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Current Hybrid Electric Vehicle Performance Based on Temporal Data from the World's Largest HEV Fleet

Keith Wipke

Prepared for the 12th International Electric Vehicle Symposium, Anaheim, California, December 5-7, 1994

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NOTICE

CURRENT HYBRID ELECTRIC VEHICLE PERFORMANCE BASED ON TEMPORAL DATA FROM THE WORLD'S LARGEST HEV FLEET

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Abstract

The United States Department of Energy (DOE) procured new data collection equipment for the 42 vehicles registered to compete in the 1994 Hybrid Electric Vehicle (HEV) Challenge, increasing the amount of information gathered from the world's largest fleet of HEVs. Data were collected through an on-board data storage device and then analyzed to determine effects of different hybrid control strategies on energy efficiency and driving performance. In this paper, the results of parallel hybrids versus series hybrids with respect to energy usage and acceleration performance are examined, and the efficiency and performance of the power-assist types are compared to that of the range-extender types. Because on-board and off-board electrical charging performance is critical to an efficient vehicle energy usage cycle, charging performance is presented and changes and improvements from the 1993 HEV Challenge are discussed. Peak power used during acceleration is presented and then compared to the electric motor manufacturer ratings. Improvements in data acquisition methods for the 1995 HEV Challenge are recommended.

Introduction

The 1994 HEV Challenge was a collegiate competition held at the Lawrence Technological University in Southfield, Michigan, June 14-20. The week-long competition and the year of vehicle preparation involved 42 schools from the United States and Canada. The HEV Challenge began in 1993 with a total of 30 vehicles in two classes: 12 vehicles that were built from the ground up (Ground-Up Class) and 18 converted 1992 Ford Escort station wagons (Escort Conversion Class). The 1994 HEV Challenge included a new class--the Saturn Conversion Class--which added 12 new schools to the 28 returning schools. The HEV Challenge involved a series of competitive events, including: emissions testing, technical papers, design review presentations, acceleration, range, road rally, energy economy, and a timed performance test. Figure 1 shows the University of Texas, Austin during the timed performance test. Before any of the teams could compete in the dynamic events, they had to pass rigorous safety inspections and dynamic qualifying, including acceleration, braking, U-turn, slalom, and a figure-8.

Figure 1
The University of Texas, Austin HEV During Commuter Challenge Event

The mission of the HEV Challenge is to provide future engineers with exceptional educational opportunities to design, build, and test "real-world" hybrid electric vehicles. The students' goal is to develop innovative and environmentally responsible vehicles that combine electric and thermal power to improve mileage and reduce emissions while maintaining performance comparable to conventional vehicles. To document the performance improvements in the vehicles and facilitate scoring of the energy efficiency events, on-board data acquisition hardware was provided to each school and data were collected after each event in both the 1993 and 1994 HEV Challenges. A detailed analysis of all electric energy usage data from the 1993 HEV Challenge and other advanced vehicle competitions was completed; the analysis verified the expected effects of mass, speed, and distance on energy usage.[1] Because of the more advanced data acquisition system (DAS) used in the 1994 HEV Challenge, additional data were collected that allowed a more detailed understanding of each individual vehicle.

Data Acquisition Systems Employed

Back-up System from 1993

The data acquisition system used in 1993 was an energy meter from Cruising Equipment that measured voltage, current, and time, and then integrated the power over time to calculate the net energy (kWh) used from the main battery pack.[2,3] A serial port could print out the voltage and current every second, but it required a laptop to record data for the duration of the event. Because 30 laptop computers were not available, no temporal data were collected during the 1993 competition. This system was already installed in three-fourths of the vehicles and was kept in the vehicles for the 1994 Challenge as a back-up energy meter.

1994 Data Acquisition System

The primary DAS used in the 1994 HEV Challenge was called the Autologger, designed by Instrumental Solutions.[4] A competitive procurement process was used to evaluate and select the DAS for the 1994 HEV Challenge. The Autologger had the following features:

- Four analog channels measured: two currents and two voltages.
- Optical isolation from high voltage on all four analog channels.
- Measurement of distance and velocity.
- Monitoring of auxiliary power unit (APU) on/off activity.
- 128K of on-board memory to store 1-second averages of all channels sampled, resulting in 6 hours of continuous second-by-second data storage.
- High sampling rate of 2500 Hz.
- Intelligence to collect data only when the vehicle was "keyed-on."
- Ability to download a summary of the energy data and a complete second-by-second log of all of the data stored in memory.

Difficulties encountered with new DAS

A number of problems were encountered with both the new DAS hardware and the way the students installed and wired the DASs in their vehicles that prevented complete data from being collected from all of the schools. First, not all of the schools had their hardware wired correctly, with one common problem being the APU on/off activity channel. Second, the DASs were often mounted in electrically and magnetically "noisy" locations under the hood, which might have been solved prior to the competition if the students had more time for their own testing. Finally, the on-board software occasionally got corrupted on ignition "key-on," causing some data to be lost by altering the program memory.

All temporal data results presented here will be based only on the data that has been determined to be reasonable, which comprises data from 19 schools. One major advantage of the new DAS is that it allows this type of determination to be made by plotting the second-by-second voltages, currents, speeds, and APU activity, making clear which schools had noise problems or incomplete data. Prior to the 1994 HEV Challenge, all HEV and electric vehicle (EV) competition energy data were "black box" data making it difficult to determine its reasonableness.

HEV Performance Analysis

Types of Drivetrains and HEV Control Strategies

Parallel and Series Drivetrains. There were three main types of hybrid vehicle drives used in the 1994 Challenge: parallel, series, and drives that could be switched between series and parallel. Parallel drive vehicles have a direct mechanical connection between the APU and the wheels, such as a transmission. Series vehicles have no such mechanical connection, with all motive power being transferred electrically to an electric motor that drives the wheels. The vehicles that had a switchable series/parallel configuration could take advantage of the load-leveling properties of a series configuration during low-speed stop-and-go city driving and use the highly efficient parallel drive configuration at higher speeds with a more constant load.[5]

Power-assist and Range-extender. A large number of titles are assigned to hybrid vehicles based on their APU and battery pack size and power ratings, but discussion here will be limited to power-assist and range-extender vehicles. Range-extender vehicles are so named because they are essentially electric vehicles that have on-board charging capability to extend the electric-only, or zero-emission vehicle (ZEV) driving range. Power-assist vehicles are on the other side of the spectrum, with the internal combustion engine (ICE) providing most of the power and range and the electric portion of the vehicle serving to "assist" the ICE during hill climbs and accelerations. The electric energy storage (normally batteries) also serves as an energy buffer to capture extra energy from the ICE and from regenerative braking. Included in the competition rules for each class are requirements that steer each class toward a different type of hybrid. The Ground-Up and Escort Conversion vehicles from the 1993 Challenge were encouraged to be range-extender vehicles with a 64.4 km ZEV range and 241.5 km total range. The Saturn Conversion vehicles added in the 1994 Challenge were encouraged to be power-assist vehicles by reducing their required ZEV range to 8.05 km, increasing the required acceleration performance, and increasing the HEV range to 483 km.

Acceleration Event

The acceleration event was held in the morning of the same day that the range event was held, at the GM Milford Proving Ground on a 3.2 km level straightaway. The event provided an opportunity to see the actual acceleration velocity profiles for the first time in the history of the engineering research competitions. Because voltage and current were also being measured, the peak powers used by the electric drives during the acceleration runs were also available. Timing lights were used at the start and finish of a 0.20 km section. Figure 2 shows a compilation of the acceleration profiles for all the vehicles for which calibrated velocity data were collected. Some of the schools did not get their vehicle running until just prior to the beginning of the events, preventing speed calibrations to be done on their vehicles. The thick black curves in Figure 2 represent an envelope that encloses all of the acceleration profiles. The thinner solid curves represent parallel drive vehicles and the dashed curves represent the series drive vehicles. Vehicles that could switch between the two were assumed to be operating in parallel mode, which would most likely have the highest power. Unfortunately, only two series vehicles had calibrated acceleration profile data, but it is interesting to note that they are beaten out only by one vehicle, the parallel configured UC Santa Barbara.

Comparing the official 0.20 km times from the acceleration event reveals a characteristic power difference between series and parallel vehicles. The range-extender vehicle acceleration times were compared for series and parallel vehicles in both HEV and ZEV modes, with the power-assist vehicles not included because they only ran in HEV mode. In HEV mode, the average acceleration times for the series vehicles was 17.0 seconds and 15.5 seconds for the parallel vehicles, while in ZEV mode the series vehicles had an average acceleration time of 15.3 seconds compared to 17.3 seconds for the parallel vehicles. This shows that in ZEV mode, the series vehicles accelerate faster because their electric motors are sized appropriately for the maximum acceleration power, whereas the parallel vehicles have a smaller electric motor that was sized with the anticipation of combining it with mechanical power from the APU. This agrees with the general electric motor sizing reported by Burke, who reveals that parallel drives only need the electric drive to provide 40% of the peak power.[6]

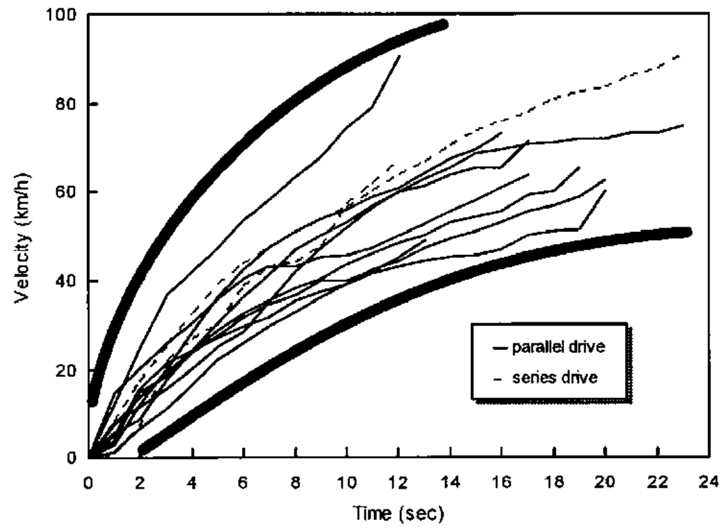

Figure 2
Acceleration Velocity Profile Comparison

Another piece of information that can be extracted from the 1994 HEV Challenge data that could not be determined in any other competition was the peak electrical power draw from each vehicle during the acceleration runs (see Table 1).

Table 1
Peak Electric Power During Acceleration: Rating vs. Measured

School	Rated Peak Power (kW)	Measured Peak Power Run 1 (kW)	Measured Peak Power Run 2 (kW)	Percent Over Reported Peak Power Rating
Cal Poly Pomona	33.6	39.9	27.9	18.8
Cal Poly SLO	18	18.6	--	3.3
Jordan College	n/a	30.5	29.1	n/a
Lawrence Tech	31.3	36.4	28.8	16.3
NYIT	n/a	27.2	27.8	n/a
U. of Maryland	13	36.9	43.5	234.6
UC Davis	45	38.5	41.8	-7.1
Weber State	37.3	31.9	29.5	14.5
Washington, S.L.	59.7	15.8	--	-73.5

The acceleration peak powers shown in Table 1 are representative of the overall peak power of their electrical drives, because the vehicles were pushed to their limits during this event. To gain some insight into how well the electric motors were rated on their peak power and to check the reasonableness of the measured values, the actual peak power can be compared to the rated peak power (as reported by the schools). Table 1 shows the peak power from the first two acceleration runs and that most schools' measured peak power was within plus or minus 10-15% of their rated peak power. Washington University, St. Louis, and the University of Maryland had measured peak powers that were different by up to a factor of four from the manufacturer's rating. Further investigation would be required to determine why there was such a large difference. As an example of the temporal data collected during the acceleration event, Figure 3 shows the acceleration profile (and return trip) for Lawrence Technological University. Notice how as a load is applied to the batteries the voltage drops, and as the vehicle slows down and energy is recaptured from regenerative braking, the current switches polarity and the voltage increases.

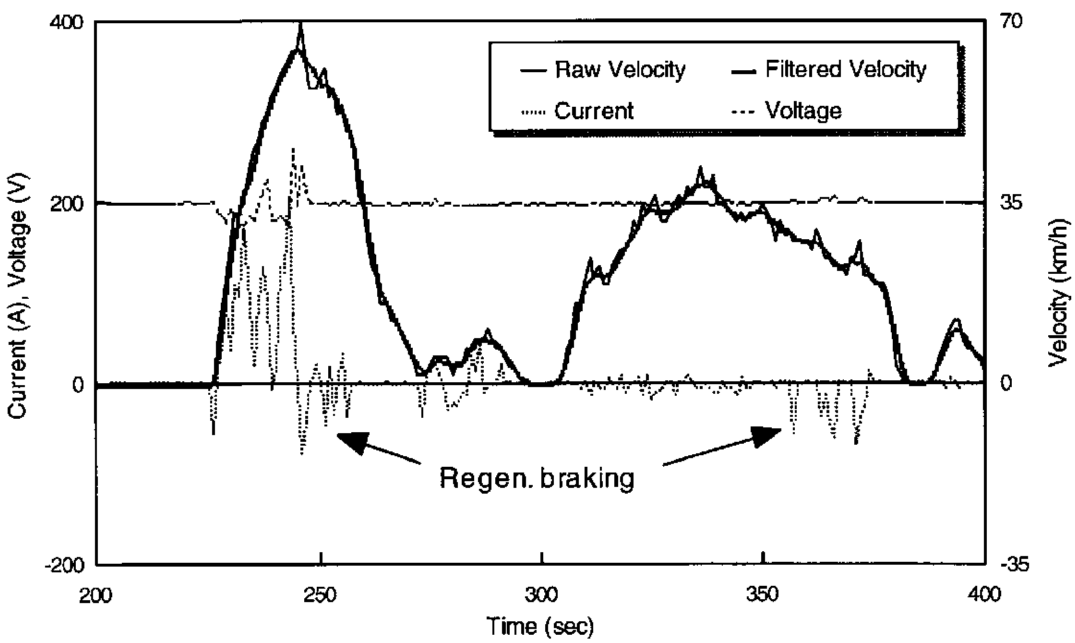

Figure 3
Temporal Acceleration Data from Lawrence Technological University

Range Event

The range event, which was a 3 hour and 20 minute timed event around the 3.42 km track at GM's Milford Proving Ground was useful for collecting energy usage data and looking at the hybrid control strategies employed by the schools. One of the benefits of the new DAS is that it enables the instantaneous electrical power usage to be calculated for any part of a recorded trip, however, the steep grades in the course used for the 1994 Challenge range event did not allow a constant driving load condition to be established (see Figure 4). The organizers of the 1995 HEV Challenge will try to hold the range event on a level track, with at least a few laps at several predetermined speeds to allow the power requirements and energy usage of each vehicle to be compared. A power analysis with parallel hybrids is difficult because the APU power is difficult to measure, suggesting that the constant road load test be run in ZEV mode for those vehicles. The differences in the driving conditions between 1993 and 1994 (track, speeds, temperature) are great enough that no comparisons between the two years will be attempted. Specific analysis of the cycling on and off of the APUs was not possible for two reasons: 1) many vehicles did not have this wiring hooked up correctly or at all, and 2) the hill was large enough that most vehicles ran the range event with their APU on the entire time. For further examination of the effect of heat engine on/off operation, refer to simulation results obtained at the Idaho National Engineering Laboratory (INEL).[7]

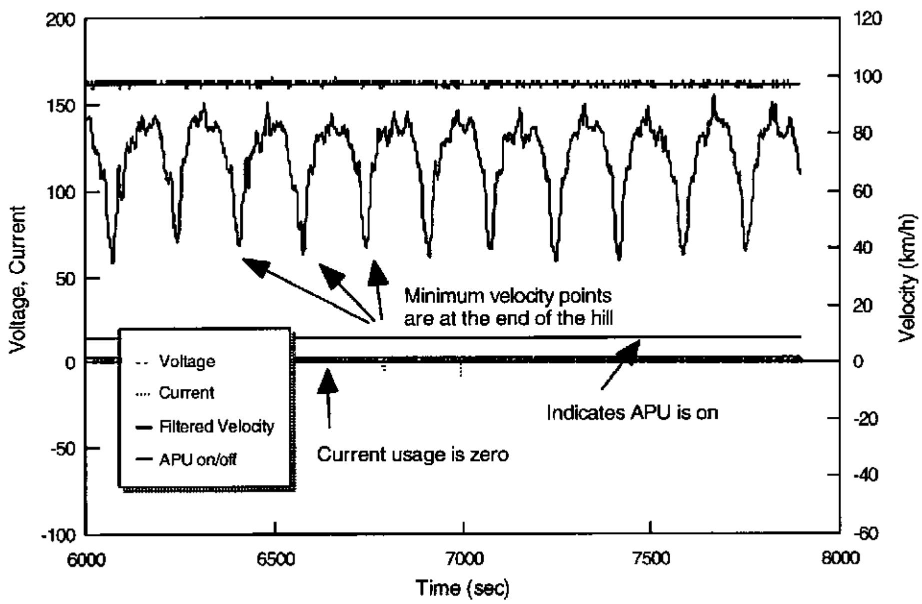

Figure 4
Temporal Data from University of Maryland During Range Event

Energy usage data was collected during the range event to allow comparisons to be made between the vehicles. Because complete electrical energy usage data were not collected from all vehicles with the Instrumental Solutions hardware, the relatively complete data set from the back-up system was used so that comparisons could be made between the different types and drivetrains of the vehicles. The way that the energy economy was determined was by taking the distance traveled in the range event divided by the total energy used, being made up of both fuel energy and electrical energy. To focus on the vehicle performance, the vehicles have been analyzed without including the effect of their charging efficiency, which will be done independently of vehicle performance in the next section.

Comparing the average energy economy of the power-assist HEVs with the range-extender HEVs shows the range-extender vehicles being 45.8% more efficient (2.45 km/kWh vs. 1.68 km/kWh) than the power-assist HEVs. There are a number of factors that contributed to this result: 1) The range-extender vehicles on average used a larger portion of their energy as electric energy from their batteries (20% electric for the range-extenders compared to 4% for the power-assist vehicles), avoiding the thermal energy conversion losses in converting fuel to useful power. 2) The range-extender vehicles were competing for the second time, and had a year and a half longer than the power-assist schools to optimize their vehicles. 3) All power-assist vehicles were required to run on either methanol (M85) or ethanol (E95) blends of fuel, adding to the challenge of an efficient vehicle conversion. See Figure 5 for a comparison between the power-assist and range-extender HEVs. The bars show the energy economy in km/kWh, and the diamonds indicate the percentage of the total energy used that came from the batteries. Notice that the two vehicles whose energy usage was greater than 90% from their batteries had a high energy economy, as would be expected because the thermal energy conversion has already taken place independent of the vehicle's power system (in this case, at a powerplant). However, these two vehicles did not drive as far in the event as the other vehicles, and therefore would not be able to sustain their high energy economy for very long. A more complete energy comparison might include electrical powerplant losses and energy expended during fuel refining. Note that there has been no state-of-charge (SOC) correction performed on this energy usage data, as would be done during the standard emissions test procedure being developed by a Society of Automotive Engineers (SAE) committee. The effect of an SOC correction would be to increase the effective fuel required to return the batteries to the same SOC. This effect would be small except for the few vehicles with a large percentage of the energy coming from electricity.

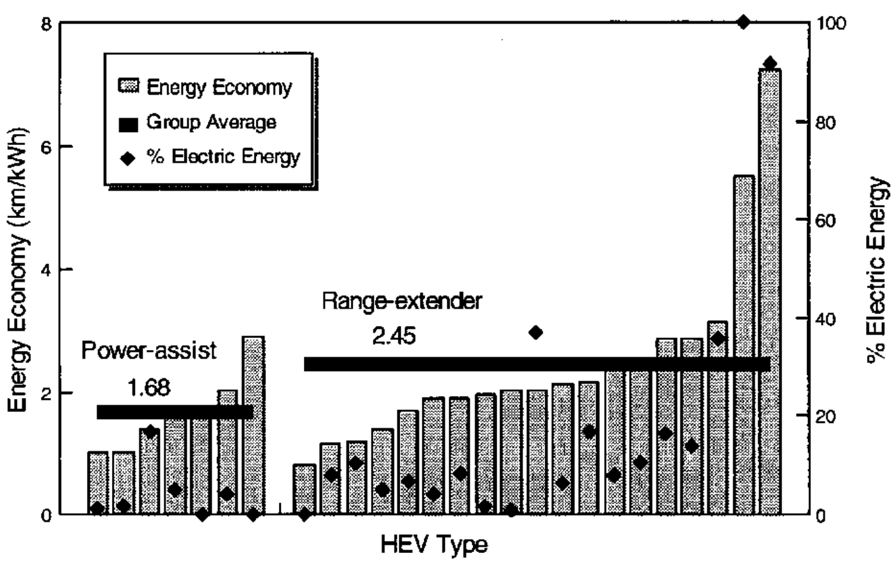

Figure 5
Power-Assist and Range-Extender Comparison for Range Event

Another distinguishing characteristic of HEVs is the drivetrain type--parallel or series. Based on the average energy economy of the vehicles competing in the range event in the 1994 HEV Challenge, the data collected show the series hybrids to be 27% more efficient than the parallel hybrids. The average energy economy was 1.96 km/kWh for the parallel vehicles and 2.49 km/kWh for the series vehicles. One of the main contributors to this could be the nature of the track used for the event and the minimum driving speeds required. Because there were no stops or starts during the event (except for driver changes every half hour) and because of the hill, the event may have favored series vehicles which could more easily do APU load-leveling by recapturing the energy from downhill braking and applying it to the hills. The advantages of the simpler, more robust series design require fewer student designed mechanical parts and less actual road testing of the vehicle (more of it can be done in the lab). Figure 6 shows a comparison between the parallel and series vehicles during the range event.

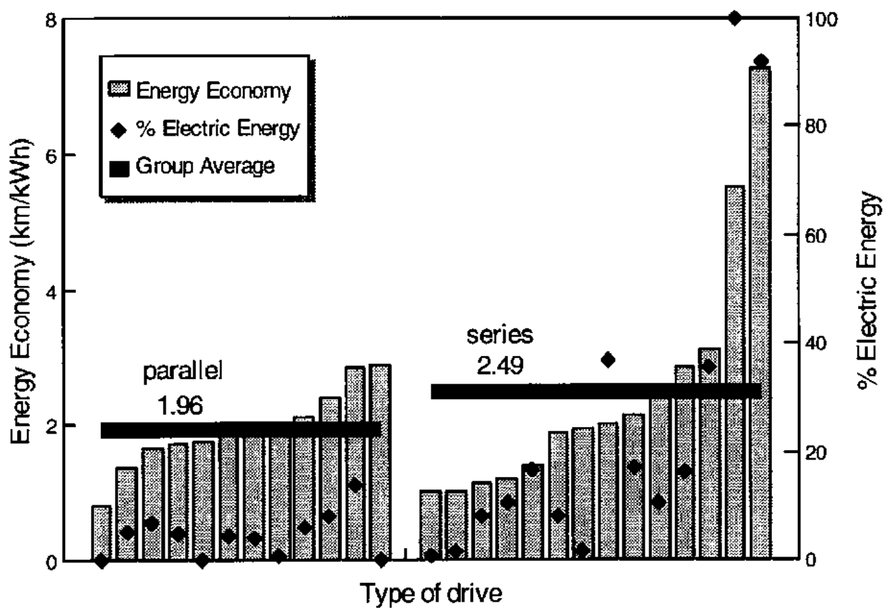

Figure 6
Parallel and Series Drivetrain Comparison for Range Event

Electrical Charging Efficiency

As was done in the 1993 HEV Challenge, Detroit Edison provided electrical charging stations for recharging the batteries of the hybrid vehicles in the 1994 HEV Challenge. The charging efficiency was calculated as the ratio of DC energy that flowed into the negative side of the main battery pack through a DC watt-meter, divided by the AC line energy that flowed through a standard house analog energy meter. Thus, the charging efficiency is always less than 100% with the system being more efficient the closer the value is to 100%. Table 2 shows the charging efficiency for the eight vehicles for which charging data were available in both 1993 and 1994. The values given represent the best out of five possible nights for charging. The data show that in seven out of the eight cases the schools were able to significantly increase their charging efficiency. The average charging efficiency for these four Escort Conversions increased 52.5%, and it increased 39.9% for the four Ground-Up vehicles. This is probably because three out of these four Ground-Up teams built completely new vehicles and had a lot of other issues to focus on, while the Escort Conversion teams were able to focus on fine tuning their existing vehicle.

All of the vehicles for which charging efficiencies were measured were then averaged together as a fleet in both 1993 and 1994 and then compared in the bottom of Table 2. This data shows that better methods were used for collecting data in 1993 than 1994 because the number of schools providing good data almost doubled, excluding the Saturn vehicles, which did not have off-board charging. The increase in the amount of charging efficiency data was due in part to the fact that all vehicles were impounded every night for charging, even if the teams still had work they wanted to do on their vehicle. This removed the incentive to not charge and get more time to work on their vehicle. The fleet charging efficiencies in Table 2 show, more importantly, that the average fleet charging efficiency increased from 56% to 78% in one year, producing an increase of 39% from the 1993 values. The significance of this can not be understated because for range-extender vehicles the overall km/L equivalent fuel economy depends in large part on how much electrical energy is used. This has even more significance for pure electric vehicles for which the charging efficiency more directly impacts their overall equivalent fuel economy.

Table 2
Vehicle Charging Efficiency Comparison

Escort Conversions	**1993**	**1994**	**Increase**
Colorado School of Mines	0.45	0.82	80.4%
Stanford University	0.68	0.80	18.4%
University of Illinois	0.40	0.68	72.0%
Weber State University	0.60	0.83	39.4%
Average	**0.53**	**0.78**	**52.5%**
Ground-Up Class			
Cal. Poly, San Luis Obispo	0.83	0.68	-17.7%
Cornell University	0.60	0.87	45.3%
Lawrence Technological University	0.34	0.44	28.9%
University of California, Davis	0.46	0.94	103.0%
Average	**0.56**	**0.73**	**39.9%**
Overall HEV Fleet Charging Efficiency			
Number of Vehicles With Charging Data	12	23	91.6%
Average Charging Efficiency	0.56	0.78	**39.3%**

Suggestions for 1995 DAS

With a new class of vehicles, the Neon Conversion Class, being added to the 1995 HEV Challenge and the potential for 30 returning schools, the competition data collection can be improved to ease the scoring of the event as well as getting good data for research purposes. A simple, reliable energy meter is required that can provide the data needed for scoring the energy economy event. A more sophisticated DAS is needed for a limited number of schools to look at the APU on/off cycling frequency, the power output from the generator on series vehicles, and other temporally dependent parameters. This detailed data provides the support for code validation efforts already underway with the 1994 HEV Challenge data. An added feature to the advanced DAS would be to manually control when data is being collected and stored because the ignition "key-on" provided only limited control of when data was collected.

Conclusions

Data was collected from the world's largest fleet of HEVs during the 1994 Hybrid Electric Vehicle Challenge using a new DAS with on-board data storage. The data were analyzed to determine the effects of different hybrid control strategies on energy efficiency and driving performance. During the range event, the range-extender vehicles were found to be 45.8% more efficient than the power assist vehicles, and the series vehicles were 27% more efficient than the parallel vehicles. The temporal data were used to calculate peak powers during the acceleration event, and it was found to be within 10-15% of the manufacturer's ratings for most vehicles. Charging efficiency data were collected and compared to the 1993 HEV Challenge charging data to reveal an increase of 39% in the average charging efficiencies from 1993 to 1994. The data collected during the 1995 HEV Challenge can be improved by simplifying the data collection performed on all vehicles and doing more sophisticated data collection on a limited number of vehicles.

Acknowledgments

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