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HEV Dynamometer Testing with State-of-Charge Corrections in the 1995 HEV Challenge

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ABSTRACT

In the 1995 HEV Challenge competition, 17 prototype Hybrid Electric Vehicles (HEVs) were tested by using special HEV test procedures. The contribution of the batteries during the test, as measured by changes in battery state-of-charge (SOC), were accounted for by applying SOC corrections to the test data acquired from the results of the HEV test. The details of SOC corrections are described and two different HEV test methods are explained. The results of the HEV test methods are explained. The results of the HEV tests and the effects on the test outcome of varying HEV designs and control strategies are examined. Although many teams had technical problems with their vehicles, a few vehicles demonstrated high fuel economy and low emissions. One vehicle had emissions lower than California's ultra-low emission vehicle (ULEV) emissions rates, and two vehicles demonstrated higher fuel economy and better acceleration than their stock counterparts.

INTRODUCTION

The HEV Challenge was an annual competition that spanned three years and involved more than 50 North American colleges and universities. The objective of the competition was to have student teams build working HEV prototypes were that were more fuel efficient and less polluting than conventional vehicles as well as to design vehicles capable of operating on only electricity. The student teams, led by faculty advisors and graduate students, were able to combine a wide range of technology, designs, and configurations that proved to be a very effective shakedown for HEV technology. Few experimental HEVs have been developed and because the enabling technologies are currently being developed at a high rate, the lessons learned by analyzing such new, unique designs have furthered the overall development of HEVs. Many important concepts related to the capabilities of HEVs are demonstrated by working vehicles, plus challenges and problems can be identified only by building an actual vehicle.

In terms of the HEV Challenge, access to the vehicles provided the organizers and interested parties with an opportunity to test new ideas and equipment. Testing the vehicles within the competition, in addition to follow-on research, has aided in the development of data acquisition systems, computer simulation validation, evaluation methods, and dynamometer testing procedures.

Incentives and mandates are accelerating the development of production HEVs within the next decade. As a result, the development of test procedures is a challenging issue facing the automotive industry and regulatory agencies. Many test methodologies are possible for evaluating the emissions and fuel economy of HEVs, but standardized procedures and concepts must be used to enable valid comparisons for future evaluation and regulation.

HEV technology is unlike conventional technologies that have advanced the development of the automobile over the last 100 years. HEVs operate in dynamic ways that are beyond the scope and capabilities of conventional test procedures. Elements of the current test procedures need to be expanded so that the operational behavior of HEVs can be analyzed accurately.

Over the course of two years, the organizers of the HEV Challenge have developed HEV dynamometer test procedures that were designed to fit the needs and constraints of the competition. Future standardized test procedures would most likely acquire more information about the HEV with a more comprehensive and lengthy test procedure, but the fundamental concepts for testing HEVs are the same, and many lessons can be learned by examining the outcome of the competition's dynamometer testing.

TEST PROCEDURES

In a manner of speaking, the energy manegement in the operation of HEVs is two-dimensional. HEVs can draw upon either of two stored energy sources, one of which (the electrical) can actively store or provide energy during operation. At any given initial state-of-charge (SOC) of the battery pack, the vehicle has a unique capacity to use its fuel and emit pollutants at particular rates. The only way to obtain a complete picture of the operation of an HEV would be to repeat the test over and over in series and average the fuel consumption and emissions rates over many cycles, but this, of course, is not a practical option.

Besides various proposal documents and position statements, to our knowledge the only sources of actual test

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procedures available for HEVs are draft forms of SAE J1711 and the California Air Resources Board (CARB) proposed test procedures. Some test approaches explored in the competition were based upon the draft SAE methods. The procedures included multiple tests at carefully selected initial battery states-of-charge (SOC) to yield results for fuel economy and emissions that can be "SOC corrected" to characterize vehicle emissions and fuel economy that come, on average, from only the fuel, thus excluding a net contribution from the battery pack. Other issues, including annualized emissions, electric-only range and efficiency, and potential charge-depleting operation, were beyond the scope of this part of the competition.

The competition vehicles consisted of three separate vehicle classes. Each class had different design philosophies and was tested in different facilities. Because of the differences, three separate HEV procedures were developed each tailored for the facilities, design type, and available testing time.

SOC CORRECTIONS - The SOC is a measure of how much charge is left in the batteries at any given time. Measuring battery SOC measurement is, without a doubt, a significant challenge. Battery energy storage has been compared to "filling a rubber bucket" -- you never really know to what extent the batteries are empty or full. But when measuring small SOC differentials in the normal operating range of a battery pack (20% to 80% SOC), the ΔSOC can be tracked with an acceptable degree of confidence.

To measure the battery SOC, we do not want to measure the *energy* (in kWh) taken out and put in because the I^2R energy losses in and out of the battery pack would give erroneous data. Ampere-hours (ΔAh) is the accepted parameter for tracking charge in and out of the pack to correlate with ΔSOC.

In correcting the SOC, we are assuming that all the energy used to propel the vehicle was produced on-board from the combustible fuel. Although the instantaneous SOC may be rising or falling during testing, if the is capable of keeping the batteries charged over many driving cycles, the HEV is said to have charge-sustaining operation. Although only the Saturn class was required to have charge-sustaining operation, most of the teams designed their vehicles to be driven without depleting their battery pack.

Although the separate classes had different test procedures, all vehicles that were tested with a significant ΔSOC were given a SOC correction on the basis of two separate dynamometer tests at different battery states-of-charge. In theory, a test at the highest SOC during operation will yield a ΔSOC < 0 (falling SOC), and a test at the lowest SOC expected will give ΔSOC > 0 (rising SOC). SOC corrections give equal measure to HEVs with radically different sized engines and control strategies.

However, if after both tests the ΔSOC is < 0, the vehicle is giving this result either because the control strategy was not fully utilizing the engine, or because the vehicle will always be charge-depleting over the test cycle. SOC-correction calculations can accommodate charge-depleting HEVs by effectively using the on-baord charging rates to account for the energy used from the batteries that would have to be taken from an off-board source.

Unlike the competition test procedure, the SAE test procedure handles charge-depleting operation by adding the fuel energy to the electrical energy used during the test with a direct energy conversion (1 gal gasoline = 36.66 kWh). This method, in the context of the competition, would have provided the Ford and Neon classes with a loophole to achieve ultra-high fuel economy and low emissions by simply operating in a highly charge-depleting mode which was not prohibited in the Neon and Ford classes.

Only a couple vehicles from the Ford class tested as charge-depleting during the FTP cycle, but the amounts were small. All Saturns were charge-sustaining (a rules requirement), and all three successful Neon HEV tests showed charge-sustaining operation.

FORD ESCORT PROCEDURE - The Escort HEVs were required to have at least a 25-mi zero-emissions vehicle (ZEV) range. Because of this significant ZEV range, a full 7.5-mi urban dynamometer driving schedule (UDDS) test cycle could be performed without an engine start. With one of the two tests in ZEV mode, only one cold-start emissions test was needed for the SOC-corrected results which saved valuable time. The test procedure is given below:

Day 1
1. Charge vehicles to 100% SOC.
2. Warm engine.
3. Bring vehicle to test lab for overnight soak.

Day 2
1. Conduct UDDS cycle in ZEV mode.
2. Deplete batteries (to lower limit of SOC during normal operation).
3. Conduct FTP emissions test

By using this procedure, the ZEV data yields the information needed to correct the emissions and fuel economy results from the FTP test. The correction is calculated with the notion that during the low-SOC FTP test, some on-board charging has occurred that makes it possible for the vehicle to be driven a small amount of extra ZEV distance as determined by the ZEV test data. This extra pollution-free and fuel-free distance is figured in the g/mi and miles per gallon (MPG) calculations from the FTP test.

Ford Class SOC Correction Calculations - This correction can only be made if the FTP test was started at the lowest SOC expected during hybrid operation; in which case, the SOC can only increase. The FTP test results were SOC-corrected by first calculating an SOC factor. SOC corrections are made by multiplying the MPG result with the SOC factor and dividing the emissions results by the SOC factor. The SOC correction factor is calculated from the equations below:

Ah_{HEVFTP}	ΔAh from HEV mode FTP test.
$(Ah/mi)_{ZEV}$	Data from ZEV to get Ah per mile.
mi_{FTPHEV}	Miles traveled in FTP test.
xm_{ZEV}	Extra ZEV miles that could be driven in ZEV mode from on-boardcharging.
SOC_{factor}	SOC factor

$xm_{ZEV} = Ah_{FTP} / (Ah/mi)_{ZEV}$

$SOC_{factor} = 1 + xm_{ZEV} / mi_{FTPHEV}$

SATURN PROCEDURE - Requirements were written in the competition rules that steered the Saturn teams to build "power-assist" hybrids. The requirements were (1) no off-board charging, (2) charge sustaining operation, and (3) only a nominal ZEV range requirement (minimum 5 mi). The 5-mi ZEV range precluded the use of the Ford class HEV test method, which includes a UDDS test in ZEV mode. Two separate FTP tests are performed at the upper and lower limits of the SOC expected during hybrid operation. Because extensive testing could not be performed to find these SOC levels, the team prescribed the correct SOC levels at the event.

The Saturns were tested at GM's Milford test facility which runs a 24-hr operation. With this schedule, both tests could be administered for each vehicle in one day, but with only a short 6-8 hr soak period. The test procedure was as follows:

Day 1
1. Condition SOC to upper limit by idle charging.
2. Bring vehicles to indoor soak area.

Day 2
1. Conduct FTP test at high SOC.
2. Deplete battery to lower SOC.
3. Soak for 6-8 hours.
4. Conduct FTP test at low SOC.

As in the SAE Draft procedures (SAE Draft J1711), the SOC correction is performed by linear interpolation of two test results. Because calculations are performed with ΔSOC in ratios, the units are arbitrary; thus, ΔAh/Ah and ΔSOC/SOC can be used interchangeably.

Saturn (and Neon Class) SOC Correction Calculations - The method used to correct the SOC of the Saturn and Neon HEVs is a simple linear interpolation of the emissions and fuel consumption rates between the two tests. SOC corrected results are calculated as follows:

$$\frac{(F_{\Delta SOC=0} - F_{SOChigh})}{(\Delta SOC_{low} - \Delta SOC_{high})} = \frac{(F_{\Delta SOC=0} - F_{\Delta SOChigh})}{(0 - \Delta SOC_{high})}$$

where the F terms are fuel consumption rates; the same equation can be used for emissions calculations where F is the respective pollutants in *mi/g*.

NEON PROCEDURE - The Neon HEV requirements were (1) minimum 5-mi ZEV range and (2) allowable off-board charging. Because of the short ZEV range requirement, the Neon vehicles needed to be tested like the Saturn class in that two separate emissions tests were conducted for the SOC corrections.

Testing time was insufficient to give all vehicles two full FTP tests as was done for the Saturns; therefore, on day 1, all the Neons were given two hot-start tests to identify vehicles with low emissions worth testing on day 2. Fuel economy scoring was taken from all the hot-start tests. The limited emissions data from the first-year Neon class was not a concern because in previous years, only a small percentage of the first-year HEVs achieved emissions that justified the extra time and effort. The test procedure used for the Neon HEVs is given below:

Day 1
1. Charge vehicles to upper SOC.
2. Warm the engine (in engine-only mode).
3. Conduct UDDS test at high SOC.
4. Deplete batteries to low SOC.
5. Warm the engine.
6. Conduct UDDS test at low SOC.
7a. High emissions: go back to competition
or
7b. Low emissions: soak for cold-start FTP.

Day 2
1. Conduct FTP test (low-emissions vehicles only)

SCORING

FUEL ECONOMY - Teams with superior SOC-corrected fuel economy were awarded with the highest points. The fuel economy results were entered in a standard scoring equation that awards full points to the best result and scales the rest of the teams linearly from this result to a cut-off point two standard deviations from the median result.

EMISSIONS - Scoring emissions results was not as straightforward as scoring the other competition events. Competition points were awarded on the basis of the simultaneous control of non-methane hydrocarbons (NMHC), carbon monoxide (CO), and oxides of nitrogen (NO_X). A table was developed with brackets that span emissions regulations from EPA & CARB, dating from pre-emissions control to values less than the CARB ULEV standard. The table was used as a relative scale that assigns a quantitative number to a set of emissions rates. Each team's emissions results were assigned the highest bracket number in which each criteria pollutant is below the level found in that bracket. The bracket number was entered into the same standard scoring equation used in the other events to determine the event scores. However, for emissions scores, the cutoff was not based upon the standard deviation; it was predetermined at bracket #5, the 1968 Federal level.

The University of Tennessee was the only vehicle that passed the pre-screen emissions rates. Tennessee earned full points and the other schools were scored based on their hot-start tests.

Table 1: Emissions Scoring Schedule

Bracket Number	NMHC (g/mi)	CO (g/mi)	NO_x (g/mi)	
1	9.222	84.00	4.100	**Pre-Control**
2	7.273	67.00	3.991	
3	5.735	53.44	3.884	
4	4.523	42.62	3.781	
5	3.567	34.00	3.680	**Fed 1968**
6	2.610	28.00	3.100	**Fed 1972**
7	2.217	22.74	3.100	
8	1.883	18.47	3.100	
9	1.600	15.00	3.100	**Fed 1975**
10	1.445	15.00	2.490	
11	1.305	15.00	2.000	**Fed 1977**
12	0.939	12.39	2.000	
13	0.676	10.25	2.000	
14	0.486	8.469	2.000	
15	0.350	7.000	2.000	**Fed 1980**
16	0.350	5.844	1.682	
17	0.350	4.879	1.414	
18	0.350	4.073	1.189	
19	0.350	3.400	1.000	**Fed Tier 0**
20	0.313	3.400	0.744	
21	0.280	3.400	0.550	
22	0.250	3.400	0.400	**Fed Tier 1 1994**
23	0.196	3.400	0.351	
24	0.154	3.400	0.351	
25	0.121	3.400	0.308	**Cal TLEV**
26	0.107	3.400	0.270	
27	0.094	3.400	0.250	
28	0.083	3.400	0.232	
29	0.073	3.400	0.216	**EPA 1997 LEV**
30	0.064	2.960	0.200	
31	0.057	2.577	0.200	
32	0.050	2.243	0.200	
33	0.044	1.953	0.200	
34	0.039	1.700	0.200	**Cal 1997 ULEV**
35	0.0335	1.470	0.170	
36	0.029	1.250	0.138	
37	0.024	1.070	0.110	
38	0.020	0.930	0.090	
39	0.017	0.800	0.072	
40	0.0145	0.680	0.058	

RESULTS

The vehicles in the Ford and Saturn classes were mistakenly tested on the dynamometer at a setting of about 300 lb too heavy. However, this error did not put any particular team within a class at a competitive advantage, but it obviously has an effect over the whole class by putting the vehicles at a disadvantage compared with their stock counterparts.

FUEL ECONOMY - The data shown in Table 2 show all successful dynamometer tests at the 1995 HEV Challenge. The Ford and Saturn class results are from FTP tests; the Neon results come from hot-start UDDS tests.

EMISSIONS - The emissions results of all the vehicles tested are listed in Table 3. Looking at the bracket numbers, we can see that only a few vehicles performed very well; only three achieved emissions better than the Tier 0 emissions rates.

Table 2: Fuel Economy Results

FORDS	ZEV Test (Ah)	FTP Test (Ah)	SOC Factor	MPG	SOC-Corrected MPG
Penn St	-18.48	-22.90	0.162	37.60	6.10
US Navy	-23.94	4.80	1.136	18.30	20.79
Alberta	-13.72	-2.30	0.886	29.56	26.18
U Cal Irvine	0.00	0.00	1.000	25.65	25.65
Wisconsin	-6.40	0.60	1.063	20.86	22.18
Wayne St	0.00	0.00	1.000	26.94	26.94
Wst Virginia	-22.57	-3.20	0.905	24.53	22.19

	High SOC FTP		Low SOC FTP		SOC-Corrected
SATURNS	Ah	Gasol. Equi MPG	Ah	Gasol. Equi MPG	MPG
Cal St, Chico	-6.6	oo	7.3	15.4	32.4
Cal St, Fresno	-1.2	29.8	2.1	23.8	27.3
ETS (Quebec)*	--	--	0	42.7	42.7
GMI	-5.3	21.8	3.4	20.6	21.0
UTastin**	--	--	-3.2	18.0	14.8
West. Ontario*	--	--	0	11.0	11.0
IIT**	--	--	-1.04	15.9	11.2
NEONS					
Texas Tech	-0.5	24.0	0	24.0	24.0
Tenn	-0.6	23.4	0	23.4	23.4
West Wash	-12	oo	0.9	20.4	21.9

* One test performed, in engine-only mode.

** SOC correction performed with estimated ZEV data.

oo Denotes infinity.

Table 3: SOC Corrected Emissions Results

FORDS	NMHC (g/mi)	NOx (g/mi)	CO (g/mi)	Bracket Number
Penn St	6.778	0.062	286.60	<1
US Navy	0.211	3.574	6.90	6
Alberta	0.203	0.147	2.16	22
U Cal Irvine	2.250	0.270	39.00	4
Wisconsin	0.160	0.103	26.16	6
Wayne St	0.040	0.090	0.54	33
Wst Virginia	0.254	0.708	8.91	13
SATURNS				
Cal St, Chico	0.444	1.286	19.29	7
Cal St, Fresno	0.293	0.312	5.07	16
ETS (Quebec)	0.214	2.826	5.50	9
GMI	0.422	2.762	30.14	<1
West. Ontario	21.812	0.073	245.34	<1
UTAstin	1.754	0.167	60.95	2
IIT	0.245	1.497	3.87	16
NEONS				
Tenn	0.019	0.050	0.50	38
Texas Tech*	*0.008*	*0.831*	*0.01*	*20*
Tenn*	*0.100*	*0.313*	*0.24*	*23*
West Wash*	*1.280*	*1.417*	*5.03*	*11*

* Results in italics are pre-screen, hot-start UDDS test results, not FTP results.

FUEL ECONOMY SOC CORRECTION GRAPHS - Test data can be expressed in a graphic format to show how two results yield the $\Delta SOC = 0$ result. For the competition, only the Saturn and Neon results were scored by using the two-point interpolation method (see Figure 1), but the Ford class data can be expressed with the interpolation method as well (see Figure 2).

The graphs are expressed in liters of fuel used in the 17.93-km (11.115-mi) FTP cycle because plotting km/L for the ZEV tests would divide by zero. Most every battery pack had a different capacity, but by multiplying the measured ΔAh by the nominal bus voltage, the data can be plotted together on the same graph when converting the ΔAh units to energy units, effectively normalizing the data.

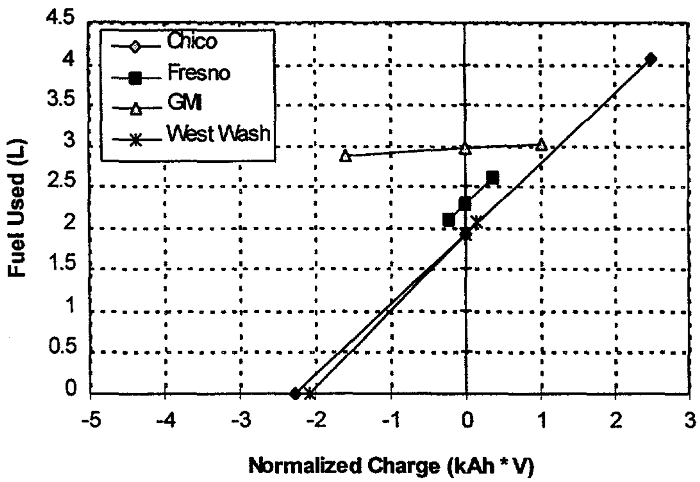

Figure 1: SOC Corrections for Saturn and Neon Class HEVs

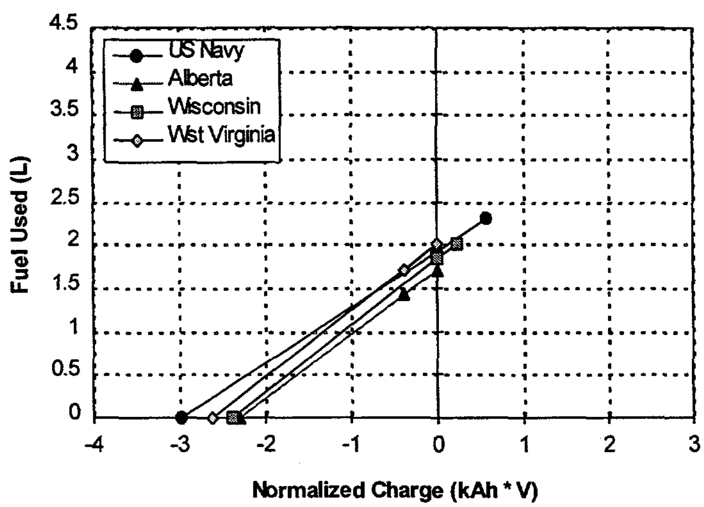

Figure 2: SOC Corrections for Ford Class HEVs

EMISSIONS SOC-CORRECTION GRAPHS - The emissions data can be expressed in the same manner as the fuel consumption SOC-correction graphs. Figures 3, 4, and 5 are SOC-correction plots of the emissions rates for three HEVs. Here, the axes are grams per mile of the criteria pollutants (NMHC, NO_X, CO) versus the change in battery charge, or ΔAh.

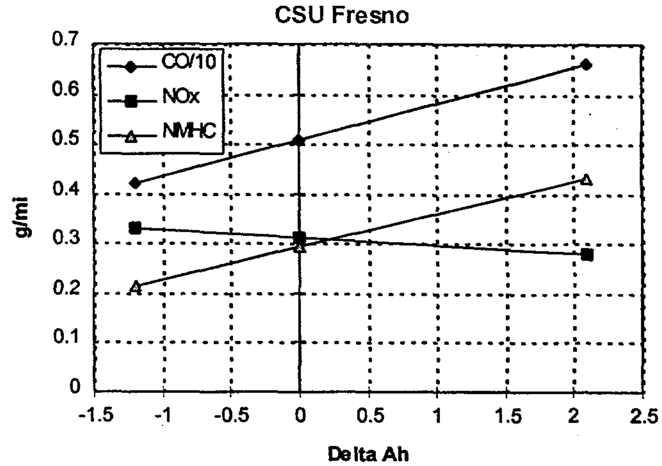

Figure 3: Emissions SOC-Correction Plot for CSU, Fresno

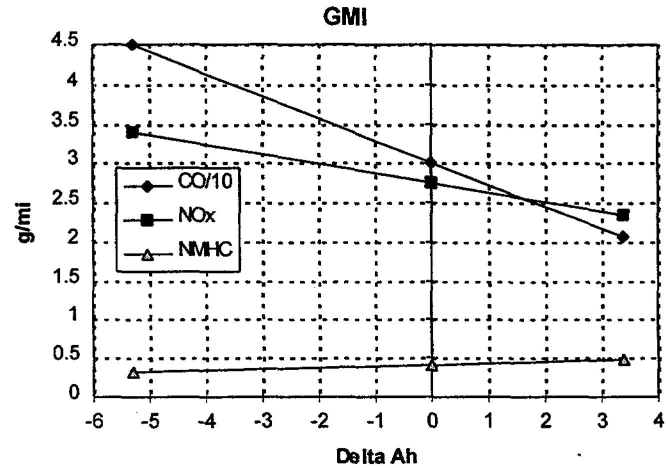

Figure 4: Emissions SOC Correction Plot for GMI Engineering and Management Institute

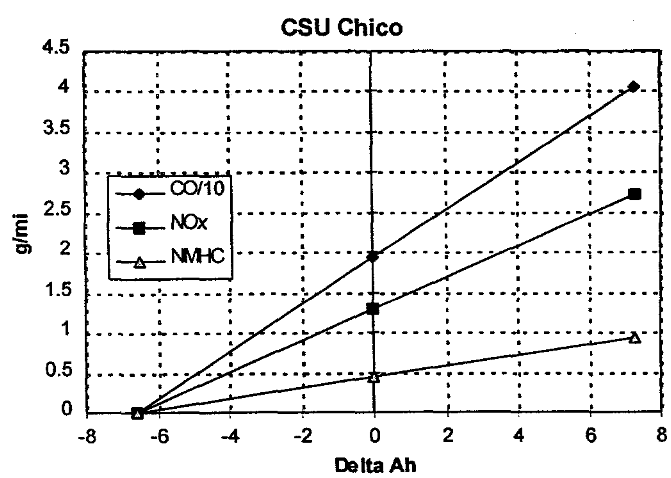

Figure 5: Emissions SOC-Correction Plot for California State University, Chico

DISCUSSION OF RESULTS

GENERAL DISCUSSION - In looking at the competition results, one must understand that the competition format is not as conducive to collecting good, accurate data compared to a controlled experimental study. The teams were required to perform when called and were not given second chances. And if the teams suffered any technical problems, we could not collect representative vehicle test data. Also, test repeatability could not be validated.

Most team members were working on their vehicles continually until the start of the competition. Teams were often plagued with difficulties throughout the competition. Of the vehicles that were working, only a small number of those worked as expected. Therefore, we only have actual test results for a small percentage of the participating teams to discuss. Though not all vehicles were successful at achieving the competition goals of high vehicle efficiency and low emissions, all vehicle testing proved to yield valuable insights into understanding HEV technology and HEV test procedures.

Fuel Economy - The best fuel economy results from the dynamometer testing cames from ETS and CSU Chico with 42.7 and 32.4 gasoline equivalent MPG respectively. The ETS result is impressive, but it does not necessarily demonstrate the efficiency gains attributable to HEV technology. The ETS HEV was a split parallel (the front axle was engine-driven and the rear axle was electrically driven) and could only be tested on the engine axle. The high fuel economy is mainly attributed to the use of a small engine, not the utilization of an HEV drivetrain. If we could have used a four-wheel-drive dynamometer, then the fuel economy may have actually improved if the engine was load-leveled effectively by the electric drivetrain.

An important aspect of the potential of hybrid vehicles was demonstrated by the HEV built by the CSU Chico team. The converted Saturn had improved fuel economy without sacrifice in acceleration performance -- in fact, both performance and efficiency were improved. The acceleration event showed acceleration times much better than the stock vehicle. This series-configured HEV had a small, efficient engine and a powerful electric motor (150 kW). In normal driving, the vehicle could be very efficient, yet the remarkable amount of reserve power is available on demand.

The MPG results from the rest of the HEVs were actually lower than the MPG of the original stock vehicles. Although we would expect increases in vehicle efficiency with typically more efficient HEV drivetrains, apparently the teams were not able to overcome the losses attributed to the added complexity and extra weight inherent with the entire HEV package.

Emissions - The emissions results listed in Table 3 show that most teams were not successful in using the benefits of an HEV system to improve emissions. The exception was the University of Tennessee; this team achieved less-than-ULEV emissions rates. The small 1.0-L engine was load-leveled with an electric motor in a parallel configuration. The engine was modified to optimize for natural gas fuel properties and was operated by a well-tuned and calibrated aftermarket engine controller. The electric motor was used during high-power demands for roughly 3-5 s providing 20-30 kW of power during the beginning of acceleration events throughout the driving cycle. Because the added electric motor power was helping the engine during high-power demands, the engine could be designed to maintain stoichiometry at all times, thus avoiding the need for a high-power, polluting, fuel-enriched mode. Regenerative braking and energy taken during low-power periods supplied the battery energy taken during the accelerations.

On the whole, out of 17 HEVs tested, 7 had very high CO and low NO_x rates, indicating fuel-rich operation. Only half of the vehicles did better than 1977 Federal emissions levels. Most often, getting the engine to run smoothly was a higher priority than achieving low emissions when time was running out for development. We were aware of at least two teams that had an electrically heated catalyst that would be invoked before engine-start, but system integration problems prevented the teams from using the devices during the competition. All Saturns used M85 and E95 fuel, all Neons used CNG. Converting the engine to run on an alternative fuel is challenging and only a few teams were fully successful at it.

SOC CORRECTION EFFECTS - Although much of the data taken during the dynamometer portion of the competition fell short of demonstrating the potentials of HEV technology, analysis of hybrid test methodology and the calculation of the results proved to be very important to the efforts in HEV test procedure development which, at this point, is still in its infancy. In fact, the data from the 1995 HEV Challenge testing represent some of the first HEV test data from vehicles with varying designs using SOC-correction methods. It is important for the development of HEV testing methods that we analyze actual results to work out problem issues and look at how various designs and control strategies affect the outcome of the test.

Differences in Ford Class Procedure and SAE-Based Procedure - The two test procedures take different approaches, but they both use a scheme in which two test results are mixed to get a single result. The Ford procedure uses emissions and fuel consumption rates on a per-mile basis, and the SAE-based procedure interpolates between two test runs to get the final result.

To quantify the difference between the calculation methods, the test data from some Ford class HEVs were SOC corrected by using the two-point interpolation method. The results of these calculations are in Table 4. The results are very close because the actual calculations are very similar, with one exception: the SAE interpolation method assumes that the distance traveled in each test is the same. Because this slight variability is taken into account in the Ford Class method, the difference in results is varied, but small.

The results in Table 4 use only the calculation methods of the SAE procedure; if the Ford HEVs were actually tested according to the SAE procedures, the vehicles would have been tested differently. The upper and lower limits tests of the SAE method are defined within HEV operation, after the ZEV range has been exhausted. In most cases, the vehicles would start running in ZEV during the upper-limit SOC test, but they would eventually switch to an engine-on operational mode at some time during the test.

Table 4: SAE Fuel Economy Calculation of Ford Class HEVs

Vehicle	Ford Class Method	SAE Calculation Method	Percent Difference
US Navy	20.79	20.76	0.15%
Alberta	26.18	26.24	-0.24%
Wisconsin	22.18	22.14	0.18%
Wst Virg	22.19	22.20	-0.06%

The SOC correction graphs illustrate differences encountered with the two test methodologies. The fuel economy graphs (Figures 1 and 2) show very predictable trend lines, but the emissions graphs (Figures 3 and 4) show data that appear much less predictable. Because much of the emissions from an entire test cycle come from the engine-start, the emissions trend lines would look very different if two engine-on tests are compared to a set of tests in which the engine was not operated in one of the tests. This anomaly will be more pronounced if the engine were to start during one of the tests, but only operate for a short period. In this situation, a significant amount of emissions would be associated with a small amount of charging and would result in shallower trend lines and higher calculated SOC-corrected emission rates.

Control Strategies and Test Results - It was encouraging to find that all the tests essentially behaved as expected with regard to changes in SOC during the HEV tests. The SOC rose and fell when expected, even though only a few vehicle-control strategies actively monitored the SOC to control hybrid operation.

Only the GMI and CSU Fresno vehicles were in an engine-on operational mode for both the upper and lower SOC tests. These two charge-sustaining HEVs were designed to operate with the engine always on. All others were in ZEV mode for the high SOC test. The CSU Fresno design was a classic "power-assist" parallel HEV design with a down-sized engine and a power-peaking electric-propulsion system. The team's hybrid control system was based upon the throttle position for input into the hybrid controller. Apparently, the interaction of throttle position with the engine and motor demands changed with SOC to yield a SOC correction plot with predictable trend lines.

The GMI hybrid control strategy was a robust passive, open-loop system. The vehicle operated with the engine always on, generating power at a higher bus voltage than the battery pack. The batteries stay within an operating SOC range with bus voltage equalization. When the electric motor is engaged, the bus voltage drops, thus causing more current to flow and the engine to work harder; when the battery SOC drops, the engine to works hard again. At a high SOC the generator voltage is matched with the bus voltage preventing charge to flow into the batteries. The high SOC test and the low SOC test did produce a SOC correction line (on Figure 1) as expected, but the slope is very level compared with that for other vehicles. Apparently, the initial SOC at which the vehicle was tested resulted in the batteries contributing significantly different amounts of energy, but with only a small difference in fuel consumption rates were associated. It appears the engine operation was effected very little by the amounts of on-board charging.

The Ford HEVs were given an FTP emissions test at a SOC low enough to cause the engine to work at its hardest, thus the vehicle should charge-sustain if it were capable. There were, however, two HEVs that were not charge-sustaining on the FTP cycle. Two factors affect the charge sustainability of an HEV: the engine / generator size, and the hybrid control strategy. The West Virginia HEV was charge-sustaining in 1994 with the same series hybrid design, but in 1995, the vehicle depleted its charge because the engine was operated at a lower power setting. The Alberta HEV was a parallel HEV with adequate component ratings; evidently, it was designed in such a way as to take more charge from the batteries than was replaced during hybrid operation. It is likely that the engine and the on-board charging system possessed the capacity to keep the charge up, but it was not designed to do so.

CONCLUSIONS

KNOWLEDGE OF CONTROL SYSTEMS - From the perspective of the test operator, the most important realization taken from this experience is the large degree of knowledge that is required of each vehicle's operational behavior to ensure a successful test. Because the test procedure is merely a "snapshot" of data to represent its performance, the HEV's operation must be understood to ensure that the data are representative and can be comparable with other HEVs with different designs.

Obvious vehicle features, such as vehicle controls, how and when to shift, selecting the correct modes, and when and if to charge the batteries, can be somewhat standardized or explained through documentation. But beyond these features, general vehicle characteristics (like charge-sustaininablility, ZEV range, and expected engine contribution) require accurate understanding. An interactive dialogue is needed for each vehicle to better understand which parameters affect vehicle operation and how the vehicle is expected to react to these inputs throughout the test procedure.

For example, a parallel load-leveling HEV control strategy may rely on any number of inputs to control the torque input to the electric motor, which will ultimately affect the SOC trend during various modes of the test procedure. Possible control inputs are throttle position, vehicle speed, engine manifold pressure, battery bus voltage, and Ah or kWh integration. We have seen control strategy complexity to the extent that throttle pedal inputs must be characterized as whether designed in series (e.g., the first half of pedal travel is zero to wide open throttle; the last half of travel is motor torque control) or in parallel (e.g., the engine throttle and motor torque are ramped up together). New and different complexities in control strategies are continually found in the student-designed vehicles.

SOC MEASUREMENT - Although we are confident in the data acquisition system's ability to measure and calculate accurate Ah integration data, the degree of correlation between Ah and actual battery SOC throughout the testing in unknown. We did not have time during the competition to pre-condition and post-test the batteries to derive margins of error in SOC measurement. Other engineers with experience in testing EVs and HEVs have indicated that SOC monitoring and repeatable battery performance is a significant challenge and may never be fully overcome.

SOC CORRECTIONS - SOC corrections are an important tool in comparing radically different HEVs side by side, but the results generated by these methods can never be fully exact. Only a comprehensive statistical database of a particular vehicle will show the full operational picture, but this approach is in conflict with applying routine, practical test procedures. Unfortunately, the limitations of SOC corrections, coupled with inherent SOC measurement problems and battery repeatability issues, make acquiring accurate vehicle test results difficult. Perhaps careful battery conditioning and additional test runs may lessen these problems and eventually become accepted requirements in future HEV procedures.

SOC-CORRECTED EMISSIONS RESULTS - The SOC-correction methods explored in our testing appeared to work well in calculating the fuel-only-based vehicle efficiency. The slope of the normalized SOC-correction graphs predictably show trend lines that are loosely equated to on-board charging rates. In contrast, the emissions data are highly unpredictable because each exhaust constituent reacts differently to changes in engine operation.

In addition to test variabilities, the test procedure itself may also radically affect the final results of emissions tests. Conventional vehicles always have a predicable engine-start at the beginning of the FTP test, but depending on the SOC, past battery history, test procedure order and duration, some HEVs may have multiple engine-starts or unique operating events occurring at any time during the test cycles. Future HEVs will likely be designed with particular test procedures in mind to achieve the best results.

FORD CLASS TEST PROCEDURE - The draft SAE procedure is very close to completion and will most likely become the standard test procedure. The concepts used in testing the Ford Class HEVs may, however, be useful to HEV experimenters who want a quick dynamometer test that does not require multiple days and yet provides enough information for SOC corrections. If the vehicle is ZEV-capable with at least 8-10 mil of ZEV range, then the vehicle is suited for this test procedure.

HEV CHALLENGE RESULTS - The actual performance of the student-built prototypes indicated the potential capabilities of HEV technology, but the unfortunate hard luck experienced by many teams left a database with little information about trends, design advantages, and emissions and fuel economy projections for future HEV technology. However, if we include the best results from the 1994 competition, the potential of HEVs look promising. On the city FTP cycle, fuel efficiency results of 48.1, 39.8 and 33.6 MPG were achieved by last year's converted HEVs and a ground-up vehicle achieved 35.0 MPG. More teams in 1994 achieved fair emissions results; two vehicles tested better than Tier 0 emissions values, and one vehicle tested better than Tier 1.

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