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Technical Report

Testing of an Electric Vehicle on a Clayton Water-Brake Chassis Dynamometer

by

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Table of Contents

I. Summary

A 1988 Ford Escort Wagon equipped with a lead-acid battery propulsion system was tested for energy consumption and range on a Clayton water-brake chassis dynamometer at the EPA National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan.

Two different test procedures were used to determine energy consumption. The first test procedure followed the newly developed SAE Recommended Practice J1634 for the testing of electric vehicles. Following this procedure will yield only a combined energy consumption value for both the city and highway driving cycles. Therefore, the vehicle was also tested separately over city and highway driving cycles which more closely follow the standard test procedure for conventional vehicles. From this procedure, energy consumption values over the city and highway cycles were determined independently of each other without deviating greatly from the current test and calculation procedures.

Presented in this report are three power consumption values. The first is System AC Energy Consumption, or the amount of power from the electrical wall plug to the on-board vehicle charging system. The second value is System DC Energy Consumption, or the amount of power from the on-board vehicle charging system to the batteries. Both these power values were measured during the battery recharging period after driving the vehicle over various cycles. The last power value measured during this program was Vehicle Net DC Energy Consumption, or the actual amount of power delivered from the batteries for propulsion of the vehicle. This power value was obtained during the actual test procedure driving cycles.

AC energy consumption values with the Clayton water-brake dynamometer averaged 504 W-hr/mile over the SAE J1634 test procedure. The values reported here are wall-power numbers and would be the amount of power for which the consumer would need to pay. The city energy consumption value was determined to be 656 W-hr/mile, and the highway value was measured to be 489 W-hr/mile. By applying the calculation method used in DOE rulemaking that will allow the conversion of individual city and highway energy consumption values into a combined petroleum-equivalent fuel economy value, a fuel economy value of 133.5 MPG was obtained.

II. Introduction

The California Air Resources Board (CARB) has mandated that 2 percent of all vehicle sales in that state shall be zero-emitting vehicles by the year 1998.[1] One possible means of obtaining zero pollution at the tailpipe in a conventional passenger vehicle is with the use of a battery-powered propulsion system.

Since battery-powered vehicles behave differently than conventional internal combustion engine (ICE) vehicles, it was necessary to develop a new test procedure to accurately determine energy consumption and range of electric-powered vehicles. A task force was formed under the Society of Automotive Engineers (SAE) Light-Duty Vehicle Performance and Economy Measurement Standards Committee with the goal of developing a standard test procedure that "establishes uniform procedures for testing electric battery-powered vehicles which are capable of being operated on public and private roads." This procedure is said to "allow for the determination of energy consumption and range based on the Federal Emission Test Procedure (FTP) and the Highway Fuel Economy Test Procedure (HWFET)."[2]

EPA has membership in this committee and followed the development of this SAE procedure. This procedure was developed and finalized, however, without testing any electric vehicles over it to determine if this procedure was reliable and repeatable.

As a result of the need to test an electric vehicle over this procedure to obtain information regarding the procedure's repeatability, a round-robin test program was formed involving the U.S. Department of Energy (DOE), Idaho National Engineering Laboratory (INEL), U.S. EPA, Ford Motor Company, and CARB. Each site agreed to test an electric battery-powered 1988 Ford Escort Wagon for energy consumption and range following the SAE J1634 procedure. EPA tested the vehicle on both a Clayton water-brake dynamometer and a Horiba electric dynamometer. EPA also conducted additional testing of the vehicle to obtain separate city and highway energy consumption values. In its current form, the SAE J1634 procedure will only yield a combined city/highway energy consumption value. The electric dynamometer results are not presented in this report but will be published at a later date.

Separate city and highway energy consumption values were required to determine a petroleum-equivalent fuel economy value based on the DOE's rulemaking released on February 4, 1994.[3] The DOE rulemaking allows a combined fuel economy value, to be used in Corporate Average Fuel Economy (CAFE) calculations, to be calculated from individual city and highway energy consumption values. The rulemaking references the SAE J1634 procedure but also requires individual city and highway energy consumption values.

This report contains energy consumption and range results when testing the vehicle over the J1634 procedure. Individual city and highway energy consumption values were also obtained so that a petroleum-equivalent fuel economy value could be determined for this vehicle. All results presented in this report were obtained on a Clayton water-brake chassis dynamometer.

III. Description of Test Procedures

The main purpose of this round-robin test program was to test a single electric vehicle at four different sites over the newly developed SAE J1634 test procedure. This procedure addresses battery conditioning, data to be recorded during testing, energy consumption testing, range testing, and coastdown testing.

The batteries were aged by INEL prior to testing at EPA. They were aged to an equivalent mileage of between 2,000 and 6,200 miles, as the procedure requires. INEL discharged the batteries both at a C/3 rate (46 amps for these batteries) on a battery test stand and when equipped on the vehicle.[4] Both methods yielded similar results and proved to be an acceptable method of verifying or measuring battery capacity.

The test procedure requires a substantial amount of data to be recorded from each test. INEL supplied EPA with a data acquisition system that measured the following data requirements over all testing described in this report. The data recorded for each test cycle were:

1. Actual miles traveled;

2. System AC Energy Consumption--Watt-hours delivered from the electrical wall socket to the on-board charging system;

3. System DC Energy Consumption--Watt-hours delivered from the on-board charging system to the batteries; and

4. Vehicle DC Energy Consumption--Watt-hours delivered from the batteries to the electric motor for propulsion of the vehicle.

The SAE energy consumption test procedure requires the vehicle to be driven over two consecutive Urban Dynamometer Driving Schedule (UDDS) cycles separated by a 10-minute soak with the key switch in the "off" position and the test cell fan not operating during this soak period. Immediately following the second UDDS cycle, two Highway Fuel Economy Test (HFET) cycles were driven separated by a 15-second soak with the key switch in the "on" position and the brake pedal depressed.

The SAE procedure requires energy consumption values to be measured during the second HFET cycle only. It was, however, not possible to adhere to this requirement, because the recharge data will automatically reflect two HFET cycles. Therefore, EPA testing deviated from this SAE requirement and measured energy consumption over two UDDS and two HFET cycles.

The SAE procedure also requires the measurement of a combined UDDS/HFET driving range. The range test requires the vehicle to be driven over two successive UDDS cycles followed by two HFET cycles. A 15-second soak is required between the two HFET cycles followed by a 10-minute soak after the second HFET cycle. The test cell fan was shut off for the 10-minute soak but remained operational for the 15-second soak. This test sequence was repeated until the test termination criteria were met, at which point the vehicle was quickly decelerated to a stop. Extended soaks between each cycle (about 40 seconds), however, resulted due to the fact that the video driver's aid could not be reloaded instantaneously.

The test termination criteria detailed in the SAE procedure were somewhat different from current existing test procedures. With the SAE J1634 procedure, the range test would continue even if the vehicle could not meet the required speed profile provided the vehicle is operated at the maximum available power output during such occurrences. The criteria for termination that ended each range test during EPA testing of the electric vehicle was the requirement to stop the test if the vehicle does not reach 45 MPH after 30 seconds from the 187-second mark and then hold a 45 MPH speed until the 305-second mark of a UDDS cycle. Each range test, therefore, ended at the 217-second mark of the UDDS cycle where a 45 MPH speed could not be attained.

The SAE procedure also describes how coastdown testing of an electric vehicle shall be performed. EPA used coastdown data supplied by INEL for setting up the dynamometer. The complete coastdown curve for this vehicle is supplied in Appendix A of this report. A Clayton water-brake dynamometer is not equipped to handle an entire coastdown curve. Therefore, an EPA determination was made to set the actual dynamometer horsepower based on the INEL supplied 55 to 45 MPH coastdown time. The actual dynamometer horsepower setting on the dynamometer control system was adjusted until a time of 23.14 seconds was achieved for coasting from 55 to 45 MPH. The resultant actual dynamometer horsepower was 5.26 hp.

EPA also tested the electric vehicle over a test procedure more similar to the conventional test procedure that would yield separate city and highway energy consumption values so that a petroleum-equivalent fuel economy value could be calculated. City values were obtained by driving two consecutive UDDS cycles separated by a 10-minute soak with the key switch in the "off" position and the test cell fan off. Similarly, highway values were obtained by driving the vehicle over two successive HFET cycles separated by a 15-second soak period with only the brake pedal depressed.

Both the city and highway cycles were started after soaking the vehicle on charge overnight so that at the beginning of each test cycle, the batteries were at a full charge, similar to the SAE procedure. For the EV tested, the city energy consumption value and the highway energy consumption value were obtained in a slightly different manner than is done for conventional vehicles.

Because it is not easy to obtain separate "hot" and "cold" energy consumption values for an EV, the subject of how the two UDDS cycles back=to-back compare with the cold/hot weighted approach used for conventional testing should be discussed. In essence, the approach used here has a weighting factor of 0.5 applied to the cold UDDS cycle and 0.5 applied to the hot UDDS cycle. These values are not the same as the 0.43 and 0.57 factors used for the conventional calculation methodology. Whether or not the 50-50 weighting favors, is neutral to, or penalizes EVs with respect to their energy consumption depends on the ratio of the energy consumed by the EV in the cold start cycle to that consumed in the hot start cycle. EVs have a lower ratio then CVs due to the lack of the need for extra fuel (energy) to start the vehicle and the substantially lower energy requirement to warm up the system to operate more efficiently. For example, fuel (energy) rate delivered to an engine is higher during the time it is warming up and reduces to the lower "hot" rate only after the coolant temperature exceeds a certain value. No similar losses exist for EVs. Both vehicles suffer losses caused by excess friction in the drivetrain during warmup. Because EVs have a more favorable cold to hot energy consumption ratio, running two UDDS cycles back to back allows this warmup benefit to be reflected in the test result.

If the energy consumed driving the latter part of the second UDDS test ("Bag 4" in conventional vehicle nomenclature) is lower than that consumed in the latter portion of the first UDDS cycle, then the EV would be treated favorably by the way these tests were run, since for conventional vehicles the assumption is made that the two portions (Bag 2 and Bag 4) of the test are identical.

For the highway cycle fuel economy determination, conventional vehicles are operated through two highway cycles. In order to reduce variability and obtain the highest MPG value, only the second of the two cycles is used for determining the MPG value even though both cycles are run "hot." This is easy to do with conventional vehicles since the fuel consumed is determined by a carbon balance of the exhaust emissions and so only the second test is sampled. With EVs, however, there isn't any convenient way to not count the energy consumed during the first highway cycles, so the way the tests were run is very slightly unfavorable to the EV.

Further study of these test procedure nuances may be warranted if the SAE procedure is revised to permit the separate determination of city and highway energy consumption. No adjustments to the data in this report have been made, and if any were contemplated, they would be quite small.

IV. Description of Test Vehicle

The test vehicle used for this round-robin test program was a 1988 Ford Escort Wagon equipped with a manual transmission and radial tires. The vehicle was tested at an equivalent test weight of 4,250 lbs and an actual dynamometer horsepower of 5.26.

The vehicle was converted to electric propulsion for DOE by Soleq Corporation. The system consists of 18 6-volt sealed lead-acid Sonnenschein batteries (Model No. DF-160) with a single electric motor.

A picture of this test vehicle is provided in Figure 1 below.

Figure 1

Ford Escort Wagon Test Vehicle

V. Test Facilities and Analytical Methods

EPA testing was conducted on a water-brake Clayton model ECE-50 double-roll chassis dynamometer using a direct-drive variable inertia flywheel unit and road load power control unit. The vehicle was equipped with its own charging system. The vehicle was recharged from a wall socket providing 125 volts at 20 amps. This amount of recharge power was ample to recharge the battery pack to a full state-of-charge during an overnight soak period.

The data acquisition system used in this test program to measure power consumption and vehicle miles travelled was provided to EPA with the test vehicle from the Idaho National Engineering Laboratory. This system measured power consumed during both vehicle testing and vehicle charging periods. Voltage and amperage data was acquired every 100 milliseconds but was not stored at this rate. The 100-millisecond data was averaged over the storage period, which was 1 second for vehicle testing and 1-minute for vehicle charging.

VI. Discussion of Test Results

A. SAE J1634 Energy Consumption Testing

The Escort electric vehicle was first tested over the SAE J1634 Energy Consumption Procedure. This testing yielded a combined city/highway energy consumption value. Table 1 includes the results from EPA testing on a Clayton water-brake dynamometer.

Table 1

SAE J1634 Energy Consumption Test Results

Water-Brake Dynamometer:	System AC (W-hr/mile)	System DC (W-hr/mile)	Vehicle Net DC (W-hr/mile)
Test #1	468	339	259
Test #2	540	378	264
Average	504	358	262

All results presented in Table 1 are in watt-hours per mile (W-hr/mile). "System AC" represents the amount of energy supplied from the wall outlet to the on-board recharging system. "System DC" represents the amount of power delivered from the on-board charging system to the batteries. "Vehicle Net DC" represents the amount of overall power delivered from the batteries during driving with the amount of energy generated from regenerative braking subtracted.

From the water-brake chassis dynamometer results, the two tests conducted differ substantially when considering System AC and DC power usage. The two power levels differ by 15 and 12 percent respectively between the two individual tests. The net DC results correspond very well, however, with only a 2 percent difference. From these results, it can also be seen that a substantial amount of power from the wall socket is apparently lost in the on-board charging system. An average of 18.4 kW-hr from the wall socket results in only 13.1 kW-hr being supplied to the batteries. This would seem to indicate that the charging system on this vehicle is only about 71 percent efficient. This results in a substantial penalty in a petroleum-equivalent fuel economy value since the calculation is based on wall-power values. A more efficient charging system would increase calculated fuel economy results.

The differences between "System DC" and "Vehicle Net DC" power values result from battery inefficiency. The average "Vehicle Net DC" power consumed over the SAE procedure was 9.5 kW-hr. Compared to the wall-power usage of 18.4 kW-hr, the overall vehicle energy efficiency from wall to battery-out is approximately 52 percent when considering charging system and battery inefficiencies. The amount of energy delivered to the batteries during this driving cycle from the use of regenerative braking was approximately 0.6 kW-hr and will be reflected in all three power consumption values.

B. Individual City and Highway Energy Consumption Testing

The vehicle was tested at EPA over separate city and highway test cycles to determine individually the city and highway energy consumption values for this vehicle. The city values were obtained by running two successive UDDS cycles separated by a 10-minute soak. The results obtained from this testing are presented in Table 2 below. Again, all values are in watt-hours per mile.

Table 2

City Cycle Energy Consumption Test Results

Water-Brake Dynamometer:	System AC (W-hr/mile)	System DC (W-hr/mile)	Vehicle Net DC (W-hr/mile)
Test #1	670	428	303
Test #2	642	395	303
Average	656	412	303

The deviations in individual test results are less than those acquired during the J1634 testing. System AC and DC results differ between individual tests by only 4 and 8 percent respectively accompanied by no deviation in vehicle net DC power usage between tests. Again, large inefficiencies were noted during this testing with the on-board recharging system and the batteries. The wall-power used during this testing averaged 9.8 kW-hr, and the amount of power supplied to the batteries during recharging averaged 6.2 kW-hr resulting in a recharging efficiency of 63 percent. During this driving cycle, the "battery-out" power averaged 4.5 kW-hr. When comparing this value to the wall-power, an overall battery power efficiency of 46 percent is achieved.

The electric vehicle was next tested to obtain a highway energy consumption value. The driving schedule used here was two successive HFET cycles separated by a 15-second soak period. Table 3 below presents the results obtained from this testing. All values are presented in watt-hours per mile.

Table 3 Highway Cycle Energy Consumption Test Results			
Water-Brake Dynamometer:	System AC (W-hr/mile)	System DC (W-hr/mile)	Vehicle Net DC (W-hr/mile)
Test #1	564	346	222
Test #2	463	287	220
Test #3	441	286	217
Average	489	306	220

A third test was conducted during this phase due to the rather large discrepancy between the results from the first two tests. All three tests, however, were included in presenting an average value.

These results again indicate a rather large inefficiency in the on-board charging system. The wall-plug power used for these three tests averaged approximately 10.4 kW-hr. The corresponding amount of power supplied to the batteries during recharging averaged 6.5 kW-hr, a recharge efficiency of 62 percent.

When driving over two successive HFET cycles, the brakes are only applied four times. Therefore, the amount of power supplied to the batteries during driving by the regenerative braking system should be very small. The overall battery efficiency obtained here for "wall to battery-out" is approximately 45 percent. (The "Vehicle Net DC" power used averaged 4.7 kW-hr for this testing.)

C. Petroleum-Equivalent Fuel Economy Results

Using the recent DOE rulemaking entitled "Electric and Hybrid Vehicle Research, Development, and Demonstration Program; Equivalent Petroleum-Based Fuel Economy Calculation,"[3] a petroleum-equivalent fuel economy value can be calculated for this electric vehicle. The only requirements needed for this calculation are the city and highway energy consumption values presented in the previous section.

The DOE rulemaking references the SAE J1634 test procedure for obtaining energy consumption values for an electric vehicle; SAE procedure J1634 will only allow for a combined city/highway energy consumption value to be measured. EPA tested the electric vehicle separately over city and highway driving cycles so that these energy consumption values could be determined independently of each other.

Presented here is a step-by-step petroleum-equivalent fuel economy calculation resulting from EPA testing on the water-brake chassis dynamometer and the use of the method outlined in the DOE rulemaking.

$$\text{City energy consumption} = 0.656\ \frac{\text{kW-hr}}{\text{mile}} = 1.524\ \frac{\text{mile}}{\text{kW-hr}}$$

$$\text{Highway energy consumption} = 0.489\ \frac{\text{kW-hr}}{\text{mile}} = 2.045\ \frac{\text{mile}}{\text{kW-hr}}$$

$$\text{City fuel economy} = 1.524\ \frac{\text{mile}}{\text{kW-hr}} \times 33.44\ \frac{\text{kW-hr}}{\text{gallon}} = 50.963\ \text{MPG gasoline-equiv.}$$

$$\text{Highway fuel economy} = 2.045\ \frac{\text{mile}}{\text{kW-hr}} \times 33.44\ \frac{\text{kW-hr}}{\text{gallon}} = 68.385\ \text{MPG gasoline equiv.}$$

It should be noted that the value for the $\frac{\text{kW-hr}}{\text{gallon}}$ of gasoline used here differs from the value suggested by DOE. The value used here is consistent with the value used by EPA in other fuel economy rulemakings that involve fuel energy content.

After applying the factor for converting a kilowatt-hour value into equivalent gallons of gasoline, a composite fuel economy value for the electric vehicle can be determined based on the 55/45 method used for CAFE calculations.

$$MPG_{composite} = \frac{1}{\frac{.55}{MPG_{city}} + \frac{.45}{MPG_{hwy}}}$$

$$MPG_{composite} = \frac{1}{\frac{.55}{50.963} + \frac{.45}{68.385}} = 57.562\ \text{MPG gasoline equiv.}$$

Now, it is necessary to apply the Petroleum Equivalency Factor (PEF) found in the DOE rulemaking for an overall petroleum-equivalent fuel economy for this electric vehicle.

$$MPG_{EV} = MPG_{composite} \times PEF$$

$$MPG_{EV} = 57.562 \times 2.32 = 133.5$$

Therefore, the value that would used for this electric vehicle in any calculations of a manufacturer's average fuel economy would be 133.5 miles per gallon.

D. SAE J1634 Range Testing

The last phase of testing with this electric vehicle consisted of range testing following the protocols outlined in the SAE J1634 test procedure. The vehicle was driven over successive UDDS and HFET driving cycles until the test termination point was reached. The driving cycles and test termination point are described in more detail in Section III of this report.

The SAE procedure is written such that the range test shall continue if the vehicle cannot meet the driving trace just as long as the vehicle is operated at maximum power output. The criteria that ended the range test at EPA was where the procedure states that "if the vehicle cannot attain 45 miles per hour 30 seconds after the 187-second in the UDDS cycle, the test shall be terminated." At the 217-second mark of the third UDDS driving cycle (after two previous UDDS cycles and two HFET cycles), the vehicle speed was not 45 MPH, the vehicle was quickly decelerated to stop, and the range determined. The resultant range was measured as 37.8 miles. INEL informally reported a similar range result to EPA.

VII. Future Efforts

The electric vehicle is currently being tested at EPA on a Horiba 48-inch single-roll electric chassis dynamometer over the same test sequence described in this report. These results will be published in a separate EPA technical report when testing is completed.

The vehicle will then be tested at Ford Motor Co. and CARB. INEL will then publish a report describing all the results from testing at the four sites included in this round-robin test program.

VIII. Acknowledgements

The authors would like to acknowledge the cooperation and support of George H. Cole and Roger A. Richardson of the Idaho National Engineering Laboratory for supplying EPA with the test vehicle and the data acquisition system.

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IX. References

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2. "Electric Vehicle Energy Consumption and Range Test Procedure," SAE Surface Vehicle Recommended Practice, SAE J1634, 1993.

3. "Electric and Hybrid Vehicle Research, Development, and Demonstration Program; Equivalent Petroleum-Based Fuel Economy Calculation," 10 Code of Federal Regulations, Part 474, Docket No. EE-RM-94-101, February 4, 1994.

4. Letter from George H. Cole, Program Manager, Electric and Hybrid Vehicle Program, INEL to Ronald M. Schaefer, Mechanical Engineer, U.S. EPA, February 7, 1994.

Appendix A

Ford Escort Electric Vehicle Coastdown Data

Speed (MPH)	Time (sec)	Speed (MPH)	Time (sec)
60	0.00	35	61.73
59	1.88	34	64.96
58	3.80	33	68.27
57	5.77	32	71.64
56	7.77	31	75.08
55	9.82	30	78.59
54	11.92	29	82.17
53	14.06	28	85.82
52	16.24	27	89.55
51	18.48	26	93.35
50	20.76	25	97.22
49	23.10	24	101.16
48	25.48	23	105.17
47	27.92	22	109.26
46	30.41	21	113.41
45	32.96	20	117.64
44	35.56	19	121.93
43	38.22	18	126.29
42	40.94	17	130.72
41	43.73	16	135.21
40	46.57	15	139.76
39	49.47	14	144.38
38	52.44	13	149.05
37	55.47	12	153.77
36	58.57	11	158.54

Inertia Wt. = 4,250 lbs

f'0 = 38.7385 lb Miw = 132.09423
f'2 = 0.0186 lb/MPH^2 Mdlc = 1.9814135

V1 (MPH) =	55	60	20
V0 (MPH) =	45	10	10
t-t0 (s) =	23.14	163.36	45.73

Hp = (f'0 + f'2*V^2) * V * (5280/(3600*550))

Speed (MPH)	Power (Hp)	(Power (kW)
60	16.91	12.61
50	11.36	8.47
40	7.31	5.45
30	4.44	3.31
20	2.46	1.84
10	1.08	0.81