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# BASELINE TESTS OF THE C. H. WATERMAN RENAULT 5 ELECTRIC PASSENGER VEHICLE

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16 Abstract The C H Waterman Renault 5, an electric passenger vehicle manufactured by C H Waterman Industries, Athol, Massachusetts, was tested at the Dynamic Science Test Track in Phoenix, Arizona, between April 6 and April 26, 1977 The tests are part of an Energy Research and Development Administration (ERDA) project to characterize the state-of-the-art of electric vehicles The Waterman vehicle performance test results are presented in this report The Waterman is a four-passenger Renault 5 GTL that has been converted to an electric vehicle It is powered by sixteen 6-volt traction batteries through a two-step contactor controller actuated by a foot throttle to change the voltage applied to the 6 7-kilowatt (9-hp) motor The motor output shaft is connected to a front-wheel-drive transaxle that contains a four-speed manual transmission and clutch The braking system is a conventional hydraulic braking system Regenerative braking was not provided			
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The Electric and Hybrid Vehicle Program  
was conducted under the guidance of the  
then Energy Research and Development  
Administration (ERDA), now part of the  
Department of Energy.

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SUMMARY

The C. H. Waterman Renault 5, an electric passenger vehicle manufactured by C. H. Waterman, Athol, Massachusetts, was tested at the Dynamic Science Test Track in Phoenix, Arizona, between April 6 and April 26, 1977. The tests are part of an Energy Research and Development Administration (ERDA) project to characterize the state-of-the-art of electric vehicles. The Waterman vehicle performance test results are presented in this report.

The vehicle is a four-passenger Renault 5 GTL that has been converted to an electric vehicle. It is powered by sixteen 6-volt traction batteries through a two-step contactor controller actuated by a foot throttle to change the voltage applied to the 6.7-kilowatt (9-hp) motor. The motor output shaft is connected to the standard Renault 5 front-wheel-drive transaxle that contains a four-speed manual transmission and clutch. The braking system is a conventional hydraulic braking system. Regenerative braking was not provided.

All tests were run at the gross vehicle weight of 1362 kilograms (3000 lbm). The results of the tests are as follows:

Test speed or driving cycle	Type of test						
	Range		Road power, kW	Road energy		Energy consumption	
	km	mile		MJ/km	kWh/mile	MJ/km	kWh/mile
40 km/h (25 mph)	188.3	117.0	2.7	0.25	0.11	0.60	0.27
56 km/h (35 mph)	128.2	79.7	4.3	28	12	74	33
Schedule B	128.6	79.9	---	----	----	83	37

The Waterman Renault 5 was able to accelerate from 0 to 32 kilometers per hour (0 to 20 mph) in 9.3 seconds and from 0 to 48 kilometers per hour (0 to 30 mph) in 34 seconds. The gradeability limit was 37 percent.

Measurements were made to assess the performance of the vehicle components. The performance was as follows:

Charger efficiency over a complete charge cycle, percent . . . . .	.80 to 94
Battery efficiency with 10 percent overcharge, percent . . . . .	.72
Controller efficiency, percent . . . . .	>99
Motor efficiency at constant speed, percent. . . . .	.75 to 80

## INTRODUCTION

The vehicle tests and the data presented in this report are in support of Public Law 94-413 enacted by Congress on September 17, 1976. The law requires the Energy Research and Development Administration (ERDA) to develop data characterizing the state-of-the-art of electric and hybrid vehicles. The data so developed are to serve as a baseline (1) to compare improvements in electric and hybrid vehicle technologies, (2) to assist in establishing performance standards for electric and hybrid vehicles, and (3) to help guide future research and development activities.

The National Aeronautics and Space Administration (NASA), under the direction of the Electric and Hybrid Research, Development, and Demonstration Office of the Division of Transportation Energy Conservation of ERDA, has conducted track tests of electric vehicles to measure their performance characteristics and vehicle component efficiencies. The tests were conducted according to ERDA Electric and Hybrid Vehicle Test and Evaluation Procedure, described in appendix E of reference 1. This procedure is based on the Society of Automotive Engineers (SAE) J227a procedure (ref. 2). Seventeen electric vehicles have been tested under this phase of the program, 12 by NASA, 4 by MERADCOM, and 1 by the Canadian government.

The assistance and cooperation of C. H. Waterman, the vehicle manufacturer, is greatly appreciated. The Energy Research and Development Administration provided funding support and guidance during this project.

U.S. customary units were used in the collection and reduction of data. The units were converted to the International System of Units for presentation in this report. U.S. customary units are presented in parentheses. The parameters, symbols, units, and unit abbreviations used in this report are listed here for the convenience of the reader.

Parameter	Symbol	SI units		U S. customary units	
		Unit	Abbrevia- tion	Unit	Abbrevia- tion
Acceleration	a	meter per second squared	m/s <sup>2</sup>	mile per hour per second	mph/s
Area	---	square meter	m <sup>2</sup>	square foot, square inch	ft <sup>2</sup> , in <sup>2</sup>
Energy	---	megajoule	MJ	kilowatt hour	kWh
Energy consumption	E	megajoule per kilometer	MJ/km	kilowatt hour per mile	kWh/mile
Energy economy	---	megajoule per kilometer	MJ/km	kilowatt hour per mile	kWh/mile
Force	P	newton	N	pound force	lbf
Integrated current	----	ampere hour	Ah	ampere hour	Ah
Length	---	meter	m	inch, foot, mile	in ft, ---
Mass, weight	W	kilogram	kg	pound mass	lbm
Power	P	kilowatt	kW	horsepower	hp
Pressure	---	kilopascal	kPa	pound per square inch	psi
Range	---	kilometer	km	mile	---
Specific energy	---	megajoule per kilogram	MJ/kg	watt hour per pound	Wh/lbm
Specific power	---	kilowatt per kilogram	kW/kg	kilowatt per pound	kW/lbm
Speed	V	kilometer per hour	km/h	mile per hour	mph
Volume	---	cubic meter	m <sup>3</sup>	cubic inch, cubic foot	in <sup>3</sup> , ft <sup>3</sup>

## OBJECTIVES

The characteristics of interest for the Waterman Renault are vehicle speed, range at constant speed, range over stop-and-go driving schedules, maximum acceleration, gradeability, gradeability limit, road energy consumption, road power, indicated energy consumption, braking capability, battery charger efficiency, battery characteristics, controller efficiency, and motor efficiency.

## TEST VEHICLE DESCRIPTION

The C. H. Waterman Renault 5 is a converted Renault 5 GTL propelled by a DC series wound traction motor and powered by sixteen 6-volt traction batteries. A two-step contactor controller, actuated by a foot throttle, changes the voltage applied to the 6.7-kilowatt (9-hp) motor. The drive train includes a four-speed manual transmission and clutch that are integral parts of the front-wheel-drive transaxle. The vehicle is accelerated by selecting second gear for level terrain and depressing the accelerator one step. As the vehicle picks up speed, the accelerator is depressed to the second step. To upshift or downshift the vehicle, the accelerator is kept in the second step, the clutch is depressed and the shift lever moved to a higher or lower gear, and then the clutch is released. When

going uphill, the vehicle must be downshifted to second or first gear to avoid drawing excessive current. The vehicle is shown in figure 1 and described in detail in appendix A. The 120-volt alternating current (AC) battery charger on board the vehicle provided charge to both the traction batteries and the accessory battery. The vehicle manufacturer specifies 10 hours to completely recharge fully discharged batteries, but for the track tests a longer period was used to assure complete recharging. No regenerative braking was provided on this vehicle. The controller, charger, and front battery pack are shown in figure 2.

## INSTRUMENTATION

The Waterman Renault vehicle was instrumented to measure vehicle speed and range, battery current, motor current and voltage, temperatures of the motor frame and battery case, and battery charger power. Most of these data were telemetered to a central instrumentation facility, where they were recorded on magnetic tape. The telemetry system is described in appendix B.

A schematic diagram of the electric propulsion system with the instrumentation sensors is shown in figure 3. A Nucleus Corporation Model NC-7 precision speedometer (fifth wheel) was used to measure vehicle velocity and distance traveled. Auxiliary equipment used with the fifth wheel included a Model ERP-X1 electronic pulser for distance measurement, a Model NC-PTE pulse totalizer, a Model ESS/E expanded-scale speedometer, and a programmable digital attenuator. The fifth wheel was calibrated before each test by rotating the wheel on a constant-speed fifth wheel calibrator drum mounted on the shaft of a synchronous AC motor. The accuracy of the distance and velocity readings was within  $\pm 0.5$  percent of the readings. Distance and velocity were recorded on magnetic tape through the telemetry system.

The integrated battery current was measured for the battery pack with a current shunt and an on-board current integrator. It was recorded manually after each test. This measurement provides the ampere-hours delivered by one-half of the battery pack. The current integrator is a Model SHR-C3 Curtis current integrator and was calibrated periodically to within  $\pm 1$  percent of reading.

Motor current and motor voltage were measured to determine motor performance. A 500-ampere current shunt was used to measure motor current. These measurements were telemetered and recorded on magnetic tape. Temperatures on the motor and on both front and rear battery packs were monitored and continuously recorded on magnetic tape during the tests. In addition, battery electrolyte temperatures and specific gravities were measured manually before and after the tests.

Power for the fifth wheel and current integrator was provided from a 12-volt starting, lighting, and ignition (SLI) instrumentation battery. A Tripp Lite 500-watt DC/AC inverter provided the AC power. The power for the telemetry system was obtained from a battery power pack described in appendix B.

All instruments were calibrated periodically. The integrators and strip-chart recorders were calibrated with a Hewlett-Packard Model 6920 B meter calibrator, which has an accuracy of 0.2 percent of reading and a usable range of between 0.01 and 1000 volts.

The current and voltage into the battery and the energy into the battery charger were measured while the battery was being recharged after each test. The current and voltage to the battery were recorded on a Honeywell 195 Electronik two-channel strip-chart recorder. The current measurement used a 500-ampere current shunt in all the tests except in one series. In these tests to measure charger efficiency, a laboratory-type wattmeter with Hall-effect current sensors manufactured by Ohio Semitronics, Inc., was used. The energy delivered to the charger was measured with a General Electric 1-50A single-phase residential kilowatt-hour meter.

#### TEST PROCEDURES

The tests described in this report were performed at the Dynamic Science Test Track, a two-lane, 3.22-kilometer (2-mile) asphalt track located in Phoenix, Arizona. A complete description of the track is given in appendix C. When the vehicle was delivered to the test track, the pretest checks described in appendix D were conducted. The first test was a formal shakedown to familiarize the driver with the operating characteristics of the vehicle, to check out all instrumentation systems, and to determine the vehicle's maximum speed (appendix D). All tests were run in accordance with ERDA Electric and Hybrid Vehicle Test And Evaluation Procedure ERDA-EHV-TEP, appendix E of reference 1, at the gross weight of the vehicle, 1362 kilograms (3000 lbm).

#### Range Tests at Constant Speed

The vehicle speed for the highest constant-speed range test was determined during checkout tests of the vehicle. It was specified as 95 percent of the minimum speed the vehicle could maintain on the test track when it was traveling at full power. This speed was 56 kilometers per hour (35 mph) for the Waterman Renault.

Range tests at constant speeds were run at 40 and 56 kilometers per hour (25 and 35 mph). The speed was held constant

within  $\pm 1.6$  kilometers per hour (1 mph), and the test was terminated when the vehicle could no longer maintain 95 percent of the test speed. The range tests were run at least twice at both speeds.

### Range Tests under Driving Schedules

Only the 32-kilometer-per-hour (20-mph), schedule B stop-and-go driving cycle, shown in figure 4, was run with this vehicle. The Waterman Renault was unable to accelerate rapidly enough to meet schedule C. A complete description of cycle tests is given in appendix E of reference 1. A special instrument, called a cycle timer, was developed at the Lewis Research Center to assist in accurately running these tests. Details of the cycle timer are given in appendix D. The cycle tests were terminated when the test speed could not be attained in the time required under maximum acceleration.

### Acceleration and Coast-Down Tests

The maximum acceleration of the vehicle was measured on a level road with the battery fully charged and 40 and 80 percent discharged. Four runs, two in each direction, were conducted at each of these three states of charge. Depth of discharge was determined from the number of ampere-hours removed from the batteries. The vehicle was accelerated by starting in second gear and shifting to third gear at approximately 35 kilometers per hour (22 mph). Acceleration runs were made on the southern straight section of the track, and coast-downs on the northern straight section (appendix C, fig. 20). Coast-down data were taken after the acceleration test with the transmission in neutral and with fully charged batteries in order to start the coast-down run from the maximum attainable vehicle speed. Because of the Waterman Renault's low road load, track grade irregularities at Dynamic Science led to more data variability than was expected, which greatly affected the road energy and road power calculations. Additional coast-down data were therefore taken at the Transportation Research Center (TRC) in East Liberty, Ohio. The TRC coast-down data are the only data included in this report.

### Braking Tests

Braking tests on the vehicle were conducted

- (1) To determine the minimum stopping distance in a straight-line emergency stop
- (2) To determine the controllability of the vehicle while braking in a turn on both wet and dry pavement

- (3) To determine the brake recovery after being driven through 0.15 meter (6 in.) of water at 8 kilometers per hour (5 mph) for 2 minutes
- (4) To determine the parking brake effectiveness on an incline

Instrumentation used during the braking test included a fifth wheel programmed to determine stopping distance, a brake pedal force transducer, and a decelerometer. A complete description of the braking tests is given in the discussion of test results and in appendix E of reference 1.

#### Tractive Force Tests

The maximum grade climbing capability of the test vehicle was determined from tractive force tests by towing a second vehicle. The driver of the towed vehicle, by applying the footbrake, maintained a speed of about 3 kilometers per hour (2 mph) while the test vehicle was being driven with a wide-open throttle. The force was measured by a 13 000-newton (3000-lbf) load cell attached to the tow chain between the vehicles. The test was run only with the batteries fully charged.

#### Charger Efficiency Tests

Two methods were used to determine charger efficiency as a function of charge time. In the first method a residential kilowatt-hour meter was used to measure input power to the charger by counting rotations of the disk and applying the meter manufacturer's calibration factor. The charger output power was determined by multiplying the average value of current by the average value of voltage. Residential kilowatt-hour meters are calibrated for sinusoidal waves only. The error in measuring input power depends on the wave shape and may be as high as 5 percent. The method of determining output power is correct only when either the voltage or the current is a constant during each charging pulse. The battery voltage does change during each charging pulse, which introduces a small error. The current shunts used to measure current are inaccurate for pulsing current. The error depends on frequency and wave shape and may exceed 10 percent.

In the other method used for determining charger efficiency, a 50-kilowatt power meter was used on both the input and output of the charger and a Hall-effect current probe was used for current measurements. To minimize errors, the same meter and current probe were used for both the input measurement and the output measurement. The average power measured was about 4 percent of full scale. The influence of these inaccuracies on the determination of charger efficiency is discussed in the component section of this report.

## TEST RESULTS

### Range

The data collected from all the range tests are summarized in table I. Shown in the table are the test date, the type of test, the environmental conditions, the range test results, the ampere-hours into and out of the battery, and the energy into the charger. These data were used to determine vehicle range, battery efficiency, and energy consumption.

During most of the test period, the winds were variable and gusty. Even though the wind was less than 16 kilometers per hour (10 mph), on several occasions the wind was blowing in different directions and at different velocities at two positions on the track. There was no indication that this variation in wind velocity significantly affected the range or other test results as long as the measured winds were less than about 16 kilometers per hour.

The maximum speed of the vehicle was measured during the checkout tests. It is defined as the average speed that could be maintained on the track under full power. The measured maximum speed was 64 kilometers per hour (40 mph) for this vehicle. This differs from the maximum speed used in the range tests.

Two 40-kilometer-per-hour (25-mph), two 56-kilometer-per-hour (35-mph), and two schedule B range tests were run. All the test results are shown in table I. All the range test results were within +5 percent of the mean.

### Maximum Acceleration

The maximum acceleration of the vehicle was determined with the batteries fully charged and 40 and 80 percent discharged. The vehicle was shifted from second to third gear during the acceleration. Vehicle speed as a function of time is shown in figure 5 and table II. The average acceleration  $\bar{a}_n$  was calculated for the time period  $t_{n-1}$  to  $t_n$ , where  $n$  the vehicle speed increased from  $V_{n-1}$  to  $V_n$ , from the equation

$$\bar{a}_n = \frac{V_n - V_{n-1}}{t_n - t_{n-1}}$$

and the average speed of the vehicle  $\bar{V}$  from the equation

$$\bar{V} = \frac{V_n + V_{n-1}}{2}$$

Maximum acceleration as a function of speed is shown in figure 6 and table II.

### Gradeability

The maximum specific grade, in percent, that a vehicle can climb at an average vehicle speed  $\bar{V}$  was determined from maximum acceleration tests by using the equations

$$G = 100 \tan (\sin^{-1} 0.1026 \bar{a}_n) \quad \text{for } V \text{ in km/h}$$

in SI units

or

$$G = 100 \tan (\sin^{-1} 0.0455 \bar{a}_n) \quad \text{for } \bar{V} \text{ in mph}$$

in U.S. customary units

where  $\bar{a}_n$  is average acceleration in meters per second squared (mph/sec<sup>2</sup>). The maximum grades the Waterman Renault can negotiate as a function of speed are shown on figure 7 and table II.

### Gradeability Limit

Gradeability limit is defined by the SAE J227a procedure as the maximum grade on which the vehicle can just move forward. The limit was determined by measuring the tractive force with a load cell while towing a second vehicle at about 3 kilometers per hour (2 mph). It was calculated from the equations

$$\text{Gradeability limit in percent} = 100 \tan \left( \sin^{-1} \frac{P}{9.8 W} \right)$$

in SI units

or

$$\text{Gradeability limit in percent} = 100 \tan \left( \sin^{-1} \frac{P}{W} \right)$$

in U.S. customary units

where

P tractive force, N (lbf)

W gross vehicle weight, kg (lbf)

The tractive force that the Waterman Renault was capable of exerting in second gear with fully charged batteries was 476 kilograms (1050 lbf). For the vehicle weight of 1362 kilograms (3000 lbf), the gradeability limit is 37 percent. The vehicle broke traction during this test, so tractive force tests at 40 percent and 80 percent discharge were not run since the vehicle is not power limited but traction limited at low speed.

#### Road Energy Consumption

Road energy is a measure of the energy consumed per unit distance in overcoming the vehicle's aerodynamic and rolling resistance plus the energy consumed in the differential drive shaft and the portion of the transmission rotating when in neutral. It was obtained during coast-down tests, when the differential was being driven by the wheels, and thus may be different than the energy consumed when the differential is being driven by the motor.

Road energy consumption  $E_n$  was calculated from the following equations:

$$E_n = 2.78 \times 10^{-4} W \frac{V_{n-1} - V_n}{t_n - t_{n-1}}, \text{ MJ/km}$$

or

$$E_n = 9.07 \times 10^{-5} W \frac{V_{n-1} - V_n}{t_n - t_{n-1}}, \text{ kWh/mile}$$

where

W vehicle mass, kg (lbm)

V vehicle speed, km/h (mph)

t time, s

The results of the road energy calculations are shown in figure 8 and table III.

#### Road Power Requirements

The road power is analogous to the road energy. It is a measure of vehicle aerodynamic and rolling resistance plus the power losses from the differential, the drive shaft, and a portion of the transmission. The road power  $P_n$  required to propel a vehicle at various speeds is also determined from the coast-down tests. The following equations are used:

$$P_n = 3.86 \times 10^{-5} W \frac{V_{n-1}^2 - V_n^2}{t_n - t_{n-1}}, \text{ kW}$$

or

$$P_n = 6.08 \times 10^{-5} W \frac{V_{n-1}^2 - V_n^2}{t_n - t_{n-1}}, \text{ hp}$$

The results of road power calculations are shown in figure 9 and table III.

#### Indicated Energy Consumption

The vehicle indicated energy consumption is defined as the energy required to recharge the battery after a test, divided by the vehicle range achieved during the test, where the energy is the input to the battery charger.

The energy input to the battery charger was measured with a residential kilowatt-hour meter following each range test. Substantial overcharge of the batteries was usually required in order to assure that all cells of the battery were fully charged and the pack was equalized. The reported energy usage may be higher than would be experienced with normal vehicle field operation. Indicated energy consumption as a function of vehicle

speed is plotted in figure 10 and is tabulated in table IV for the constant-speed tests.

### Braking Capability

Simplified braking capability tests were conducted according to the procedure outlined in appendix E of reference 1, in order to provide a preliminary evaluation of the vehicle's braking capabilities. The procedure also includes tests for handling, but at ERDA's direction they were not conducted on this vehicle.

Straight line stops - Six straight-line stops from 56 kilometers per hour (35 mph) were made, three from each direction. Stopping distance varied from 18.9 meters (62 ft) to 20.4 meters (67 ft).

Stops on a curve - Three stops were made going into a 0.3-g curve from 56 kilometers per hour (35 mph) on dry pavement turning right, and three stops were made in the same curve turning left. No difficulties were encountered in stopping within the 3.6-meter (12-ft) lane. The stopping distance varied from 21.6 meters (71 ft) to 23.2 meters (76 ft). The tests were repeated in a 0.2-g turn on wet pavement. Again the vehicle stopped smoothly with no problems. The stopping distances varied from 23.8 meters (78 ft) to 25.9 meters (85 ft).

Wet brake recovery - Three baseline stops were made from 48 kilometers per hour (30 mph) with dry brakes, decelerating at 3 meters per second squared ( $10 \text{ ft/sec}^2$ ). The average pedal force was 214 newtons (48 lbf). After the vehicle was driven through 0.15 meter (6 in.) of water at 8 kilometers per hour (5 mph) for 2 minutes, the tests were repeated. The first stop was made with a pedal force of 256 newtons (57.5 lbf). The brakes had fully recovered on the fourth stop.

Parking brakes. - Tests were conducted to determine parking brake effectiveness. The braking force required to hold the vehicle facing downhill on a 30-percent slope was 489 newtons (110 lbf) with the force being applied 3.8 centimeters (1.5 in.) from the top of the brake handle. The vehicle would not hold on this slope facing uphill with the same force applied.

## COMPONENT PERFORMANCE AND EFFICIENCY

### Battery Charger

The Waterman Renault battery charger consists of a transformer that has a tapped primary and two center-tapped secondary windings. One of the secondaries is used to charge the traction batteries. The other secondary is used to charge the 12-volt accessory battery. Both of the center-tapped secondaries

are connected through diodes to form full-wave rectifiers. The outputs of each system may be simultaneously adjusted by means of the primary tap.

The battery charger efficiency test data are presented in table V and in figure 11. The indicated efficiencies of the charger, as calculated from the readings on the residential kilowatt-hour meter and the average values of charger output voltages and amperes, are up to 10 percent less than the efficiencies that were calculated using wattmeter readings. Which set of values is more nearly correct has not been determined. Since the power efficiency is fairly constant over the entire time period, the energy efficiency is approximately equal to the average of the power efficiencies.

The total amount of energy that is delivered to the battery depends not only on the charger efficiency, but also on the system used to terminate the charge. The C. H. Waterman charger uses a timer set by the operator to terminate the charge and a switch on the transformer primary to adjust the charging current. The charging current is controlled by the difference between the applied voltage and the battery voltage, divided by the circuit impedance. Slight changes in the applied voltage or slight variations in the battery voltage (due to temperature, age, etc.) can drastically affect the charging current and the time required to attain full charge. Consequently, the amount of energy that is delivered to the battery is largely determined by the judgement of the operator. During the track tests the battery was always purposely overcharged.

### Batteries

Manufacturer's data. - The batteries supplied with the Waterman Renault were Electric Storage Battery (ESB) Incorporated Exide or Willard EV-106 electric vehicle batteries. The EV-106 is a 6-volt, three-cell module rated at 106 minutes discharge at a current of 75 amperes to a voltage cutoff of 1.75 volts per cell at a temperature of 25° C (77° F). Specifications as supplied by battery manufacturers are shown in table VI.

Battery manufacturer's discharge data are presented in figures 12 and 13. Figure 12 gives the relationship of discharge current and voltage to the length of time the battery is able to deliver this current. As shown, the battery can deliver 10 amperes for 20 hours, or 200 ampere-hours, but it can deliver 250 amperes for only 0.37 hour, or 92.5 ampere-hours. At a discharge current of 10 amperes, the mean cell voltage is 2.0 volts; at a discharge current of 250 amperes, the mean cell voltage drops to 1.5 volts during the discharge period. The batteries rated capacity is about 15 percent lower than the capacity shown in figure 12, and this rated capacity is what is used to evaluate the battery.

Figure 13 gives the battery manufacturer's relationship of specific power to the specific energy available from a three-cell module. At a low specific power of 2 watts per kilogram the available energy is 0.15 megajoule per kilogram (41.7 Wh/kg). At a high specific power of 40 watts per kilogram (18 W/lbm), the available energy decreased to 0.052 megajoule per kilogram (14.6 Wh/kg). At the manufacturer's rated discharge rate of 75 amperes, which is equivalent to 14 W/kg, the available specific energy is 0.096 megajoule per kilogram (26.7 Wh/kg).

Battery acceptance. - Prior to the road tests, the batteries supplied by the vehicle manufacturer were tested for battery capacity and terminal integrity as specified in appendix E of reference 1.

A 300-ampere discharge test was run using an electronic load. The temperatures of the terminals were determined with temperature-sensitive tape. The test was run twice; an attempt was made to lower terminal temperatures by cleaning all terminals before the second test. The temperature of the terminals remained in the 60° to 82° C (140° to 180° F) range for both tests. This temperature rise is about 50° C above ambient, thus the battery terminals are within specifications.

A capacity check was run twice. The capacity was determined by a constant current discharge of 75 amperes to a voltage cutoff of 1.75 volts per cell. The capacity check was run using an electronic load. The first capacity check was run in conjunction with the 300-ampere tests; while the last capacity check was run at 75 amperes after a recharge. The resultant capacity was 139 ampere-hours for the first test and 135 ampere-hours for the second test. Since the rated capacity of the batteries is 132.5 ampere-hours, the batteries passed this test.

Battery performance at constant speed. - During the road tests, motor current and voltage were recorded. The vehicle's contactor speed controller switches battery voltage from 0 to 24 volts to 48 volts (nominal) when the accelerator pedal is depressed. In the driving tests performed on 4/21/77 and 4/20/77 and reported in this section, the nominal motor voltage was either 24 or 48 volts. As a result the current, voltage, and power reported for the motor are equal to those of the battery. The losses in the contactor are negligible.

Figure 14 shows the battery characteristics during the 40-kilometer-per-hour (25-mph) test of 4/21/77 and the 56-kilometer-per-hour (35-mph) test of 4/20/77. Figure 14(a) gives the battery current, voltage, and power for the first 25 percent of the vehicle's range; figure 14(b) gives the same

parameters for the last 25 percent of the vehicle's range in the 56-kilometer-per-hour (35-mph) run and the last 13 percent in the 40-kilometer-per-hour (25-mph) test.

Battery performance under driving schedules. - The battery current and power during the various phases of driving schedule B are tabulated in table VII. The current and power reported are the time-averaged values over the acceleration and cruise phases of the cycle, where battery power is required. Peaks in both current and power occur since the driver is attempting to match a programmed speed-time profile. Currents as high as 290 amperes and powers as high as 13 kilowatts occur during the acceleration phase, and peaks of 150 amperes and 7.5 kilowatts occur in the cruise phase.

The total energy delivered by the battery during the third cycle was 59.8 watt hours; during the 324th cycle it was 52.5 watt-hours.

Battery performance during maximum acceleration. - Battery performance data at selected times during the maximum acceleration tests for three depths of battery discharge are presented in table VIII. The power at 20 seconds was substantially higher than the power at 10 and 50 seconds because the vehicle was undergoing a gear change at this time.

Battery system performance. - Shown in table IX are battery data for the driving tests. The electrolyte specific gravities of the fully charged battery are about 1.285; while those of the fully discharged battery are about 1.135. The overcharge in ampere-hours varies from 23 to 43 percent. While the overcharge is necessary to equalize the cells in order to assure full charge for every cell, it significantly increases energy consumption. A charge cycle that results in only a 10-percent overcharge would be better if minimum energy consumption is desired.

The battery temperature increases from ambient at the start of the test to about 14° C (25° F) above ambient at the end of test.

Charging. - A typical charge profile for the Waterman Renault is shown in figure 15. This profile occurred after the 56-kilometer-per-hour (35-mph) constant-speed range test performed on 4/20/77. The battery voltage, current, and power as a function of charge time are shown in figure 15. Since the battery pack is charged in a 48-volt configuration (i.e., two 48-volt packs in parallel), the input current per cell can be determined by dividing the current shown in figure 15 by two.

Battery efficiency. - The battery energy efficiency is calculated as the total energy removed from a battery during a

test divided by the total energy restored during subsequent charging. The battery energy efficiency thus determined must be qualified since overcharge does occur during charging. Representative energy efficiencies for two constant-speed tests are shown in table X. Also shown are the actual energies removed and restored to a battery and the associated overcharge.

The energy restored, as noted in table X, is higher than expected because of the excessive overcharge required during testing. The restored energy values can be reduced substantially by correcting them to levels expected for an overcharge of 10 percent. Since there is a linear relationship between the energy restored to the battery and the capacity restored during charging, the correction can be easily made. The battery efficiency calculated for a 10-percent overcharge increases to 71 percent for the test run on 4/14/77 and to 73 percent for the test run on 4/20/77.

The high overcharge experienced in the actual road tests was required for balancing (equalizing) the battery. In actual use situations, the balancing would only be required periodically (once per week). Thus, normal energy efficiencies with only a 10-percent overcharge would be closer to the 70- to 75-percent region than the 53 to 64 percent shown in table X.

#### Controller

The Waterman Renault is controlled by battery-switching contactors. The battery modules are connected in 24- or 48-volt arrangements by energizing the proper contactors. Under all operating conditions, the voltage drop across the contacts is less than 100 millivolts and the coil dissipation is less than 100 watts. Consequently, the controller efficiency is greater than 99 percent. In a vehicle the operation of the controller varies depending on the type of test being run. In maximum acceleration tests, 48 volts is applied to the motor continuously. In constant-speed tests the driver closes the contactors, applying 48 volts to the motor and accelerating the vehicle until it exceeds the target speed. Then the driver opens the contactors, disconnecting the motor from the power source and allowing the vehicle to coast down to a speed below target speed. The driver then recloses the contactors and repeats the cycle. During these constant-speed tests the speed actually varied  $\pm 1.6$  kilometers per hour (1 mph).

#### Motor

The Waterman Renault motor is a conventional DC series-wound traction motor originally designed for use in industrial trucks. The motor was manufactured by the Prestolite Electrical Division of Eltra Corp. A data sheet dated November 15, 1971, and

cold-performance curves (fig. 16) dated February 15, 1968, for this motor were supplied by C. H. Waterman. The data sheet gives the 1-hour rating of the motor as 6.7 kilowatts (9 hp) at 1630 rpm, 250 amperes, and 36 volts. The motor has Class H insulation and has an internal cooling fan. The combined resistance of the armature and series field is given as 0.0124 ohm.

Figure 16 shows that at 36 volts the motor efficiency rises from zero at no load to a peak value of 80 percent at 75 amperes and drops to 62 percent at 575 amperes. Since the vehicle operates at nominal voltage levels of 24 and 48 volts, the curves are not directly applicable. The speed and horsepower curves may be approximately scaled in proportion to the voltage change. When the curves are scaled to 48 volts, the scaling error gives values of speed and horsepower that are less than the true values. Consequently, the efficiency at 48 volts should be higher than the values shown.

Representative values of motor current for the constant-speed test are listed in table XI. The current flows only during the period when the contactors are closed. For the 56-kilometer-per-hour test the values range from about 175 amperes to about 250 amperes. The motor curves indicate that the motor efficiency at 36 volts varies from 74 percent to 78 percent in the interval from 175 to 250 amperes. Consequently, the motor efficiency at 48 volts is estimated to vary from about 75 percent to 80 percent.

Plots of speed, current, voltage, and power for two cycles of SAE J227a driving schedule B are shown in figure 17. Cycle 2 is near the start of the test and cycle 79 is approximately 1.5 hours into the test.

#### VEHICLE RELIABILITY

Except for one problem related to charging, no difficulties were encountered during the testing of the Waterman Renault. The charger transformer would overheat on days when the garage temperature was greater than 32° C (90° F). An external cooling fan had to be used to cool the charger so that charging could continue

APPENDIX A

VEHICLE SUMMARY DATA SHEET

1.0 Vehicle manufacturer C. H. Waterman  
Athol, Massachusetts

2.0 Vehicle Renault 5 GTL conversion

3.0 Price and availability \$7000; production on request

4.0 Vehicle weight and load

4.1 Curb weight, kg (lbm) 1171 (2580)

4.2 Gross vehicle weight, kg (lbm) 1362 (3000)

4.3 Cargo weight, kg (lbm) \_\_\_\_\_

4.4 Number of passengers 4 places

4.5 Payload, kg (lbm) 191 (420)

5.0 Vehicle size

5.1 Wheelbase, m (in ) 2.44 (96.0)

5.2 Length, m (ft) 3.6 (11.75)

5.3 Width, m (ft) 1.52 (5.0)

5.4 Height, m (in ) \_\_\_\_\_

5.5 Head room, m (in.) 0.98 (38.5)

5.6 Leg room, m (in ) 0.71 (28)

5.7 Frontal area, m<sup>2</sup> (ft<sup>2</sup>) \_\_\_\_\_

5.8 Road clearance, m (in.) \_\_\_\_\_

5.9 Number of seats 3

6.0 Auxiliaries and options

6.1 Lights (number, type, and function) 2 head, 2 park and tail,  
2 brake, 2 front parking, backup

6.2 Windshield wipers 2 on front windshield

6.3 Windshield washers yes

6.4 Defroster optional

6.5 Heater optional

6.6 Radio optional

6.7 Fuel gage voltmeter with red-line

6.8 Amperemeter yes, with red-line

6.9 Tachometer no

6.10 Speedometer yes, in mph

6.11 Odometer yes, in miles

6.12 Right- or left-hand drive left

6.13 Transmission 4-speed manual with clutch

6.14 Regenerative braking no

6.15 Mirrors rearview

6.16 Power steering no

6.17 Power brakes no

6.18 Other \_\_\_\_\_

7.0 Batteries

7.1 Propulsion batteries

7.1.1 Type and manufacturer lead-acid golf car; EV-106, ESB, Inc.

7.1.2 Number of modules 16

7.1.3 Number of cells 48

7.1.4 Operating voltage, V 24 and 48 (switchable)

7.1.5 Capacity, Ah 132.5 (106 min at 75 A)

7.1.6 Size of each battery, m (in ) height, 0.248 (9.75); width, 0.178 (7); length, 0.260 (10.25)

7.1.7 Weight, kg (lbm) \_\_\_\_\_

7.1.8 History (age, number of cycles, etc.) \_\_\_\_\_

7.2 Auxiliary battery

7.2.1 Type and manufacturer lead-acid SLI; Renault AS3105

7.2.2 Number of cells 6

7 2 3 Operating voltage, V 12  
7.2.4 Capacity, Ah 50  
7 2 5 Size, m (in -) height, 0.178 (7); width, 0.165 (6.5)  
7 2 6 Weight, kg (lbm) 20.4 (45)

8 0 Controller

8 1 Type and manufacturer contactor; C. H. Waterman Industries  
8.2 Voltage rating, V \_\_\_\_\_  
8 3 Current rating, A \_\_\_\_\_  
8 4 Size, m (in ) height, 0.127 (5); width, 0.203 (8);  
length, 0.229 (9)  
8.5 Weight, kg (lbm) 9 (20) est.

9 0 Propulsion motor

9 1 Type and manufacturer DC series; Prestolite Electrical  
Div., Eltra Corp.  
9 2 Insulation class H  
9.3 Voltage rating, V 36  
9 4 Current rating, A 250, 1-h rating  
9.5 Horsepower (rated), kW (hp) 6.7 (9), 1-h rating  
9.6 Size, m (in ) diameter, 0.190 (7.5); length, 0.356 (14)  
9 7 Weight, kg (lbm) 45.4 (100)  
9 8 Speed (rated), rpm 1630 (max. unknown)

10 0 Battery charger

10 1 Type and manufacturer full wave, center tapped;  
C. H. Waterman Industries  
10 2 On- or off-board type on board  
10 3 Input voltage required, V 120 AC  
10.4 Peak current demand, A 20  
10 5 Recharge time, h 10

10 6 Size, m (in ) height, 0.203 (8); width, 0.178 (7);  
length, 0.279 (11)  
10 7 Weight, kg (lbm) 22.7 (50)  
10.8 Automatic turnoff feature yes, timer

11 0 Body

11 1 Manufacturer and type Renault 5 GTL  
11 2 Materials steel  
11 3 Number of doors and type 2  
11 4 Number of windows and type 6  
11 5 Number of seats and type 2 front (bucket), 1 rear (bench)  
11 6 Cargo space volume, m<sup>3</sup> (ft<sup>3</sup>)  
11 7 Cargo space dimensions, m (ft)

12 0 Chassis

12.1 Frame

12 1 1 Type and manufacturer welded construction; DAF  
12 1 2 Materials steel  
12 1.3 Modifications battery retaining members added

12 2 Springs and shocks

12 2 1 Type and manufacturer independent torsion bar  
12 2 2 Modifications

12 3 Axles

12 3 1 Manufacturer  
12,3 2 Front  
12 3 3 Rear

12.4 Transmission

12 4.1 Type and manufacturer 4-speed manual

- 12 4.2 Gear ratios first, 3.667; second, 2.235; third, 1.456; fourth, 1.026
- 12 4.3 Driveline ratio 3.629
- 12.5 Steering
- 12 5 1 Type and manufacturer rack and pinion
- 12 5.2 Turning ratio 20
- 12 5 3 Turning diameter, m (ft) 10.1 (33)
- 12 6 Brakes
- 12 6 1 Front disk
- 12 6 2 Rear hydraulic
- 12 6 3 Parking mechanical (rear wheels)
- 12 6.4 Regenerative no
- 12 7 Tires
- 12 7 1 Manufacturer and type Michelin radial
- 12 7 2 Size 145SR13
- 12 7.3 Pressure, kPa (psi).
- Front 248 (36)
- Rear 248 (36)
- 12.7 4 Rolling radius, m (in ) 0.274 (10.8)
- 12 7 5 Wheel weight, kg (lbm)
- Without drum 11.2 (24.8)
- With drum \_\_\_\_\_
- 12 7 6 Wheel track, m (in.):
- Front \_\_\_\_\_
- Rear \_\_\_\_\_
- 13 0 Performance
- 13 1 Manufacturer-specified maximum speed (wide-open throttle), km/h (mph)
- 13 2 Manufacturer-recommended maximum cruise speed (wide-open throttle), km/h (mph)
- 13 3 Tested at cruise speed, km/h (mph) 56.3 (35) and 40.2 (25)

## APPENDIX B

### DATA ACQUISITION

Data acquired from the test vehicle are conditioned on board the vehicle and transmitted to the Data Acquisition Center where they are demodulated and recorded on magnetic tape (fig. B-1).

The following paragraphs provide a detailed description of system components. Instrumentation calibration procedures and test procedures relative to the data acquisition system are also described.

#### Signal Conditioning Equipment

The signal conditioning equipment has a modular or building-block configuration. The basic building block is the remote signal conditioning module (RSCM), which consists of all the necessary functions required to take the basic transducer information and store it on magnetic tape. Each RSCM handles 14 data channels.

Internally, the RSCM consists of all the necessary components required to signal condition, modulate onto Inter-Range Instrumentation Group (IRIG) constant-bandwidth frequency-modulated (FM) channels, and transmit a transducer output signal to a remote tape recorder. Figure B-2 is the system diagram defining this RSCM.

The signal conditioning amplifiers in the front end of the RSCM provide suitable gain and balance to normalize all transducer outputs into common formats and to drive the voltage-controlled oscillators (VCO's). Each amplifier has a built-in, isolated bridge power supply regulated at 5.0 volts DC that negates loading effects from other transducers and changes in output due to supply battery variations. This power supply is used either alone, divided down by 0.1-percent metal film resistors, or in series with other supplies to provide a highly accurate and stable voltage insertion calibration of the entire system, channel by channel.

The VCO's convert analog voltages to a frequency-modulated unbalanced signal. The center frequencies of the VCO's are set at values defined by IRIG 106-71 for constant-bandwidth channels (table B-1). The  $\pm 2.5$ -volt outputs from the amplifier provide  $\pm 100$ -percent deviation of the VCO's. Using a mix of A and B channels

provides an optimum combination of data frequency response, resolution, percentage of deviation, and channel density in each multiplex.

The system is designed to provide 1000-hertz data channel bandwidth on all A channels and 2000-hertz channel bandwidth on all B channels. The 14 VCO outputs are mixed onto a common bus which provides the output signal to be recorded. An external 28-volt battery is used to power the RSCM.

Each RSCM weighs under 9 kilograms (20 lbm) and covers approximately 390 square centimeters (60 in<sup>2</sup>) of floor space. All input and output connections and final adjustments are accessible from the top of the module.

### System Accuracy

Table B-2 represents the system errors for the data acquisition system. The values are taken from the component specifications. As there are several information conversions through the system, there was an attempt to translate the specifications into a "common error domain." Each device in the system has a set of parameters that represent its performance in a particular region of the multidimensional space (e.g., an accelerometer converts an acceleration into a voltage (actually an energy conversion) with some nonlinearity of information conversion). There is a conversion from analog voltage to frequency with a corresponding nonlinearity in the VCO. The tape recorder has to handle the information mechanically with high accuracy because a change in tape speed represents a change in frequency which, in turn, represents a change in the original analog voltage.

### Tape Recorders

The tape recorder has 14 IRIG-compatible channels, with the recording channels individually controlled so that multiple recording passes may be made on the same tape. Capstan speed accuracy of 0.01 percent is obtained by use of a tape speed compensator system while flutter is held to 0.22 percent. Time base and dynamic skew are 0.5 and 25 microseconds, respectively.

## APPENDIX C

### DESCRIPTION OF VEHICLE TEST TRACK

The test track used to conduct the tests described in this report is located in Phoenix, Arizona. The track is owned and operated by Dynamic Science, a subsidiary of Talley Industries.

The test track is a paved, continuous two-lane, 3.2-kilometer- (2-mile-) long oval with an adjacent 40 000-square-meter (10-acre) skid pad. The inner lane of the track is not banked and was used for all cycle tests and all constant-speed tests of 56 kilometers per hour (35 mph) or under. The outer lane has zero lateral acceleration at 80 kilometers per hour (50 mph) and was used for tests over 56 kilometers per hour (35 mph). An elevation survey of the track is shown in figure C-1. Average grade is 0.66 percent on the northern straight section and 0.76 percent on the southern straight section. The surface of the track and skid pad is asphaltic concrete with a dry locked-wheel skid number of 82 and a wet locked-wheel skid number of 71.

Wet and dry braking-in-turn tests were conducted on the skid pad. Wet recovery tests were conducted on the test track after driving through the wet-brake water trough located near the northern straight section of the track. Both 20- and 30-percent grades are available for parking brake tests.

## APPENDIX D

### VEHICLE PREPARATION AND TEST PROCEDURE

#### Vehicle Preparation

When a vehicle was received at the test track, a number of checks were made to assure that it was ready for performance tests. These checks were recorded on a vehicle preparation check sheet, such as the one shown in figure D-i. The vehicle was examined for physical damage when it was removed from the transport truck and before it was accepted from the shipper. Before the vehicle was operated, a complete visual check was made of the entire vehicle including wiring, batteries, motor, and controller. The vehicle was weighed and compared with the manufacturer's specified curb weight. The gross vehicle weight (GVW) was determined from the vehicle sticker GVW. If the manufacturer did not recommend a GVW, it was determined by adding 68 kilograms (150 lbm) per passenger plus any payload weight to the vehicle curb weight.

The wheel alignment was checked, compared, and corrected to the manufacturer's recommended alignment values. The battery was charged and specific gravities taken to determine if the batteries were equalized. If not, an equalizing charge was applied to the batteries. The integrity of the internal interconnections and the battery terminals was checked by drawing either 300 amperes or the vehicle manufacturer's maximum allowed current load from the battery through a load bank for 5 minutes. If the temperature of the battery terminals or interconnections rose more than 60 degrees Celsius above ambient, the test was terminated and the terminal was cleaned or the battery replaced. The batteries were then recharged and a battery capacity check was made. The battery was discharged in accordance with the battery manufacturer's recommendations. To pass this test, the capacity must be within 20 percent of the manufacturer's published capacity at the published rate.

The vehicle manufacturer was contacted for his recommendations concerning the maximum speed of the vehicle, tire pressures, and procedures for driving the vehicle. The vehicle was photographed head-on with a 270-millimeter telephoto lens from a distance of about 30.5 meters (100 ft) in order to determine the frontal area.

## Test Procedure

Each day, before a test, a test checklist was used. Two samples of these checklists are shown in figure D-2. The first item under driver instructions on the test checklist is to complete the pretest checklist (fig. D-3).

Data taken before, during, and after each test were entered on the vehicle data sheet (fig. D-4). These data include

- (1) Average specific gravity of the battery
- (2) Tire pressures
- (3) Fifth-wheel tire pressure
- (4) Test weight of the vehicle
- (5) Weather information
- (6) Battery temperatures
- (7) Time the test was started
- (8) Time the test was stopped
- (9) Ampere-hours out of the battery
- (10) Fifth-wheel distance count
- (11) Odometer readings before and after the tests

The battery charge data taken during the charge cycle were also recorded on this data sheet. These data include the average specific gravity of the battery after the test, the kilowatt-hours and ampere-hours put into the battery during the charge, and the total time of the charge.

To prepare for a test, the specific gravities were first measured for each cell and recorded. The tire pressures were measured and the vehicle was weighed. The weight was brought up to the GVW by adding sandbags. The instrumentation was connected, and power from the instrumentation battery was applied. All instruments were turned on and warmed up. The vehicle was towed to the starting point on the track. If the data were being telemetered, precalibrations were applied to both the magnetic tape and the oscillograph. The fifth-wheel

distance counter and ampere-hour integrator counter were reset to zero, and thermocouple reference junctions were turned on. The test was started and was carried out in accordance with the test checklist. When the test was terminated, the vehicle was brought to a stop and the post-test checks were made in accordance with the post-test checklist (fig. D-5). The driver recorded on the vehicle data sheet the time, the odometer reading, the ampere hour integrator reading, and the fifth-wheel distance reading. The post-calibration steps were then applied to the magnetic tape and the oscillograph. At the end of the test, weather data were recorded on the vehicle data sheet. All instrumentation power was turned off, the instrumentation battery was disconnected, and the fifth wheel was raised. The vehicle was then towed back to the garage, the post-test specific gravities were measured for all cells and the vehicle was placed on charge.

After the test, the engineer conducting the test completed a test summary sheet (fig. D-6). This data sheet provides a brief summary of the pertinent information received from the test. Another data sheet, the engineer's data sheet (fig. D-7), was also filled out. This data sheet summarizes the engineer's evaluation of the test and provides a record of problems, malfunctions, changes to instrumentation, etc., that occurred during the test.

Weather data. - Wind velocity and direction and ambient temperature were measured at the beginning and at the end of each test and every hour during the test. The wind anemometer was located about 1.8 meters (6 ft) from the ground near the southern straight section of the track. The ambient temperature readings were taken at the instrumentation trailer near the west curve of the track. During most of the test period the winds were variable and gusty.

Determination of maximum speed. - The maximum speed of the vehicle was determined in the following manner. The vehicle was fully charged and loaded to gross vehicle weight. After one warmup lap, the vehicle was driven at wide-open throttle for three laps around the track. The minimum speed for each lap was recorded and the average was calculated. This average was called the vehicle maximum speed. This speed takes into account track variability and maximum vehicle loading. This quantity was then reduced by 5 percent and called the recommended maximum cruise test speed.

Cycle timer. - The cycle timer (fig. D-8) was designed to assist the vehicle driver in accurately driving SAE schedules B, C, and D. The required test profile is permanently stored on a programmable read-only memory (PROM), which is the heart of the instrument. This profile is continuously reproduced on one needle of a dual-movement analog meter shown in the figure. The second needle is connected to the output of the fifth wheel and the driver "matches needles" to accurately drive the required schedule.

One second before each speed transition (e.g., acceleration to cruise or cruise to coast), an audio signal sounds to forewarn the driver of a change. A longer duration audio signal sounds after the idle period to emphasize the start of a new cycle. The total number of test cycles driven is stored in a counter and can be displayed at any time with a pushbutton (to conserve power).

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## REFERENCES

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2. Society of Automotive Engineers, Inc.: Electric Vehicle Test Procedure - SAE J227a. Feb. 1976.

TABLE I. - SUMMARY OF TEST RESULTS FOR WATERMAN RENAULT

(a) SI units

Test date	Test condition (constant speed, km/h; or driving schedule)	Wind velocity, km/h	Temper- ature, °C	Range, km	Cycle life, number of cycles	Current out of batteries, Ah	Current into batteries, Ah	Energy into charger, MJ	Indicated energy consumption, MJ/km
4/13/77	40 2	8	21 - 28	188 4	---	165 2	239.0	117 4	0 63
4/14/77	56.3	11 - 16	27	128 1	---	145.7	180 0	85 3	.67
4/18/77	B	11	31	124.1	326	177 7	225 8	108 0	.87
4/20/77	56.3	3 - 11	21	128 4	---	146.5	210 0	101 5	.78
4/21/77	40 2	10	18 - 27	187.9	---	166 2	223 4	107.3	.58
4/22/77	B	8	17 - 32	132 9	348	184 1	219 1	104 4	.78

(b) U.S. customary units

Test date	Test condition (constant speed, mph, or driving schedule)	Wind velocity, mph	Temper- ature, °F	Range, miles	Cycle life, number of cycles	Current out of batteries, Ah	Current into batteries, Ah	Energy into charger, kWh	Indicated energy consumption, kWh/mile
4/13/77	25	5	70 - 83	177 1	---	165 2	239 0	32 6	0 28
4/14/77	35	7 - 10	80	79 6	---	145.7	180 0	23.7	30
4/18/77	B	7	88	77.1	326	177.7	225 8	30 0	39
4/20/77	35	2 - 7	70	79 8	---	146 5	210.0	28.2	.35
4/21/77	25	6	64 - 81	116.8	---	166.2	223.4	29 8	26
4/22/77	B	5	62 - 89	82 6	348	184 1	219.1	29.0	35

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TABLE II - ACCELERATION AND GRADEABILITY FOR WATERMAN RENAULT

(a) At full battery charge

Vehicle km/h	speed mph	Time to reach designated vehicle speed, s	Vehicle acceleration		Gradeability, percent
			m/s <sup>2</sup>	mph/s	
0	0	0	0	0	0
2 0	1 2	5	1 17	2 61	12 0
4 0	2 5	1 0	1 68	3 75	17 4
6 0	3 7	1 2	2 31	5 16	24 3
8 0	5 0	1 4	2 42	5 42	25 7
10 0	6 2	1 7	2 42	5 42	25 7
12 0	7 5	1 9	2 27	5 08	23 9
14 0	8 7	2 2	2 02	4 51	21 1
16 0	9 9	2 4	1 92	4 29	20 1
18 0	11 2	2 7	1 85	4 15	19 4
20 0	12 4	3 0	1 45	3 24	15 0
22 0	13 7	3 5	1 09	2 43	11 2
24 0	14 9	4 1	91	2 03	9 3
26 0	16 2	4 8	65	1 45	6 7
28 0	17 4	5 8	47	1 06	4 9
30 0	18 7	7 2	34	75	3 4
32 0	19 9	9 3	24	54	2 5
34 0	21 1	11 9	17	39	1 8
36 0	22 4	16 1	16	36	1 7
38 0	23 6	19 8	27	61	2 8
40 0	24 9	20 6	34	75	3 4
42 0	26 1	22 4	24	53	2 4
44 0	27 4	25 9	15	34	1 6
46 0	28 6	29 6	14	32	1 5

(b) At 40-percent battery discharge

0	0	0	0	0	0
2 0	1 2	3	1 64	3 67	17 1
4 0	2 5	7	↓	↓	↓
6 0	3 7	1 0	↓	↓	↓
8 0	5 0	1 4	↓	↓	↓
10 0	6 2	1 7	↓	↓	↓
12 0	7 5	2 0	↓	↓	↓
14 0	8 7	2 4	↓	↓	↓
16 0	9 9	2 7	1 61	3 60	16 7
18 0	11 2	3 1	1 44	3 23	15 0
20 0	12 4	3 5	1 31	2 92	13 5
22 0	13 7	3 9	1 09	2 44	11 2
24 0	14 9	4 6	80	1 79	8 2
26 0	16 2	5 3	61	1 36	6 3
28 0	17 4	6 4	10	90	4 1
30 0	18 7	8 2	31	70	3 2
32 0	19 9	10 0	28	62	2 8
34 0	21 1	12 3	23	52	2 4
36 0	22 4	14 7	25	56	2 6
38 0	23 6	16 8	31	69	3 2
40 0	24 9	18 4	31	69	3 1
42 0	26 1	20 5	23	50	2 3

(c) At 80-percent battery discharge

0	0	0	0	0	0
2 0	1 2	4	1 57	3 50	16 3
4 0	2 5	7	↓	↓	↓
6 0	3 7	1 1	↓	↓	↓
8 0	5 0	1 4	↓	↓	↓
10 0	6 2	1 8	↓	↓	↓
12 0	7 5	2 1	↓	↓	↓
14 0	8 7	2 5	↓	↓	↓
16 0	9 9	2 8	1 37	3 06	14 2
18 0	11 2	3 3	1 07	2 40	11 1
20 0	12 4	3 9	93	2 71	9 6
22 0	13 7	4 5	76	1 70	7 8
24 0	14 9	5 4	50	1 12	5 1
26 0	16 2	6 9	38	84	3 9
28 0	17 4	8 3	40	89	4 1
30 0	18 7	9 7	35	77	3 5
32 0	19 9	11 7	27	60	2 8
34 0	21 1	13 9	24	53	2 4
36 0	22 4	16 4	22	49	2 2
38 0	23 6	19 0	24	54	2 5
40 0	24 9	21 1	29	65	3 0
42 0	26 1	22 8	26	59	2 7

TABLE III. - ROAD ENERGY AND ROAD POWER FOR WATERMAN RENAULT

[Coast-down data.]

Vehicle speed		Test time, s	Road power		Road energy	
km/h	mph		kW	hp	MJ/km	kWh/mile
62.0	38.5	9	0	0	0	0
60.0	37.3	1.6	7.87	10.55	.47	.21
58.0	36.0	3.2	6.03	8.08	.37	.17
56.0	34.8	5.9	4.30	5.77	.28	.12
54.0	33.6	8.7	4.30	5.75	.29	.13
52.0	32.3	11.2	4.34	5.82	.30	.13
50.0	31.1	13.7	3.94	5.29	.28	.13
48.0	29.8	16.5	3.57	4.78	.27	.12
46.0	28.6	19.4	3.56	4.77	.28	.12
44.0	27.3	22.0	3.30	4.42	.27	.12
42.0	26.1	25.0	2.90	3.88	.25	.11
40.0	24.9	28.1	2.72	3.64	.25	.11
38.0	23.6	31.2	2.48	3.32	.23	.10
36.0	22.4	34.5	2.33	3.12		
34.0	21.1	37.7	2.19	2.95		
32.0	19.9	41.1	2.08	2.78		
30.0	18.6	44.2	1.90	2.55		
28.0	17.4	47.7	1.61	2.15	.21	.09
26.0	16.2	51.5	1.46	1.95	.20	
24.0	14.9	55.2	1.34	1.80	.20	
22.0	13.7	59.1	1.18	1.58	.19	
20.0	12.4	63.1	.96	1.29	.17	.08
18.0	11.2	67.9	.82	1.10	.16	.07
16.0	9.9	72.3	.78	1.05	.18	.08
14.0	8.7	76.5	.66	.88	.17	.08
12.0	7.5	81.3	.55	.74	.16	.07
10.0	6.2	85.7	.44	.59	.16	.07
8.0	5.0	90.0	.33	.44	.15	.07
6.0	3.7	95.9	.24	.32	.14	.06
4.0	2.5	101.5	.16	.21	.14	.06
2.0	1.2	106.7	.07	.09	.12	.06

TABLE IV. - ENERGY CONSUMPTION FOR  
WATERMAN RENAULT AS FUNCTION  
OF VEHICLE SPEED

Vehicle speed		Energy consumption	
km/h	mph	MJ/km	kWh/mile
40.2	25	0.63	0.28
40.2	25	.58	.26
56.3	35	.67	.30
56.3	35	.78	.35

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TABLE V - CHARGER EFFICIENCY TEST DATA FOR WATERMAN RENAULT

Time	Input power from kilowatt- hour meter, $P_{in}$ kW	Output power calculated from $V_{av} \times I_{av}$ $P_{out}$ kW	Energy efficiency, percent	Input power from watt- meter, $P_{in}$ kW	Output power from watt- meter, $P_{out}$ kW	Power efficiency, percent
2 00 p m.	2 99	2.49	83.3	3 08	2 71	88 0
3 30	2 73	2 20	80 6	2 78	2 43	87 4
5 00	2 45	2 09	85 4	2 58	2.27	88 0
8:30 a m	2 01	1 77	87 9	2.10	1 90	90 5
10-00	2 03	1 73	85.6	2 12	1 93	91.0
11.00	1.53	1.33	86.6	1 54	1 38	89 6
11 30	1.30	1 23	94.3	1 35	1.27	94 1
12.30 p m	1 08	.96	89.0	1 12	1.03	92.0
2 15	.96	.84	87 2	1.02	.91	89.2

TABLE VI. - BATTERY SPECIFICATIONS FOR WATERMAN RENAULT

Length, m (in) . . . . .	0 26 (10 375)
Width, m (in) . . . . .	0.18 (7 188)
Height, m (in) . . . . .	0 28 (11.219)
Weight, kg (lbm)	
Dry . . . . .	21 4 (47 2)
Wet . . . . .	29 5 (65 1)
Electrolyte, liters (qt) . . . . .	6 2 (6 6)
Number of life cycles (laboratory) . . . . .	400 - 450
Fully charged specific gravity . . . . .	1 280
Number of plates per cell . . . . .	19

TABLE VII. - SCHEDULE B BATTERY PERFORMANCE

FOR WATERMAN RENAULT

[Test date, 4/18/77.]

	Third cycle		324 <sup>th</sup> Cycle	
	Current, A	Power, kW	Current, A	Power, kW
Acceleration	158	6.4	140	5.9
Cruise	105	4.4	83	3.4

TABLE VIII. - MAXIMUM-ACCELERATION BATTERY PERFORMANCE FOR

WATERMAN RENAULT

Time, s	Vehicle speed		Current, A	Voltage, V	Power, kW	Amount of discharge, percent
	km/h	mph				
<sup>a</sup> 18 - 22	10	20.3	149	47.4	7.1	0
	22	24.3	245	46.1	11.3	0
	50	33.5	131	47.9	6.3	0
<sup>a</sup> 14 - 20	10	19.9	148	46.1	6.9	40
	20	24.3	237	45.3	10.7	40
	50	33.0	130	47.2	6.1	40
<sup>a</sup> 15 - 22	10	16.2	149	44.2	6.5	80
	22	22.7	229	42.8	9.8	80
	50	31.6	124	44.7	5.5	80

<sup>a</sup>Time depends on shift point (current peaks at shift point).

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TABLE IX - BATTERY TEST DATA SUMMARY FOR WATERMAN RENAULT

Test date	Vehicle speed or driving schedule		Battery capacity, Ah		Average electrolyte specific gravity		Battery temperature			
	km/h	mph	In	Out	Before test	After test	Before test		After test	
							°C	°F	°C	°F
4/21/77	40	25	223	166	1 286	1 130	--	--	--	----
4/14/77	56	35	180	146	1 285	1 135	27	80	41	106
4/20/77	56	35	210	147	1 286	1 135	--	--	--	----
4/18/77	Schedule B		226	178	1 283	1 136	--	--	--	----

TABLE X - BATTERY ENERGY EFFICIENCY FOR WATERMAN RENAULT

Test date	Energy removed		Energy restored		Energy efficiency, percent	Amount of overcharge (in Ah), percent
	MJ	kWh	MJ	kWh		
4/14/77	0 049	13.6	0 077	21.3	64	23
4/20/77	047	13.0	089	24.6	53	43

TABLE XI - TYPICAL CONSTANT-SPEED MOTOR

DATA FOR WATERMAN RENAULT

[Test date, 4/20/77, vehicle speed, 56.3 km/h (35 mph)]

	Near beginning of test	Near end of test
Motor voltage, V	48.6	44.4
Motor current, A	244	175
Motor speed, rpm	2110	2000

TABLE B-1. - CONSTANT-BANDWIDTH CHANNELS  
 IN EACH REMOTE SIGNAL-CONDITIONING  
 MODULE FOR WATERMAN RENAULT

IRIG <sup>a</sup> constant- bandwidth channel	Center frequency, kHz	Deviation, kHz
1A	16	+2
2A	24	↓
3A	32	
4A	40	
5A	48	
6A	56	
7A	64	
8A	72	
9A	80	
11B	96	+4
13B	112	↓
15B	128	
17B	144	
19B	160	

TABLE B-2. - DIRECT-CURRENT AMPLITUDE ACCURACY

Transducer	Parameter	Accuracy, percent
DC voltage	Tolerance	±0.4
Calibration resistors	Tolerance	±.1
Amplifier	Nonlinearity	±.5
Voltage-controlled oscillator	Nonlinearity	±.25
Recorder	Speed inaccuracy	±.01
Data demodulator	Nonlinearity	±.1



Figure 1. - C. H. Waterman Renault on Dynamic Science Test Track.



Figure 2. - View under hood of Waterman Renault, showing controller, charger, and front battery pack.

□-80% DISCHARGE  
 X-40% DISCHARGE  
 H-80% DISCHARGE

VEHICLE PERFORMANCE  
 C H WATERMAN RENAULT 5

DATE RECORDED  
 APRIL 23, 1977

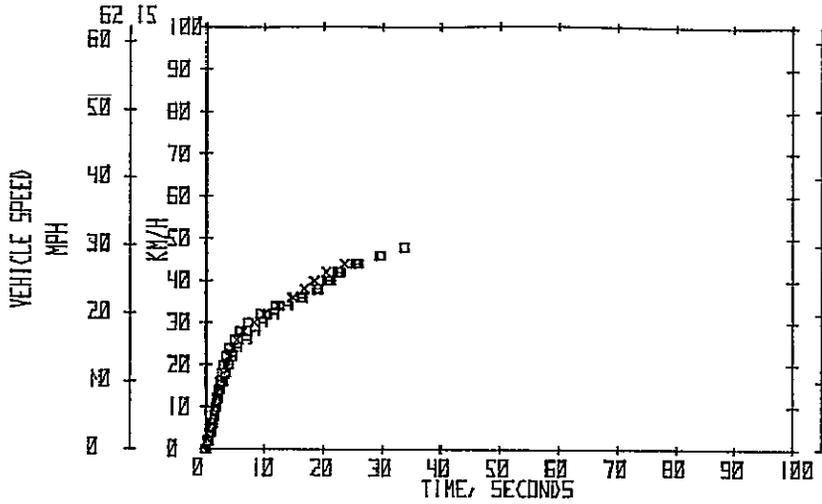


Figure 5 - Vehicle acceleration

□-80% DISCHARGE  
 X-40% DISCHARGE  
 H-80% DISCHARGE

VEHICLE PERFORMANCE  
 C H WATERMAN RENAULT 5

DATE RECORDED  
 APRIL 23, 1977

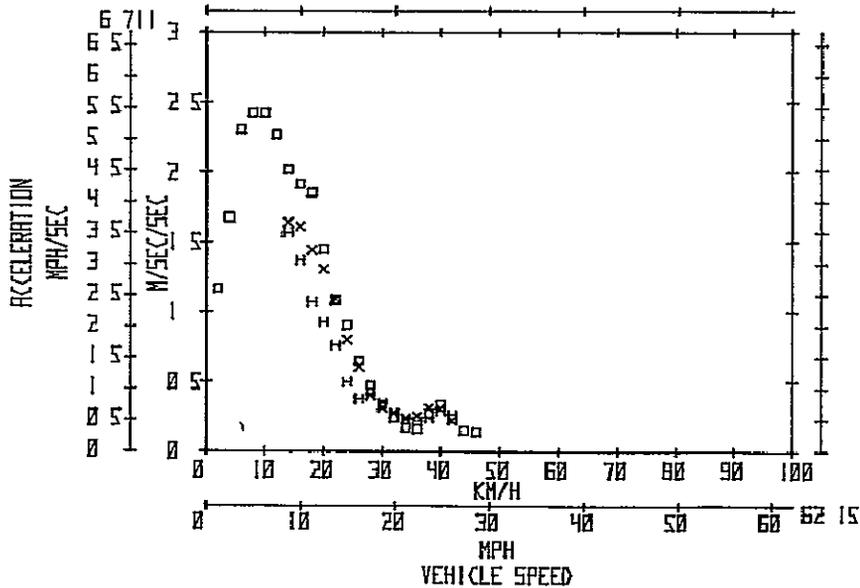


Figure 6 - Acceleration as a function of speed

□=25% DISCHARGE  
 X=40% DISCHARGE  
 H=60% DISCHARGE

VEHICLE PERFORMANCE  
 C H WATERMAN RENAULT 5

DATE RECORDED  
 APRIL 23, 1977

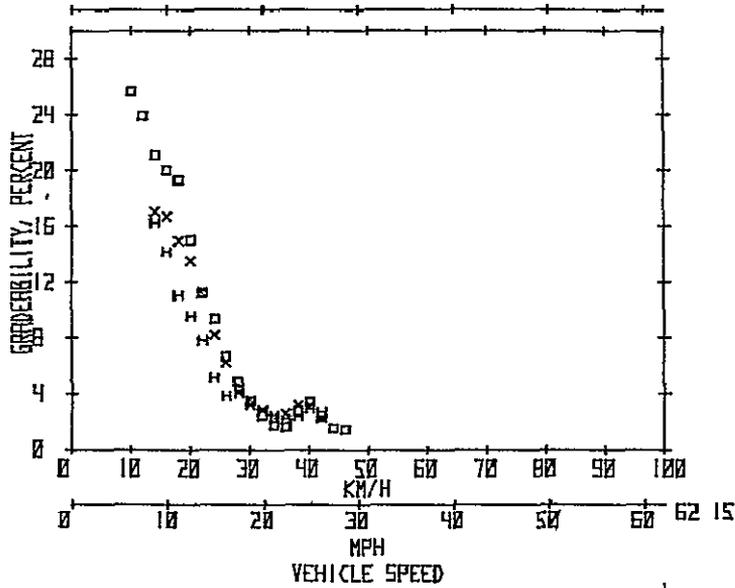


Figure 7 - Gradeability as a function of speed

VEHICLE PERFORMANCE  
 C H WATERMAN RS

DATE RECORDED  
 14 SEP 77

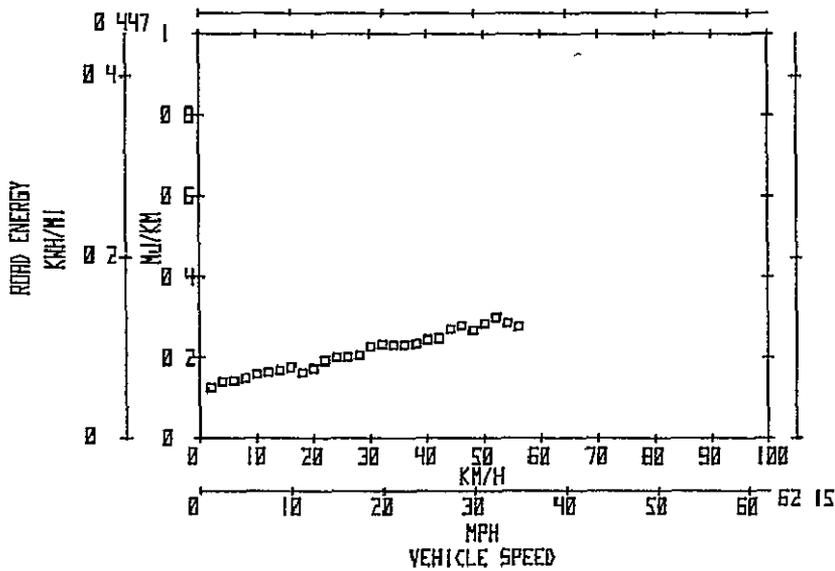


Figure 8 - Road energy as a function of speed

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VEHICLE PERFORMANCE  
C H WATERMAN RS

DATE RECORDED  
14SEP77

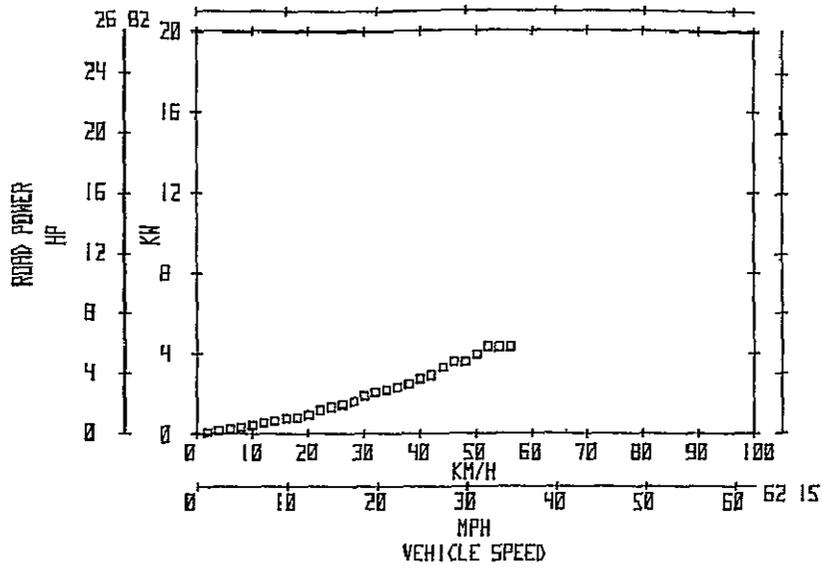


Figure 9 - Road power as a function of speed

VEHICLE PERFORMANCE  
C H WATERMAN RENAULT 5

DATE RECORDED  
APRIL 6-26, 1977

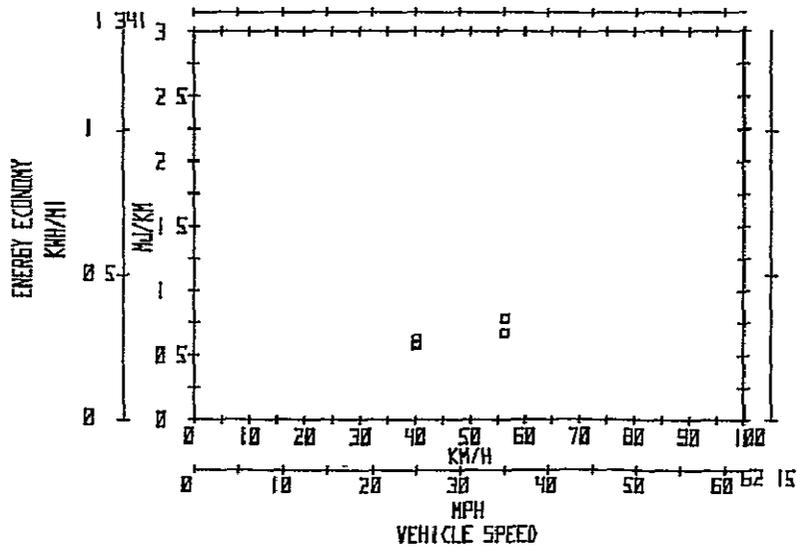


Figure 10 - Energy consumption as a function of speed

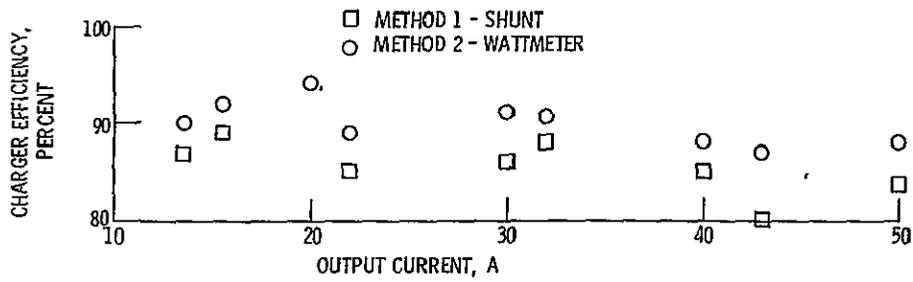


Figure 11 - Charger efficiency for Waterman Renault.

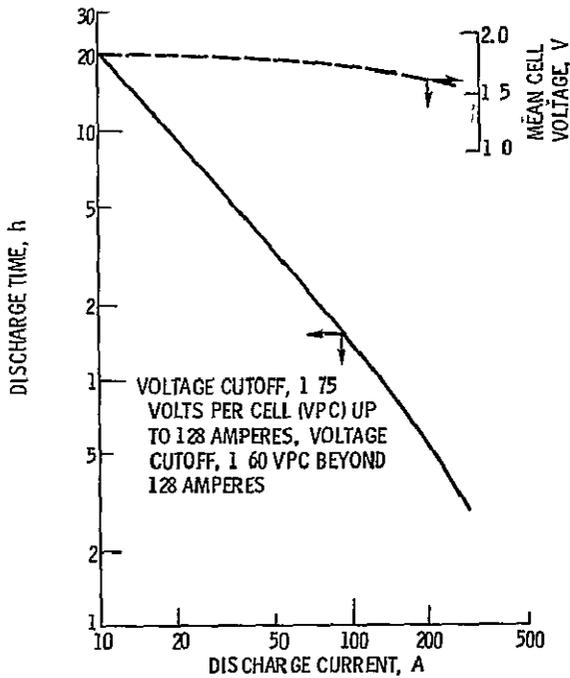


Figure 12 - Battery discharge characteristics for Waterman Renault

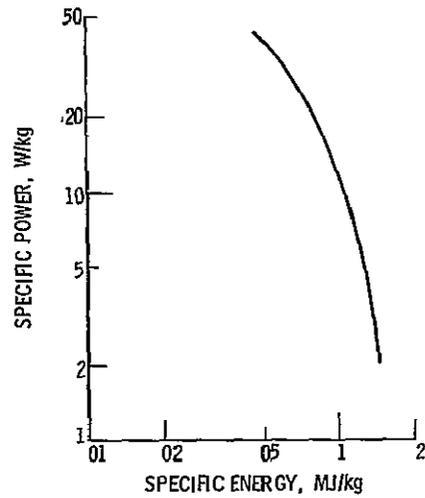


Figure 13 - Battery energy/power relationship for Waterman Renault

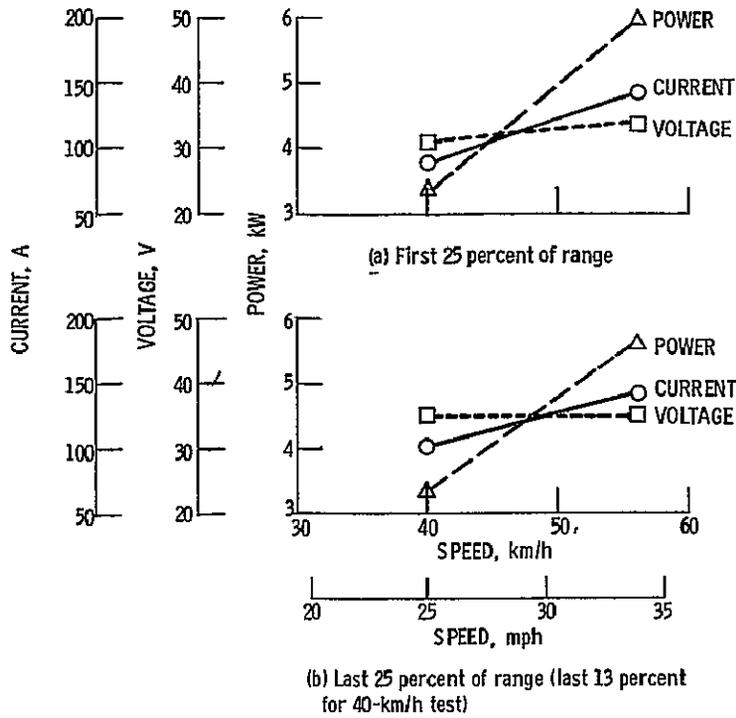


Figure 14 - Constant-speed battery performance for Waterman Renault

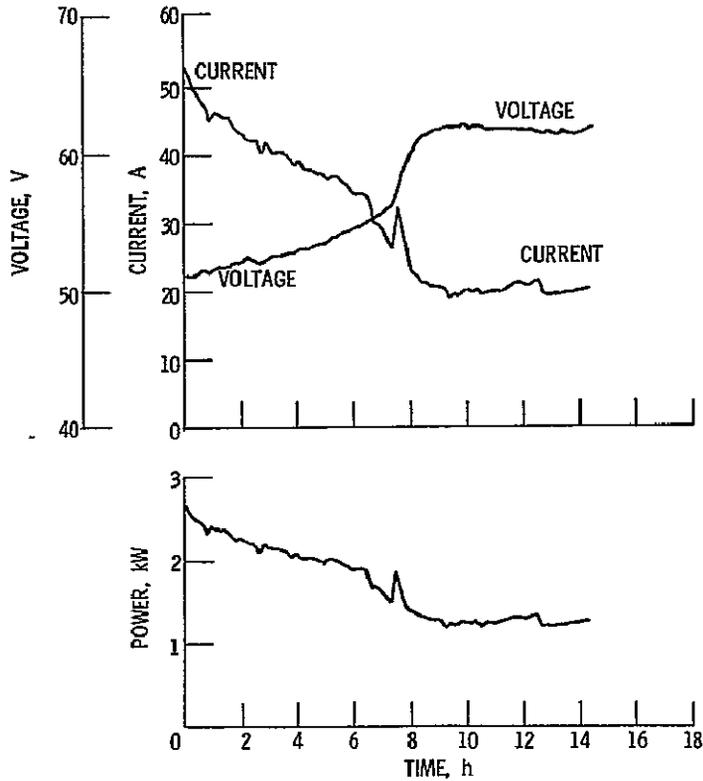


Figure 15 - Battery charger output for Waterman Renault

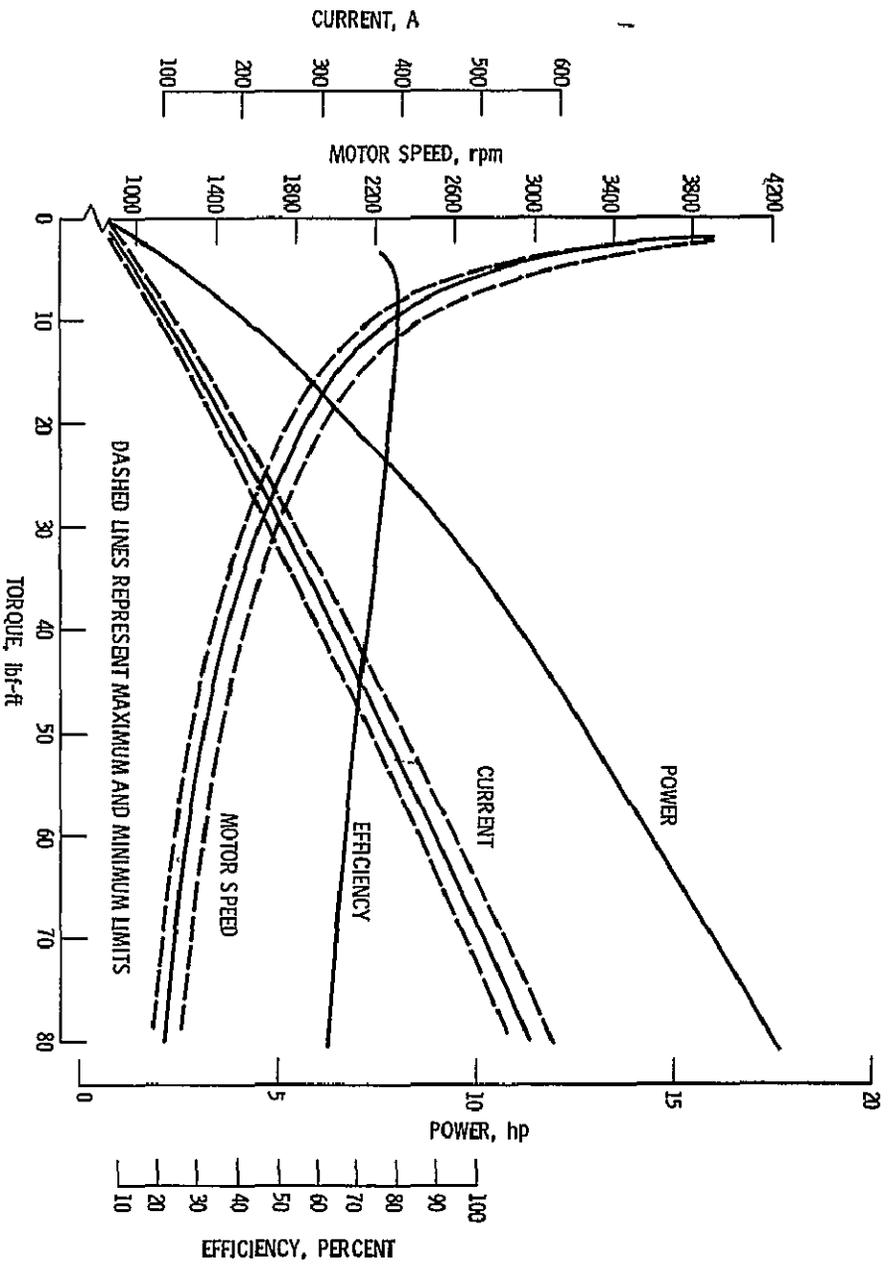


Figure 16 - Cold performance characteristics for Waterman Renault

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SCHEDULE 'B'  
CYCLE 2

COMPONENT DATA  
C H WATERMAN RENAULT S

DATE RECORDED  
APRIL 22, 1977

SCHEDULE 'B'  
CYCLE 79

COMPONENT DATA  
C H WATERMAN RENAULT S

DATE RECORDED  
APRIL 22, 1977

46

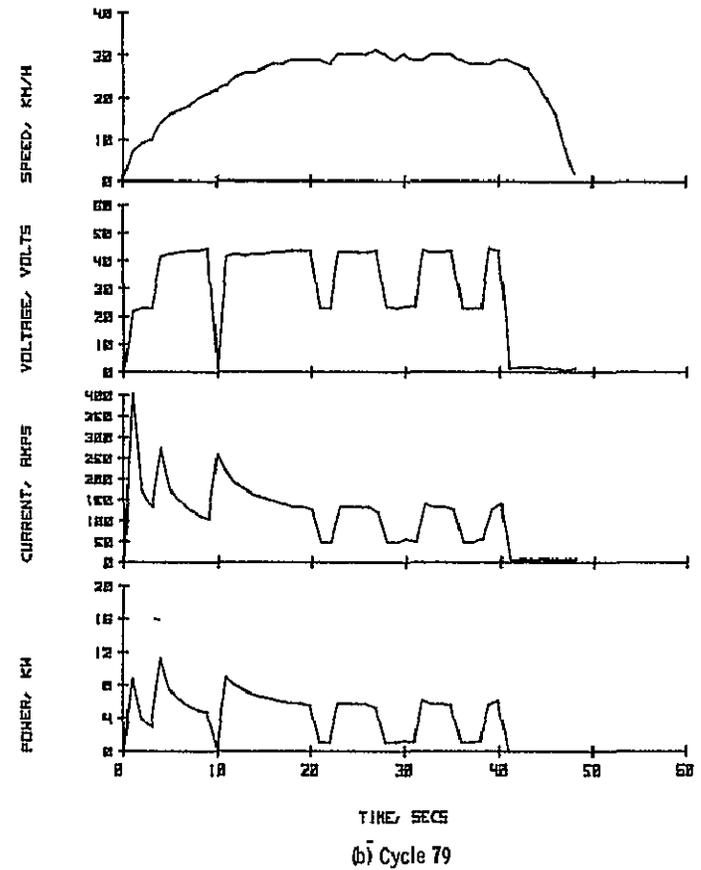
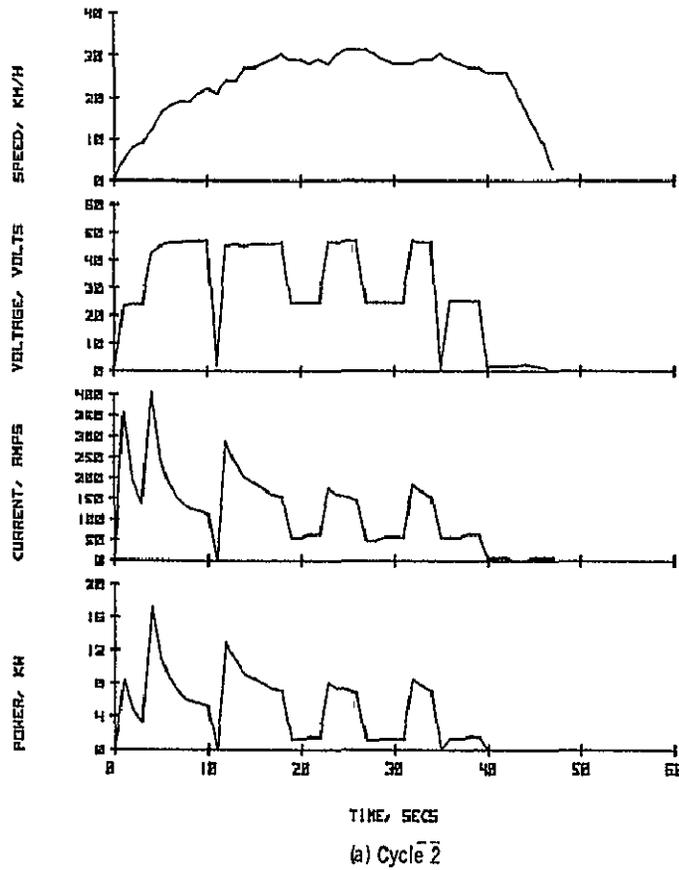


Figure 17 - Motor input as a function of time.

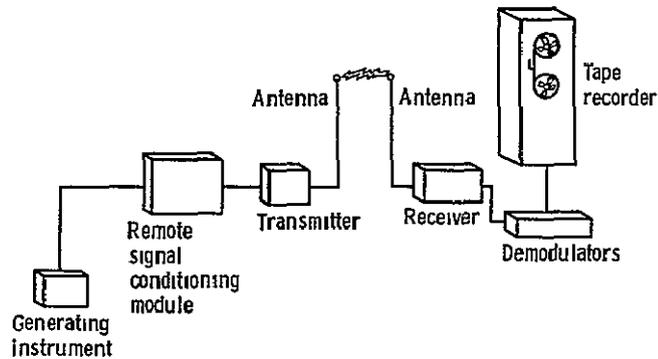


Figure B-1 - Data acquisition system schematic

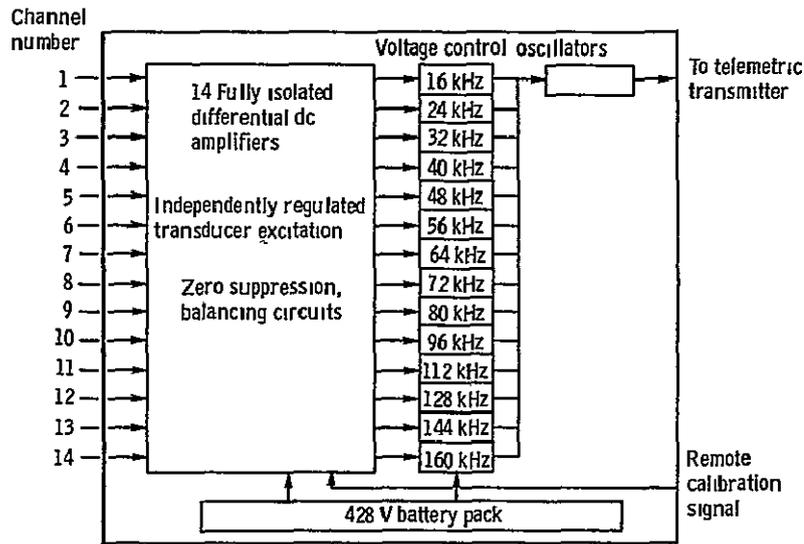
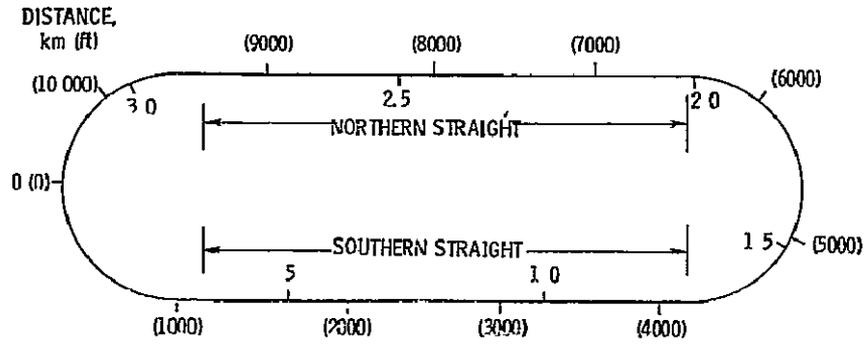
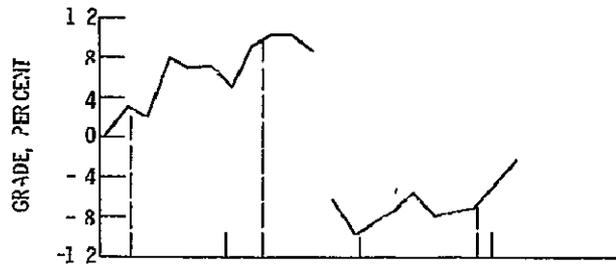


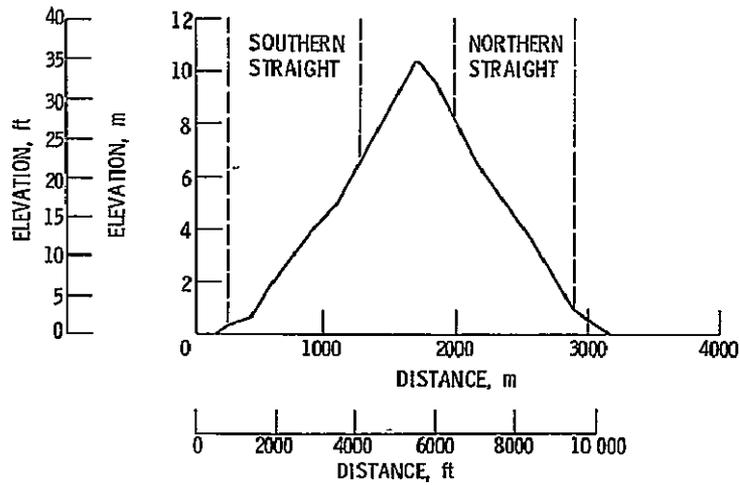
Figure B-2 - Remote signal conditioning module diagram



(a) Track diagram



(b) Grade



(c) Elevation

Figure C-1 - Characteristics of Dynamic Science Test Track, Phoenix, Arizona

1	Vehicle _____
2	Date received _____
3	Checked for damage - date _____
4	Wheel alignment - date _____
5	Battery checked and equalized - date _____
6	Curb weight determined, lbm _____ Date _____
7	Gross vehicle weight, lbm _____
8	300-Ampere test - date _____
9	Manufacturer's recommendations
	Maximum speed, mph _____
	Tire pressures, psi Front _____, Rear _____
	Driving procedures _____

Figure D-1 - Vehicle preparation check sheet

Vehicle \_\_\_\_\_, \_\_\_\_\_ mph range test, \_\_\_\_\_ gear

Driver Instructions

- 1 Complete pretest checklist
- 2 While on track recheck
  - Integrator - light on, in "operate" position, zeroed
  - Speedometer - set on \_\_\_\_\_ mph center
  - Distance - on, reset, lighted
  - Attenuator - on, reset, lighted
- 3 At signal from control center accelerate moderately to \_\_\_\_\_ mph
- 4 Maintain  $\pm 1$  mph with minimal accelerator movement
- 5 When vehicle is no longer able to maintain \_\_\_\_\_ mph, brake moderately to full stop
- 6 Complete post-test checklist and other documentation

Recording:

1	Set oscillograph zeros at	<u>Channel</u>	<u>Zero, in</u>
		3	3 0
		4	4 5
		6	5 0
		10	7 5
		12	1 1
		13	1 2
		14	2 0

- 2 Record all channels on magnetic tape Check inputs at beginning of test to verify recording
- 3 Run cal's on all channels
- 4 Remove all channels from oscillograph except 3 and 4
- 5 Start recording 15 s before start of test at oscillograph speed of 0.1 in/s and tape speed of \_\_\_\_\_ in/s
- 6 After 15 min into test connect channels 6, 10, 12, 13, and 14 to oscillograph and record a burst at 100 in/s while vehicle is in chopper mode
- 7 Remove channels 6, 10, 12, 13, and 14 from oscillograph and continue test at 0.1 in/s with channels 3 and 4 only
- 8 Document all ambient conditions at beginning, once every hour, and at the end of the test Items recorded shall include temperature, wind speed and direction significant wind gusts and corrected barometric pressure

(a) Constant-speed test

Figure D-2 - Test checklists

Vehicle \_\_\_\_\_, \_\_\_\_\_ cycle test, \_\_\_\_\_ gear

Driver Instructions

- 1 Complete pretest checklist
- 2 While on track recheck
  - Integrator - light on, in "operate" position, zeroed
  - Speedometer - set on \_\_\_\_\_ mph center
  - Distance - on, reset, lighted
  - Attenuator - on, reset, selector on 100
  - Cycle timer - verify scheduled timing with stop watch
- 3 At signal from control center perform cycle test using cycle timer as basis for determining length of each phase of performance cycle Use programmed stop watch as backup device Cycle consists of
  - Accelerate to \_\_\_\_\_ mph in \_\_\_\_\_ s
  - Cruise at \_\_\_\_\_ mph for \_\_\_\_\_ s
  - Coast for \_\_\_\_\_ s
  - Brake to complete stop in \_\_\_\_\_ s
  - Hold in stop position for \_\_\_\_\_ sRepeat entire cycle until vehicle is unable to meet acceleration time Moderately brake to a complete stop

- 4 Complete post-test checklist and other documentation

Recording:

- 1 Record all channels on magnetic tape at \_\_\_\_\_ in/s Check all channels to verify input at beginning of test
- 2 Record speed and distance on oscillograph at \_\_\_\_\_ in/s
- 3 Start recording data 15 s before beginning test
- 4 Document ambient conditions at beginning, once every hour, and at the end of the test Items recorded shall include temperature, wind speed and direction, significant wind gusts, and corrected barometric pressure

(b) Driving cycle test

Figure D-2 - Concluded

- 1 Record specific gravity readings after removing vehicle from charge, and disconnect charger instrumentation. Fill in charge data portion of data sheet from previous test. Add water to batteries as necessary, recording amount added. Check and record 5th wheel tire pressure and vehicle tire pressure.
- 2 Connect. (Connect alligator clips to instrumentation battery last)
  - (a) Inverter to instrument battery
  - (b) Integrator input lead
  - (c) Integrator power to inverter
  - (d) Starred (\*) 5th wheel jumper cable
  - (e) Cycle timer power and speed signal input cables. Check times.
  - (f) Spin up and calibrate 5th wheel.
- 3 Record test weight - includes driver and ballast with 5th wheel raised.
- 4 Turn on
  - (a) Inverter, rotor speed sensor, thermocouple reference junctions, integrator, and digital voltmeter. Set integrator on "Operate".
  - (b) Fifth wheel readout and switching interface units (2). (Select distance for expanded scale range.)
- 5 Tow vehicle onto track with 5th wheel raised.
  - Recalibrations
  - Tape data system
  - Oscillograph
  - Reset.
  - 5th wheel distance
  - Ampere-hour meter
  - Thermocouple readout switches on "Record"
  - Turn on thermocouple reference junctions
  - Lower 5th wheel. Set hub loading.
- 6 Be sure data sheet is properly filled out to this point. Check watch time with control tower.
- 7 Proceed with test.

Figure D-3 - Pretest checklist

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Vehicle _____	Battery system _____
Test _____	Date _____
Track data.	
Driver _____	Navigator _____
Average pretest specific gravity _____	
Open-circuit voltage, V _____	
Tire pressure before test, psi	
Right front _____	Left front _____
Right rear _____	Left rear _____
Tire pressure after test, psi	
Right front _____	Left front _____
Right rear _____	Left rear _____
Fifth-wheel pressure, psi _____ (calibrated, _____ psi)	
Weather	
Temperature, °F	Initial _____
Wind speed, mph	During test _____
Wind direction	Final _____
Pressure, in Hg	_____
Battery temperature, °F	Before _____
Motor temperature, °F	After _____
Time Start _____	Stop _____
Odometer reading, miles	Start _____
Current out, Ah _____	Stop _____
Current in (regenerative), Ah _____	
Fifth wheel _____	
Basis for termination of tests _____	
Charge data	
Average post-test specific gravity _____	
Open-circuit voltage, V _____	
Charger used _____	
Charger input voltage, V _____	
Battery temperature, °F	Before charge _____
Power, kWh	After charge _____
Time Start _____	End _____
Total charge time, min	Total _____
Current input, Ah _____	
Average specific gravity after charge _____	
Approval _____	

Figure D-4 - Track and charge data

- 1 Record time immediately at completion of test Turn off key switch
- 2 Complete track data sheet.
  - (a) Odometer stop
  - (b) Ampere-hour integrator
  - (c) 5th wheel distance
  - (d) Read temperature
  - (e) Calibrate data system
  - (f) Record weather data
- 3 Turn off inverter, thermocouple reference junctions
- 4 Disconnect 12-volt instrument battery red lead
- 5 Raise 5th wheel
- 6 Tow vehicle off track
- 7 Start charge procedure (specific gravities)
- 8 Check specific gravity on instrument battery If less than 1.220 remove from vehicle and charge to full capacity
- 9 Check water level in accessory batteries Add water as necessary

Figure D-5 - Post-test checklist

Vehicle _____	Test _____	Date _____
<b>Test conditions</b>		
Temperature, °F _____	Wind speed, mph _____	at _____
Barometer reading, in Hg _____		Other _____
<b>Test results</b>		
Test time, h _____		
Range, miles _____		
Cycles _____		
Current out of battery, Ah _____		
Current into battery, Ah _____		
Charge time, h _____		
Power into battery, kWh _____		
<b>Magnetic tape:</b>		
No _____		Speed, in/s _____
<b>Comments</b> _____		
_____		
_____		
_____		
_____		
_____		

Figure D-6 - Test summary sheet

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Vehicle _____	Test _____	Date _____
Engineer _____		
Reason for test (checkout, component check, scheduled test, etc ) _____		
Limitation on test (malfunction, data system problem, brake drag, etc ) _____		
Changes to vehicle prior to test (repair, change batteries, etc ) _____		
Other comments _____		
Evaluation of test		
Range, miles _____		
Current out, Ah _____		
Current in, Ah _____		
Power in, kWh _____		
Energy consumption, kWh/mile _____		
Was planned driving cycle followed? _____		
General comments _____		
_____		
_____		
_____		
_____		

Figure D-7 - Engineer's data sheet

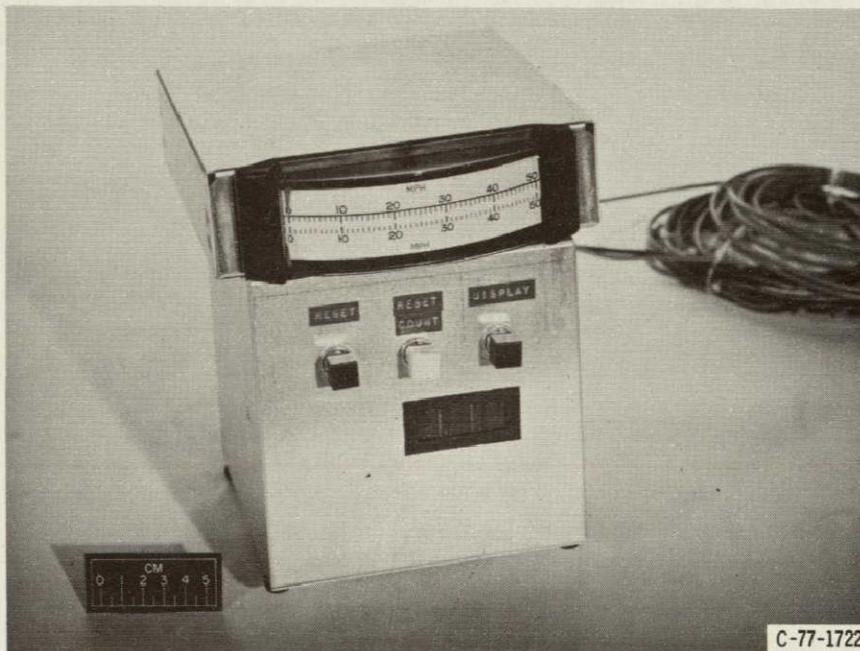


Figure D-8. - Cycle timer.

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