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PAPER TITLE (upper and lower case):

Electric Vehicle Performance in 1994 DOE Competitions

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ABSTRACT

The U.S. Department of Energy (DOE) through Argonne National Laboratory sponsored and recorded energy data of electric vehicles (EVs) at five competitions in 1994. Each competition provided different test conditions (closed-track, on-road, and dynamometer). The data gathered at these competitions includes energy efficiency, range, acceleration, and vehicle characteristics. The results of the analysis show that the vehicles performed as expected. Some of the EVs were also tested on dynamometers and compared to gasoline vehicles, including production vehicles with advanced battery systems. Although the EVs performed well at these competitions, the results show that only the vehicles with advanced technologies perform as well or better than conventional gasoline vehicles.

INTRODUCTION

DOE alternative transportation competitions offer an excellent opportunity to analyze different types of EVs in a low-risk, low-cost setting. With up to 50 vehicles at each competition and a wide range of technologies, the events show the effect of different components and designs on performance.

These events also offer an opportunity to showcase alternative-fuel vehicles and their technologies to the public. Competitions are held throughout the year at several different locations across the nation; this increased visibility will improve the awareness and public image of EVs. Participants include schools, private, and corporate manufacturers. The student competitors also gain experience in automotive technology, energy efficiency, and alternative transportation.

This paper analyzes the results from three types of test conditions at the competitions: closed-track, on-road, and dynamometer testing. The document also analyzes the effect of the vehicle parameters on the performance of the vehicle and compares the results of the different tests.

ELECTRIC VEHICLE COMPETITIONS

All the EV competitions are designed to test the vehicles' performance, efficiency, and range. Three of the competitions occurred on closed tracks: Solar/Electric 500 (S/E 500) in Phoenix, Clean Air Grand Prix (CAGP) in Atlanta, and EV Grand Prix (EVGP) in Richmond. Participants in these events consisted of private, corporate, and scholastic groups. Only colleges and universities were part of the CAGP, and the participants in the EVGP were from high schools. All the EVs in the closed-track events were converted from conventional vehicles. Teams scored points in several events including acceleration, handling, range, and efficiency. The acceleration event was defined as the time the vehicles took to travel 0.2 km. The handling event consisted of a timed slalom or autocross course. The range event measured how far a vehicle could travel in a fixed time. Finally, the efficiency event measured the amount of energy used by each vehicle at constant speeds. Oral and written design review events were also part of the student competitions.

The two on-road competitions provided a different setting in which to evaluate EVs. The World Clean Air Road Rally (WCARR) took place on the surface streets and highways of the Los Angeles area, and the American Tour de Sol (ATdS) traveled for seven days from New York City to Philadelphia. The scores of the competitors were based upon the time their vehicle took to complete each leg compared to the perfect time. That is, a team lost points if the vehicle was late or early compared to an ideal time. The teams could also score additional points by completing "range laps" at the end of the day.

In addition to the rally, some of the vehicles in the ATdS were tested on a dynamometer to measure their performance. Although the testing had no effect on the scores of the participants, the acceleration, energy efficiency, and power consumption of the vehicles was measured.

BACKGROUND

DATA ACQUISITION SYSTEMS - In each of these competitions, some or all the vehicles used a kilowatt-hour meter to measure the energy consumption. The meter, from Cruising Equipment Co., measured the current from the battery pack using a shunt and the voltage through a 100:1 voltage divider on the battery pack terminals. The energy was calculated by integrating the voltage and current readings. The meter sampled the vehicle data at a rate of 128 units per second, and recorded the current and voltage at a frequency of 1.2 kHz. The meter had a resolution of 0.5 V and 1 A. Real-time information could also be recorded by attaching a computer or memory module to the meter (1).

The data measured on the dynamometer before the ATdS used a National Instruments Labview system. This device was also used to collect real-time information from some vehicles at the Richmond competition. The Labview system used A/D converters to monitor the battery voltage. The current from the battery pack was measured using a shunt (50 mV/500 A) and had a two-stage low-pass filter. The system measured 256 samples per second and recorded the data at a rate of 1 Hz. Software averaging was also used to reduce noise. The accuracy was 0.25 % of full scale (500V/500A).

ELECTRIC VEHICLE THEORY - The power necessary to power an electric vehicle depends on the sum of four forces (rolling resistance, aerodynamic, gravitational, and acceleration) multiplied by the velocity and the efficiency. The equation that describes these forces is:

$$P = VE(F_{rr} + F_D + F_g + F_a) \quad (1)$$

where

- F_{rr} = Rolling resistance force
- F_D = Aerodynamic drag
- F_g = Gravitational force
- F_a = Acceleration force
- E = Vehicle efficiency

Figure 1: Effect of aerodynamic drag compared with other forces on the power consumption of a vehicle.

Because the aerodynamic drag is cubically dependent on the velocity of the vehicle (i.e., $F_D = f(V) = 1/2\rho C_d A V^2$), the drag strongly affects the performance of the vehicle at higher speeds as shown in Figure 1. The vehicle will consume more power to overcome aerodynamic drag than the other forces at higher speeds (2).

CLOSED-TRACK COMPETITIONS

The competitions at Richmond (EVGP) and Atlanta (CAGP) were on a closed-track, which allowed the organizers an opportunity to test the vehicles under partially-controlled conditions during the efficiency and range events. At both competitions, the vehicles used DC-drive systems and lead-acid batteries. The nominal battery pack voltage was limited to 96 V at Richmond, and 120 V at Atlanta. All the EVs were conversions and were required to have roll-cages, which increased the weight of the vehicles.

During the efficiency event, the participants followed a pace car around the track at three constant speeds. At Richmond the vehicles drove at 88, 64, and 40 km/h, and at Atlanta the vehicles traveled at 88, 56, and 40 km/h. Once the vehicles completed a fixed distance (8 km at Atlanta and 12 km at Richmond) at each speed, they stopped and the in energy use was recorded from the kilowatt-hour meter. Figure 2 shows the results of efficiency event by comparing the weight to the energy efficiency (km/kWh) of the vehicles. To compare the vehicles at the two competitions, the results from the 56 km/h efficiency event at Atlanta were projected to reflect the energy efficiency at 64 km/h using regression techniques. As expected, the energy efficiency decreased as the vehicle weight increased. The trend line at 88 km/h shows that for every 125 kg increase in vehicle weight, the energy efficiency decreased by one km/kWh. At 64 and 40 km/h, the slope of the trend line was 1/200 km/kWh per kg.

Figure 2: Energy efficiency versus vehicle weight during the efficiency event at the EVGP and CAGP.

Driving style and variations in speed resulted in the wide variations of data, some of which were not included in the analysis. For example, the team with the best energy efficiency coasted through the turns to conserve energy, which resulted in an artificially high efficiency of 30.9 km/kWh at 40 km/h. Only the vehicles that completed the required distance at each speed were recorded.

At Atlanta, the ranges of the vehicles were measured by demonstrating which vehicle could travel the farthest in two hours. Vehicles were removed from the track if they had an average lap speed of less than 40 km/h. Figure 3 compares the range of the vehicles to the vehicle and battery weights. EVs that did not complete the event due to technical problems are not included in the graph. Also, Car #00 was still able to complete laps at the end of the two hours.

Figure 3 shows that vehicle weight and battery capacity are important in determining the range of the vehicle. For example, Car #14 had a battery capacity of 22.1 kWh, but only traveled 78.8 km due to its vehicle weight (1,605 kg). In contrast, Car #4 traveled 101.0 km, yet had half the capacity (11.0 kWh) and weighed 1,255 kg. Although Car #4 came in fourth place, its lighter weight allowed it to compete with vehicles with larger battery packs (Car #72, 93, 00).

Figure 3: Comparison of battery weight, vehicle weight, and range on CAGP vehicles.

As stated above, the aerodynamic drag accounts for a larger portion of a vehicle's energy at higher speeds. Figure 4 shows the energy economy during the efficiency events for three different shapes of vehicles: small cars, trucks, and sports cars (sports cars were defined as having sloped rear ends). All three types of vehicles show a decrease in energy economy as speed increases. Due to the more aerodynamic shapes and sizes of the sports cars, their efficiency decreases 20% from 40 to 88 km/h, compared with 45% and 40% for trucks and small cars, respectively. This corresponds to the expected EV performance as shown in EQ (1).

Figure 5 shows a histogram of the 0.2 km acceleration runs of the vehicles at the Richmond and Atlanta events. Since many

of the vehicles used similar drive systems (General Electric or Advanced DC Brushed Motors), a large number of acceleration times are close to 17 s.

Figure 4: Comparison of vehicle efficiency at different speeds to vehicle shape at Richmond and Atlanta.

Figure 5: Histogram of acceleration times at EVGP and CAGP competitions.

Real-time data were also collected from one vehicle during the efficiency event (shown in Figure 6). Information was gathered during the 40- and 56-km/h runs. Table 1 shows a summary of the data for Car #35. The information collected includes the voltage, energy, and current. As expected, the current and energy draws were greater at the higher speed. The voltage drop from the battery also increased as the speed increased due to the internal resistance of the battery pack. Figure 6 also shows that no regenerative braking was present during the runs (current and slope of energy curve were both always positive). The plateau in the middle of graph is the time between the runs for which the vehicles stopped to record their energy consumption from the meter.

Overall, the closed-track competitions offer an opportunity to test EVs on-the-road under semi-controlled conditions. The results from the EVGP and CAGP showed a close correlation to expected values. Driving style and variations in speed account for the deviations from expected results.

Run	Avg. Speed (km/h)	Total Energy (kWh)	Avg. Power (kW)	Average Efficiency (km/kWh)
40	37.0	0.37	1.13	32.6
56	56.3	0.54	2.52	22.3

Table 1: Summary of real-time data from Car #35 at the EVGP.

Figure 6: Instantaneous data from Car #35 Raleigh County School, during the efficiency event.

ON-ROAD COMPETITIONS

The WCARR and ATdS competitions were rally events and both occurred on surface streets. These on-road events offer the opportunity to measure the performance of the vehicles under typical driving and road conditions. Unfortunately, due to the nature of an on-road rally, the driving style, road conditions, and traffic conditions may vary for each vehicle.

Thirty-five vehicles were monitored during the two competitions. As previously discussed, the ATdS road rally was seven days long and the WCARR lasted three days (data were collected for two days). Only five vehicles were monitored during the Los Angeles competition. These consisted of privately owned EVs with lead-acid batteries and DC drive systems. The competitors in the ATdS were divided into four classes: American Commuter (AC), Tour de Sol Commuter (TdS), Production (Prod), and Open. The AC class had the most participants and consisted of registered and practical vehicles with no battery limitations. The TdS class included three teams and had a limitation on solar array size and battery capacity depending on the number of passengers. The Production class was the most interesting with participants from Ford, Chrysler, Electricar, and Solectria. The EVs in this class

had to be driven "as sold." The Open class consisted of all other vehicles, including two and three wheel EVs (3, 4).

The ATdS and WCARR routes and driving conditions were significantly different. The ATdS took place on back-roads with few traffic controls or other cars. The average speed during the rally portion of the ATdS was generally higher than during WCARR, which took place in city driving conditions. The WCARR rally had more accelerations and stops, which resulted in a slower average speed. Thus, the efficiencies and range of the WCARR EVs were considerably less than the ATdS vehicles. In both competitions, the EVs were driven with a more-efficient style than used by a typical driver to save energy and increase range.

Some of the vehicles with advanced technologies or excellent performance are shown in Table 2. These included and Solectria Force with nickel metal-hydride batteries and the University of California, Davis EV with a zinc-bromine battery. The efficiency (eff.) was averaged over the rally portion of the seven-day competition. The range was the longest distance the vehicle traveled between charges and included the rally and the extra laps at the end of the day.

Vehicle	Class	Eff. (km/kWh)	Range (km)	Battery
Ford Ecostar	Prod	8.74	304	Sodium-Sulfur
Chrysler TEVan-NJ	Prod.		101	Nickel-Iron
Chrysler TEVan-PECO	Prod.		109	Ni-Cd
Solectria ForceRS	AC	11.65	344	Ni-MH
Bolton HS	AC	7.40	228	Pb-Ac
UC Davis	AC	8.07	281	Zn-Br

Table 2: Performance of some vehicles at ATdS. (3)

Figure 7: Energy efficiency histogram of EVs in the ATdS and WCARR (LA) during the rally.

Figures 7 and 8 show a histogram of the energy efficiency and maximum range of the EVs in the competitions. The Open and TdS classes tended to have a better efficiency because these vehicles were extremely lightweight and aerodynamic compared to the practical vehicles in the other classes. In contrast, the Production and AC classes tended to have a longer range because these vehicles could carry more batteries (LA refers to the WCARR vehicles).

Average daily efficiency varied from 5.23 to 65.74 km/kWh and the maximum range was between 29 and 344 km. The most efficient vehicle was from Team New England and was a small, three-wheeled, one-person vehicle. The vehicle with the longest range was the Solectria ForceRS with nickel metal-hydrate batteries.

Figure 8: Range histogram of the EVs in the ATdS and WCARR (LA) competitions.

Figure 9: Average energy during the rally portion of the ATdS compared to vehicle weight.

Figure 9 shows the comparison of vehicle weight and vehicle efficiency during the ATdS competition. In this event, the trend line on the graph shows that for every 50-kg increase in vehicle weight, the efficiency decreases by 1 kWh. The energy efficiency per weight decreased compared with the closed-track events because of accelerations, traffic, and other road conditions.

Figure 10 shows the instantaneous data gathered from Sungo, Car #32 during Day 2 of the ATdS rally. The Sungo used lead-acid batteries and a DC brushless motor. This allowed the vehicle to capture 21% of the energy used through regenerative braking during the time shown in Figure 10. The regenerative braking is in effect when the current and the slope of the energy line is negative (4).

Figure 10: Instantaneous data from Car #32, Sungo, during one portion of the ATdS rally.

Overall, rally-style competitions show the effects of real-life driving and road conditions on the performance of EVs. Unfortunately, the information gathered depends on driving style, traffic, and traffic controls. Yet, some of the vehicles at the rallies showed impressive performance.

DYNAMOMETER TESTING

Before the start of the ATdS nine vehicles were evaluated on a dynamometer at the New York City Environmental Protection facility (5). Due to the limited test time, each vehicle was tested for approximately one hour. Valuable information was gathered on all the vehicles during the testing including energy efficiency, acceleration, and power consumption at constant speeds. In addition, three gasoline vehicles were tested as a reference.

Real-time data collected during the testing included battery voltage, current from the battery pack, and other dynamometer measurements. The Labview system previously discussed collected all the data. A hall-effect sensor rather than the shunt used in the other vehicles, measured the current from the TEVans and Ecostar.

The dynamometer settings for the EVs were difficult to evaluate. The few teams that performed extensive coast-down testing on their vehicles produced accurate results. For those EVs that did not perform these tests, the horse power load was set to the original certified value of the converted vehicle. The weight settings used the actual vehicle weight plus a standard payload. In all cases, the road load was verified by matching the coast down on the dynamometer.

Three tests were performed on each vehicle: urban driving schedule (UDS), acceleration, and steady-state speed. Table 3 shows the results of the UDS testing. The energy efficiency refers to the amount of energy the EVs used during the UDS cycle. Percent regenerative (regen.) energy is the amount of energy captured during the UDS through regenerative braking compared with the total energy used. "Equivalent MPG" compares the fuel efficiency of the gasoline vehicles to the EVs. To convert the electrical energy into equivalent gallons of fuel the following equation was used:

$$MPG = EE \times G \times \eta \quad (2)$$

where

EE = Electrical Energy Efficiency

G = 33.8 kWh of electrical energy/Gallon gasoline

η = Electrical System Efficiency compared to
Gasoline System Efficiency
=0.226

The electrical system efficiency refers to the difference in the energy loss of converting oil into electricity at the plug, to converting oil into gasoline at the pump. This includes gasoline production, oil power plant losses, and distribution losses. The reference by Wang and DeLuchi (6) uses 0.324 as the system efficiency, but does not include battery and charger efficiency. The value of 0.226 was derived by using a battery efficiency of 75% and charger efficiency of 93% (5). The battery efficiency value may be low when considering EVs with advanced battery systems.

Vehicle	Type	Energy Efficiency (km/kWh)	% Regen. Energy (%)	Equivalent MPG (mpg)
Ford Escort	Gas			28.40
Dodge Caravan	Gas			20.60
Geo Metro	Gas			36.20
Chrysler TEVan1	EV	3.18	5.24	15.12
VW Rabbit	EV	5.95	0.00	28.26
SAAB 99	EV	4.74	0.00	22.53
Chrysler TEVan2	EV	3.20	5.00	15.20
Ford Festiva	EV	5.37	1.20	25.51
Geo Storm	EV	6.00	4.24	28.49
MG B	EV	4.94	0.00	23.45
Ford Ecostar	EV	6.72	17.30	31.93

Table 3: Results of the UDS testing during the ATdS.

The data in Table 3 show that the production vehicles captured a significant amount of energy from regenerative

braking. Also, some of the conversion vehicles and the Ford Ecostar have equivalent fuel efficiencies comparable to the gasoline vehicles.

The performance of the vehicles was also measured at constant speeds from 16 to 96 km/h at 16-km/h increments, as shown in Figure 11. Again, Equation 2 was used to convert the EV electrical efficiency to equivalent mpg. The gasoline vehicles were not tested at 16 km/h because it was difficult to maintain the steady-state speed. Also, the Ford Festiva could not reach 96 km/h during the testing. In most cases, the internal combustion (IC) vehicles tested at the ATdS were more efficient than their EV counterparts when the energy system efficiency was considered (except for the Ford Ecostar). The electric vehicles are more efficient when comparing the vehicle, not the system.

Figure 11: Equivalent fuel efficiency of gasoline and EV at steady-state speeds.

During the steady-state speed tests, instrumentation also recorded the power required to maintain the speeds (Figure 12). The plateau in the Ford Ecostar plot may be due to changes in the motor performance at different speeds or anomalies in the measurements (the Ecostar used a direct-drive system).

Figure 13 shows the fuel consumption of the control gasoline vehicles at the same constant speeds. One important fact is that the gasoline vehicles consume fuel at idle, but the EVs use no energy when their speed is zero. The fuel consumption rate was measured by capturing the emissions at each speed and using the carbon count of the exhaust to calculate the amount of fuel used.

Figure 12: Power required at constant speeds for EVs.

Figure 13: Fuel consumption of gasoline vehicles at constant speeds.

The vehicles also performed two acceleration runs on the dynamometer. Figure 14 shows the average of these two runs. The EVs performed better than their IC counterparts during this test. The Ford Ecostar had an impressive 0-96-km/h time of 18.1 s.

Although the dynamometer testing provides an excellent baseline measurement of EVs, it does not account for variations in performance due to driving and traffic. Table 4 compares the UDS and on-road efficiencies. The average percentage increase in the on-road efficiency was 39.6%. This large variation in performance is caused by the efficient driving styles of the competitors to extend their ranges (for example, coasting long distances to stop and slow accelerations). Also the UDS has more accelerations and stops than the rally route.

Figure 14: Average acceleration times of EV and gasoline vehicles at ATdS.

Vehicle	UDS Eff. (mi/kWh)	Rally Eff. (mi/kWh)	% Change
VW Rabbit	3.70	4.33	17.1%
Ford Festiva	3.34	5.38	60.8%
Geo Storm	3.73	5.53	48.3%
MG B	3.07	4.53	47.4%
Ford Ecostar	4.18	5.43	30.1%
SAAB	2.95	3.95	33.7%

Table 4: Comparison of UDS and on-road energy efficiency during the ATdS.

Most of the EVs tested on the dynamometer before the ATdS performed well, but not as good as the IC cars, except for the advanced Ford Ecostar with sodium-sulfur batteries.

CONCLUSION

Overall, student competitions not only offer an opportunity to educate future engineers, but also allow the testing of a wide range of vehicles with varying technologies. The closed-track competitions provided a semi-controlled atmosphere in which to test the EVs. The efficiencies of the vehicles in these events were affected by the vehicle weights, battery weights, and the vehicle aerodynamics. The ranges of the vehicles were strongly dependent on battery and vehicle weights. Both efficiency and range measurements provided results which correlated to expected values.

The on-road rallies also show on-road performance, but in a more realistic setting with traffic and different driving conditions. The on-road competitions, especially at the ATdS, have shown the benefits of advanced battery technology such as sodium-sulfur and nickel metal-hydride batteries. In general, the smaller vehicles had better efficiencies, but shorter ranges than the heavier vehicles with larger battery capacities.

In contrast to on-road measurements, dynamometer testing offers the opportunity to test the vehicles in a controlled atmosphere and provides a reference for comparing different vehicles to each other, including EV and gasoline cars. The EVs performed the same as conventional vehicles in efficiency and worse in power consumption, but were equal to or better than their gasoline counterparts in acceleration. Still, the testing showed that advanced EVs in the future have the potential of equaling or surpassing current IC technology. By comparing the results of the dynamometer testing to the on-road data, the effect of driving style and road conditions is easily seen. All the EVs had better performance on-the-road than during dynamometer testing.

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