Evaluation of Nickel Cadmium Battery-Electric Subcompact Automobile in Connecticut as an Alternative for Work-trips and Commutes

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May 2004

Report No.
CT-2223-1-04-6

Research Project: SPR-2223

Connecticut Department of Transportation
Bureau of Engineering and Highway Operations
Research and Materials

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A Project in Cooperation with the U.S. Department of Transportation
Federal Highway Administration

1.Report No. FHWA-CT-RD-2223-1-04-6	2. Government Accession No.	3. Recipients Catalog No.
4. Title and Subtitle Evaluation of Nickel Cadmium Battery-Electric Subcompact Automobile in Connecticut as an Alternative for Work-trips and Commutes		5. Report Date May 2004 6. Performing Organization Code SPR-2223
7. Author(s) James M. Sime, P.E.		8. Performing Organization Report No. FHWA-CT-RD-2223-1-04-6
9. Performing Organization Name and Address Connecticut Department of Transportation Division of Research 280 West Street Rocky Hill, CT 06067-3502		10. Work Unit No. (TRIS) 11. Contract or Grant No. CT-SPR Study No. 2223 13. Type of Report and Period Covered Interim Report 1999 to 2003
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		14. Sponsoring Agency Code SPR-2223

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

To comply with federal regulations resulting from the federal Energy Policy and Conservation Act of 1992 (EPACT), the Connecticut State fleet manager began purchasing non-emergency automobiles (cars) and light trucks that run on alternate fuels (Alt-Fuel). The Department and The Rideshare Company (Rideshare) previously partnered to evaluate electric subcompact cars that utilized lead acid batteries. A nickel cadmium (NiCd) battery, popular in European electric vehicles, was anticipated to provide longer and more reliable service. The accuracy of marketing claims of battery electric vehicle (BEV) and battery manufacturers was uncertain. There was a need to obtain and disseminate some first-hand information about the practicality of this Alt-Fuel option.

This evaluation was accomplished in partnership with Rideshare. Rideshare administered the conversion of one of its lead-acid BEV subcompacts to a NiCd BEV in 1999. The car's manufacturer performed the work. The NiCd pack consisted of 26 six-volt batteries (pack capacity is 15,600 Watt-hours) and had a battery-pack replacement value in 1999 of $8,450. A favorable cost-per-mile statistic for battery-replacement was possible in Connecticut if the NiCd battery were as long-lived as was claimed by its manufacturer.

This research report presents interim results from a 30,000-mile evaluation of this subcompact electric car powered by nickel cadmium batteries (NiCd). The study examines claims that the NiCd-powered BEV will provide not less than 70 miles per recharge year-round for 65,000 miles or more. In a small state (50 miles from north to south and 100 miles from east to west), a 70-mile range was anticipated to be capable of meeting 20 to 30 percent of the fleet's daily driving needs.

17. Key Words	18. Distribution Statement
Electric vehicle, battery electric vehicle, nickel cadmium battery, federal Energy Policy and Conservation Act of 1992 (EPACT), state fleet, automobile	No restrictions. Hard copy of this document is available through the National Technical Information Service, Springfield, VA 22161. The report is available on-line from the National Transportation Library at http://ntl.bts.gov

19. Security Classif. of this report	20. Security Classif. of this page	21. No. of Pages	20. Price
Unclassified	Unclassified	61	

Executive Summary

This research presents the results of a 30,000-mile evaluation of a battery-electric subcompact car in the context of their possible future use in state fleet. A nickel cadmium (NiCd) battery powered the car. This evaluation examines claims that NiCd batteries both last longer and provide double the range of cars with lead acid batteries. These characteristics, if verified, would demonstrate better practicality than observed in earlier evaluations of lead acid battery-electric subcompact cars. Also, the cost of NiCd batteries has declined in recent years, which would improve the economics of battery electric vehicles if the batteries have sufficiently long service lives.

From an earlier study, it was observed that the vehicle chassis, body, interior and drive train of the subcompact in this study would be adequate for the transport of personnel within Connecticut for most routine non-emergency state business. However, reported in an earlier report, drivers will notice that the drive train of the battery electric vehicle (BEV) subcompact is somewhat underpowered as compared with most other vehicles on the road. This BEV design clearly placed priority on efficiency over power, acceleration and speed./1/

The battery itself must be evaluated separately since several different batteries could power this car. A nickel cadmium (NiCd) battery is evaluated in this project. The NiCd battery has 100 ampere-hour capacity (C3). Twenty-six 6-Volt batteries are connected, in series, to form the battery pack that provides 15,600 Watt-hours of power.

From the earlier Department study, it was recommended that a fuel-fired heater be evaluated as a means to address heating and windshield defrosting requirements in Connecticut in a manner that would use very little electricity from the battery pack, which supplies both motive power and power for all accessories./1/ During the first year of this study, a liquid-fuel-fired heater/defroster was installed in the NiCd car. About eight gallons of kerosene were used per winter. Over four winters we observed that even in very cold weather the 70-mile driving range was available. We conclude that a fuel-fired heater/defroster is essential in a BEV operating in Connecticut.

NiCd and BEV technology must be demonstrated to work well and provide sufficiently long service life in Connecticut before they can be seriously considered for a role in the state fleet. One key interim finding after 30,000 miles of driving is that the NiCd battery configuration was reliable in its four years of operation. The most significant problems observed from 1999 to 2003 were difficulties with battery recharging during hot weather [80˚F+] and periodic internal-fuse failures in the onboard battery charger. This interim report presents data and information that generally verifies manufacturer claims as to BEV performance, and provides direction on modifications to the car that are anticipated to improve its performance and acceptability in Connecticut.

Following this 30,000-mile report, the evaluation of this NiCd-powered subcompact will be continued until the service life of the battery pack is reached. Two additional NiCd cars with nearly identical specifications will be added to broaden the number and type of driving situations and gather more data to complete this evaluation project.

Disclaimer

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not reflect the official views or policies of the Connecticut Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Acknowledgements

The author wishes to acknowledge the support of both the Federal Highway Administration and The Rideshare Company of Hartford, Connecticut (Rideshare). Rideshare provided the electric vehicle for this project. The author also wishes to acknowledge several individuals.

In the ConnDOT Bureau of Public Transportation the author recognizes the involvement of Bureau Head Harry P. Harris, manager Michael A. Sanders, and engineer Dennis A. Jolly. Their efforts and continuing support of research in alternative-fuel technologies for transportation deserve recognition.

Mr. Jon Colman, President of The Rideshare Co., and Anne Burns, V.P., are excellent partners in this research project. Mr. David Fabricatore, formerly with Rideshare, was the manager responsible for the BEV. Dave was the lead in arranging for the retrofit of the BEV to utilize Nickel-Cadmium (NiCd) batteries, a direct drive powertrain and fuel-fired heater/defroster. Dave and I teamed in 1999 and 2000 to participate in the annual weeklong American Tour del Sol (ATdS) road rally for EVs, which produced valuable data and information for this study. Without Dave’s active involvement and support, the NiCd study would not have been undertaken.

Mr. John Hudson of our Research Division (now retired) was the third team member for the 1999 and 2000 ATdS. John handled logistics and drove the support van, which allowed Dave and me to concentrate on the rally.

CEO James Worden and engineer Andrew Heafitz of Solectria Corp., the BEV manufacturer, generously taught efficient driving techniques on several occasions. Their instruction was important to our developing understanding of BEVs and the efficient-driving skills they taught became habitual practice in daily driving.

METRIC CONVERSION TABLE

English to Metric			Metric to English		
LINEAR					
inches (in.)	X 25.4	= millimeters (mm)	millimeters (mm)	X 0.3937	= inches (in.)
feet (ft.)	X 0.3048	= meters (m)	meters (m)	X 3.281	= feet (ft.)
miles (mi.)	X 1.6093	= kilometers (km)	kilometers (km)	X 0.6214	= miles (mi.)
AREA					
inches^2 (sq.in.)	X 645.15	= millimeters^2 (mm^2)	millimeters^2 (mm^2)	X 0.000155	= inches^2 (sq.in.)
feet^2 (sq.ft.)	X 0.0929	= meters^2 (m^2)	meters^2 (m^2)	X 10.764	= feet^2 (sq.ft.)
VOLUME					
inches^3 (cu.in.)	X 0.01639	= liters (l)	liters (l)	X 61.024	= inches^3 (cu.in.)
quarts (qts.)	X 0.94635	= liters (l)	liters (l)	X 1.0567	= quarts (qts.)
gallons (gal.)	X 3.7854	= liters (l)	liters (l)	X 0.2642	= gallon (gal.)
inches^3 (cu.in.)	X 16.39	= centimeters^3 (cc)	centimeters3 (cc)	X 0.06102	= inches^3 (cu.in.)
feet^3 (cu.ft.)	X 28.317	= liters (l)	liters (l)	X 0.03531	= feet^3 (cu.ft.)
feet^3 (cu.ft.)	X 0.02832	= meters^3 (m^3)	meters3 (m3)	X 35.315	= feet^3 (cu.ft.)
fluid ounce (fl.oz.)	X 29.57	= millileters (ml)	milliliters (ml)	X 0.03381	= fluid ounce (fl.oz.)
MASS					
ounces (oz.)	X 28.35	= grams (g)	grams (g)	X 0.03527	= ounces (oz.)
pounds (lbs.)	X 0.4536	= kilograms (kg)	kilograms (kg)	X 2.2046	= pounds (lbs.)
tons (2000 lbs.)	X 907.18	= kilograms (kg)	kilograms (kg)	X 0.001102	= tons (2000 lbs.)
tons (2000 lbs.)	X 0.90718	= metric tons (t)	metric tons (t)	X 1.1023	= tons (2000 lbs.)
tons (long) (2240 lbs.)	X 1013.05	= kilograms (kg)	kilograms (kg)	X 0.000984	= tons (long) (2240 lbs.)
PRESSURE					
inches Hg (60ºF)	X 3600	= kilopascals (kPa)	kilopascals (kPa)	X 0.2961	= inches Hg (60ºF)
pounds/sq.in. (PSI)	X 6.895	= kilopascals (kPa)	kilopascals (kPa)	X 0.145	= pounds/sq.in. (PSI)
pounds/sq.in. (PSI)	X 0.0703	= kilograms/sq.cm. (kg/cm^2)	kilograms/sq.cm. (kg/cm2)	X 14.22	= pounds/sq.in. (PSI)
pounds/sq.in. (PSI)	X 0.069	= bars	bars	X 14.5	= pounds/sq.in. (PSI)
inches H_2O (60ºF)	X 0.2488	= kilopascals (kPa)	kilopascals (kPa)	X 4.0193	= inches H_2O (60ºF)
bars	X 100	= kilopascals (kPa)	kilopascals (kPa)	X 0.01	= bars
POWER					
horsepower (hp)	X 0.746	= kilowatts (kW)	kilowatts (kW)	X 1.34	= horsepower (hp)
ft.-lbs./min.	X 0.0226	= watts (W)	watts (W)	X 44.25	= ft.-lbs./min.
TORQUE					
pound-inches (in.-lbs.)	X 0.11298	= newton-meters (N-m)	newton-meters (N-m)	X 8.851	= pound-inches (in.lbs.)
pound-feet (ft.-lbs.)	X 1.3558	= newton-meters (N-m)	newton-meters (N-m)	X 0.7376	= pound-feet (ft.-lbs.)
pound-feet (ft.-lbs.)	X .1383	= kilograms/meter (kg-m)	kilogram/meter (kg-m)	X 7.233	= pound-feet (ft.-lbs.)
VELOCITY					
miles/hour (m/h)	X 0.11298	= kilometers/hour (km/hr)	kilometers/hour (km/hr)	X 0.6214	= miles/hour (m/h)
feet/second (ft./sec.)	X 0.3048	= meter/second (m/s)	meters/second (m/s)	X 3.281	= feet/second (ft./sec.)
feet/minute (ft./min.)	X 0.3048	= meter/minute (m/min)	meters/minute (m/min)	X 3.281	= feet/minute (ft./min.)

TEMPERATURE

ºCelsius = 0.556 (ºF - 32)   ºFahrenheit = (1.8ºC) + 32

COMMON METRIC PREFIXES

mega	(M)	= 1,000,000 or 106	deci	(d)	= 0.1 or 10^{-1}
kilo	(k)	= 1,000 or 10^3	centi	(c)	= 0.01 or 10^{-2}
hecto	(h)	= 100 or 10^2	milli	(m)	= 0.001 or 10^{-3}
deka	(da)	= 10 or 10^1	micro	(m)	= 0.000.001 or 10^{-6}

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Evaluation of Nickel Cadmium Battery-Electric Subcompact Automobile in Connecticut as an Alternative for Work-trips and Commutes

Background

In Connecticut, the State Department of Administrative Services is responsible for the state central vehicle fleet of about 4,041 vehicles, which are mostly light trucks and cars. State fleet has 222 vehicles assigned to the Connecticut Department of Transportation (ConnDOT), of which 129 are compact cars, 43 are midsize cars, and one full-size car. The other 49 vehicles are a mix of minivans, wagons, compact and midsize SUV, compact and full size trucks. In addition, ConnDOT is responsible for an additional 2,000-vehicle fleet, which includes everything from hundreds of transit buses to hundreds of dump/snow-plow trucks, but only 7 cars and 275 pickups. To comply with federal regulations resulting from the federal Energy Policy and Conservation Act of 1992 (EPACT), the Connecticut State fleet manager began purchasing non-emergency automobiles (cars) and light trucks that run on alternate fuels (Alt-Fuel), which are fuels other than gasoline or diesel. Since 2001, EPACT requires that 75% of new vehicles purchased for the State fleet operate on an alternate fuel (see Appendix B).

Under EPACT, one fleet-vehicle option that can satisfy the car and light truck requirements is the battery-electric vehicle (BEV). BEVs are anticipated to provide three benefits as compared with cars powered by the internal combustion engine: (1) reduced airborne emissions (improved urban air quality),(2) reduced energy consumption per vehicle mile traveled, and (3) reduced use of petroleum and dependence on foreign oil.

ConnDOT previously evaluated electric subcompact cars that utilized lead acid batteries. /1/ The Nickel-Cadmium (NiCd) battery, popular in European electric vehicles, was anticipated to provide longer and more reliable service. The accuracy of marketing claims of BEV and battery manufacturers was uncertain. There was a need to obtain and disseminate some first-hand information about the practicality of this Alt-Fuel option.

ConnDOT initiated this research project in 1998. The project was made possible through The Connecticut Rideshare Company’s (Rideshare’s) loan of a 1995 battery electric vehicle (BEV) to the Department with approval to modify the vehicle as necessary for the evaluation of nickel cadmium batteries (NiCd).

Rideshare managed the conversion of the lead-acid BEV subcompact to a NiCd BEV in 1999. The car manufacturer performed the conversion. The NiCd pack consists of 26 six-volt batteries (pack capacity is 15,600 Watt-hours) and had a battery-pack replacement value in 1999 of $8,450. A favorable cost-per-mile statistic for battery-replacement was possible if the NiCd battery were as long-lived as was claimed. The driving range design goal for the NiCd-powered BEV was to provide not less than 70 miles per recharge year-round. Eight (8) ConnDOT research personnel were approved as drivers. Rideshare provided automobile insurance coverage.

The evaluation of the NiCd BEV included the following: observations and data gathered by driver participants in commuting and work trips, data gathered through the American Tour del Sol (ATdS) electric vehicle road rally, troubleshooting and repair after breakdowns, and subsequent data analyses. The combination of driving activities conducted under a variety of battery states-of-charge, weather, traffic, and roadway conditions was anticipated to provide a balanced first-hand evaluation of 1999 production BEV technology with a NiCd battery system.

Another decision-making issue concerning the incorporation of electric vehicles into a centralized fleet is vehicle substitutability. In the publication, Transportation Research Record 1049, Mark Berg wrote that the trip patterns of a fleet could be analyzed to determine where electric vehicles can be substituted, based on typical miles-per-day (mpd) requirements. /2/ In Berg's research, he studied commercial fleets, but the same approach and general conclusions are anticipated to apply to a government fleet.

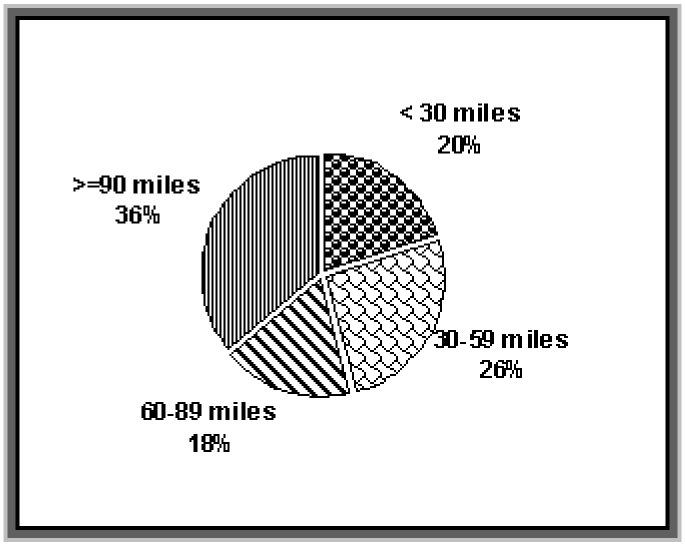


Figure 1 Daily distances driven as percent of fleet vehicles in commercial fleets studied by Berg. /2/

In each mile-per-day (mpd) group, Berg observed that a fleet manager could determine the occurrences of occasional higher-mileage trips (see Figure 1). Berg argued that an electric vehicle could be driven most of the time if the driver had ready access to a longer-range vehicle when occasionally needed. A longer-range vehicle could be provided for the occasional higher-mileage day from either the fleet or through mileage reimbursement to the employee for the use of his/her private vehicle. Berg went on to conclude that in commercial fleets, although 46% of all fleet vehicles "typically" did not exceed 60 mpd, practical limitations on making other vehicles available for occasional longer trips meant that 30 percent of the fleet's cars and light trucks could almost always function within a 60-mpd-range limitation.

If a similar 60-mpd pattern was found in the Connecticut state government fleet, perhaps battery electric cars and light trucks could be substituted for as many as 136 non-emergency vehicles utilized by ConnDOT (54 cars and 82 pickups). If you generalize for our statewide (all agencies) fleet, perhaps battery electric cars and light trucks could be substituted for as many as 1,000 conventional non-emergency vehicles, if battery-electric compact and midsize cars plus pickup type vehicles were available for about 25 percent of the daily trips.

In Connecticut, if a BEV were shown to provide a reliable 70-mpd range and the six-year longevity comparable to conventional vehicles, it would have good potential as a practical substitute for up to 30 percent of the gasoline-powered cars and light trucks in the state fleet. The 70-mpd capability of the NiCd BEV would provide a 10-mpd margin of extra range against the 60-mpd parameter identified in Berg’s analysis of fleets. Should the NiCd BEV prove suitable for use in Connecticut, State fleet managers could utilize data in their fleet-usage records and the approach developed by Berg to develop their own vehicle-substitution plans.

Study Objective

The objective was to conduct an evaluation of a Nickel Cadmium (NiCd) battery-electric vehicle (BEV) provided by The Connecticut Rideshare Company (Rideshare). The hypothesis to be evaluated was that a NiCd-powered BEV subcompact with fuel-fired heater/defroster would provide a year-round minimum 70-mile range in Connecticut (Table 1), would be reliable, and would operate for six years on one battery pack, providing more than 65,000 miles of service before the battery pack needed replacement.

At low ambient temperatures, a NiCd battery was not anticipated to suffer much loss in efficiency; however, the range in winter was anticipated to be slightly less than its range in the other three seasons, due to the greater use of accessories (battery pack warmers, passenger electric seat warmers, fuel-fired heater/defroster, rear-window defroster, windshield wipers, and headlights). That said, the hypothetical seasonal driving ranges of the NiCd BEV were all anticipated to exceed 70 miles on a battery charge.

Description of Nickel Cadmium Battery for Motive Power

A 100-Ampere-hour nickel cadmium battery powers the BEV. The battery is manufactured in Europe where it is commonly used in battery electric vehicles. The manufacturer’s claimed battery attributes for the NiCd are: sintered-plate positive electrode and plastic-bonded negative electrode with integrated liquid cooling; low maintenance, lifetime of over 100,000 km (65,000 miles); operational from -20°C to +40°C; rapid recharging; fully recyclable; specific energy at three-hour discharge (C/3) is 54 Wh/kg; energy density at C/3 is 87 Wh/dm3; and specific power at 80% DOD is 120 W/kg. Each 6 V battery weighs 12.7 kg (28 lbs). Battery module dimensions are 246x123x260 mm for a volume of 7.87 dm3. In the pack, 26 batteries times 6 Volts (each) equals 156 Volts (nominal), times 100 Ampere-hours equals a total of 15,600 Watt-hours of power. NiCd batteries don't require charge equalization the way lead acid batteries do.

Table 1 Battery Electric Vehicle (BEV) Facts

Vehicle Battery Type	Nickel Cadmium (NiCd)
Number of Batteries in pack	26
Battery Pack Voltage (volts)	156[1]
Battery Capacity (Ah)	100[2]
Battery Capacity (kWh)	15.6
Battery Pack Weight (lbs.)	675
Battery Cooling/Thermal Management	Liquid-type
Anticipated Winter, Spring, Summer & Fall Driving Range (miles)	70+

NOTES: [1] The 26 batteries are connected in series to produce a 156 V pack voltage.
[2] C/3 is a three-hour discharge rating for the Nickel Cadmium (NiCd) battery.

This motive-power battery is available in air- and liquid-cooled versions. The liquid-cooled version was recommended for the Southern New England climate. Table 1 summarizes various facts about the battery that powered the BEV in this project.

One maintenance procedure is required periodically to service the battery. Approximately two gallons of distilled water must be added to the battery pack after every 1,000 Ah of battery overcharging (about every 3,500 miles).

Rideshare contracted with the automobile original equipment manufacturer (OEM) to retrofit the 1995 vehicle with the "all new for 1999" "production NiCd Force design" motor and direct-drive train with 26 batteries. The OEM wanted to deliver a retrofitted car that was a 1999-model NiCd under the hood. This would enable them to receive relevant real-world data and information on the performance of their 1999 model year NiCd model through ConnDOT’s project. However, later we learned that the standard 1999 NiCd car model had one less 6 V battery module in its pack.

Description of Basic Vehicle

The subcompact BEV is a General Motors (GM) Geo Metro 4-door sedan that is retrofitted by the Solectria Corporation to become their

“Force” model. The GM model years 1995 through 1999 are essentially identical.

The vehicle examined in this study had a 1995 model-year body/chassis. This subcompact car was one of the least expensive, no-frills economy cars on the market./3/ As a subcompact car, it had adequate seating for four adults, but limited interior room. Trunk space in the NiCd car is smaller than in the General Motors internal combustion engine (ICE) version of this subcompact car due to the space required for a battery box and on-board charger.

A Solectria motor, model ACgtx20, replaced the original Solectria motor. Manufacturer’s specifications for the new AC induction motor state that it will deliver approximately 44 HP and is a brushless sealed design that weighs 78 pounds (lbs). Company specifications further state that it has extremely low electrical resistance; nominal power is 12 kW and nominal torque is 20 Nm; while maximum power and torque are 37 kW and 70 Nm, respectively. Nominal motor speed is 4,000 rpm and maximum motor speed is 12,000 rpm. The manufacturer states the motor has an efficiency of 92%.

By comparison, the 1995 gasoline-powered version of this car, a General Motors Geo Metro 4-door sedan, was powered by a 1.3-liter four-cylinder engine, providing 70 horsepower (hp).

The vehicle retained its original Solectria model AC 325 electrical controller. A new Solectria model AT1200 gearbox with the standard 12:1 gear ratio replaced the belt drive assembly. The manufacturer describes the gearbox as lightweight, weighing 35 pounds, and supporting a maximum input torque of 100 Newton-meters (Nm). The factory upgrade also included new watertight electrical connectors, an Electromagnetic Interference (EMI) sock around high-voltage wires under the hood to improve radio reception, and a newer fuse box design. The onboard battery charger was a Solectria Model BC 3300 high-frequency type that operated on 220 V at 16 Amperes (peak) on a 20-Amp circuit.

The wheels on the car were replaced with lighter, wider (13x5.5 inch) alloy wheels, lowering the total wheel+tire weight by four pounds over the OEM. The OEM tire was the Goodyear Invicta P155/80R13 model, a 44-psi low-rolling resistance (LLR) P175/70R13 tire. In April 2000, tires were changed to a lightweight 51-psi LLR P165/70 R13 radial tire, a tire make/model optimized for electrically powered and ultra-efficient vehicles. These Michelin Proxima tires carried an "S" rating; Traction "A" rating, Temperature "B" rating, and Tread wear rating of 200 on DOT Quality Grade Scale. The 14-inch size, which is the tire make and model used on the GM EV1 electric car, has one special feature not available in the 13-inch tire, a self-sealing, run-flat capability.

In a standard OEM vehicle, a 1500-Watt electrical resistance heater/defroster provides cabin heating and windshield defrosting. The energy required from the battery pack for heating and defrosting, lights, and wipers was observed in an earlier study to reduce the driving range by as much as 20 miles (20 ampere-hours) per drive/battery-discharge cycle. Fuel-fired heater/defrosters had been the subject of earlier research conducted by EVermont (www.evermont.org)./4/ EVermont’s findings were that fuel-fired heaters had an overall efficiency of 62 percent versus electrical resistance heater system total system efficiency of approximately 39 percent. High efficiency fuel-fired heater/defrosters perform their intended function and provide safety, comfort, and economy.

Between the 1999 ATdS and 2000 ATdS events, the air conditioner components were reinstalled and a fuel-fired heater system was added, which increased the weight of the car. EVermont handled the installation of the fuel-fired heater plus electrically warmed seats for this project. To partially compensate for the weight gain, the OEM steel hood and trunk lid were replaced with lighter weight fiberglass. The net increase in vehicle weight was observed to be 219 pounds, which equates to a 4.6 percent increase over the previous year (see Table 2).

Table 2 Vehicle weight at 2000 ATdS was 4.6 percent greater than the previous year due to the installation of the air conditioner and fuel-fired heater/defroster.

1999

	Left	Right
Front	625	579
Rear	696	687
Subtotal	1,321	1,266
Total		2,587

2000

	Left	Right
Front	646	697
Rear	679	684
Subtotal	1,325	1,381
Total		2,706
Percent Increase		4.6%

Near the end of a 70- mile drive, battery temperatures would naturally rise somewhat. In spring 2000, we experimented with a timer/switch device to shift the start of recharging to a later, cooler nighttime period when it was anticipated that charging could occur more efficiently after battery temperatures had had a chance to come down. We installed the ‘charge later’ mechanical timer in the power cord with the intention of providing a set-and-forget capability. During the evaluation, other problems with recharging, which were unrelated to the timer/switch, overshadowed this early attempt to squeeze a little more efficiency out of the battery recharging system.

Performance Observations – 1999-2003

On November 28, 1999, the NiCd BEV was put into service and the data acquisition evaluation began for later analysis and reporting. The car was not equipped with a sophisticated battery-management and data-acquisition system, so data collection consisted of manually reading and recording data from various gauges that monitor electrical usage in the BEV and from an electric meter that measured the electricity used to recharge the battery. The electric meter was carried in the trunk and wired between the external receptacle and the internal battery charger. Data and written comments about the performance of the BEV in daily commuter service were manually recorded for every drive during the four-year period, spring 1999 to spring 2003. About three minutes were required to record all data from dash and trunk readouts. The OEM provided computer software to read various battery charge attributes through the serial port on the smart charger. To take readings, a laptop PC was booted and a MS-DOS session opened. Next, the DOS-based software read the data parameters and displayed them. A Windows copy/paste procedure was used to manually transfer the data to a text file, which could then be saved or printed. The procedure required about 20 minutes. Because the procedure was time consuming, we changed our data acquisition requirements to record these data only in conjunction with battery watering and for troubleshooting.

Drive Distances of the NiCd Car

In all, data were recorded for 428 drives covering just over 30,000 miles. This equates to an overall average driving distance between recharges of 70 miles. Included in these 428 drives are the data acquired through participation in two weeklong road rallies for electric vehicles (years 1999 and 2000). In Figure 2, the distances driven for all 428 drives are simply plotted against time. Four periods when the car was out of service are marked in the figure as A, B. C, and D.

During Period A for 55 consecutive days, the car was at the factory for installation of the air conditioner and repairing of the ‘smart charger.' During Period B for 106 consecutive days, the car was at EVermont for installation of the fuel-fired heater/defroster and Watt-hour meter, followed by the body shop for installation of lightweight trunk lid and front hood. During Period C for 191 consecutive days, the car was at the manufacturer for troubleshooting and repairs of a mysterious battery-undercharge problem. During the winter of 2002/2003, the car's heater/defroster was inoperable.

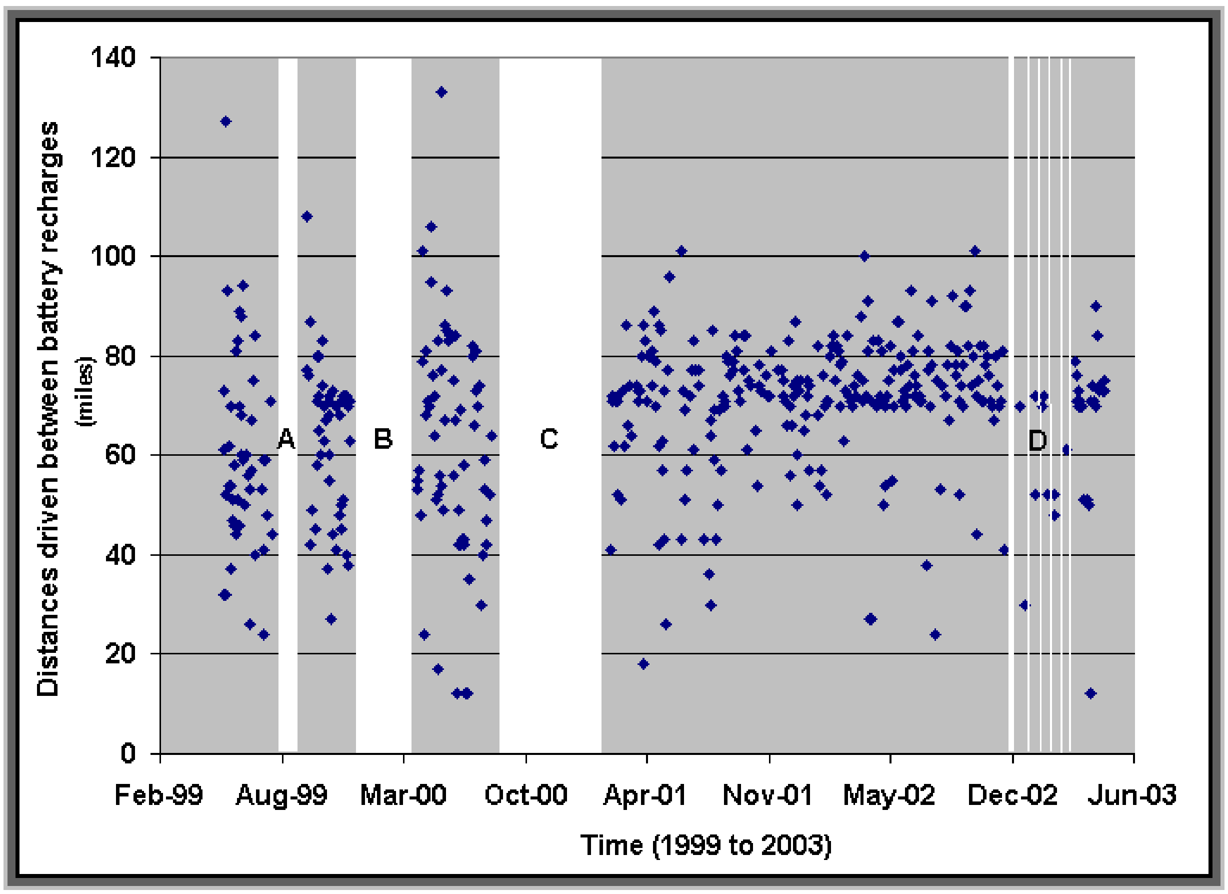


Figure 2. Miles driven in 428 drive/recharge cycles during the evaluation

As a result, for 42 non-consecutive days during period D, the car was parked on eight occasions of frigid temperatures and/or winter storms, which ranged from 2 to 14 consecutive days each. During two other periods in 2001, for 12 and 19 consecutive days, the car sat idle while the manufacturer was replacing an internal blown fuse in the on-board battery charger. In all, the car was unavailable for 426 days or 29.3 percent of the 1,451-day evaluation period, which ended on May 11, 2003.

Taken together the overall distribution of 428 single-charge distances driven can be shown in a boxplot (Figure 3). Here, we see that half the drives were shorter than 71 miles and half were longer. On a single charge the shortest distance driven was 12 miles and the longest distance driven was 133 miles. Short drives like the eleven that were 27 miles and less do not represent the distance the car could have been driven on a charge. In these cases, the shorter distances driven represent situations where the car battery pack was recharged in preparation for a longer 'next' drive.

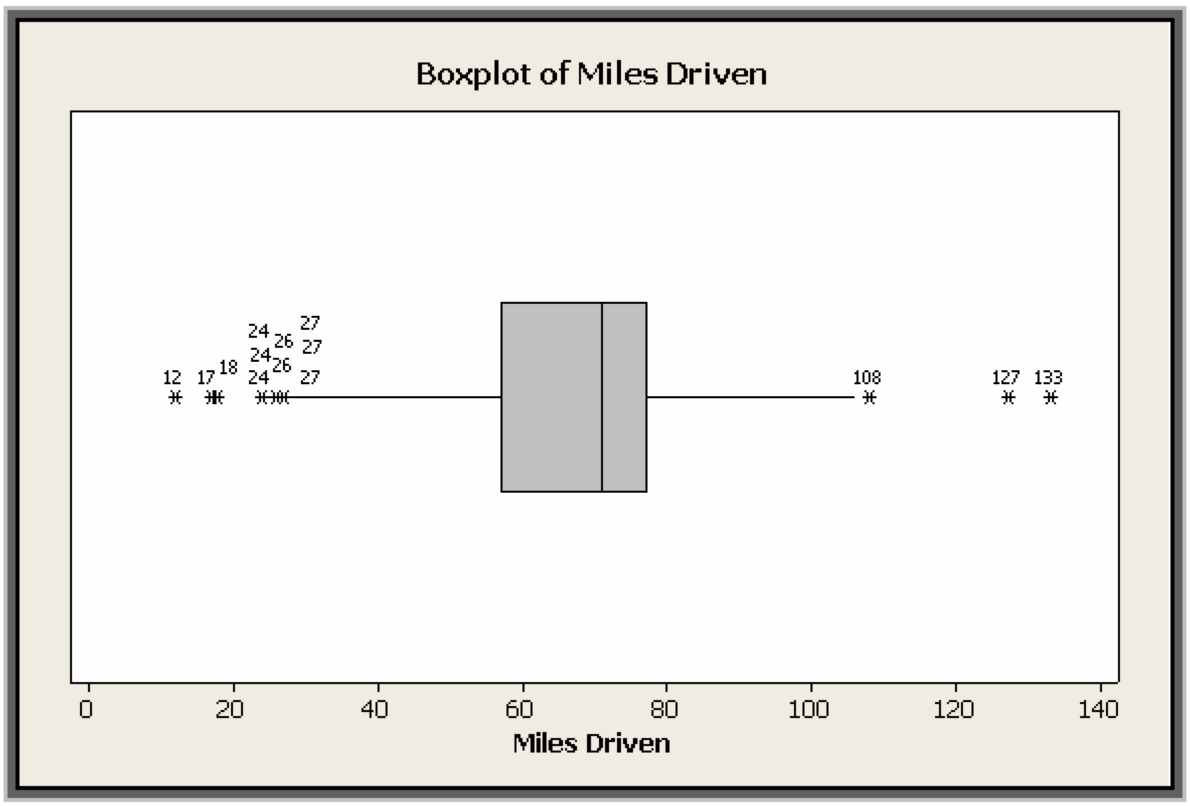


Figure 3. Box plot of miles driven per battery recharge

Overall, Figure 3 presents a graphical display of all 428 drives in the NiCd car, covering 30,000 miles in a wide variety of weather and traffic conditions. Later in this report, a seasonal analysis of the miles driven per battery recharge will be presented.

Performance Information from ATdS

Comparative data and information about battery electric vehicles were obtained from the Northeast Sustainable Energy Association (NESEA), which is the organizer of the annual ATdS road rally for electric and other environmentally responsible ('green') vehicles (http://www.nesea.org).

The ATdS scheduled hilly and seacoast terrain for its rally routes in alternating years. The 1999 route had hilly-terrain that was generally up-hill, starting in Waterbury, CT, and ending in Lake George, NY. On the first day of the 1999 ATdS, the Rideshare NiCd BEV (Vehicle A) experienced battery-recharging difficulties, and the OEM stepped in and replaced the 'smart charger' with a standard battery charger (same model number). No other car problems were experienced during the weeklong ATdS.

Table 3 Comparative results from ATdS in 1999

	Vehicle	**Efficiency** MPGe[1]	**1/4th mile Acceleration** Seconds	**Range** Single charge And 5.5 hr driving limit	**Autocross Handling** Seconds
A.	Rideshare Force BEV (Solectria with NiCd)	86.01	24.79	130	34.97
B.	Ovonic Force BEV (Solectria with NiMH)	57.69	23.17	217	35.30
C.	EVermont Force BEV (Solectria w/ NiMH)	73.38	22.11	142	34.60
D.	Ethel Walker Force BEV (Solectria with Interstate PbA)	78.01	26.45	54	35.93
E.	Toyota RAV4 EV BEV (NiMH batteries)	46.75	23.40	118	N/A

[1]NESEA formula: MPG_e is the miles per gallon-equivalent of gasoline = miles driven divided by KWh(A) times 0.0759 gal. per KWh (AC)

In Table 3, data are shown for five vehicles selected from the 38 entries. Vehicles A-D had the same body/chassis, with different power trains and batteries. Vehicle E was included as a familiar benchmark vehicle and because it had a similar battery capacity to that of Vehicle B. Table 3 shows the relative parity in acceleration and handling among the four vehicles with similar Solectria chassis and powertrains (rows A, B, C and D). Rideshare's vehicle (A) carried 15,600 watt-hours (wh) of capacity in its NiCd batteries, which weighed 675 lbs. Vehicle B used a 180-Volt pack of Nickel Metal Hydride (NiMH) batteries with 27,000 wh, which weighed 800 lbs. The NiMH pack weighed 18.5% more than Vehicle A's NiCd pack, yet provided 73% more energy storage than vehicle A's NiCd. This illustrates the higher energy density of the NiMH. Vehicle C was similarly equipped with NiMH batteries with 16,200 wh./5/ Vehicle D used conventional lead acid batteries that provided 144 volts and 10,000 wh. Its single-charge range of 54 miles was similar to the everyday performance of Rideshare's other lead-acid-powered Solectria BEVs. Vehicle D was equipped with roof-top photovoltaic cells that improved the efficiency of the vehicle by supplying some of the recharge and drive electricity from the sun. Vehicles A and D weighed in at 2,587 and 2,570 lbs, respectively. Vehicle E was powered by a 984-lb NiMH battery pack that provided 28,224 wh, or 4.5 percent more storage than Vehicle B. However, Vehicle E weighed 34 percent (873 lbs) more than Vehicle B. Vehicle C was quicker than the others, but not by much. The range of acceleration times was only 4.34 seconds from slowest to quickest in this group. The NiCd-powered car, Vehicle A, had the highest efficiency, even out-performing solar-assisted Vehicle D.

The 2000 ATdS route had level coastal terrain that started in Manhattan, NY, and ended in Washington, DC. Table 4 shows the relative parity in acceleration and handling among the three vehicles with similar Solectria chassis and powertrains (rows A, B and C). Rideshare's vehicle

(A) carried 15,600 watt-hours of capacity in its NiCd batteries. Vehicle B used the same NiCd battery as our vehicle (A), but was also was equipped with an experimental hydrogen-gas powered fuel cell that extended that driving range.

In addition, under the rules of the ATdS, vehicle B's efficiency was enhanced by recharging its battery from a large solar array system that was trailered by the support team. The batteries in C were the lead acid type, which have lower energy density than the NiCd but Vehicle C pulled a small trailer with additional batteries wired to the car's electrical system, which extended its range.

Table 4 Comparative results from ATdS in 2000

	Vehicle	**Efficiency** MPGe[1]	**1/8th mile Acceleration** top speed, mph	**Range** Single charge And 5.5 hr driving limit	**Tech Testing Handling** Seconds
A.	Rideshare NiCd BEV (Solectria)	70.71	43.54	130.73	7.76
B.	New Jersey Venturer Hydrogen-fuel cell/BEV Hybrid (Solectria)	87.20	43.24	175.29	8.54
C.	Solectria SuperForce BEV (extra lead-acid batteries in trailer)	73.78	42.11	156.85	8.42
D.	GM EV1 Generation II BEV (NiMH batteries)	63.31	61.36	224.45	6.84
E.	2000 Honda Insight Gas/Electric Hybrid (four vehicle entries)	40.44 to 79.26	51.14 to 57.02	202 to 268	6.81 to 9.68

[1]NESEA formula: MPG_e is the miles per gallon-equivalent of gasoline = miles driven divided by KWh(A) times 0.0759 gal. per KWh (AC)

The combined car and battery trailer provided 27,360 watt-hours of power. Vehicle D accelerated quicker than A, B and C; had greater range; and, better handling. This BEV had a high-energy density nickel metal hydride (NiMH) battery, providing 26,400 watt-hours of power. The NiMH battery has a higher energy density than the NiCd as well. The efficiency of vehicle D was about ten percent lower than ConnDOT's vehicle (A) since General Motor's two-seater was designed to deliver sports-car performance. Vehicle E consisted of four entries. One possible reason for the two-seater hybrids' widely varying performance results is the possible variability in driving styles among the four participants in those vehicles. The gasoline-powered hybrid carries 900 watt-hours of battery capacity. All four entries were unmodified production vehicles, so I believe that the best acceleration, handling, range and efficiency results could most likely be achieved in any of the four identical vehicles if driven by a sufficiently skillful driver.

Grade Climbing Information from Mount Washington Autoroad

Immediately following the 1999 ATdS, in May, the work-trip and commuting element of the evaluation was initiated. Instrument data and narratives of significant events were recorded in accordance with project requirements. The car functioned normally throughout this period with the substitute battery charger. In August, arrangements were made to transport the BEV to the manufacturer where remaining retrofit work would be completed and the OEM 'Smart Charger' was to be reinstalled.

August 12, 1999, was a day scheduled for the transport of the BEV back to the manufacturer. Researchers transported the vehicle first to Mount Washington in New Hampshire. The purpose of this trip was to drive the Mount Washington Autoroad to the summit. For about one hundred years, New Englanders have looked to the Mount Washington "Autoroad" as the classic test of a vehicle's ability to climb long steep grades.

The summit of Mount Washington is 6,288 feet above mean sea level. The Mt. Washington "Autoroad" is approximately 7.6 miles long and rises roughly 4,600 feet to about 6,227 feet elevation (you have to climb the rest of the way by foot to the summit). The average grade (slope) on this road is 12%, while actual grades vary between 8 and 15%, with maximum grades of about 22% very near the top. The road contains about 35% paved and 65% unpaved sections.

The EV manufacturer was consulted prior to our drive. They modeled the drive and assured us there was ample battery power in the nickel cadmium (NiCd) pack. The NiCd BEV was successfully driven up the Mt. Washington "Autoroad" on a single charge. The car had ample capacity for this hill climb. In fact, as a result of regenerative braking on the descent, the car appeared to have enough energy in its batteries to repeat the drive to the summit, but our schedule did not allow sufficient time for a second drive up the mountain.

Summary of Ascent

The distance registered on the car odometer during the ascent was 7.6 miles. In all, 47.06 Amp-hours were used to drive to the top. This equates to 7.02 Kilowatt-hours (DC). The speed-limit advisory is 20 mph on the Autoroad. The elapsed time to the top was one hour with four planned roadside stops.

The principal concern of all drivers on the "Autoroad" is overheating. There are eleven pull-off/parking areas on the way up. The mid-point pull-off has water available for conventional automobiles that are experiencing overheating engines/radiators. Conventional automobiles are susceptible to overheating engines on the drive up and overheating brakes on the drive down. The NiCd BEV OEM identified four components of the BEV that could heat up during the ascent and descent; however, they felt the electrical controller was the only component at risk for overheating. The controller will normally heat up during the ascent to power the motor, and on the descent from regenerative braking.

Photo 2 Vehicle is shown on the Autoroad near the summit of Mount Washington in New Hampshire.

We drove the mountain road in five segments with short breaks for photography. The four stops were at scenic roadside parking areas located at elevations of 3,000, 4,000, 5,000 and 6,000 ft. During these breaks, we observed that the controller's built-in cooling system operated for 1-5 minutes and then shut itself off. We concluded that our strategy for the drive was conservative.

Summary of Descent

The downhill distance registered on the car odometer was 7.3 miles. The car recovered 17.93 Amp-hours through its regenerative brakes. This equates to 2.71 kWh Kilowatt-hours (DC). The downhill speed varied, but was generally about 15-18 mph. Table 5 shows the data recorded for both the ascent and descent on the Mount Washington “Autoroad.”

Regenerative braking was all the braking required for most of the descent. Recovered energy was stored in the NiCd battery. The regenerative braking system recovered 38.6% of the energy expended for the uphill drive.

Table 5 - Energy Data from the 1999 Mount Washington "Autoroad" Drive

Ascent					
Time	Elapsed Miles	Approx. Elevation (ft above sea level)	Ampere-hours Ah (DC)	Kilowatt-hours kWh (DC)	Comments
11:30 AM	0.0	1,600	1.87	0.23	24.7˚C at base
11:37 AM	1.7	3,000	11.91	1.71	Speed was 18-23 mph
11:47 AM	3.4	4,000	22.70	3.73	Speed was 18-23 mph
12:08 PM	5.1	5,000	33.50	4.95	Speed was 18-23 mph
12:16 PM	6.8	6,000	46.70	6.90	Speed was 18-23 mph
12:30 PM	7.6	6,227	48.93	7.25	17.3˚C at summit

Descent					
Time	Elapsed Miles	Approx. Elevation (ft above sea level)	Ampere-hours Ah (DC)	Kilowatt-hours kWh (DC)	Comments
1:30 PM	0.0	6,224	49.73	7.37	17.3˚C at summit
1:45 PM	2.3	5,000	44.37	6.56	Speed was 15-18 mph
1:55 PM	3.8	4,000	40.46	5.97	Partial & Full Regen
2:09 PM	5.4	3,000	36.16	5.32	Headlights ON for entire descent
2:20 PM	7.3	1,600	31.80	4.66	Arrive at base of “Autoroad”

The elapsed time to the bottom was 50 minutes and included three roadside stops.

In summary, grades encountered in the Mount Washington “Autoroad” were steeper than those generally found in Connecticut. The NiCd car demonstrated that although it is underpowered, it had sufficient motor torque to climb the most severe grades (22%) at the “Autoroad’s” posted speed limit (20 mph) with two adults, in harmony with other traffic on the road. Regenerative braking recovered 38.6 percent of the power (kWh, DC) that was required to climb the mountain.

Efficiency of the NiCd Car

During the four-year period from spring 1999 to spring 2003, sufficient data were acquired from 426 of the 428 drives for an analysis of the efficiency of the NiCd BEV subcompact. The bar chart, Figure 4, displays the number of drives in each season for which energy-use and recharge data were collected. The greatest amount of data was collected in the spring seasons. The least amount of data was collected during winter seasons because it was during these periods that remaining retrofit work or repairs on the vehicle were scheduled. For example, during the ‘99/’00 winter the air conditioner and fuel fired heater/defroster were installed. During the winter of ‘00/’01, the vehicle was at the manufacturer for troubleshooting on a battery charging problem. The problem was solved during the winter and the car was returned to service in the spring of 2000. Thirty-three of the forty-four data points for the winter season were collected from the ‘01/’02 winter.

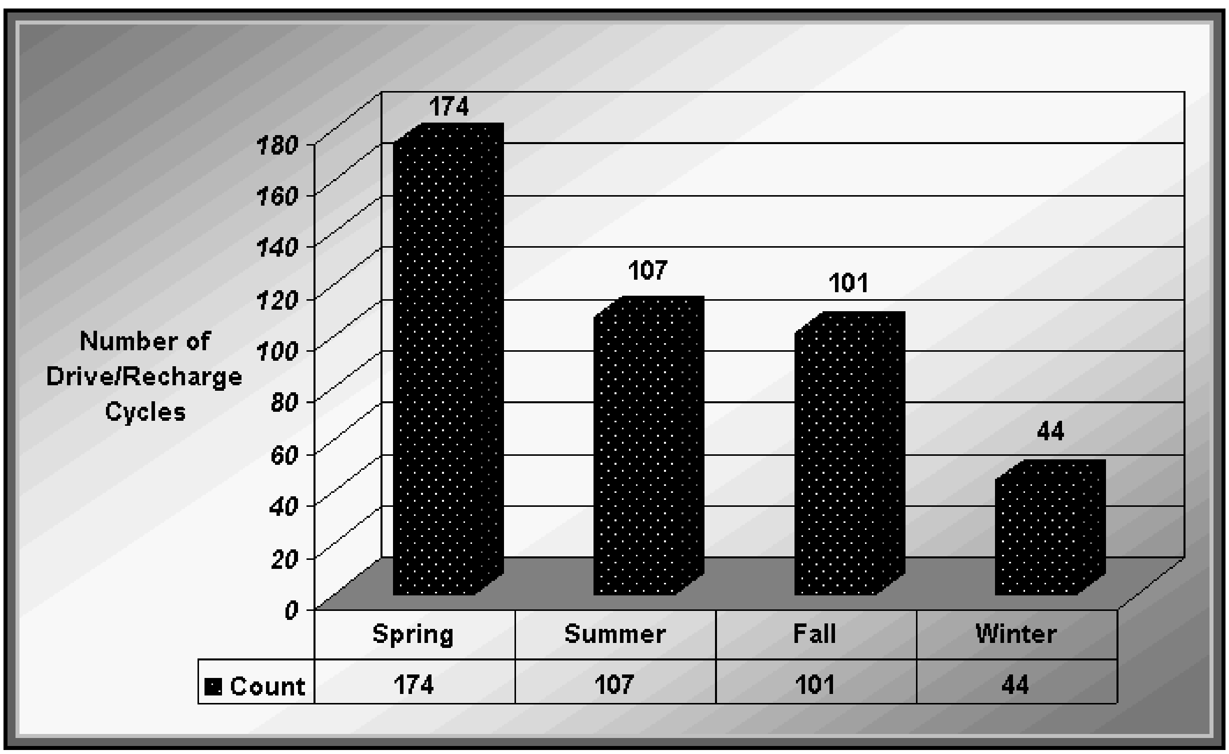


Figure 4. Number of Drive/Recharge Cycles by Season

During the winter of ‘02/’03 the vehicle’s fuel-fired heater/defroster stopped working, so drives were limited to fair weather periods. It was decided to delay heater repairs until the spring of 2003 when the car was scheduled to be taken out of service to receive various other system upgrades. These reasons are responsible for the reduced quantity of winter-season data during the 1999-2003-evaluation period.

The Overall efficiency of the NiCd BEV subcompact, expressed as Watt-hours (AC) per mile over 426 drives and 30,000 miles is shown in Figure 5 as a boxplot. This measure of electrical usage and efficiency is based on the ‘wall-plug’ electricity that was purchased to recharge the battery. The median value, 228 Watt-hours (AC) per mile, is the labeled data point. The average efficiency was 234 Watt-hours (AC) per mile.

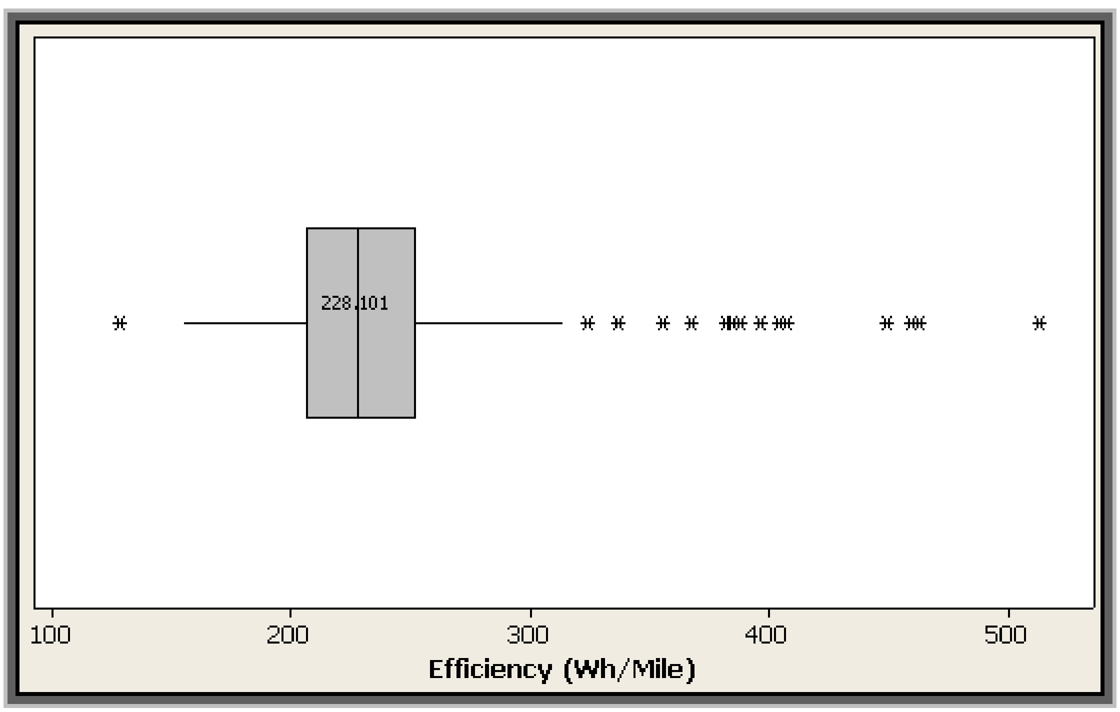


Figure 5. Boxplot of wall-plug efficiency, Wh (AC) per mile

All four years of data are shown in Figure 6, below, for the 426 drives. The overall distribution of drives is displayed in a bar chart on top, while efficiency is shown in the bar chart on the right. One can see from the plot of these drives that efficiencies are not even weakly

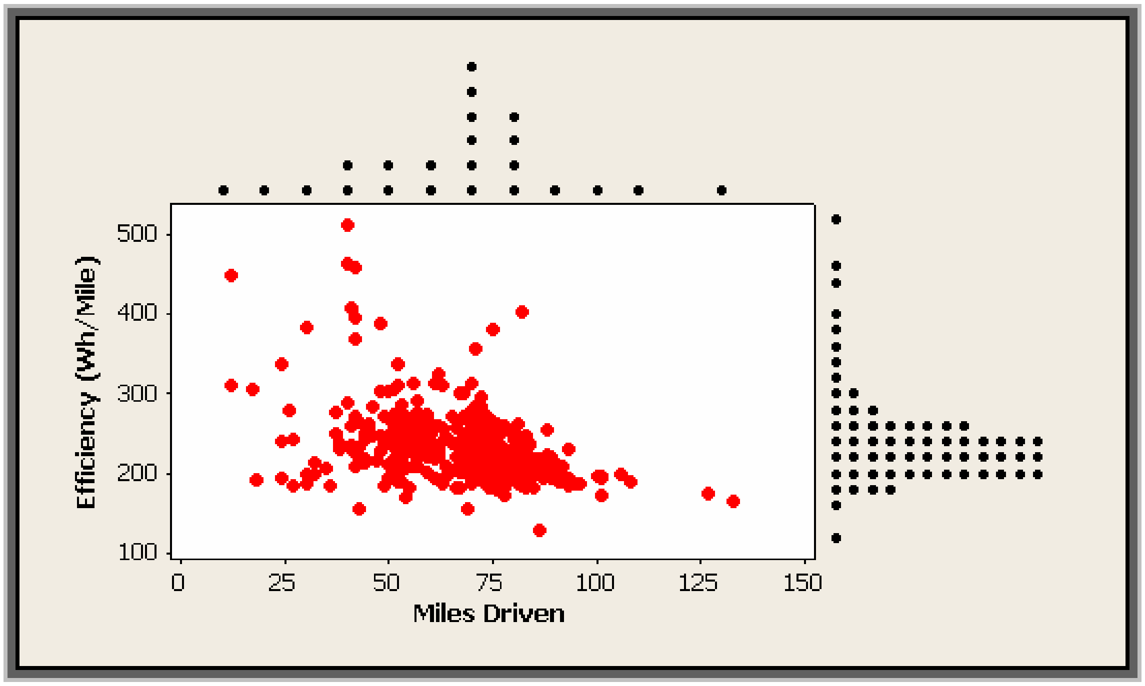


Figure 6. Summary plot of efficiency, Wh (AC)/Mile versus Miles Driven

related to the distances driven. Statistical calculations support this observation, where the R^2 for a linear regression between efficiency and miles driven was only 0.15. (R^2 = 0 means no linear relation)

For NiCd BEV cost-per-mile calculations in this report, we are using the average rate paid in central Connecticut from the 12-month moving average for the period April 2003 to March 2004, which was 12.1¢ per kilowatt-hour. Table 6 shows the NiCd BEV is estimated to save about 51 percent over the fuel cost for a comparable subcompact car, where we used the following assumptions: recent Spring 2004 gasoline price levels in Connecticut of $1.849/gallon for regular unleaded gasoline; representative electricity prices for the same period; driving each vehicle 30,000 miles; US DOE's 'City/Hwy MPG' data for the model year 2000 Geo Metro four-door subcompact; and, 55 percent city and 45 percent highway driving in the gasoline-powered vehicle. The Appendix provides some additional information from the Department of Energy on both historical and recent energy prices in New England.

For further comparison with newer technology, the NiCd BEV is estimated to save 27 percent and 15 percent versus the fuel costs of two 2004 gasoline-electric hybrids, Honda Civic Hybrid and Toyota Pius, respectively. In all fairness, one must remember that an expensive component of the NiCd BEV is the battery pack itself. Later in this study we will have an observation on the life of the battery and at that time we will calculate the capital cost to replace the battery and express that as an additional cost-per-mile element that should be added to the electricity cost to represent the total fuel/energy-storage system. The same method should be applied to hybrid vehicles once their average battery life has been established for them in the Connecticut environment.

Table 6. Comparative analysis using Spring 2004 energy-pricing data

Vehicle Description	Automobile Size	Fuel/Energy Type	MPG City/Hwy	Gal. Gas Req'd	Fuel Cost	Savings with BEV	Percent Savings with BEV
1999 Solectria Force,NiCd	subcompact	156V NiCd BEV			$ 851		
2000 Geo Metro, 1.3 L, auto	subcompact	gasoline ICE	30/34	947	$ 1,751	$ 900	51%
2004 Civic Hybrid, auto	compact	gasoline hybrid	47/48	632	$ 1,169	$ 319	27%
2004 Toyota Pius, auto	compact	gasoline hybrid	60//51	540	$ 998	$ 147	15%

In Appendix C, this comparative analysis is repeated, but with average energy prices from the period 2/99 to 5/03. The results are similar in percentage savings.

Seasonal differences in efficiency of a BEV would be of interest to a fleet manager if it materially affected where s/he could assign the car and where s/he could not, so we will next examine seasonal performance of the NiCd during our 30,000-mile evaluation (see Figure 7).

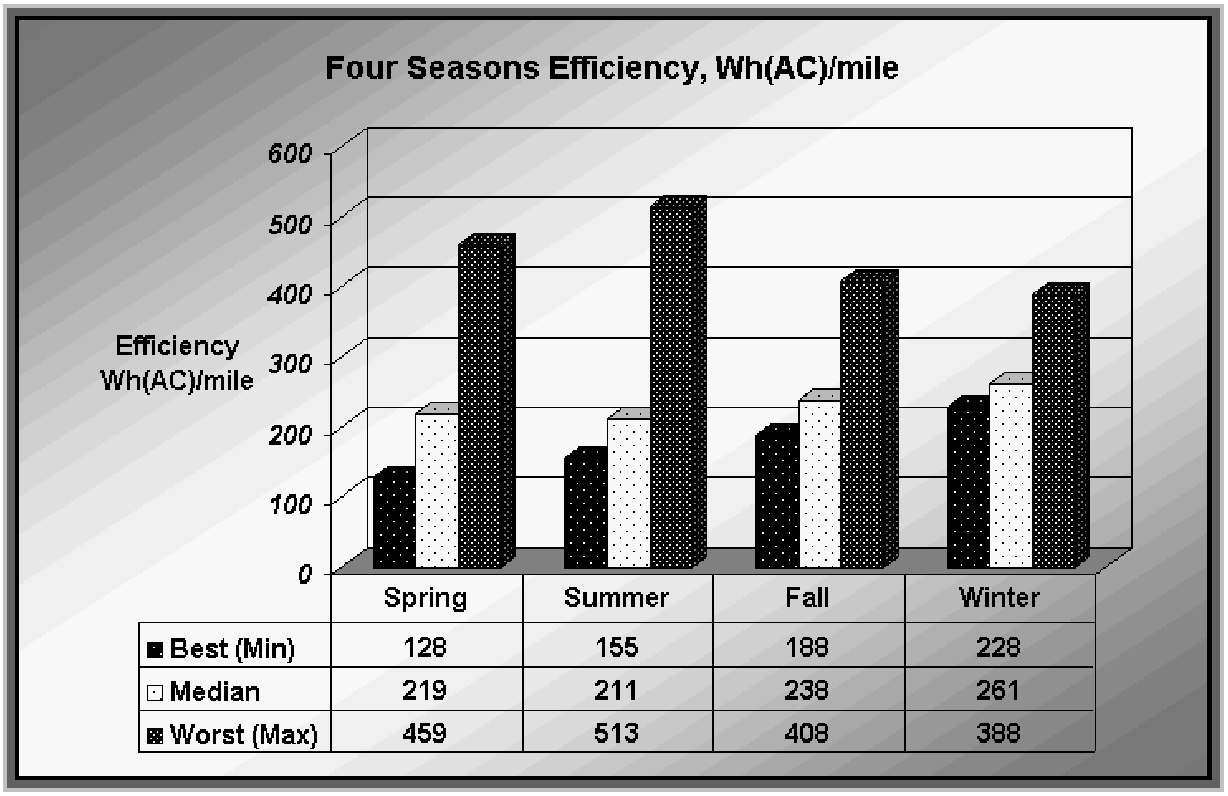


Figure 7. Wall-Plug Efficiency of NiCd BEV by Season

The summer and fall seasons produced energy-usage data for 107 and 101 drives, respectfully. In general, sufficient data were collected to characterize energy-use performance and drive distances by season. The average wall-plug efficiency is most representative of what can be expected from the NiCd BEV versus best and worst data. Spring and summer efficiencies were about the same, while efficiency in the fall was about 13 percent lower than summer and 24 percent lower in winter.

The seasonal electricity costs per mile were calculated using Connecticut's electric rates, as follows: spring = 2.74¢ per mile, summer = 2.72¢ per mile, fall = 2.93¢ per mile, and winter = 3.28¢ per mile.

Battery Charger Efficiency

Limited data are available to define the efficiency of the battery charging system. A Watt-hour meter (DC) was present in the car for forty-seven drive/recharge cycles in 1999. The meter was on loan from the manufacturer and was returned in the fall of 1999.

The basic descriptive statistics for the battery-charger efficiency data are as follows: average battery charging efficiency equaled 61.15%; maximum observed efficiency was 76.5%, while the lowest was 47.4%. From these same data, a relationship between wall plug electricity (Wh, AC) going into the charger and electricity ending up in the battery (Wh, DC) was defined by a regression equation, as shown in Figure 8. The high R-Square value indicates a good relationship, so the algorithm was used to estimate the Wh (DC) in the battery for the remaining 380 charge/drive cycles.

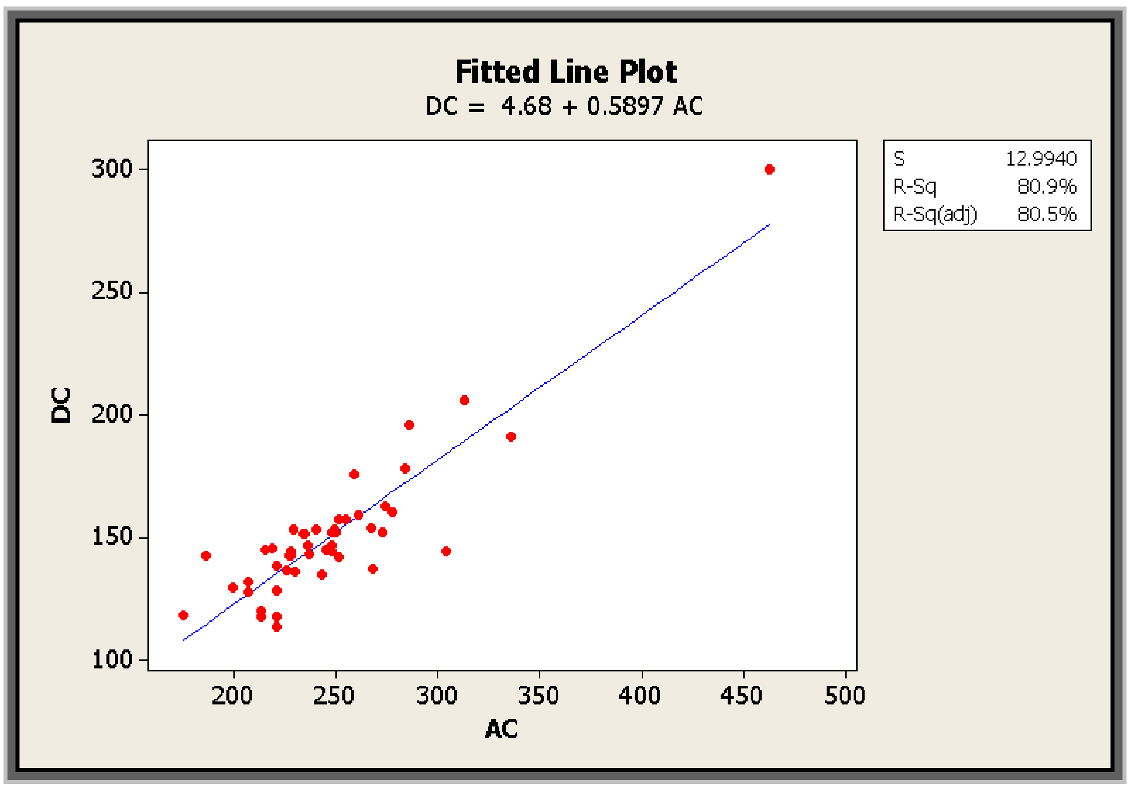
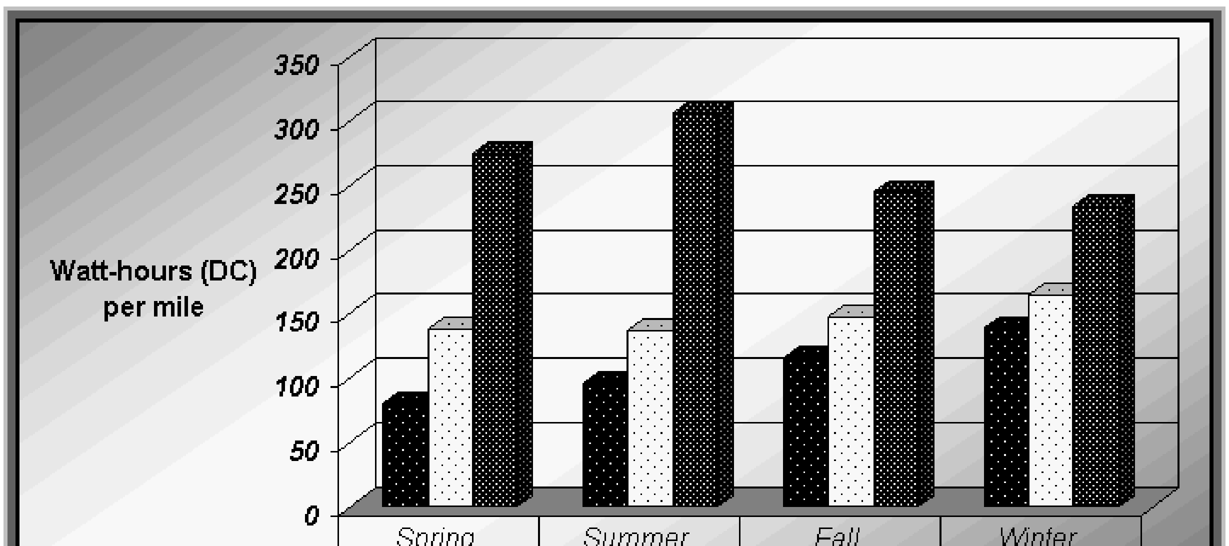


Figure 8. Charging Efficiency Relationship

This linear equation (Figure 8) was used in the following analysis of seasonal driving efficiency as measured by the use of stored energy (Wh, DC) from the battery to operate the car.

Driving Efficiency

The very best driving efficiency was achieved at the weeklong ATdS events in spring 1999 and 2000; however, it is the mean value of efficiency that is the most representative of the vehicle’s seasonal driving efficiency on Connecticut roads. As you can see in Figure 9, the efficiency was about the same in both spring and summer. Efficiency appeared to be approximately seven percent lower in the fall and 20 percent lower in the winter.



	Spring	Summer	Fall	Winter
Best (Min)	80	96	116	139
Mean	139	138	147	165
Worst (Max)	275	307	245	234

Figure 9. Battery/Driving Efficiency by Season

Without measurements of actual charging efficiency in the fall and winter, we can’t be too sure about the accuracy of our statements about cold-weather driving efficiency. We know that some of the lower efficiency happens because energy is required for thermal management of the battery in cold weather. In general, it cost us more electricity to recharge the NiCd battery (or any battery) in cold weather.

Depth-of-Discharge of the NiCd Battery Pack

Depth of Discharge (DOD) data are skewed towards lower DOD values (see Figure 10). The median value is 71.8 percent, while the average value is 68.5 percent. A representative DOD value for the NiCd BEV is 70 percent.

Using 70 percent of the nominal battery pack capacity of 15,600 Wh, i.e., 70 percent DOD, we can calculate the nominal seasonal driving range of the NiCd car. At 70 percent DOD, this equates to a representative 79-mile driving range per charge in spring and summer.

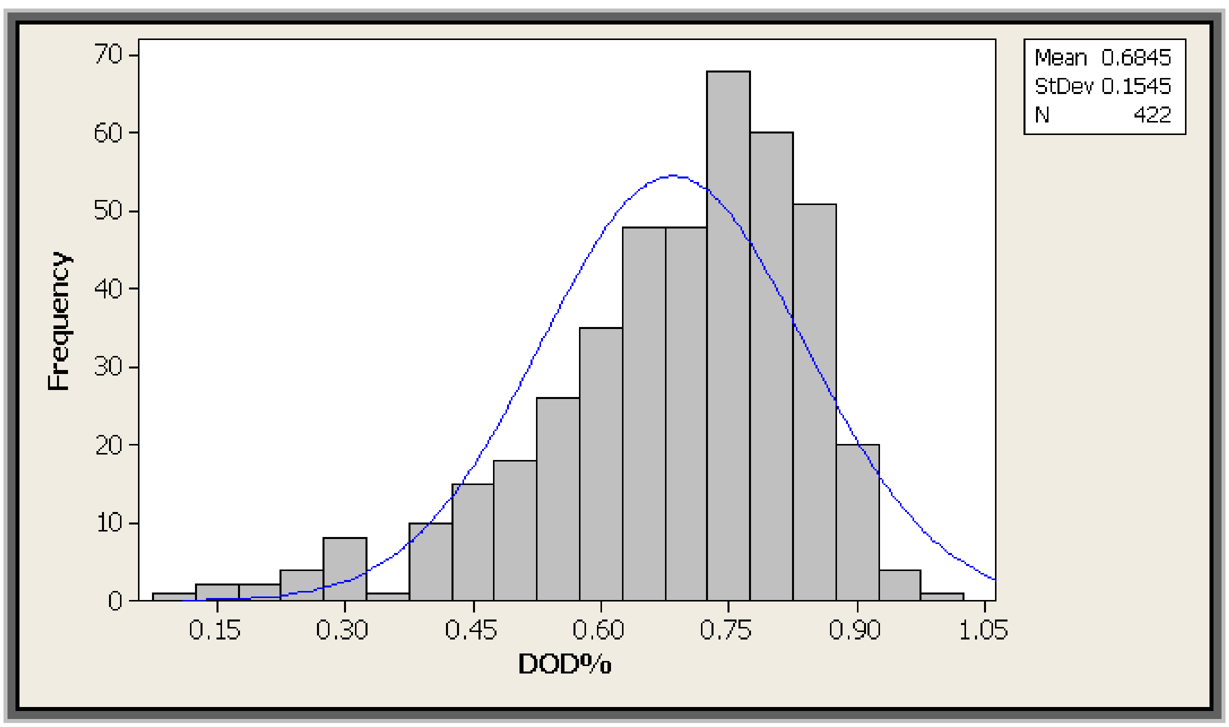


Figure 10. Barchart of Depth-of-Discharge Data from 422 drives/discharges

At the slightly higher average energy usage per mile that we observed in fall (147 Wh (DC)/mile), the representative driving range is reduced to about 74 miles for a 70 percent DOD. In winter, the representative driving range based on an average efficiency of 165 Wh (DC)/mile is about 66 miles. Next, is a discussion of the actual distances the car was driven seasonally.

Seasonal Distances Driven

Statistics on seasonal driving distances were compiled and are presented below in Figure 11 as boxplots together with a mean-connected line.

While drive distances in spring have the widest range and winter driving has the narrowest range, the average distances driven in these two seasons is almost the same (68.1 versus 67.8 miles/charge).

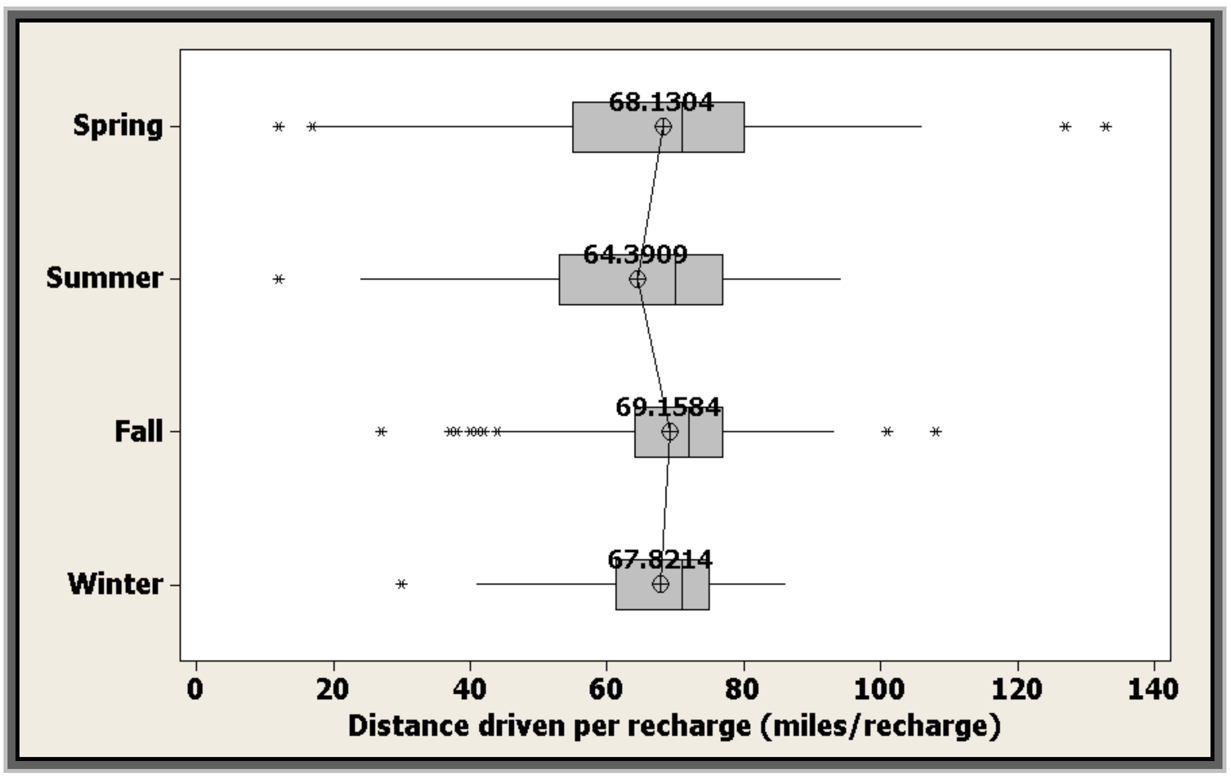


Figure 11. Seasonal distances driven on a single battery recharge

The interquartile range of drive distances in spring and summer is similar, but drive distances in the spring averaged about 4 more miles than in summer. The interquartile range of drive distances in the fall and winter is similar. The median distances driven were very close: spring, 71 (miles/charge); summer, 70; fall, 72; and, winter 71. This reflects the driver's emphasis on demonstrating that the car's range was at least 70 miles on every battery charge.

Seasonal Battery Depth of Discharge

We have seen that the car was realizing an average driving distance in the mid to upper 60 miles daily. We will next look at the energy required from the battery to drive those distances. When the energy use data are separated out into seasons, an energy-use pattern emerges. In Figure 12, below, we see a box plot of the NiCd depth of discharge with the seasonal average values and a mean-connected line.

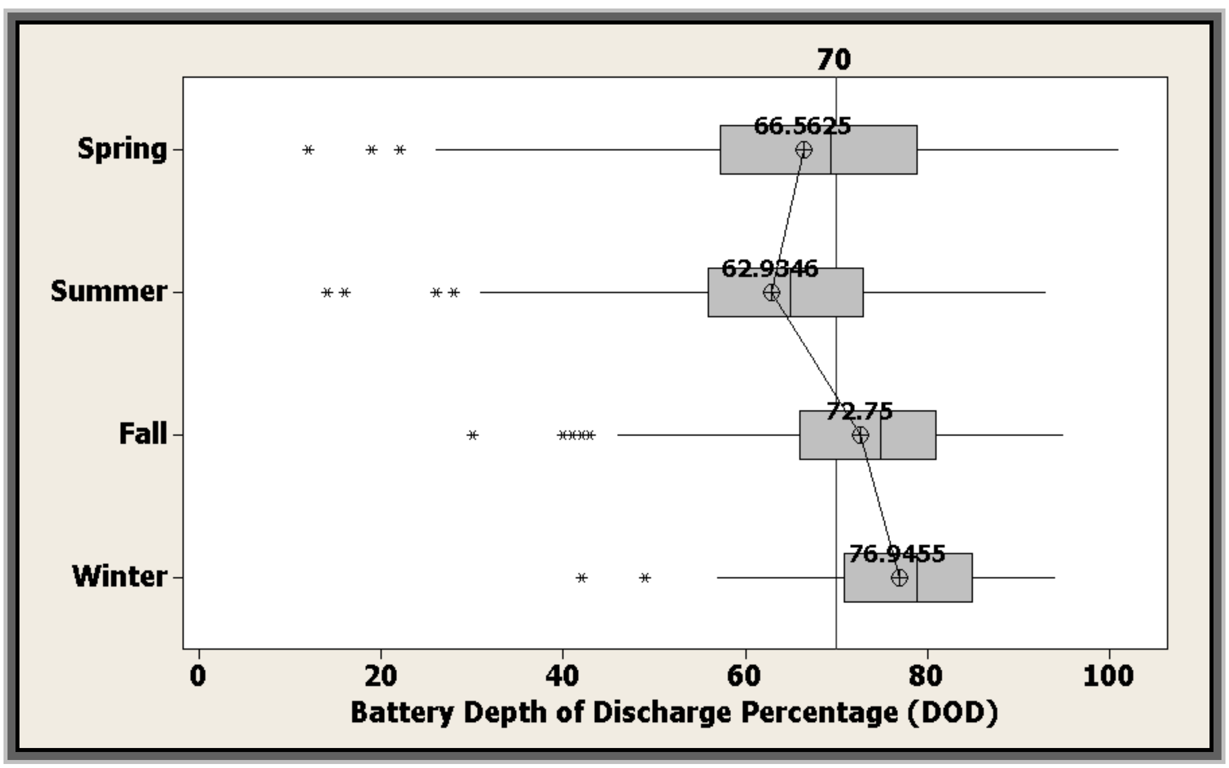


Figure 12. Seasonal patterns in NiCd Depth of Discharge

The nominal 70 percent DOD value is plotted as a visual reference. You can see that generally less power was drawn from the battery in spring and summer, and more power was drawn out of the NiCd battery in fall and winter. Recalling that the average distances driven in spring and fall were about the same, observe that in winter the battery needed to be drawn down on average about 10 percentage points lower than in spring. In general, to provide the 70-mile drive per charge in winter, the battery must be discharged more deeply than in any other season in Connecticut.

Maintenance and Repair

Nickel Cadmium Battery Performance

The nickel cadmium (NiCd) battery was completely reliable during the four-year evaluation period. Very simple battery maintenance was required approximately every 3,500 miles, which required less than two gallons of distilled water. The watering procedure was easily learned and performed by the vehicle operator. Over the 30,000 miles the vehicle was driven between May 1999 and May 2003, the battery pack was watered seven times, requiring a total of 14 gallons of distilled water.

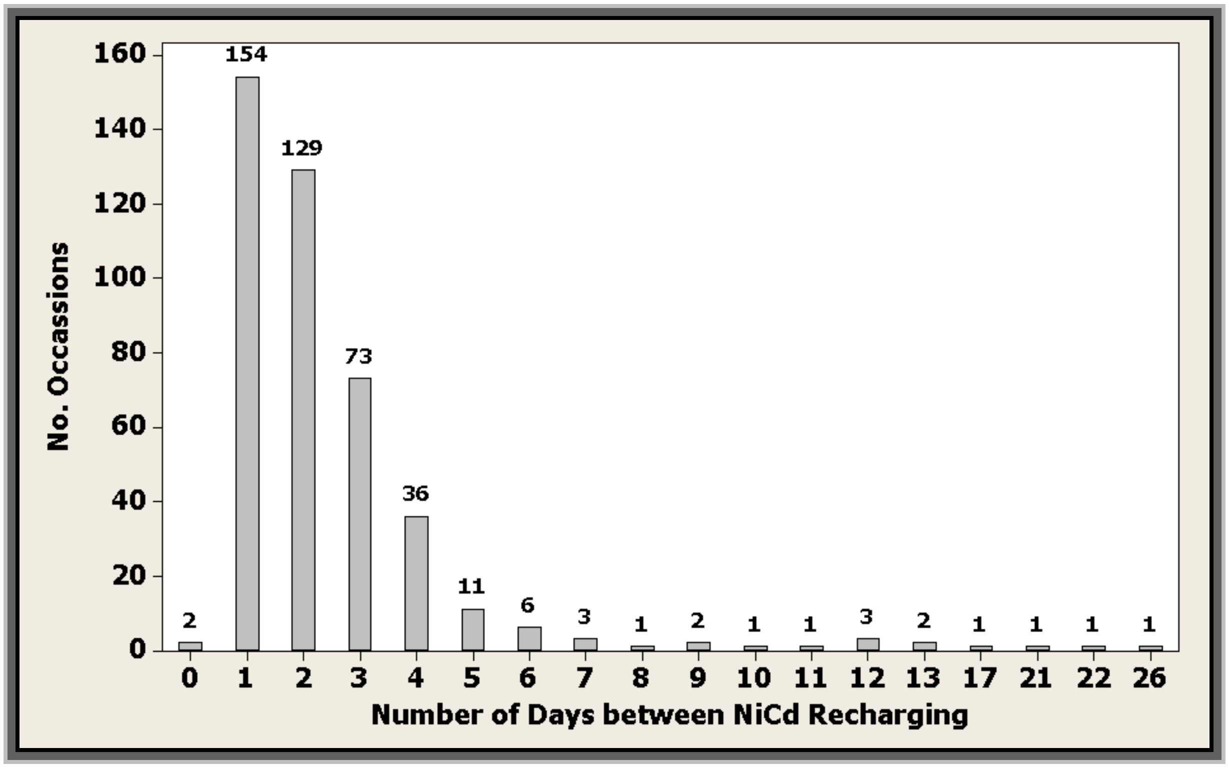


Figure 13. Distribution of Recharging Frequency over four years (428 total occasions)

While a freshly charged NiCd-powered BEV could be expected to provide a range of at least 70 miles in Connecticut year-round, the same car could be driven and parked and driven some more and parked and driven some more and parked and driven some more, etc., and finally recharged after several days; and, the car could reliably and repeatedly be driven in this fashion. This was true year-round, and so the car appears to have operational characteristics that would be desirable for fleets. In Figure 13, the recharge statistics are shown for the entire four-year period. On 154 occasions out of 428 drives (36 percent of all drives), the car was driven one day before recharging the battery. On 129 occasions (30 percent of all drives), the car was driven for two days before recharging. On 73 occasions (17 percent of all drives) the car was driven for 3 days before recharging the NiCd battery. On 36 occasions (8 percent of all drives), the car was driven over a four-day period before being recharged.

Below, in Figure 14, are pie charts showing the number of days between battery recharges within each season. In the spring, summer, fall, and winter, the car was driven one day before recharging the battery on 45, 35, 32, and 20 percent of their respective seasonal drives. In the spring, summer, fall, and winter, the car was driven two days before recharging the battery on 31, 29, 34, and 23 percent of their respective seasonal drives. In the spring, summer, fall, and winter, the car was driven three days before recharging the battery on 13, 14, 18, and 34 percent of their respective seasonal drives. The high percentage for three-day drives in winter reflects the difficulties with the heater/defroster, which are described later in this report. In the spring, summer, fall, and winter, the car was driven four days before recharging the battery on 6, 11, 10, and 9 percent of their respective seasonal drives. The car was driven five days before recharging the battery on only 5 occasions in spring, 4 occasions in summer, and one occasion each in fall and winter seasons over the four year evaluation period. Most of the rest of the drives were single occurrences of different periods ranging up to a 21-day period in spring, 12-day period in summer, 26-day period in fall, and 22-day period in winter. The NiCd performed well under all these recharge intervals.

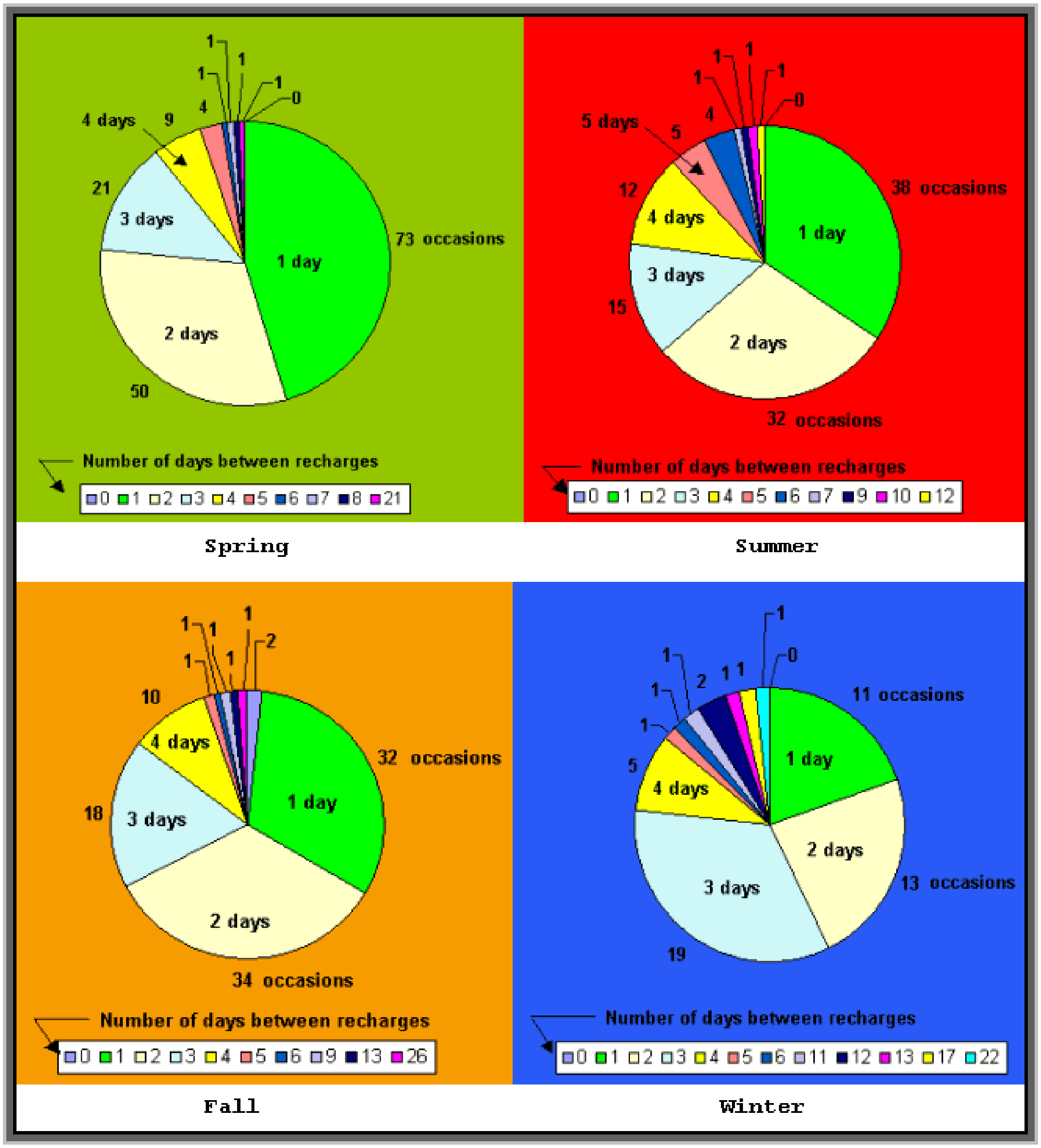


Figure 14. Seasonal Patterns for Number of Days between Recharges
(Spring = 161 charges, Summer = 110 charges, Fall = 101 charges, Winter = 56 charges)

Another desirable characteristic of the NiCd was its good performance in cold weather. Unlike other batteries such as lead acid and nickel metal hydride, the NiCd did not lose appreciable capacity in cold weather. The NiCd was observed to have a low ‘mid-drive’ self-discharge rate, even when the car was parked (unplugged) for hours or even several days. We had no difficulty driving the car day after day for 70 miles per recharge throughout the winter months. The same cannot be said for lead acid and nickel metal hydride BEV’s we have evaluated. /1/

A third desirable feature of the NiCd battery is a storage characteristic. During the periods in this evaluation when the car was out of service for months at a time, no damage or capacity losses in the NiCd were observed as a result of sitting parked and unplugged for those extended periods. In every case, once repairs were completed and the car was ready to return to service, the battery received a re-initialization charge and was ready to return to daily ’70-mile-per-charge’ service. This is again a desirable characteristic for fleets where there are always vehicles parked in reserve or waiting repairs of one type or another.

Electric Drivetrain, Brakes and Wheel Alignment

The electric motors, gearboxes, motor controllers, regenerative brakes, and other components unique to the battery/electric cars were very reliable in the NiCd car we drove during the four-year period. No service of any kind was required for these components.

No service was required for the conventional braking system on the NiCd BEV subcompact over the 30,000 miles of driving. Brake checks were performed when the car was scheduled for front wheel alignment checks. The front wheels were aligned at the beginning of the evaluation period; were checked once again in the spring of 2000 (no adjustment needed); and, after completion of the four-year evaluation period. After 30,000 miles, mechanics reported that very little brake wear had occurred and no brake service was required.

Seven Problem Areas Observed

Four of the seven problem areas contributed to downtime for the NiCd BEV subcompact. Reliability shortcomings were almost exclusively in the area of battery recharging and battery thermal control systems. One additional problem relates to a driver/passenger satisfaction issue. Lastly, researchers experienced two additional problems that were related exclusively to electric-car data acquisition for the study.

Firstly, a recurring problem that plagued the car over the four-year period was battery charging during hot summer days. At temperatures above 80˚F the microprocessor-controlled charging/battery cooling system would not recharge the battery. Charging was initiated by the automatic system only after ambient air temperatures dropped below 80˚F, which during the summer in central Connecticut generally occurred sometime between 11:00 p.m. and 1:00 a.m., after which the normal battery recharge occurred. On a few occasions each summer the charge would not be completed by 7:30 a.m., the time that the car was required for the morning commute. On those occasions, the vehicle was left plugged in to complete its charge and another vehicle was utilized for transportation. The battery cooling system design was based on a radiator and fan to chill an antifreeze solution that circulates through cooling jackets in the forward and rear battery compartments. Under hot summer temperatures, there was an insufficient difference in temperature between ambient air and battery temperatures so there was an insufficient thermodynamic force to effect cooling of the battery. Ultimately, no satisfactory solution to summertime temperatures was identified during the four-year evaluation (see Findings).

The second problem occurred twice during 2001. The ‘smart charger’ blew its internal fuse. The first blown fuse happened on May 24, 2001, and kept the vehicle out of service for 20 days. The second happened on November 7, 2001, and kept the vehicle out of service for 13 days. The positive element of these two occurrences was that the fuse protected an expensive battery charging system. The negative element was that the ‘smart charger’ had to be removed from the car and shipped to the manufacturer for replacement of the internal fuse (soldered connections), because only trained personnel were allowed to make the repair. The explanation given was that an electric shock was possible during the replacement of the internal fuse. There was no cost associated with these warrantee repairs.

A third problem developed on July 12, 2002, when electric cabin heat turned on itself during battery recharging and drained the battery. The heater on/off switch was definitely in the OFF position. I checked the cabin-preheat computer to be sure it had not been inadvertently turned on; it was definitely OFF. I do not know why this occurred, but ultimately, the 60-Amp fuse in the electric heater circuit was simply removed every time the car was being charged and almost every time the car was parked to prevent reoccurrences. On several occasions when the fuse was not removed while the car was parked and unplugged during the day, battery discharge occurred that reduced the remaining available driving range by as much as twenty miles. However, at no time, was the remaining range reduced to a point where it prevented completion of a required drive to a recharging facility.

A fourth problem occurred on November 8, 2002, when the fuel-fired heater stopped working. For the remaining six-month evaluation period, the car did not have operable cabin heat or front windshield defrosting. The front electric seat warmers worked, and it was decided to continue driving the car and acquiring data as weather conditions allowed. During days when precipitation or low daytime temperatures were forecast, the car remained parked. Ultimately, the fuel-fired heater was repaired under warrantee during the vehicle retrofit that followed this study phase.

A driver/passenger satisfaction problem was poor radio reception in the BEV subcompact. Electro magnetic fields (EMF) in the radiofrequency range are especially disruptive for AM radio and to a much lesser extent for FM radio. Based on our prior experience with three different types of motive batteries in the same model BEV subcompact, where all three cars had severe AM radio interference, we observe that the problem is not related to the type of battery, and therefore, the problem does not reflect on NiCd performance in particular. The NiCd vehicle had a manufacturer-installed EMF shielding sleeve in the motor compartment, but it was not effective.

A study-data-acquisition problem was the lack of a sophisticated data system to acquire data for this study. Although manual data recording did provide sufficient information to prepare this report, the data on seasonal charging efficiency was weak, and we have no information about energy usage in the car as it is being driven such as for heated seats, defroster, cabin heat, wipers, headlights, etc. The lack of more detailed energy-use data also limits the type and kind of suggestions for future improvements in the NiCd BEV.

A second study-data-acquisition problem was most unfortunate and should not reflect negatively on the performance of the NiCd car. It occurred during a 106-day period in 2000 (see earlier Figure 2, Period B). This problem was eventually identified in the wiring of an auxiliary energy-use meter that was added to gather data for this project. The problem was manifested in the battery-charging system and affected performance during the period April 2000 to August 2000. A gradually increasing battery-undercharge condition developed. The battery-charging control program algorithm was not receiving correct amperage data inputs for its calculations. By July 7, 2000, the charger was undercharging the battery pack to a degree that noticeably reduced the driving range of the car. The single-charge driving range declined to below 70 miles per charge in early July 2000. For example, on July 7, 2000, after driving off 71 Ah, both 'low voltage' and 'limp-home mode' conditions were triggered, ending the drive. The declining range problem was reported to the manufacturer and a technical representative evaluated the situation in August 2000. The vehicle was removed from service and transported to the manufacturer for troubleshooting on August 8, 2000. What followed was a three-month delay in paperwork to authorize the repair work, and a four-month period of troubleshooting by the manufacturer, before the problem was traced to a newly installed battery monitoring device, a DC watt-hour meter, which was found to have been installed (wired) incorrectly during period B (periods are defined in Figure 2). The incorrect wiring bypassed the current measurement device and lead to cumulative electrical measurement errors in the computer-controlled battery-recharging system. Initially, this resulted in a slight undercharge of the battery pack. Over six months of driving and recharging, as the cumulative undercounted amperage values grew in the memory of the 'Smart Charger,' the problem worsened. Repairs to the wiring were completed and the car was again ready to go back on the road. The vehicle was returned and we resumed our on-road evaluation on February 15, 2001.

Findings

The nickel cadmium (NiCd) battery was completely reliable during the four-year evaluation period. Very simple battery maintenance was required approximately every 3,500 miles, which required less than two gallons of distilled water.

The seasonal electricity cost per mile to drive the NiCd BEV were calculated using representative Connecticut electric rates (12.1 ¢/kWh), as follows: spring = 2.74¢ per mile, summer = 2.72¢, fall = 2.93¢, and winter = 3.28¢. If an average national electric rate were used, the costs per mile would have been lower. For conventional Geo Metro subcompact assuming 30/34 mpg (DOE efficiency in 2000) and gasoline costing $1.859 per gallon, the cost per mile for a comparable gasoline subcompact would be 5.86¢/mile for fuel.

The nominal seasonal driving range of the NiCd car at 70 percent DOD (percent battery drawdown before recharging) equated to the following nominal single-charge ranges: spring = 79 miles per charge (MPC); summer = 79 MPC; fall = 74 MPC; and, winter = 66 MPC. To deliver the 70 MPC in winter, the battery was drawn down further than in the other three seasons, i.e., the average DOD was about 10 points higher than in the spring for the same distance driven.

To reach 30,000 miles of driving, the 100 Ah NiCd batteries have delivered a combined 428 partial and complete cycles. The manufacturer claims that the battery should provide at least 600 cycles and perhaps as many as 1,000. During the next phase of this evaluation, it is anticipated we will reach and report on the total lifespan of the NiCd battery pack.

In this project, we found marketing claims of both the electric car and NiCd-battery manufacturers have been fairly accurate as applied to Connecticut. It is unlikely that a fleet manager will make decisions about the acquisition of BEVs for the fleet based solely on manufacturers’ claimed performance and warrantees. Prudent decision-making will likely involve careful assignment of BEVs to daily driving missions that are well within the vehicles' capabilities and close monitoring, thereafter, to build experience.

Table 7. Comparison of Observations on BEV Cars in Connecticut

Vehicle Battery Type	Conventional Sealed Lead Acid (CSLAB, 156V)		Nickel Cadmium Battery (NiCd, 156V)	
Motor Vehicle Registration Number	CT:EV-2		CT:EV-1	
Evaluation Years	1995, 1996		1999 - 2003	
Battery Capacity, Ah	50		100	
Battery Capacity, kWh	7.8		15.6	
Time of Year	Winter Months	Spring, Summer, Fall Months	Winter Months	Spring, Summer, Fall Months
Anticipated Driving Range	<50[1]	50	>=70	>=70
Observed Driving Range, miles	~30[1]	~40	>=70	>=70
Nominal Range at 70% DOD, miles	N/A	N/A	66	79,79,74
Observed Median Range, miles	N/A	N/A	71	71,70,72
Observed Average Range, miles	N/A	N/A	67.8	68,64,69
Cost/mile for electricity at $0.121/kWh (CT rate)	6.85¢[1]	3.425¢[2]	3.28¢	2.74¢, 2.72¢, 2.93¢
Battery Cost per mile (between 'pack' replacements)	11¢ to 19¢[2]		TBD later in this study	

NOTES to Table 7:

[1] Range in winter varied inversely with use of accessories (electric heater/defroster, rear-window defroster, windshield wiper, headlights). Also, at low ambient temperatures, battery is anticipated to be less efficient. Cost/mile is higher in winter that summer due to use of these electric accessories.

[2] Data provided by Rideshare from Connecticut Commuter Electric Vehicle Demonstration (CCEVD) project. Average economy in spring, summer and fall months was 0.287 AC kWh/mile. Capital cost/mile based on experience with four CSLAB cars and CSLAB replacement cost per pack. Distances driven in the four CSLAB cars on their battery packs were from 11,300 to 22,100 miles over 24 to 32 months.

The on-board charger was beneficial because it provided the driver with greater locational versatility when the battery required recharging, because the electric car was equipped with common extension cords and electrical adapters. Also, opportunity charging could occur at a variety of unplanned locations if required.

Recommendations

It is recommended that the batteries in the NiCd car, with 30,000 miles of use over four years so far, remain in service for a second phase of driving and data acquisition in Connecticut driving situations. The car should be operated until the NiCd battery pack reaches its end-of-life. For a life cycle cost analysis, the project will then be able to document the cost and level of effort to change the battery pack.

Expand the NiCd Car Evaluation

By the fall of 2000 it was apparent that the NiCd vehicle was showing promise as a potentially practical fleet vehicle that might be able to provide year-round 70+ mile driving range at a lower cost per mile than other battery technologies available at that time. Therefore, it was decided to expand the evaluation of the NiCd subcompact. Rideshare agreed to provide two additional electric subcompact cars. A research project modification was developed to add two cars to project. The two Rideshare cars were the same year, make and model as the NiCd BEV in this study, but with lead-acid batteries, 110V battery charger, and an older drivetrain (belt drive). The plan called for the two cars to be retrofitted to match the NiCd-powered BEV. Three NiCd vehicles were anticipated to result in data and observations from a greater range of drivers and driving situations, which would result in findings that were anticipated to have greater credibility.

During ConnDOT’s retrofitting work on the cars, it was anticipated that the seven problem areas identified during this 30,000-mile evaluation could be addressed through engineered changes to the vehicles. Additionally, if one or two additional 6-Volt NiCd batteries could be added to the pack, then the winter DOD values would be closer to, or below, 70% for 70-miles-per-charge drives. Also, an improved monitoring and study-data-acquisition system could be added to the cars. Once completed, a second phase of driving and data collection would commence to accumulate experience and observational data for completion of the project.

Don’t Explore Further a Supercapacitor for Supplementary Energy Storage

Additionally, the modified project scope incorporated an optional evaluation of a super capacitor energy buffer between the regenerative brakes and the battery pack. ConnDOT personnel were following the progress of research work by EVermont, done in cooperation with Solectria, on a BEV subcompact fitted with a supercapacitor./5/ In the EVermont car, the supercapacitor entirely replaced the battery. Early progress reports were encouraging, but after reading the final evaluation report and speaking with both the principal investigator at EVermont and engineers at Solectria, the idea of converting one of Connecticut’s cars to use a supercapacitor was subsequently discarded. From an energy-storage perspective, the supercapacitor performed better than batteries in some driving situations, but worse in others. On balance, the state-of-the art supercapacitor appeared to lack significant energy storage advantages over a NiCd, and the supercapacitors took up too much space in the car (filled up the trunk), which reduced the practicality of the car in a fleet application. It is recommended that at this time, this project not explore further the use of supercapacitors for supplementary energy storage.

Explore a Fuel Cell for Supplementary Energy

At the time the decision was made to add two NiCd cars to this project for the next phase of the evaluation, the possibility of exploring the addition of a small fuel cell to the BEV was discussed. If a small, practical, affordable fuel cell with safe, manageable fuel became available, the ConnDOT and Rideshare should consider the future integration of a fuel cell to supplement the NiCd battery pack and extend the driving range of the vehicle to accommodate a larger percentage of the fleet’s daily round-trip drive needs.

References

1. Sime, James M., “Evaluation of Electric Vehicles as an Alternative for Work-Trip and Limited Business Commutes,” ConnDOT Report No. FHWA-CT-RD-343-30-99-1, December 1999.

2. Berg, Mark R., “The Potential Market for Electric Vehicles: Results from a National Survey of Commercial Fleet Operators,” Transportation Research Record 1049, 1985.

3. Consumer Reports, “Small, Cheap Cars,” Consumer Reports, September 1995, PP 614-619.

4. M. J. Bradley & Associates, “Advanced Battery Management and Technology Project, Executive Summary,” Vermont Electric Vehicle Demonstration Project, Vermont Agency of Natural Resources, Northeast Alternative Vehicle Consortium Agreement No. NAVC1096-PG009524, September 20, 1999.

5. Wright, Gregory, Garabedian, Harold, Arnet, Beat, and Morneau, Jean-Francois, “Integration and Testing of a DC/DC Controlled Supercapacitor into an Electric Vehicle,” EVS18 Conference, October 2001.

Appendix A

Lead Acid Battery-Electric Vehicle Background Information

This section reports some highlights from an earlier Rideshare evaluation of four lead acid BEV subcompact cars.

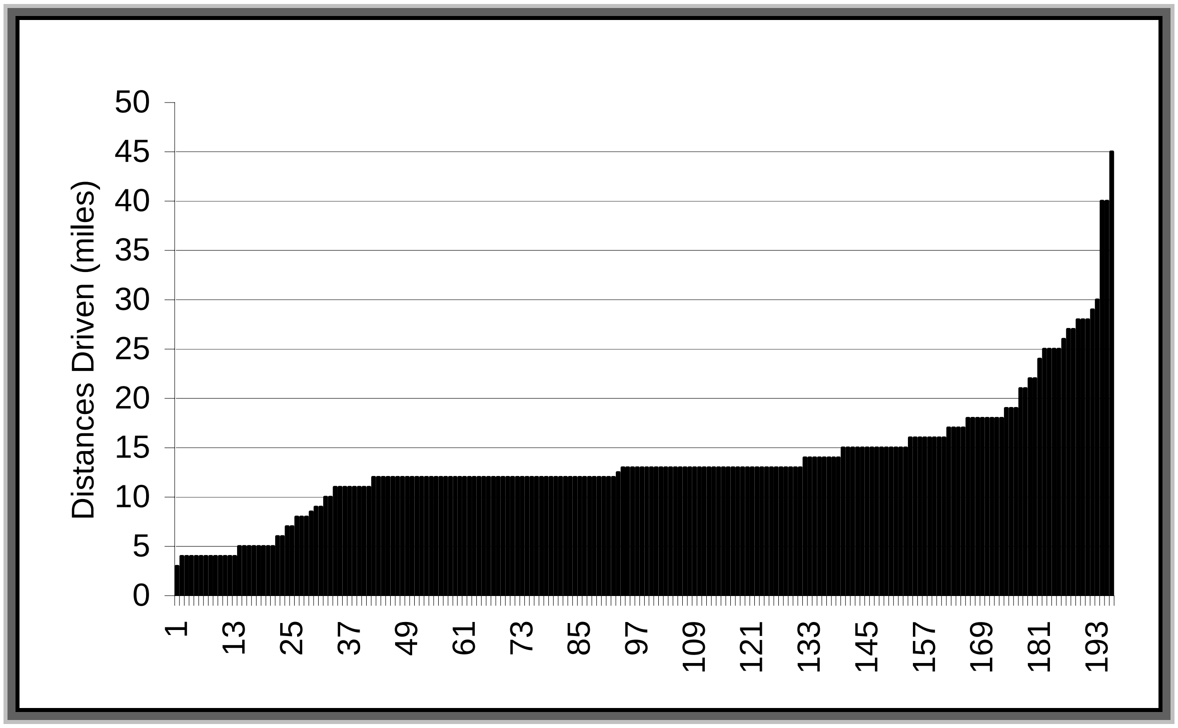


Figure 15. Single-charge distances from 196 drives in CSLAB Cars during winter of 1995/1996

Figure 15 shows the record of 196 single-charge drives in four Conventional Sealed Lead Acid Battery (CSLAB) electric subcompacts, from November 7, 1995, to March 29, 1996. The average distance driven was 13.6 miles between charges, which was the approximate one-way commuting distance for the two-person car pool. The shortest drive was three miles. The longest drive on a single charge was 45 miles. Researchers followed the manufacturer's recommendation that the CSLAB car be plugged in whenever the car was parked. This procedure is called "opportunity charging."

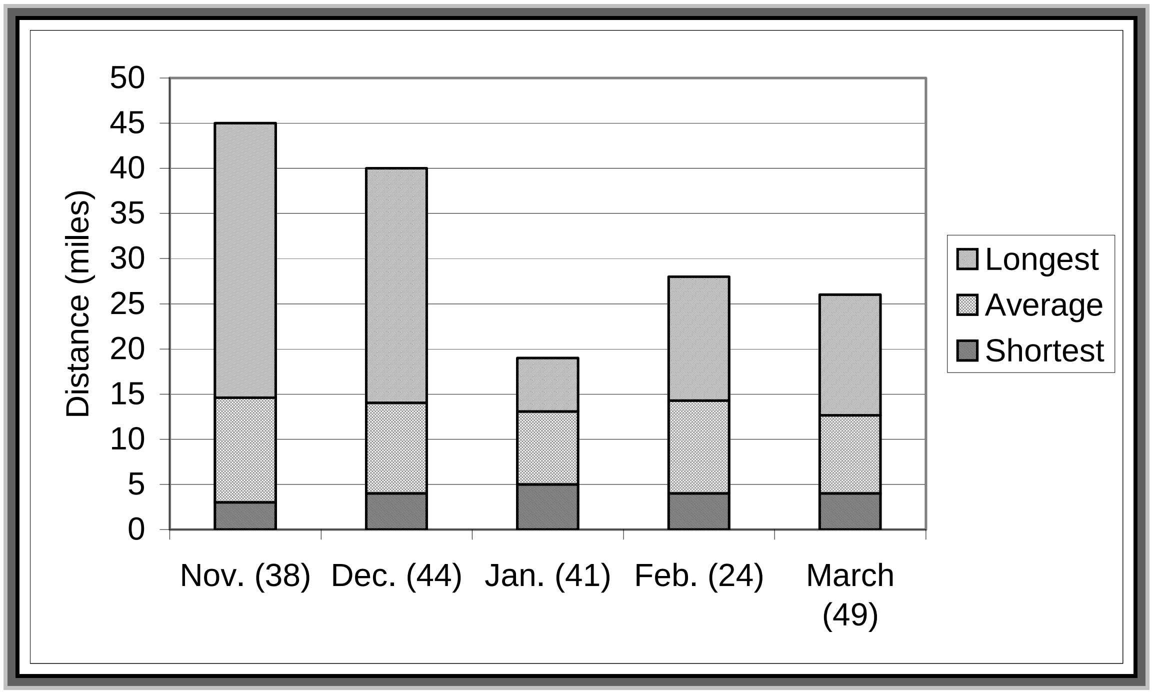


Figure 16. Monthly distribution of 196 single-charge drives in CSLAB cars during winter of 1995/1996

The number of drives in each month is shown in parentheses (Figure 16). In all, the cars were driven 2,828 miles in cold weather. The electric heater was used on 125 of the 196 drives. Electric windshield wipers were used on 28 drives and electric lights were run on 31 drives. Energy was measured with a separate AC kWh meter at the point where electricity entered the cars. The energy consumed during this winter period was 1,582 AC kWh, which is the total “wall-plug” energy used for motive power plus all automobile accessories. Based on a $0.106/kWh utility rate in Connecticut at the time, the retail cost for electricity was approximately $0.06/mile driven. At the lower national average cost of electricity of $0.086/kWh, the cost of electricity per mile calculated to $0.05/mile.

Appendix B

Energy Policy and Conservation Act of 1992 (EPACT)

In Connecticut, the State Department of Administrative Services is responsible for the state central vehicle fleet. It is comprised of approximately 4,041 vehicles, which are primarily automobiles and light trucks. Vehicles are assigned to each state agency. This fleet includes over 500 emergency vehicles, and most of these are full-size cars assigned to the Department of Public Safety.

To comply with federal regulations resulting from the federal Energy Policy and Conservation Act of 1992 (EPACT), the Connecticut State fleet manager began purchasing non-emergency automobiles (cars) and light trucks that run on alternate fuels (Alt-Fuel), which are fuels other than gasoline or diesel. EPACT requires 75% of new vehicles purchased for the State fleet since 2001 to operate on an alternate fuel.

Under EPACT, one fleet-vehicle option is the battery-electric vehicle (BEV). BEVs are anticipated to provide three benefits as compared with cars powered by the internal combustion engine: (1) reduced airborne emissions (improved urban air quality), (2) reduced energy consumption per vehicle mile traveled, and (3) reduced use of petroleum and dependence on foreign oil.

Appendix C

Fuel Costs in New England and Electricity Costs in Connecticut

In this report, 12.1 c/kWh and $1.849/gallon were used to translate energy usage data into economic costs that would be understandable to the reader and would support future economic analyses. Those values are representative of energy costs at the time the report was being written, not of past energy prices because it is believed that current prices are more indicative of future prices and have greater relevancy in decision-making.

For completeness, regular conventional retail gasoline prices in New England are presented below in Figure 17. The data were published by the Federal Department of Energy.

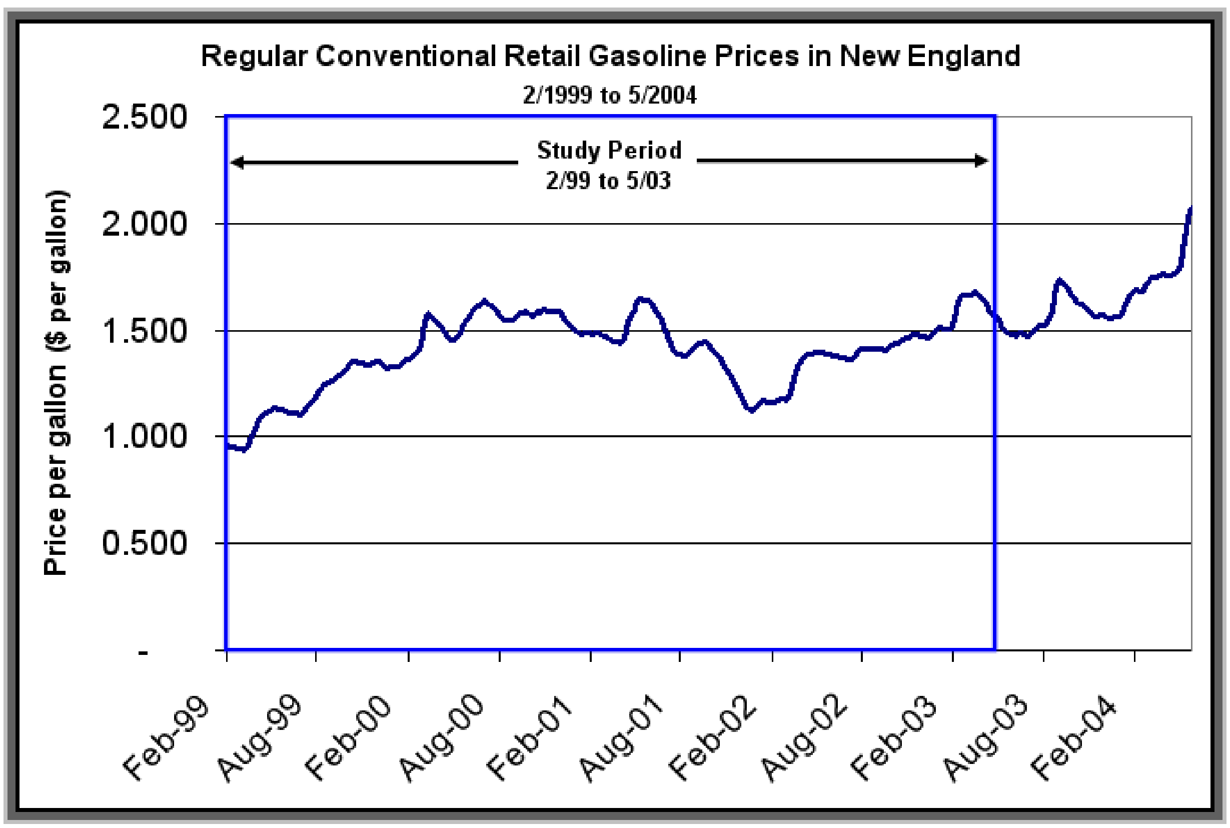


Figure 17. Federal Department of Energy data on gasoline prices

From February 1999 to May 2003, the average cost of a gallon of gasoline was $1.403 in New England, with prices ranging from $0.936 to $1.68 per gallon (See Figure 17). These data were obtained from the Department of Energy Web site at http://www.eia.doe.gov (PSWRGVWRNE.xls).

Average electricity rates, expressed as cents per kilowatt-hour are presented in the graph below (see Figure 18). These data were obtained from information published by the Federal Department of Energy.

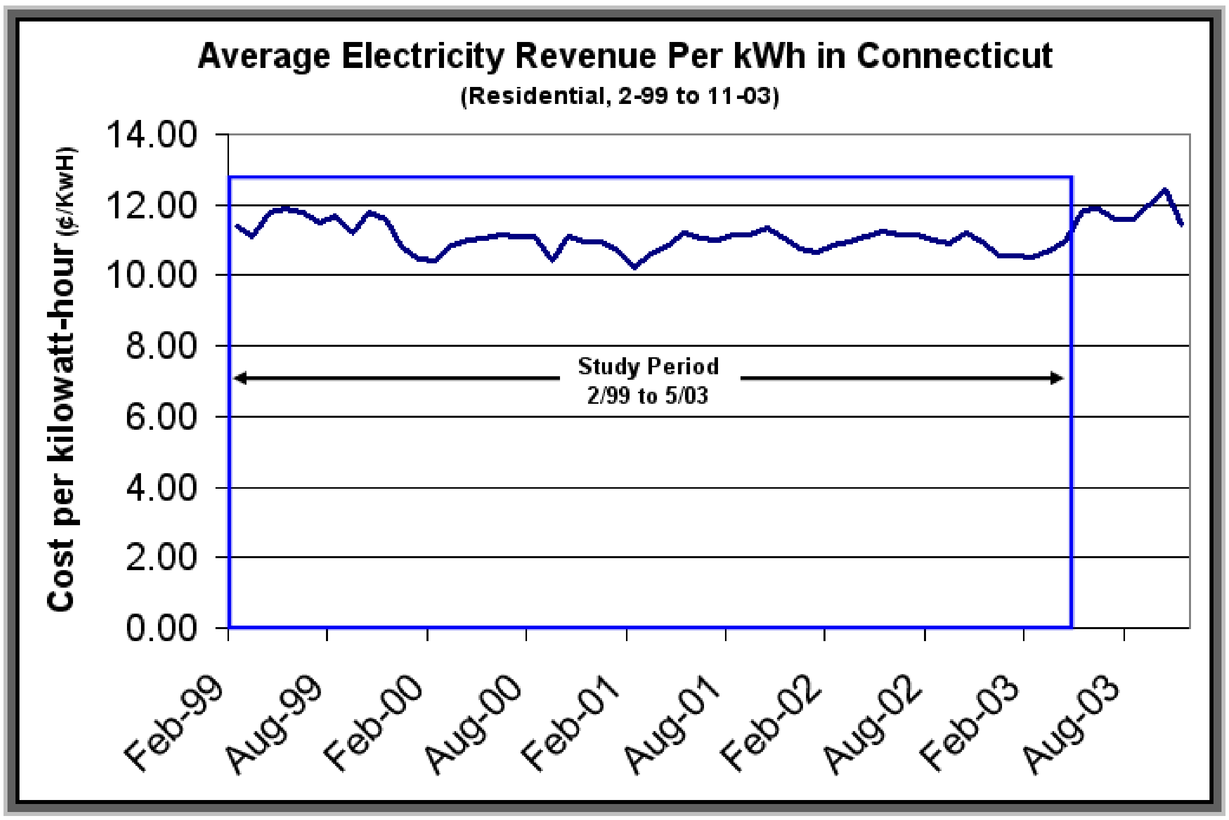


Figure 18. Federal Department of Energy data on electricity prices

From February 1999 to May 2003, the average cost per kilowatt-hour of electricity in Connecticut was 11.0¢, with prices ranging from 10.23¢ to 11.91¢ per kilowatt-hour. These data were also obtained from the Department of Energy Web site at http://www.eia.doe.gov.

Using the values of $1.403 per gallon for gasoline and 11.0¢ per kilowatt-hour for electricity, the following economic analysis was performed for the period 2/1999 to 3/2003 (see Table 8).

Table 8. Comparative analysis using DOE energy-pricing data for period 2/99 to 3/03

Vehicle Description	Automobile Size	Fuel/Energy Type	MPG City/Hwy	Gal. Gas Req'd	Fuel Cost	Savings with BEV	Percent Savings with BEV
1999 Solectria Force,NiCd	subcompact	156V NiCd BEV			$ 773		
2000 Geo Metro, 1.3 L, auto	subcompact	gasoline ICE	30/34	947	$ 1,751	$ 978	56%
2004 Civic Hybrid, auto	compact	gasoline hybrid	47/48	632	$ 1,169	$ 396	34%
2004 Toyota Pius, auto	compact	gasoline hybrid	60//51	540	$ 998	$ 225	23%

Table 8 shows the NiCd BEV is estimated to save about 56% over the fuel cost for a comparable gasoline-powered subcompact car, where we used the following assumptions: average historical gasoline price levels for the period 2/99 to 5/03, average historical electricity prices for the same period; driving each vehicle 30,000 miles, US DOE's 'City/Hwy MPG' data for the model year 2000 Geo Metro four-door subcompact, and 55 percent city and 45 percent highway driving in the gasoline-powered vehicles.

For further comparison with newer technology, at those historic energy price levels, the NiCd BEV is estimated to save 34% and 23% versus the fuel costs of two 2004 gasoline-electric hybrids, Honda Civic Hybrid and Toyota Pius, respectively. Data for the 2004 hybrid automobiles were obtained from the Department of Energy web site at http://www/eit.doe.gov.