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Evaluation of High-Energy-Efficiency Powertrain Approaches: The 1996 FutureCar Challenge

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ABSTRACT

Twelve colleges and universities were selected to design, build, and develop a mid-size vehicle that could achieve high energy economy while maintaining the performance characteristics of today's mid-size vehicle. Many of the teams were able to increase the fuel economy of their vehicles, but most of these increases came at the expense of decreased performance or worsened emissions. This paper evaluates and summarizes the high-energy-efficiency powertrain technology approaches that were utilized in the 1996 FutureCar Challenge, which was the first evaluation of these vehicles in a two-year program. Of the 11 vehicles evaluated in the competition, nine utilized hybrid electric vehicle approaches. This paper discusses the design trade-offs made by the teams to achieve high efficiency while trying to maintain stock performance.

INTRODUCTION

The FutureCar Challenge is a two-year competition sponsored by the U.S. Department of Energy (DOE) and the U.S. Council for Automotive Research (USCAR). The mission of this competition is to develop and demonstrate advanced fuel-efficient vehicles that parallel the technology development path of the Partnership for a New Generation of Vehicles (PNGV). The PNGV development path culminates in a mid-size car having up to three times the fuel efficiency while maintaining the performance, safety, and affordability of today's production vehicles.

Teams from 12 North American colleges and universities were selected to each receive a mid-size car (Taurus, Lumina, or Intrepid) from Ford, GM, and Chrysler. The teams were challenged to dramatically improve the fuel efficiency of their vehicles without sacrificing performance or safety, and to demonstrate this new vehicle technology during competitions in June of 1996 and 1997.

The 1996 FutureCar Challenge competition included many events aimed at verifying the safety, performance, and efficiency of the converted vehicles. The vehicles first

underwent a thorough safety and technical inspection, followed by such events as an acceleration test, design reviews, and dynamometer-based fuel economy and emissions testing. The results presented in this paper represent a set of preliminary results from the first year of competition.

TECHNOLOGIES PRESENTED

The FutureCar Challenge is a goal-oriented competition that encourages innovation. Examples from a variety of vehicle technologies were presented. Of the 11 vehicles evaluated during the competition, five were parallel hybrid electric vehicles (HEVs), four were series HEVs, one was a stored-air supercharged design, and one was a diesel conversion. The conversions utilized a variety of fuels, including reformulated gasoline (RFG), fuel ethanol (E85), compressed natural gas (CNG), liquefied petroleum gas (LPG), and diesel fuel.

Although a variety of fuels and strategies were demonstrated, only a few base engines were utilized. All of the diesel-fueled entries (which include all but one of the parallel HEVs) utilized the Volkswagen 1.9-L turbocharged, direct-injection diesel (TDI) engine. Only three other engines were utilized: the Suzuki 1.0-L 3-cylinder, the Saturn 1.9-L-4 cylinder, and the Honda 0.66-L 3-cylinder. The small number of base engines selected no doubt mirrors the small number of production engines suitable for use in a hybrid electric drivetrain.

In contrast to the relatively small number of engines represented, the vehicles presented a wide variety of combinations of electric drivetrain components. Examples of lead-acid, nickel-cadmium, and nickel-metal hydride batteries were presented, as well as examples of synchronous AC, AC induction, and advanced DC motor technologies. The range of control strategies for the vehicles was similarly diverse, including thermostatic strategies, electric launch strategies, and many others. Examples of both charge-sustaining and charge-depleting HEV designs were presented. Table 1 shows some of the important components for the vehicles. Vehicle control strategies are listed in Table 2.

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Table 1. 1996 FutureCar Challenge Vehicle Powertrain Components

School	Powertrain	Fuel	Engine	Motor Manufacturer and Type	Battery Manufacturer	Battery Chemistry	Pack Voltage (V)	Pack Capacity (kWh)	Transmission
Virginia Tech	Series HEV	LPG	Geo 1.0-L SOHC	GE AC Induction	Hawker Genesis	Lead-Acid	324	7.1 (c/2)	Direct Drive
Concordia University	Parallel HEV	Diesel	Volkswagen 1.9-L TDI	Solectria Advanced DC	Power Battery Sales	Lead-Acid	144	3.0 (c/2)	4-Speed Autostick
West Virginia University	Series HEV	CNG	Saturn 1.9-L SOHC	Uniq Mobility Synchronous AC	Hawker Genesis	Lead-Acid	192	4.2 (c/2)	5-Speed Manual
Lawrence Tech	Parallel HEV	Diesel	Volkswagen 1.9-L TDI	Uniq Mobility Advanced DC	Ovonics	Ni-MH	171	16.25 (c/20)	4-Speed Automatic
U. Michigan, Ann-Arbor	Parallel HEV	Diesel	Volkswagen 1.9-L TDI	Uniq Mobility Advanced DC	Saft	Ni-Cd	96	3.8 (c/2)	5-Speed Manual
U. Calif., Davis	Parallel HEV	RFG	Honda 0.66-L	Uniq Mobility Advanced DC	Ovonics	Ni-MH	185	16.6 (c/20)	5-Speed Manual
Michigan Tech	Series HEV	RFG	Geo 1.0-L SOHC	Uniq Mobility Advanced DC	Johnson Controls	Lead-Acid	333	8.65 (c/2)	Single-Speed Direct Drive
U. Maryland	Series HEV	E85	Geo 1.0-L SOHC	Northrop Grumman AC Induction	Hawker Genesis	Lead-Acid	324	7.1 (c/2)	Single-Speed Direct Drive
Cal. State Univ., Northridge	Parallel HEV	RFG	BMW 1.1-L	Uniq Mobility Brushless DC	GM Hughes Electronics	Lead-Acid	300	7.2 (c/3)	2-Speed Automatic
U. Wisconsin, Madison	Parallel HEV	Diesel	Volkswagen 1.9-L TDI	Baldor AC Induction	Hawker Genesis	Lead-Acid	333	2.8 (c/2)	5-Speed Manual
U. Illinois, Chicago	Non-HEV	CNG	Daihatsu 0.85-L	N/A	N/A	N/A	N/A	N/A	4-Speed Automatic
Ohio State	Non-HEV	Diesel	Volkswagen 1.9-L TDI	N/A	N/A	N/A	N/A	N/A	5-Speed Manual

Table 2. 1996 FutureCar Challenge Vehicle Control Strategies

School	Vehicle Control Strategy
Virginia Tech	Operates as an electric vehicle until the battery reaches 30% state-of-charge. The engine is then activated to both drive the vehicle and recharge the batteries. The engine is turned off when the batteries achieve 80% state-of-charge.
Concordia University	Electric powertrain load-levels the heat engine. Driver shifts optimally in the economy mode; the vehicle controller shifts automatically at predetermined points in normal operation.
West Virginia University	Operates as an electric vehicle until the battery reaches 35-40% state-of-charge. The heat engine is then activated to provide energy to both drive the vehicle and recharge the batteries.
Lawrence Tech	Electric powertrain is used to begin vehicle acceleration, with the heat engine activating at vehicle speeds in excess of 5 mph. Regeneration during braking events recharges the batteries, but the vehicle is designed to be charge-depleting.
U. Michigan, Ann-Arbor	The electric powertrain is used to load-level the heat engine.
U. Calif., Davis	Operates as an electric vehicle below 35 mph. The heat engine is activated during peak-power events below 35 mph, as well as providing the total motive power for speeds higher than 35 mph. At low state-of-charge, the speed at which the engine is activated to provide total motive power decreases. The vehicle captures energy during braking events but is designed to be charge-depleting.
Michigan Tech	The electric drivetrain load-levels the heat engine, which is always activated. At low speed, the engine drops to idle for better driveability. The vehicle is designed to be charge sustaining.
U. Maryland	Operates as an electric vehicle until battery state-of-charge drops to 45%, when heat engine activates to recharge the battery pack. The heat engine is also activated during peak-power events, utilizing the throttle position sensor. A peak-power event is determined by the throttle position exceeding 85%. Engine activation may in both cases be delayed if the catalyst is cold in order to allow an electrically-heated catalyst to achieve operating temperature.
Cal. State Univ., Northridge	Operates as an electric vehicle during urban driving. Engine on during highway driving and during low state of charge.
U. Wisconsin, Madison	Electric drive load-levels the heat engine. Rates of electrical energy use during accelerations and regeneration during braking events are controlled by battery state-of-charge.
U. Illinois, Chicago	Stored-air supercharging of a small CNG-fueled heat engine. Off-peak engine capacity is used to store pressurized air in onboard tanks for use during peak-power events.
Ohio State	Not applicable. Utilized conventional diesel engine and controls.

FUTURECAR CHALLENGE EVENTS

The FutureCar Challenge was designed to produce vehicles which are highly fuel-efficient without sacrificing the performance, cost, and comfort of today's vehicles. The competition, therefore, included a variety of events designed to individually evaluate a wide range of vehicle characteristics. Attachment A shows the final scores from each of the events.

The Technical Report event was designed to encourage the teams to document their design strategy and implementation, along with predictive modeling and testing. This event required each team to produce a 15-page (maximum length) technical document in SAE format that summarized the important points in the design of their vehicle. This event was won by the University of California - Davis. The UCD paper provided insights into each of the critical decisions made by the team [1].

The Engineering Design - Quality and Execution event was intended to evaluate how well each team executed their particular design strategy, regardless of the merit of the strategy itself. This event featured a review of the vehicle at the component level to assess the design and the quality of manufacture of the various components required to successfully integrate each team's powertrain into the vehicle. This event was won by Virginia Tech.

The Engineering Design - Application of Advanced Technology Event was intended to evaluate how each entry utilized technology to solve the problems associated with producing a high-efficiency vehicle that met all of the goals set forth by the competition. This event was won by Lawrence Technological University. LTU's vehicle featured nickel-metal hydride batteries and a state-of-the-art diesel engine in a parallel configuration [2].

The Acceleration event was intended to assess how well the FutureCars matched the performance of their stock counterparts. This event was an acceleration from a standing start to 0.2 km on a section of track at Ford Motor Company's Dearborn Proving Grounds. The acceleration times were measured by the vehicle breaking light beams at both the start and finish line, so that driver reaction time was not included. This event was won by Ohio State University. Table 3 shows the 0.2-km acceleration time for the FutureCars and for three representative stock vehicles.

The Handling event was held on an evaluation road at the Dearborn Proving Grounds. Some maneuvers, such as a slalom and tighter corners, were added to sections of the road to increase the difficulty of the course. This event was intended to ensure that the maneuverability of the FutureCars had not been severely reduced. Ohio State University won the

Table 3. 0.2 km Acceleration Results

School Name	0.2 km Acceleration Time (s)
Virginia Tech	11.21
Concordia University	13.84
West Virginia University	16.62
Lawrence Tech	12.57
Univ. California - Davis	14.40
Michigan Tech	13.29
University of Maryland	12.63
Univ. Wisconsin - Madison	12.52
Univ. Illinois - Chicago	20.92
Ohio State University	11.17
Stock Ford Taurus	11.46
Stock Chevrolet Lumina	10.76
Stock Dodge Intrepid	11.07

event, with a time of 88.17 seconds, as compared to 85.98 seconds for a stock Lumina driven by an experienced performance driver.

A Consumer Acceptability event was held to ensure that increases in fuel economy did not come at the expense of features deemed necessary by consumers. This event had both a static and a dynamic evaluation of each vehicle. Complexity of operation and interior comfort for five people were among the criteria used to evaluate each vehicle in this event, which was won by Concordia University of Montreal.

The Endurance event was a road-rally style event that tested the ruggedness of the vehicles on public streets. The vehicles completed two 30-mile laps on Dearborn's city streets. The laps featured time-to-distance measures of the performance of each vehicle in order to capture information about vehicles that had to be repaired by the side of the road. In addition, each chase vehicle carried an official observer. There was no individual winner for this event, as several vehicles completed the laps within the appropriate amount of time.

The Emissions and Fuel Economy events were of pivotal importance. These events will be described in depth in the following section.

DYNAMOMETER TEST METHODOLOGY

Defining a generic emissions and fuel economy test procedure that can adequately test all types of HEVs utilizing a variety of control strategies is a daunting task and continues to be a challenge. As yet, a single-day emissions testing procedure has not been proposed for HEVs. In fact, more rigorous tests have been proposed that span three or four days [3]. Since only two days were available for dynamometer testing during the competition, a shorter and slightly less generalized methodology was used. This test methodology was to some degree vehicle-specific. Non-hybrid vehicles, for example,

underwent the standard Federal Test Procedure and the Highway Fuel Economy Test. Charge-sustaining hybrids were tested by means of back-to-back pairs of LA-4 cycles with a 10-minute soak in between, performed both at low- and high-state-of-charge in order to derive state-of-charge corrected results for emissions and fuel economy. A set of powerplant emissions factors and an efficiency correction factor were utilized for charge-from-the-wall HEVs [4]. These factors are laid out in Table 4.

Table 4. Off-Board Electrical Energy Efficiency and Powerplant Emissions Factors

CO Emission Factor	0.117 g / AC kWh
NMHC Emission Factor	0.016 g / AC kWh
NO _x Emission Factor	1.250 g / AC kWh
Electrical Energy content of Reformulated Gasoline	0.321 * 9.685 kWh AC Energy / liter RFG

Because reduction of the weight and driving losses is important to producing a high-efficiency vehicle, teams were encouraged to take steps to reduce these losses in their competition vehicles. Accurate assessment of the importance of these efforts demanded that a coastdown test be performed on each vehicle and the dynamometer road load be set accordingly for each vehicle. Vehicles that were not able to perform a coastdown at the competition were tested by using a road load calibrated to a stock Taurus equipped with low-rolling-resistance tires. The stock vehicle was tested at three different weights in order to provide a close match to the weights of the FutureCars. Table 5 shows the coastdown times for the FutureCars and the stock Taurus.

Electrical energy usage for HEVs was measured by using an onboard data-acquisition system. The DAS measured both the kWh and the Ah drawn from the battery by time-integrating measurements of battery voltage and current [5]. Fuel usage was measured by carbon balance analysis of the exhaust gases.

MOST SUCCESSFUL STRATEGIES

Several of the teams were able to produce vehicles that were successful in demonstrating increased fuel economy. Most of them sacrificed performance in other areas, such as emissions or acceleration; however, these results are only preliminary results from the first year of the program. It is unreasonable to expect fully-optimized vehicles after only nine months of work. The second year of the competition will no doubt produce vehicles that are even more improved. It is also important to realize that the results presented here represent only one dynamometer test; further testing is necessary before strong conclusions can be drawn from the preliminary results.

Table 5. Coastdown Times for 1996 FutureCars

Vehicle	Coastdown Times (s)			
	24.6 - 22.3 m/s	20.1 - 17.9 m/s	15.6 - 13.4 m/s	11.2 - 8.9 m/s
U. Wisconsin, Madison	8.345	10.535	13.205	16.135
Ohio State	9.975	12.515	17.625	23.67
Lawrence Tech	11.075	14.225	18.075	23.36
Virginia Tech	12.25	15.77	19.39	23.06
Concordia University	7.84	9.81	11.99	14.325
Stock Taurus @1694 kg	9.21	12.595	15.91	20.815
Stock Taurus @ 1830 kg	9.515	12.205	17.235	21.67
Stock Taurus @1967 kg	10.45	13.255	17.48	22.09

Virginia Tech's FutureCar was a propane-fueled series HEV that utilized a traditional thermostatic control strategy. The vehicle operated as an electric vehicle until the battery state-of-charge reached a low value (30%), at which time the engine/generator system was engaged [6]. The engine/generator system was shut down when the state-of-charge reached 80%. The control strategy was well-developed and did not display any anomalous behavior. Virginia Tech's vehicle demonstrated average exhaust emissions and dramatically improved fuel economy during both the city and highway driving simulations.

Lawrence Tech produced a parallel hybrid that was designed to be charge-depleting. The onboard electrical energy was used only to begin accelerations from a standing start, with the heat engine (a state-of-the-art diesel) engaged once the vehicle reached a certain speed. The speed at which the engine was engaged was less than 13 kph. This speed was not constant; it was a function of both the state-of-charge and the load, as determined by the throttle position sensor. The LTU vehicle also featured modest body modifications aimed at reducing weight and aerodynamic losses. These modifications included rear wheel fairings, a composite hood, and modifications to the rear deck lid to promote stable vortex shedding [2]. This vehicle demonstrated a significant improvement in fuel economy, but average in terms of exhaust emissions.

The University of Wisconsin - Madison entry was another parallel entry, but this car utilized a load-leveled heat engine strategy [7]. This strategy focused on maintaining the engine speed and load within its most efficient region by utilizing the electric drive to adjust the required engine output. The onboard electrical energy storage for this vehicle was relatively small, owing to the lower energy and power requirements of this strategy. Combined with a high-efficiency diesel engine, this strategy has the potential for substantial increases in fuel efficiency. Although it demonstrated significant gains in fuel efficiency, this vehicle

seemed to be in need of optimization of the control strategy, as it was charge-depleting on the highway cycle, where one might expect charge-sustaining operation from such a design.

Ohio State produced a vehicle that utilized a state-of-the-art diesel engine with a manual transmission [8]. The transmission was a stock Volkswagen transmission, but the gear ratios were optimized for the increased weight of the Lumina over the Volkswagen vehicle for which the transmission was originally designed. This vehicle did not suffer the weight penalty associated with hybridization. Low vehicle weight, combined with the benefits of a high-efficiency heat engine, allowed this vehicle to accomplish significant gains in fuel efficiency without sacrificing emissions or acceleration performance.

The emissions and fuel economy results for these vehicles are shown in Tables 6 and 7. The results demonstrate that while these teams were able to increase the fuel economy of their vehicles, they were not able to maintain the emissions levels of the stock vehicles. The indicated results are state-of-charge-corrected and include powerplant contributions where appropriate.

Table 6. Fuel Economy Results

School Name	Fuel Econ., City (km/l)	Fuel Econ., Highway (km/l)	Fuel Econ., Combined (km/l)
Virginia Tech	20.91*	17.10	19.00
Lawrence Tech	12.84	21.09	15.60
Univ. Wisconsin, Madison	10.79	17.35	13.01
Ohio State	15.05	24.45	18.20
Stock Taurus**	10.88	13.69	11.99
Stock Intrepid**	10.37	12.75	11.48
Stock Lumina**	10.88	13.69	11.99

* The fact that the city fuel economy result is higher than the highway result is anomalous; these results should be confirmed with additional testing before conclusions can be drawn from them.

** Test results for the stock vehicles do not represent tests performed at the competition. These results were based upon data from the "Fuel Economy Guide - Model Year 1996," published by the U.S. Environmental Protection Agency. The results were corrected to reflect raw test results.

OTHER POTENTIALLY EFFICIENT STRATEGIES

Several other teams produced entries for the competition but for a variety of reasons were not able to demonstrate their efficiency and emissions potential. Some of these were the Michigan Tech vehicle, the University of Maryland's vehicle,

West Virginia University's vehicle, and the vehicle entered by the University of California - Davis.

Table 7. Emissions Results

School Name	NO _x (g/mi)	NMHC (g/mi)	CO (g/mi)	PM (g/mi)
Virginia Tech	1.15	0.20	3.1	N/A
Lawrence Tech	1.68	0.08	0.12	0.00*
Univ Wisconsin, Madison	1.79	0.10	0.12	0.14
Ohio State	0.92	0.02	0.17	0.075

* The particulate matter measurement for Lawrence Tech was lower than the measurement capability of the instruments.

Michigan Tech produced a rear-engine series HEV which utilized a load-following heat engine. The heat engine (a Geo 1.0-L) operated at one of several speeds, depending upon driving conditions [9]. Unfortunately, this approach did not result in significant gains; this is likely due to implementation difficulties rather than the concept. The engine appeared to be running extremely rich. The MTU team was later able to determine that a throttle actuator was "hunting," causing the high emissions levels.

The University of Maryland produced a series HEV utilizing and E85-fueled Geo 1.0-L engine. The engine intake and exhaust systems were optimized for the application, as were the spark and fuel controls [10]. The vehicle control system appeared to be well-developed. Unfortunately, a mechanical difficulty forced by spatial constraints under the hood prevented the vehicle from being able to operate as an HEV, although it was able to perform some events running on its battery pack.

Another series design vehicle was entered by West Virginia University. This vehicle was fueled with CNG and utilized a Saturn 1.9-L engine [11]. This design holds potential for increasing fuel economy with vastly decreased emissions. Although the vehicle performed each event, the engine/generator was not able to produce enough electrical energy, even though it appeared to be sized adequately. An electrical problem with the generator seemed to be the difficulty.

Concordia University of Montreal designed a vehicle that was a parallel vehicle utilizing the Volkswagen TDI diesel engine. The Concordia control strategy focused on increasing the efficiency of the diesel engine by load-leveling during accelerations, while relying on the steady-state efficiency of the diesel for cruising conditions. Regenerative braking would provide enhanced efficiency by capturing what would have been wasted energy [12]. Although this vehicle achieved just under 17 km/L on the highway cycle, it only

at West Virginia University." Morgantown, West Virginia, November 1996.

12. Achilles Nikopoulos et al. "The Concordia University 1996 FutureCar Hybrid Electric Vehicle." Montreal, Quebec, Canada, November 1996.

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ATTACHMENT A

Table 8. 1996 FutureCar Challenge Event Scores

Car #	School Name	Readiness	Written Technical Report	Engineering Design Q&E	Engineering Design AAT	Energy Economy- City	Energy Economy- Hwy	Emissions	Acceleration	Handling	Consumer Acceptability	Endurance	Penalties & Bonus	Total FCC Score	Standing
Available Points		50.00	100.00	50.00	100.00	150.00	100.00	150.00	100.00	50.00	150.00	100.00		1100.00	
1	Virginia Tech.	45.00	74.00	45.10	64.00	150.00	57.74	141.43	99.56	43.59	105.35	60.43	-1.00	885.20	1
2	Concordia University of Montreal	48.00	71.30	29.70	73.20	35.74	56.68	72.86	72.07	30.06	108.43	100.00	15.00	713.05	5
3	West Virginia University	31.00	65.10	40.50	63.20	67.45	32.21	124.29	0.00	21.87	74.33	100.00	-100.00	519.95	6
4	Lawrence Technological Univ.	35.00	71.60	43.60	78.00	69.19	80.67	124.29	85.35	38.09	92.27	100.00	15.00	833.05	3
5	Univ. of Michigan, Ann Arbor	10.00	56.00	37.30	50.60	0.00	0.00	0.00	0.00	0.00	28.65	0.00	-205.00	0.00	11
6	Univ. of California, Davis	8.00	80.90	35.40	71.80	72.98	0.00	90.00	66.17	40.69	79.33	35.89	-210.17	371.00	8
7	Michigan Technological Univ.	30.00	53.20	36.90	50.20	30.00	32.70	0.00	77.81	34.91	24.65	96.32	40.00	506.69	7
8	University of Maryland	38.00	77.90	42.40	70.80	0.00	0.00	0.00	84.77	27.67	62.93	0.00	-100.00	304.48	9
9	Cal. State Univ., Northridge	5.00	74.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-320.00	0.00	12
10	Univ. of Wisconsin-Madison	45.00	71.30	38.70	67.80	48.68	59.13	115.71	85.88	43.94	103.82	100.00	40.00	819.97	4
11	Univ. of Illinois at Chicago	10.00	57.30	0.00	60.00	0.00	0.00	0.00	0.00	10.00	54.80	20.00	-205.00	7.10	10
12	Ohio State Univ.	37.00	46.50	23.60	40.80	91.28	100.00	150.00	100.00	50.00	100.27	100.00	40.00	879.44	2