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Technical Analysis of the 1994 HEV Challenge

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ABSTRACT

The 1994 Hybrid Electric Vehicle Challenge provided the backdrop for collecting data and developing testing procedures for hybrid electric vehicle technology available at colleges and universities across North America. The data collected at the competition was analyzed using the HEV definitions from the draft SAE J1711 guidelines. The energy economy, percentage of electrical to total energy used, and acceleration performance was analyzed for any correlation between the over-the-road data and the commuter-sustaining, commuter-depleting, and reserve-sustaining hybrid vehicles.

The analysis did not provide any direct correlation between over-the-road data and the three hybrid types. The analysis did show that the vehicle configurations provide the best information on vehicle performance. It was also clear that a comprehensive data analysis system along with a well-defined testing procedure would allow for a more complete analysis of the data.

INTRODUCTION

The 1994 Hybrid Electric Vehicle (HEV) Challenge involved 36 universities and colleges. The intent of the Challenge was to have teams design and build hybrid electric vehicles with performance targets similar to that of today's vehicles, while meeting stringent safety requirements. These vehicles provided data on current hybrid electric vehicle technology and were not considered as near-term production vehicles. These vehicles were quite complex and varied in design. This large number of complex vehicles made the analysis of the data difficult.

The HEV Challenge tested these vehicles for acceleration, range, emissions, and energy economy. The HEV Challenge consisted of three distinct classes of vehicles: Escort Conversion Class, Ground-Up Class, and Saturn Conversion Class. Except for the Saturn Conversion Class, there was no limitation on the type of hybrid electric vehicle a team could design. While the vehicles competed in these three distinct classes, this paper focuses on classifying the hybrids on the basis of performance data and the intent of the vehicle design.

BACKGROUND

The hybrid electric vehicles in the 1994 HEV Challenge consisted of one of three types of hybrids (termed commuter-sustaining, commuter-depleting, and reserve-sustaining). The vehicle control strategies were to be passive, and the battery minimum range was specified for certain vehicle classes. A hybrid electric vehicle type refers to the intent of the vehicle control strategy and the intent of the vehicle design. The vehicle could be an urban vehicle which incorporates an internal combustion engine (ICE) for extended range or high load situations. Another role for a hybrid electric vehicle may require that it operates as an all-purpose vehicle, not limited to designated driving cycles.

The students were required to define use of their HEV. Because the vehicles differed in design and purpose, analyzing the data became difficult. The industry has only recently begun developing formal performance characteristics and design specifications for a hybrid electric vehicle. The Society of Automotive Engineers established a task force to develop a recommended practice for uniform testing of HEVs. This draft procedure is called the *Recommended Practice for Measuring the Electric Energy Consumption, All Electric Range, Fuel Economy, and Exhaust Emissions of Hybrid Electric Vehicles -- SAE J1711* [1]. The structure of this paper follows these guidelines for defining hybrid vehicles.

The basic philosophy of the draft HEV procedure focused on "defining hybrids via the vehicle driving mission (available combination of driving modes) and not concentrating on the vehicle design" (Task Force Draft Minutes 1/24/93[2]). The HEVs involved in the Challenge have not been defined through these test procedure, but by the vehicle driving mission, using the vehicle specifications.

MASTER

The data analyzed was collected during the Range Event, Emissions Event, and Acceleration Event. The Range Event was limited to 3 hours, and 20 minutes over a 3.54km loop. Vehicles traveled in HEV mode and, because of extreme weather conditions, the teams made stops every 30 minutes for a driver change. Speeds were limited to a top instantaneous speed of 88 km/h and a minimum of 64 km/h with an average of 72 km/h. The terrain consisted of straight-aways and hills with grades close to 8.22% over 4.6m. The amount of liquid fuel, electrical fuel, and distance covered was collected to analyze the energy economy of these vehicles.

The Emission Event for the Ground-Up and Escort Conversion Class consisted of a modified Federal Test Procedure (FTP). Four pollutants, total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and nitrogen oxides (NOx), were tested. The vehicles began the test completely charged. The vehicles ran phases 1 and 2 of the FTP (one Urban Driving Schedule (UDS)) in the zero emissions vehicle (ZEV) mode and a typical FTP in HEV mode. The portion of the ZEV emissions test provided the data for state of charge (SOC) adjustments to the hybrid gram per mile values. The vehicles had to attain simultaneous control of all four pollutants to score in this event. Using the results from the HEV Challenge Emissions Event, the hybrids that successfully completed the test could be labeled using the SAE draft guidelines.

The Acceleration Event was held over a 201m straight-away. Vehicles started from rest and accelerated over the complete distance for the fastest times. The Ground-Up and Escort Conversion Class had to run in both ZEV and HEV modes to be eligible for the total points. The Saturn Conversion class ran only in HEV mode.

RESULTS

COMMUTING ELECTRIC RANGE, CHARGE - DEPLETING (CD) HEVS - These HEVs contain a usable all-electric range that is greater than twice the UDS measured from a 100% SOC and at least two Highway Fuel Economy Test (HWFET) cycles. This is the definition for the commuting, all-electric range. The vehicle is considered to have a battery-depleting hybrid mode if the electrical energy originally supplied from an off-board charger is depleted during the same time that the consumable fuel on-board is used [1].

Generally, the vehicle design incorporated an electric motor configuration with a large battery capacity (for a greater electric vehicle (EV) range) combined with a smaller kW powered engine. The vehicles consisted of both parallel or series configuration.

There were three vehicles that tested as CD hybrids from the emissions tests. These vehicles included the ones from Califonia State Polytechnic University, Pomona, University of Tulsa, and University of Alberta. The remaining HEVs categorized as CDs had control strategies that were battery depleting. Information provided in the team technical reports was used to classify these vehicles. Where information on the control strategy was missing, the description of the intent of the design of the vehicle was used to classify the vehicles. Teams described their vehicle as a CD or described the use of the vehicle for urban commuting with the internal combustion engine (ICE) available for supplemental power for additional range. The vehicle would be used primarily as an EV for urban commuting, but would utilize the ICE for high-power situations or extended range with no battery state of charge sustaining capabilities.

COMMUTING ELECTRIC RANGE, CHARGE-SUSTAINING (CS) HEVS - This HEV contains usable all-electric range requirements of a CD but has a battery-sustaining hybrid mode. Battery-sustaining means these vehicles are able to drive continuous UDS cycles without a net drop in SOC and they are able to drive continuous HWFET cycles without a net drop in SOC [1].

CS hybrids consist of parallel or series configurations. The range performance of the CS hybrid in HEV mode is limited to the amount of liquid fuel available for the ICE.

Three vehicles that successfully completed the emissions testing for the HEV Challenge tested as CS hybrids. These vehicles are from the University of California, Davis, University of Illinois - Urbana, and West Virginia University. The University of Illinois stated in their technical report that their vehicle was designed as a range-extender but they are categorized in this paper as a CS hybrid on the basis of their performance data [3]. Based on the descriptions of the control strategies and hybrid modes, the remaining teams were categorized as CS hybrids.

RESERVE ELECTRIC RANGE, CHARGE-SUSTAINING (RS) HEVS - These HEVs have little or no all-electric range, but are able to drive continuous UDS cycles without a net drop in SOC, and they are able to drive continuous HWFET cycles without a net drop in SOC. Therefore, they are considered battery-sustaining hybrids [1].

The RS hybrid has a minimal electric-only range and operates in a hybrid mode at all times. The strategy of this type of hybrid uses the auxiliary power unit to provide additional power at high-load situations. There was not enough data available from emissions tests that could be used to categorize the Saturn Class hybrids as was done for the Ground-Up and Escort Classes.

The Saturn Conversion Class was structured to have the teams design a power assist hybrid. Analysis of the Saturn Class is based on the assumption that all of these vehicles were designed as RS hybrids.

TECHNOLOGY OVERVIEW - The component selection of the teams ranged from lead-acid batteries to nickel metal hydrides; dc series motors to ac induction motors; and a 570cc Briggs & Stratton engines to Geo 1.0L engines. There was no difference in the component selection due to the type of hybrid vehicle or due to the vehicle configuration (series and parallel).

The size of the electric motor (EM), the ICE, and the total battery energy available are graphed for each type of hybrid (Charts 1 & 2). The CD and CS hybrids were comparable in total battery energy ranges and sizing of the EM and ICE. Each type of hybrid is further broken down in these charts by the parallel configuration and the series configuration. The series configurations for both hybrid types have total battery energy available averaging 11.5kWh (CS) and 13.6kWh (CD) compared to 11.6kWh (CS) and 12.6kWh (CD) for the parallel configurations. The power selection of the electric motor did not vary from the CD to CS hybrids. The power selection range of the

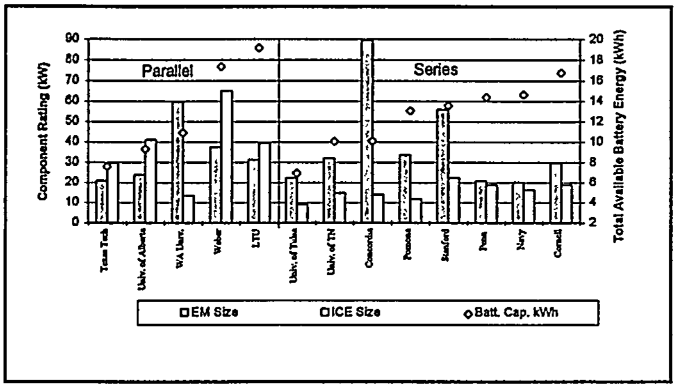

CHART 1. Breakdown of Component Power and Total Available Battery Energy for Commuter-Depleting Hybrids.

EM in the RS hybrids was smaller, ranging from 13.0kW to 53.7kW compared to 8.9kW to 89.5kW for CD and CS hybrids.

Chart 3 shows the component selection for the RS hybrids. The RS hybrids had a smaller total battery energy, as expected for this hybrid type, averaging 5.0 kWh. The ICE power selection was 18% higher for the RS hybrid

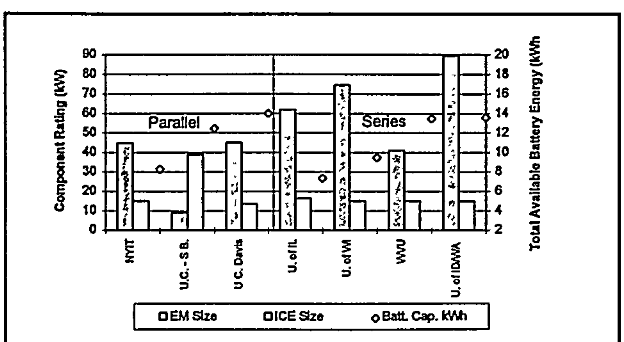

CHART 2. Breakdown of Component Power and Total Available Battery Energy for Commuter-Sustaining Hybrids.

than for the CS and 41% higher than for CD hybrids (averages 18.9kW and 26.1kW, respectively). The lowest ICE power (31.9kW) selection was found in the University of Tulsa's vehicle, a series configuration CD hybrid (9.10kW).

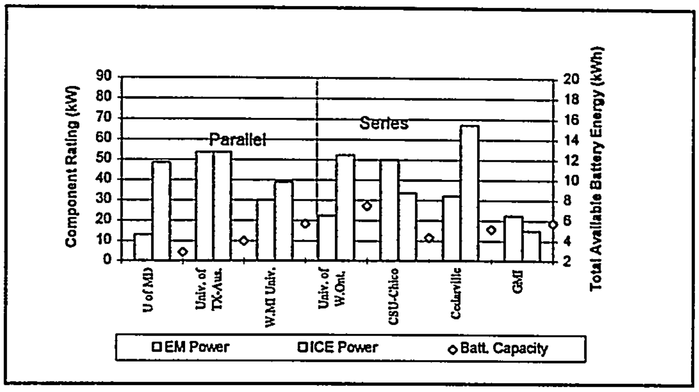

CHART 3. Component Power Rating and Total Available Battery Energy for Reserve-Sustaining Hybrids.

The majority of the control strategies of these vehicles used feedback from the battery pack's SOC to determine the ICE operation schedule. Other systems were manually controlled, on the basis of the power requirements for the current driving conditions. The summaries of a few of the vehicles presented are simplified descriptions the control strategies.

Cal. Poly-Pomona stated that the design of their vehicle emphasized the ZEV operation. There were control switches for ZEV and HEV modes as required from the rules of the HEV Challenge. This series configuration controlled the power output of the ICE to equal the amount of energy used to drive the vehicle. The battery voltage was monitored for any drops below 110 V. There was some on-board charging that was self-regulating [4]. Another series configuration CD hybrid regulated the ICE differently. Stanford operated the ICE at a constant speed. The ICE operated at a constant load while the alternator regulated the power output of the engine. In the team's paper, the control strategy ideally would monitor the battery state of charge (volts and amps), along with the battery temperature and fuel level [5]. Texas Tech a parallel configuration CD hybrid, monitored the ICE operation for constant revolutions per minute (RPM) and torque. The controller matched the output of the electric motor to the ICE drive shaft [6].

The CS hybrids showed up with similar systems. The University of Wisconsin a series CS hybrid, used the battery state of charge as the determining factor in the start-up of their ICE. The power from the ICE was delivered to the batteries, which is a similar setup to Cal. Poly-Pomona [7]. West Virginia's strategy varied slightly from the other series hybrids. The controller of the ICE sent power to the system controller, where the power was distributed to the motor and batteries. The SOC of the battery pack was still monitored to determine the allocation of the power from the

ICE. The ICE output was kept constant [8]--a slightly different twist to the strategy.

University of California, Davis had a parallel, CS hybrid. Unique to this vehicle was the component selection for a parallel configuration. Instead of utilizing the ICE as the primary power source, the electric motor provided the motive power. Similar to a CD series design, the EM provided power for city driving, while the ICE took over at highway speeds. The control strategy involved monitoring the battery pack's SOC to determine remaining range. The EM started the ICE for high-speed starts. The fuel management system disabled the electronic fuel injection until the ICE reached the proper speed. Under high discharge conditions, the ICE provided the cruising power, while the electric motor assisted in high load situations [9].

The University of Maryland, a parallel, RS hybrid had one of the most complicated control systems of these vehicles. The control strategy used inputs from the battery state of charge and the accelerator pedal position, to control the load level of the ICE, which is assisted from the EM. This scheme would operate the ICE at its more efficient range. The second stage of the strategy required the controller to monitor the manifold air pressure to adjust for the necessary power requirements to optimize fuel economy [10].

ENERGY ECONOMY RESULTS - The HEVs from the 1994 HEV Challenge were sorted into the hybrid classes on the basis of the emissions testing performed at the competition and the description of the control strategies in the technical papers. While only seven vehicles had enough complete data to break down into hybrid types, the majority of the vehicles did have data collected from performance events at the competition. These seven vehicles completed the emissions test cycle (FTP) in ZEV and HEV or ICE-on modes. The energy consumption for each vehicle was graphed (see Chart 4) to show the comparison of electrical energy used in the ZEV and HEV modes (or ICE-on mode). The ICE-on mode forced the ICE to be

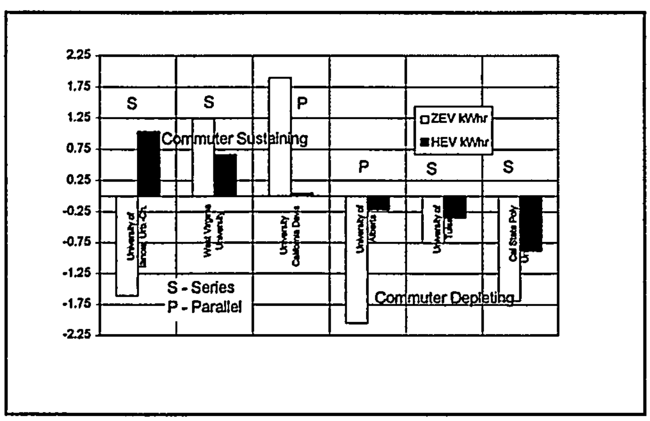

CHART 4. Break down of CD and CS hybrids on the basis of the HEV Challenge Emission Results.

operational. If the vehicle completed the HEV test without depleting the SOC of the battery, then the vehicle was assumed to be a CS hybrid.

The comparison of the HEV electrical to the total HEV energy was made from over-the-road data collected during the Range Event and the Emissions Event. These two events did not use the same cycle. Converting to kilowatt-hours, the percentage of electrical to total energy was calculated for the University of Alberta, West Virginia University, Cal Poly.-Pomona, University of California, Davis, and University of Tulsa. By comparing the amount of electrical energy to the total energy in the hybrid mode, some correlation between the results of the emissions testing and the Range Event can be seen (see Chart 5). The results from the Range Event followed the trend in the Emissions results. It must be pointed out that this analysis

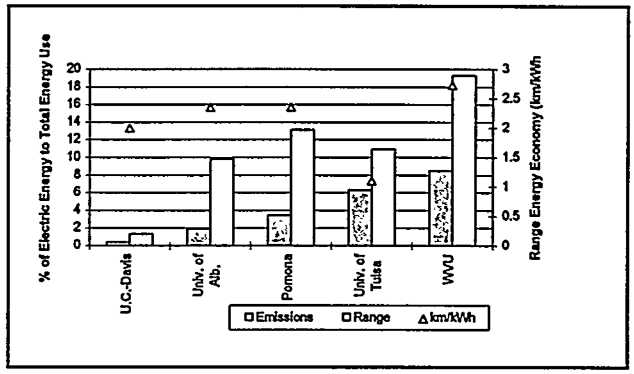

CHART 5. Comparison of the Percentage of Electrical to Total Energy Used in the Hybrid Mode for the Emissions and Range Events.

did not take into account the strategy of the ICE. University of California, Davis used the lowest percentage of electrical energy in both instances, whereas West Virginia University used the largest percentage electrical energy. University of California, Davis was the only one of these vehicles that used the ICE without any input from the EM during their emissions test. Their vehicle would have been battery-depleting if both power sources were invoked.

The percentage of electrical energy increased for vehicles in the Range Event compared to the results from the dynamometer rolls. This increase is due primarily to the variation in the track and change of drivers during the Range Event.

From the Emissions Event, University of California, Davis had the lowest percentage of electrical energy, 0.2%, following a battery-sustaining hybrid strategy. West Virginia University, also a CS hybrid as defined from the Emissions Event, was at the other end of the spectrum, using close to 8.6% of the total energy for electrical power. The management of the energy consumption by the control strategy cannot be determined through this analysis. Analysis of the second-by-second data and a larger data sampling would help support this analysis. Preliminary analysis of these control strategies suggest that they are still in their infancy and require further refinement.

The remaining hybrid vehicles were categorized based on the description of the control strategy stated in the technical papers. Without the battery depletion information from the state of charge, no direct comparison could be made using the guidelines from the draft SAE HEV Emissions Test Procedure. This information is critical to the analysis of the road data and analyzing the effectiveness of the vehicle's hybrid strategy.

The road data collected from the Range Event was used to compare energy economy of the three hybrid types. Chart 6 shows the energy economy (km/kWh) for each vehicle which was categorized as a CD, CS, or RS hybrid. Though there is not a large difference between these vehicles in the lower economy ranges, CS hybrids show a tendency to have slightly higher economies than the other categories. The average energy economy for the CD hybrids was 2.23km/kWh compared to 1.83 and 1.48km/kWh for the CS and RS, respectively. The reserve-sustaining group had the poorest performance of the three. This class, new in 1994, had the least amount of time to optimize their vehicles which would also account for lower energy economy results.

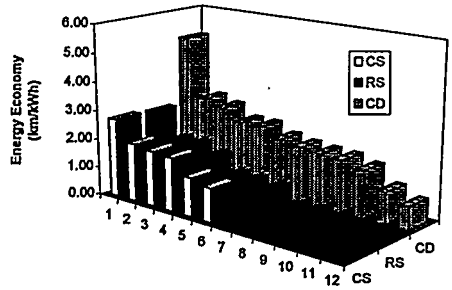

CHART 6. Energy Economy Results for the CS, CD and RS Hybrids.

Breaking down the comparison between the series and parallel configurations, the parallel vehicles demonstrated greater energy economy values (see Chart 7). This correlation supports the higher fuel economy for the CS hybrids, since the majority of the CS hybrids were of parallel configurations.

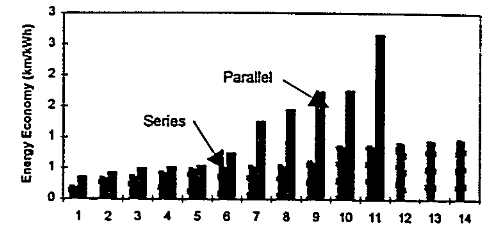

CHART 7. Range Event Energy Economy of All Vehicles by Hybrid Configuration.

ACCELERATION PERFORMANCE RESULTS-The Acceleration Event consisted of a 201m straight-away. The Escort Conversion and Ground-Up Classes were required to make a minimum of two runs, one in HEV mode and the other in ZEV mode. Runs in both modes were required since these classes had to have a minimum 40.2km range in electric-only mode. The Saturn Conversion Class ran only in HEV mode. Only the acceleration runs made in the HEV mode were examined for all vehicles.

To see if there were any performance differences in the acceleration of the hybrid type, a comparison was made of the combined available power for both the CS and CD and the acceleration times. The power ratings for the EM and the ICE were combined for the parallel configurations (see Chart 8), while the series configurations (see Chart 9) showed the power ratings side by side. Parallel hybrids had faster times for the 201m run. Weber State, a CD, split-parallel hybrid, had the fastest time at 12.44 seconds. This vehicle incorporated a 1.0 L Geo engine combined with an Advanced DC series motor (37.3 kW). The slowest time was recorded at 22.63 seconds for the University of Tulsa. This vehicle was a CD series hybrid. The University of Tulsa's hybrid was under-powered, using a 22.39kW Baldor Electric AC Induction motor and a 9.10kW, 359cc Honda engine.

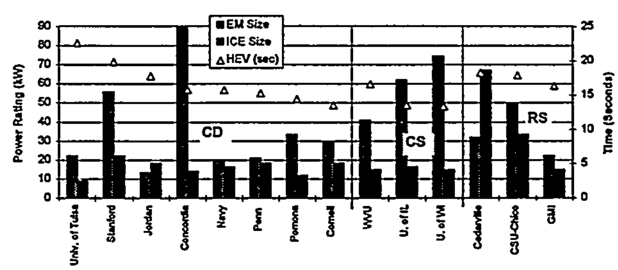

CHART 8. Acceleration Times for CD, CS, and RS Series Configuration Hybrids.

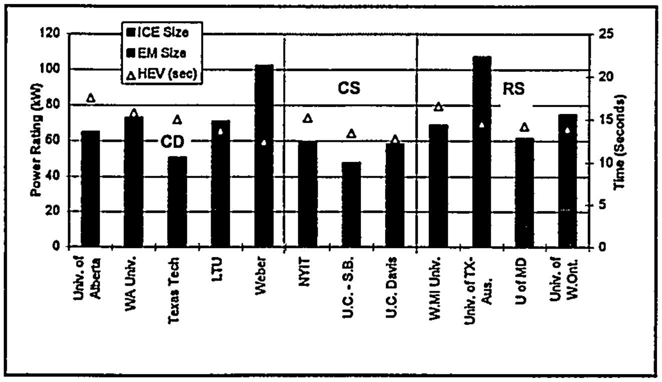

CHART 9. Acceleration Times for CD, CS, and RS Parallel Configuration Hybrids.

While the acceleration times are distributed over a larger range, there does not appear to be any distinct difference in the times for the CS, CD, and RS hybrids. Those vehicles incorporating a large EM had faster acceleration times for the CS and CD hybrids.

DISCUSSION OF RESULTS

The analysis compared energy economy, percent of electrical-to-total energy, and vehicle acceleration for the three hybrid types. By breaking down each hybrid type into the two configurations for hybrids, a comparison was made to try to better understand the vehicles and their control strategy with available performance data.

The CD hybrids demonstrated slightly higher energy economies than the CS and RS hybrids. These hybrids may have fewer losses as a result of the control strategy. There is no need to redirect the power of the ICE to maintain the SOC of the battery pack. Both the RS and CS must continuously provide energy to the battery pack to remain battery-sustaining. There are more losses associated with a system where the energy from the ICE charges the battery pack, which in turn provides energy to the EM to power the vehicle compared to systems that direct energy to power the vehicle. The RS showed the lowest energy economy results. The RS hybrid's strategy utilized the ICE throughout operation of the vehicle to maintain the battery SOC, which would account for some of the lower energy economy results. Another impact on the energy economy was the amount of time available to the students to optimize their design and thoroughly test their vehicles. This class was newest to the 1994 HEV Challenge.

The breakdown of the electrical energy to total energy used in both the Emissions test and the Range Event did not provide any new information on hybrid types. It was apparent from Chart 5 that a larger percentage of the electrical energy is used on the road versus on the dynamometer rolls. This discrepancy between the energy consumption results from the variation of the road and drivers in the Range Event. The configuration of the vehicles is still the dominant factor in the allocation of energy and performance of the vehicle. In Chart 10, the number of vehicles in each hybrid type did not show any trends in the amount of electrical energy used compared to the total energy. The CS hybrids stayed within the lower end (less than 20%) of the amount of energy used.

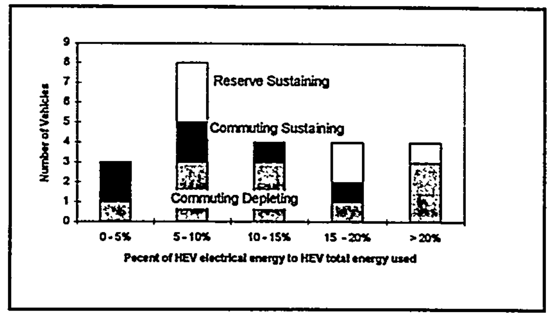

CHART 10. Breakdown of CD, CS, and RS Hybrids by Percentage of Electrical Energy to Total Energy Used in HEV Mode.

The control strategies of these vehicles require the systems to maintain a constant SOC on the battery pack, so the total electrical energy used should be small. The CD hybrids ranged from the very low to an excessive amount of electrical energy used. This scattering of results indicates the system configuration of the CD hybrid was the primary indicator of the amount of electrical energy used. The RS hybrids did not fall into any one percentile range.

A final analysis centered on the acceleration performance characteristics of the hybrids. Further breakdown of the vehicles by system configuration provided more information on the vehicles. The parallel configurations in all three hybrid types had consistent acceleration times. The parallel configurations had slightly faster acceleration times than the series vehicles. Since the power of both the ICE and the EM go to the wheels instead of one system powering the other, the parallel systems had lower acceleration times. The combined power of the EM and ICE ranged between 32kW and 107kW, as seen consistently throughout each parallel, hybrid type. The variation of the power ratings for the EM and ICE does not seem to have any impact on the acceleration times for the parallel configurations.

The differences between the hybrid types in the series configuration is more apparent. Throughout the series configurations, the size of the EM is significantly higher than the ICE (as much as 6 times larger). This is especially the case with the CS hybrids, where their overall acceleration performance is faster. The CD hybrids also have larger EMs than ICEs, but the difference is not nearly as large (factor of 2.8). The slowest series configurations are the RS hybrids.

CONCLUSIONS

The 1994 HEV Challenge had three distinct hybrid electric vehicle types participate. The raw data presented in this paper provides a general overview of the vehicles at the competition. The Commuter-Sustaining hybrid vehicles had slightly lower energy economy, higher usage of electrical energy, and slightly faster accelerations then the Commuter-Depleting or the Reserve-Sustaining hybrids. The Reserve-Sustaining hybrids were the weakest performers in all areas, but this is most likely due to the short amount of time teams had to fully develop their vehicles. The second year vehicles, both CD and CS hybrids, were more reliable and demonstrated better overall performance. The raw data presented shows a large range of vehicle design, systems integration and performance from the HEV Challenge. These vehicles were hand-built with technology currently available and affordable. The control strategies of these vehicles show promise, but they require further development.

The raw data and the vehicle descriptions provided by the teams were useful in breaking down the vehicles based on the SAE J1711 guidelines, but they were not sufficient. The HEV Challenge provided the testing ground for collecting data on a multitude of hybrid electric vehicle technology. What is apparent is that these vehicles are complex and the method of collecting data and testing these vehicles is just as complex. Each year this process is modified and further refined. The 1995 HEV Challenge will provide another opportunity to test these vehicles and collect more comprehensive data on the most successful hybrid designs in energy economy, performance and reliability.

ACKNOWLEDGEMENT

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APPENDIX

Table 1. Vehicles listed by hybrid type with EM and ICE size and hybrid configuration.

School	EM Power (kW)	ICE Power (kW)	Hybrid Config.
Commuter-Depleting			
Cal Poly-San Luis Obispo	18	36.5	Parallel
CO School of Mines	32	16.4	Series
Concordia University	89.5	14.2	Series/parallel
Cornell University	29.8	18.6	Series
Jordan College	n/a	18.6	Series/parallel
Lawrence Tech. Univ.	31.3	39.5	Parallel
Michigan State Univ.	38.5	63.4	Series
Penn State	21	18.6	Series
Stanford University	55.9	22.4	Series
Texas Tech	21	29.8	Parallel
U.S. Naval Academy	20.1	16.4	Series
University of Alberta	23.8	41	Parallel
University of Tennessee	32	14.8	Series
University of Tulsa	22.4	9.1	Series
Washington Univ.	59.7	13.4	Parallel
Weber State Univ.	37.5	65	Parallel
Commuter-Sustaining			
NYIT	44.7	14.9	Parallel
Univ. of Cal. Davis	45	13.4	Parallel
Univ. of Cal. - SB	8.9	38.8	Parallel
Univ of ID/WA State	89.5	14.8	Series
University of Illinois	62	16.4	Series
University of WI	74.6	14.9	Series
West Virginia Univ.	36.1	41	Series
Reserve-Sustaining			
Cal State Univ.-Chico	50	33.6	Series
Cedarville	32	67.2	Series
GMI	22.4	14.9	Series
Univ. of Maryland	13	48.5	Parallel
Univ. of Texas-Austin	53.7	53.7	Parallel
Univ. of W. Ontario	22.4	52.2	Parallel
West. Michigan	30	38.8	Parallel

Table 2. Ground Up Class Vehicle Data

SCHOOL	Cornell University	CSPTU, Pomona	Lawrence Tech.	Michigan State University	New York Inst. Tech.	University of Texas, Arlington	UC Santa Barbara	USPSU, San Luis Obispo	Univ. of Idaho/ Washington State	University of California, Davis	University of Tennessee	University of Tulsa
VEHICLE INFO												
CAR_NUMBER	16	37	5	19	15	32	39	25	27	40	21	20
HYBRID_CONFIGURATION	Series	Series	Parallel	Series	Parallel	Parallel	Parallel	Parallel	Series	Parallel	Series	Series
VEHICLE_WEIGHT (kg)	1221.1	1116.3	1623.4	1490.9	1229.7	1091	1237.4	1261.4	1832.1	1198.4	1216.5	1625.22
CHARGING EFFICIENCY	0.87	0.79	0.44	0.75	0.75	0.75	0.79	0.68	0.85	0.82	0.76	0.73
ENGINE_MANUFACTURER	Kohler	Briggs & Straton	Geo	Suzuki	Kawasaki	Honda	Geo	GEO	Kohler	Briggs & Straton	Kohler	Honda
ENGINE SIZE (cc)	725	480	1000	1000	617	600	1000	993	622	570	624	359
ENGINE_POWER (kW)	18.6	12	39.5	63.4	15	74.5	38.8	36.5	15	13.4	15	9.1
FUEL_TYPE	M85	R GAS	R GAS	M85	R GAS	M85	E100	R GAS	R GAS	R GAS	R GAS	R GAS
TANK_CAPACITY (l)	42.4	38	37.8	28	x	37.8	30.3	11	56.8	34	30.3	30
MOTOR_MANUFACTURER	Unique Mob/Adv. DC	Advanced DC	Unique Mobility	GE / LEM	Advanced DC	Solectria	Solectria	Solectria	AC Propulsions	Unique Mobility	Unique Mobility	Baldor Electric
MOTOR_TYPE	Brushless DC	DC Brush	18 pole PM DC	AC Induction	DC	3phase Brushless DC	AC Induction	AC Induction	AC Induction	DC	DC	AC Induction
MOTOR_POWER (kW)	30	33.5	31.3	38.5	44.7	22.4	9	18	89.5	45	32	22.4
BATTERY_TYPE	Pb-acid	Pb-acid	Pb-acid	NiMH	Pb-acid	Ni-Cad	Pb-acid	Pb-acid	Pb-Acid	Ni-Cad	Pb-Acid	Pb-Acid
VOLTAGE	168	120	192	340	96	170	144	120	336	156	180	348
BATTERY_CAPACITY (kWh)	16.8	13.12	19.2	11.56	8.31	6.8	12.47	12.79	13.61	14.04	10.08	6.96
GENERATOR	Fisher	Fisher Elec.	x	Fisher Elec.	Unique Mobility	x	x	x	Fisher Elec.	x	Leece-Neville	Honda
EMISSIONS												
ZEV												
DISTANCE (km)	11.23	12	0	10.66	0	0	0	0	10.49	12.08	7.76	6.32
AMP-HOURS	-8.12	-15.02	0	0	-17.34	0	0	0	-6	0	0	-3
kWh	-1.34	-1.69	0	0	-1.73	0	0	0	-1.53	0	0	-0.76
km/kWh	-8.38	-7.1	0	0	0	0	0	0	-6.86	0	0	-8.32
HEV												
DISTANCE (km)	16.56	17.8	0	17.17	13.95	0	17.49	0	17.64	16.77	0	6.8
AMP-HOURS	0	-7.85	0	0	0	0	0	0	0	0.35	0	-1
kWh	0	-0.88	0	0	0	0	0	0	0	0.04	0	-0.35
km/kWh	0	-20.23	0	0	0	0	0	0	0	419.25	0	-19.43
FTP g/m												
HC	0.305	0.877	0	0.177	1.016	0	0.578	0	0.334	0.208	0	1.647
NMHC	0.775	0.775	0	0.142	0.855	0	0.182	0	0.24	0.182	0	1.549
CO	18.06	13.82	0	0.2	48.58	0	26.07	0	28.37	2.47	0	28.1
NOX	0.02	0.06	0	13.33	0.03	0	0.58	0	0.05	0.34	0	0.03
CORRECTED g/m												
HC	0	0.427	0	0.177	0	0	0	0	0.334	0.204	0	1.313
NMHC	0	0.378	0	0.142	0	0	0	0	0.24	0.178	0	1.235
CO	0	6.734	0	0.2	0	0	0	0	28.37	2.417	0	22.4
NOX	0	0.029	0	13.33	0	0	0	0	0.05	0.333	0	0.024
ENERGY ECONOMY												
ACCELERATION												
EQ_GAL (kWh)	7.08	24.01	13.16	0	25.98	25.32	4.87	0	0	5.92	1.32	30.92
NET_ELEC (kWh)	0	0	1.6	0	0.84	0	1.15	0	0	0.64	0	0
DISTANCE (km)	9.33	9.33	9.33	10.62	10.62	8.05	933	6.76	0	9.33	6.76	9.33
km/kWh	0.73	0.73	0.63	0.73	0.39	0.73	1.54	0.73	0	1.42	0.73	0.73
LOW ZEV TIME	13.71	14.38	17.13	14.92	16.82	22.78	20.03	19.81	0	13.7	14.62	22.98
LOW HEV TIME	13.6	14.5	13.7	14.86	15.22	15.8	13.39	0	0	12.71	0	22.63
RANGE												
EQ_GAL (kWh)	22.53	67.75	86.5	65.73	115.77	0	98.88	0	101.96	53.61	0	22.04
NET_ELEC (kWh)	14.42	1.26	16.61	0	8.55	0	1.56	0	14.55	0.72	4.05	2.69
DISTANCE (km)	109.9	184.7	195	191.6	167.64	0	195	3.43	138.85	109.5	17.1	27.37
km/kWh	2.98	2.68	1.89	1.67	1.35	0	1.94	1.67	1.17	2	1.67	1.1
ELAPSED TIME	3:21:16	3:26:44	3:24:19	3:23:11	3:25:24	DNS	3:25:05	0:07:58	2:52:41	3:25:56	0:25:05	0:47:22
RALLY												
EQ_GAL (kWh)	0	64.46	64.46	0	0	0	70.78	0	35.19	14.8	0	25
NET_ELEC (kWh)	0	6.74	0	0	0	0	6.29	0	0	8.51	0	1.32
DISTANCE (km)	0	134.86	134.86	0	0	0	134.86	0	8.05	134.86	0	20.63
km/kWh	0	1.89	1.56	0	0	0	1.75	0	1.56	5.75	0	0.78
ZEV Information (km/kWh)	7.42	11.71	7.07	x	x	x	7.73	x	4.87	12.51	9.60	x

Table 3. Escort Conversion Class Vehicle Data.

SCHOOL	Colorado School of Mines	Concordia University	Jordan College	Penn State	Stanford University	Texas Tech.	U.S. Naval Academy	U. C. Irvine	University of Alberta	University of Illinois, Urbana-Ch.	University of Wisconsin	Washington University	Weber State University	West Virginia University
VEHICLE INFO														
CAR_NUMBER	4	11	12	1	14	29	31	7	33	8	34	33	3	28
HYBRID_CONFIGURATION	Series	Series	Series/Parallel	Series	Series	Parallel	Series	Parallel	Parallel	Series	Series	Parallel	Parallel	Series
VEHICLE_WEIGHT (kg)	1617.9	1725.5	1728.2	1742.2	1616.1	1649.3	1778.1	1797.6	1641.1	1733.6	1731.8	1705.9	1796.2	1646.1
CHARGING EFFICIENCY	0.82	0.91	0.88	0.68	0.8	0.89	0.81	0.62	0.81	0.68	0.89	0.87	0.83	0.81
ENGINE_MANUFACTURER	Kawasaki	Brig/ Strat.	Kohler	Kohler	Honda	Kawasaki	Kawasaki	Geo	Suzuki	Kawasaki	Kohler	Brig/ Stat.	Ford	Kawasaki
ENGINE_SIZE_CC	620	540	725	725	250	650	617	1000	1000	628	624	570	1900	620
ENGINE_POWER kW	16.4	14.2	18.6	18.6	22.4	30	16.4	37.3	41	16.4	15	13.4	65	15
FUEL_TYPE	E100	R GAS	R GAS	R GAS	R GAS	E100	R GAS	R GAS	R GAS	E100	R GAS	R GAS	R GAS	R GAS
TANK_CAPACITY (l)	63.6	28	45.5	30.3	40	45	45	45.4	38	41.6	38	45.4	45	45
MOTOR_MANUFACTURER	Unique Mobility	Solectria/ Adv. DC	Advanced DC	Solectria	Student designed w/ FMC	Solectria	General Elec.	Electragear	Unique Mobility	Magnetek/Cent	Lincoln Elec.	Advanced DC	Advanced DC	Advanced DC
MOTOR_TYPE	Brushless DC	P. M. Brush	DC Series	AC Induction	AC Induction	AC Induction	Shunt Wound	AC Induction	PM Brushless	AC Induction	3 phase AC	DC Series	DC Series	DC Series
MOTOR_POWER (kW)	32	89.5	0	21	55.9	21	20.1	11.2	32	62	74.5	59.7	37.3	41
BATTERY_TYPE	Ni-Cad	Pb-Acid	Pb-Acid	Pb-Acid	Ni-Cad	Gel-Cell	Pb-Acid	Pb-Acid	Ni-Cad	Pb-Acid	Pb-Acid	Pb-Acid	Ni-Cad	Pb-Acid
VOLTAGE	180	156	96	144	108	120	120	312	170	312	360	132	96	120
BATTERY_CAPACITY (kWh)	6.71	10.14	11.72	14.4	13.61	7.63	14.65	12.93	9.35	7.39	9.5	10.94	17.37	13.5
GENERATOR	Unique Mobility	Fisher Elec.	x	Unique Mobility	Solectria	x	Fisher Elec.	x	x	Unique Mobility	Fisher Elec.	x	x	Fisher Elec.
EMISSIONS														
ZEV														
DISTANCE (km)	12.02	11.71	11.73	0	0	2.2	11.99	0	11.97	11.7	11.99	11.97	11.3	11.91
AMP-HOURS	-15.23	-21.74	-28.16	0	0	0	0	0	-12.18	-6.24	0	0	0	-20.33
kWh	-2.78	-3.04	-2.4	0	0	0	0	0	-2.05	-1.61	0	0	0	1.24
km/kWh	-4.32	-3.85	-4.88	0	0	0	0	0	-5.85	-7.27	0	0	0	35.87
HEV g/m														
DISTANCE (km)	0	16.67	17.01	0	0	14.15	17.54	0	17.64	17.53	17.88	17.77	17.73	17.76
AMP-HOURS	0	0	0	0	0	0	-11.39	0	-1.29	2.33	0	-27.08	0	2.64
kWh	0	0	0	0	0	0	-1.2	0	-0.22	1.03	0	-3.45	0	0.66
km/kWH	0	0	0	0	0	0	-14.62	0	-80.18	17.02	0	-5.15	0	26.89
FTP g/m														
HC	0	1.022	1.13	0	0	11.65	1.24	0	0.339	3.591	0.977	0.56	0.109	0.05
NMHC	0	0.8871	0.83	0	0	10.533	1.02	0	0.307	2.872	0.785	0.515	0.086	0.046
CO	0	61	66.95	0	0	266.47	67.36	0	1.979	118.85	61.52	9.922	0.998	0.332
NOX	0	1.95	0.15	0	0	0.09	0.02	0	0.645	0.076	1.338	0.014	0.395	2.692
CORRECTED g/m														
HC	0	0	0	0	0	0	0	0	0.366	2.875	0	0	0	0.046
NMHC	0	0	0	0	0	0	0	0	0.331	2.299	0	0	0	0.043
CO	0	0	0	0	0	0	0	0	2.133	95.135	0	0	0	0.305
NOX	0	0	0	0	0	0	0	0	0.695	0.061	0	0	0	2.476
ENERGY ECONOMY														
ACCELERATION														
EQ_GAL (kWh)	9.51	0.99	3.29	2.96	14.14	34.95	13.81	0	15.79	3.32	3.29	3.29	11.84	4.93
NET_ELEC (kWh)	0	0.3	1.02	2.35	4.3	0.3	1.37	0	0.15	1.14	0	0	0.51	0
DISTANCE (km)	8.05	9.33	10.62	8.05	9.33	8.05	10.62	0	8.05	9.33	9.33	8.05	8.05	10.62
km/kWh	0.69	7.3	2.5	1.52	0.51	0.22	0.7	0	0.5	1.96	0.69	0.69	0.65	0.69
LOW HEV TIME	17.99	16.82	17.81	15.31	19.88	15.02	15.8	0	17.54	13.6	13.43	15.84	12.44	16.59
LOW ZEV TIME	17.84	19.17	17.72	15.31	20.25	16.11	16.3	0	14.04	13.63	13.8	15.79	17.63	16.56
RANGE														
EQ_GAL (kWh)	0	84.2	106.89	0.66	8.55	216.55	17.1	0	75.65	62.38	121.36	3.95	59.86	17.1
NET_ELEC (kWh)	0	8.41	9.06	8.31	5.76	0.44	4.32	0	8.19	1.75	0	0	11.78	4.1
DISTANCE (km)	13.68	174.5	191.6	58.16	27.38	174.5	44.5	0	198.4	123.2	205.3	150.5	198.4	58.16
km/kWh	1.92	1.89	1.66	6.44	1.92	0.8	2.06	0	2.36	1.92	1.92	1.92	2.7	2.7
ELAPSED TIME	0:18:33	3:27:31	3:25:12	1:46:34	0:42:02	3:26:16	1:06:00	DNS	3:25:23	3:25:19	3:24:57	3:03:03	3:26:03	2:17:02
RALLY														
EQ_GAL (kWh)	0	126.63	96.7	0	35.85	115.02	0	0	65.45	67.69	93.08	0	44.07	89.46
NET_ELEC (kWh)	0	0	7.68	0	4.65	0.01	0	0	6.35	0	0	0	10.94	2.29
DISTANCE (km)	0	134.86	134.86	0	41.89	41.89	0	0	134.86	134.86	134.86	88.22	134.86	134.86
km/kWh	0	0.98	1.29	0	1.03	0.36	0	0	1.87	0.98	0.98	0.98	2.44	1.48
ZEV Information (km/kWh)	x	8.15	5.09	5.94	x	x	5.50	x	9.00	11.96	8.03	6.37	7.14	7.87

Table 4. Saturn Conversion Class Vehicle Data

SCHOOL	Alfred University	Cedarville College	Ecole de Technologie Superieure	GMI Engineering & Mgmt. Inst.	University of Texas, Austin	California State University, Chico	University of Maryland	University of Western Ontario	Wentworth Institute of Technology	Western Michigan University
VEHICLE INFO										
NUMBER	36	9	3	17	2	18	24	22	26	35
HYBRID_CONFIGURATION	Parallel	Series	Parallel	Series	Parallel	Series	Parallel	Parallel	Series	Parallel
VEHICLE_WEIGHT (kg)	1550	1545.8	1528	1773.5	1406.6	1510.5	1461.5	1538.6	1674.7	1492
CHARGING EFFICIENCY	0	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
ENGINE_MANUFACTURER	Suzuki	Honda	Subaru	Kawasaki	BMW	BMW	Geo/Suzuki	Honda	Suzuki	Suzuki
ENGINE SIZE (cc)	750	1500	1189	617	750	750	1000	1300	993	1000
ENGINE_POWER (kW)	93	67	82	15	52.2	34	48.5	52	41	39
FUEL_TYPE	M85	M85	M85	E100	M85	E100	M85	E100	M85	M85
TANK_CAPACITY (l)	37.9	48.5	48.5	56.8	48.5	45	42	50	48.5	60.6
MOTOR_MANUFACTURER	M. Aerospace	Unique Mobility	Baldor	Magnetek	BMW	Unique Mobility	Unique Mobility	Solectria	Solectria	Advanced DC
MOTOR_TYPE	DC Brushless	DC Brushless	DC Brushless	AC	AC	DC Brushless	DC Brushless	DC Brushless	AC	DC Brushless
MOTOR_POWER (kW)	0	32	50	22	54	50	13	22.4	24	30
BATTERY_TYPE	Pb-acid	Pb-Acid	Ni-Cd	Pb-Acid	Pb-Acid	Pb-Acid	Ni-Cd	Pb-Acid	Pb-Acid	Gel Acid
VOLTAGE	120	180	288	288	120	120	153.696	96	144	108
BATTERY_CAPACITY (kWh)	0	5.18	3.74	5.76	4	4.32	2.9	7.46	11.19	5.7
GENERATOR	none	Westinghouse	Baldor	Fisher	Unique Mobility	Bendix	E.M.	Solectria	General Electric	Power Tech Inc.
EMISSIONS										
FTP g/m										
HC	0	0	0	0.75	0	0	0.31	0	0	0
NMHC	0	0	0	0.56	0	0	0.29	0	0	0
CO	0	0	0	54.2	0	0	2.6	0	0	0
NOx	0	0	0	0.3	0	0	0.68	0	0	0
CORRECTED g/m										
HC	0	0	0	0	0	0	0.31	0	0	0
NMHC	0	0	0	0	0	0	0.29	0	0	0
CO	0	0	0	0	0	0	2.6	0	0	0
NOx	0	0	0	0	0	0	0.68	0	0	0
ENERGY ECONOMY										
ACCELERATION										
EQ_GAL (kWh)	0	16.76	0	6.64	17.88	25	6.64	122.77	0	13.59
NET_ELEC (kWh)	0	21.18	0	7.425	0.9	2.9	7.42	0.27	0	0
DISTANCE (km)	0	8.05	8.05	8.05	8.05	8.05	8.05	8.05	0	8.05
km/kWh	0	0.21	0.23	0.57	0.43	0.29	0.57	0.07	0	0.59
LOWHEV	0	18.29	12.27	16.37	14.52	17.91	14.24	13.92	0	16.58
RANGE										
EQ_GAL (kWh)	0	124.01	0	6.19	49.16	139.8	41.52	96	0	81.56
NET_ELEC (kWH)	0	6.65	0	5.61	3.53	11.4	5.75	23.35	0	0
DISTANCE (km)	0.00	126.64	198.46	10.27	102.63	143.74	119.75	174.51	0.00	143.74
km/kWh	0	0.97	1.29	0.87	1.95	0.95	2.53	1.46	0	1.76
TIME	x	3:19:54	3:00:31	0:08:20	3:25:49	3:20:00	3:25:24	3:24:48	x	3:25:22
RALLY										
EQ_GAL (kWh)	0	185.27	0	0	77.27	0	75.78	205.05	0	0
NET_ELEC (kWh)	0	10.9	0	0	0.36	0	2.44	0.86	0	0
DISTANCE (km)	0	134.9	0	8.05	24.4	115.5	134.9	134.9	0	0
km/kWh	0	0.69	0	0.59	0.31	0.59	1.72	0.66	0	0
ZEV Information (km/kWh)	x	x	x	34.91	7.84	5.82	14.77	20.76	x	x