Four separate buses are required to prevent collisions between CAN message IDs that are common between the components. Required CAN messages for logging and real-time data analysis are transmitted to the Equinox CAN bus as needed.

Torque demand is read from the driver via the accelerator pedal position (APP) sensor. This demand is analyzed by the HVCU and converted into torque requests for the diesel and the electric motor. These requests are sent to the diesel ECU as analog voltages and to the Ballard IPT as CAN messages.

The driver selects a gear using a conventional gearshift and clutch pedal. The HVCU recommends an optimum gear to the driver and monitors the driver's choice to protect the drivetrain from damaging gear selections and clutch usage.

The driver uses the stock brake pedal and vacuum-assisted hydraulic brakes to slow the vehicle. Pedal travel sensors have been added to the brake pedal, and the HVCU monitors these sensors to decide when to request regenerative braking from the Ballard IPT. The operation of the stock anti-lock braking system is not modified in any way.

### Control Strategy Goals

The control strategy has four primary goals:

1. Achieve a driving feel comparable to a traditional vehicle.
2. Maintain the Cobasys battery's SOC within a range that is compatible with high fuel economy and long battery life.
3. Increase the overall efficiency of the internal combustion engine (ICE) by limiting its use in low efficiency situations and using it extensively when high efficiency is possible.
4. Provide on-demand power capabilities to increase performance.

### Operational Modes of TUCX Vehicle

The vehicle has seven main modes of operation. These include Zero-Emissions (ZEV), Hybrid-Electric (HEV) or power-blending, ICE, regenerative braking, hard acceleration (FUN), and towing.

TUCX plans to start the vehicle from a complete stop in the ZEV mode where the only means of propulsion is the Ballard IPT. The electric motor is the sole source of propulsion up to about 20 mph. At this point, the vehicle enters HEV mode, where the diesel engine starts to take over a progressively larger share of the load. Above about 30 MPH, the diesel engine will be the only source of propulsion in ICE mode.

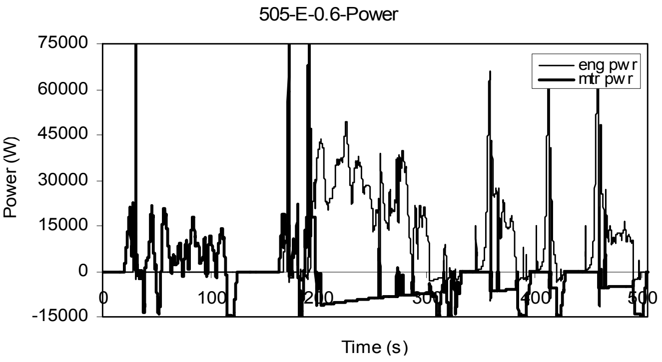

**Figure 5. Power variation with time for the electric motor and diesel engine for the 505 drive cycle, control strategy E, and HF = 0.6.**

To demonstrate this, the speed and power demands for the TUCX hybrid were modeled with PSAT. The power required from the diesel engine and electric motor on the PSAT 505 drive cycle is shown in Figure 5, while Figure 6 shows the corresponding speeds. The speed of the vehicle is less than 20 mph for about the first 60 s, so the electric motor alone propels the vehicle. From about 60 to 120 s, the diesel engine kicks in to help the motor to meet the demand as the vehicle speed increases to 30 mph. Regenerative braking is used as the vehicle brakes to a stop. At around 150 s, the motor again propels the vehicle to 20 mph, and then the diesel engine takes over entirely for about two minutes of high-speed driving. During this time, the control system requests from the diesel engine a higher torque than required by the road loads, and uses the extra power to charge the battery with a regenerative torque request to the electric motor. At around 350 s, the vehicle again brakes to a stop, and undergoes several rapid start and stop cycles. The electric motor is responsible for the initial acceleration, the diesel is used at the 30-35 mph peaks, and the electric motor is used for regenerative braking during stops.

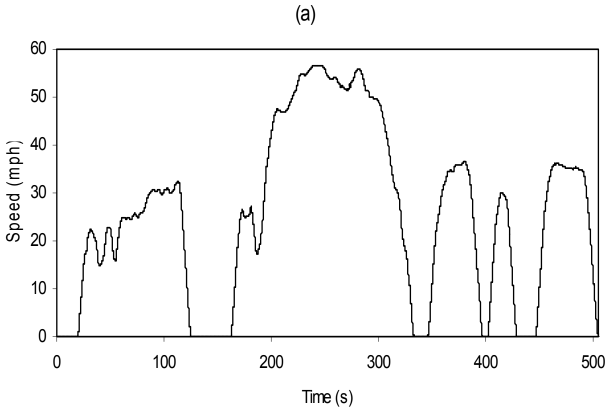

**Figure 6. Speed variation with time for the 505 drive cycle**

The HEV mode is the focus of ongoing operational testing. During this state, the torque required to move the vehicle is gradually changed from the electric motor to the diesel engine. The required interaction between the HVCU and the driver (proper gear selection) makes this mode difficult.

In ICE mode, the vehicle largely operates in a conventional manner. The HVCU usually passes the accelerator pedal position directly to the diesel ECU. However, the HVCU also monitors the battery SOC and the recent vehicle speed profile. If the vehicle is cruising at a fairly constant speed, and does not require the full torque of the diesel engine, the HVCU requests additional torque from the diesel engine. At the same time, the HVCU requests negative torque (generation) from the electric motor, and charges the battery.

In the regenerative braking mode, the first portion of the brake pedal travel is translated into regenerative torque commands to the IPT that will recharge the Cobasys battery and help slow down the vehicle. As the vehicle slows, the battery will be charged until $SOC_{max}$ is achieved. When the vehicle speed is above a certain minimum, and the battery SOC is below $SOC_{max}$, the regeneration torque requested $T_{regen}$ is given by

$$B_{pp} \times \left( P_{\mathrm{Re}gen\max} \times \frac{r}{V} \times n_{regen} \right)$$

where $B_{pp}$ = brake pedal percent of full travel, $P_{regenmax}$ = maximum allowed regen power, r = tire radius, V = vehicle speed, and $n_{regen}$ = regeneration efficiency.

As the battery SOC approaches $SOC_{max}$, the requested regeneration torque is lowered. This may feel to the driver as if the brakes are not applying as hard as they should be, and the natural response to push harder on the brake pedal to slow the vehicle will be correct. In the event of rear wheel slip (as determined by the ABS sensors), regenerative braking is disabled until the wheel speeds have stabilized.

In the hard acceleration or FUN mode, both the electric motor and diesel engine provide their maximum available torques to propel the vehicle. In this mode, the HVCU is not concerned with the battery SOC unless it is very low (under about 20%), in which case the torque request to the electric motor will be reduced. As the torque to the wheels increases rapidly, the HVCU monitors the ABS data for signs of wheel slip. If wheel slip occurs, the HVCU uses wheel speed data to determine which propulsion system to throttle back. If the front wheels are slipping, the torque request to the diesel engine is reduced, and if the rear wheels are slipping, the torque request sent to the electric motor is reduced.

The towing mode is similar to ICE mode. Generally, the torque requested by the driver does not reach the peaks seen in FUN mode, but is at a consistent high level. With a high SOC, the electric motor is used to assist with torque peaks. As the SOC falls, the diesel engine handles the torque peaks, and only a minimal amount of regenerative torque from the motor is used to maintain a minimum SOC.

Unique Features of Control Strategy

The TUCX Control Strategy will implement a highly versatile power-blending map. By using a dynamic weighting system of various parameters, the TUCX control system will be able to adjust to the many demands placed upon the vehicle by even the most demanding driver.

Another unique feature is that the NiMH battery can be recharged through both regenerative braking and from the two Ballard Nexa fuel cells. The power created by the fuel cells is relatively small, however it should be sufficient to meet the demands off accessory loads and prolong the driving range while the vehicle is in ZEV mode. Calculations show that the fuel cells will add to the overall mile-per-gallon gasoline equivalent ratings, but testing has not yet been done to confirm this.

Although the manual transmission might be a detriment to drivability, it is favorable for maximizing fuel efficiency as it allows the driver to choose the most efficient state to meet driving demands that require the diesel engine. The manual transmission also eases the workload of the HVCU since complicated efficiency equations and maps are not required.

## UNIQUE FEATURES OF THE TUCX VEHICLE

TUCX's parallel through-the-road design allows for the all-wheel-drive capability that is a desirable feature for many SUV buyers.

TUCX has designed the vehicle's electrical system to be self-sufficient. With the power supplied by the fuel cells, regenerative braking, and torque from the diesel engine, the batteries will maintain sufficient SOC. This means the owner never has to worry about plugging the vehicle in to recharge.

The fuel cells enable extended use of vehicle accessories while the diesel engine is not running and thus not producing emissions. Instead, the fuel cells can recharge the NiMH batteries as long as there is hydrogen available.

Ideally, the vehicle would be a single fuel design. However, dual-fuel architecture was chosen because reformer technology is not yet commercially available to provide the 99.99% pure hydrogen needed for the Nexa fuel cells awarded to TUCX. The design is flexible enough to incorporate such technology if it becomes available.

Since the fuel cell output is converted to 120 V AC as an intermediate step, this power can also be made available to run standard household equipment and appliances, another desirable feature for buyers.

## CONCLUSION

The University of Tulsa Challenge X team has used its 10 plus years of experience in hybrid vehicles to modify the Chevrolet Equinox into a through-the-road diesel-electric hybrid with auxiliary fuel cells for the Challenge X competition. The team has modeled and simulated the vehicle and its components, installed the components, and is testing the modified vehicle to optimize its performance. TUCX is convinced that the vehicle will meet the competition goals for performance, fuel economy, and emissions. TUCX is confident that they are prepared for the challenges facing them during year two and three of the Challenge X competition.

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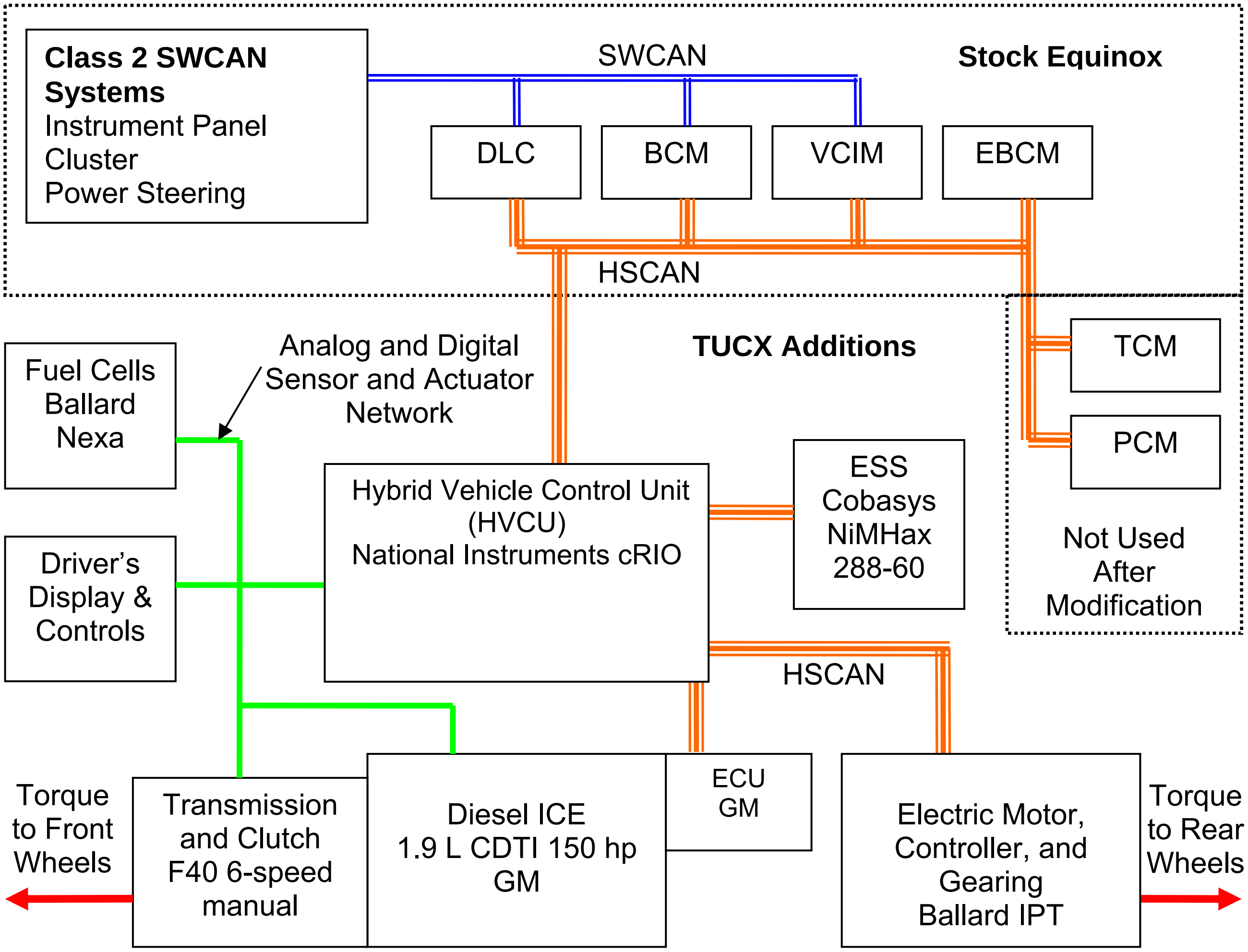
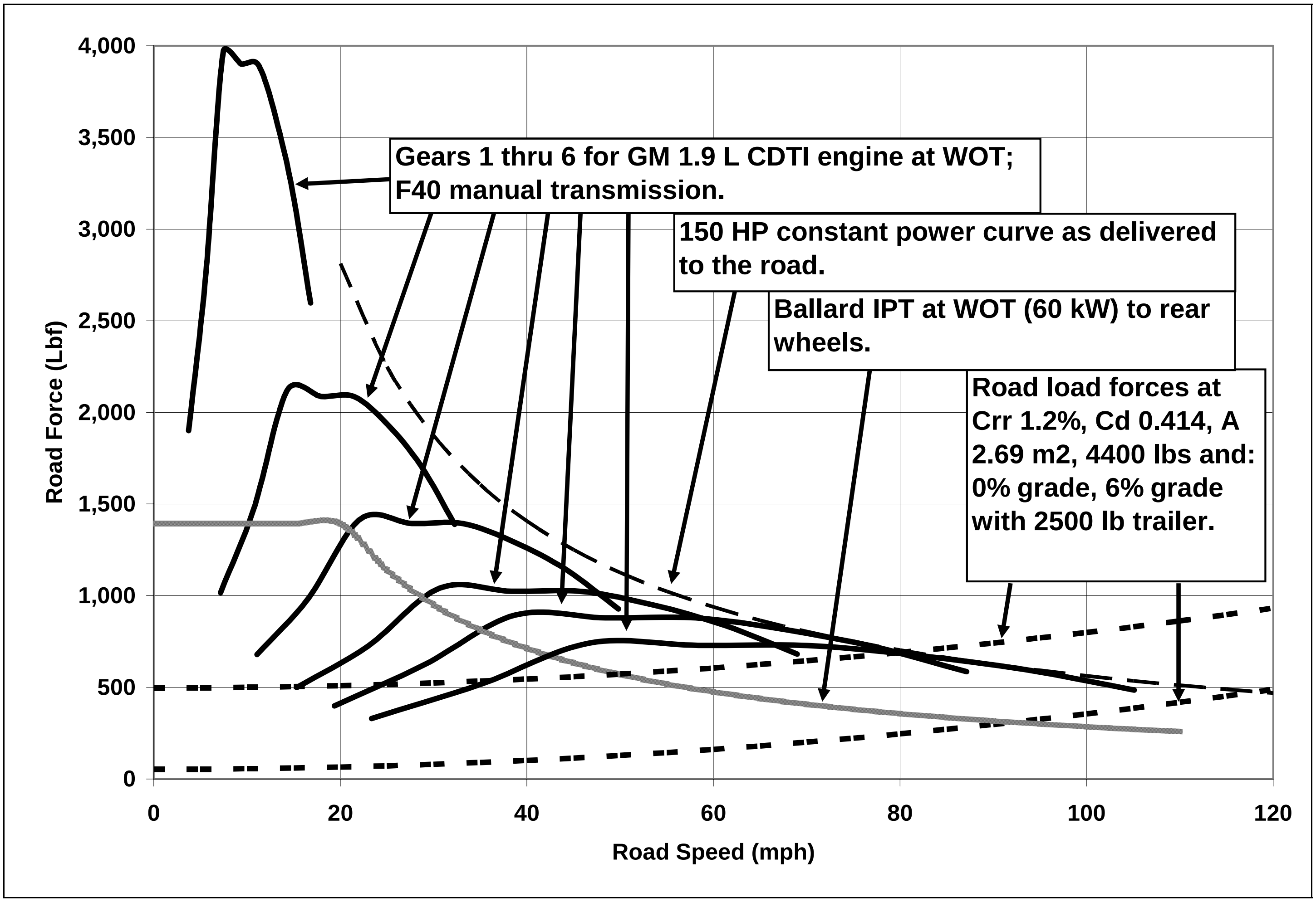
# APPENDICES

## APPENDIX A: CONTROL NETWORK BLOCK DIAGRAM



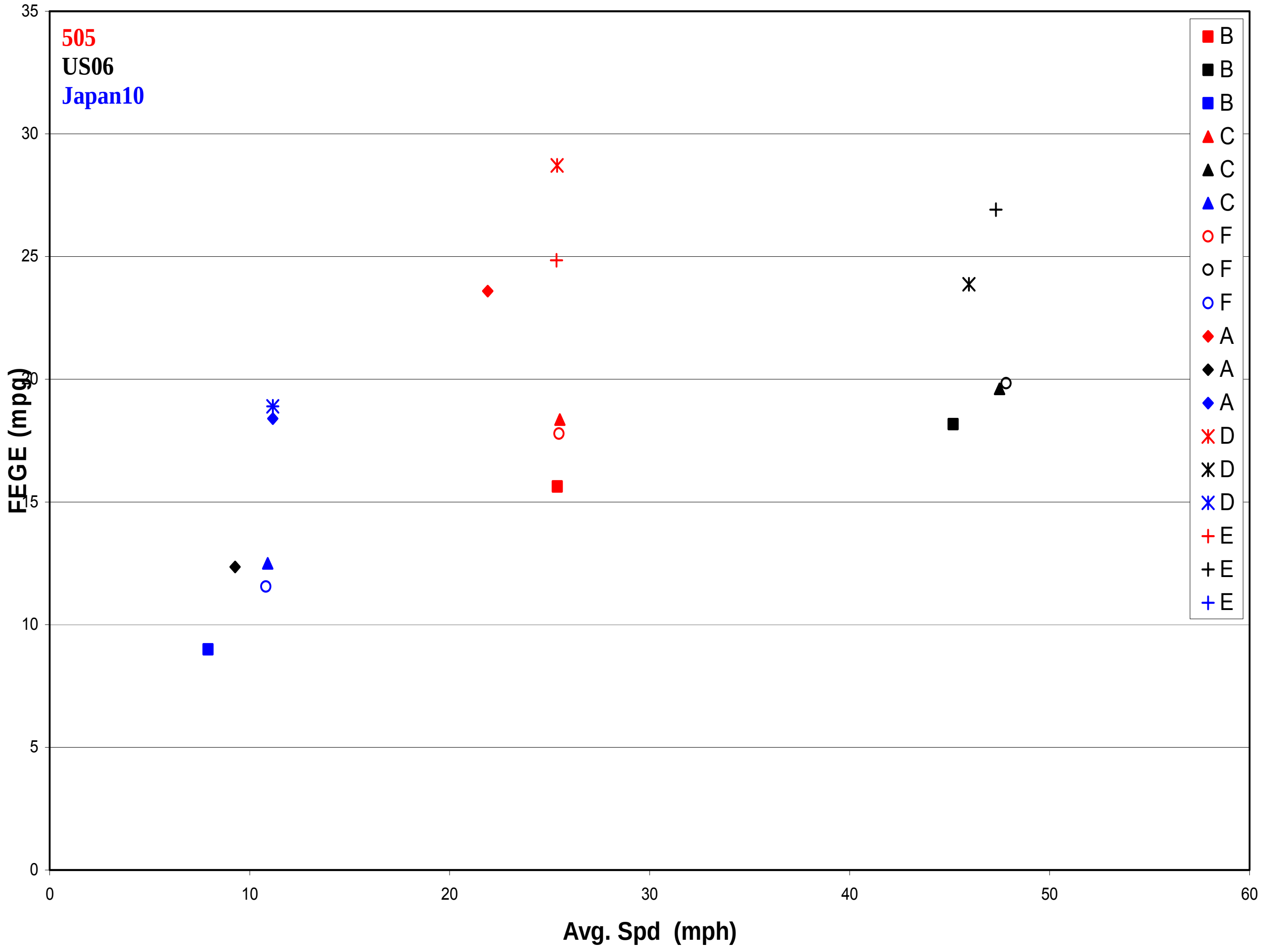
## APPENDIX B: TUCX MODIFIED EQUINOX THRUST FORCE CHART



# APPENDIX C. PSAT RESULTS FOR COMBINATIONS OF CONTROL STRATEGIES WITH A HYBRIDIZATION FACTOR OF 0.5

| Control Strategy | | | | Driving Cycle | | | |
|---|---|---|---|---|---|---|---|
| Code | Goals | | | 505 | | US06 | |
| | Braking | Propelling | Shifting | Hybrid Equinox mpgge | Stock Equinox mpgge | Hybrid Equinox mpgge | Stock Equinox mpgge |
| A | Braking | Performance | Performance | 15.63 | 11.79 | 18.17 | 14.60 |
| B | Braking | Performance | Best Engine Curve | 18.63 | 23.70 | 19.61 | 21.39 |
| C | Braking | Performance | Vehicle Speed | 17.78 | 22.92 | 19.84 | 21.61 |
| D | Braking | Consumption | Performance | 23.59 | 11.79 | 12.35 | 14.60 |
| E | Braking | Consumption | Best Engine Curve | 28.72 | 23.70 | 23.87 | 21.39 |
| F | Braking | Consumption | Vehicle Speed | 24.85 | 22.92 | 26.91 | 21.61 |

# APPENDIX D: FUEL ECONOMY VS. AVERAGE SPEED FOR 505 AND US06 DRIVING CYCLES



## APPENDIX E: SUMMARY OF VALIDITY OF SIMULATION RESULTS FOR VARIOUS COMBINATION OF DRIVING CYCLES AND CONTROLLER STRATEGY MODELS

<table>
<tr><th>Control Strategy</th><th>505 driving cycle</th><th>US06 driving cycle</th></tr>
<tr><td>A</td><td colspan="2">• Worked well for all HF values.</td></tr>
<tr><td>B</td><td colspan="2">• Worked well for all HF values.<br>• Did not show any fuel economy improvement due to controller model mismatch.</td></tr>
<tr><td>C</td><td colspan="2">• Worked well for all HF values.<br>• Did not show any fuel economy improvement due to controller model mismatch.</td></tr>
<tr><td>D</td><td>• Worked well for all HF values except 0.3 and 0.4.<br>• Unfeasible improvements obtained due to controller model mismatch.</td><td>• Worked well for all HF values except 0.3.<br>• Unfeasible improvements obtained due to controller model mismatch.</td></tr>
<tr><td>E</td><td>• Worked well for all HF values except 0.4.<br>• Performed simulations with SOC correction methods.</td><td>• Worked well for all HF values.<br>• Performed simulations with SOC correction methods.</td></tr>
<tr><td>F</td><td>• Worked well for all HF values.<br>• Performed simulations with SOC correction methods.</td><td>• Worked well for all HF values except 0.3.<br>• Performed simulations with SOC correction methods.</td></tr>
</table>