The 1995 HEV Challenge: Results and Technology Summary

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ABSTRACT

The objective of this paper is to analyze and summarize the performance results and the technology used in the 1995 Hybrid Electric Vehicle (HEV) Challenge. Government and industry are exploring hybrid electric vehicle technology to significantly improve fuel economy and reduce emissions of the vehicles without sacrificing performance. This last in a three-year series of HEV competitions provided the testing grounds to evaluate the different approaches of 29 universities and colleges constructing HEVs. These HEVs competed in an array of events, including: acceleration, emissions testing, consumer acceptance, range, vehicle handling, HVAC testing, fuel economy, and engineering design. The teams also documented the attributes of their vehicles in the technical reports. The strategies and approaches to HEV design are analyzed on the basis of the data from each of the events. The overall performance for promising HEV approaches is also examined. Additional significant design approaches employed by the teams are presented, and the results from the events are discussed.

INTRODUCTION

The 1995 HEV Challenge was the final hybrid electric vehicle competition in a three-year series. Co-sponsored by the U.S. Department of Energy, the Chrysler Corp., and Natural Resources - Canada, the 1995 HEV Challenge determined the best overall performing HEV in each of three distinct classes. As a result of innovative and advanced designs, the HEV Challenge provided a wealth of technical data that complement and enhance industry's and government's research and development efforts. Collegiate teams had to develop innovative and environmentally responsible vehicles that combine electric and thermal power to improve mileage and reduce emissions and yet perform like conventional vehicles.

The classes were the Ford Escort Class, the Saturn Sedan Class, and the Chrysler Neon Class (new for 1995). Each class was evaluated independently of the other, and each class had distinct design criteria specified by the competition organizers (see Appendix A, Table 6. for a summary of the vehicle specifications).

Ford Escort Class - These hybrids, based on the 1992 Ford Escort Wagon, had significant electric-only range. These vehicles were required to have a minimum electric-only range of 40 km at a speed of 48 km/h. The HEV range required a minimum of 482 km at 72 km/h. The teams were limited to reformulated gasoline (Phase I), methanol (85%), and ethanol (95%). The weight of the vehicles was limited to the gross vehicle weight plus 15%.

Saturn Sedan Class - These hybrids were charge-sustaining hybrids with minimal electric-only range and were based on 1991 SL2 Saturn Sedans. These vehicles could not be charged from the grid. The vehicles were required to have a minimum electric-only range of 8 km at 48 km/h and a minimum HEV range of 482 km at 72 km/h. The vehicles used methanol (85%) or ethanol (95%) for liquid fuel. Vehicle weight was limited to the gross vehicle weight plus 15%.

Chrysler Neon Class - The Neons converted to HEVs in this class were not limited to a specific hybrid design. The required ranges for the Neon class were 8 km at 48 km/h for electric and 241 km at 89 km/h under hybrid power. The vehicles were limited to compressed natural gas and had to remain under the gross vehicle weight. The vehicles were allowed to charge from the charging station. This class was the only class required to have an operating heating ventilation and air-conditioning (HVAC) system.

DISCLAIMER

The HEV Challenge consisted of events in which vehicle designs and overall dynamic performance were evaluated. The events included Acceleration, Handling, Range, Emissions, Fuel Economy, Consumer Acceptability, Engineering Design Review, and Technical Reports [1]. This paper presents the results of this competition and analyzes the best vehicle designs.

HEV CHALLENGE EVENTS

ACCELERATION AND HANDLING EVENTS

The performance events, such as the Acceleration and Handling Events, are designed to test vehicle power, maneuverability, and handling. The Acceleration Event involved a hard acceleration over a 201-m straight-away. The Handling Event involved an obstacle course that includes a slalom, figure eight, quick accelerations, park and reverse, and a driver change over a 96.5 m distance (see Attachment B, Figure 5). Timing lights were used in both events to signal the start and end of the run. The operation mode of the vehicle was specified only in the Acceleration Event. All classes had to make at least one run in the hybrid mode, and the Escort Class had to make an additional run in electric-only mode.

The top speeds of the vehicles during the acceleration run are listed in Table 1. Of the top five parallel and series vehicles, the parallel vehicle demonstrated higher speeds by 13.2% over the series. The average acceleration times show the parallel hybrids outperforming the series hybrids by 2.38 s.

Table 1. Acceleration Times of the Five Top-Performing Parallel and Series Vehicles

Parallel	Time (s)	Top Speed (km/h)	Series	Time (s)	Top Speed (km/h)
ETS	**10.75**	**95**	CSU, Chico	**10.34**	**100**
Texas Tech	**11.10**	**93**	VA Tech	**13.04**	**71**
WWU	**11.23**	**85**	Navy	**14.03**	**71**
Wayne St.	**11.41**	**87**	U. of WI	**14.19**	**72**
U. of Alberta	**11.71**	**87**	Penn St.	**14.55**	**74**
Average	**11.24**	**89.4**	**Average**	**13.21**	**77.6**

The results of the Handling Event paralleled those of the Acceleration Event, with the series vehicles performing, on average, slower than the parallel hybrids by 1.32 s. The Handling Event was greatly influenced by the driver's skill in comparison with the Acceleration Event. The times between the two classes were much closer; the averages differed by only by 1.2% (see Table 2). The fastest hybrid was the University of Wisconsin's vehicle, which was a series hybrid.

Table 2. Handling Times of the Five Top-Performing Parallel and Series Vehicles

Parallel	Times (sec)	Series	Times (sec)
Texas Tech	**106.18**	U. of WI	**100.56**
U. of Tenn.	**107.94**	Penn State	**109.25**
Wayne St.	**108.41**	CSU, Chico	**112.69**
CSU, Fresno	**110.48**	WVU	**113.35**
U. of Alberta	**112.60**	U. of FL	**116.34**
Average	**109.12**	**Average**	**110.44**

RANGE EVENT

The Range Event was designed to demonstrate vehicle reliability and range potential on a 2.89-km closed track (see Attachment B, Figure 6). The vehicles were given a limited amount of gasoline-equivalent fuel (11 L for the Neons and Escorts and 12 L for the Saturns), a maximum time, and minimum average lap speeds. Only one to two vehicles were expected to still be on the track at the end of the event. Only one class was allowed on the track at a time (a maximum of 12 vehicles). The teams were able to choose the optimal starting state of charge (SOC) in their battery packs on the basis of their driving strategy. The average lap speeds were limited to a minimum of 64.4 km/h and a maximum of 88.5 km/h on the basis of prudent speed limitations of the track.

Because the objective of the Range Event was to have the vehicles "run-till-they-drop," the amount of fuel for each class had to be calculated. The liquid fuel limits were based on previous HEV Challenge results and hybrid types. As an example, estimations were based on a maximum of 3.5 h of track time for the Escort Class at an average lap speed of 67.5 km/h. From the total distance estimated (236.5 km), a spreadsheet calculated fuel economy on the basis of possible combinations of electric and hybrid ranges. Thus, the Range Event for the Escort Class included 3.5 h of track time with only 11 L of liquid fuel, a volume based on estimations that vehicles would not achieve greater than 20.1 km/L in hybrid mode (see Table 3).

Table 3. Range Event

Class	Time (h)	Fuel (L)	Est. Fuel Economy*
Escort Class	3.5	11	20.1 km/L
Saturn Class	3.0	12	15.6 km/L
Neon Class	3.0	11	17.0 km/L

* Fuel Economy calculations based only on the estimated HEV miles. Estimates do not include the electric-only miles, which would reflect a higher fuel economy.

Only one vehicle from each class was left on the track at the end of the Range event. The teams with vehicles on the track were the University of Alberta (Escort), Western Washington University (Neon), and California State University, Fresno (Saturn). Because of the structure of this event, the remaining liquid fuel on board was not measured.

HEV Range Results

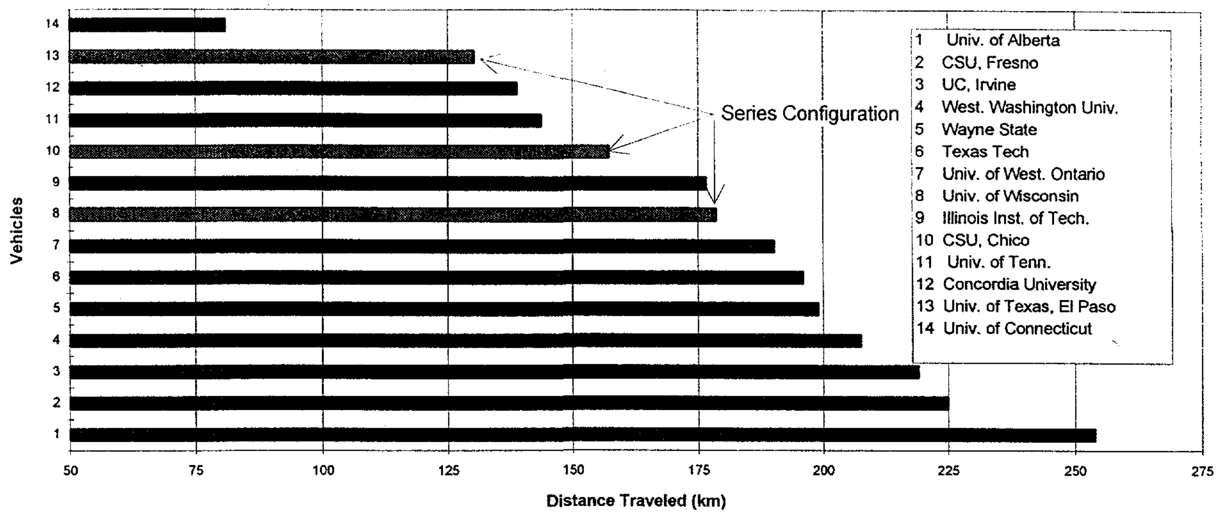

Figure 1. Range Event Results of Vehicles Completing More Than 50 km.

Reliable Vehicle Designs - The Range Event also identified vehicles with reliability problems. Only eight vehicles traveled over 160.9 km. Four of the Escort Class vehicles ran for over 160.9 km, although it was expected that most, if not all, of the vehicles would run until they were out of fuel and not break down. The Saturn and Neon Classes both had two vehicles that ran for more than 160.9 km (see Figure 1).

The robustness of the parallel hybrids is best seen in this event. There was only one series vehicle, that was built by the University of Wisconsin, that completed over 160.9 km, and it traveled the shortest distance of the Escort vehicles. The vehicles that were out last on the track in the Saturn and Neon Classes were both parallel configurations.

ENERGY ECONOMY

Energy economy was measured during the Emissions Event. The city cycle of the Federal Test Procedure was used as the basis for calculating fuel economy. The raw data were adjusted for state of charge (SOC) corrections and displayed in gasoline-equivalent values. These results are analyzed in detail in "Hybrid Electric Vehicle Dynamometer Testing with State-of-Charge Corrections of 1995 HEV Challenge Vehicles," SAE paper 96P-176 by Michael Duoba et al.

Most of the second- and third-year vehicles were tested in the Energy Economy Event. The Neon Class suffered from first-year reliability problems, resulting in the fewest number of vehicles tested from any class. Data were collected from 7 out of the 8 Escorts, 7 out of 10 Saturns, and only 3 out of 11 Neons. By mistake, the Escorts and Saturns were tested at dynamometer inertia settings of 113 kg - 136 kg above their actual weight.

Table 4. Best Fuel Economy Performances

School	Class	Fuel Economy (km/L)*	Vehicle Weight (kg)
ETS	Saturn	18.1	1447.4
CSU, Chico	Saturn	13.8	1709.4
CSU, Fresno	Saturn	11.6	1438.8
'91 Saturn SL2	Stock	12.3	1040.4
Wayne State	Escort	11.4	1800.0
U. of Alberta	Escort	11.1	1617.3
U.C., Irvine	Escort	10.9	1675.8
'92 Ford Escort	Stock	14.0	1090.2
Texas Tech	Neon	10.2	1575.6
Univ. of Tenn	Neon	9.9	1496.0
W.W.U.	Neon	9.3	1576.5
'95 Chrysl. Neon	Stock	12.3	1057.6

* SOC-corrected in gasoline equivalent kilometers per liter.

Although two of the three classes were tested at artificially high inertia weights on the dynamometer rolls, fuel economy was still lower than that of comparable gasoline equivalent-vehicles. Only in the case of ETS and CSU, Chico (both Saturn Class), did hybrids demonstrate higher fuel economy than the stock vehicle. There was no correlation between vehicle weight and fuel economy. There was no operator control over such factors as hybrid-control strategy and configuration that could affect fuel economy. No comparisons are made between parallel and series hybrids because of the lack of data from series hybrids from this event.

Energy economy in electric-only mode was collected on the test track at the Chrysler Technology Center. Each class had to demonstrate minimum electric-only ranges: 40 km at 48 km/h for the Escort Class and 8 km at 48 km/h for the Saturn and Neon Classes. The results from the Escort Class are shown in Figure 2 by configuration. The Saturn and Neon Classes are shown together in Figure 3, because both classes were required to go the same minimum distance.

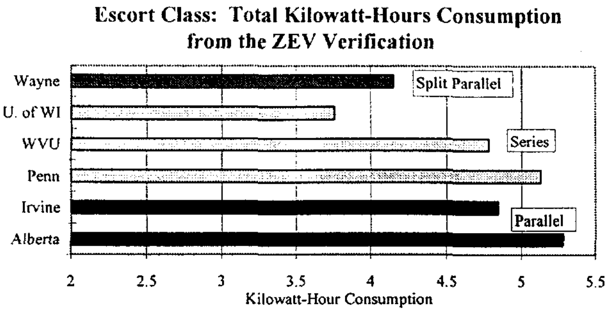

Figure 2. Total Kilowatt-Hour Consumption from the ZEV Verification for the Escort Class over a 40 km Distance.

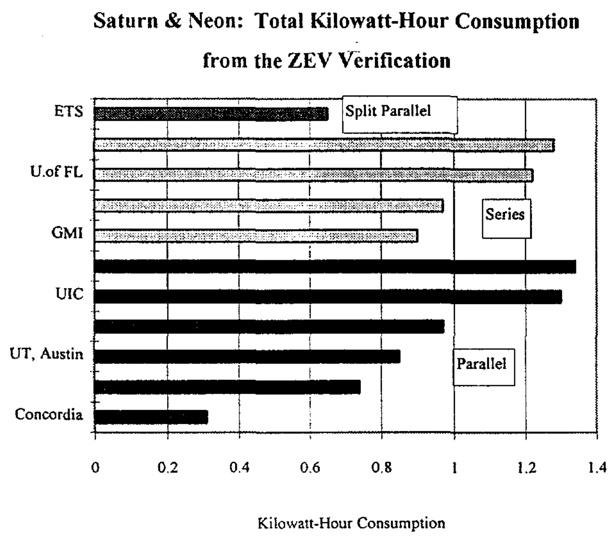

Figure 3. Total Kilowatt-Hour Consumption from the ZEV Verification for the Saturn and Neon Classes over a 8 km Distance.

The difference between the average kilowatt-hour consumption for the parallel and series configurations is small for both the Escorts (Figure 2) and the Saturns/Neons (Figure 3). The average kilowatt-hour consumptions for the parallel and series Escorts are 5.06 kWh and 4.56 kWh, respectively. Because of the few data points for the Escort Class, no conclusions can be drawn from the efficiency differences between parallel and series configurations. There was also no correlation between vehicle weight and energy consumption for the Escorts.

For the Saturns and Neons, the parallel and series average kilowatt-hour consumptions were 0.92 kWh and 1.09 kWh, respectively. The correlation between a heavier vehicle and greater energy consumption is seen in Figure 4 by using the "corner test of association" developed by Olmstead and Tukey [2]. The series hybrids were heavier overall than the parallel hybrids. Why did the series hybrids have a lower energy economy? Could it be a result of the additional weight from a larger battery capacity? Looking at the relationship between the battery pack weight to total vehicle weight and the energy consumption, there was no direct correlation. Because of the few data points available, drawing any conclusions about the effect of hybrid configuration efficiency is difficult. The losses associated with the onboard generation of electricity and the in/out losses of the battery pack are other factors that could help explain the differences in efficiency. However, a common factor of the higher efficiency vehicles was their lower overall vehicle weight. For every 100-kg increase in weight, energy consumption increased by 0.37 kWh at an average constant lap speed of 48 km/h. Noted that the vehicle weights reflected in the figure below consist of fully loaded vehicles (fuel and passengers).

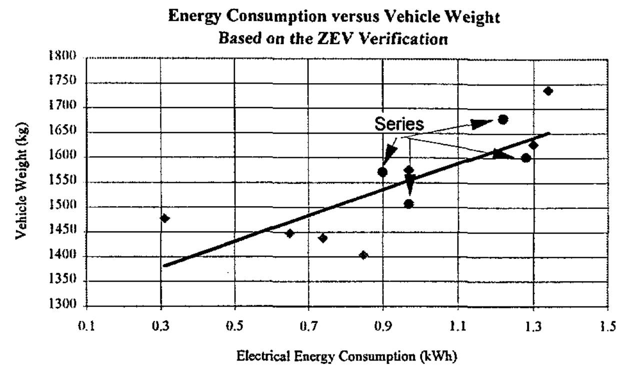

Figure 4. Energy Consumption versus Vehicle Weight Based on ZEV Range Verification for Series and Parallel HEVs.

EMISSIONS EVENT

The best emissions results of each vehicle in each class are presented in Table 5. Although a few of the teams demonstrated good simultaneous control of pollutants, even as low as California's ULEV requirements, the remaining hybrids showed room for improvement. As shown by the median emission results of each class in Table 6, the Saturn Class had one of the largest variation in results. The spread in the emissions results from this class could be linked to the initial HEV Challenge requirements. This class was required to remove the original engine and drivetrain of the vehicle when the teams first received it. The use of non-OEM engines made tuning the engine for low emissions difficult, especially with the use of alcohol fuels.

California State University (CSU), Fresno team indicated that its emissions results were affected by the control strategy. CSU, Fresno had a parallel hybrid that incorporated the electric motor for load-leveling the engine (a Suzuki 1.3-L engine running on ethanol). The control strategy was not fully operational at the competition. To meet the passive control system requirements, the electric motor was set at an average operating range on the basis of previous testing. The operation of the electric motor was implemented through the position on the accelerator pedal. This set up left the engine operating at full open throttle during the trace where the electric motor should have been off-setting the load requirements on the engine [3].

Problems with developing a sufficiently sophisticated control strategy to realize the potential energy economy and emissions gains possible with HEVs, such as shown by CSU, Fresno, illustrate of the some of the difficulties the teams encountered. In addition, reliability issues attributed to prototype vehicles also plagued the schools. GMI reported electrical problems, and UTEP experienced a small electrical fire while running the HVAC testing. The Escort Class, third-year competitors, had the fewest mechanical/electrical problems overall. Seven out of the eight vehicles completed the emissions testing with no major failures.

Only three Neon vehicles finished emissions testing. Although this class had its share of control strategies that were not fully operational and vehicle breakdowns, the University of Tennessee was able to obtain ULEV emission control. The vehicle was a parallel hybrid that used a 1.0-L Geo engine converted to run on natural gas. This vehicle demonstrated that low-emission results could be obtained with a reliable, fully functioning control system.

Table 5. Best Emissions Performances

School	Class	NMHC (g/mi)	CO (g/mi)	NO_X (g/mi)
Wayne St.	Escort	0.040	0.540	0.090
CSU, Fresno	Saturn	0.293	5.074	0.312
IIT	Saturn	0.245	3.874	1.497
U. of Tenn.	Neon	0.019	0.504	0.050

Table 6. The Median of Each Class Emissions Results.

School	NMHC (g/mi)	CO (g/mi)	NO_X (g/mi)
Ford Class	0.211	6.901	0.708
Saturn Class	0.422	19.287	1.286
Neon Class	0.010	0.240	0.831

CONSUMER ACCEPTABILITY

The Consumer Acceptability Event was added for the 1995 HEV Challenge as a result input from the teams and Chrysler. In most cases, these prototype vehicles have had only a few hundred miles of development on them, with only one or two drivers. This event was developed to qualitatively evaluate a prospective buyer's acceptability of the finished HEV conversions. There was a static and dynamic portion of the event. The judges for the static portion evaluated the following:

- Comfort/roominess;
- Usable interior storage;
- Instrument panel and cluster;
- Controls;
- Cargo space;
- Customer maintenance labels; and
- Miscellaneous items, such as the audio system, alarms, and interior lighting.

The dynamic portion of this event involved one judge, a professional driver, driving all of the vehicles in one class. The score sheet used to evaluate the vehicles is shown in Attachment C. It covered such items as handling, directional stability, maneuvering and parking, brake feel and effectiveness, road noise, driver control position, performance feel and responsiveness, transaxle operation, powertrain noise, ease of starting, idle noise or roughness, hesitation or sag, shutdown characteristics, and response to full-steering turn. All vehicles were tested under the same driving conditions, and the driver was accompanied by a team member. The Neon class was also tested for the controls, operation, and response of the climate control system with the AC both on and off while the vehicle was running.

The Escort and Neon Classes were tested by the same driver. The University of Wisconsin, Madison, placed highest in the dynamic portion of the event for the Escort Class. The team scored high because its vehicle handled well, which was primarily because the batteries were moved from the back seat to under the passenger area of the car, thereby lowering of the center of gravity. Western Washington scored first in the Neon class because its car had a good feel in terms of overall performance with only the electric motor in use (the ICE did not operate because of the high SOC of the batteries). The driver did note it was difficult to shift this vehicle because the clutch was not used in electric-only mode and the driver had to synchronize the motor speed to the gear ratio. The driver for the Saturn Class said he was impressed with all of the vehicles. CSU, Chico scored highest overall in the dynamic event. The driver said the car was exceptional in all three categories (vehicle, powertrain, and driveability). He did note that the vehicle could be improved in terms of stability and hesitation.

The areas highlighted by the drivers for improvement included:

Power Requirements - Several vehicles were under powered, making them difficult to launch.
Interior Noise - Almost all of the vehicles had high interior noise levels that would be unacceptable to a customer, especially the high-pitched whine associated with the electric motors.
Start-Up Schemes - A majority of the vehicles had complicated start-up schemes.
Steering - Manual steering during parking maneuvers would not be a customer-acceptable configuration. Teams implemented the manual steering to decrease power requirements and reduce weight.
Braking - Brake regeneration can provide great benefits to brake performance feel, but it was unrefined.

The scoring of these vehicles was subjective, and every effort was made to obtain judges who were experienced professional drivers. They acknowledged the engineering challenge a hybrid electric vehicle presents. The judges noted the trade-offs in vehicle handling and performance that must be considered when the weight is increased and two powertrains or sources of power are implemented. They also emphasized the need to concentrate on a vehicle system that is easy to operate, quiet, has adequate acceleration, adequate braking performance, and safe handling, qualities that would be found in a production vehicle.

HYBRID DESIGNS

The hybrid designs were documented through Technical Design Reports, the Engineering Design Review, and special awards. This section discusses successful hybrid vehicles in terms of their performance, reliability, or ingenuity. The intent is not to determine that one approach is better than another, but to examine each approach for its strengths.

The team from Pennsylvania State University (Penn State), a third-year Escort Class team, received the Best Application of Advanced Technology award for its approach to monitoring the charging of the advanced lead-acid batteries. Penn State used Electro Source Horizon batteries to help power its series, charge-sustaining, large electric-only range, hybrid vehicle [4]. Although there was not a problem with the Horizon battery itself, trying to charge 12 of them wired in series did present a problem. These batteries are high-energy-density batteries that have strict charging requirements. The charging cycle recommended by the manufacturer involves a minimum amount of current-limited charging, followed by a voltage-limited charging cycle. The Penn State team was developing a charger to charge the batteries in parallel, but they were unable to complete the charger for the competition, so the team reverted to charging the batteries in series. The team was well aware of the sensitivity of charging these batteries, so within the first two days of the competition, the team developed a 12-channel device that monitored the voltage across each battery which would protect the batteries from overcharging. Each channel was tied into a circuit that was independently powered from the other. A channel monitored the voltage across the battery and compared it with an independent reference voltage. If the battery voltage was greater than the reference voltage, then the extra energy would be diverted to a small lamp. Through this process, the team could determine when the batteries were fully charged. Although the team admits this is not a highly efficient method for charging the batteries, it was considerably less expensive than the only charger recommended for this battery, of which Penn State would have needed four for their system. Penn State's approach, although seemingly simple in concept, was a workable, low-cost solution to a problem with a new advanced technology.

The University of Wisconsin, an Escort Class competitor, was a strong contender in all events and was one of the few reliable series configurations throughout the entire competition. The vehicle was recognized in the design-based events for battery pack design and location, the passive control system (PCS), and the data-logging system.

The location of the battery box was new for 1995. The previous configuration consisted of a single tunnel box through the middle of the vehicle. This design left the vehicle's center of gravity high and resulted in poor handling. In the new design, the battery box was moved to the floor pan below the passenger seats. This design slightly elevated the floor and returned the wagon trunk to its original carrying capacity and even improved the vehicle's handling characteristics. In the Dynamic Event, this team's vehicle had the fastest handling time (100.56 seconds) of any vehicle except the stock neon (100.00 s), which was driven by a professional driver.

The Wisconsin vehicle was an on-road laboratory for the team. The data-logging system, developed by the team, monitored the regenerative brake feel, drive tuning, energy data, and engine power control. A user-friendly display included the vital information collected by the system.

Hybrid passive-control systems are inherently complicated when two sources of power are combined to drive a vehicle. Optimization of a passive control system requires developing a system that monitors each component and implements an operating strategy to run the vehicle at the desired performance level. The team must first determine the objective of the vehicle. Will this vehicle demonstrate high speed, torque, long range, low emissions, high fuel economy, or a combination of these features? The University of Wisconsin team wanted a vehicle that had ultra-low emissions, was easy to use, acceptable to the consumer, and energy-efficient. Wisconsin's vehicle was driven by the electric drivetrain, which drew its power from the lead acid battery pack and a gasoline-powered alternator. Optimization of this series design involved modifying the operation of the vehicle's engine because this was the most inefficient component of the system. The engine had to be optimized to maximize efficiency and minimize emissions. To implement this strategy, the passive control system (PCS) determined when the engine started, idled, increased/decreased power requirements, and shut down on the basis of inputs from the voltage of the battery pack. The PCS had built in strategies for handling unsafe conditions that may arise with the operation of this vehicle. Before it continued implementing changes in vehicle operation, the PCS did the following:

1. Determining if the battery was connected;
2. Made sure the key switch was in the "on" position before the engine started (preventing the car from starting while not being driven); and
3. Determined if the engine was out of fuel to reduce potential damage to the batteries and starter electrical system if the engine was continuously cranked;
4. Determined if the engine was running, which is necessary for switching from hybrid mode to engine-only mode [5].

The University of Tennessee in the Neon Class won top honors. In the Emissions Event, the performance of Tennessee's vehicle led to the first-place finish. The team was also recognized for the level of detail in which it converted the gasoline-powered engine to natural gas with the receipt of the Best Use of Alternative Fuels award.

The team rebuilt the Geo 1.0-L 3-cylinder, 4-stroke engine. The compression ratio in the cylinders was increased from

9.2:1 to 9.9:1 and timing adjustments were made. Siemens Automotive donated prototype CNG fuel injectors, which were installed in the cylinder head, converting the engine to port injection. An Electromotive TEC 2 engine controller was incorporated into the design because it was easy to mount on the engine for dyno testing and because of the team's previous experience with the system. The Electromotive TEC 2 also has a programmable general-purpose output, which aids in controlling EGR. The vehicle showed the team's attention to detail; for example, the team retained the function of the fuel door for the quick-connect fuel fill, the high-pressure gauge, and the manual shut-off. An EDO composite natural gas fuel tank was used to reduce weight.

This hybrid strategy involved initiating the electric motor when the engine surpassed a threshold absolute manifold air pressure (MAP). At that point, the amount of electric assist was proportional to the MAP. Recharging takes place below a threshold MAP if the SOC reading indicates charging is needed. These thresholds vary for the assist or charging modes, depending on the vehicle's operating conditions. Aside from the technology incorporated into the CNG conversion, the team extensively tested the engine to maximize overall performance. This parallel, electric-assist hybrid obtained ULEV emissions during testing, although fuel economy on the dynamometer rolls was poor [6].

Western Washington University (WWU), a Neon hybrid, placed third in the Neon Class. This vehicle was one of the few vehicles that performed reliably from one event to the next. The team designed the vehicle with the intent that it would achieve ULEV emission levels, demonstrate high fuel economy, acceptable to the consumer, have transparent HEV operation, and maintain comparable performance characteristics. The team placed first in the Range Event and Consumer Acceptability and second in the Acceleration Event.

The WWU vehicle was a parallel engine-assist hybrid with a small electric range (5.5 kWh battery capacity @ C/20 discharge rate). The passive control strategy was developed to initiate IC engine operation for its power and range under three specific conditions: the battery pack SOC drops below a predetermined limit, the load on the electric motor exceeds a preset limit for more than 30 s, or the vehicle's speed exceeds 48 km/h for more than 30 s [7].

California State University, Chico was part of the Saturn Class. This team's goal was to design a vehicle with improved fuel economy, reduced emissions, and comfort and performance that match those of today's production vehicles. This series hybrid was driven by AC Propulsion's 150-kW electric motor/controller and was powered by nickel metal hydride batteries and an ethanol-fueled Kohler engine. Chico's control strategy used an off/on approach that was based on the SOC of the battery pack. The vehicle runs on electric power until the SOC drops to 40%. At that point, the generator is engaged and runs until the battery pack returns to 80% SOC.

The high-efficiency components and the vehicle configuration were selected to increase fuel economy. In the Fuel Economy Event, Chico had the highest hybrid fuel economy at 13.8 km/L (SOC-corrected, gasoline equivalent). ETS had a higher fuel economy, but this parallel hybrid was operating in engine-only mode because no four-wheel dynos were available for testing. The Chico team wanted to demonstrate the vehicle's good performance in addition to higher fuel economy. The 150-kW motor provided the power to give Chico's vehicle the fastest acceleration time (10.34 s) of any Challenge vehicle while in electric-only mode [8].

California State University, Fresno was the top overall performer in the Saturn Class. The vehicle performed well in the Emissions and Range Events; as a result, the team took top honors. Reliability of the vehicle was essential to its good performance. Although this team experienced problems with the passive control strategy (see EMISSIONS), there were no component or mechanical system breakdowns. The team used off-the-shelf components and attempted a load-leveling passive-control strategy. CSU, Fresno had a Suzuki 1.3-L, 4-cylinder, DOHC, 16-valve engine modified to run on ethanol (E95). The electrical side consisted of a Unique Mobility DC brushless motor and controller powered by Exide lead acid batteries [3].

SUMMARY

The results from the 1995 HEV Challenge document the performance of 29 student-built, prototype HEV designs. The week-long competition was designed to test a large number of vehicles under similar conditions to find the overall best-performing vehicle in each of the three classes and to gain insights into the technical potential of HEVs (see Attachment D for complete HEV Challenge Scoring Summary). The individual classes were developed to focus on a particular hybrid type or specific fuels or components (HVAC systems, CNG, or alcohol fuels).

Given the limited time and resources available to the teams of student engineers and the difficulty of the task they faced, the teams built vehicles that performed well. Although a long way from production, the prototypes showed the potential of HEVs to be energy-efficient future vehicles and yet perform like present production vehicles. The ability to capture braking energy is particularly important for improving the efficiency of future HEV designs, and virtually every school employed this technology.

As in past HEV Challenges, the schools were hampered by the lack of a well-developed heat engine in a size appropriate to their applications, and the difficulty in control system design. The challenge to design a control system that is sufficiently sophisticated to maximize the advantages of the hybrid drivetrain and yet minimize the losses in efficiency that can occur in these complex systems is formidable for professionals, let alone undergraduate engineering students. Although also constrained by available energy-storage technologies and the limitations of existing vehicle platforms, the schools fielded the best-performing and most reliable HEVs in the competition's history.

The three HEV Challenges represented the most ambitious and difficult engineering research competitions to date. Although they showed that HEV technology is still developing, these competitions set performance benchmarks and established testing procedures that will affect the engineering community far after the last event was completed.

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6. J.W. Hodgson, D. Birdwell, B. Bohannon, L. Bowers, T. DaCunha, W. Dickson, B. Green, B. Fraser, M. Hardin, Y. Isoda, "University of Tennessee 1995 Hybrid Electric Vehicle Design," Knoxville, TN, May 1995.

7. R. Riels and E. West, "Western Washington University 1995 HEV Challenge Vehicle," Bellingham, WA, May 1995.

8. C. Christianson, E. Harrison, J. Moore, S. Brennan, "LAKI, California State University, Chico Hybrid Electric Vehicle," Chico, CA, May 1995.

Table 7. 1995 HEV Challenge Vehicle Specification Summary

School	Car Number	Hybrid Configuration	Vehicle Wt. (kg)	Engine Manufacturer	Engine size (L)	Engine power (kW)	Fuel type	Tank Capacity (l)	Motor Manufacturer	Motor Type	Motor power cont. (kW)	Battery Manufacturer	Battery type	Battery pack wt. (kg.)	Battery pack voltage	Batt. pack capacity @ c/20 (kWh)	Generator	Charging efficiency (%)
[illegible]ort Class																		
California State University-Northridge	30	Series	1464.0	Kawasaki	1.00	16	RFG	47.3	Unique Mobility	DC Brushless	30.0	Teledyne	Pb-Acid	400.0	120.0	9.05	Uniq	N/A
Pennsylvania State University	1	Series	1702.4	Kawasaki	0.62	16	RFG	37.9	Solectria	AC Induction (2 motors)	38 each	Horizon	Pb-Acid	324.0	144.0	15.40	Uniq	90
U.S. Naval Academy	31	Series	1638.4	Kawasaki	0.62	16	RFG/CNG	48.3	GE	DC Series Wound	15.6	Horizon	Pb-Acid	275.0	120.0	15.40	Fisher	90
University of Alberta	8	Parallel	1617.3	Suzuki	0.99	41	RFG	28.6	Unique Mobility	DC Brushless PM (2 motors)	32 and 15.8	SAFT-NIFE	Ni-Cad	284.0	170.4	10.39	N/A	90
University of California, Irvine	7	Parallel	1724.8	Suzuki	1.00	41	RFG	46.9	Electrica Gear	AC Induction	11.2	Trojan	Pb-Acid	381.0	336.0	13.44	N/A	N/A
University of Wisconsin, Madison	34	Series	1712.1	Kohler	0.73	16	RFG	37.8	Lincoln Electric	AC Induction	18.3	Johnson Controls	Pb-Acid	354.0	384.0	8.02	Fisher	88
Wayne State University	15	Split Parallel	1800.0	Ford	1.90	67	RFG	45.4	GE	DC	24.0	Interstate	Pb-Acid	262.0	192.0	22.90	N/A	N/A
West Virginia University	28	Series	1675.8	Kawasaki	0.62	16	RFG	45.8	Adv DC	DC Series	15.0	GNB	Pb-Acid	300.0	120.0	13.20	Fisher	90
[illegible] Sedan Class																		
California State University, Chico	18	Series	1709.4	Kohler	0.75	19	E95	39.0	AC Propulsion	AC Induction	52.0	Ovonic	NiMH	459.0	343.0	31.56	Fisher	N/A
California State University, Fresno	38	Parallel	1438.8	Suzuki	1.30	75	E95	43.7	Unique Mobility	DC Brushless	32.0	Exide	Pb-Acid	143.0	180.0	6.79	N/A	N/A
Cedarville College	9	Series	1609.4	Honda	1.50	67	M85	48.2	Unique Mobility	DC Brushless PM	32.0	Exide/Napa	Pb-Acid	206.0	180.0	N/A	Sunstrand	N/A
Ecole de technologie superieure	3	Split Parallel	1447.4	Subaru	1.19	82	M85	48.5	Baldor	AC Brushless PM	16.0	Marathon	Ni-Cad	145.0	288.0	N/A	Baldor	N/A
GMI Engineering & Mgmt. Inst.	17	Series	1571.3	Kawasaki	0.63	15	E95	50.0	Magnetek	AC Induction	22.0	Hawker Energy	Pb-Acid	150.0	300.0	3.70	Fisher	N/A
Illinois Institue of Technology	41	Parallel	1657.5	Suzuki	0.99	37	E95	50.0	GE	DC Shunt	20.1	Exide	Pb-Acid	267.0	120.0	7.26	NA	N/A
University of Maryland	24	Parallel	1527.3	Geo/Suzuki	0.99	45	M85	56.0	Unique Mobility	DC Brushless	13.0	SAFT-NIFE	Ni-Cad	142.0	154.8	3.25	NA	N/A
University of Texas, Austin	2	Parallel	1404.3	BMW	0.75	56	M85	57.0	Unique Mobility	DC Brushless PM	32.0	Union Batt.	Pb-Acid	154.5	132.0	5.28	NA	N/A
University of Western Ontario	22	Parallel	1501.9	Honda	1.30	45	E95	50.0	Solectria	DC Brushless PM	24.0	Hawker energy	Pb-Acid	120.0	144.0	3.74	NA	N/A
Wentworth Institute of Technology	26	Parallel	1754.8	Suzuki	0.99	73	M85	45.5	Solectria	AC Induction	14.0	Johnson Controls	Pb-Acid	299.0	144.0	N/A	Bendix	N/A
[illegible] Neon Class																		
Concordia University	11	Parallel	1477.4	BMW	0.74	56	CNG	22.0	Adv. DC	DC Series	7.5	East Penn	Pb-Acid	114.3	96.0	5.00	N/A	N/A
Texas A&M University	5	Parallel	1737.7	Honda	0.50	30	CNG	61.0	Adv.DC	DCSeries, Shunt Brush	16.3	Horizon	Pb-Acid	270.0	120.0	15.40	N/A	N/A
Texas Tech University	29	Parallel	1575.6	Chrysler	2.00	104	CNG	64 ea (2 tanks)	Unique Mobility	DC Brushless	15.8	Power Sonic	Pb-Acid	113.0	180.0	3.15	N/A	92
University of Connecticut	23	Parallel	1658.4	Chrysler	2.00	98	CNG	64.0	GE	DC Shunt	20.1	Eagle Picher	Pb-Acid	181.4	120.0	N/A	N/A	92
University of Florida	19	Series	1679.5	Kawasaki	0.62	15	CNG	9.0	Unique Mobility	DC Brushless	32.0	SAFT-NIFE	Ni-Cad	295.0	180.0	8.10	Fisher	97
University of Illinois, Chicago	20	Parallel	1628.2	Diahatsu	0.85	N/A	CNG	72.1	Adv.DC	DC Series	21.5	Exide	Pb-Acid	205.0	144.0	6.62	N/A	N/A
University of Michigan, Ann Arbor	12	Series	1506.9	Kawasaki	0.62	15	CNG	80.0	Unique Mobility	DC Brushless, PM	32.0	Johnson Controls	Pb-Acid	192.0	180.0	5.18	Fisher	N/A
University of Tennessee, Knoxville	21	Parallel	1496.0	Suzuki/Geo	1.00	37	CNG	75.6	Unique Mobility	DC Brushless, PM	32.0	Exide	Pb-Acid	145.0	192.0	4.16	N/A	98
University of Texas, El Paso	37	Series	1654.3	Geo/Suzuki	1.00	37	CNG	49.7	AC Prop	AC Induction	84.0	Concorde Batt. Corp.	Pb-Acid	293.0	336.0	11.09	Fisher	80
Virginia Tech	27	Series	1601.9	Suzuki	1.00	41	CNG	26.5	GE	AC Induction	60.0	Hawker Energy	Pb-Acid	135.0	312.0	3.70	Fisher	96
Western Washington University	25	Parallel	1576.5	Chrysler	2.00	90	CNG	80.0	Unique Mobility	DC Brushless	32.0	SAFT-NIFE	Ni-Cad	144.0	172.8	5.50	N/A	80

ATTACHMENT B

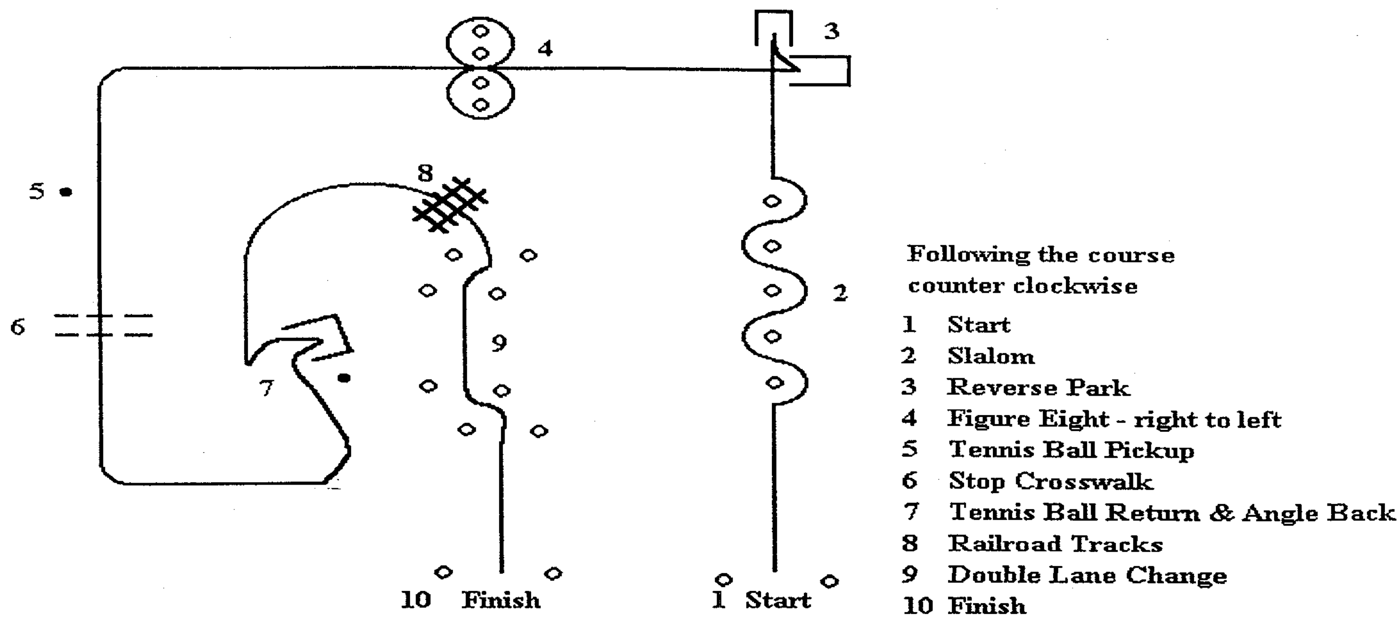

Figure 5. Diagram of a Proposed Handling Course

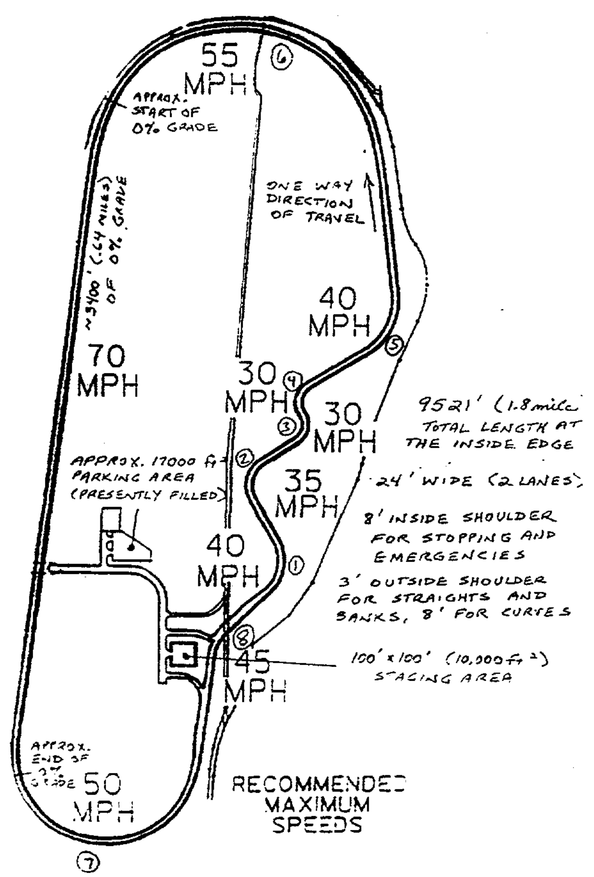

Figure 6. Chrysler Tech. Center's Vehicle Evaluation Road

ATTACHMENT C

1995 HEV Challenge
Consumer Acceptability Event - Dynamic
Neon Class

School ______________________________ Vehicle # ________

Judge ______________________________

Vehicle Ride/Drive Evaluation

Vehicle	<-- poor								excellent-->
Handling	1	-	2	-	3	-	4	-	5
Directional Stability	1	-	2	-	3	-	4	-	5
Manuevering/Parking	1	-	2	-	3	-	4	-	5
Brake Feel/Effectiveness	1	-	2	-	3	-	4	-	5
Road Noise	1	-	2	-	3	-	4	-	5
Driver Control Position	1	-	2	-	3	-	4	-	5

Powertrain	<-- poor								excellent-->
Performance Feel, Responsiveness	1	-	2	-	3	-	4	-	5
Transaxle Operation	1	-	2	-	3	-	4	-	5
Powertrain Noise	1	-	2	-	3	-	4	-	5

Driveability	<-- poor								excellent-->
Ease of Starting	1	-	2	-	3	-	4	-	5
Idle Noise, Roughness	1	-	2	-	3	-	4	-	5
No Hesitation/Sag	1	-	2	-	3	-	4	-	5
Shut Down Characteristics	1	-	2	-	3	-	4	-	5
Response to Full Steering Turn	1	-	2	-	3	-	4	-	5
Response to AC On/Off, where applicable	1	-	2	-	3	-	4	-	5

BONUS POINTS (Judge's discretionary points) 0 1 2 3 4 5 6 7 8 9 10 11 12

Total Points __________/87

Please provide any scoring comments below:

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ATTACHMENT D

Table 7. 1995 HEV Challenge Summary of Final Scores

School Name	Car #	HVAC Event	Acceleration Event	Cons. Accp. Event	Emissions Event	Eng. Design Review	Range Events	Dynamic Performance	Economy Event	Technical Report	Total Score	Place
Available Points		200	100	100	200	100	150	100	150	100		
Ford Escort Class												
University of Alberta	8		97.7	61.5	137.1	76.9	150.0	83.4	145.2	96.1	848.0	1
Wayne State University	15		78.3	28.6	200.0	20.0	120.4	89.2	150.0	77.0	763.5	2
University of Wisconsin, Madison	34		71.7	100.0	45.7	100.0	109.5	100.0	120.0	100.0	746.9	3
West Virginia University	28		58.3	26.5	85.7	59.3	30.0	79.6	120.1	61.3	520.8	4
United States Naval Academy	31		75.8	44.6	45.7	61.6	39.4	72.9	111.3	59.5	510.7	5
Pennsylvania State University	1		70.2	35.1	40.0	91.4	36.2	82.9	30.0	75.2	461.2	6
University of California, Irvine	7		20.0	20.0	40.0	30.4	131.3	20.0	141.8	27.9	431.4	7
California State University, Northridge	30		0.0	0.0	0.0	29.9	0.0	0.0	0.0	20.0	49.9	8
Colorado School of Mines	10		0.0	0.0	0.0	0.0	0.0	0.0	0.0	43.3	43.3	9
Neon Class												
University of Tennessee	21	86.6	85.3	82.5	200.0	100.0	111.2	87.6	115.2	100.0	968.4	1
Texas Tech University	29	80.0	100.0	91.6	100.0	70.6	142.9	100.0	150.0	66.8	901.9	2
Western Washington University	25	182.4	99.3	100.0	52.0	76.9	150.0	74.4	30.0	68.4	833.3	3
University of Florida	19	135.1	76.4	76.7	0.0	61.0	0.0	78.2	0.0	68.1	495.5	4
Virginia Polytechnic Institute	27	89.1	90.1	70.8	0.0	83.6	0.0	47.0	0.0	97.6	478.3	5
University of Michigan, Ann Arbor	12	176.5	20.0	21.2	0.0	77.3	30.0	0.0	0.0	94.2	419.3	6
University of Illinois, Chicago	20	0.0	84.4	74.4	0.0	33.0	42.4	0.0	0.0	83.7	317.8	7
Texas A&M University	5	0.0	85.3	59.5	0.0	29.2	49.4	54.7	0.0	20.0	298.1	8
University of Connecticut	23	0.0	44.1	76.5	0.0	20.0	0.0	20.0	0.0	52.6	213.2	9
Concordia University	11	0.0	0.0	20.0	0.0	74.9	0.0	0.0	0.0	84.5	179.4	10
University of Texas, El Paso	37	0.0	0.0	0.0	0.0	38.8	0.0	0.0	0.0	58.7	97.5	11
Saturn Class												
California State University, Fresno	38		92.1	97.1	200.0	65.5	150.0	100.0	91.8	55.2	851.7	1
Ecole de Technologie Superieure	3		97.7	100.0	98.2	77.6	30.0	87.0	150.0	88.7	729.2	2
California State University, Chico	18		95.0	96.9	69.1	68.3	112.1	93.1	110.8	70.6	715.9	2
University of Western Ontario	22		20.0	91.4	40.0	87.3	130.5	20.0	30.0	76.6	495.9	4
University of Texas, Austin	2		60.9	30.1	40.0	100.0	0.0	0.0	108.9	100.0	439.9	5
GMI Engineering & Management Institute	17		71.0	73.8	40.0	24.6	43.5	83.5	68.1	34.5	439.0	6
Illinois Institute of Technology	41		80.6	20.0	200.0	20.0	0.0	20.5	51.4	30.2	422.7	7
Wentworth Institute of Technology	26		71.0	79.6	0.0	34.4	46.7	81.0	0.0	55.8	368.5	8
University of Maryland	24		0.0	29.9	0.0	75.3	0.0	0.0	0.0	84.8	189.9	9
Cedarville College	9		0.0	24.0	0.0	58.6	0.0	0.0	0.0	78.2	160.7	10
Alfred University	36		0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	20.0	11