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# TESTING HYBRID ELECTRIC VEHICLE EMISSIONS AND FUEL ECONOMY AT THE 1994 HYBRID ELECTRIC VEHICLE CHALLENGE

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## ABSTRACT

From June 12-20, 1994, an engineering design competition called the 1994 Hybrid Electric Vehicle (HEV) Challenge was held in Southfield, Michigan. This collegiate-level competition, which involved 36 colleges and universities from across North America, challenged the teams to build a superior HEV. One component of this comprehensive competition was the emissions event. Special HEV testing procedures were developed for the competition to find vehicle emissions and correct for battery state-of-charge while fitting into event time constraints. Although there were some problems with a newly-developed data acquisition system, we were able to get a full profile of the best performing vehicles as well as other vehicles that represent typical levels of performance from the rest of the field. This paper will explain the novel test procedures, present the emissions and fuel economy results, and provide analysis of second-by-second data for several vehicles.

## INTRODUCTION

The Hybrid Electric Vehicle (HEV) Challenge, sponsored by the U.S. Department of Energy (DOE), is a collegiate-level engineering design competition that involved 36 universities and colleges from across North America. The winner is found through a comprehensive test of the student-built HEVs in the areas of efficiency, performance, range, design, and emissions.

The HEV Challenge in 1993 was hosted by Ford Motor Company. In 1994, the automotive sponsor was the Saturn Corporation. Three separately competing classes made up the field in 1994. 1993 competitors from the Ford conversion class and the Ground-Up class were back again to compete. Added for 1994 was the Saturn conversion class.

Teams take a new production vehicle, or fabricate a ground-up vehicle, and add batteries, electric motors and controllers and, in most cases, a different internal combustion engine. The challenge is to make them all work together harmoniously to provide gains in fuel efficiency and reduce emissions while maintaining vehicle performance and utility. The HEV also adds the capability of driving with zero emissions (ZEV mode). The Ford class converted production Ford Escort wagons and the Saturn class converted SL2 sedans to HEV operation. Members of the Ground-up class hand-built their own unique hybrid vehicles.

The Ford and Ground-up classes had similar requirements; they needed to demonstrate at least a 25-mile range at 45 mph (72 km/h) driving in ZEV mode. The Saturn class could not charge from the wall and was only required to demonstrate 5 miles of range in ZEV mode at 30 mph (48 km/h).

The emissions event was held June 11-13, 1994, at three separate vehicle emissions testing facilities; one for each class. This was the first event at the 1994 HEV Challenge and proved to be the best event to collect comparable test data from the HEVs.

## EMISSIONS EVENT GOALS

Vehicle exhaust emissions are very important to a vehicle designer because, before any passenger vehicle can be sold, it must pass the appropriate emissions standards. Because one of the anticipated benefits of HEV technology is reduction of emissions compared with conventional vehicles, this characteristic was given a high level of importance for the competition. Two hundred of the competition's 1,000 total points were based on emissions test results. The challenge for the schools to achieve low emissions with their HEVs was matched by the organizers' challenge to provide a concise, accurate, and equitable test procedure for their HEVs. An added dimension in measurement and testing was introduced with the contribution of the electric drivetrain. Although there are definite challenges in testing HEVs for emissions (and fuel economy), a new HEV Challenge emissions test procedure was desired for a good competition event and excellent data collection.

In the 1993 HEV Challenge, held at Ford Motor Company facilities in Dearborn, Michigan, the emissions event was based on tailpipe emissions collected during a hot 505 cycle after battery depletion miles were accumulated in ZEV mode. While this can give some relative comparison

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among vehicles, the data do not enable comparisons with conventional tests and do not fully address battery state-of-charge issues. It was decided by the organizers that a cold-start emissions test procedure should be employed for the 1994 competition that included an Federal Test Procedure (FTP) emissions test that would account for battery SOC differences.

To date, formalized HEV test methods exist only in various draft forms. The California Air Resources Board (CARB), the Society of Automotive Engineers (SAE) HEV Test Procedure Task Force, and each automobile company has its own idea about HEV testing procedures. The exact methodology is a controversial and political issue because differences in the test procedures could greatly affect how HEVs compare with conventional vehicles.

Although there was a definite need for a comprehensive test, the overriding factors that influenced the emissions event at the 1994 HEV Challenge were time and facilities. The draft SAE HEV procedure described a test that could last as long as five (5) days. Limited, donated dynamometer time dictated a short, concise testing procedure. The organizers had to balance the comprehensiveness of the testing with the available facilities and time.

Issues such as ZEV range affecting vehicle life cycle emissions and charging habits were ignored for the Challenge test procedures. The procedures used for the HEV Challenge emissions event were based on the SOC correction concepts proposed by members of the SAE HEV Test Procedure Task Force. SOC corrections are made to emissions test results, thus eliminating the net contribution of the battery energy. Extrapolation of the emissions results can predict emissions with zero SOC differences by careful monitoring of the battery during the test cycles.

FORD AND GROUND-UP CLASSES - The Ford and Ground-Up classes were tested a few days ahead of the competition at Ford's Certification Test Laboratory in Dearborn, Michigan and Chrysler's Highland Park facility in Highland Park, Michigan respectively.

The Ford and Ground-up classes were required to have three separate modes of operation. In HEV mode the vehicle can draw energy from either the batteries or engine depending on the design of their control system, In ZEV-mode the vehicle can drive normally as a ZEV. A third mode, APU-on-mode bypasses the control system to keep the engine on.

Day one of this test procedure included a ZEV mode test using the Urban Driving Dynamometer Schedule (UDDS), a battery depletion cycle, in HEV mode until the engine starts (if applicable), then a prep cycle (505 or full UDDS, depending on the amount of available time) in HEV mode to warm up the engine. Day two included a cold-start FTP test in APU-on mode or HEV mode, depending upon control strategies. See Table 1 for a summary of this procedure.

The FTP emissions and fuel economy results were corrected for SOC using delta Ampere-hour ($\Delta$Ah) information from the ZEV test and the HEV FTP test. The SOC difference at the end of the FTP test indicated the magnitude that the emissions and fuel economy results need to be corrected (higher or lower). The amount of energy put into or taken out of, the battery pack during the FTP test was applied to the emissions and fuel economy results as either a "tax" or a "bonus." If, for example, extra energy was put back into the batteries, we can extrapolate extra ZEV distance that could be driven without emissions until the $\Delta$Ah reaches zero. The net grams per mile (g/mi) emissions and consumed miles per gallon (mi/gal) are adjusted based on this correction distance.

**Table 1:** HEV Dynamometer Emissions Testing Procedure for Ford and Ground-Up Classes

| | |
|---|---|
| | **DAY 1** |
| **ZEV Test** | UDDS in ZEV-mode |
| **Battery Depletion** | Run in HEV mode until engine turns on |
| **Engine Prep** | UDDS in HEV mode while engine is on |
| **Soak** | Overnight |
| | **DAY 2** |
| **HEV Test** | FTP test in HEV-mode |

Figure 1 is a plot of the net integrated ampere-hours in and out of the batteries during the entire procedure. These data were plotted to graphically demonstrate the SOC corrections employed for this test procedure. The West Virginia HEV is a series hybrid with an on/off engine control strategy. The test started with the engine off, then the engine turned on at 2 minutes, then shut down two thirds into the test.

The accumulated Ah into the battery during engine-on precipitated down toward the zero $\Delta$Ah point after the engine was shut down. However, at the end of the test, a positive $\Delta$SOC remained. The accumulated Ah indicated a differential amount of extra SOC that could potentially be used to drive without fuel consumed or pollutants emitted. The ZEV efficiency data tell us how much extra distance to credit the FTP emissions, in g/mi, and fuel economy, mi/gal.

FORD AND GROUND-UP DAS AND DYNAMOMETER SETTINGS - A new data acquisition system (DAS) was developed for the 1994 HEV Challenge. This system was developed by Instrumental Solutions (IS), of Ottawa, Canada. As a backup, last year's system from Cruising Equipment (CE), of Seattle, Washington, was used when incomplete or unreliable data was obtained from the IS system. The new DAS was designed to acquire vehicle speed, sense engine-on, voltage and amperes of the battery system and generator (if series HEV) and integrate Ah and kilowatt-hours (kWh). However, the new system was very susceptible to noise generated by the high-power electronics, had calibration problems, and had limited resolution (8 bit). Last year's system was more robust with better resolution (10 bit), but was only designed to acquire battery pack data (Voltage, Amperes, kWh, Ah).

During the emissions event at Chrysler and Ford, data were logged in memory from the IS system, which was then downloaded after the test. The CE meter has a digital display,

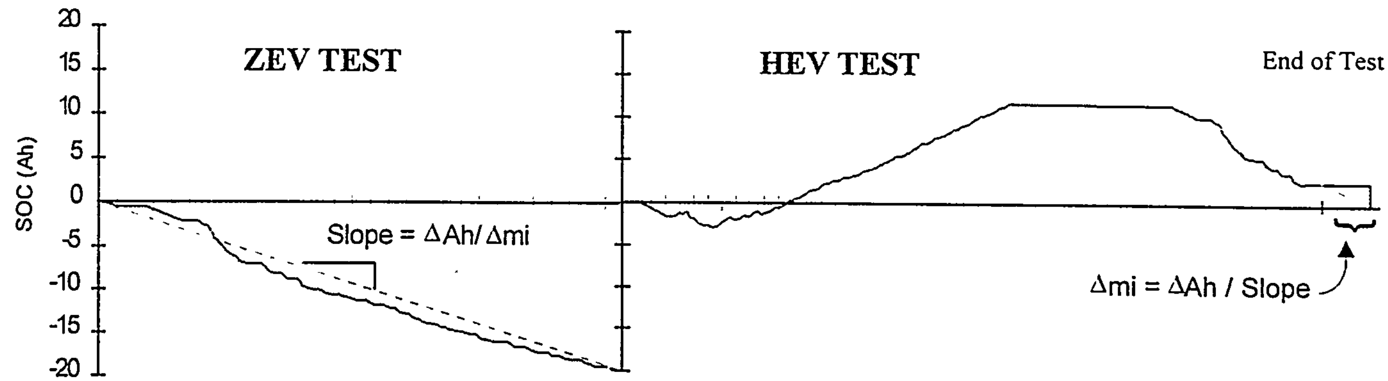


**Figure 1:** Graphic Representation of State-Of-Charge Correction for West Virginia Using Real Test Data

and real-time information was logged with a laptop computer or a special data memory module. Because the CE did not log speed data, the standard speed trace was later superimposed on Figures 2, 3, and 5.

The dynamometer inertia weight was set to the vehicle weight plus the standard payload. The dynamometer road load setting at 50 mph (80.5 km/h) was based on the stock body style. The Ground-Up class performed calculations of their estimated road load based on vehicle geometry and frontal area using a Dynamometer Power Consumption model. Unfortunately, there was no possible way to perform coast-down testing for each competition vehicle.

SATURN CLASS - The Saturn class was given the task of building a power-assist HEV. The Saturn HEVs were only required to have a minimum 5-mile ZEV range and were not allowed to charge off-board during the competition; the vehicle could use only on-board fuel energy. The power-assist description implies a parallel, power-peaking configuration, but several teams chose to build series systems. Because a parallel HEV with a small electric motor may not be able to drive in ZEV over the UDDS, the Saturn HEVs needed a different test than the Ford and Ground-Up procedures.

The Environmental Protection Agency's (EPA) National Fuel and Vehicle Emission Laboratory volunteered its facilities to be used during the 3 weeks prior to the competition for testing the Saturn HEV Challenge vehicles. The draft SAE HEV test procedure for power-assist hybrids prescribes a 3-day test. However, because EPA could not schedule multiple-day testing, the agency formulated a special test procedure that would account for differences in SOC.

The test included a typical vehicle prep performed the day before a cold start, multiple-cycle emissions and fuel economy test. The redundant cycle data of emissions and fuel economy may be correlated with differences in SOC, thus enabling SOC-corrected results.

In theory, this procedure can work but, the results from the two HEVs tested did not provide enough information to make the necessary correlation for SOC corrections. The University of Maryland HEV had a near-zero ΔSOC after the first three bags of the test (one FTP test). The other tested HEV, GMI Institute of Engineering and Management, could not be SOC corrected because it had a SOC-accumulating engine generator set that never powered down.

SATURN DAS AND DYNAMOMETER SETTING - At EPA a multi-channel DAS product from National Instruments (called Labview) collected information from the battery and generator and accepted inputs from the dynamometer to collect the real trace and the actual trace.

As with the Ford class, the inertia setting for the Saturn HEVs was based on measured vehicle weight plus the standard payload and road load of the stock vehicle.

## OUTCOME OF TESTING

For various reasons, not all vehicles were tested. Table 2 is a breakdown of the entire field of vehicles showing the number of many vehicles tested, the number that achieved 1994 EPA levels, and the number for which we have full test data. Problems with the data acquisition system and the vehicles themselves prevented analysis of all the tested vehicles.

**Table 2:** Breakdown of Vehicles for Emissions Testing

| | |
|---|---|
| Total Number of Participants | 36 |
| Showed up to Emissions Event | 23 |
| Performed Whole Test | 18 |
| Passed 1994 EPA Standards | 4 |
| Tested EV-Only | 3 |
| Tested Engine-Only | 1 |
| Malfunctioned During Testing | 3 |
| Full Test Data of Battery, Emissions, and Fuel Economy | 9 |

THE VEHICLES - Of the 18 vehicles tested, only the nine vehicles listed in Table 2 have full test data for battery, emissions, and fuel economy. This number is low, but the vehicles included are a good representation of the entire field of vehicle types. Poor results or incomplete data prohibits complete comparisons.

Looking at the vehicles listed in Table 3, we can see the trends in designing different kinds of HEVs. Parallel hybrids

Table 3: Attributes of Nine HEV Competition Vehicles

| *Class* | *School* | *Fuel* | *Vehicle Wt. (kg)* | *Series/ Parallel* | *Engine* | *Motor* | *Battery* | *Total kWh* | *Battery Wt.(kg)* |
|---|---|---|---|---|---|---|---|---|---|
| *Ford* | U of Alberta | RFG | 1644 | P | Suzuki 1.0L | Brushless DC, 32kW | NiCd | 9.4 | 284 |
| | U of Illinois | E100 | 1737 | S | Kohler 0.6L | AC Ind., 63kW | Pb-Acid | 7.4 | 320 |
| | Weber St. U | RFG | 1800 | P | Ford 1.9L | Series DC, 37kW | NiCd | 17.4 | 370 |
| | West Virg. U | RFG | 1649 | S | Kawasaki 0.6L | Series DC, 41kW | Pb-Acid | 13.5 | 272 |
| *Ground-Up* | Cal. Pol. Pomona | RFG | 1118 | S | Brig/Strat, 0.48L | Series DC, 34kW | Pb-Acid | 13.1 | 262 |
| | UC Santa Barb. | E95 | 1237 | P (split) | Suzuki, 1.0L | Ind. AC, 9kW | Pb-Acid | 12.5 | 246 |
| | U.C. Davis | RFG | 1200 | P | Brig/Strat, 0.57L | Brushless DC, 45kW | NiCd | 14.0 | 340 |
| *Saturn* | U of Maryland | M85 | 1464 | P | Suzuki 1.0L | Brushless DC, 13 kW | NiCd | 2.9 | 141 |
| | GMI Eng. & Man. | E95 | 1773 | S | Kawasaki, 0.6L | AC Ind., 22kW | Pb-Acid | 5.8 | 182 |

typically had smaller electric motors and more powerful engines than the series HEVs. The parallel HEVs typically used automotive engines; the series HEVs utilized small utility engines. The Saturn HEVs, which were not required to drive long distances in ZEV-mode, had smaller battery packs.

CONTROL STRATEGY EFFECTS - Only a portion of the vehicles had the potential for the engine to automatically turn on and off during the emissions event. We were not able to fully investigate how this kind of operation affects the test results and the vehicle performance. In addition, the data acquisition equipment that monitored the engine was not fully reliable.

The West Virginia HEV (a series configuration) was equipped with an engine that provided enough power to accumulate a charge with the engine off during roughly one third of the HEV test. The efficiency of their engine/generator set enabled them to achieve 44 MPG (18.7 km/L), corrected to 48 mi/gal (20.4 km/L) the highest tested fuel economy in any class.

The University of Alberta entry did have a working electrically heated catalyst activated by the ignition. They were allowed to key-on for a few seconds before the test was started.

SOC CORRECTIONS - As mentioned earlier, SOC corrections were not made for the Saturn HEVs. Of the two Saturns tested, one had a very small deviation from zero net change in Ah, and the other had high enough emissions that a SOC correction would have been academic.

Table 4 shows the applied SOC corrections. A positive SOC correction means that energy was put into the batteries; this causes the final results of the emissions levels to *decrease* and the fuel economy to *increase.*

With the exception of two vehicles, the degree of corrections applied to the raw emissions results for the Ford and Ground-Up classes was fairly low (see Table 4). The engine in the Illinois HEV never turned off during the test; they subsequently accumulated a large amount of battery SOC during the test, which earned them a +19.9% correction. The -54.4% SOC correction indicates a problem with the California Poly Pomona HEV (a series HEV). Their engine/genertor set did not supply enough energy during the test to keep up with the average load of the electric motor. The second-by-second test data from the generator output and the battery utilization presented later will show details of their problem.

Table 4: SOC Corrections

| *Team* | *ΔAh in ZEV test* | *ΔAh in HEV test* | *%SOC* Correction* |
|---|---|---|---|
| Univ. of Illinois | -6.24 | +2.33 | +19.9% |
| Univ. of Alberta | -12.18 | -1.29 | -7.7% |
| West Virginia | -20.33 | +2.64 | +8.0% |
| Weber State | not tested | 0.00 | 0 % |
| Cal Poly Pom. | -15.02 | -7.85 | -54.4 |
| UC Santa Barb. | 0.0 | 0.0 | 0% |
| Cal. Davis | -11.50 | 0.35 | -1.9% |
| GMI | n/a | +6.44 | n/a |
| Maryland | n/a | +0.05 | n/a |

** A positive SOC correction indicates an adjustment of g/mi lower and FE higher.*

Because the electric motor was not utilized during the HEV mode test in two of the parallel hybrids, these vehicles did not need SOC correction.

Three of the eight tests showed a negative net change in SOC (energy taken from the batteries). The data show that all but one vehicle remained within 1.0 kWh of the starting conditions of the HEV test.

**EMISSIONS RESULTS**

As a whole, the emissions results from the 1994 HEV Challenge vehicles were less than impressive. Many of the vehicles were using alternative fuels that required reworking of their engines. Most used small utility engines that do not have intrinsic design characteristics for good emissions control.

**Table 5:** Emissions Event Scoring Schedule

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| THC | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| NMHC | | 0.36 | 0.33 | 0.3 | 0.25 | 0.2 | 0.16 | 0.13 | 0.11 | 0.09 | 0.07 | 0.06 | 0.06 | 0.05 | 0.04 | 0.04 |
| CO | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3 | 2.55 | 2.17 | 1.88 | 1.7 |
| NOx | 1 | 0.8 | 0.63 | 0.5 | 0.4 | 0.35 | 0.31 | 0.27 | 0.23 | 0.21 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Points: | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 |

Event scoring was based on simultaneous control of total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and oxides of nitrogen ($NO_x$). A team scored the assigned points in a particular bracket if the emissions results were below all four listed pollutant levels in the bracket. The scoring schedule is shown in Table 5.

The emissions results of our nine vehicles are listed in Table 6. All four teams that did score in the emissions event are listed. The other results are typical of the rest of the HEVs that did not score. Many schools had CO values ranging from 15 to 100 g/mi. Only one HEV ran lean; this vehicle had high $NO_x$ (13.33 g/mi) and low CO (0.2 g/mi) readings. Vehicles either had adequate emissions control, or were far from meeting any current emissions standards.

**Table 6:** Emissions Results from HEV Challenge Test Procedure

| | SOC Corrected Values | | | | |
|---|---|---|---|---|---|
| School | THC (g/mi) | NMHC (g/mi) | CO (g/mi) | $NO_x$ (g/mi) | Emissions Points (/200) |
| Un. of Illinois | 2.87 | 2.29 | 95.13 | 0.061 | 0 |
| Un. of Alberta | 0.366 | 0.331 | 2.133 | 0.695 | 70 |
| West Virginia | 0.046 | 0.043 | 0.305 | 2.476 | 0 |
| Weber State | 0.109 | 0.085 | 0.332 | 0.395 | 90 |
| Cal Poly Pom. | 1.354 | 1.197 | 21.34 | 0.093 | 0 |
| Santa Barb. | 0.578 | 0.182 | 26.07 | 0.58 | 0 |
| Cal. Davis | 0.204 | 0.178 | 2.417 | 0.333 | 100 |
| Maryland | 0.31 | 0.29 | 2.6 | 0.68 | 60 |
| GMI | 0.75 | 0.56 | 54.2 | 0.3 | 0 |

Based on the emissions results, we should not conclude that hybrid electric vehicles are less capable of achieving lower tailpipe emissions. The technology for emissions controls for smaller engines is many years behind that for production car engines. The student teams that scored well in emissions did very well considering the challenges of using alternative fuels and small engines.

All four vehicles that scored in the emissions event were parallel hybrid types. Three of the schools used automotive engines. However, the teams with series configurations that showed promise in the emissions event admitted that their emissions control systems were not operating at their full potential.

## FUEL ECONOMY RESULTS

Four hybrids were able to demonstrate superior fuel economy: University of Alberta with 32.09 mi/gal (13.6 km/L); West Virginia University with 48.1 mi/gal (20.4 km/L); University of California, Davis with 35.1 mi/gal (14.9 km/L); and University of Maryland with 39.8 mi/gal (16.9 km/L). The fuel economy results of our nine HEVs are listed with the production equivalents in Table 7. The listed fuel economy results are corrected for SOC (see Table 6) and for gasoline equivalent gallons.

**Table 7:** Vehicle Efficiencies for Competition HEVs and Various Comparison Vehicles

| *Class /Type* | *Team* | *ZEV % off trace*[f] | *ZEV Efficiency (mi/kWh)* | *HEV % off trace* | *HEV Efficiency (MPGs)*[a] |
|---|---|---|---|---|---|
| Ford | Alberta | 1.28 | 3.63 | -1.39 | 27.65 |
| | Illinois | -1.03 | 4.52 | -1.99 | [b] |
| | Wst. Virg. | +0.69 | 5.97 | -0.76 | 48.1 |
| Ground -Up | Cal Poly Pomona | +1.55 | 4.42 | -0.46 | 14.65 |
| | UC Davis | +2.15 | 3.95 | -6.29 | 35.07 |
| | Santa Barb. | -- | -- | -2.24 | [b] |
| | Tulsa | -46.47 | 5.18 | -61.98 | 25.75 |
| Saturn | Maryland | -- | -- | -1.29 | 39.8 |
| | GMI | -- | -- | -1.12 | 33.6[c] |
| Gasoline | Escort Wgn. | n/a | n/a | - | 33 |
| | Saturn SL2 | n/a | n/a | - | 27 |
| EV | EV Geo[d] | unknown | 6.75 | n/a | n/a |
| | Ecostar[e] | +1.8 | 4.18 | n/a | n/a |

[a] Gasoline Equivalent Gallons
[b] Data exists, but was not available at time of printing.
[c] SOC Correction not possible. A Correction would boost FE.
[d] Tested at CARB, April 1994.
[e] Taken from 1994 American Tour de Sol Efficiency Testing.
[f] The measured vehicle distance driven compared to the test speed trace distance.

It is hard to draw any conclusions from the Ground-Up FTP (city) fuel economy results because there are no gasoline-equivalent vehicles with which to make a comparison. The vehicle weights vary a great deal. Some vehicles used a sturdy, welded-steel, tube frame, while others fabricated a light-weight, aluminum sub-frame. The average fuel economy of the Ground-Ups tested was 24 mi/gal (10.2 km/L), but two ground-ups were able to achieve greater than 30 mi/gal (12.8 km/L).

An indication of a vehicle's ability to follow the trace is shown by the "% off trace" column, which is the measured vehicle distance driven compared to the theoretical trace distance. Some vehicles had trouble maintaining the power demands required for the vehicle to keep up with the prescribed speed trace. Obviously, if a vehicle falls short of the prescribed driving speeds, its fuel economy may be artificially high. At the event, HEVs were run at best effort.

The Tulsa HEV was added in Table 7 to illustrate the potential problems with testing underpowered vehicles. The very large "% off trace" values (-49% and -61%) indicate that the inability of the vehicle to follow the trace must be taken into account in the 25.75 mi/gal (10.94 km/L) result. Similarly, the UC Davis vehicle, (a parallel HEV with a small engine), which demonstrates the ability to follow the trace in ZEV mode (ZEV: +2.15%), shows that the vehicle could have been aided by the motor to drive the trace in HEV mode (HEV: -6.29%).

In almost all cases, the vehicles were able to follow the trace better in ZEV mode. The reasons for this may have to do with throttle response for parallel systems, and more accurate torque response from driver input from the EV drivetrain. It may also mean that series systems have more power from their batteries in ZEV mode with a full charge than with the engine on and a partially depleted battery pack.

## ZEV EFFICIENCY RESULTS

Because the Ford and Ground-up emissions test procedure had a ZEV portion, we were able to look at ZEV efficiency under the same city cycle used in the FTP emissions test. The electrical efficiency results varied from 2.4 mi/kWh to 5.97 mi/kWh (9.61 km/kWh). Results from seven HEVs, two EVs, and two conventional vehicles are listed in Table 7.

## REAL-TIME DATA ANALYSIS

During the ZEV and HEV tests, we collected second-by-second data of the energy going into and out of the battery pack. In some vehicle tests, the DAS collected data from the battery and engine generator. This information shows us the power demands from the electric drivetrain during the ZEV test and during the HEV test. The net effect of the motor demands subtracted from generator output can also be seen in some vehicles. With these data, regenerative braking can be observed for each braking event and power management can be characterized.

University of Illinois - Figure 2 is a second-by-second plot of the ZEV test, which was one part of the HEV Challenge emissions testing procedure. Values of battery current and voltage were collected on a laptop computer from outputs given by a CE meter. The battery power trace in the plot is calculated from the battery current and voltage values.

The University of Illinois vehicle uses a Magnetek electric motor[2] with a home-built controller that provides nominal rating of 22.4 kW. This series-configuration HEV uses sealed Pb-Acid batteries.

The dynamics of the electric propulsion system can be seen throughout the UDDS. The batteries are experiencing 15-25 kW of load during acceleration and 10-15 kW of regenerative braking power during the braking events.

Power trace plots in ZEV mode such as in Figure 2 will show immediately whether or not the vehicle has regenerative braking capabilities. The characteristic power bumps during the decelerations indicate regenerative braking energy put back into the batteries.

An analysis of the Ah in and out of the batteries during the ZEV test indicates a projected range increase of 16.7% by utilizing regenerative braking. This Ah analysis assumes that ΔAh correlates with ΔSOC and that ΔSOC is proportional to the added amount of potential ZEV range. Using kWh would not be a good indication of SOC because energy measured in and out of the batteries is subject to energy losses each way (equal to the current squared times the resistance of the battery pack).

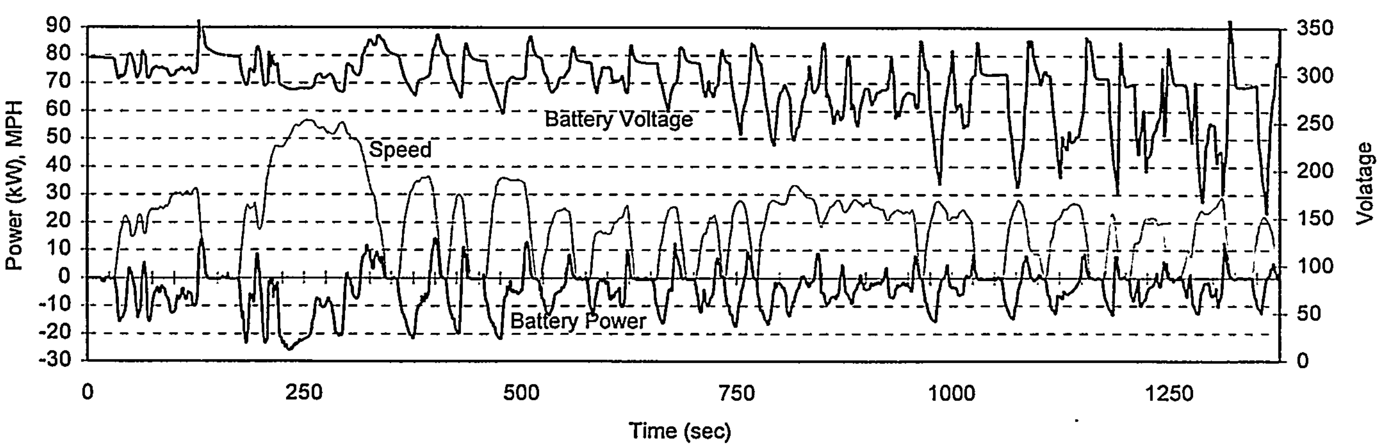


**Figure 2:** Battery Power and Voltage Trace During UDDS of University of Illinois ZEV Test

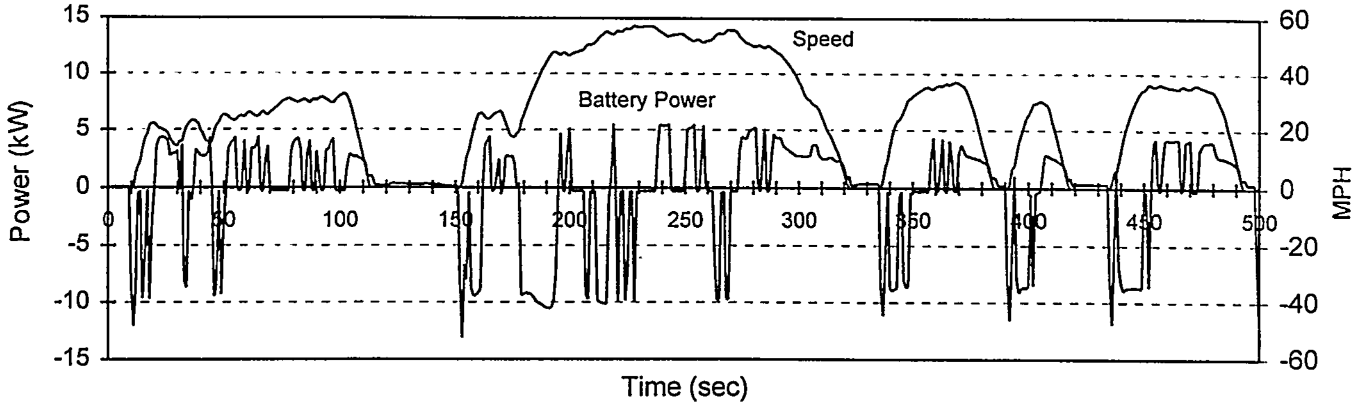


**Figure 3:** Power Trace During First 505 Seconds ofUniversity of Maryland HEV Test

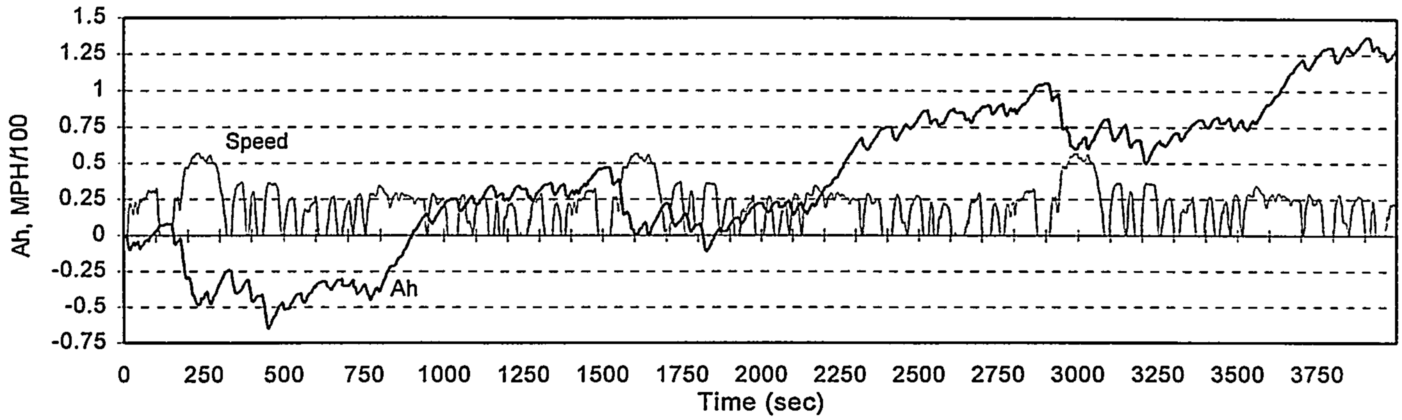


**Figure 4:** Ah Trace During Three UDDS cycles of University of Maryland HEV Test

One interesting note about the voltage trace of the University of Illinois vehicle: it appears that the resistance of the battery pack increased throughout the test. It is possible that the team did not have a fully charged battery pack at the emissions event, causing the batteries to operate in the lower SOC range where Pb-Acid batteries are less efficient.

We know from inspecting their vehicle and drive system[2] that their vehicle should have been very efficient in ZEV mode; less than exceptional efficiency results were obtained from the ZEV test (4.52 mi/kWh, 7.27 km/kWh), perhaps because of increasing losses from the battery during the test.

University of Maryland - Figure 3 is a plot of the first 505 seconds of the emissions test from the Maryland HEV. This vehicle was a parallel hybrid that used a small UNIQ Mobility electric motor/generator to complement a 1.0-liter engine. The control strategy kept the SOC of the batteries very close to the same level by adding and taking power from the engine throughout operation[3]. As seen from the plot, the magnitudes of the power spikes were similar for the entire cycle; throughout the test, the batteries give out roughly 10 kW during acceleration modes and accept about 5 kW of power generation.

When the speed incrementally increased or decreased, a power spike (indicating the addition or substraction of torque to the engine) was seen from the battery power trace. This highly active control system produced the very jittery battery power trace in the graph.

Unlike the ZEV test, when a test in HEV mode is examined, what is seen is the power demand trace of the motor/generator as it is coupled to the engine and vehicle. The positive battery power bumps under decelerations look similar to the regenerative braking bumps seen in ZEV tests, but if we look closely, we can see they are sustained for longer periods and sometimes during areas of stable speed, not just deceleration.

On the basis of the University of Maryland design paper[3] and discussions with the team, we know that the motor supplies energy back to the batteries during light loads at speed and during deceleration events. However, at a stop the engine power level is brought to near idle so that engine noise and vibration are not disconcerting to the driver. The engine was effectively buffered from harsh transients; this approach made possible their significant gains in fuel economy.

Figure 4 is the Ah trace throughout three UDDS tests. The net usage of the batteries during the first UDDS was matched well, but as the cycles progress, the motor/generator was accumulating SOC. This continued until the computer-monitored SOC reached a set point, as determined by the control strategy, to use less of the generator's output during the light load conditions. Note the scale of this graph;

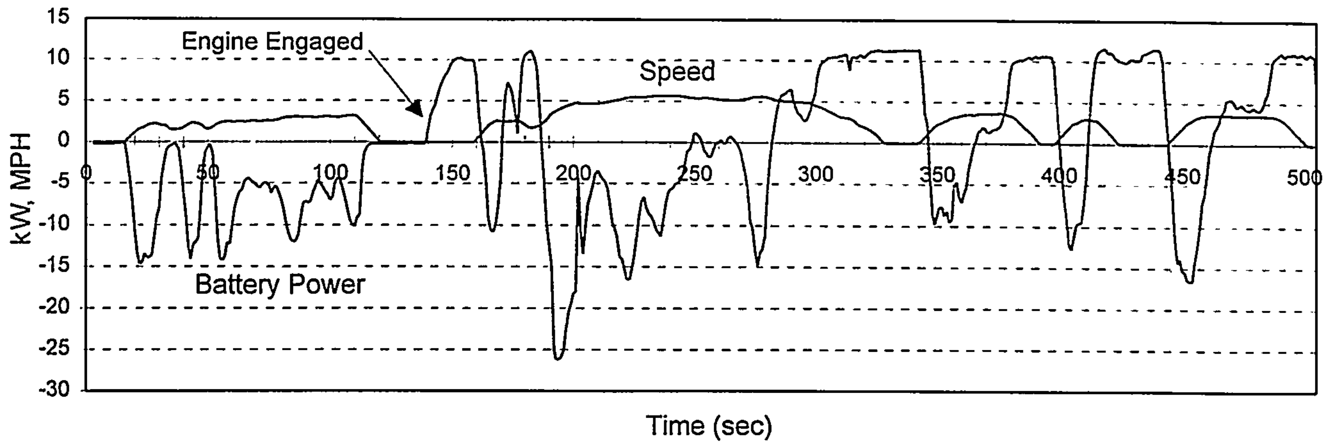


**Figure 5:** Battery Power Trace During First 505 Seconds of West Virginia University HEV Test

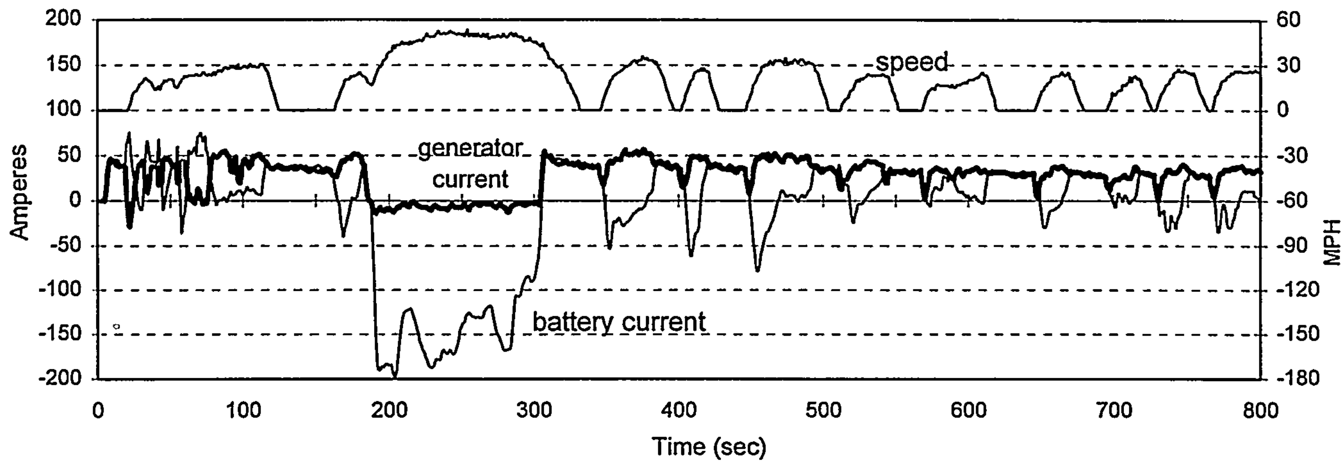


**Figure 6:** Battery and Generator Current Trace During First 800 Seconds of Cal. Poly. Pomona HEV Test

the battery capacity is roughly 19 Ah, and during this extended test, the vehicle stays within 1.5 Ah. This illustrates the effectiveness of the control strategy to keep the net usage of the batteries to a minimum.

West Virginia University - Figure 5 is a plot of the first 505 seconds of the West Virginia FTP emissions test. This series HEV utilizes a series-wound DC motor with a Kawasaki 0.6L water-cooled engine and a Fisher alternator. The West Virginia team used Pb-Acid batteries[1].

As mentioned before, the vehicle control system engaged the engine roughly 120 second into the test (this point is labeled on the graph). The power to drive the vehicle came solely from the battery during the first acceleration "hill." After that, the generator was observed giving power to the batteries.

The rest of the battery power trace shows the generator power subtracted by the electric drivetrain demands. At a stop, the engine generator set is putting out a constant 11kW. The other DAS system was also monitoring the generator and confirmed that output was constant during the test. Utilizing the engine at an efficient and powerful point proved successful, with a corrected 48.1 mi/gal (20.4 km/L) fuel economy result.

California State Polytechnic, Pomona - The trace in Figure 6 is a plot of the data taken from the IS DAS for the California Poly Pomona HEV test. This time, the outputs of the generator and battery are expressed in current. This robust HEV used components that emitted minimal noise and subsequently allowed relatively smooth data traces of the speed, generator current, and battery current. However, the plots shown in Figure 6 did require (three point) data smoothing.

The Pomona HEV used a Briggs and Stratton engine coupled to a Fisher alternator and a basic series-wound DC motor[4]. This vehicle has proven to be fairly successful because of its robust and simple design.

This figure demonstrates operational characteristics similar to those shown in Figure 5, but there was an apparent problem in the generator current trace. At high loads, particularly during the second acceleration "hill," the generator current quickly dropped to zero. During subsequent accelerations, there was a dip in the generator current.

While we do not know for sure what caused this to happen, it seems that under high loads (perhaps induced by low bus voltage) the generator momentarily did not produce any power. This adversely affected the vehicle efficiency in two ways. The engine momentarily did not produce power while it was running, thus making the vehicle deplete the batteries while consuming fuel producing a negative SOC correction. Also, the generator was not providing power under the highest load conditions where the batteries need it most. Battery efficiency is lowest under high load conditions, thus losses were increased without the needed contribution from the generator.

## CONCLUSIONS

The DOE-sponsored HEV Challenge competition is a significant project because it puts a significant number of HEVs on the road. Engineers have modeled and studied the capabilities of hybrid electric drivetrains in vehicles, but there are very few real HEVs accessible for testing and data collection. The creative energies of student engineers and the resources of 36 colleges and universities have produced HEVs that have set performance benchmarks and demonstrated the potential of this important future vehicle technology.

The emissions event provided an opportunity to obtain data from many vehicles with a standard test procedure. The HEV test procedure used for ZEV-capable HEVs proved to work well by quickly testing HEVs and applying an SOC correction to the results.

The potential for increased emissions and fuel economy can only be realized if full utilization of the HEV's load-leveling properties can be accomplished. The best vehicles from the 1994 HEV Challenge show benchmark efficiency and emissions results that establish levels of efficiency and emissions performance that represent starting points for future HEVs.

Two student vehicles were able to achieve roughly 40 mi/gal (17 km/L) or greater in the city driving cycle; this represents an increase of roughly 30-40% in fuel economy over the stock vehicles. Three competition vehicles were able to achieve electrical efficiency results better than a production EV for the city driving cycle in ZEV mode. The data from the road events loosely match the efficiency test results, but mechanical failure and control strategy effects from these student-built prototype vehicles generate variance in the comparisons.

Results from the emissions event illustrate the need for highly developed internal combustion engines for HEVs with state-of-the-art emissions-control technology. Such engines are well within the current state of knowledge, but they have not been fully developed for these applications.

Development of effective control systems remains a formidable task in unlocking the potential of HEVs and satisfying the particular goals that HEV technology will be designed to accomplish. Although the computer technology exists, such control systems are only now being developed.

Many worthwhile lessons were learned from this ambitious, but detailed emissions test procedure for the student-built HEVs. With use of a different DAS, a new Saturn test procedure, and improved SOC correction calculations, 1995 promises to build on what was accomplished in 1994.

## ACKNOWLEDGMENT

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## REFERENCES

1. W. Taylor and C. Atkinson, "The Design and Development of an Efficient Series Hybrid Electric Vehicle at West Virginia University," design paper submitted for the 1994 HEV Challenge competition (June 1994).

2. T. Roethemeyer, B. Masterson, M. Stiller, "University of Illinois Hybrid Electric Vehicle: An Electric Vehicle for Today," design paper submitted for the 1994 HEV Challenge competition (June 1994).

3. J. Wilkerson, Fred Householder, Mark Caggiano, D. Holloway, "The University of Maryland at College Park Methanol Hybrid Electric Vehicle," design paper submitted for the 1994 HEV Challenge competition (June 1994).

4. Augenstein, "California State Polytechnic University, Pomona," design paper submitted for the 1994 HEV Challenge competition (June 1994).