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Baseline Testing of the Club Car Carryall With Asymmetric Ultracapacitors

Dennis J. Eichenberg
Glenn Research Center, Cleveland, Ohio

November 2003

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BASELINE TESTING OF THE CLUB CAR CARRYALL WITH ASYMMETRIC ULTRACAPACITORS

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SUMMARY

The NASA John H. Glenn Research Center initiated baseline testing of the Club Car Carryall with asymmetric ultracapacitors as a way to reduce pollution in industrial settings, reduce fossil fuel consumption and reduce operating costs for transportation systems. The Club Car Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application.

The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future space applications. The work was done under the Hybrid Power Management (HPM) Program, which includes the Hybrid Electric Transit Bus (HETB). The Carryall is a state of the art, ground up, electric utility vehicle. A unique aspect of the project was the use of a state of the art, long life ultracapacitor energy storage system. Innovative features, such as regenerative braking through ultracapacitor energy storage, are planned. Regenerative braking recovers much of the kinetic energy of the vehicle during deceleration. The Carryall was tested with the standard lead acid battery energy storage system, as well as with an asymmetric ultracapacitor energy storage system. The report concludes that the Carryall provides excellent performance, and that the implementation of asymmetric ultracapacitors in the power system can provide significant performance improvements.

INTRODUCTION

The NASA Glenn Research Center initiated baseline testing of the Club Car Carryall as an excellent opportunity to transfer technology from the aerospace and military industries to a commercial venture. The project is seen as a way to reduce pollution in industrial settings, reduce fossil fuel consumption and reduce operating costs for transportation systems. The Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future space applications.

A unique aspect of the work is the implementation of asymmetric ultracapacitors. An ultracapacitor is an electrochemical energy storage device, which has extremely high volumetric capacitance energy due to high surface area electrodes, and very small electrode separation. Since there is no chemical reaction occurring in an ultracapacitor, very high charge and discharge currents are possible, limited only by the resistance of the conductors. The power control system for ultracapacitors is more reliable than that for batteries because the charge level of ultracapacitors is based strictly upon voltage level, whereas for batteries, the charge level is determined by voltage, temperature, age, and load conditions. Ultracapacitors have many advantages over batteries. Batteries can only be charged and discharged about

300 times, and then must be replaced. Ultracapacitors can be charged and discharged over 1 million times. The long cycle life of ultracapacitors greatly improves system reliability, and reduces life-of-system costs. Long ultracapacitor life significantly reduces environmental impact, as ultracapacitors will probably never need to be replaced and disposed of in most applications, whereas batteries require frequent replacement and disposal. The environmentally safe components of ultracapacitors greatly reduce disposal concerns over those of batteries. The recyclable nature of ultracapacitors also reduces the environmental impact, as well as the life-of-system costs. High ultracapacitor power density provides high power during surges, and the ability to absorb high power during recharging. Ultracapacitors are extremely efficient in capturing recharging energy, whereas batteries are not. Ultracapacitors are extremely rugged, reliable, and maintenance free. Ultracapacitors have excellent low temperature characteristics, unlike batteries. Ultracapacitors provide consistent performance over time, unlike batteries. Asymmetric ultracapacitors provide much higher energy density than any other available capacitor technology.

The NASA Glenn Research Center provides overall project coordination and is responsible for testing the vehicle. This includes instrumenting the vehicle and developing instrumentation and control programs. Wherever practical, off-the-shelf components have been integrated into the test configuration.

TEST OBJECTIVES

Testing of the vehicle was performed at the NASA Glenn Research Center. Of particular interest are the following characteristics: range, vehicle speed, and acceleration time. The performance of the various vehicle components, especially the motor, controller, energy storage system, and charger are also of interest. The tests conducted for this report covered the standard lead acid battery system, as well as an asymmetric energy storage system.

TEST VEHICLE DESCRIPTION

The Carryall is a state of the art, ground up, electric utility vehicle. The vehicle is shown in Fig. 1 and described in detail in Appendix A. The Carryall is a series electric vehicle as shown in Fig. 2. As a series electric vehicle, all power is provided to the drive wheels from an electric drive motor, powered by an electric drive system.

The standard energy storage system consists of six 8 volt, 150-amp hour sealed lead acid, deep discharge batteries to store electrical energy. The complete battery pack is shown in Fig. 3. The battery pack is installed beneath the seat on the interior of the vehicle. The seat is removed for battery maintenance, which is required weekly. Maintenance includes inspecting the electrolyte level, and adding electrolyte as required. The battery charger is an off board unit. The charger is rated at 48 volts, 17 amps DC.

The asymmetric ultracapacitor energy storage system tested is rated at 1996.5 Farads. The asymmetric ultracapacitor is shown in Fig. 4. This state-of-the-art technology not only has much longer life than conventional batteries, but also provides much higher current capacity than batteries. Ultracapacitors are maintenance free, and have excellent low temperature characteristics.

The electric traction motor is a 3.1 horsepower series wound unit. This is a direct drive system with double reduction helical gears. A pulse width modulated motor controller allows for efficient speed control over a wide speed range.

The total vehicle weight as tested was 1454 lbs. This included the standard lead acid batteries and the asymmetric capacitor, as well as all test instrumentation and two passengers.

The vehicle incorporates Department of Transportation specified safety features including lights, mirror, and horn.

Figure 1.—Club Car Carryall

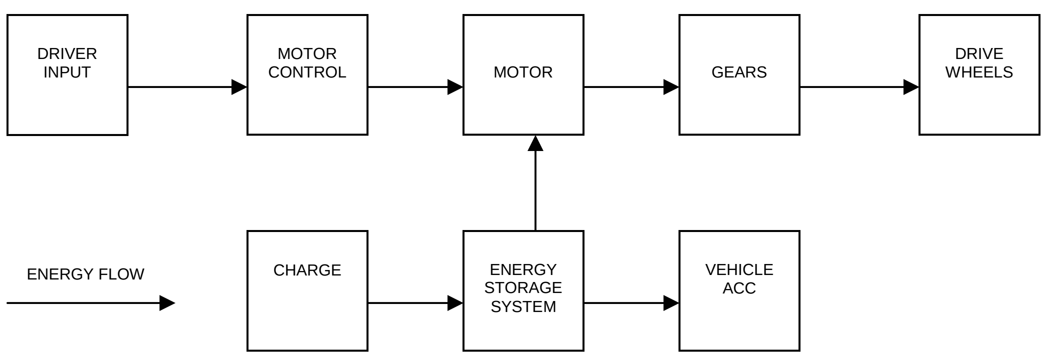


Figure 2.—Carryall Schematic Diagram

Figure 3.—Battery Pack

Figure 4.—Asymmetric Ultracapacitor

INSTRUMENTATION

The Carryall was instrumented to measure vehicle speed and distance. These data were sent to an on-board digital data acquisition system, sampled continuously and stored on a laptop PC. Additional channels measured the traction voltage and current, as well as the following temperatures: traction motor, motor controller, energy storage, and the ambient temperature. These data were sent to an on-board digital data acquisition system and stored on a laptop PC. Power for the data acquisition system, was derived from a portable power system. The instrumentation configuration is described in Appendix B.

TEST PROCEDURES

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio. A description of the test is given in Appendix C. The tests were conducted in accordance with the test matrix provided in Appendix D.

TEST RESULTS

Vehicle Performance

Ten tests were conducted to determine vehicle performance, per Table 1:

Table 1.—Performance Tests Conducted on the Club Car Carryall

Test Number	*Grade (%)*	*Vehicle Mode*	*Top Vehicle Speed*	*Energy Source*	*Test Mode*
1	+0	Normal	Maximum	Capacitor	Range test.
2	+0	Normal	Maximum	Battery	Acceleration test.
3	+0	Normal	Maximum	Capacitor	Acceleration test.

A similar set of plots have been included in Appendix E for each of the vehicle tests:

a. Vehicle speed vs. elapsed time.
b. Vehicle voltage and current vs. elapsed time.
c. Component temperatures vs. elapsed time.

A summary of the test results is shown in Table 2 at the end of this section.

Maximum Speed

The maximum speed of the vehicle was measured to be 10.1 mph with no grade under full power with battery energy storage. The maximum speed was measured to be 10.4 mph with no grade under full power with asymmetric ultracapacitor energy storage. Figure 5 indicates the maximum speeds achieved with the various energy storage systems.

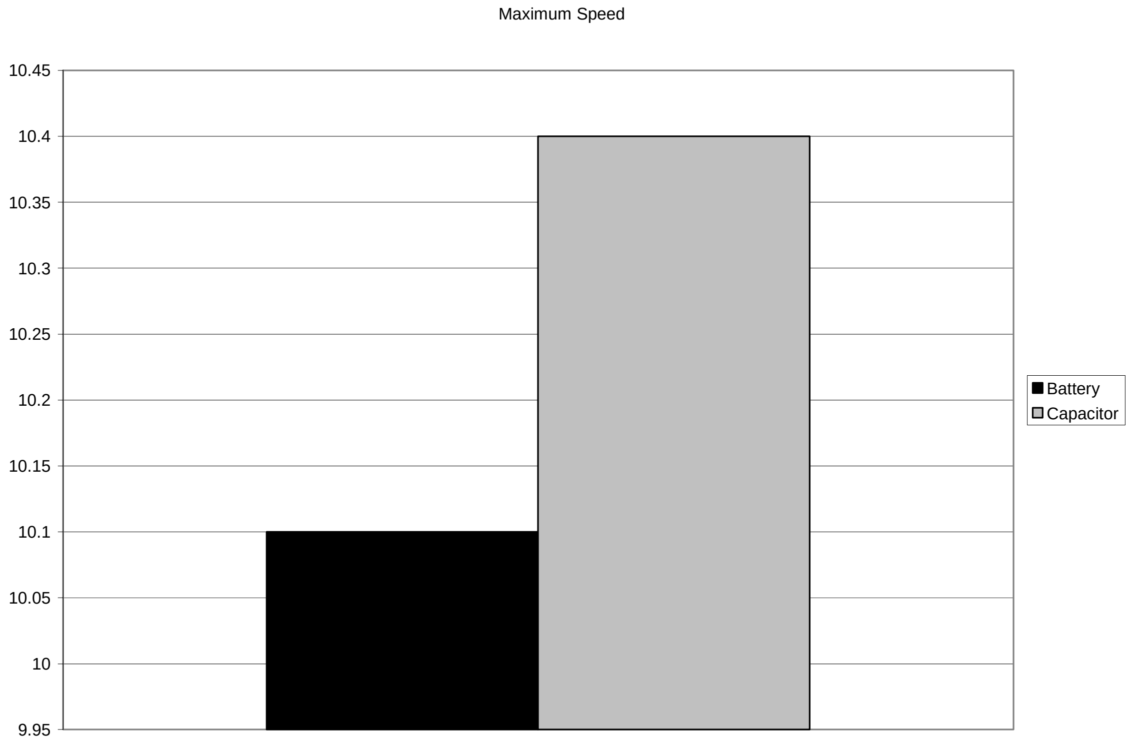


Figure 5.—Maximum Speed for Various Configurations

Acceleration

The average acceleration, a_n, of the vehicle is computed as a change in vehicle speed as a function of time.

$$a_n = \frac{v_n - v_{n-1}}{t_n - t_{n-1}}$$

Acceleration times are given in Table 2.

Range

The range of the vehicle was determined from the range test. The results are indicated in Figure 6. The maximum range achieved with asymmetric ultracapacitor energy storage was 3.01 miles with no grade and an initial speed of 10.4 mph. The duration was 29.6 minutes.

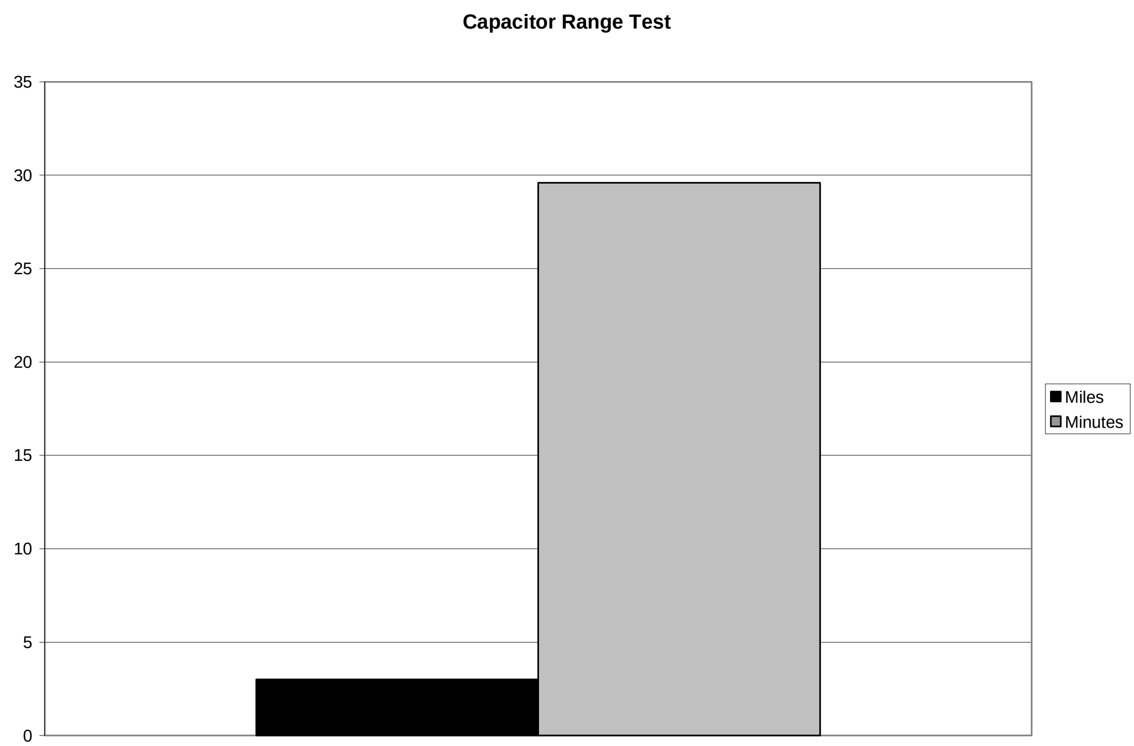


Figure 6.—Range with Various Speeds

Summary

An overall summary of the vehicle testing is shown in Table 2.

Table 2.—Summary of Test Results for the Club Car Carryall with Batteries, and Asymmetric Ultracapacitors

Parameter	Configuration	Test Conditions	Test Results	Remarks
Acceleration Times				
5.0 mph	Battery Asymmetric Cap	0% Grade, Normal Mode	4.0 sec 3.5 sec	
6.3 mph	Battery Asymmetric Cap	0% Grade, Normal Mode	7.5 sec 5.2 sec	
Range				
Maximum Speed	Asymmetric Cap	0% Grade, Normal Mode	3.01 miles	0.49 hr, 10.4 mph
Top Speed	Battery Asymmetric Cap	0% Grade, Normal Mode	10.1 mph 10.4 mph	
Charging				Energy storage system recharged after 1 mile test. Battery charging results are only until initialization of steady state 100 watt equalization charge.
Time	Battery Asymmetric Cap	118.8 vac line 118.8 vac line	3.6 hr 1.0 hr	
Maximum AC Current	Battery Asymmetric Cap	118.8 vac line 118.8 vac line	6.48 amps 9.00 amps	
Maximum AC Power	Battery Asymmetric Cap	118.8 vac line 118.8 vac line	770 watts 1070 watts	
Total Energy	Battery Asymmetric Cap	118.8 vac line 118.8 vac line	1.296 kWh 0.748 kWh	

CONCLUDING REMARKS

The Club Car Carryall as tested and described in this report with the standard battery pack is a commercially available vehicle that is fully prepared for the mass market. The Carryall has also been tested very successfully with asymmetric ultracapacitor energy storage. The primary focus of this report is the test results with asymmetric ultracapacitor energy storage. The vehicle, nor the energy storage systems, exhibited any problems under the rigorous test conditions that it was exposed to. The performance of the vehicle proved to be excellent.

The vehicle acceleration tests were very revealing. The acceleration tests were performed with battery energy storage, and asymmetric ultracapacitor energy storage. The acceleration performance was markedly improved with the asymmetric ultracapacitor in all cases. The most significant improvement was the acceleration performance to 6.3 mph. The time to 6.3 mph with the asymmetric ultracapacitor was about 50 percent less than that with the standard battery pack. The asymmetric ultracapacitor is capable of supplying very high power, which is required to accelerate the vehicle quickly.

The top speed of the vehicle with no grade and full throttle with the standard battery pack was 10.1 mph. The maximum top speed was achieved with the asymmetric ultracapacitor, which provided a top speed of 10.4 mph.

The range achieved with the asymmetric ultracapacitor energy storage system with a fully loaded test vehicle was 3.01 miles, which required 0.49 hours. The range would be greater without the additional payload of the battery pack and instrumentation.

A one mile test was performed with battery energy storage and asymmetric ultracapacitor energy storage to compare the charging characteristics of each configuration. 1.296 kWh was required to recharge the batteries, whereas 0.748 kWh was required to recharge the asymmetric ultracapacitor. Ultracapacitor charging is significantly more efficient than battery charging, since there is no chemical reaction occurring.

The baseline testing of the Carryall with the standard battery pack was the first step in the testing process. The baseline testing of the Carryall with asymmetric ultracapacitor energy storage was the second step. Future plans for the Carryall includes the testing of the vehicle with regenerative braking. Ultracapacitors will be used for regenerative braking, because of their superiority to batteries in accepting high braking currents, allowing for less usage of the mechanical brakes.

The Club Car Carryall provides an inexpensive approach to advance the state of the art in electric vehicle technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future space applications.

APPENDIX A

VEHICLE SUMMARY DATA SHEET

1.0 Vehicle Manufacturer	Club Car Inc. Augusta, GA
2.0 Vehicle	Carryall 1
3.0 Vehicle Configuration	Series Electric
4.0 Traction Motor	
4.1 Traction Motor Configuration	Series Wound DC
4.2 Traction Motor Power	3.1 horsepower
4.3 Traction Motor Cooling	Air cooled
5.0 Drivetrain	
5.1 Traction Motor Drivetrain	Direct Drive, Double Reduction Helical Gears
6.0 Vehicle Dimensions	
6.1 Wheel Base	65.5 in (166.4 cm)
6.2 Overall Length	103.5 in (262.9 cm)
6.3 Overall Width	48 in (121.9 cm)
6.4 Overall Height	48 in (121.9 cm)
6.5 Ground Clearance	4.5 in (11.4 cm)
6.6 Front Tread	34.5 in (87.6 cm)
6.7 Rear Tread	38.5 in (97.8 cm)
6.8 Cargo Bed Load Size	37.6 in (95.6 cm) x 45.1 in (114.6 cm) x 9.3 in (23.5 cm)
6.9 Cargo Bed Load Height	27.5 in (69.9 cm)
6.10 Cargo Bed Load Capacity	300 lb. (272.4 kg)
6.11 Vehicle Load Capacity	800 lb. (363.2 kg)
6.12 Dry Weight (Less Energy Storage)	530 lb. (240.6 kg)
6.13 Outside Clearance Circle	17.5 ft (5.3 m) dia.
6.14 Turning Radius	8.4 ft (2.6 m)
6.15 Intersecting Aisle Radius	72 in (182.9 cm)

7.0 Energy Storage

7.1 Battery Pack

7.1.1	Configuration	Six in series
7.1.2	Battery Type `	Deep discharge, ventilated lead acid
7.1.3	Battery Energy Rating	150 amp hours each, 25.9 MJ total
7.1.4	Battery Voltage Rating	8 volts each
7.1.5	Battery Dimensions	10.375 in x 7.125 in x 10.875 in
7.1.6	Battery Weight	63 lb each, 378 lb total
7.1.7	Charger Input	115 volts ac, 60 Hz, 2 amps (rated)
7.1.8	Charger Output	48 volts dc, 17 amps
7.1.9	Charger Dimensions	15 in x 4 in x 4 in
7.1.10	Charger Weight	22.3 lb

7.2 Asymmetric Ultracapacitor Pack

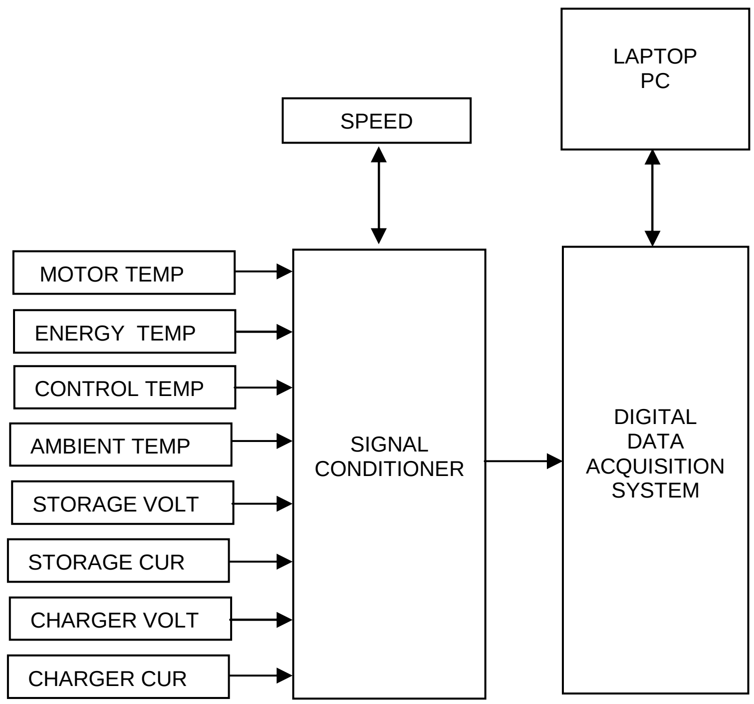
7.4.1	Configuration	Single ultracapacitor
7.4.2	Capacitance	1996.5 F
7.4.3	Capacitor Energy Rating	2300 kJ
7.4.4	Capacitor Voltage Rating	24 V to 48 V
7.4.5	Capacitor Dimensions	24.29 in x 18.8 in x 11.26 in
7.4.6	Capacitor Weight	192.9 lb
7.4.7	Charger Input	120 volts ac, 60 Hz, 8.5 amps
7.4.8	Charger Output	48 volts dc, 18 amps
7.4.9	Charger Dimensions	3.5 in x 8.5 in x 18.6 in
7.4.10	Charger Weight	14 lb

APPENDIX B

DESCRIPTION OF THE INSTRUMENTATION SYSTEM

A block diagram of the instrumentation system is shown in Fig. B-1.

All measurements were obtained with a Hewlett Packard data acquisition system, sampling at 100 Hz. Type K thermocouples were used for all temperature measurements. Hall effect transducers were used for all current measurements. Speed and distance were monitored by a proximity sensor. These data are transmitted to the laptop PC via a serial interface. The PC logs the data.



VEHICLE INSTRUMENTATION SYSTEM
Figure B-1

APPENDIX C

DESCRIPTION OF DIGITAL DATA ACQUISITION SYSTEM

The digital data acquisition system used for testing is an Agilent Model 34970A. It is a high performance, microprocessor controlled, portable, data acquisition system. It consists of a half-rack mainframe with an internal 6 1/2-digit (22 bit) digital multimeter. Three module slots are built into the rear of the unit to accept a combination of switch and control modules.

Tests documented in this report were conducted with the digital data acquisition system programmed to meet the test matrix requirements.

APPENDIX D

DESCRIPTION OF TEST CYCLES

Testing of the vehicle was based on the test matrix shown in table D-1.

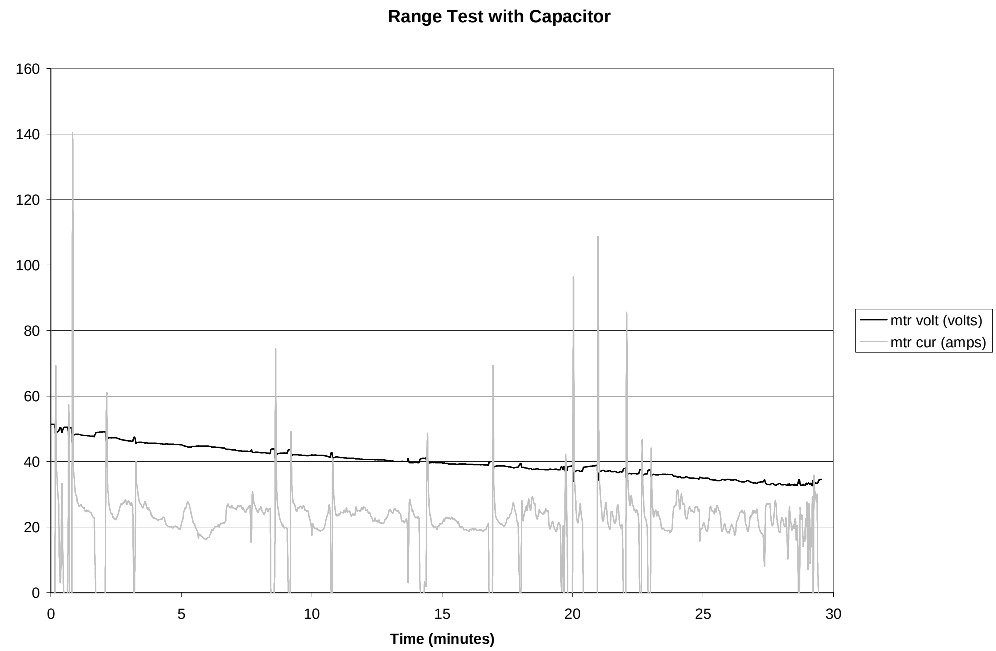
Table D-1.—Club Car Carryall Test Matrix

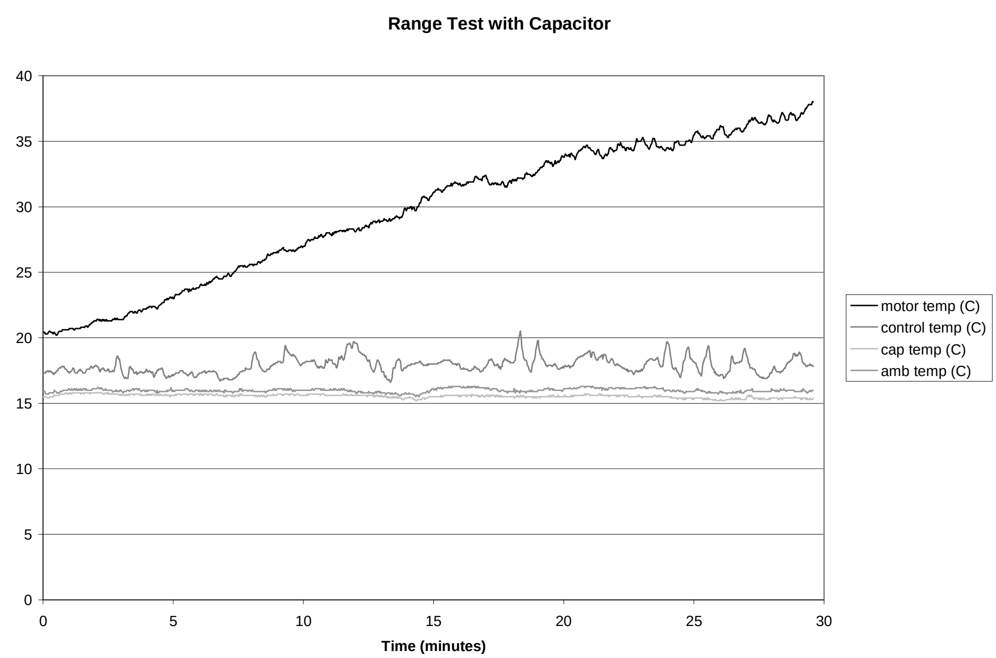
PARAMETER	CONDITIONS
Acceleration	To maximum speed at 0% grade with lead acid battery energy storage system, and with asymmetric ultracapacitor energy storage system.
Range	To maximum speed at 0% grade with asymmetric ultracapacitor energy storage system.
Top Speed	To maximum speed at 0% grade with lead acid battery energy storage system, and with asymmetric ultracapacitor energy storage system.
Charging	Charging lead acid battery energy storage system, and charging asymmetric ultracapacitor energy storage system.

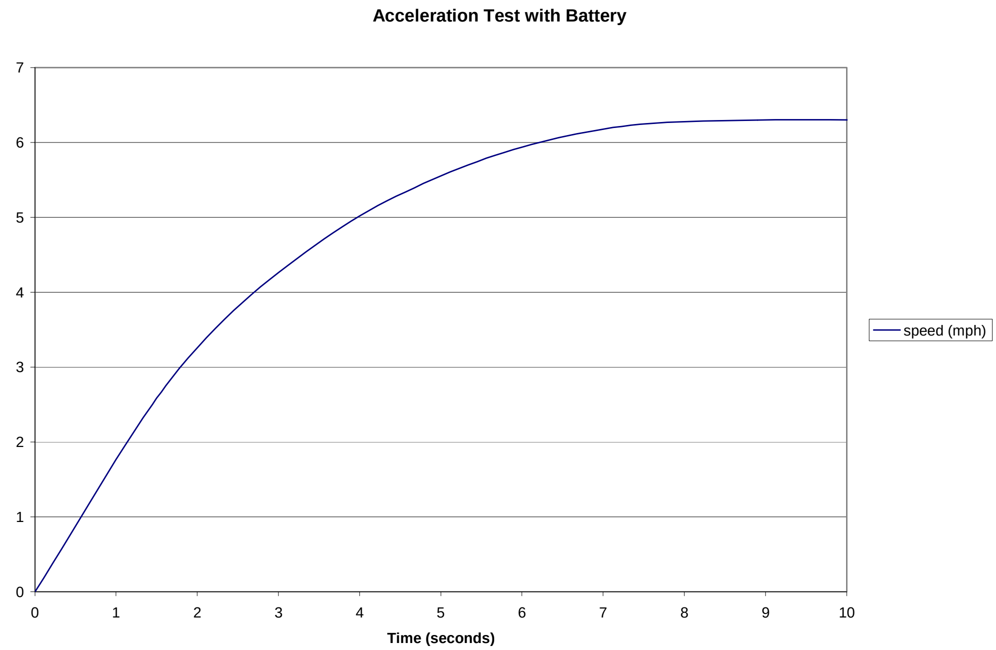
APPENDIX E

VEHICLE PERFORMANCE TEST RESULTS

A complete set of plots of the test results are included here. Table 1 identifies the tests that were conducted.






Acceleration Test with Battery
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1
2
3
4
5
6
7
0
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2
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4
5
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7
8
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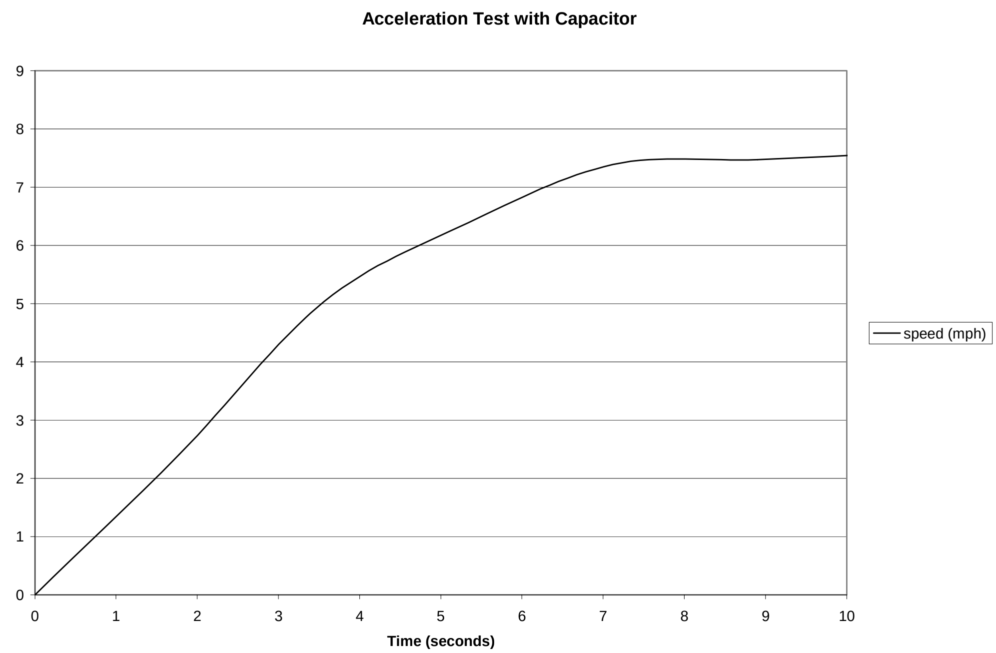
10
Time (seconds)
speed (mph)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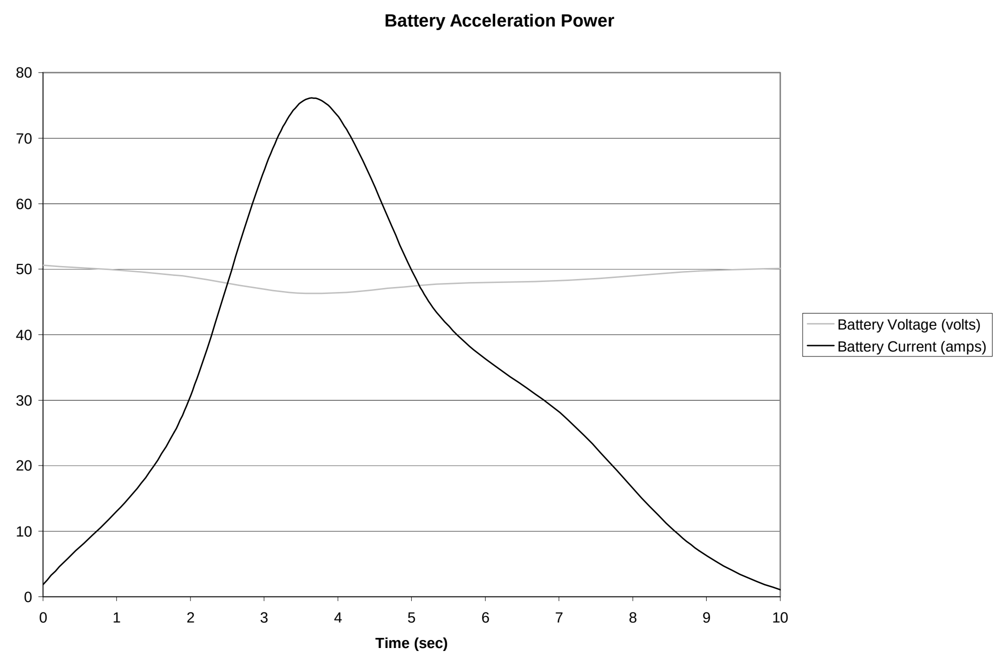
Time (seconds)
speed (mph)


Battery Acceleration Power
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50
40
30
20
10
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9
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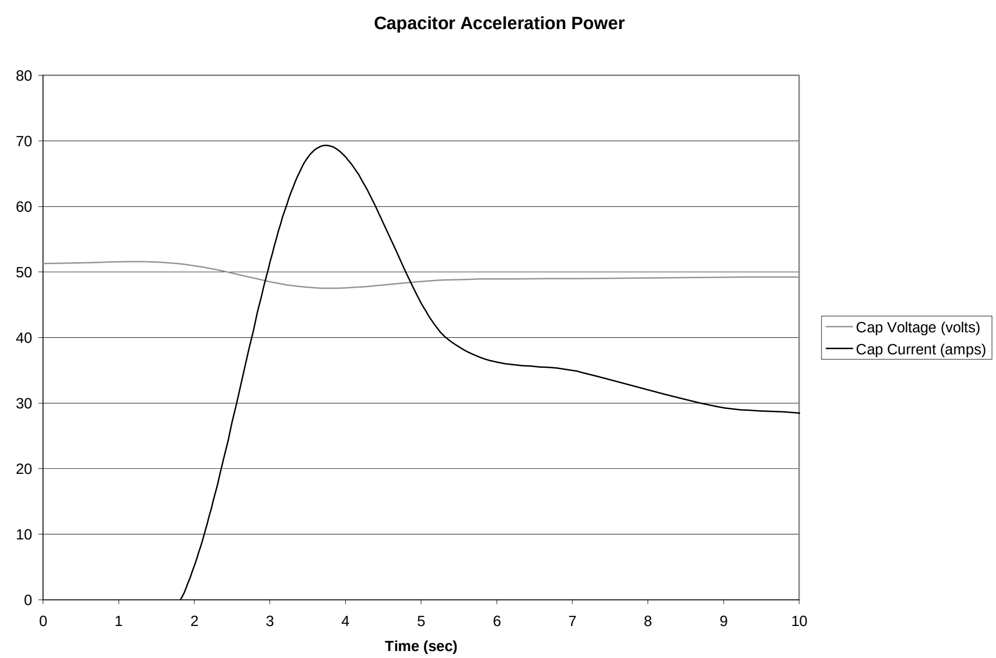
Time (sec)
Battery Voltage (volts)
Battery Current (amps)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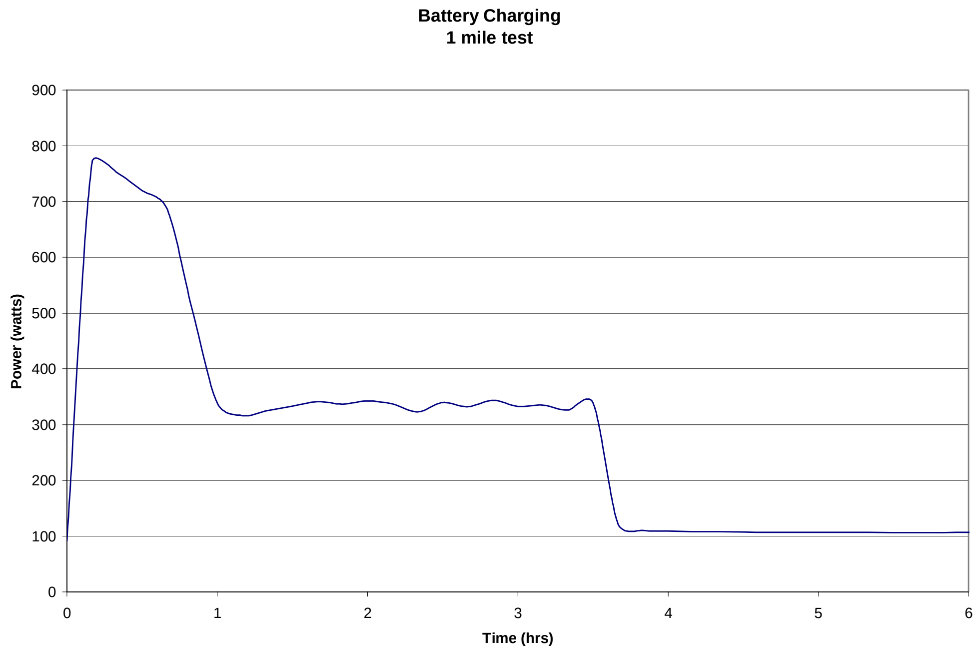
Cap Voltage (volts)
Cap Current (amps)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1 mile test
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800
700
600
500
400
300
200
100
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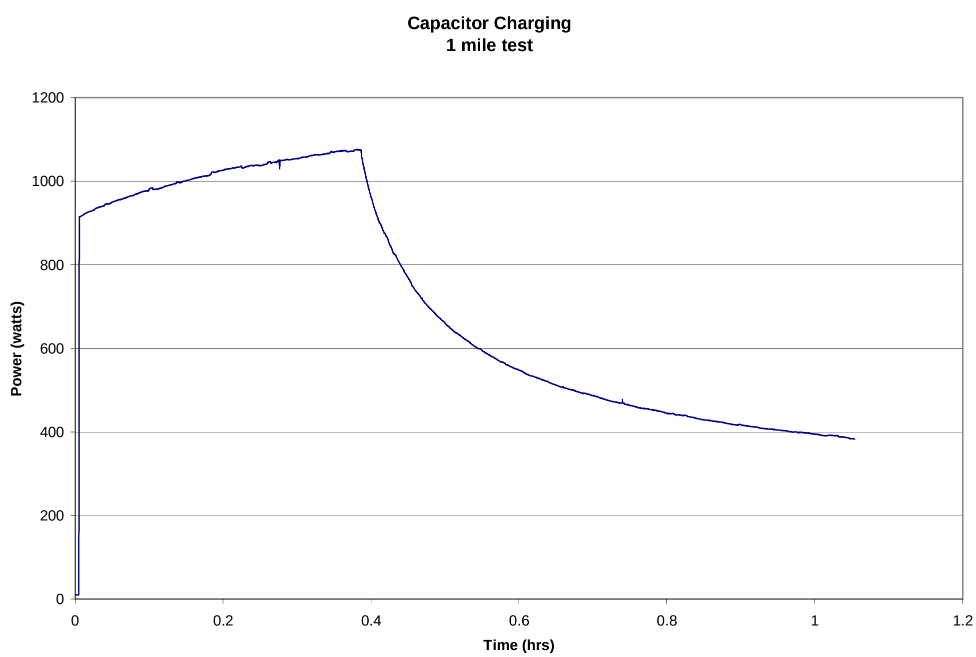
0
1
2
3
4
5
6
Time (hrs)


Capacitor Charging
1 mile test
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1000
800
600
400
200
0
Power (watts)
0
0.2
0.4
0.6
0.8
1
1.2
Time (hrs)

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