The Design and Development of a Through-the-Road Parallel Diesel Electric Hybrid

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Abstract—Mississippi State University students in their third year of Challenge X competition have transformed a 2005 Chevrolet Equinox into a diesel-electric hybrid at a 99% buy-off vehicle readiness level. The vehicle, configured in a charge sustaining, through-the-road parallel architecture, offers significant improvements over the stock vehicle with a 45% increase in fuel economy and a 3.5% increase in 0 – 60 mph acceleration, while maintaining a Tier 2 Bin 8 EPA emissions rating with an impressive towing capacity of 2500 lbs.

The MSU Equinox utilizes a 1.9 L diesel engine burning B20 biodiesel fuel with a six-speed manual transmission that is augmented by an ac induction electric motor-transaxle assembly. A nickel metal hydride (NiMH) battery pack provides sufficient energy storage to accomplish peak shaving so that the engine operates in its most efficient regime. Optimal vehicle performance was achieved with the Powertrain System Analysis Toolkit (PSAT™) and MATLAB™ that facilitated the design of an advanced vehicle architecture and control strategy to reduce energy consumption and emissions. Simulation results are compared with actual experimental data obtained on a four-wheel chassis dynamometer and road tests so as to validate the mathematical model. These studies together with several documented vehicle improvements bring the MSU Equinox to a 99% buy-off readiness level so as to comply with competition requirements.

Index Terms—diesel electric, hybrid, parallel hybrid, through-the-road

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I. Introduction

With gasoline consumption growing at a rate of more than 1% per year and domestic production declining by 1.4% per year, the Energy Information Administration predicts that imported petroleum will account for over 60% of the total U.S. consumption by 2010 [1]. The increased need to reduce vehicle emissions and the growing reliance on imported petroleum is a national concern that has recently been exasperated by widespread public concern regarding global warming. In response, the U.S. and Canadian governments, along leading automotive manufacturers have worked together toward the development of advanced vehicle technologies that address these energy and environmental issues. Competitive student programs, such as Challenge X (cX), are one such example that engages engineering students in the search for alternative solutions with the prospect that some of the students will become future leaders in the automotive industry. *Challenge X: Crossover to Sustainable Mobility* is a four-year student design competition with General Motors (GM) and the U.S. Department of Energy (DOE) as headline sponsors; program direction and leadership is provided by Argonne National Laboratory (ANL) [2]. The competition goal is to demonstrate solutions to sustainable mobility by redesigning a conventional gasoline-fueled, 2005 Chevrolet Equinox to reduce energy consumption and emissions while maintaining or exceeding stock vehicle performance characteristics.

This paper provides a comprehensive overview of the design and component selection for the Mississippi State University (MSU) competition vehicle together with the decision process for the overall vehicle development. Simulations of the vehicle performance were acquired using the Powertrain System Analysis Toolkit (PSAT™) so as to evaluate the Equinox in comparison with the selected *vehicle technical specifications* (VTS). The simulation studies are then compared with actual test data. Particular emphasis is devoted to the hybrid control strategy and its implementation. An overriding concern is passenger safety and the identification of potential fault scenarios and how such situations might be mitigated.

II. Overview of Vehicle Powertrain Component Selections

As part of the cX Vehicle Development Process, the transformation of the MSU Equinox began in the first year with an extensive literature review of the crossover sport utility vehicle (SUV) market. This review gave the team insight into features that are currently available. The performance of the stock Equinox was also quantified and evaluated in the competitive vehicle analysis. After reviewing the current market and considering the competition requirements, the MSU team established the goal to build an Equinox with performance that exceeds 30% improved fuel efficiency, 5% better acceleration performance, and 200-mile highway range. While at the same time, it will retain the stock vehicle's 5 passenger capacity, Tier 2 Bin 5 emissions rating and a 2500 lbs. trailer towing capacity, as shown in Table I. Through the competitive vehicle review process, the team also decided that the MSU Equinox should be charge sustaining such that no external grid-generated energy will be required. It should also be capable of being mass-produced within the next five years which limits the use of expensive, exotic, lightweight materials, as well as, fuel alternatives for which a refueling infrastructure would not be readily available. Lastly, the team required that the MSU Equinox offer the same conveniences, amenities, and roominess to the consumer as the stock vehicle.

A through-the-road (TTR) parallel diesel hybrid configuration was chosen as the vehicle architecture that could accomplish the team and competition goals. During Year I of the competition the team extensively researched advanced vehicle technologies such as fuel cells, hybrid electric powertrains, hydraulic hybrids, and alternatively fueled internal combustion engines as possible vehicle architectures for the MSU Equinox as outlined in Table II.

TABLE I
COMPARISON OF COMPETITION REQUIREMENTS, STOCK EQUINOX PERFORMANCE, AND TEAM SELECTED VTS GOALS

Category	cX Required	Stock Equinox	MSU VTS Goals
IVM60 mph (sec)	$\leq$ 9.0	8.5	< 8.2
50-70 mph (sec)	$\leq$ 6.8	6.3	< 6.1
Vehicle Mass(curb)(lbs)	$\leq$ 4400	3776	< 4200
Mpg Combined EPA (mpg)	$\geq$ 32	22	> 32
Highway Range(Miles)	$\geq$ 200	365	> 200
Passenger Capacity	5	5	5
Emissions Certification Level	Tier 2 bin 5/LEV2	Tier 2 bin 5/LEV2	Tier 2 bin 5/LEV2
Towing Capacity (lbs)	2500	3500	2500
Vehicle Start Time (sec)	< 5	< 2	< 2

TABLE II
EVALUATION OF POSSIBLE VEHICLE ARCHITECTURES

Advanced Vehicle Architecture	Feasibility of Near-Term Production	Ability to Meet Competition and MSU Requirements
Fuel Cells	Poor	Poor
Hybrid Electrics	Excellent	Excellent
Hydraulic Hybrids	Good	Good
Alt. Fuel Engines	Good	Good

Note: Feasibility of near term production includes: fueling infrastructure availability, no consumer inconveniences, and component availability.

Hybrid electric vehicles (HEVs) offer a viable near-term solution for reducing energy consumption and emissions [3]. Most HEVs utilize a downsized spark ignition (SI) or compression ignition (CI) internal combustion engine that is currently available and an electric motor(s) working in unison to improve the overall vehicle efficiency while maintaining or exceeding the conventional vehicle performance. HEVs offer the travel range and flexibility of conventional ICE vehicles but can appreciably increase fuel-efficiency and reduce emissions by removing inefficient modes of operation by discriminately employing two power sources [3]. The purchase price of HEVs is competitive with conventional vehicles with HEVs averaging $3000 more than its counterpart [1]. Since HEVs utilize existing engines and fuels, this technology does not require a new storage and delivery infrastructure. The many attributes of the HEV technology make it a feasible solution for reducing energy consumption and emissions while maintaining or exceeding conventional gasoline vehicle performance.

The team selected B20 biodiesel to fuel the MSU Equinox. The four fuels allowed in the cX competition are reformulated gasoline, B20 biodiesel, E85 ethanol, and gaseous hydrogen. To objectively evaluate these fuels in a well-to-pump manner, the team utilized the *Greenhouse Gases, Regulated Emissions and Energy use in Transportation* program (GREET). GREET compares the energy consumption and emissions of different fuels in a well-to-pump (WTP) and well-to-wheel (WTW) manner that takes into account the full life processes of the fuels. Table III shows the GREET WTP energy consumption and emissions data for the selected fuels.
Reformulated gasoline and biodiesel have similar WTP energy consumption, efficiency, and emissions, but both are considerably more favorable than hydrogen or E85. With compression ignition engines generally operating at higher efficiencies than spark ignited, the team opted to use the B20 biodiesel fuel for the MSU Equinox.

A. Engine Selection

The MSU team has retained its first year selection of the 1.9L GM turbo diesel engine. The engine has an approximate peak torque and power of 326 N-m and 109 kW, respectively. The MSU cX team estimated minimal engine requirements of 294 N-m and 82 kW using stock Equinox road loads and steady-state equations to calculate the minimum torque and power required to tow a 2,500 lb. trailer on a 7% grade at 55 mph as per the competition requirements. To maintain the team's goal of a charge-sustaining vehicle, the engine must be sized to supply adequate power to fulfill this gradeability requirement operating alone without depleting the HV battery pack [1]. The other engines the team considered were the 1.9 L TDI VW and the 1.9 L dCi Renault; the 1.9 L GM diesel was selected due to its availability and performance advantages.

B. *Electric Traction System*

The initial motor requirements were defined using the team's goal for an IVM-60 mph acceleration time of 8.2 seconds. Calculations were performed to examine the motor performance characteristics required to meet the 0 - 60 mph acceleration time.

The Ballard IPT is specified as a 65 kW peak power, 45 kW continuous three-phase AC induction, electric motor (EM). The motor's higher continuous power provides improved vehicle acceleration performance and the opportunity for increased electric assist at higher speeds, thus improving fuel economy. The IPT also offers an increase in regeneration capability due to a higher output voltage from its inverter. The Ballard drive is used in the MSU HEV powertrain for electric-boost during times of acceleration and serves as a buffer to the downsized ICE during periods of high torque demand. Fig. 1 below shows the peak power comparison for the Ballard Ranger EM used in Year II and the Ballard IPT EM used during Year III of the competition.

The Ballard drive includes a Controller Area Network (CAN) interface with the hybrid-electric vehicle controller [4]. The motor controller and associated inverter operate with an input voltage in the range of 200 V to 400 V. The integrated transaxle has a gear ratio of 10.66:1 (fixed-ratio speed reducer). With an allowable top speed of about 14,500 rpm, the motor reaches its maximum speed when the vehicle is traveling at approximately 110 mph. The Ballard drive system, including the motor and inverter, is liquid cooled, and a heat exchanger is located in the front of the vehicle along with a small electric pump used to circulate the water/glycol coolant.

TABLE III
GREET WTP ENERGY CONSUMPTION AND EMISSION INFORMATION IN BTU OR G/MMBTU

Well-to-Pump Energy Consumption and Emissions				
	RFG	B20	H2	E85
Total Energy	270040	272527	714311	556478
WTP Efficiency	0.79	0.79	0.58	0.64
Fossil Fuels	265902	266427	684076	553485
Petroleum	103873	99345	15587	84507
GHGs	20231	7160	101293	-1033
VOC	15.85	37.46	2.64	55.47
CO	15.56	30.13	21.14	51.32
NOx	41.95	65.64	54.73	125.52
PM10	3.23	3.37	4.03	61.08
SOx	26.63	26.06	49.48	82.68

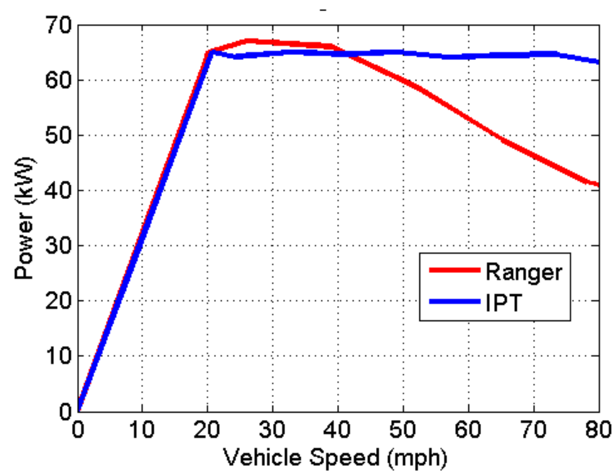

Fig. 1. Peak power comparison for Ballard IPT and Ranger electric motors.

C. *Energy Storage System*

The energy storage selection was based upon the team's minimum battery rating criteria of 270 V and 6.5 A-hr at 60 kW. These parameters were calculated from the power required to meet the team's 0-60 mph acceleration target. Additionally, based on the sizing calculation constraint, weight, and cost analysis, the MSU cX team estimated an optimal choice of batteries to be 8.5 A-hr, 288 V, and 60 kW. The MSU cX team was one of the teams awarded a Johnson Controls (JCI) 330 V, 7.0 A-hr, Nickel-Metal Hydride (NiMH) battery pack. Although the capacity rating of 7.0 A-hr that the JCI battery pack provides is less than the team's predicted optimal needs, it is above the minimum requirement. The JCI battery pack is a 6NP1 HV NiMH battery module [5]. It has a built-in VARTA battery management system (BMS). It also supports CAN communication capabilities, which allowed for easy integration with the HEV controller [6]. A pre-charge circuit was also included in the battery power circuit.

The team has repackaged the JCI system into a smaller unit in order to meet rear cargo packaging requirements. For thermal management, the new battery packaging is equipped with integrated air-cooling, which utilizes an inlet duct at the bottom of the pack and outlets on two sides. Two blowers, located on each side of the pack are used to pull cabin air across the batteries where it is then vented under the vehicle through exit vents. One-way check valves are implemented on the air inlets as a safety precaution against harmful fumes entering the cabin area in the event of a battery malfunction.

D. *Exhaust Aftertreatment*

The use of the 1.9 L GM diesel engine by the MSU cX team presents a demanding challenge in meeting the team's Tier 2 Bin 5 emissions goal. The emissions evaluated by the Tier 2 standards are oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO), non-methane organic gases (NMOG), and formaldehyde (HCHO). Literature research proved that CO, NMOG, and HCHO emissions levels are rarely concerns for the diesel engine; however, NO_x and PM emissions are commonly high, thus are the focus in meeting the team's emissions VTS.

The two NO_x aftertreatment systems considered for the MSU Equinox were the urea selective catalytic reduction (SCR) and the lean-NO_x trap (LNT). A literature review revealed that the urea SCR system is more effective over a wider temperature range than the LNT [7]. Studies show that NO_x reduction of 95% is possible via urea SCR at exhaust temperatures as low as 200 °C, thus urea SCR was selected for this application [7]. To determine the feasibility of urea SCR for the MSU Equinox, exhaust temperatures were evaluated using highway and urban driving schedules. The results indicated 68% of the data points exceeded 200°C, making the use of urea SCR viable for the MSU Equinox.

To clean the diesel particulate emissions, the team chose to use a diesel particulate filter (DPF). A DPF is commonly used for diesel PM reduction and has been credited with PM reduction up to 95%. A reduction of 95% would be adequate in achieving Tier 2 Bin 5 regulations for PM.

E. *Miscellaneous Selections*

A 12 V subsystem is required to operate the lights, ignition, various controllers, and several other electronic accessories. For this system, the team retained the GM diesel alternator and a 12 V Optima battery. The battery is sized to meet the cranking needs of the ICE, and the alternator meets the power requirements of all the accessories. In accordance with the competition guidelines, the team is utilizing the Michelin PAX run-flat tire system. The system is equipped with a SmarTire® tire pressure monitoring system (TPMS). The system allows the team to remove the spare tire well and use the area for packaging of the hybrid powertrain components. The tire also offers decreased rolling resistance over stock. Final component selections are summarized in Table IV.

TABLE IV
MSU EQUINOX DESIGN SUMMARY

Architecture	Parallel Through the Road Hybrid Electric AWD
Fuel	B20 Biodiesel
Engine	1.9 L GM Turbo Diesel, 109 kW, 326 N-m
Emission Control	Diesel oxidation catalyst, diesel particulate filter, urea SCR system
Transmission	GM 6 speed manual
Rear Traction Motor	Ballard IPT AC induction transaxle, 45 kW continuous, 230 N-m peak
Energy Storage	Johnson Controls NiMH 330 V, 7.0 A-hr
Controls	MotoTron ECU555-80
Tires	Michelin PAX run-flat, 235-710 R460A

III. HYBRID CONTROL HARDWARE SELECTION AND STRATEGY DEVELOPMENT

This section outlines the control hardware selections and control strategy development process for the MSU Equinox.

A. *Control Hardware Selections*

Control of the MSU Equinox is accomplished using the MotoTron™ ECU555 80-pin controller, which serves as the vehicle system controller (VSC). The central position of the MotoTron controller within the hierarchical network of other OEM vehicle controllers. An additional MotoTron ECU555 48-pin controller is used to control the urea injection system.

Communication between the controllers is carried out through two CAN busses running at 500 kbps. One CAN bus communicates with the Equinox body control module and ABS while the other communicates with all the additional components. PSAT / MATLAB was used to design the control strategy. MotoHawk™ was used to directly convert the strategy into VSC language, and MotoTune™ was used to download the strategy and perform real-time control strategy calibration.

In the MSU Equinox, the engine is the main fuel converter in the vehicle; thus the objective of the hybrid control strategy is to maximize efficient engine operation while also considering engine emissions, as well as, motor and battery losses. The through-the-road parallel hybrid configuration of the MSU Equinox allows for the control strategy to be developed in a modular fashion. The team first developed off-line diesel "engine only" and "electric only" control operation. Next, the electric drive and high voltage battery pack were implemented into the stock gasoline powered Equinox. This allowed control testing and debugging of the electric drive, BMS, and regenerative braking system without the engine control concerns. Finally, the diesel engine was implemented into the MSU Equinox and full diesel–electric hybrid controls testing was performed. This modular approach allowed for verification of safety and drive quality in a convenient piecewise manner.

B. *Control Strategy Development*

The MSU cX team's initial efforts of developing a control algorithm for the MSU Equinox involved pursuing a strategy with no engine idle-off condition or pure electric launch mode. A belted alternator starter (BAS) was not part of the original MSU vehicle design because the team felt it posed too big of a technical challenge for a novice team. With the experience and knowledge gained in the past two years, the team now feels it could successfully implement a BAS. However the current rules would inflict a severe penalty for changing the MSU vehicle design and implementing a BAS. The team realizes that without a BAS and engine idle-off strategy, the MSU Equinox will not fully utilize the capabilities of having dual power sources. PSAT vehicle simulations predict a 6% improvement would be expected on the FTP-75 drive cycle if idle-off had been implemented.

C. *Fuel Economy and Emissions Trade-Offs*

In the MSU control strategy, the torque demand from the driver is read by the vehicle system controller (VSC). The VSC then decides the most efficient way to satisfy this torque demand based on the current vehicle status. The objective of the MSU control strategy is to maximize fuel economy and minimize emissions while maintaining drive quality and safety. The engine operating points which maximize fuel economy often are not favorable operating points to minimize emissions. In an attempt to better evaluate this tradeoff, a map of engine efficiency as a function of torque and engine speed was developed, as shown in Fig. 2. The trace of exhaust gas recirculation (EGR) operation is also shown in Fig. 2. With significantly lower NO_x emissions achieved by using the EGR, this portion of the map represents favorable operating points for the minimization of NO_x emissions. The engine operating points for the FTP-75 drive cycle for Year II and Year III control strategy when operating in hybrid mode are also shown. In Fig. 2, the dark blue points represent engine operating points from the Year II control strategy, while the light blue point represent the Year III control strategy. For Year III, the MSU cX team was able to shift the engine operating point using an optimized shift strategy that operated the engine at higher engine speeds and lower torques. Also the team was able to improve load balancing on the engine through use of the electric motor.

D. Modes of Operation

The two major modes of operation in the MSU hybrid strategy are blending and braking. The blending mode includes an engine only drive mode that is activated when the clutch is disengaged. The “engine only” drive mode is also part of an emergency shut-down procedure for the electric motor (EM) allowing for a limp-home mode of operation. Blending between the ICE and the EM is activated when the clutch is engaged, a valid gear transmission ratio is detected, and the vehicle is in motion.

The blending includes logic specified by accelerator pedal position, vehicle speed, and battery SOC, which is set from 40% to 90% absolute SOC. Within the blending mode, the following three distinct powertrain operating states are defined [8]:

- Acceleration: where the vehicle velocity is increasing.
- Deceleration: where the vehicle velocity is decreasing. This mode encompasses the case only when the driver “tips out” of the accelerator.
- Cruising: when the road load and the vehicle velocity are constant. This mode encompasses steady states, light accelerations, and decelerations, which do not necessarily require motor assist.

1) Acceleration

The MSU cX control strategy uses the EM to provide additional torque during acceleration. The torque supplemented by the EM is managed by the VSC based on the driver “tipping out” or “tipping into” the accelerator pedal. For a wide open throttle (WOT), both the ICE and the EM provide maximum available torque. The operation during acceleration is further classified on the basis of battery SOC. As SOC decreases, a smaller amount of motor torque is requested. The exception is WOT where full torque is requested at 100% accelerator pedal at any battery SOC, except the very lowest. The motor torque request progression based on battery SOC is shown in Fig. 3.

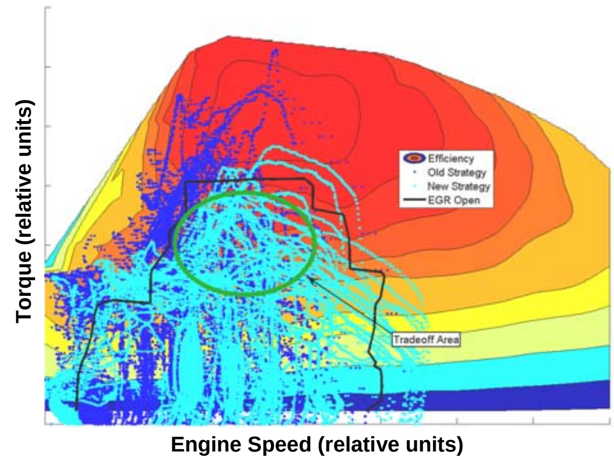

Fig. 2. Year II and Year III shift strategy operating points for the FTP-75 drive cycle plotted on the engine efficiency map along with the engine EGR operation envelope.

2) Cruising

Cruising occurs when the vehicle has reached a steady state operating speed. Under cruising, the most efficient operation is simply to provide the needed driver torque by the ICE alone as in a conventional powertrain. The ICE responds to the accelerator pedal and the EM is not expected to provide any motoring torque. However, the EM may be operated at a low recharging level depending on present battery SOC to restore the battery SOC.

3) Deceleration

During deceleration, the EM regenerates at a greater value than in cruising. This mode occurs when the accelerator pedal is in its initial position. The amount of braking applied is restricted by the maximum negative torque of the EM for that particular speed. This mode imparts added battery charge enhancing capability to the powertrain.

4) Braking

The braking mode in the MSU control strategy consists of coasting and parallel regenerative braking. Coasting occurs when the driver does not press any pedals. During coasting, a fixed ratio of regenerative braking is applied based on the SOC of the battery pack and drive quality. During application of the brake pedal, parallel regenerative braking is actuated. The first 20% of brake pedal travel engages only the regenerative braking. This free-play at the beginning of the pedal travel has been accomplished by adding a small orifice to the internal bore of the master cylinder. This relief allows for reduced mechanical brake application when the pedal is slowly applied. The extent of regenerative braking increases linearly as brake pedal travel increases from 0 to 33%. Beyond 33% brake pedal travel, the maximum motor torque available for regeneration is requested. Extensive tuning of the regenerative braking portion of the control strategy was performed to ensure consistent stock brake feel and function. The braking progression can be seen in Fig. 4.

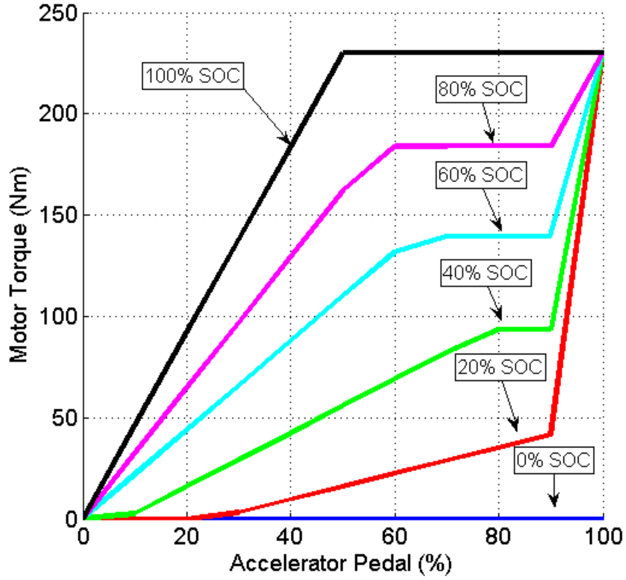

Fig. 3. Map of motor torque requested by vehicle system controller based on battery SOC during vehicle acceleration.

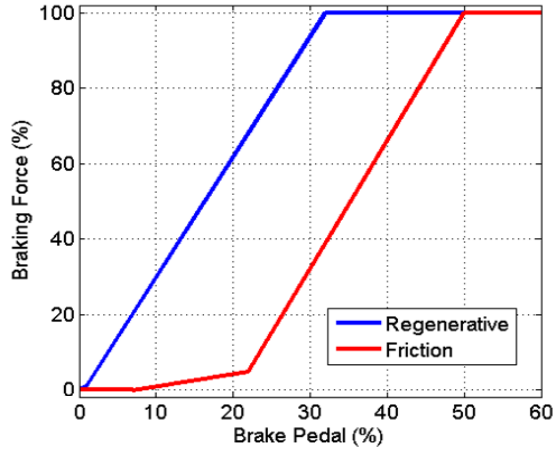

Fig. 4: Braking force versus brake pedal position

IV. Vehicle Technical Specifications And Design Validation

Having selected the MSU Equinox components, VTS predictions were made through extensive PSAT vehicle modeling and simulation. This section presents the finalized Year III VTS values for the MSU Equinox along with Year II vehicle test data, which supports the design satisfying the team's specifications. Table V outlines the various VTS categories and compares the predicted Year III MSU VTS values with the corresponding Year II measured values. For clarity, the VTS results will be discussed as they relate to the following four areas: fuel economy, emissions, performance and utility.

A. Fuel Economy

The combined EPA fuel economy of the MSU Equinox, is determined using Standard Governmental drive cycles (ie. FTP-75 and HWFET). As shown in Table V, the MSU Equinox produced a combined EPA fuel economy of 30.5 mpgge, as measured in Year II. Through control strategy tuning and with the implementation of the Ballard IPT, the MSU team's PSAT simulations predict a combined EPA fuel economy of 32 mpgge for Year III.

The cX 2007 combined fuel economy listed in Table V was simulated using a drive cycle that was derived to match the event description described in the cX 2007 rules. The cX 2007 combined fuel economy value of 29.5 mpgge is an unadjusted, SOC corrected, gasoline equivalent fuel economy obtained in PSAT at standard atmospheric conditions.

B. Emissions

Meeting the cX competition goal of a Tier 2 Bin 5 emissions certification has proven to be a very difficult task for the MSU team. Elevated NO_x levels kept the MSU Equinox from achieving Tier 2 Bin 10 emissions levels in Year II, as shown in Table V. The team based their original Tier 2 Bin 5 VTS on a greater than 90% NO_x reduction through the use of an SCR system, which was feasible according to literature. The greater than 90 % reduction was applied to the GM diesel engine-out emissions which were measured at Euro III levels in a 2,520 lbs. Fiat Stilo. The team anticipated slightly increased engine-out emissions with the engine operating in the heavier, (4,200 lbs.) MSU Equinox, but felt they could still meet Tier 2 Bin 5 NO_x levels.

Since the Year II competition, the team measured the raw NO_x emissions to be 1.39 g/mile, 73% more as compared with the .805 g/mile Euro III level. Thus a NO_x reduction of >95% is needed to meet the original Tier 2 Bin 5 VTS value. The team also found the Year II SCR system was accomplishing only a 50% reduction as compared with the anticipated greater than 90%. The team investigated SCR catalyst size, chemistry and temperature along with urea injection spray patterns in an attempt to increase the NO_x reduction to the anticipated levels.

TABLE V
COMPARISON OF CX COMPETITION TARGETS, MEASURED YEAR II VALUES AND PREDICTED YEAR III MSU VTS

Category Description	cX Target	Year II Measured Values	Year III MSU VTS
IVM – 60 MPH	≤ 9.0 sec	8.17 sec	7.9 sec
50 – 70 MPH	≤ 6.8 sec	4.68 sec	4.5 sec
Vehicle Mass	≤ 4400 lbs	4167 lbs	4200 lbs
MPG Combined EPA	≥ 32.0 mpgge*	30.5 mpgge*	32.0 mpgge*
cX 2007 Combined	-	NA	29.5 mpgge*
Highway Range	≥ 200 miles	150 miles	240 miles
Passenger Capacity	5	5	5
Emissions Certification Level	Tier 2 Bin 5	> Tier 2 Bin 10	Tier 2 Bin 8
Trailer Towing 16% grade, 1000ft, 2500 lbs trailer	-	NA	17
Starting Time	< 5.0 sec	< 2.0 sec	< 2.0 sec

*miles per gallon gasoline equivalent

The original SCR catalyst was a 20 L vanadium pentoxide (V_2O_5) catalyst, which is oversized for the small 1.9 L diesel engine. The team was successful in obtaining a more suitable 5 L V_2O_5 catalyst for Year III of the competition. Both the original 20 L catalyst and the new 5 L catalysts were tested for NO_x reduction and temperature drop. Temperature drop across the catalysts was considered due to the strong dependence of the urea SCR system's effectiveness on temperature. In both tests, the 5 L SCR catalyst outperformed the 20 L catalyst. The 5 L catalyst exhibited improvements of 78.4% for temperature drop and 26.1% for NO_x reduction. The results are shown in Table VI.

In addition to the 5 L V_2O_5 catalyst, a 5 L zeolite SCR catalyst was also obtained. Both catalysts were extensively compared at Southwest Research Institute (SwRI). The results proved that the zeolite catalyst was more effective for the MSU Equinox, accomplishing an average of 8% more NO_x reduction.

After completing tests at SwRI, it was observed that large deposits of urea had formed in the bottom of the exhaust pipe. Investigation revealed that the urea solution did not atomize quickly enough to support the original design of injecting the solution perpendicular to the exhaust stream. For Year III the urea injection system was redesigned in order for the urea to be injected downstream with the exhaust flow.

With the raw engine emissions being considerably higher than anticipated and the less than expected SCR reduction, the team decided to reevaluate their emissions VTS for Year III. To estimate a feasible VTS value the team performed PSAT simulations using raw NO_x versus load and engine speed data maps created from dynamometer and on-road testing. To predict tailpipe NO_x levels, a constant NO_x reduction value was assumed to be achieved by the urea SCR system. Based on improvements accomplished by appropriate sizing and chemistry selection of the SCR catalyst and planned injection spray improvements, an 80% NO_x reduction is predicted. Incorporating the Year III control strategy improvements discussed in the Fuel Economy and Emissions Trade-Offs section, simulation results show a 16% decrease in raw NO_x levels. After the estimated 80% NO_x conversion, the new NO_x emissions are estimated to be 0.18 g/mile, which allows the MSU Equinox to meet Tier 2 Bin 8 emissions levels. According to Tier 2 regulations, Bin 8 certification would allow for the production and sale of the MSU Equinox, as long as the corporate light-duty fleet average is below 0.07 g/mile of NO_x.

TABLE VI
COMPARISON BETWEEN 20 L AND 5 L V_2O_5 CATALYSTS

	Temperature Drop	NOx Emissions (g/mile)
20 Liter V_2O_5 Catalyst	52.2 °C	0.92
5 Liter V_2O_5 Catalyst	11.3 °C	0.68
Improvement	78.4%	26.1%

C. Performance

The performance portion of the VTS includes initial vehicle movement (IVM) to 60 mph time, 50 to 70 mph time and trailer towing capacity. PSAT simulations were used to predict the acceleration and towing capabilities of the MSU Equinox. On-road testing was used to measure the Year II vehicle acceleration values. As shown in Table V, the MSU Equinox exceeds the team's acceleration VTS, and easily satisfies the competition targets. Simulation results show a 3% improvement in acceleration performance for Year III due to the implementation of the more powerful Ballard IPT electric drive.

The trailer towing capacity of the MSU Equinox was defined in Year I and II as the ability to tow a 2,500 lbs. trailer up a 7% grade while sustaining 55 mph. For the third year of the cX competition, the trailer towing capacity has been redefined to towing a 2,500 lbs. trailer up a 1,000ft, 16% grade in the longest elapsed time of three consecutive attempts. As shown in Table V, the PSAT vehicle simulations predict the MSU Equinox elapsed time to traverse the 1,000 ft., 16% grade hill climb to be 17 sec.

V. CONCLUSION

The Mississippi State University Challenge X team has transformed a Chevrolet Equinox so that it represents a viable solution to the sustainable mobility concerns of our nation. The vehicle offers a significant reduction in the consumption of petroleum as compared to the stock vehicle. Impressively, it meets or exceeds the team and cX competition technical specifications and has been validated at a 99% buy-off readiness level. Compared to the stock configuration, the MSU Equinox offers a 45% increase in fuel economy, 3.5% increase in the 0 - 60 mph acceleration, has a Tier 2 Bin 8 emissions rating, and a towing capacity of 2500 lbs.

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