Integrated Photovoltaics in Nickel Cadmium Battery Electric Vehicles

Final Report

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16. Abstract

This research report presents Connecticut Department of Transportation's (ConnDOT's) evaluation of preproduction prototype nickel-cadmium (NiCd) battery-powered electric vehicles (BEVs) as an alternative-fuel (alt-fuel) option for local trips averaging less than 70 miles. If feasible as an alt-fuel vehicle, the BEV could be used to help lower overall energy consumption, reduce greenhouse gases (GHGs) and reduce dependence on foreign oil. This report was intended to highlight the findings of the study as well as illustrate some of the problems associated with current battery electric vehicle (BEV) technology.

ConnDOT partnered with The Rideshare Company of Greater Hartford (Rideshare) to retrofit three subcompact BEVs with nickel-cadmium (NiCd) batteries to conduct the two-phase study. The vehicles used were 1995 General Motors Geo Metro(s) retrofitted by the Solectria Corporation. For Phase 2, thin-film photovoltaic laminates were integrated in the NiCd BEVs in order to provide power to offset the small power losses experienced while parked and unplugged.

The study accumulated data from more than 550 individual trips, spanning a distance of nearly 35,000 miles over an eight year period. While researchers were able to attain the 70 mile range in Phase 1, they were unable to replicate the results in Phase 2, as the nominal range of the retrofitted vehicles was approximately 57 miles.

17. Key Words
Battery-electric vehicle, BEV, photovoltaic, thin-film photovoltaic, nickel-cadmium battery, electric vehicle, alternative-fuel, solar-powered electric vehicle

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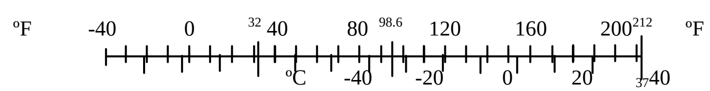
METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
ac	Acres	0.405	hectares	ha
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb.)	0.907	Megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	ºC

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
km^2	square kilometers	0.386	square miles	mi^2
ha	hectares (10,000 m^2)	2.47	acres	ac
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	Megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 (then add 32)	Farenheit temperature	ºF



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INTRODUCTION

In 1895, only the wealthy could afford to own a “horseless carriage.” Some early pioneers of the automobile industry, employed by the Pope Manufacturing Company in Hartford, Connecticut, believed that gasoline cars would be too noisy, greasy, complicated to operate and vibrate too much for their wealthy customers. So, they concentrated their efforts on the design of a battery electric vehicle (BEV) *(1)*.

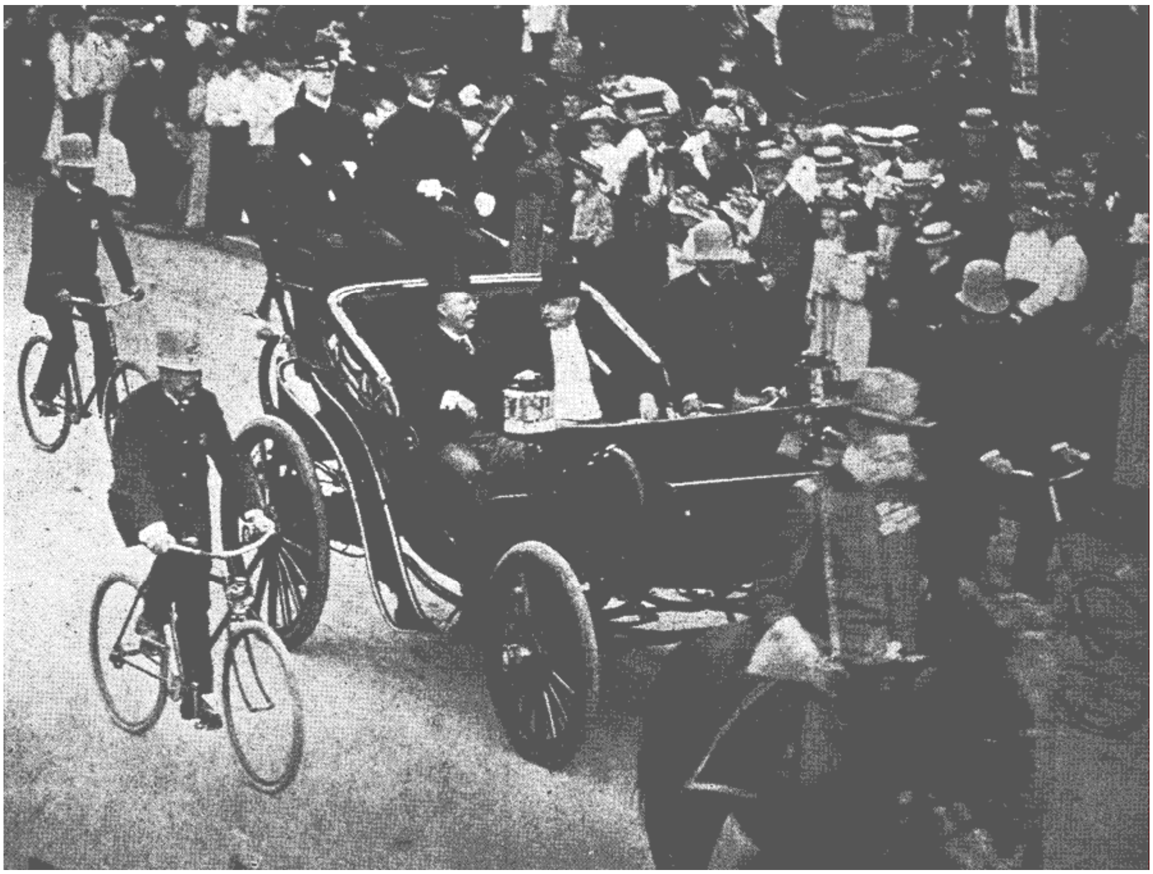

Figure 1 “Teddy” Roosevelt with Colonel J.L. Greene riding in a Columbia electric Victoria on his 1902 visit to Hartford. Possibly the first presidential use of an automobile. *Courtesy Henry Cave and Belltown Antique Car Club East Hampton, CT (1).*

Within a couple of years, they designed and manufactured a BEV and offered it to the public on May 13, 1897. The Hartford Times announced: “Its cost of maintenance and operation should be much less than that of a pair of horses…never found anyone so stupid that they could not run the carriage but there are many who can’t handle a horse… 6 or 8 inches of snow ‘no obvious obstacle’.”*(1)*

The 1897 electric surrey had an operating range of 30 miles on level roads. It sold for $3,000. The Hartford Courant proclaimed, “Horseless Era Comes.”*(1)*

The Pope Manufacturing Company, Columbia, and other manufacturers began producing these electrics in large numbers and sold them to wealthy people of the day. They were continuously manufactured in Hartford, Connecticut from 1895 to 1914. Unknown at the time, these BEVs were merely transitional vehicles to the gasoline powered vehicles that are still driven today. Their capability and limitations were demonstrated early in the horseless-carriage era.

From the time of Pope Manufacturing through the 1980’s, small-volume production of battery electric vehicles focused on niche markets. Taxi companies in major cities successfully used BEV cabs with central charging garages. The operating parameters, capabilities and limitations of various battery chemistries and designs would continually shape the BEV market.

In the 1980’s, concerns over air quality and dependence on foreign oil lead to passage of legislation such as the Energy Policy Act of 1992 (EPACT ’92). The California Air Resources Board was instrumental in focusing the attention of major automobile manufacturers on various technologies that included battery electric propulsion.

The environmental impacts caused by green house gases (GHGs) are well documented *(2,3,4)*. The extent to which BEVs reduce GHG emissions strongly depends upon the type of fuel used by electric power plants to generate electricity. In 1999, the Transportation Research Board (TRB) published a peer-reviewed paper by Wang which presented estimates of GHG emissions reduction potentials for various advanced vehicle technologies *(5)*. Wang indicated that BEVs charged by electricity generated with a California electric generation mix, primarily nuclear and renewable sources, can reduce GHG emissions by 80 percent relative to emissions of internal combustion engines fueled with reformulated gasoline. Wang found that other electric generation mixes can reduce GHG emissions by 40 to 60 percent.

A more modest estimate was presented by Singh, also in a 1999 peer-reviewed TRB publication. This paper presented results of a total energy cycle analysis of BEVs. It indicated that GHG emissions of BEVs are 24 to 37 percent lower than those of conventional gasoline vehicles that they replace *(6)*. Singh estimated that energy consumption can be reduced by 24 to 35 percent relative to gasoline vehicles, and that total oil use can be reduced by 55 to 85 percent *(6)*. If these estimates are realized by replacing conventional gasoline vehicles with BEVs, dependence on foreign oil and individual monthly fuel expenses would obviously be reduced.

Widespread usage of BEVs, as compared to cars powered by the internal combustion engine was viewed as providing the following four benefits: (1) reduced airborne emissions (especially greenhouse gases), (2) reduced energy consumption per vehicle mile traveled, (3) reduced use of petroleum and dependence on foreign oil, and (4) reduced individual monthly fuel expenses. With the capabilities of BEV technology still uncertain amid growing pressure from EPACT ’92 and air quality concerns, Connecticut Department of Transportation (ConnDOT) initiated this research into the feasibility of using nickel-cadmium (NiCd) BEVs as an alternative-fuel (alt-fuel) option for local trips averaging less than 70 miles.

RESEARCH PROGRAM

ConnDOT initiated a research project in 1998 (Phase 1) to evaluate a nickel cadmium (NiCd) BEV. The project was made possible through a partnership with The Rideshare Company of Greater Hartford’s (Rideshare). Rideshare loaned a 1995 BEV to ConnDOT, together with approval to modify it from a lead-acid BEV subcompact to a NiCd BEV in 1999. The driving range design goal was to provide not less than 70 miles per recharge year-round in Connecticut. In a state that is roughly 50 miles north to south and 100 miles east to west, 70 miles was a driving distance thought to be useful for the purposes of the state government fleet of cars as well as achievable with NiCd batteries.

The NiCd battery, popular in European electric vehicles, was anticipated to provide longer and more reliable service than a lead-acid battery. NiCd was more economical than other advanced battery technologies available at that time. 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, including information on how long the NiCd battery pack could be expected to function before replacement was needed.

Description of Nickel Cadmium Battery for Motive Power

A 100-Ampere-hour NiCd battery powered the vehicle. The battery was manufactured in Europe where it is commonly used in BEVs. The manufacturer's claimed battery attributes for the NiCd included: sintered-plate positive electrode and plastic-bonded negative electrode with integrated liquid cooling; low maintenance, lifetime of over 65,000 miles; operational from -4°F to 104°F; rapid recharging; and fully recyclable. Each battery weighs about 26 pounds. In the pack, 26 batteries at 6 Volts (each) provided 156 Volts (nominal), and at 100 Ampere-hours, this provided a total of 15,600 Watt-hours of energy. The NiCd batteries do not require charge equalization the way lead acid batteries do.

TABLE 1 Phase 1 Battery Electric Vehicle Facts

Vehicle Battery Type	Nickel Cadmium (NiCd)
Number of Batteries in pack	26
Battery Pack Voltage (volts)	156
Battery Capacity (Ah)	100
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+

Description of Basic Vehicle

The subcompact BEV was a General Motors (GM) Geo Metro 4-door sedan that was retrofitted by the Solectria Corporation (Massachusetts) to become their "Force" model. The Geo model years 1995 through 1999 were essentially identical.

The vehicle examined in this study had a 1995 model-year body and chassis. This subcompact car was one of the least expensive, no-frills economy cars on the market *(7)*. As a subcompact car, it had adequate seating for four adults, but limited interior room. Trunk space in the NiCd car was smaller than in the OEM Geo Metro due to the greater space required for a battery box and on-board charger in the trunk.

A Solectria motor, model ACgtx20, replaced the original Solectria motor. Manufacturer's specifications for the new AC induction motor stated that it would deliver approximately 44 horsepower (hp). It was a brushless sealed design that weighed 78 pounds (lbs). Company specifications further stated that it had extremely low electrical resistance; nominal power was 12 kilo-Watts (kW) and nominal torque was 15 foot-lbs (ft-lbs); while maximum power and torque were 37 kW and 52 ft-lbs, respectively. Nominal motor speed was 4,000 rpm and maximum motor speed was 12,000 rpm. The manufacturer stated the motor had an efficiency of 92%.

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

In the 1999 factory upgrade, the vehicle retained its original 1995 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 74 ft-lbs. 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.

In a standard original equipment manufacturer (OEM) Solectria vehicle, a 1500-Watt electrical resistance heater and 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 and battery-discharge cycle *(8)*. Fuel-fired heaters and defrosters had been the subject of earlier research conducted by EVermont *(11)*. 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. EVermont concluded that a high efficiency fuel-fired heater/defroster did perform its intended function and provide safety, comfort, and economy. Therefore, our 1999 retrofit included the installation of a fuel fired heater system.

EVermont handled the installation of the fuel-fired heater plus electrically warmed seats for this project. Between the 1999 and 2000 American Tour del Sol (ATdS) events, the air conditioner components were reinstalled, which increased the weight of the car. To partially compensate for the weight gain, the OEM steel hood and trunk lid were replaced with lighter weight fiberglass, and the car received lighter-weight alloy wheels and low rolling resistance tires. To improve aerodynamics, the headlamps were upgraded to 1999-model year lights. The net increase in vehicle weight from all upgrades was observed to be 219 pounds, which equates to a 4.6 percent increase over the previous year.

PHASE 1 EVALUATION (1999-2003)

Prior to testing, researchers had hypothesized that a NiCd-powered BEV subcompact with fuel-fired heater/defroster would provide a reliable year-round minimum 70-mile range in Connecticut. 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 ATdS electric vehicle road rally, troubleshooting and repair after breakdowns, and subsequent data analysis. The combination of driving activities conducted under a variety of battery states-of-charge (SOC), weather, traffic, and roadway conditions was anticipated to provide a balanced first-hand evaluation of 1999 production BEV technology with a NiCd battery system. By the time the evaluation was complete, the vehicle had been driven approximately 30,000 miles.

Sime presented the results of this 30,000 mile evaluation in an interim report, published by ConnDOT in May 2004, titled "Evaluation of Nickel Cadmium Battery-Electric Subcompact Automobile in Connecticut as an Alternative for Work-trips and Commutes." His findings were that the NiCd battery "was completely reliable during the four-year evaluation period" from 1999 to 2003 *(10)*.

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 Figure 2 as A, B, C, and D. 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.

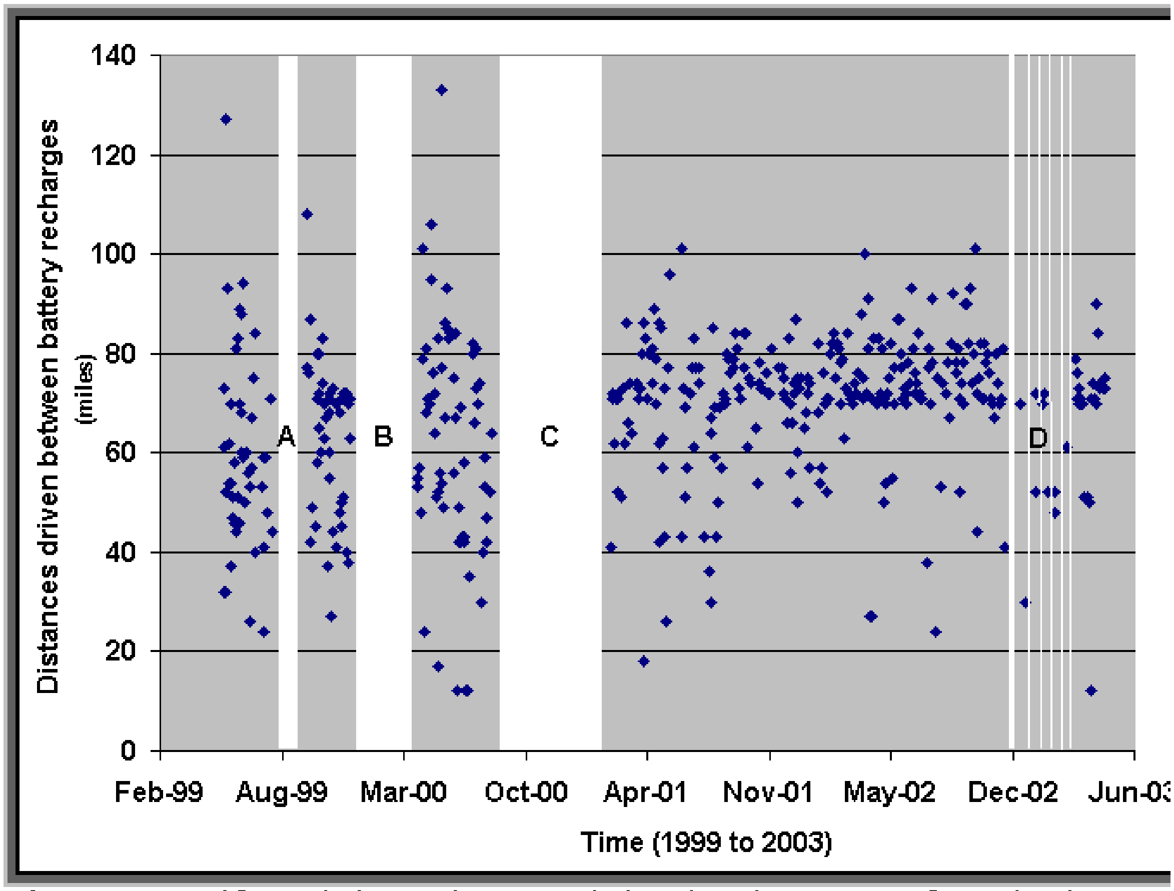

Figure 2 Miles driven in 428 drive/recharge cycles during the evaluation.

The vehicle's SOC was monitored during the study. From the SOC, the Depth of Discharge (DOD) was calculated. For example, when the starting SOC was 100% and the vehicle was driven until the SOC was 30%, the DOD equaled 70%. DOD data were skewed towards lower values (see Figure 3). The median value was 71.8 percent, while the average value was 68.5 percent. 70% was considered a representative DOD value for the NiCd BEV.

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. At the slightly higher average energy usage per mile that was observed in the fall, the representative driving range was reduced to about 74 miles for a 70 percent DOD. In winter, the representative driving range was about 66 miles. Note that 70 miles per charge was attainable during the winter, but at a DOD greater than 70 percent. Thus, Sime was able to demonstrate a year-round minimum 70-mile range capability *(10)*.

Energy usage was calculated by dividing the 70 percent nominal battery pack capacity (10920 Watt-hours) by the miles driven for a 70 percent DOD. The lowest energy usage rate (highest efficiency) was achieved at the weeklong ATdS events in spring 1999 and 2000; however, it is the mean value of energy usage rate that is most representative of the vehicle's seasonal performance on Connecticut roads. The nominal mean rates of energy usage for the spring, summer, fall and winter were 139, 138, 147 and 165 Watt-hours (DC)/mile, respectively.

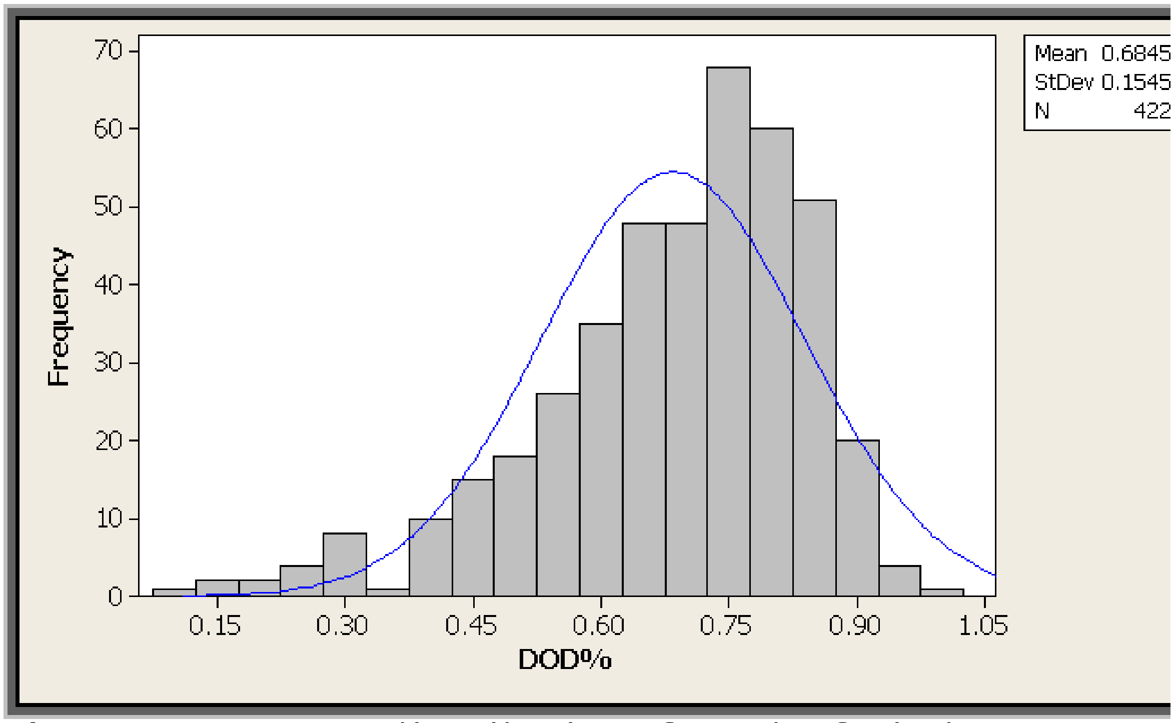

Figure 3 Frequency distribution of Depth-of-Discharge Data from 422 drives/discharges.

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 efficiency was calculated by dividing the 'wall-plug' electricity (AC Watt-hours) that was purchased to recharge the battery by the miles driven since the last recharge. The average efficiency was 234 watt-hours (AC) per mile and the median was 228 watt-hours (AC) per mile.

Problem Areas Observed During Phase 1

During Phase I, reliability shortcomings were almost exclusively in the area of battery recharging and battery thermal control systems. A recurring problem that plagued the car over the four-year Phase I period was battery charging during hot summer days. At temperatures above 80˚F the microprocessor-controlled battery charging 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. 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 Phase I four-year evaluation.

Other problems were encountered. The ‘smart charger’ blew an internal fuse and had to be shipped back to the manufacturer for the fuse to be replaced (under warranty), which resulted in the BEV being kept out of service for a total of 33 days. In one instance, electric cabin heat turned on itself during battery recharging and completely drained the battery. In other instances the driving range was reduced by as much as twenty miles due to the battery being drained while parked by this same cabin-heat power circuit. Removal of the 60-amp fuse in the electric heater circuit every time the vehicle was being charged or parked prevented reoccurrences, but was an inconvenient stop-gap measure. In December 2002, the fuel-fired heater stopped working, which resulted in the vehicle not having operable cabin heat or front windshield defrosting until six months later. Poor radio reception caused by electromagnetic fields in the radiofrequency range resulted in some driver and passenger satisfaction problems. Finally, a more sophisticated study-data-acquisition system was needed to provide better data for research analysis purposes.

PHASE 2 EVALUATION

By the fall of 2000 it was apparent that the NiCd vehicle was showing promise as a potentially practical short commute vehicle that might be able to provide a 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 the project. The two Rideshare cars were the same year, make and model as the first NiCd BEV, 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, as well as making changes to all three that address problems and shortcomings observed in Phase 1. 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, two 6-Volt NiCd batteries were added to each BEV pack, increasing the total number of batteries to 28 per pack. The two additional batteries increased the BEV’s battery capacity by 1,200 Watt-hours, bringing the total nominal power to 16,800 Watt-hours. The addition of two batteries necessitated replacing the Solectria AC 325 electrical controller with a new Solectria controller interface kit (Model TMOC425TF). In addition to the new controller, a direct-drive system, including a hardware mounting package, was installed. The on-board Solectria BC3300 220V charger was replaced by a newly-designed Odyne smart charger with integrated data acquisition system. This new charger could accept 110V or 220V single or three-phase power. The retrofit included the conversion of the existing air conditioning unit to also function as a heat exchanger to cool the battery pack during charging and driving. A photo of the Phase 1 vehicle being retrofitted is presented in Figure 4.

The vehicles were arbitrarily called EV-1, EV-3, and EV-5 because those were their respective license plate identifications. The original NiCd BEV used in the Phase 1 evaluation was called EV-1 (not to be confused with General Motor’s 1996-1999 BEV model EV1, available only in CA and AZ).

Photovoltaic laminates were attached to the tops of the hood, trunk and cab of each BEV (see Figure 5). The photovoltaics were integrated with the NiCd BEV in order to offset the DC kilowatt-hours required from the battery pack while the car was parked and unplugged. Electricity in excess of those needs would trickle charge the NiCd pack. Each vehicle was equipped with eight (8) LM-11 and five (5) LM-5 rectangular shaped laminates from Unisolar. The LM-11 laminates measured 19.33-in x 15.04-in, and the LM-5 laminates measured 19.34-in x 8.07-in. A total surface area of 3,106-in^2 was covered by these laminates. Each LM-11 laminate had a maximum power output of 10.3-watts and each LM-5 laminate had a maximum of 5-watts. Thus, the maximum solar power output for each vehicle equaled 107.4-watts.

Figure 4 Retrofitting of Phase 1 EV-1 BEV in Preparation for Phase 2 BEV Study

A second phase of driving and data collection commenced upon completion of the retrofitting work in order to accumulate experience and observational data for completion of the project.

Since the retrofitted vehicles included a data acquisition system, the data collected included: Date, Time, Odometer, Pack SOC (battery pack state-of-charge), Pack Volt (battery pack voltage), Pack Current (battery pack current usage), Pack WH (battery pack (DC) watt-hours), Solar Cell WH (photovoltaic watt-hours generated), and AC-kWh (kilowatt-hours (AC) of electricity to recharge battery pack), temperatures of motor, ambient, cabin and batteries, and various other electrical, charging and automotive-system status parameters. A complete list data collected is provided in Appendix A.

Figure 5 Photovoltaic laminates on Phase 2 battery-electric vehicle (typical of others).

In order to compare vehicle performance for different drivers, they were assigned arbitrary identifications. The Phase 1 driver was called “Driver 1”. This driver also drove a vehicle during Phase 2. The other two drivers included in this evaluation were called “Driver 2” and “Driver 3”. Table 2 below presents Phase 2 BEV usage reports for these three drivers.

TABLE 2 Summary of Four (4) BEV Usage Reports

BEV ID	Driver	Total Miles	Mean DOD (%)	Est. 70% DOD Range (mi)	DCWH/ Mile (WH/mi)	ACWH/ Mile (WH/mi)	Mean Pack Current (amps)
EV-1	1	2169.8	70.0%	58.6	190	222	-31.3
EV-1	2	318.6	57.0%	55.9	190	394	-33.9
EV-3	2	917.3	53.7%	57.9	195	472	-36.2
EV-5	3	1393.2	65.6%	24.3	473	557	-50.3

Figure 6 The fleet of Phase 2 Battery-Electric Vehicles

"Driver 1" EV-1 Usage, September 12, 2004 to July 18, 2005

"Driver 1" drove EV-1 from September 12, 2004 to July 18, 2005 for his daily commute to and from work plus work trips. In total, data for 37 drives were recorded covering just over 2,100 miles. Data are presented in Table 2. For these 37 drives, the median DOD was 69%, the mean was 70%, the minimum was 41%, and the maximum was 96%. The average distance traveled per drive was 58.6 miles. Thus, at 70% DOD, this equated to a representative 58.6-mile driving range per charge, which was less than that attained during the Phase 1 evaluation and short of the 70-mile goal. Descriptive statistics and graphs are presented in Appendix B.

A total of 412,732 Watt-hours of energy (DC) were used during these 37 drives, which totaled 2,169.8 miles. The overall energy usage equated to 190 Watt-hours (DC) per mile. This is 15 to 37% higher than the energy usage estimated for EV-1 during Phase 1, suggesting that changes to charging, battery thermal management, data acquisition, and DC-DC voltage converter created new inefficiencies. but is more accurate because of the addition of the onboard data acquisition system.

Overall efficiency was calculated by dividing the AC-kWh by the miles driven. In total, 482,060 Watt-hours of energy (‘wall-plug’ electricity) were used to recharge the EV-1 battery pack for these 37 drives. Thus, the efficiency was 222 Watt-hours (AC) per mile. This compares similarly to the average efficiency of 234 Watt-hours (AC) per mile calculated for the Phase 1 (“Driver 1”) drives. The overall efficiency of the NiCd/battery recharging system is calculated to be 85.6%.

The manner in which EV-1 was driven during this period is illustrated in Figure 7. Figure 7 presents a histogram of 500 randomly selected representative pack currents. Only pack currents recorded while the vehicle was driven, defined as when the ignition switch was “on” and for which the speed was greater than zero were selected for this analysis. Pack currents were recorded at approximately one minute intervals, so the recorded data were basically systematic samples with a random start; because the vehicle could be accelerating, decelerating, or coasting depending upon when a reading was taken. However, over time these peaks and valleys balance out and the data sets are a good statistical representation of how the vehicles were operated. The frequency and magnitude of the peaks provide an indication of vehicle acceleration, deceleration, constant speed and braking.

There are three peaks that are of interest when looking at Figure 7. The most frequent pack currents recorded were between 0 and -10 amps (34% of the data set), but many of these were likely recorded while EV-1 was coasting in traffic and the power demand was low. The peak that is of most interest is between -70 and -90 amps because those were the most frequent pack currents recorded during power demands. The third peak was for positive pack currents, which indicates that regen-braking was being used, which recharged the NiCd pack. High frequencies of positive pack currents suggest that the regen-braking feature was being optimized. The most frequent positive pack currents recorded ranged between 30 and 50 amps. The overall mean pack current was -31.3 amps.

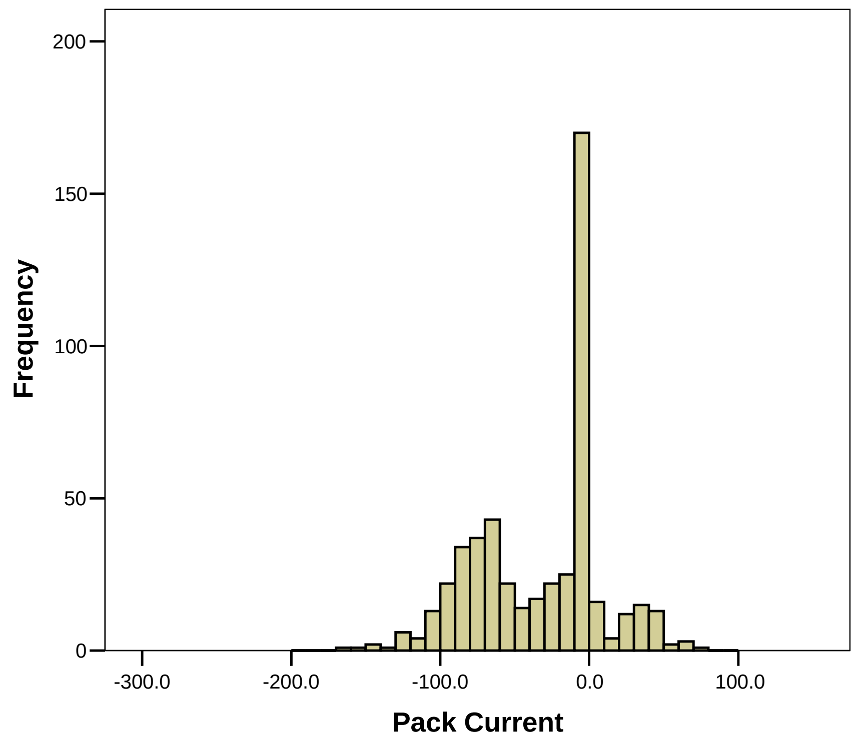

Figure 7 Histogram for the Frequency Distribution of 500 Randomly Selected Pack Currents for "Driver 1" EV-1 Usage.

"Driver 2" EV-1 Usage from April 7 – 21, 2006

During April 7-21, 2006, "Driver 2" drove EV-1 approximately 40 miles (20 miles each way) back and forth between the ConnDOT Central Laboratory (Lab) in Rocky Hill, CT and Vernon, CT. In total, seven of these drives were made before the powertrain direct-drive unit failed. Attempts to arrange for repairs were unsuccessful and EV-1 was not returned to service thereafter.

Upon arriving at the Lab, EV-1 was plugged in to commence recharging. It took about 6½ hours to fully recharge the battery, and so the NiCd pack was normally fully charged by the end of the workday. Otherwise, the driver would either have to wait until the BEV was fully recharged, or would drive home with less than a complete recharge. Descriptive statistics and graphs are presented in Appendix B.

For these 7 drives, the median and mean DODs were both 57%, the minimum was 52%, and the maximum was 63%. The average distance driven was 45.5 miles. By proportion, at 70% DOD, the estimated driving range would be 55.9 miles.

A total of 60,649 Watt-hours of energy (DC) were used to drive a total of 318.6 miles during this period. So, the overall energy usage equaled 190 Watt-hours per mile, which was the same energy usage for “Driver 1” from September 12, 2004 to July 18, 2005. This demonstrates that “Driver 1” and “Driver 2” were operating the vehicle in a similar manner.

Recorded AC-kWH data were volatile for these seven drives. Efficiencies for three of them were consistent with those for “Driver 1”, as they were 197, 226, and 235 Watt-hours (AC) per mile. However, efficiencies for the other four drives were much higher: 603, 568, 437, and 477 Watt-hours (AC) per mile. This was surprising because the DC energy usages for these four drives were similar to the three discussed above. It does not appear the vehicle was driven any differently. The time for which the battery cooling system ran was checked to see if longer cooling periods related to low-efficiency recharges, but no association was found. Two different 220-V (nominal) outlets were used. One provided 208V three-phase and the other 220V single phase. One may have altered the way data were collected.

The manner in which EV-1 was driven during this period is presented in Figure 8 and Figure 9. The green line in Figure 8 represents currents of -50 amps, the yellow line represents currents of -100 amps, and the red line represents currents of -150 amps.

Similar to Figure 7, 500 randomly selected representative pack currents were selected for the histogram presented in Figure 9. Again, only pack currents recorded while the ignition switch was “on” and for which the speed was greater than zero were selected for this analysis.

There are three peaks in the frequency distribution shown in Figure 9. Twenty-six percent (26%) of the recorded pack currents were between 0 and -10 amps. These likely occurred when the vehicle was coasting, or the demand for power was low. Conversely, the peak on the left represents the most frequent pack currents recorded when there was a demand for power. These data ranged between -60 and -80 amps. The peak to the far right represents pack currents recorded during regen-braking, which ranged from 30 to 50 amps. Considering all of these data, the mean pack current equaled -33.9 amps, which is slightly greater than the “Driver 1” mean pack current (-31.3 amps) used while driving EV-1.

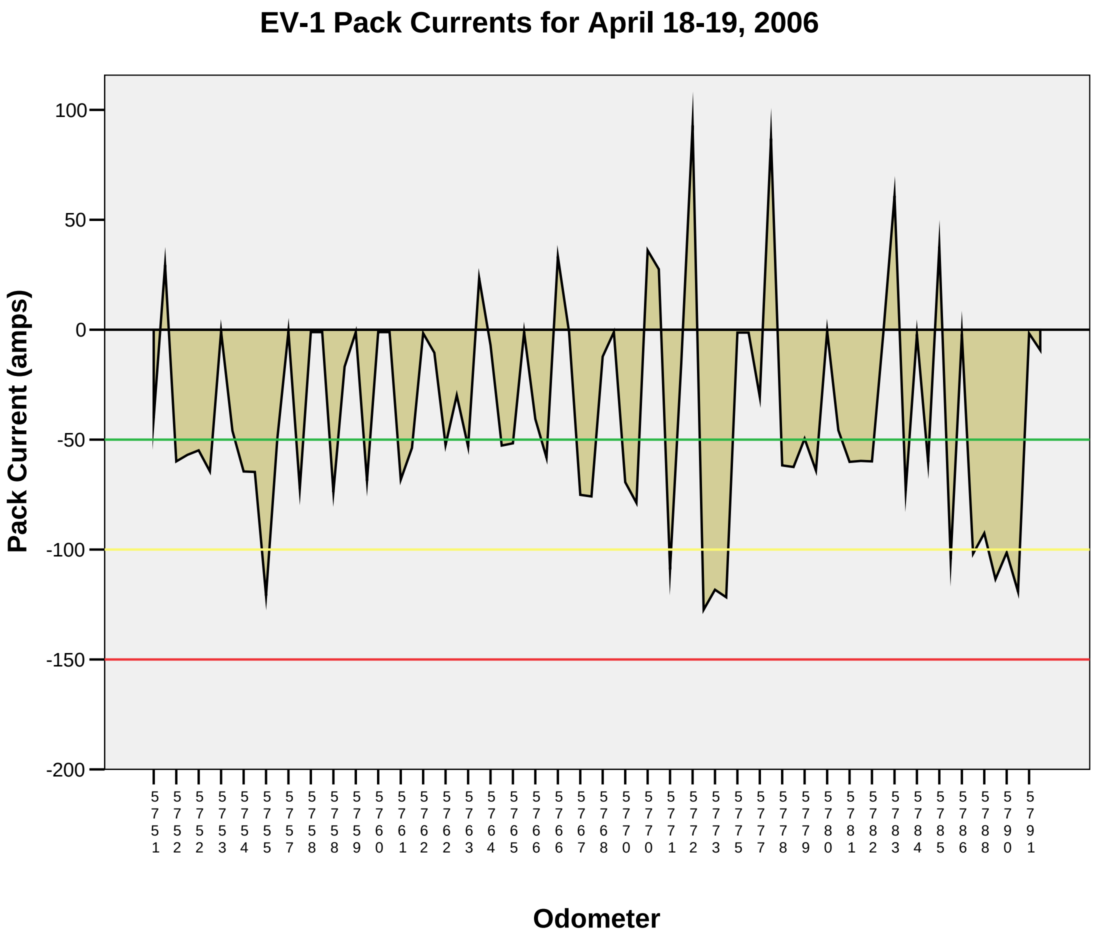

Figure 8 Pack Currents vs. Mileage for EV-1 for April 18-19, 2006 (typical of other “Driver 1” and “Driver 2” EV-1 Usages). Note: Pack Currents were recorded at arbitrary 1-minute intervals.

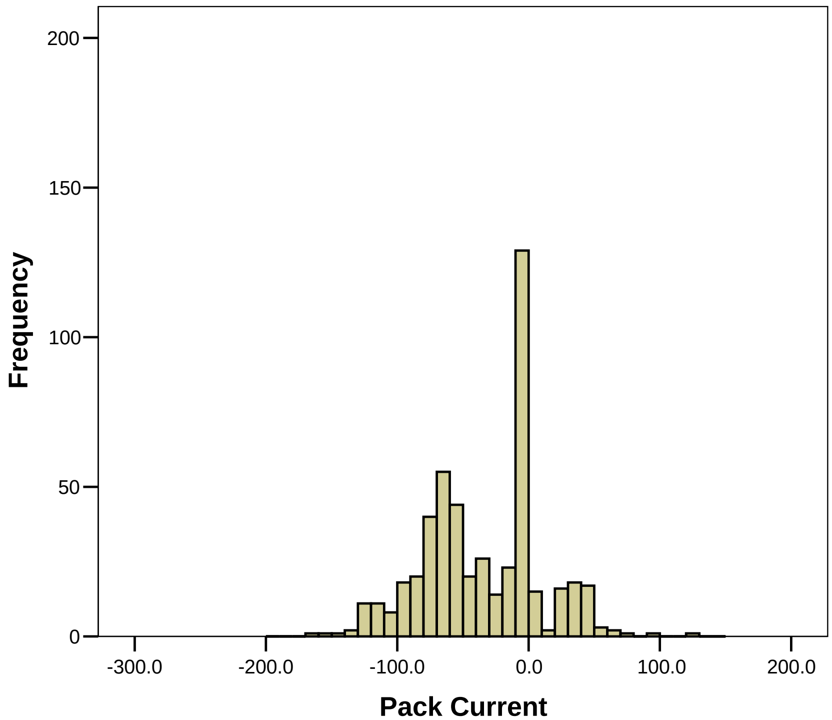

Figure 9 Histogram for the frequency distribution of 500 randomly selected pack currents for "Driver 2" EV-1 usage.

"Driver 2" EV-3 Usage from April 27 to June 26, 2006

"Driver 2" made 21 drives with EV-3 from April 26 to June 26, 2006. "Driver 2" continued to make the same commute back and forth between Rocky Hill and Vernon, CT as he did with EV-1. Recharging commenced upon arrival to Rocky Hill in the morning. By the time "Driver 2" departed for home at the end of the workday, EV-3 was typically recharged and ready to drive.

For these 21 drives, the median DOD was 52%, the mean was 53.7%, the minimum was 41%, and the maximum was 67%. The average distance traveled was 43.7 miles. By proportion, at 70% DOD, the estimated driving range would be 57.0 miles.

A total of 179,298 Watt-hours (DC) of energy were used during these 21 drives totaling 917.3 miles. The overall energy usage equaled 195 Watt-hours per mile, which was slightly greater (<3%) than that consumed for both EV-1 drivers (190 Watt-hours per mile). Note that power for EV-1 could be controlled continuously with a dial, while there were only three available modes for EV-3 (see Figure 10): Max Range, Mid Range, and Max Power. The energy usage was stable from drive-to-drive, as it ranged from 174 to 218 Watt-hours per mile.

The energy required to recharge EV-3 fluctuated considerably from cycle-to-cycle. The efficiency ranged from 199 to 851 Watt-hours (AC) per mile. Two different 220-V outlets were used, and the recorded AC-kWh data are suspect for the same aforementioned reasons described for the “Driver 2” EV-1 drives.

Figure 10 Photo of drive controller used in EV-3 and EV-5. Note the three modes: Max Range, Normal Range and Max Power.

Pack current-draw-while-driving frequencies are presented in Figure 11. 30% of the currents were between -50 and -70 amps, which likely occurred while EV-3 was driven in the Max Range mode. This was by far the most frequent range of pack currents recorded. There was a slight peak between -180 and -190 amps, which probably occurred while EV-3 was driven in the Max Power mode. The mean EV-3 pack current during this period equaled -36.2 amps.

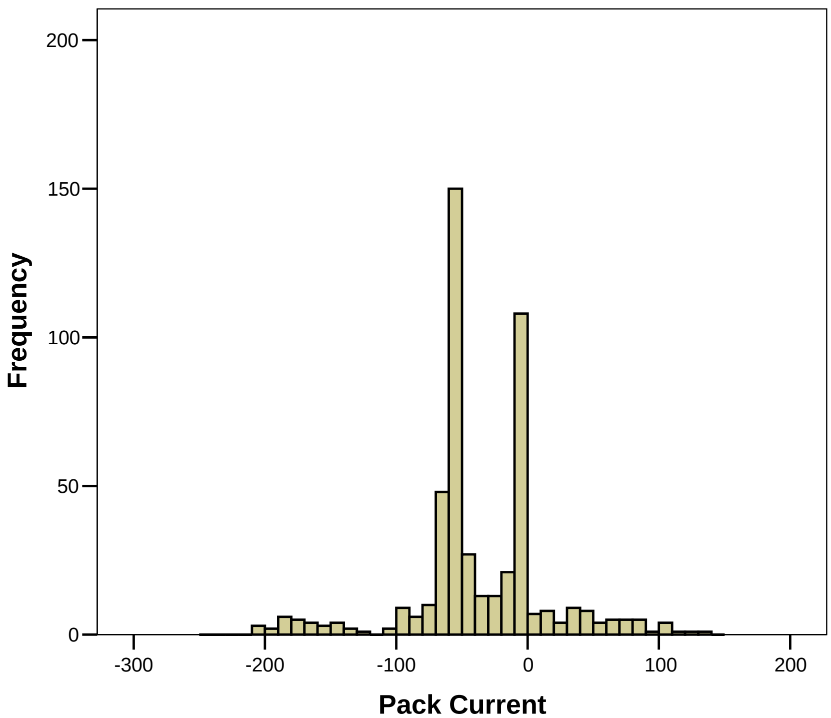

Figure 11 Histogram for the Frequency Distribution of 500 Randomly Selected Pack Currents for "Driver 2" EV-3 Usage

"Driver 3" EV-5 Usage from October 11, 2005 to August 30, 2006

From October 11, 2005 to August 30, 2006, "Driver 3" drove EV-5 back and forth between the Lab and Newington for his daily 14-mile (approximately 7 miles each way) commute plus work trips. All driving was on local roads. In total, 61 drives were made for 1,393.2 miles.

For these 61 drives, the median DOD was 68%, the mean was 65.6%, the minimum was 35%, and the maximum was 92%. The average distance traveled was only 22.8 miles. By proportion, at 70% DOD, the estimated driving range would be 24.3 miles.

A total of 659,383 Watt-hours (DC) of energy were used during these 61 drives. The overall energy usage was 473

Watt-hours (DC) per mile, which was significantly greater than the usage by the other BEVs. Unlike the other BEVs, energy usage was volatile from drive-to-drive, as it ranged from 221 to 913 Watt-hours (DC) per mile.

Similar to EV-1 and EV-3, recorded data for EV-5 should have included AC-kWh, but unbeknownst to the driver, until early May 2006, these data were not being recorded automatically by the data acquisition system. When it was realized that AC-kWh were not being recorded, a separate AC-kWh meter was installed in the vehicle and the AC-kWh were manually recorded.

The first meter reading was recorded on May 10, 2006. It was 112.127 kWH. The SOC was 60% at that time. After it was charged that same day, the meter reading was recorded again at 119.672 kWH. The respective odometer reading was 24,837 miles. The last reading of 651.801 kWH taken after a full charge at 25,793 miles was recorded on August 30, 2006. The calculated AC-Wh per mile equated to 557 WH/mile. Note: this value was computed by using the full SOC reading of 119.672 in order that the first and last readings were both at a full SOC. Considering that the overall energy usage was 473 Watt-hours (DC) per mile, the AC Watt-hour per mile value of 557 seems reasonable. The overall NiCd battery/charging system efficiency calculates to approximately 84.9%.

A histogram for the frequency distribution of EV-5 pack currents is presented in Figure 12. Five peaks can be seen in this graph. The most frequent current interval ranged between 0 and -10 amps. This accounted for 39% of all data. Again, this interval consisted primarily of pack currents recorded while the vehicle was coasting. The next most frequent interval ranged between -100 and -120 amps. 10% of all the observations occurred within this interval. Other peaks occurred between -200 and -210 amps and between -40 and -50 amps. These intervals probably represent the Max Power and Max Range modes, respectively, while the -100 to -110 amp interval likely represents the Mid Range mode. The last peak represents regen-braking currents, as this interval ranged between 70 and 90 amps. The overall mean pack current was -50.3 amps, which is significantly higher than that calculated for EV-1 and EV-3 (ranged from -31.3 to -36.2 amps). It should be noted that the power ranges (Max Range, Mid Power & Max Power) for EV-5 were factory-set at higher amperage levels than the other two cars.

Typical pack currents for a drive cycle are presented in Figure 13. Note that more pack currents were measured near the yellow line (-100 amps) and few were measured near the greed line (-50 amps). This demonstrates that EV-5 was driven more aggressively (compare to Figure 8); however, it should be noted that the amperage levels for the individual modes were inherently higher for EV-5 than for EV-3.

These higher pack currents partly explain why EV-5 was less efficient than the other BEVs, but there is another reason: EV-5 had a certain inherent energy loss associated with its battery pack. The rate of loss while EV-5 was parked was approximately 1.5 Watt-hours per minute, which adds up to 90 Watt-hours per hour, 2160 Watt-hours per day and 15,120 Watt-hours per week. For the 323 day period considered here, a total loss of approximately 697,680 Watt-hours occurred. This loss also helps explain why the estimated 70% DOD driving range was so low (24.3 miles). Finally, the loss explains why the energy usage fluctuated from drive to drive. More energy was used for longer intervals between charges because the batteries continuously lost their charge while EV-5 was parked. For shorter intervals between charges, the energy usage was lower because the car didn’t sit idle loosing power for as long a period of time.

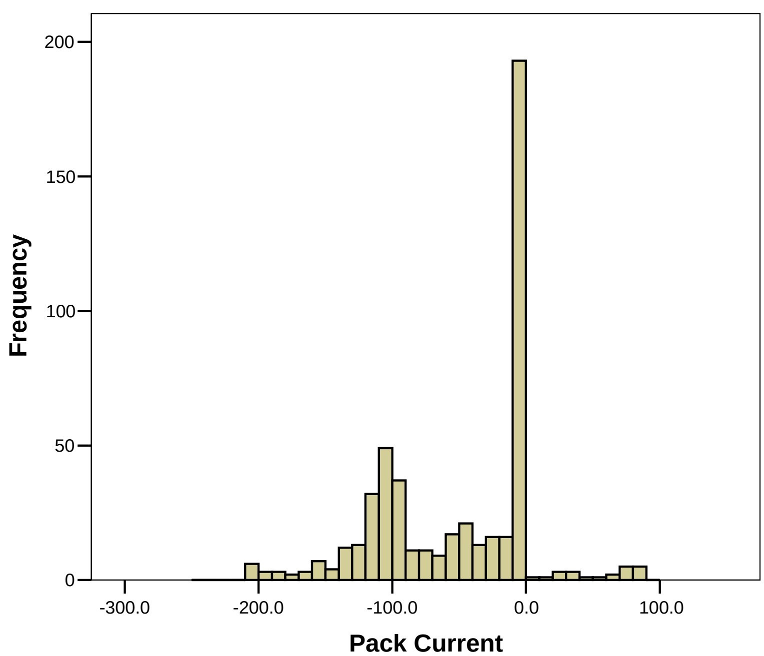

Figure 12 Histogram for the Frequency Distribution of Pack Currents for “Driver 3” EV-5 Usage

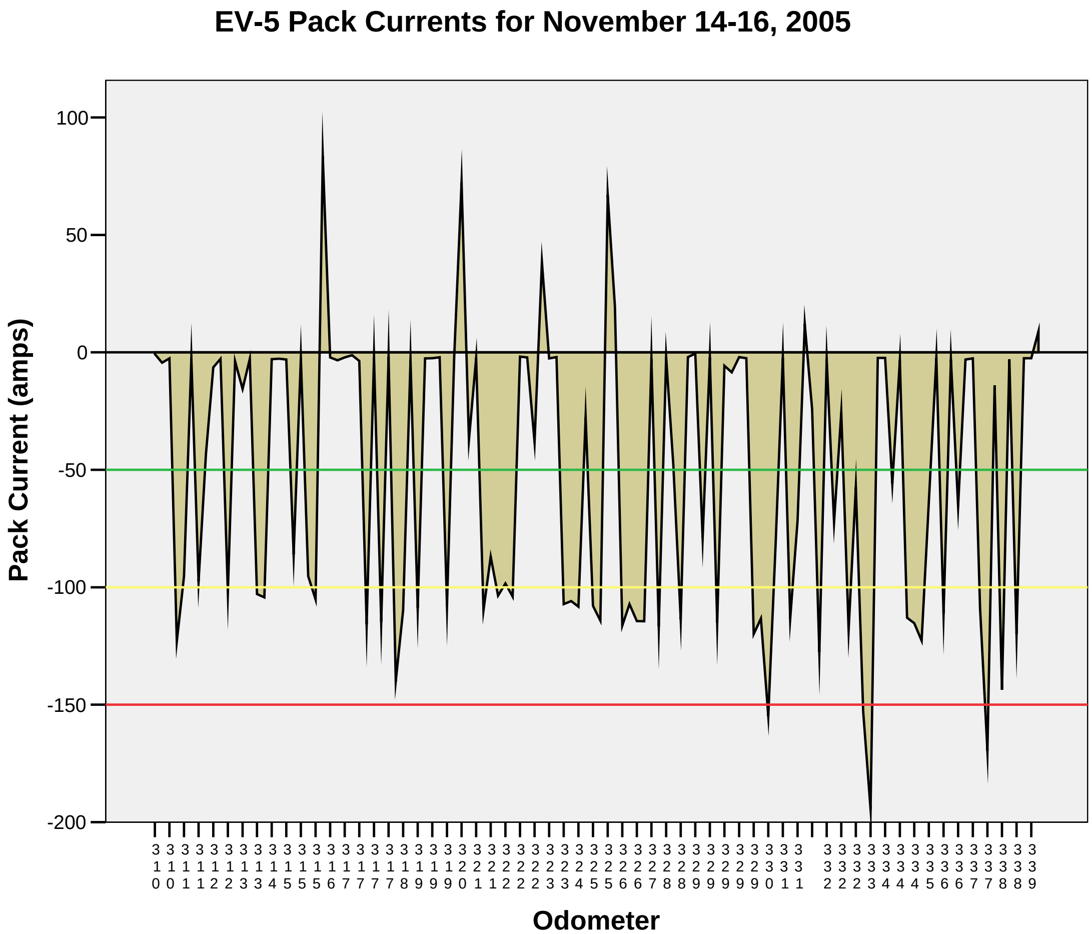

Figure 13 Pack Currents vs. Mileage for EV-5 for November 14-16, 2005 (Typical of other "Driver 3" EV-5 Usages). Note: Pack Currents were recorded at arbitrary 1-minute intervals.

Problem Areas Observed During Phase 2

EV-3's NiCd batteries performed better when they were cycled frequently to deeper DODs by driving the vehicle routinely. Following long periods for which EV-3 was not driven, it tended to loose range and the battery pack experienced sudden voltage drops at lower DODs. Sudden voltage drops resulted in vehicle break downs and towing expenses.

As described earlier, EV-5 had a certain inherent energy loss. Although all batteries tend to lose power while idle, a loss of this extent was not evident in EV-1 or EV-3. It is unlikely the loss was related to the NiCd batteries themselves, but rather parasitic losses of electrical components and systems. Perhaps something was different about the retrofit components, wiring or set-up of this car.

As Sime indicated, EV-1’s 1998 NiCd battery pack was completely reliable during the Phase 1 part of the study *(8)*, but during Phase 2 when the odometer read 35,000 miles the electric powertrain direct-drive unit failed, and a repair could not be arranged. The battery pack itself continued to perform reliably during Phase 2.

There were a few problems encountered with the data acquisition systems. EV-5 did not collect data for the variable called AC-kWh, so a power meter had to be attached and Watt-hours (AC) manually recorded after each recharge. As stated previously, some of the AC-kWh data were suspect for EV-1 and EV-3, especially when an alternative 208-V outlet was used. Additionally, EV-1 and EV-3 did not adequately collect and record data on the solar energy generated for the Solar WH variable. Finally, EV-5’s clock stopped working on May 13, 2006. Time data were eventually regenerated with MS Excel, but this was a painstaking process.

TRANSPORTATION RESEARCH BOARD'S 87th ANNUAL MEETING

On January 15, 2008, a paper based upon an excerpt of this report was presented in a Meet the Author Poster Session at the Transportation Research Board's 87th Annual Meeting in Washington DC. A photo of the display presented there is shown below in Figure 14. The presentation was well attended and ConnDOT Researchers responded to questions and engaged in technical discussions with interested attendees, many of which were European transportation professionals.

Figure 14 Display presented in a Poster Session at the Transportation Research Board's 87th Annual Meeting in Washington DC on January 15, 2008.

FINDINGS

- A year-round minimum 70-mile nominal (at 70% DOD) range capability was demonstrated for the Phase 1 NiCd-powered BEV via a 30,000-mile evaluation, and longer ranges were attained at greater DODs. A range of over 100-miles was attained on seven occasions and a 120-mile plus range was attained on two occasions.
- In Phase 2, the nominal 70% DOD range of the NiCd BEVs dropped to approximately 57 miles for EV-1, 57.9 miles for EV-3 and 24.3 miles for EV-5; which suggests the hand-retrofitted vehicles were not identical.
- A certain inherent energy loss was observed in EV-5 of approximately 1.5 Wh per minute. A loss of this extent was not observed for EV-1 or EV-3.
- During Phase 1, in addition to normal maintenance, such as tire rotation, only simple battery maintenance was needed, which included the addition of less than two gallons of distilled water every 3,500 miles.
- During Phase 2, three hand-retrofitted battery-electric subcompact cars experienced substantially more problems, including: limited driving range, poor overall reliability, battery self discharge when sitting idle, sudden voltage drops, no photovoltaic kWh data captured by data acquisition system, and an electric powertrain direct-drive unit failure.
- The BEVs performed better when driven on a routine basis and charged at night with their NiCd batteries frequently cycled, helping to maintain consistent DOD and drive ranges. Infrequent use resulted in reduced drive ranges and lower DODs.
- The duel use of the car’s air-conditioning system for passenger cabin cooling and battery-pack cooling worked well. In Phase 2, the batteries could be charged at any time, whereas the original design wouldn’t initiate recharge while ambient air temperatures were above 80 degrees Fahrenheit.

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APPENDIX A
Data Fields Monitored in Phase 2 with Custom Smart Charger

TABLE A-1 Data Collected by Phase 2 Data Acquisition System

Field	Data Output
Sector	
Byte	
Date	dd/mm/yyyy
Time	hh:mm:ss
Time Mode	AM or PM
Cabin	Temperature (C°)
Outside	Temperature (C°)
Motor	Temperature (C°)
Sensor 4	Temperature (C°) [not used]
Sensor 5	Temperature (C°) [not used]
Battery 1	Temperature (C°), front box
Battery 1	Temperature (C°), front box
Battery 2	Temperature (C°), rear box
Battery 2	Temperature (C°), rear box
Battery 2	Temperature (C°). rear box
Speed	Miles per hour
Odometer	Miles
Ign SW	0/1
Chrg Port	Not Connected/Stationary
Chrg Status	Not Allowing Ch/20A (Step 1)/Overcharge (Step 4)/Stat Chg Complete/Not Allowing Ch/Not Conn
Allow Ch	0/1
Mem OvrFlw	0/1
Low Batt	0/1
Fans	0/1
Current Request	status
Charger PWM	status
Calculated Vlid	status
Cumulative Overcharge AH	Amp-hours
Maintenance Charge Status	Needed/Not Needed
Maintenance Charge Enabled	0/1
Pack SOC	Percent State of Charge, battery pack
Pack Volt	Volts, battery pack
Pack Current	Amps, battery pack
Pack WH	Watt-hours, battery pack
Pack AH	Amp-hours, battery pack
Seat Volt	Volts, front seat warmers
Seat Current	Amps, front seat warmers
Seat WH	Watt-hours, front seat warmers
Seat AH	Amp-hours, front seat warmers
Solar Cell Volt	Volts, photovoltaic laminates
Solar Cell Current	Amps, photovoltaic laminates
Solar Cell WH	Watt-hours, photovoltaic laminates
Solar Cell AH	Amp-hours, photovoltaic laminates
ACKWH	AC Kilowatt-hours

APPENDIX B

EV-1
Sample Data and
Descriptive Statistics from Phase 2

TABLE B-1 EV-1 Case Summaries for 2004

	Start Date	End Date	Days Between Charges	Miles Driven	SOC Used (%)	Pack WH Used	ACWH Used to Charge
1	09/12/2004	09/15/2004	3	78.4	82	13083	13442
2	09/15/2004	09/16/2004	1	94.2	96	15517	15306
3	09/20/2004	09/22/2004	2	71.1	84	13883	13382
4	09/22/2004	09/23/2004	1	81.5	93	14967	20053
5	09/23/2004	09/25/2004	2	73.2	81	12983	13231
6	09/25/2004	09/25/2004	0	46.0	55	9050	14442
7	09/25/2004	09/27/2004	2	71.3	81	12983	13349
8	10/31/2004	11/01/2004	1	68.3	72	11917	11779
9	11/05/2004	11/09/2004	4	77.1	92	14317	17634
10	11/09/2004	11/10/2004	1	52.2	67	11067	11496
11	11/18/2004	11/21/2004	3	55.4	67	11000	13016
12	11/21/2004	11/24/2004	3	72.4	88	13883	16378
Total N	12	12	12	12	12	12	12

TABLE B-2 EV-1 Case Summaries for 2004

	Start Date	End Date	ACWH per Mile	DC WH per Mile	Energy Cost (cents/mile)	Efficiency (%)	SOC per Mile
1	09/12/2004	09/15/2004	171	167	2.7	97.3	1.0
2	09/15/2004	09/16/2004	162	165	2.6	101.4	1.0
3	09/20/2004	09/22/2004	188	195	3.0	103.7	1.2
4	09/22/2004	09/23/2004	246	184	3.9	74.6	1.1
5	09/23/2004	09/25/2004	181	177	2.9	98.1	1.1
6	09/25/2004	09/25/2004	314	197	5.0	62.7	1.2
7	09/25/2004	09/27/2004	187	182	3.0	97.3	1.1
8	10/31/2004	11/01/2004	172	174	2.8	101.2	1.1
9	11/05/2004	11/09/2004	229	186	3.7	81.2	1.2
10	11/09/2004	11/10/2004	220	212	3.5	96.3	1.3
11	11/18/2004	11/21/2004	235	199	3.8	84.5	1.2
12	11/21/2004	11/24/2004	226	192	3.6	84.8	1.2
Total N	12	12	12	12	12	12	12

TABLE B-3 EV-1 Descriptive Statistics for 2004

	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Miles Driven	12	46.0	94.2	841.1	70.092	13.3708
SOC Used (%)	12	55	96	958	79.83	12.364
Pack WH Used	12	9050	15517	154650	12887.50	1855.354
ACWH Used to Charge	12	11496	20053	173508	14459.00	2500.037
ACWH per Mile	12	162	314	2533	211.06	43.101
DC WH per Mile	12	165	212	2229	185.77	13.864
Energy Cost (cents/mile)	12	2.6	5.0	40.5	3.377	.6896
Efficiency (%)	12	62.7	103.7	1083.0	90.254	12.6939
SOC per Mile	12	1.0	1.3	13.8	1.148	.0797
Valid N (listwise)	12					

Energy cost based upon rate of 16 cents/kWH

TABLE B-4 EV-1 Case Summaries for 2005

	Start Date	End Date	Days Between Charges	Miles Driven	SOC Used (%)	Pack WH Used	ACWH Used to Charge
1	02/28/2005	03/05/2005	5	46.5	63	9683	15028
2	03/05/2005	03/06/2005	1	32.1	42	7167	8337
3	03/06/2005	03/08/2005	2	59.3	75	12050	13203
4	03/08/2005	03/09/2005	1	25.9	41	7033	7946
5	03/09/2005	03/10/2005	1	39.8	61	10017	11880
6	03/10/2005	03/13/2005	3	67.4	93	14367	15778
7	03/13/2005	03/14/2005	1	50.5	62	10283	12330
8	03/14/2005	03/16/2005	2	54.6	68	11117	11731
9	03/16/2005	03/17/2005	1	50.5	62	10383	11006
10	03/17/2005	03/18/2005	1	58.4	67	11033	11646
11	03/18/2005	03/19/2005	1	57.3	53	5383	11760
12	03/19/2005	03/21/2005	2	43.6	64	10217	12153
13	03/21/2005	03/22/2005	1	43.3	52	8700	9460
14	03/22/2005	03/24/2005	2	56.4	69	11150	12830
15	03/24/2005	03/25/2005	1	61.2	80	13100	14396
16	03/25/2005	03/26/2005	1	43.4	54	8900	9652
17	03/26/2005	03/29/2005	3	60.9	73	11583	13991
18	03/29/2005	03/31/2005	2	79.1	94	14700	16027
19	03/31/2005	04/01/2005	1	71.0	79	12800	12955
20	05/14/2005	05/17/2005	3	45.2	45	8300	10739
21	05/17/2005	05/19/2005	2	65.3	74	11700	12373
22	05/21/2005	05/25/2005	4	41.5	51	7733	11478
23	05/31/2005	06/02/2005	2	63.8	69	10833	15034
24	07/13/2005	07/14/2005	1	60.1	69	10783	14228
25	07/14/2005	07/18/2005	4	51.6	60	9067	12591
Total N	25	25	25	25	25	25	25

TABLE B-5 EV-1 Case Summaries for 2005

	Start Date	End Date	ACWH per Mile	DC WH per Mile	Energy Cost (cents/mile)	Efficiency (%)	SOC per Mile
1	02/28/2005	03/05/2005	323	208	5.2	64.4	1.4
2	03/05/2005	03/06/2005	260	223	4.2	86.0	1.3
3	03/06/2005	03/08/2005	223	203	3.6	91.3	1.3
4	03/08/2005	03/09/2005	307	272	4.9	88.5	1.6
5	03/09/2005	03/10/2005	298	252	4.8	84.3	1.5
6	03/10/2005	03/13/2005	234	213	3.7	91.1	1.4
7	03/13/2005	03/14/2005	244	204	3.9	83.4	1.2
8	03/14/2005	03/16/2005	215	204	3.4	94.8	1.2
9	03/16/2005	03/17/2005	218	206	3.5	94.3	1.2
10	03/17/2005	03/18/2005	199	189	3.2	94.7	1.1
11	03/18/2005	03/19/2005	205	94	3.3	45.8	.9
12	03/19/2005	03/21/2005	279	234	4.5	84.1	1.5
13	03/21/2005	03/22/2005	218	201	3.5	92.0	1.2
14	03/22/2005	03/24/2005	227	198	3.6	86.9	1.2
15	03/24/2005	03/25/2005	235	214	3.8	91.0	1.3
16	03/25/2005	03/26/2005	222	205	3.6	92.2	1.2
17	03/26/2005	03/29/2005	230	190	3.7	82.8	1.2
18	03/29/2005	03/31/2005	203	186	3.2	91.7	1.2
19	03/31/2005	04/01/2005	182	180	2.9	98.8	1.1
20	05/14/2005	05/17/2005	238	184	3.8	77.3	1.0
21	05/17/2005	05/19/2005	189	179	3.0	94.6	1.1
22	05/21/2005	05/25/2005	277	186	4.4	67.4	1.2
23	05/31/2005	06/02/2005	236	170	3.8	72.1	1.1
24	07/13/2005	07/14/2005	237	179	3.8	75.8	1.1
25	07/14/2005	07/18/2005	244	176	3.9	72.0	1.2
Total N	25	25	25	25	25	25	25

TABLE B-6 EV-1 Descriptive Statistics for 2005

	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Miles Driven	25	25.9	79.1	1328.7	53.148	12.3006
Pack WH Used	25	5383	14700	258082	10323.29	2244.081
ACWH Used to Charge	25	7946	16027	308552	12342.08	2133.241
ACWH per Mile	25	182	323	5944	237.75	35.708
DC WH per Mile	25	94	272	4949	197.97	32.155
Energy Cost (cents/mile)	25	2.9	5.2	95.1	3.804	.5713
Efficiency (%)	25	45.8	98.8	2097.1	83.884	12.1869
SOC per Mile	25	.9	1.6	30.9	1.236	.1498
Valid N (listwise)	25					

Energy cost based upon rate of 16 cents/kWH

TABLE B-7 EV-1 Case Summaries for 2006

	Start Date	End Date	Days Between Charges	Miles Driven	SOC Used	Pack WH	ACWH to Recharge
1	04/07/2006	04/12/2006	5	51.1	58	9000	30810
2	04/12/2006	04/13/2006	1	47.7	57	8717	9387
3	04/13/2006	04/17/2006	4	41.9	52	7883	23793
4	04/17/2006	04/18/2006	1	42.5	53	8383	18566
5	04/18/2006	04/19/2006	1	41.2	53	8133	9327
6	04/19/2006	04/20/2006	1	47.0	60	9150	22400
7	04/20/2006	04/21/2006	1	47.2	63	9383	11115
Total N	7	7	7	7	7	7	7

TABLE B-8 EV-1 Case Summaries for 2006

	Start Date	End Date	ACWH per Mile	DCWH per Mile	Energy Cost	Efficiency
1	04/07/2006	04/12/2006	603	176	9.6	29.2
2	04/12/2006	04/13/2006	197	183	3.1	92.9
3	04/13/2006	04/17/2006	568	188	9.1	33.1
4	04/17/2006	04/18/2006	437	197	7.0	45.2
5	04/18/2006	04/19/2006	226	197	3.6	87.2
6	04/19/2006	04/20/2006	477	195	7.6	40.8
7	04/20/2006	04/21/2006	235	199	3.8	84.4
Total N	7	7	7	7	7	7

TABLE B-9 EV-1 Descriptive Statistics for 2006

	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Miles Driven	7	41.2	51.1	318.6	45.514	3.6921
SOC Used	7	52	63	396	56.57	4.117
Pack WH	7	7883	9383	60649	8664.14	553.737
ACWH per Mile	7	197	603	2743	391.84	170.595
DCWH per Mile	7	176	199	1335	190.73	8.673
Energy Cost	7	3.1	9.6	43.9	6.269	2.7295
Efficiency	7	29.2	92.9	412.8	58.975	27.8856
Valid N (listwise)	7					

Energy cost based upon rate of 16 cents/kWH

FIGURE B-1 EV-1 Pack Currents for September 12-15th, 2004

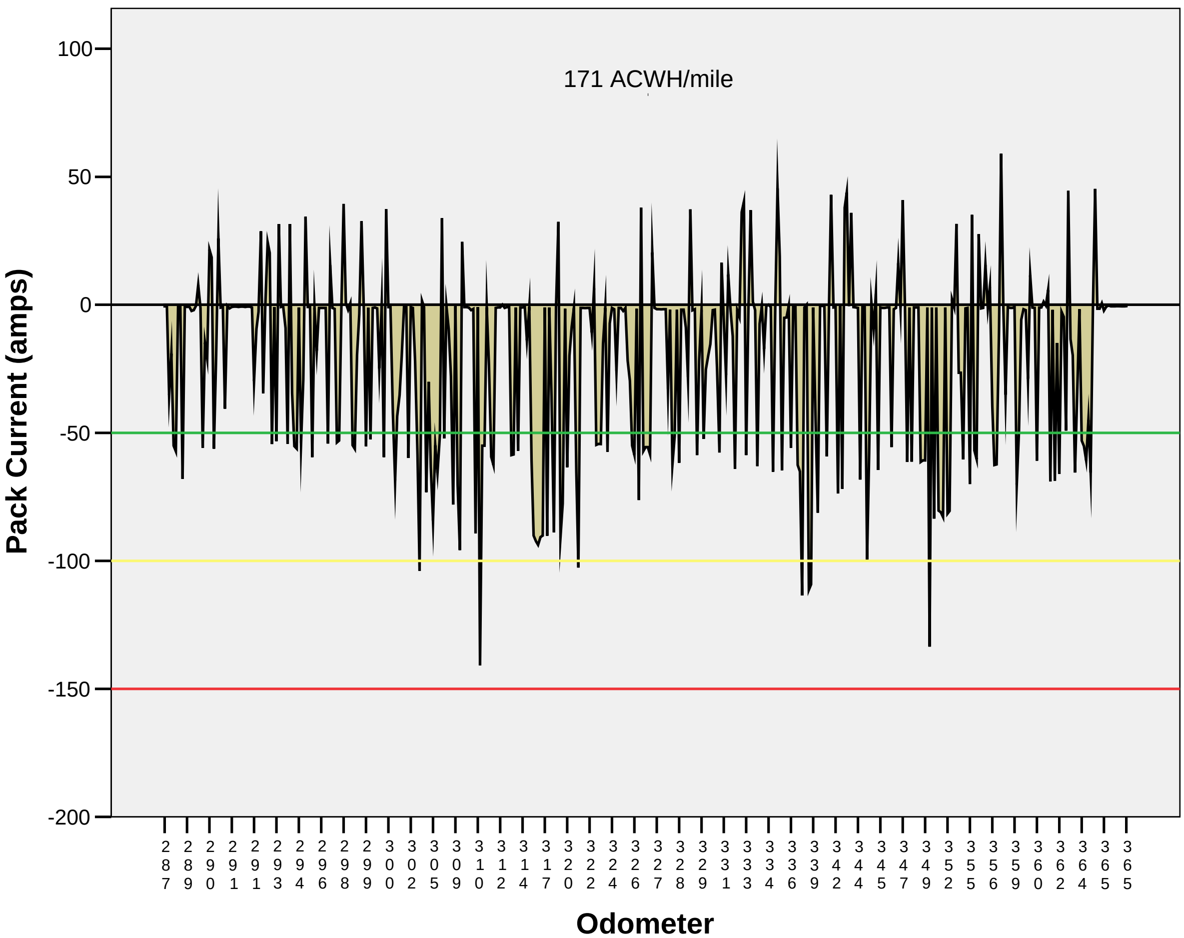


FIGURE B-2 EV-1 Pack Currents for September 15-16, 2004

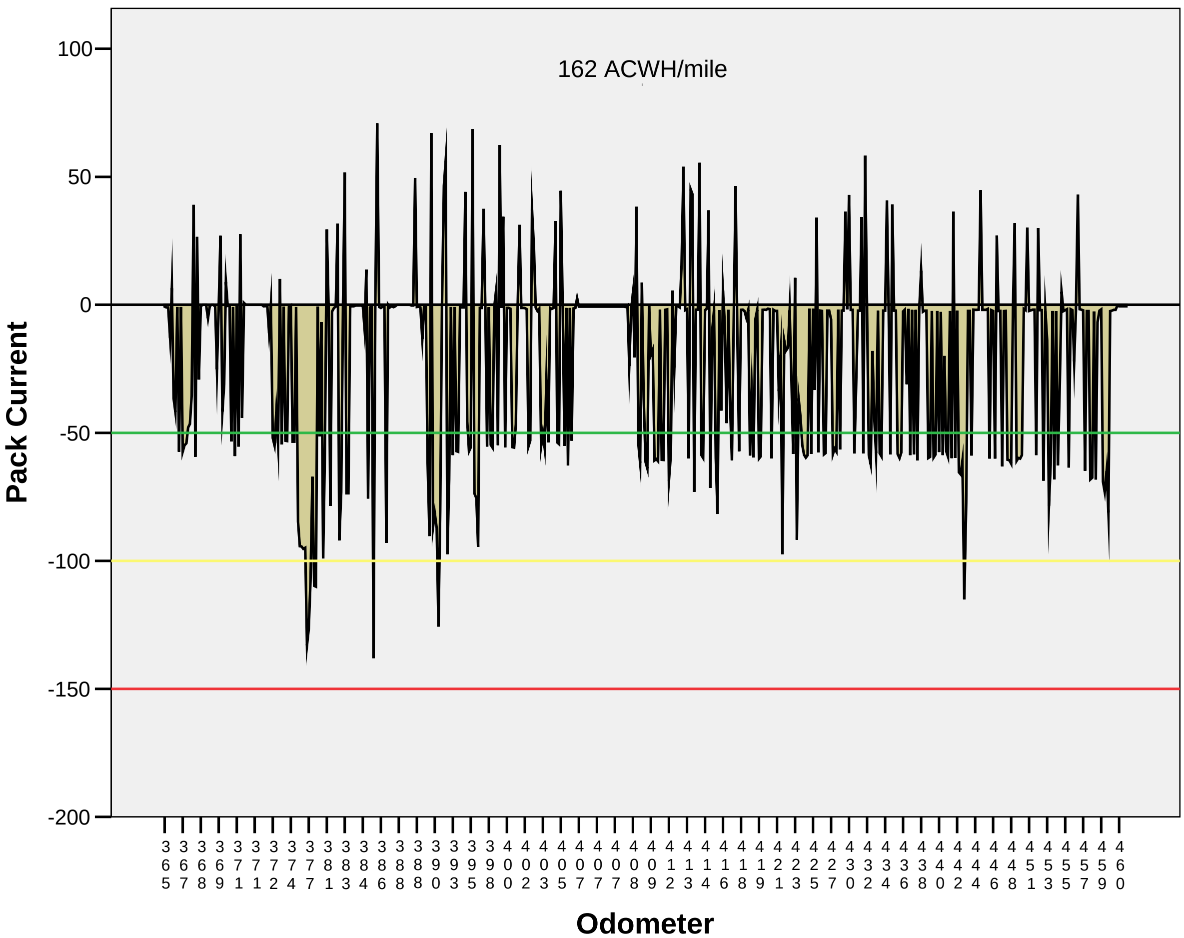


FIGURE B-3 EV-1 Pack Currents for September 20-22nd, 2004

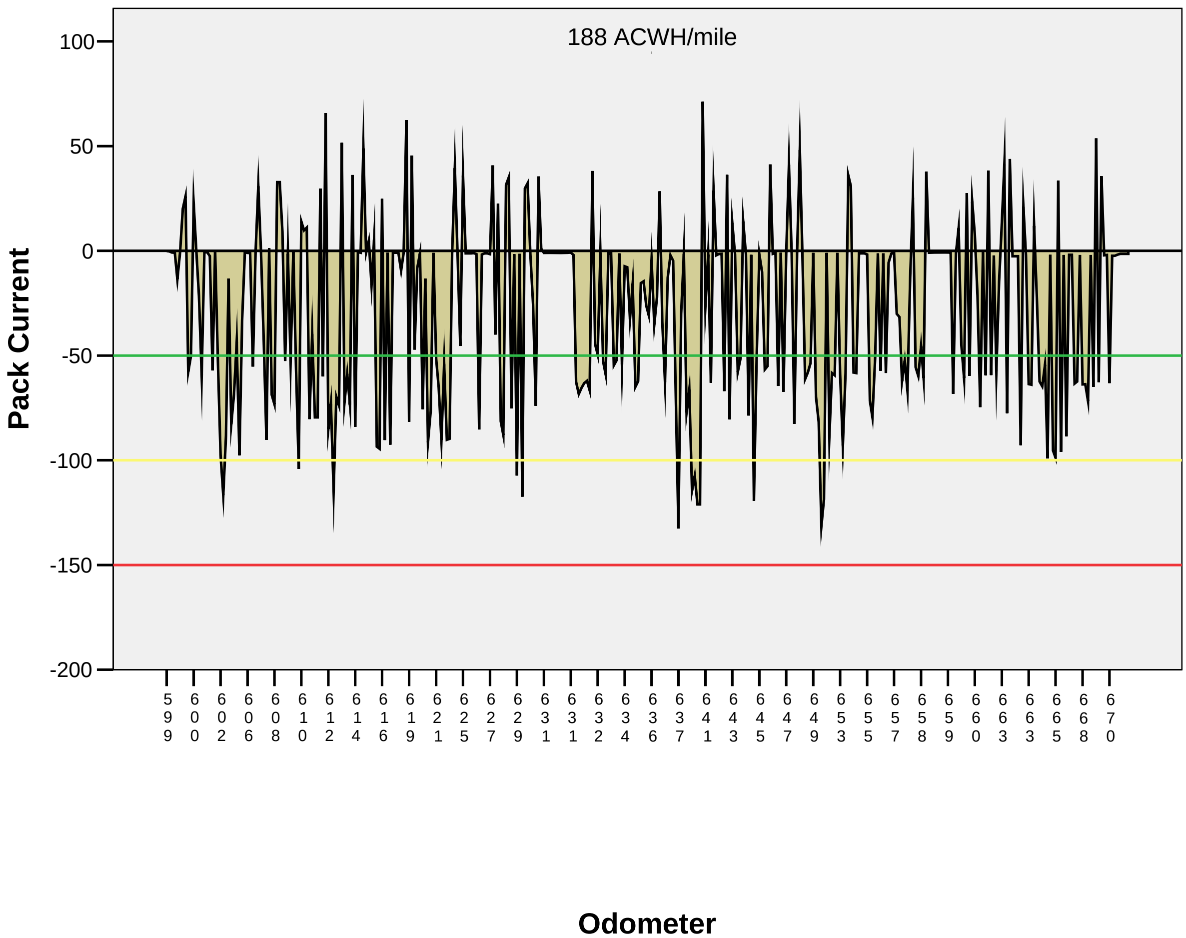


FIGURE B-4 EV-1 Pack Currents for September 22-23rd, 2004

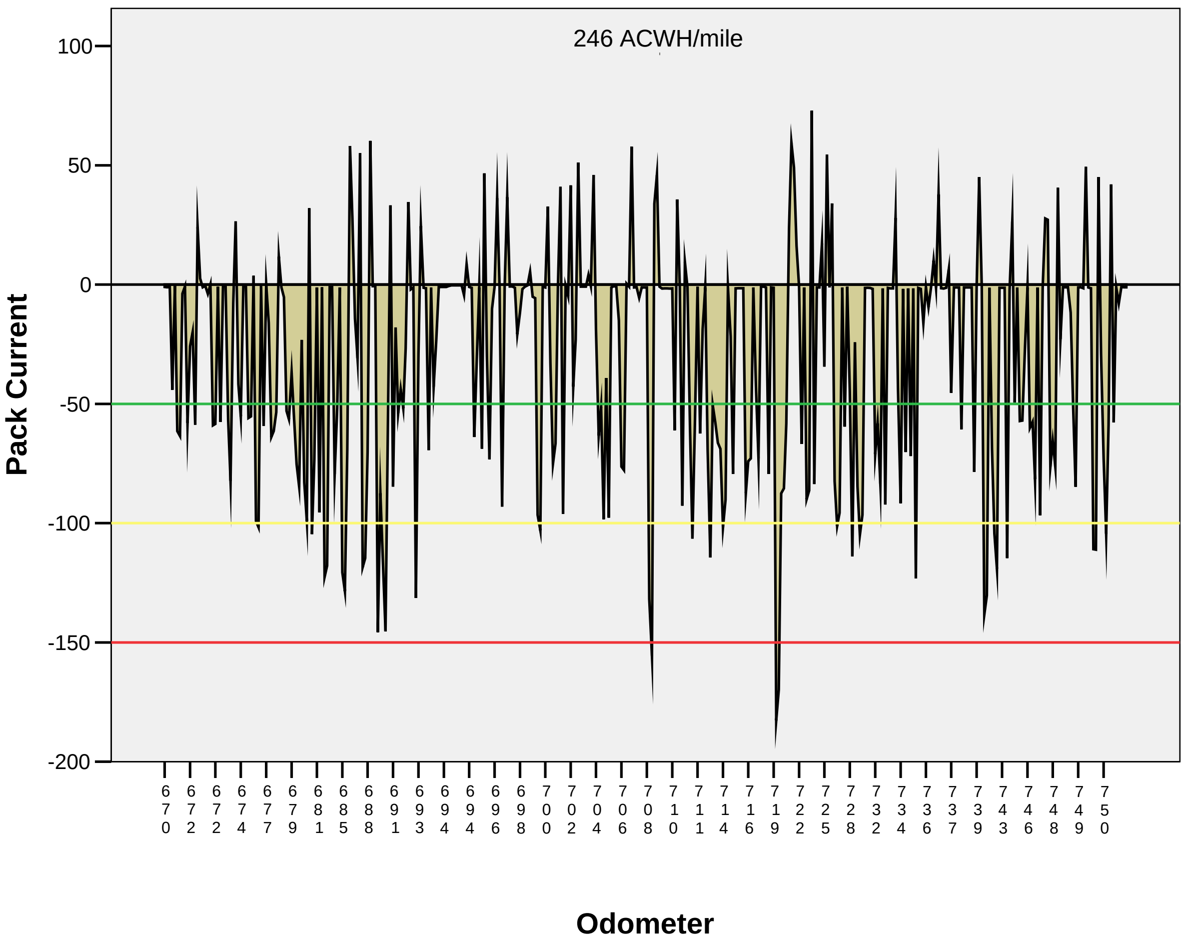


FIGURE B-5 EV-1 Pack Currents for September 23-25, 2004

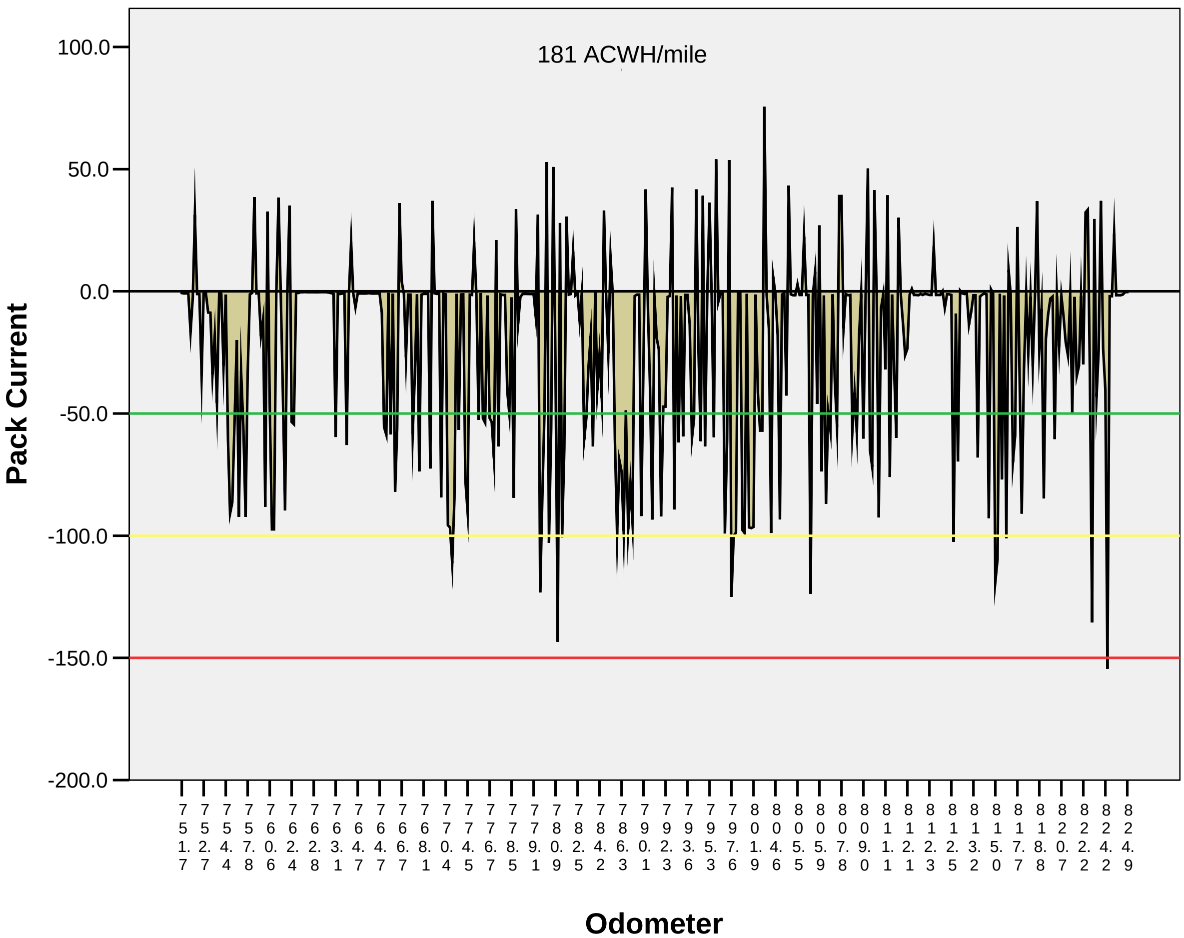


FIGURE B-6 EV-1 Pack Currents for September 25, 2004

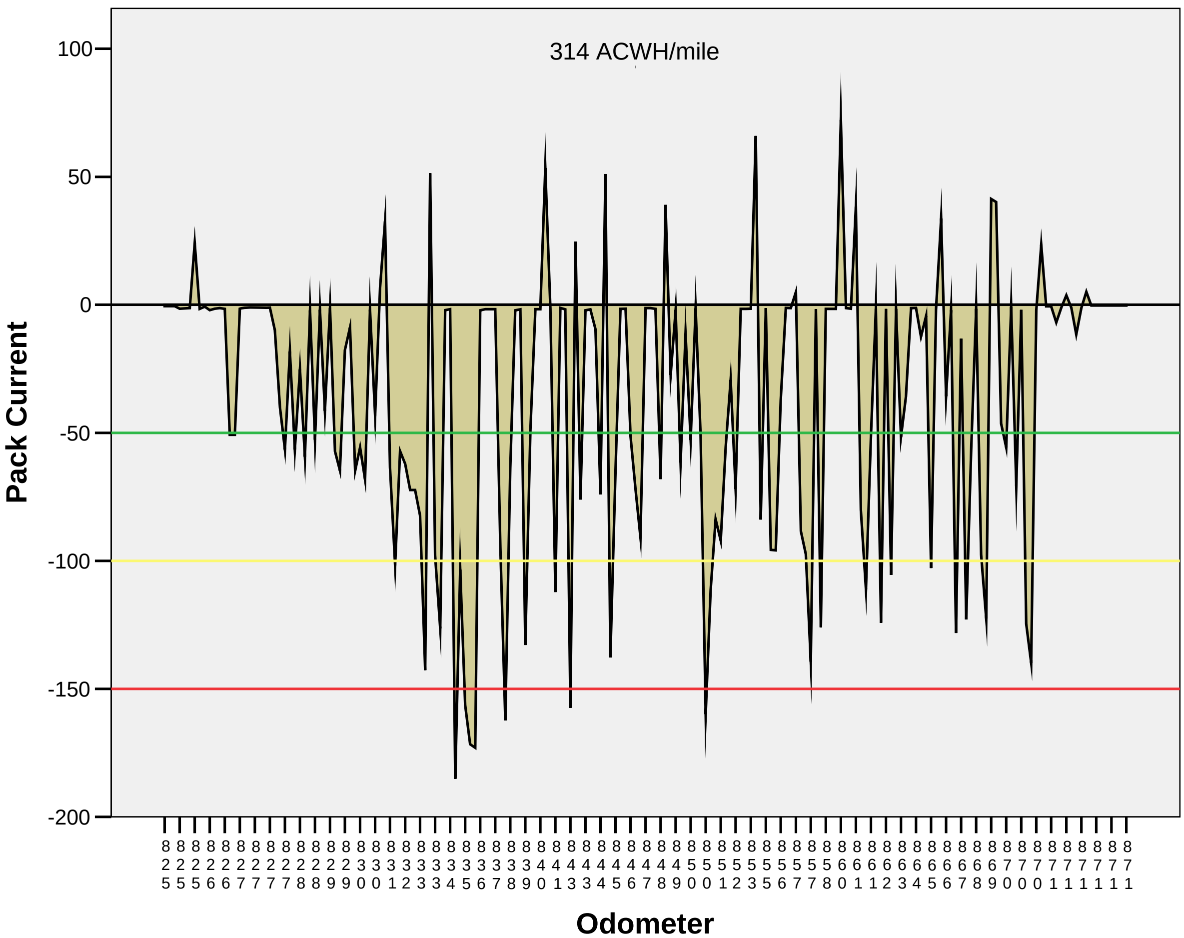


FIGURE B-7 EV-1 Pack Currents for September 25-27, 2004

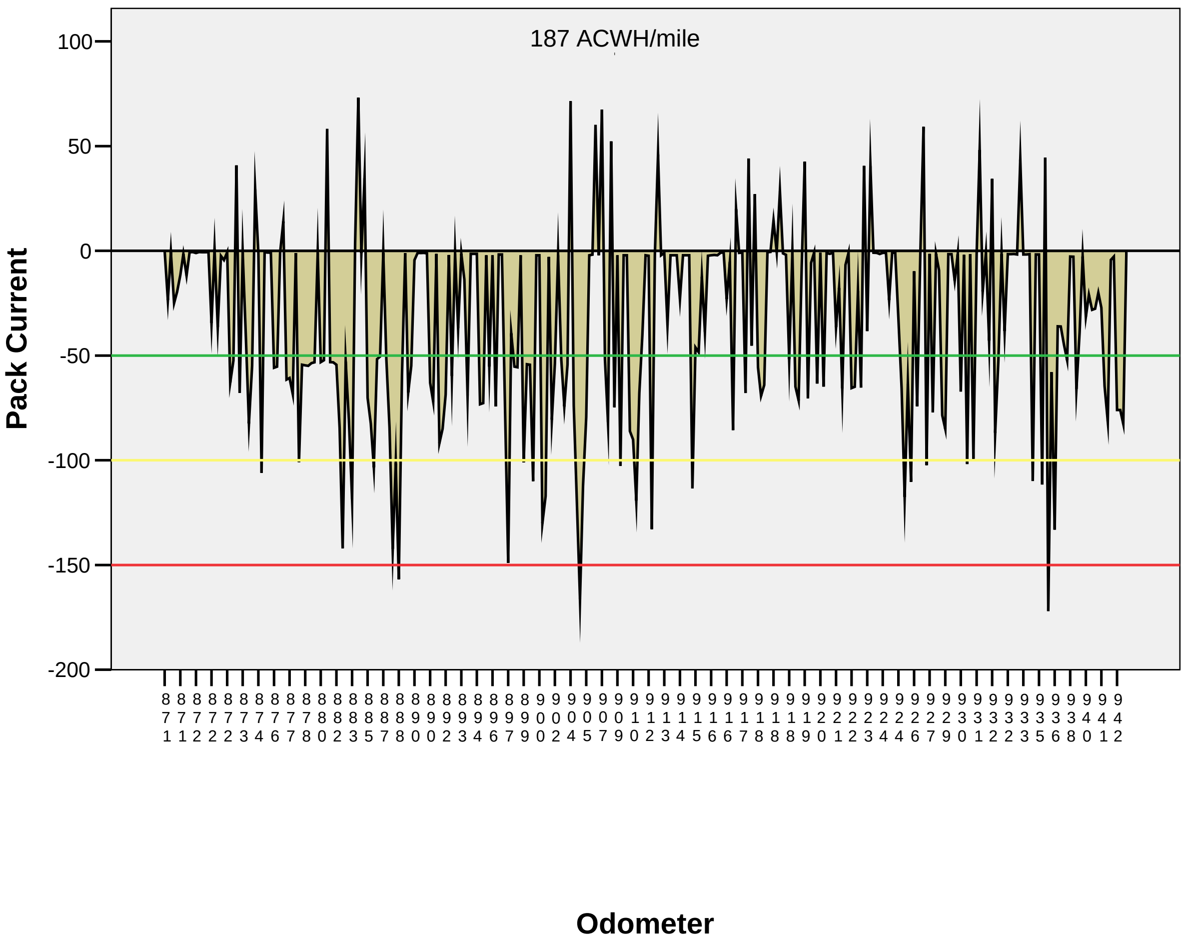


FIGURE B-8 EV-1 Pack Currents for October 31 to November 1, 2004

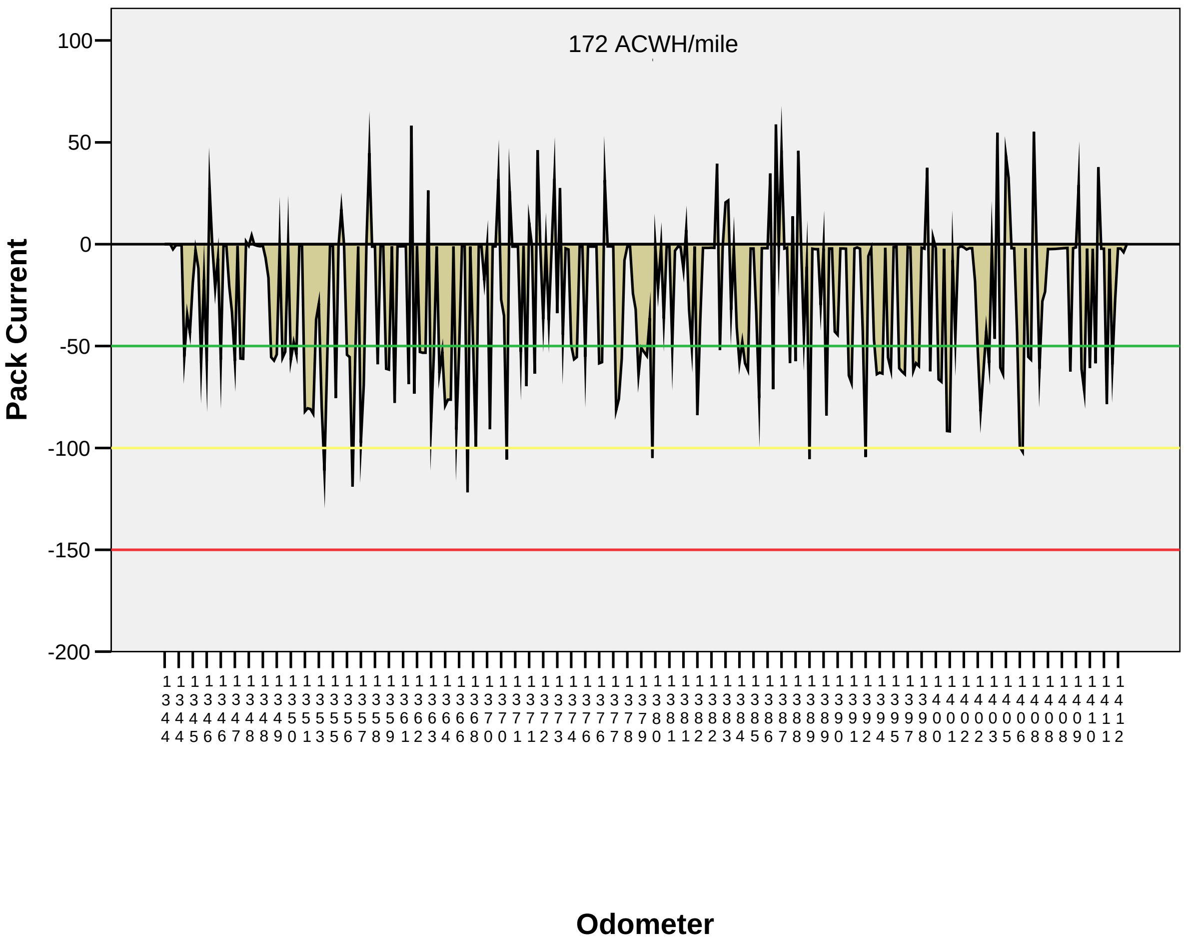


FIGURE B-9 EV-1 Pack Currents for November 5-8th, 2004

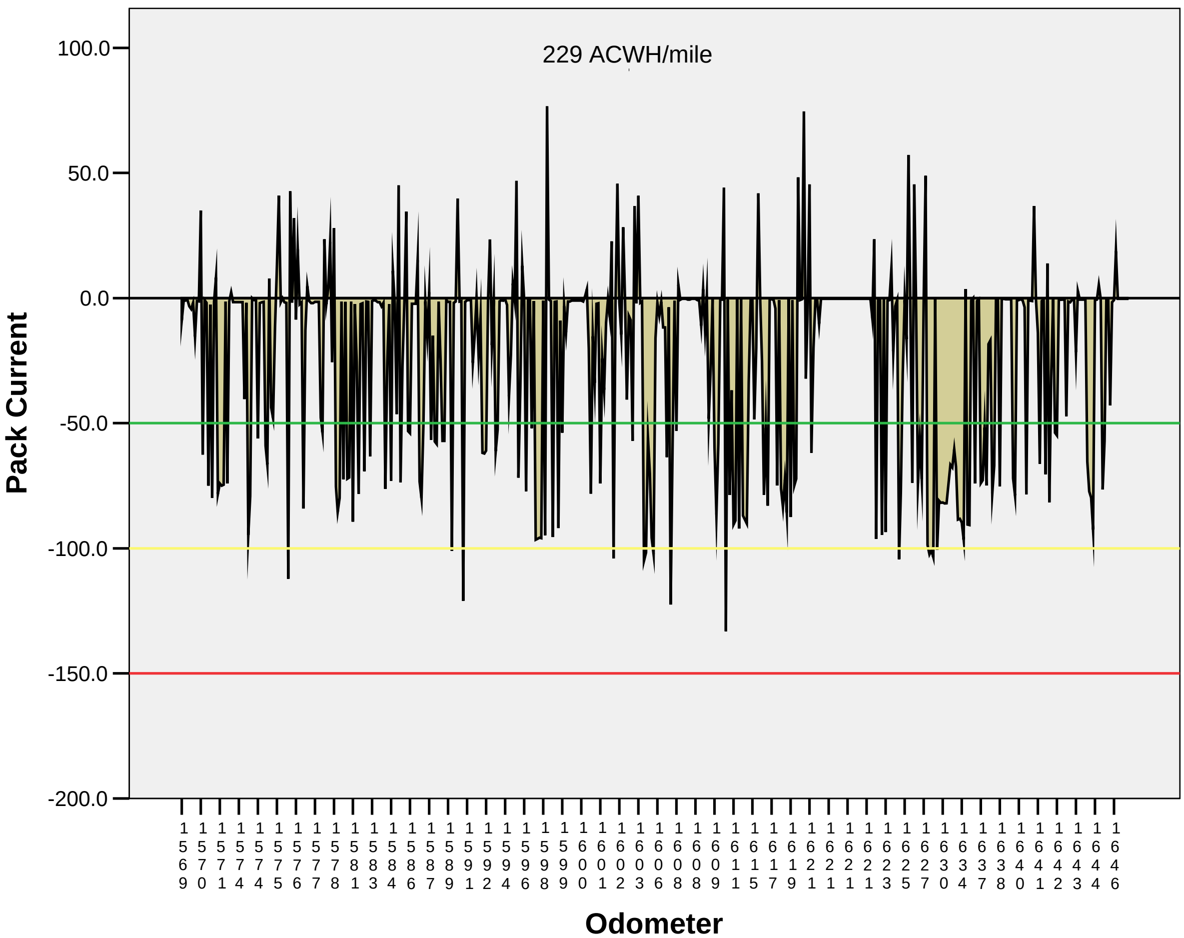


FIGURE B-10 EV-1 Pack Currents for November 9-10, 2004

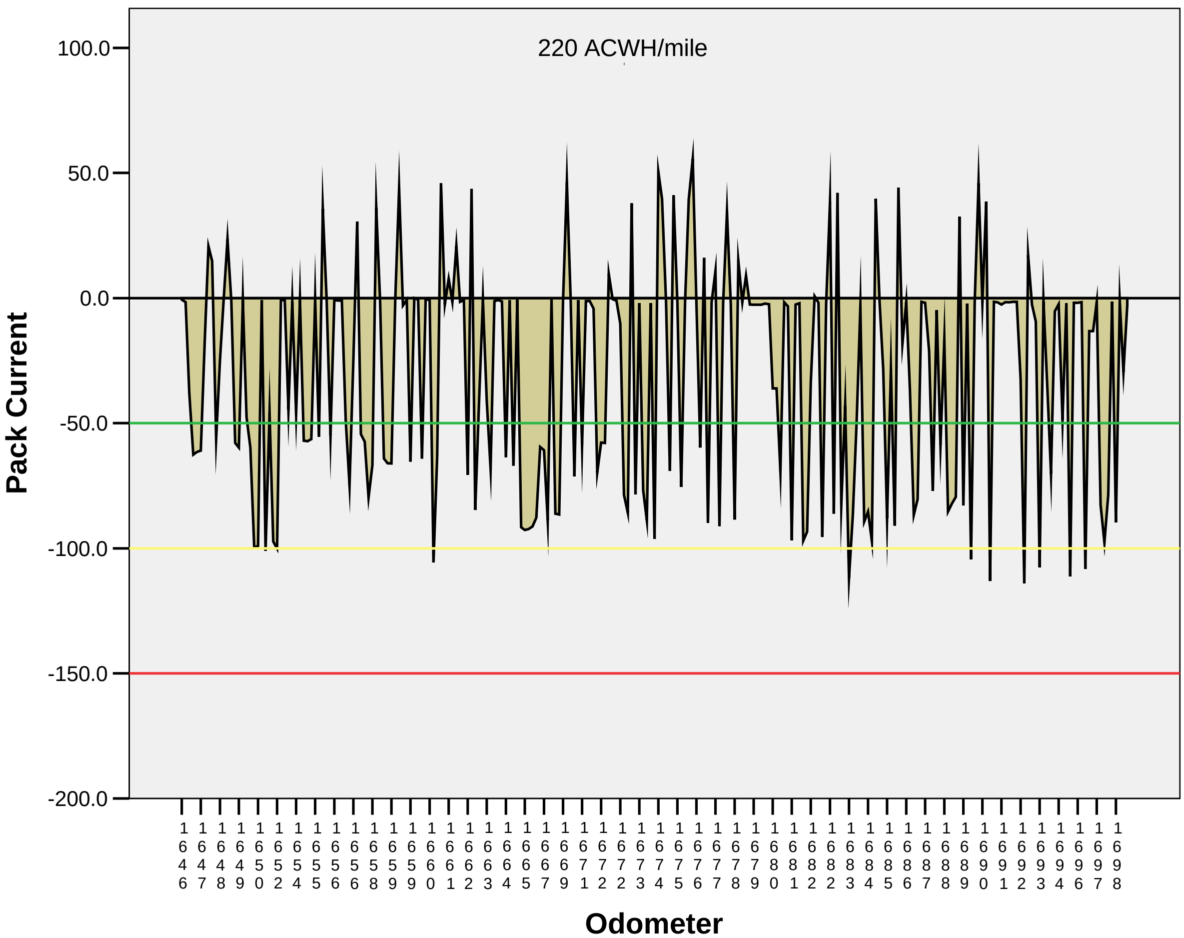


FIGURE B-11 EV-1 Pack Currents for November 18-21, 2004

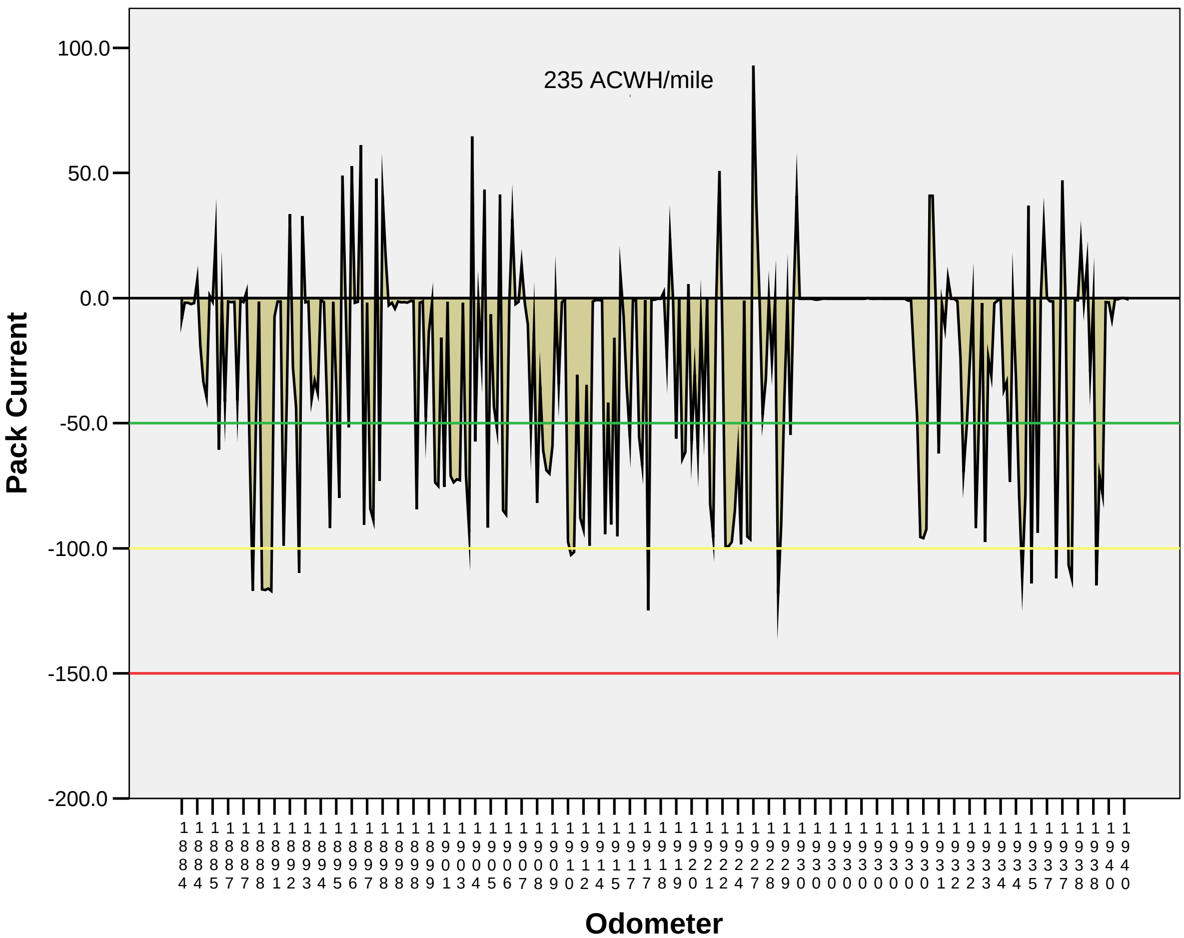


FIGURE B-12 EV-1 Pack Currents for November 21-24, 2004

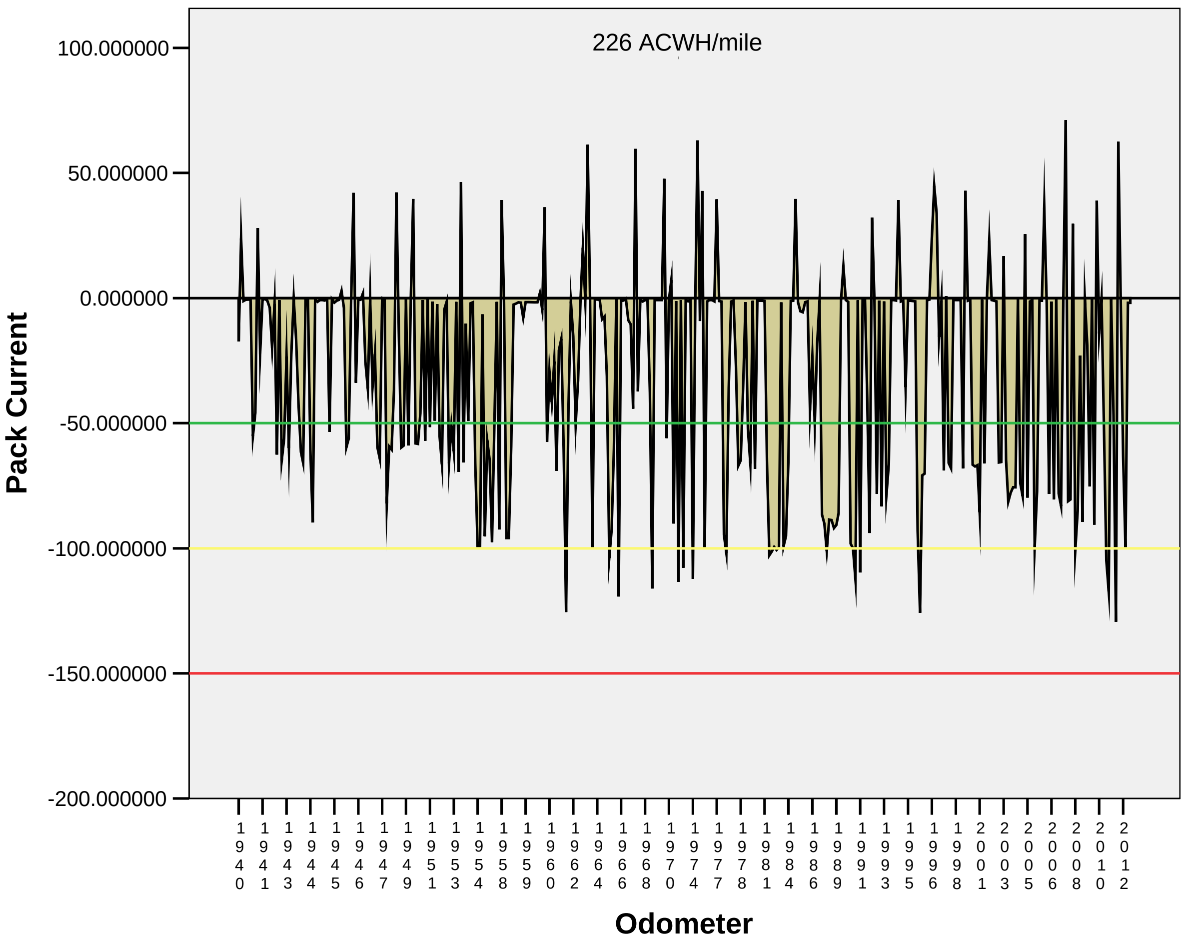


FIGURE B-13 EV-1 Pack Currents for February 28 to March 5, 2005

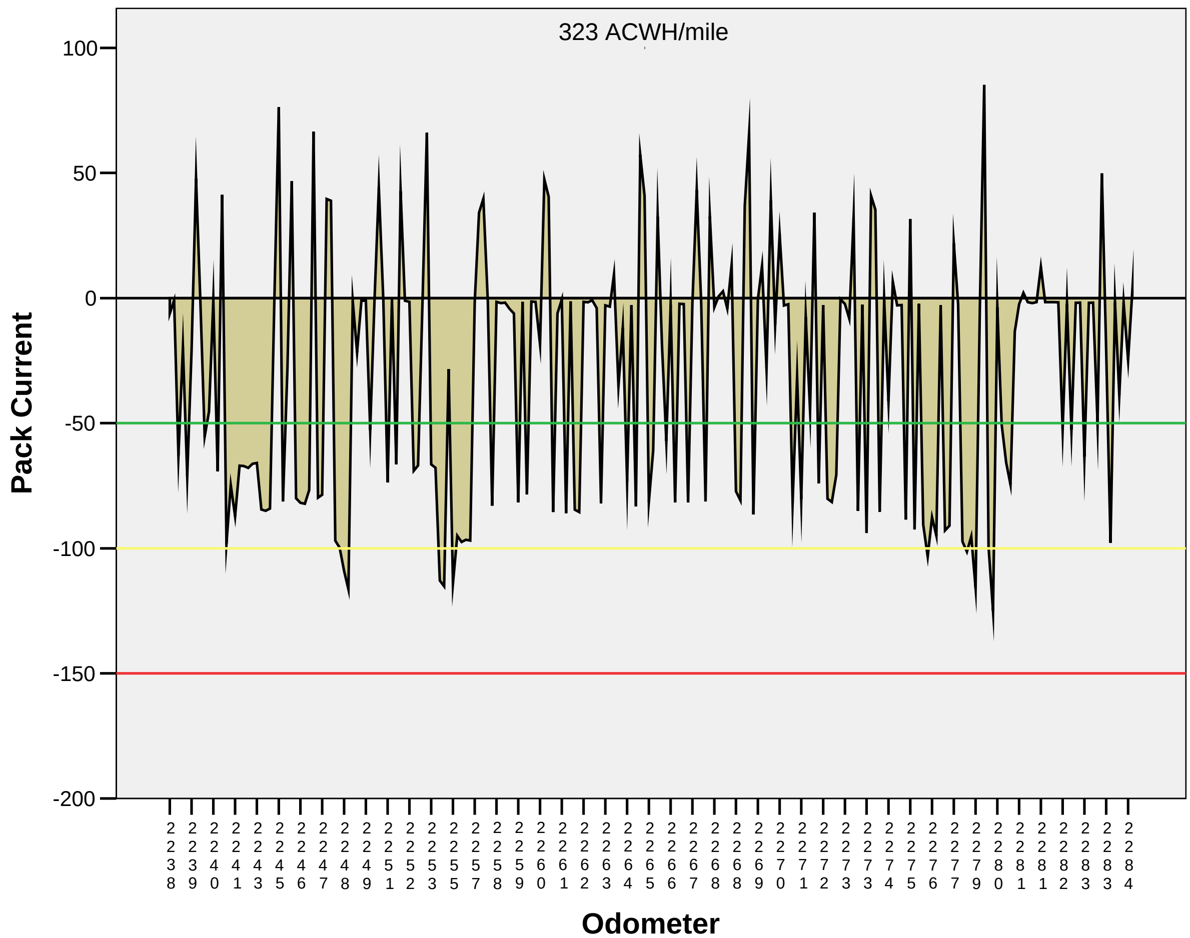
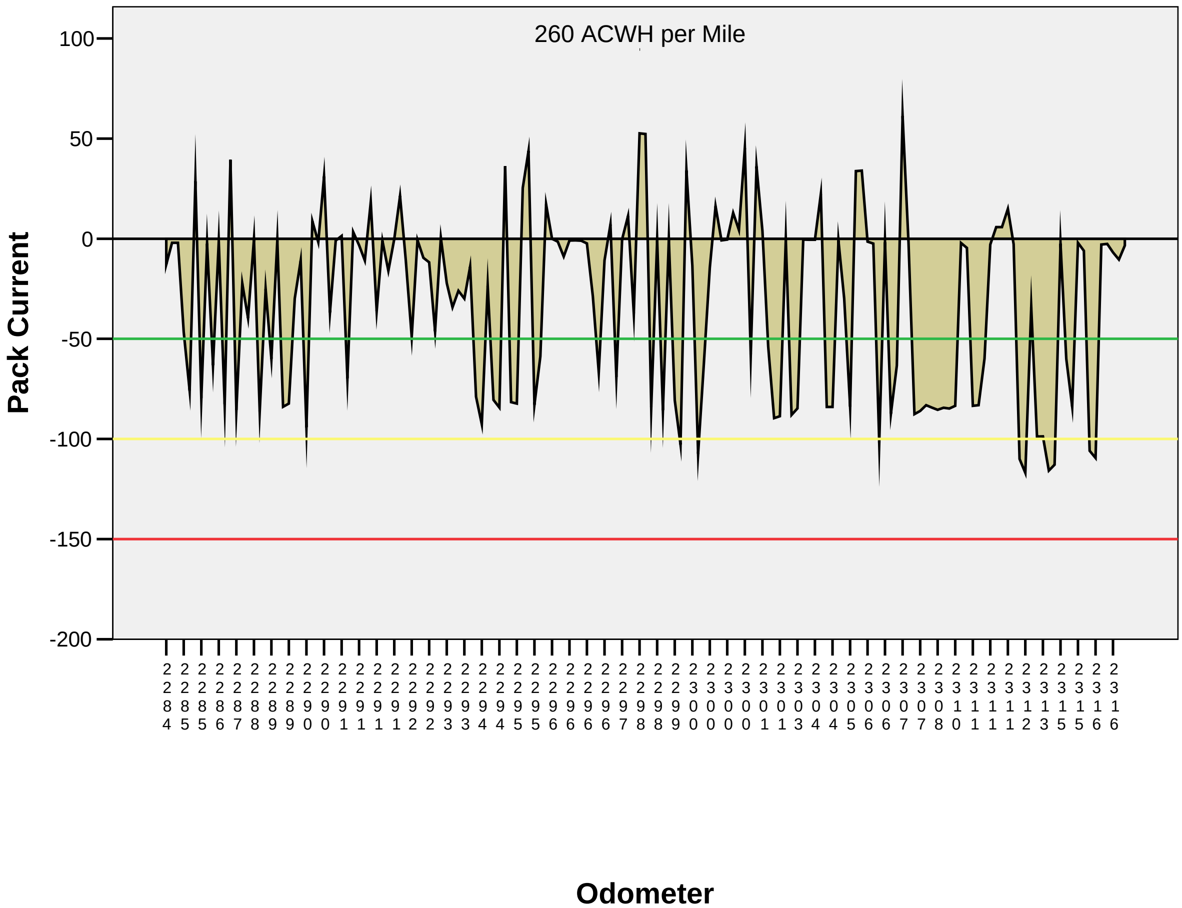


FIGURE B-14 EV-1 Pack Currents for March 5-6, 2005



FIGIRE B-15 EV-1 Pack Currents for March 6-8, 2005

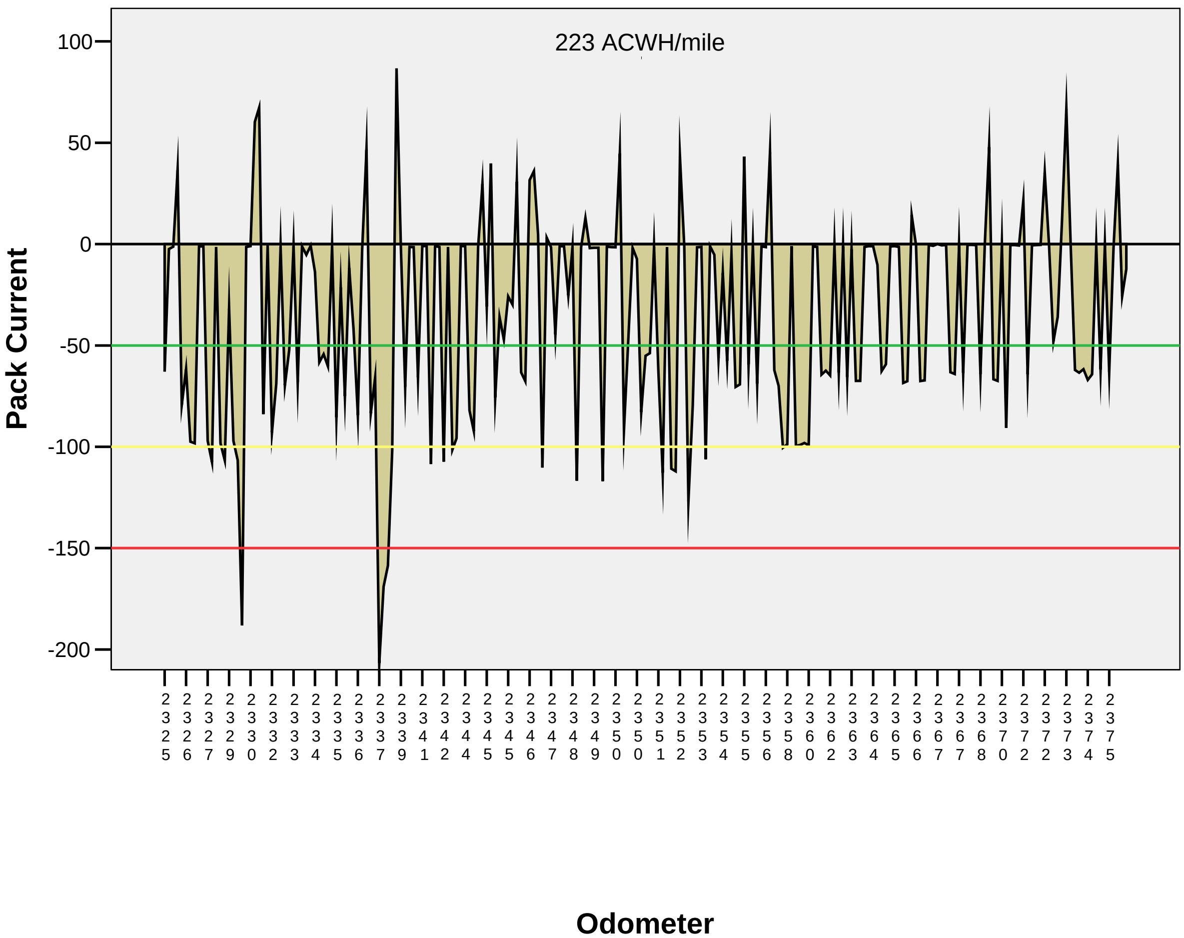


FIGURE B-16 EV-1 Pack Currents for March 8-9, 2005

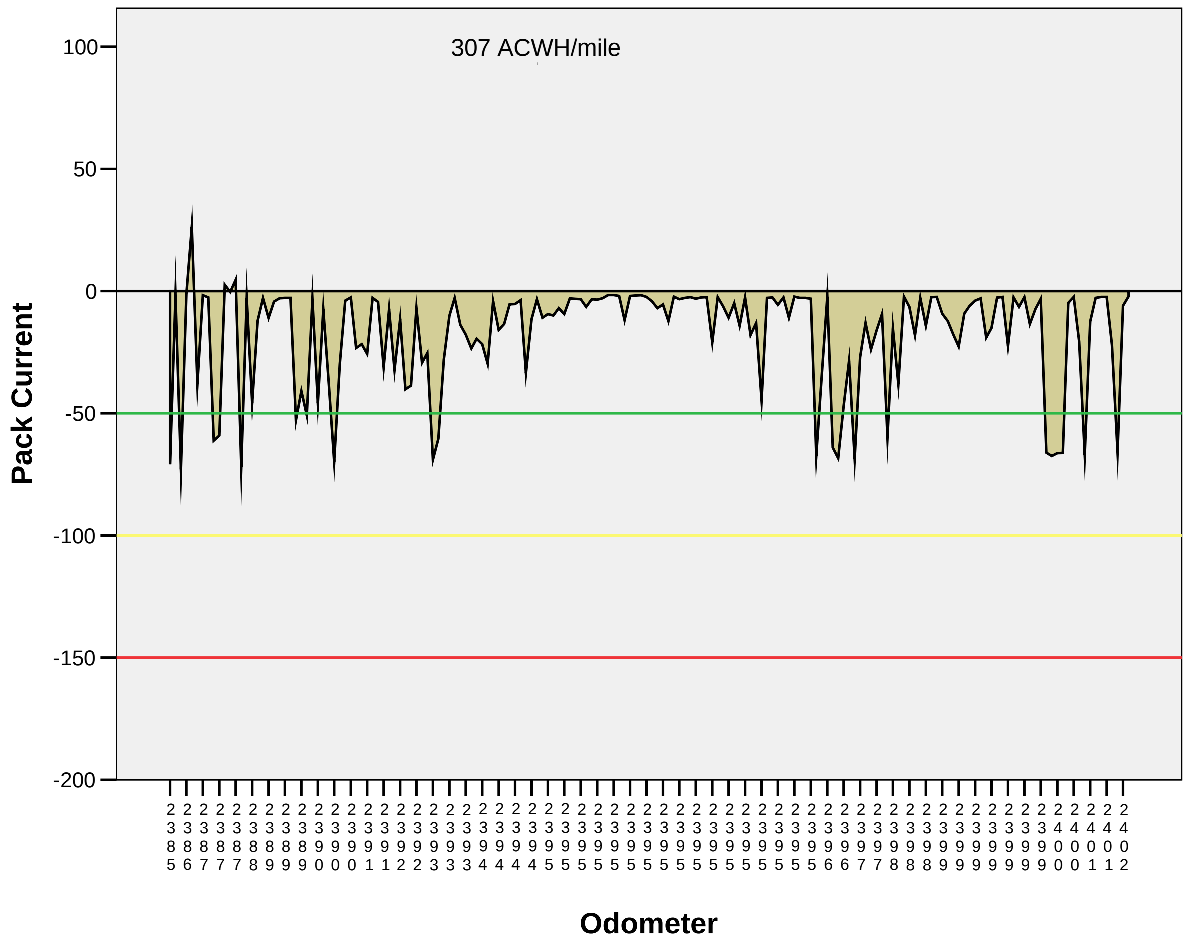


FIGURE B-17 EV-1 Pack Currents for March 9-10, 2005

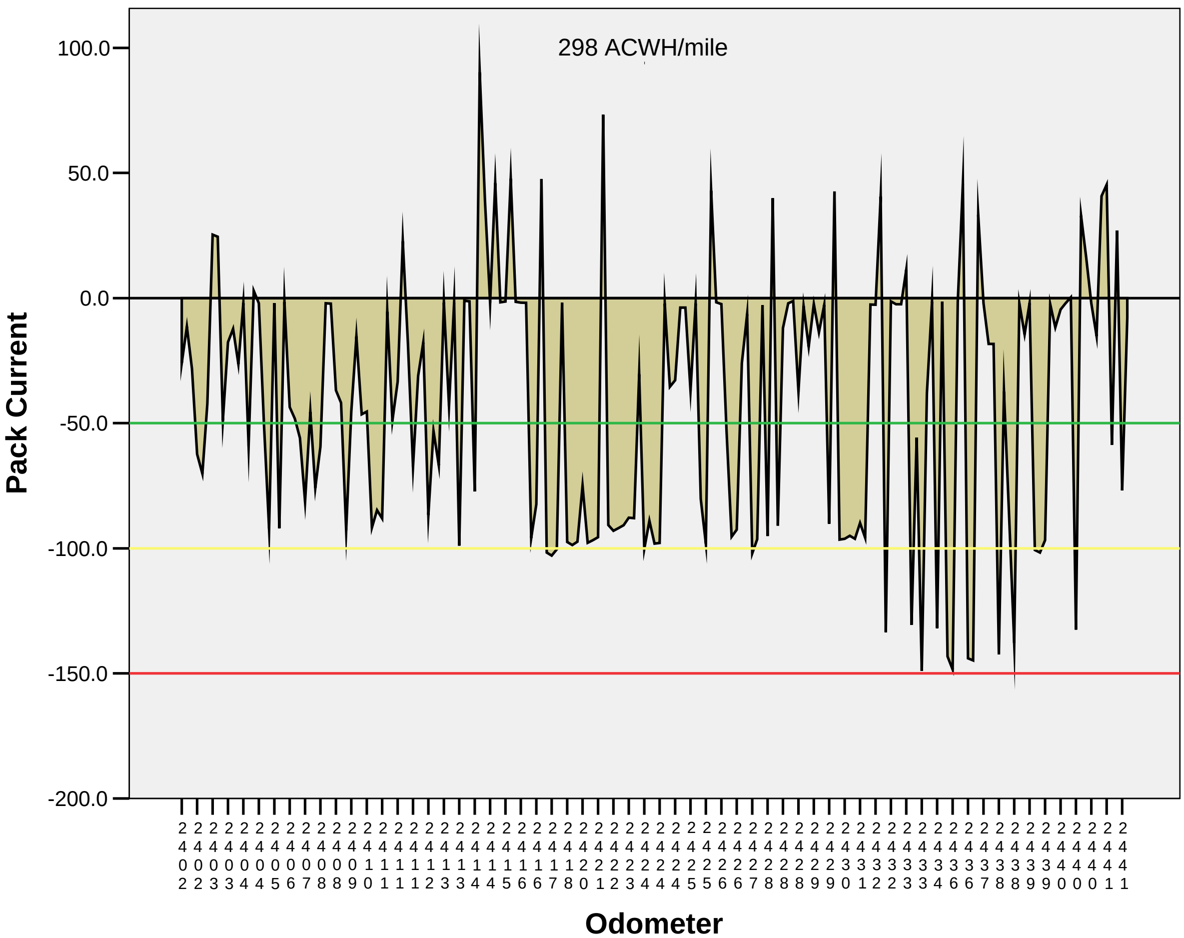


FIGURE B-18 EV-1 Pack Currents for March 10-13, 2005

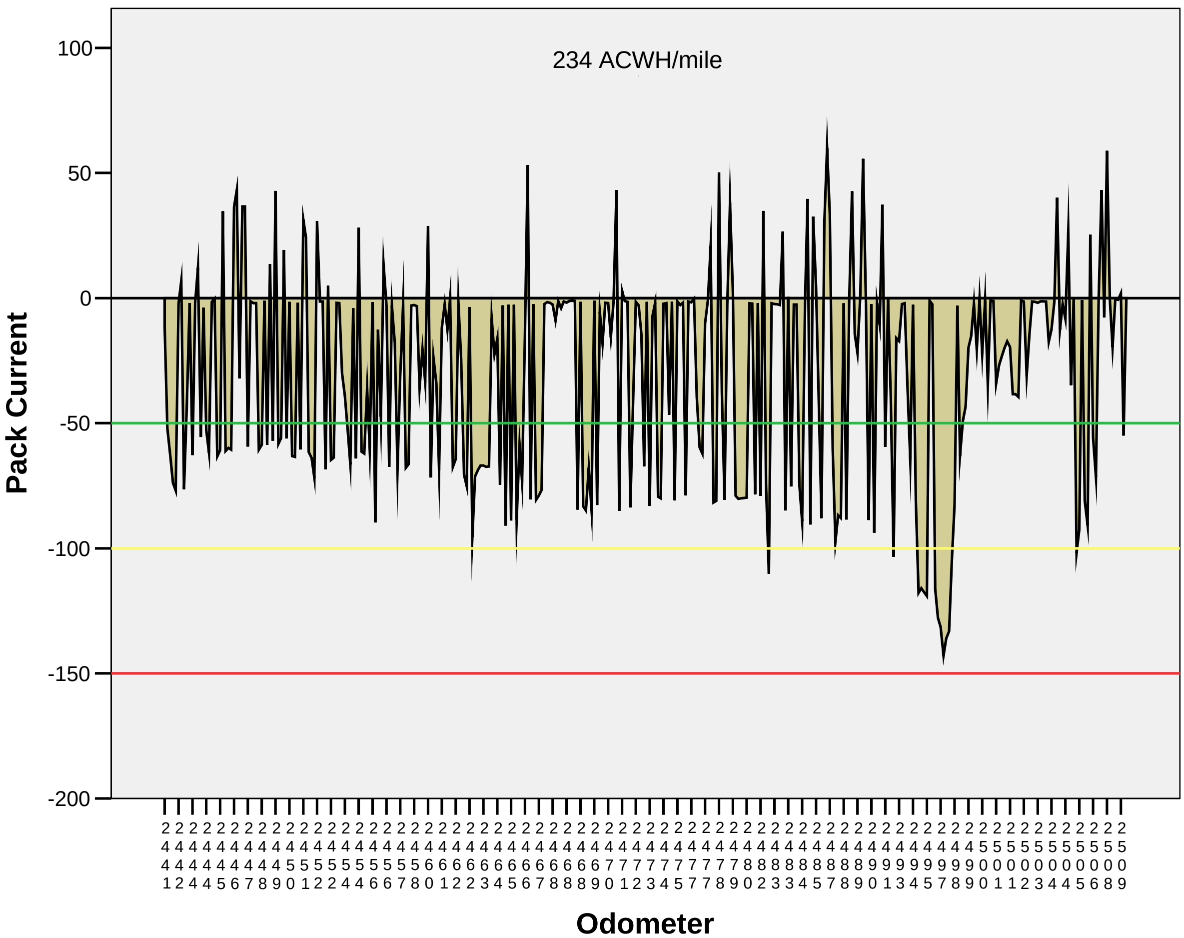


FIGURE B-19 EV-1 Pack Currents for March 13-14, 2005

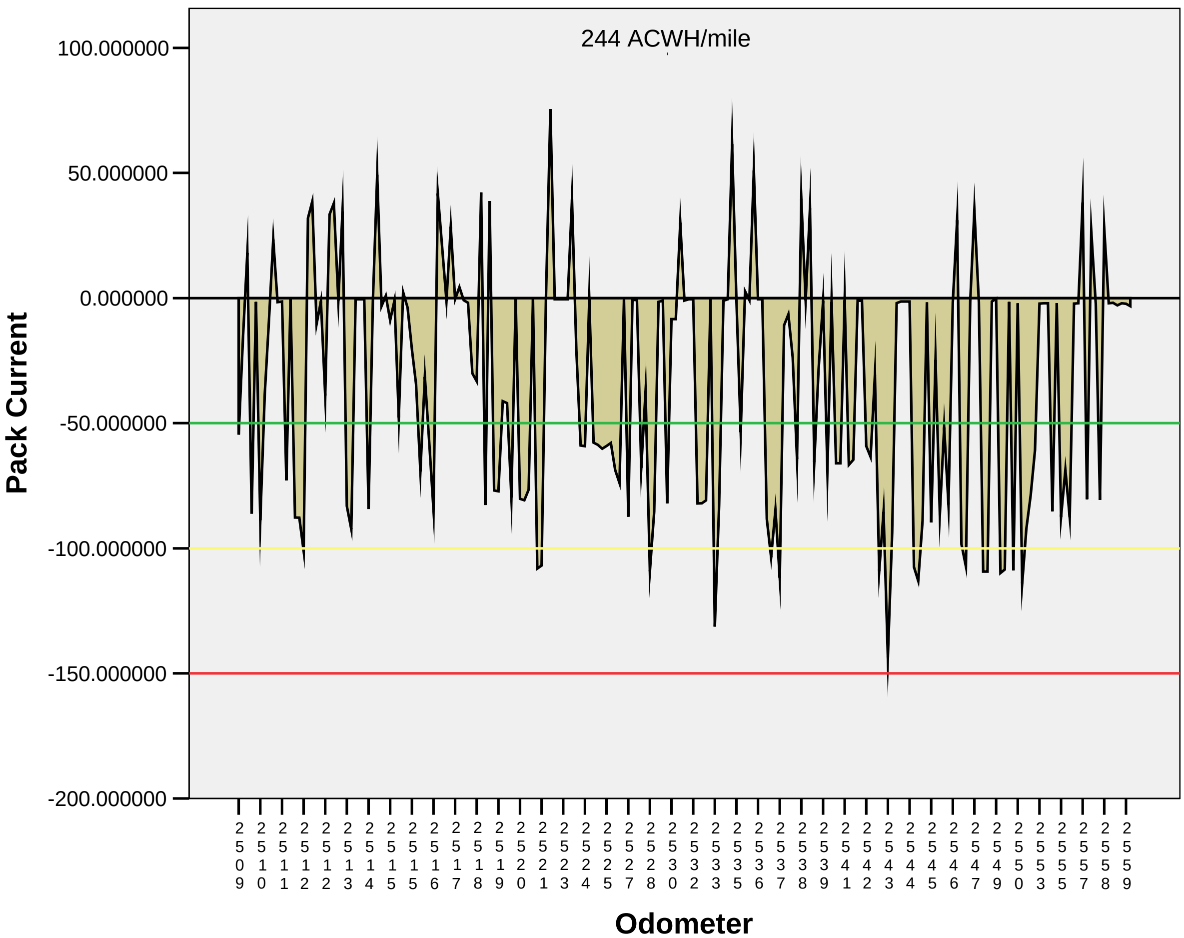


FIGURE B-20 EV-1 Pack Currents for March 14-16, 2005

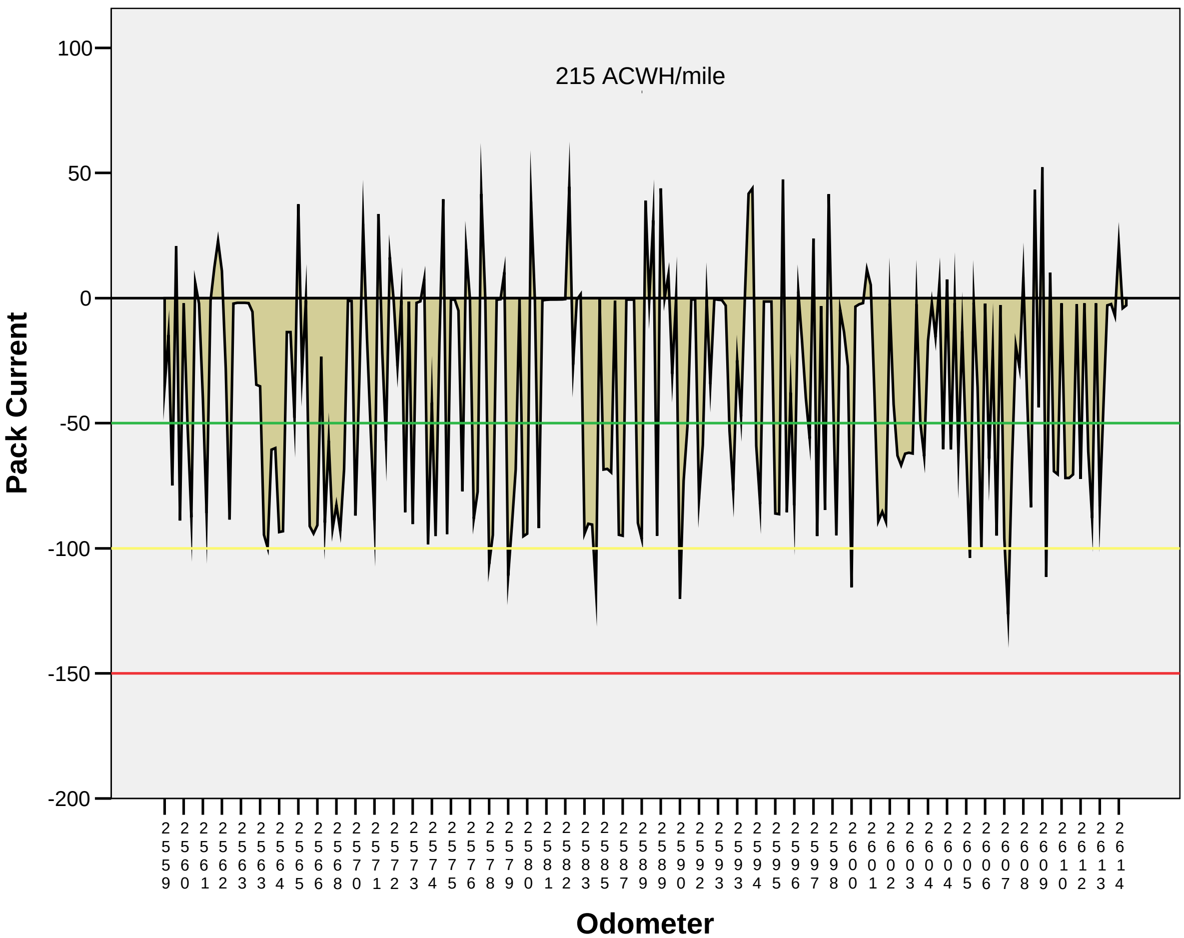


FIGURE B-21 EV-1 Pack Currents for March 16-17, 2005

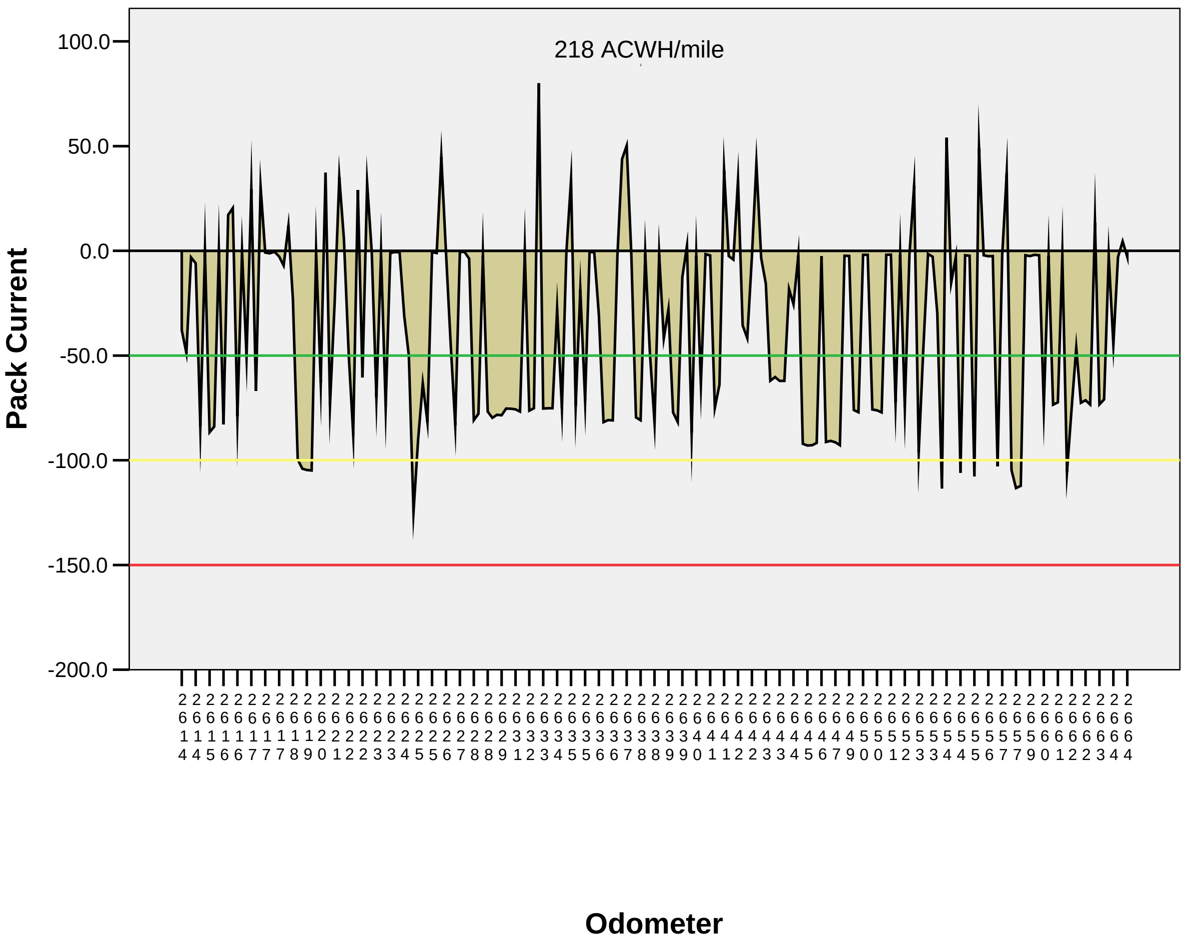


FIGURE B-22 EV-1 Pack Currents for March 17-18, 2005

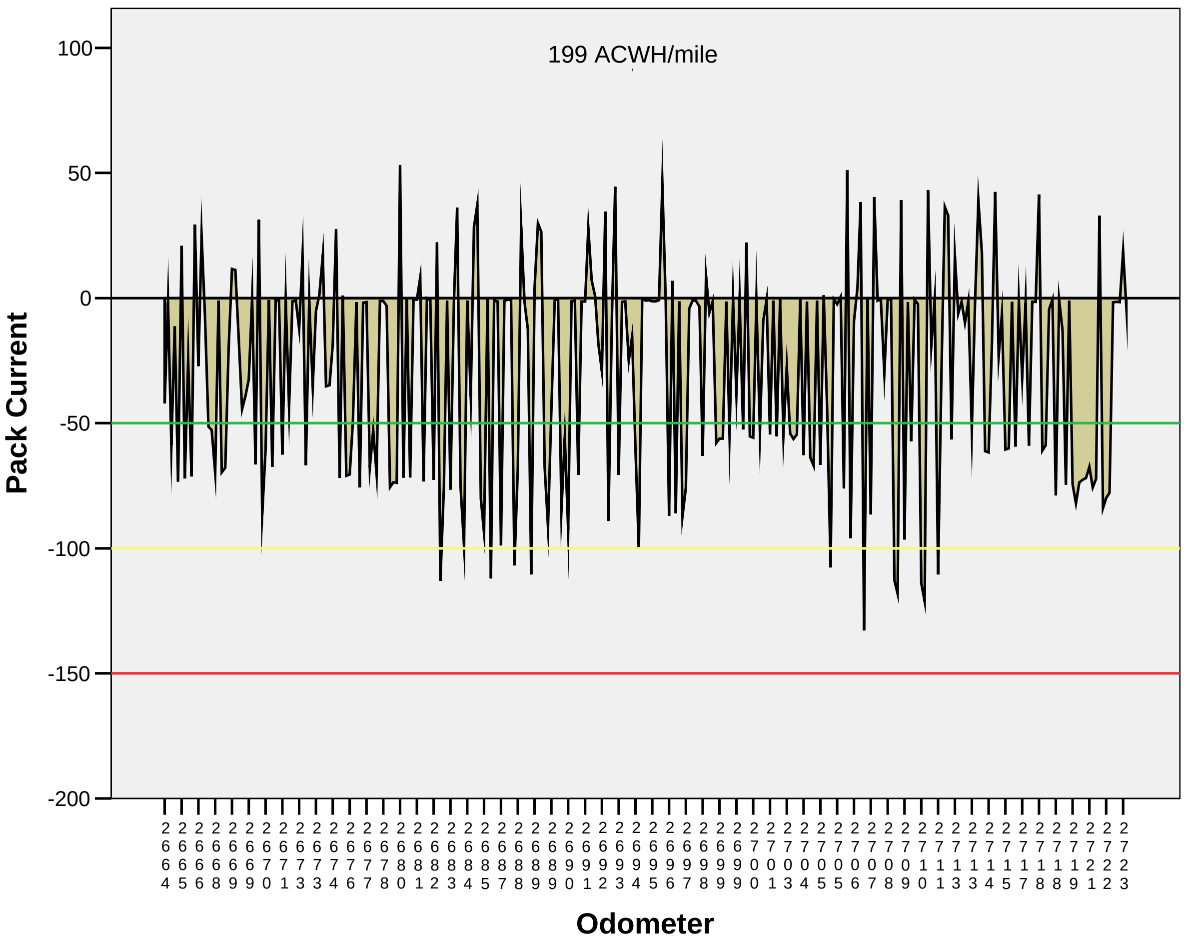


FIGURE B-23 EV-1 Pack Currents for March 18-19, 2005

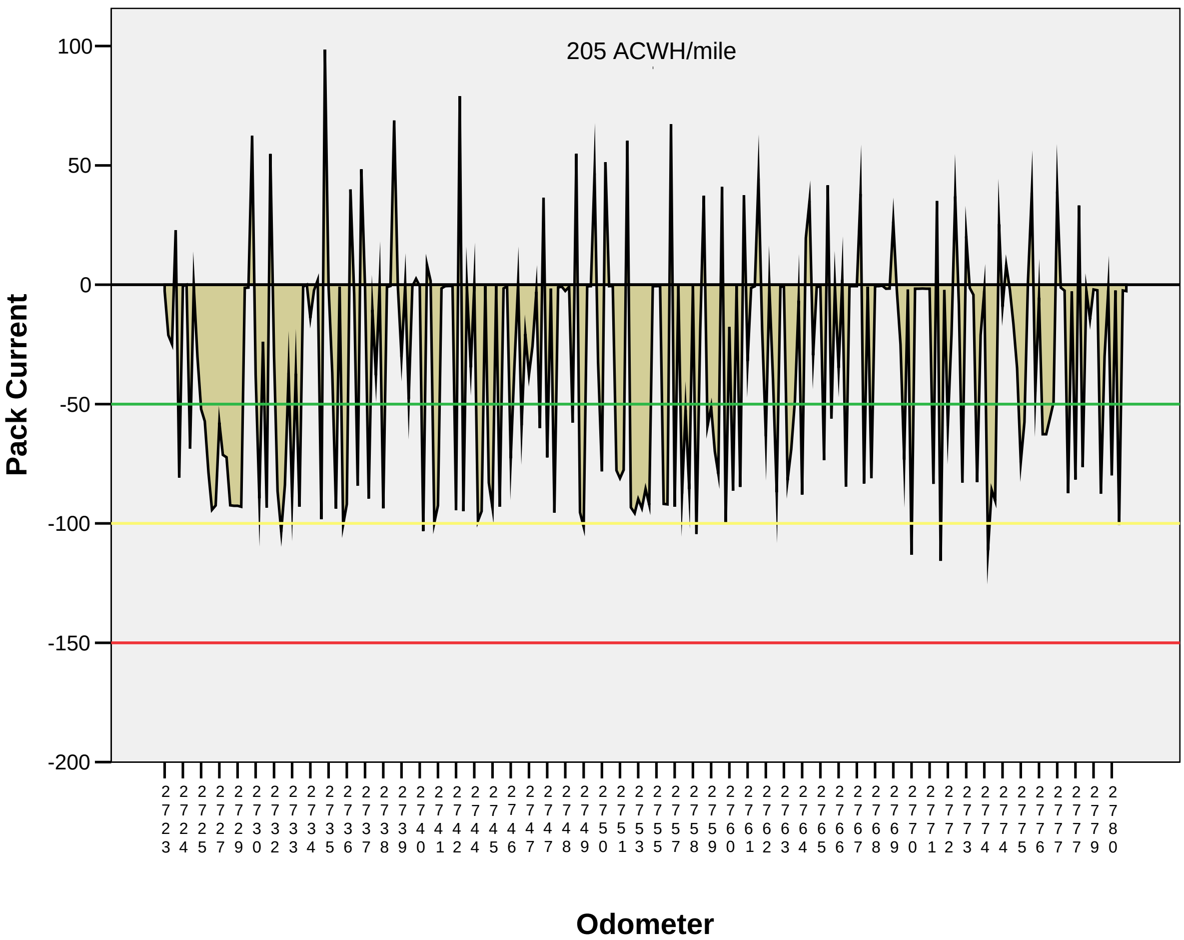


FIGURE B-24 EV-1 Pack Currents for March 19-21, 2005

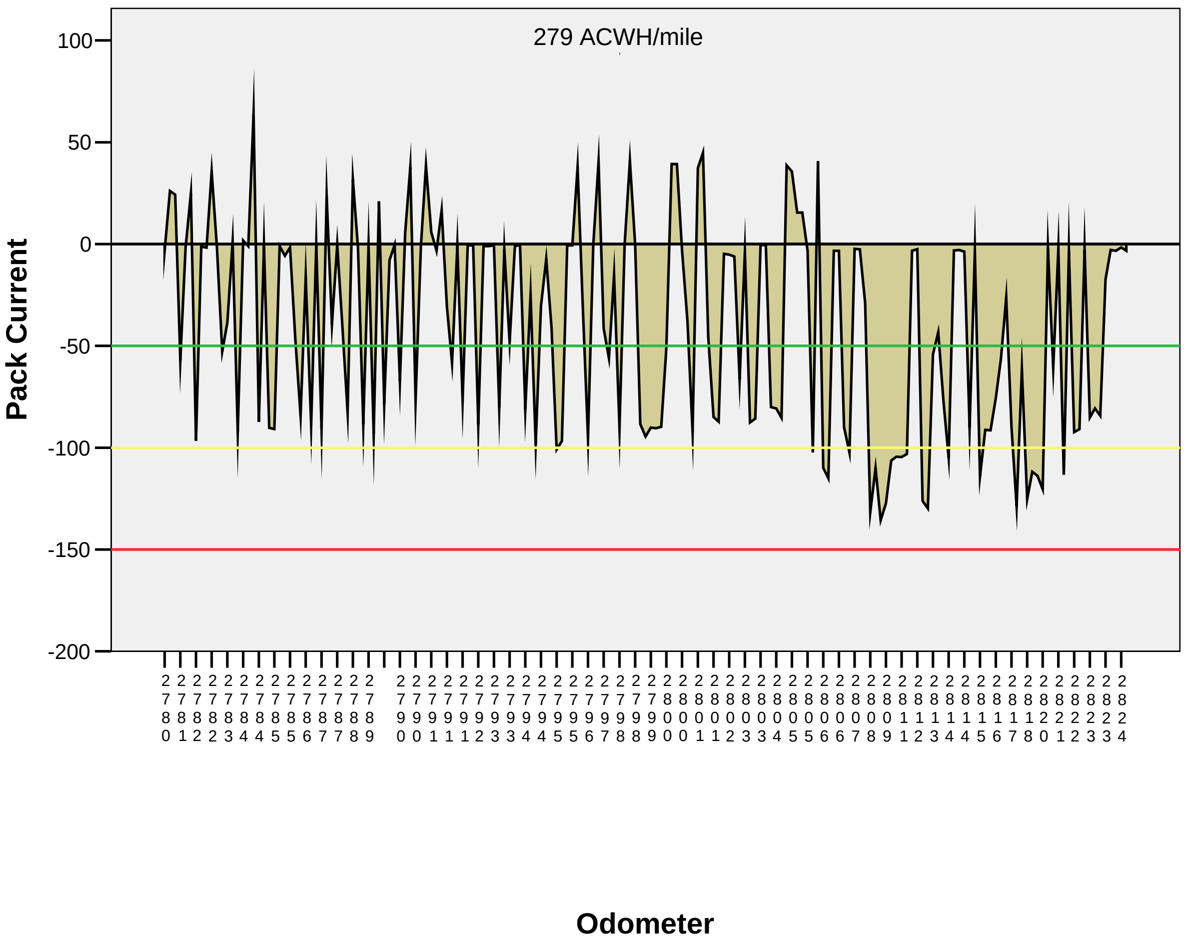


FIGURE B-25 EV-1 Pack Currents for March 21-22, 2005

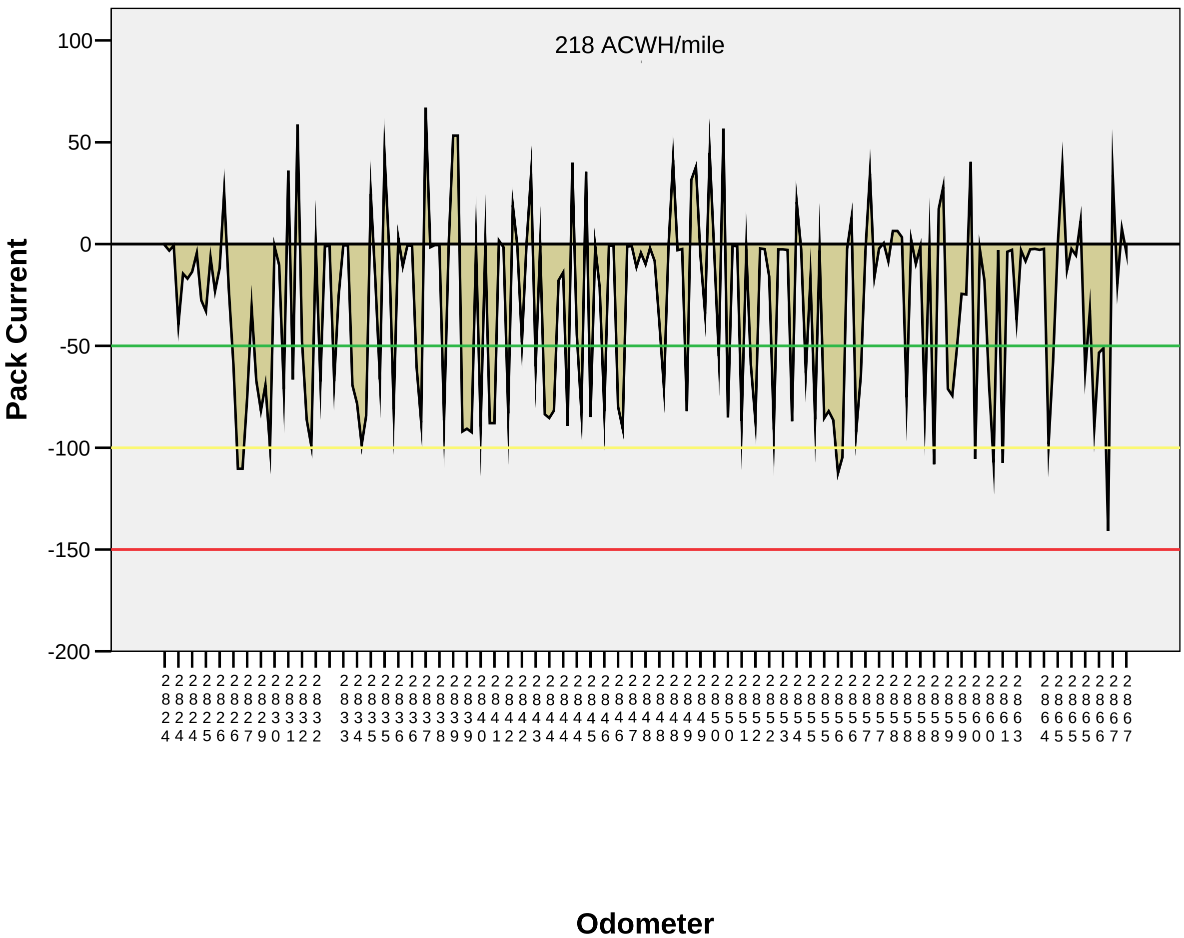


FIGURE B-26 EV-1 Pack Currents for March 22-24, 2005

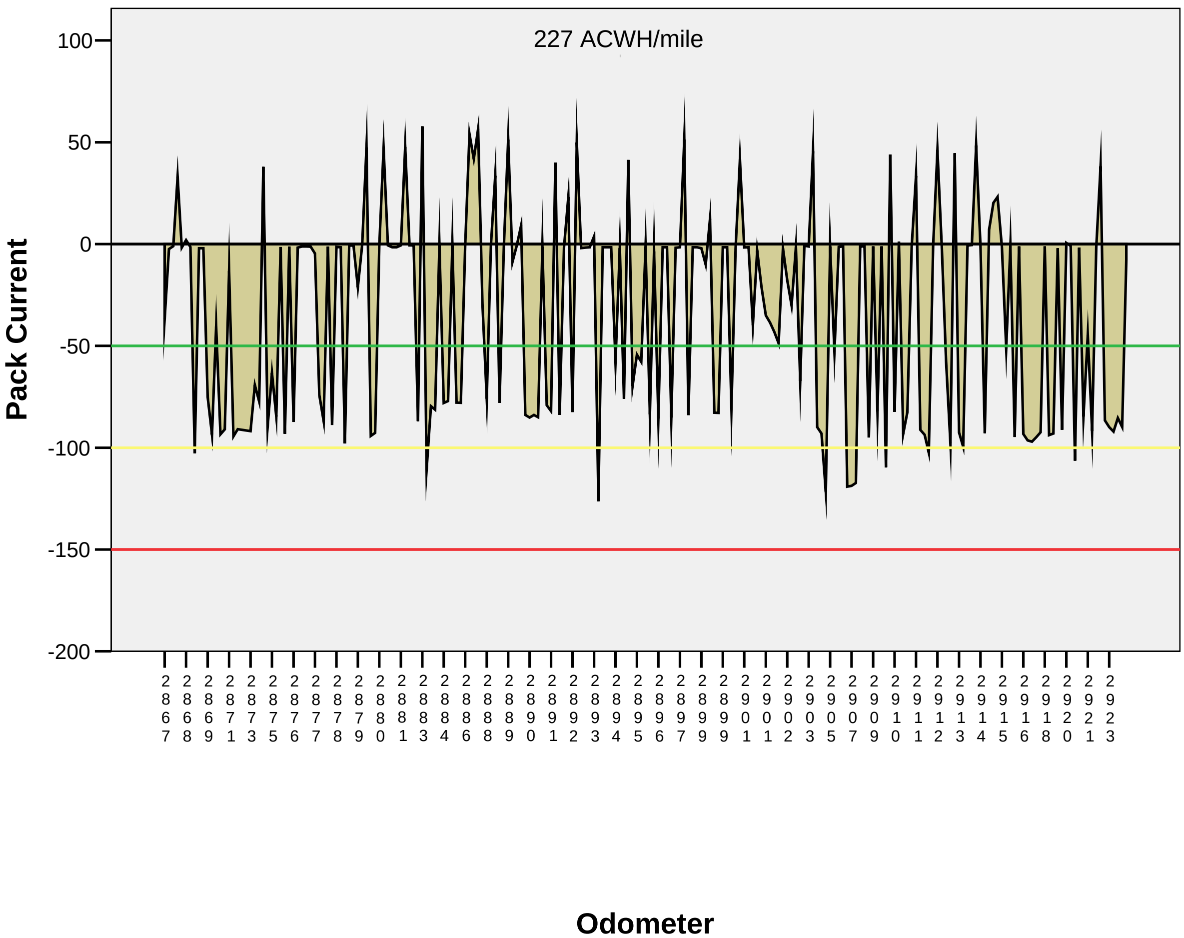


FIGURE B-27 EV-1 Pack Currents for March 24-25, 2005

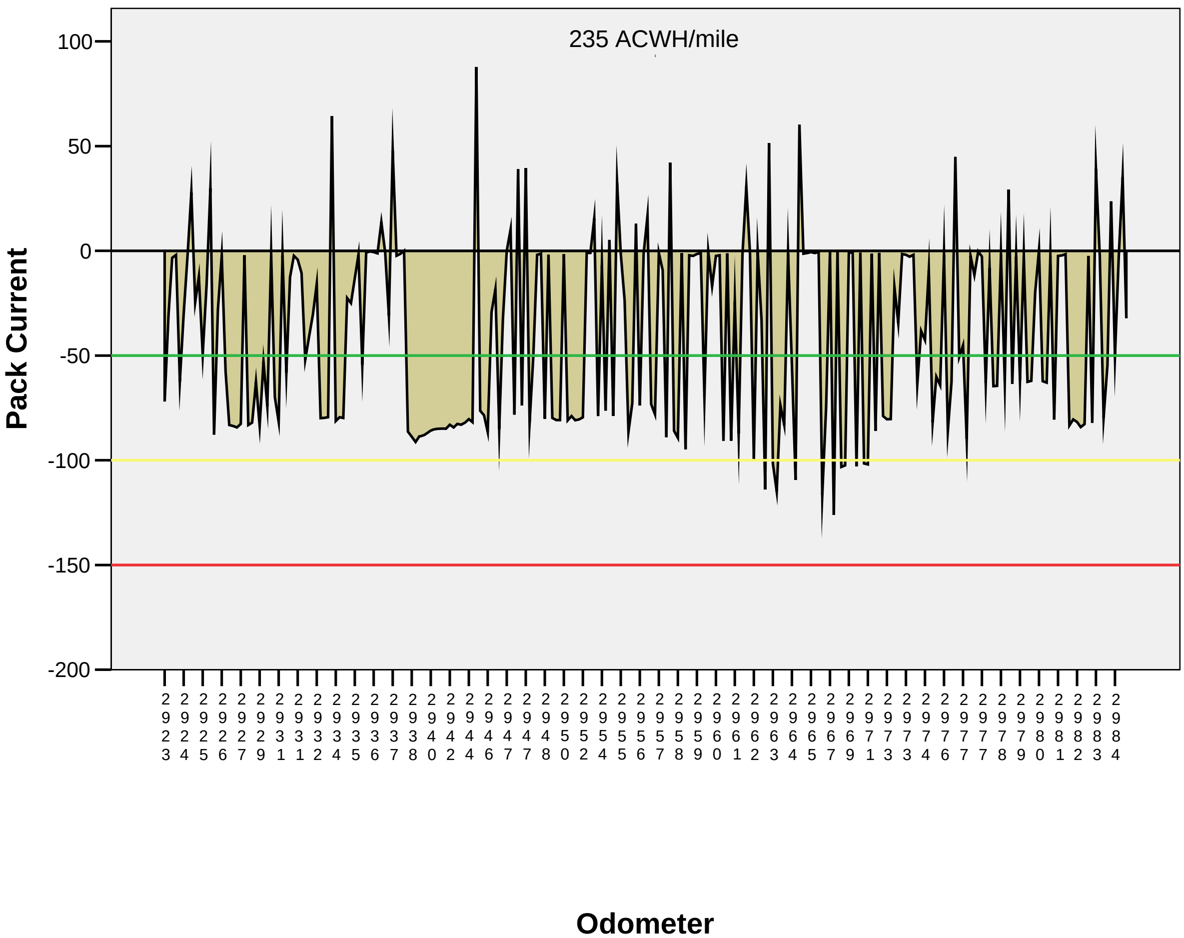


FIGURE B-28 EV-1 Pack Currents for March 25-26, 2005

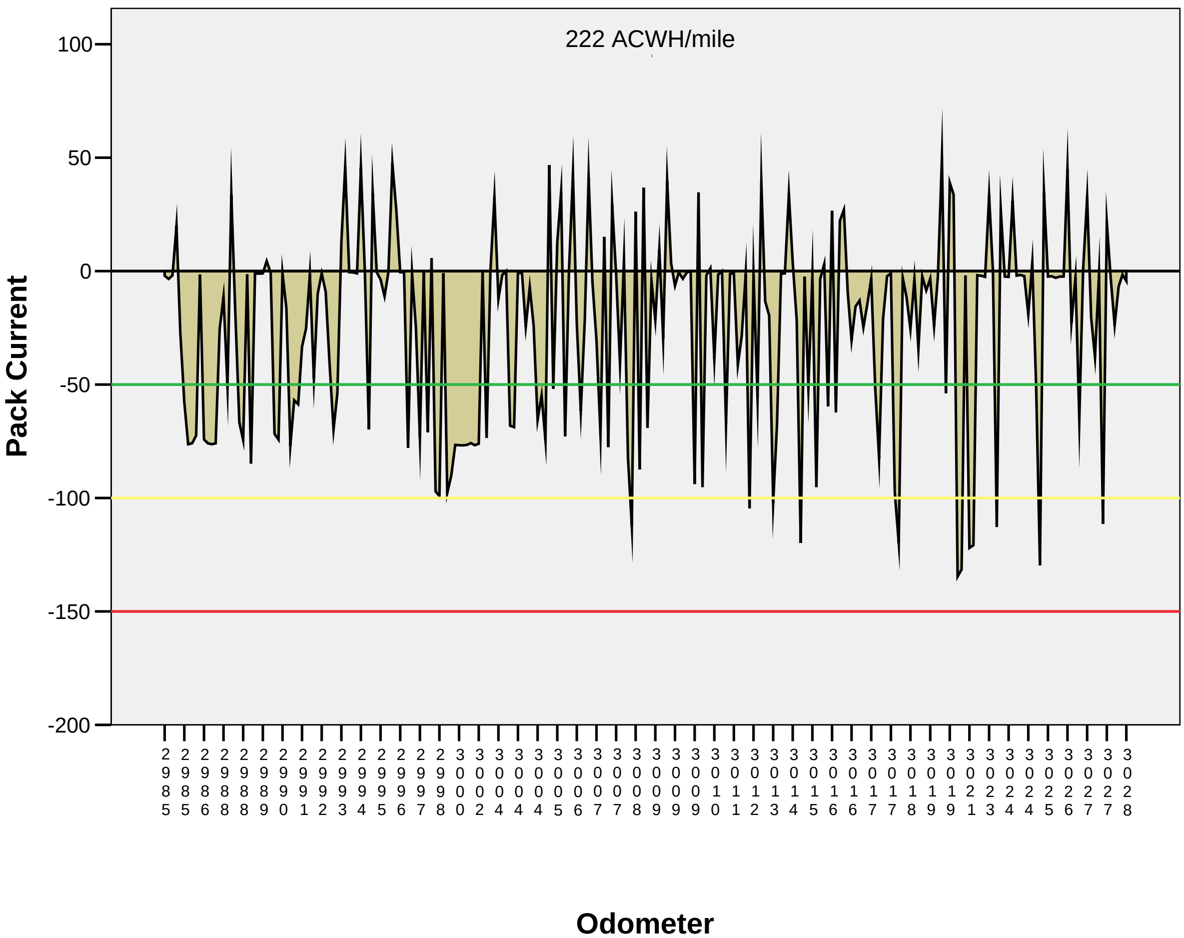


FIGURE B-29 EV-1 Pack Currents for March 26-29, 2005

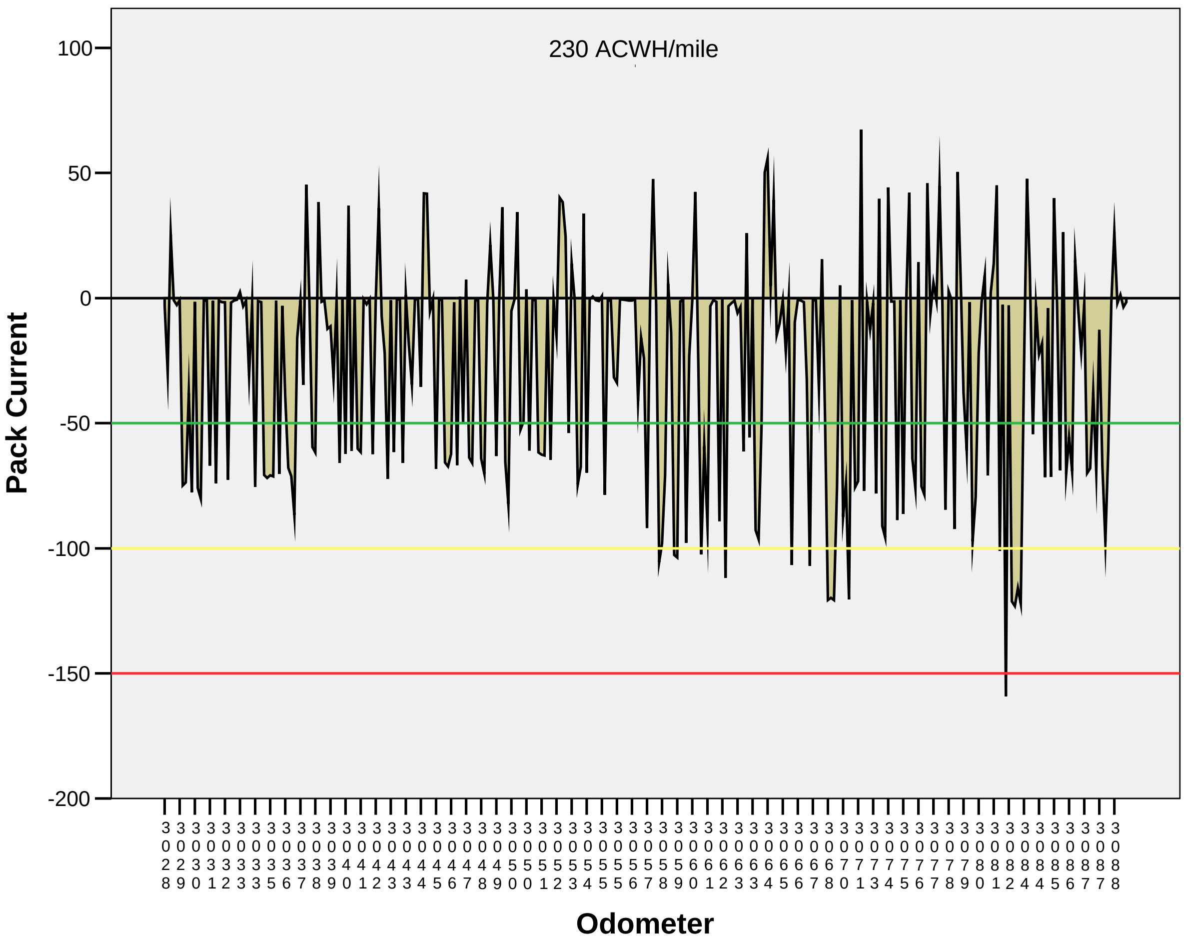


FIGURE B-30 EV-1 Pack Currents for March 29-31, 2005

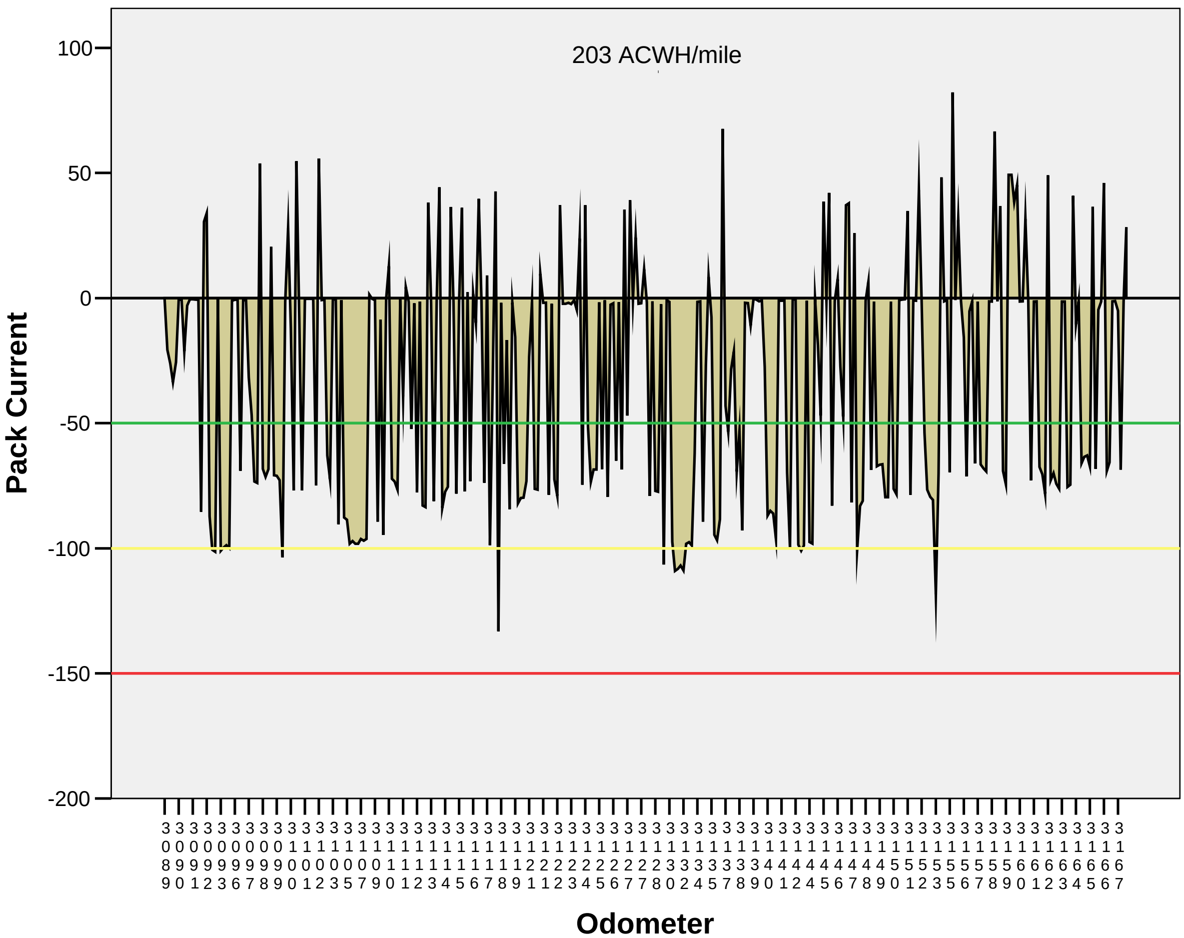


FIGURE B-31 EV-1 Pack Currents for March 31 to April 1, 2005

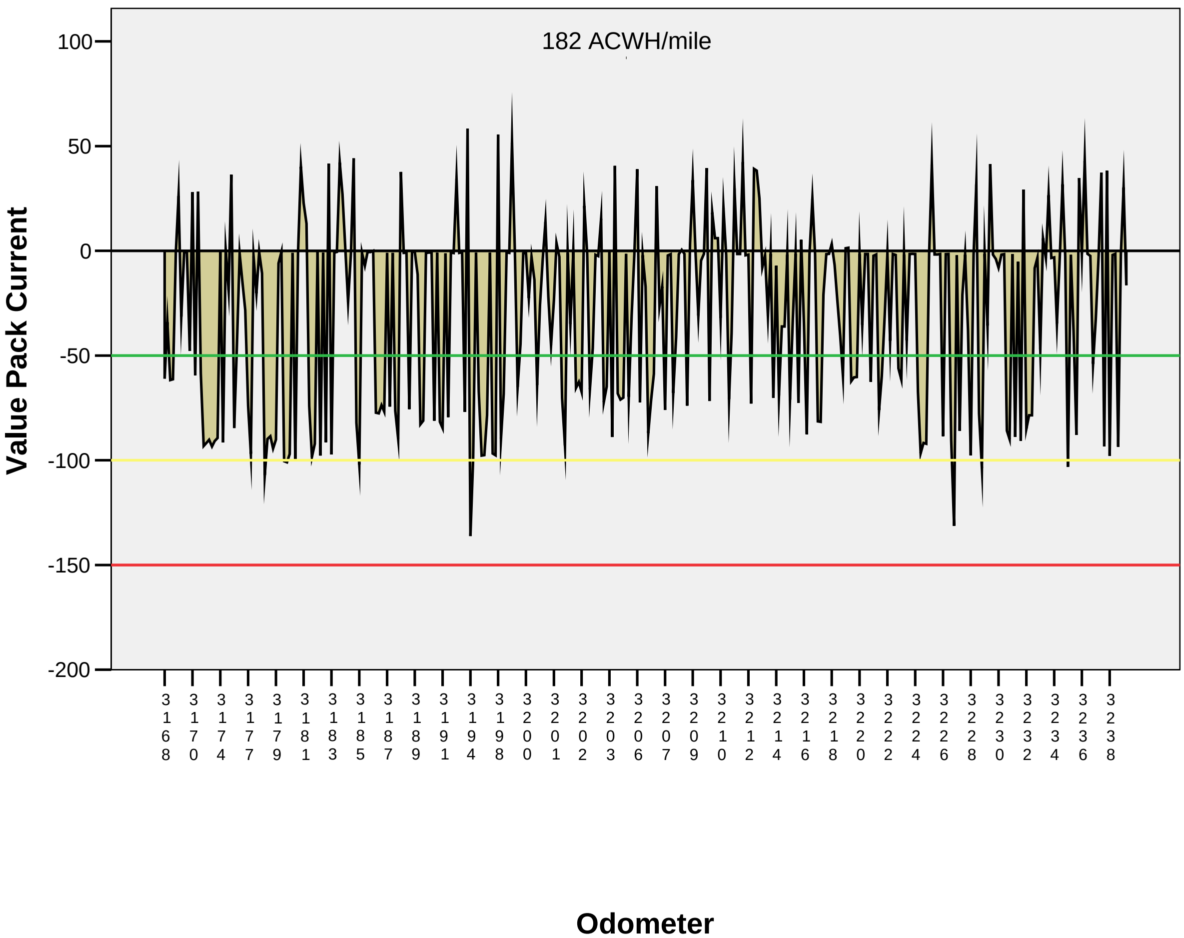


FIGURE B-32 EV-1 Pack Currents for May 14-17, 2005

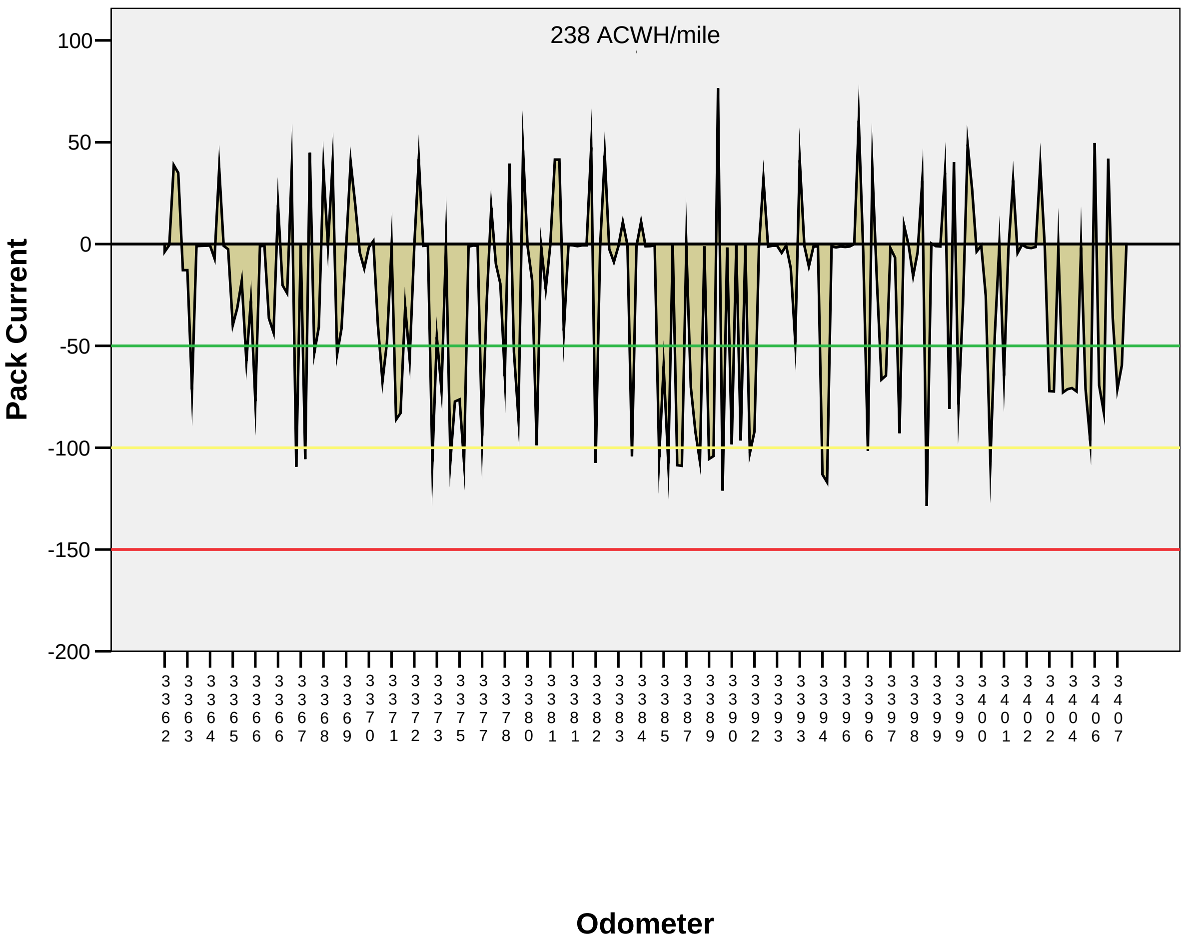


FIGURE B-33 EV-1 Pack Currents for May 17-19, 2005

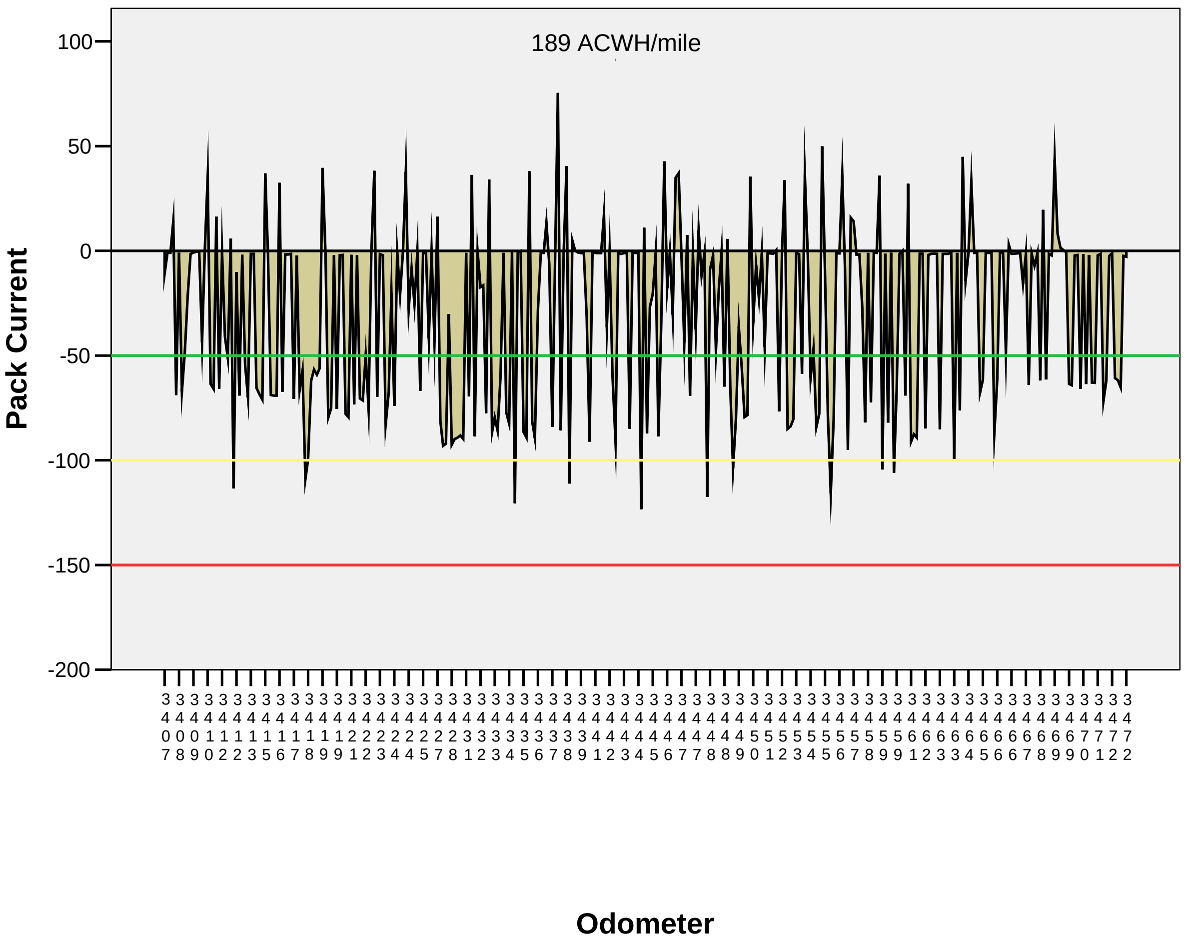


FIGURE B-34 EV-1 Pack Currents for May 21-26, 2005

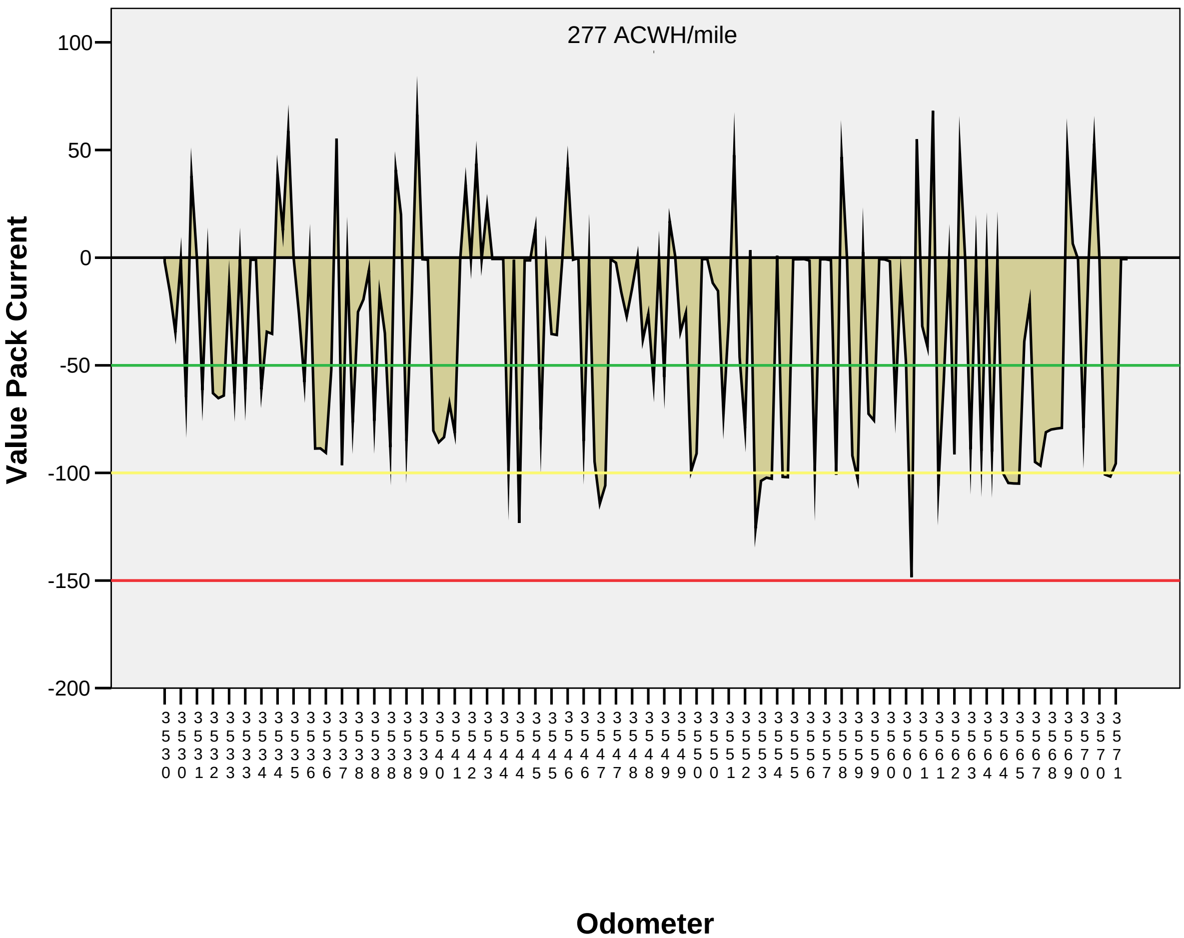


FIGURE B-35 EV-1 Pack Currents for May 31 - June 2, 2005

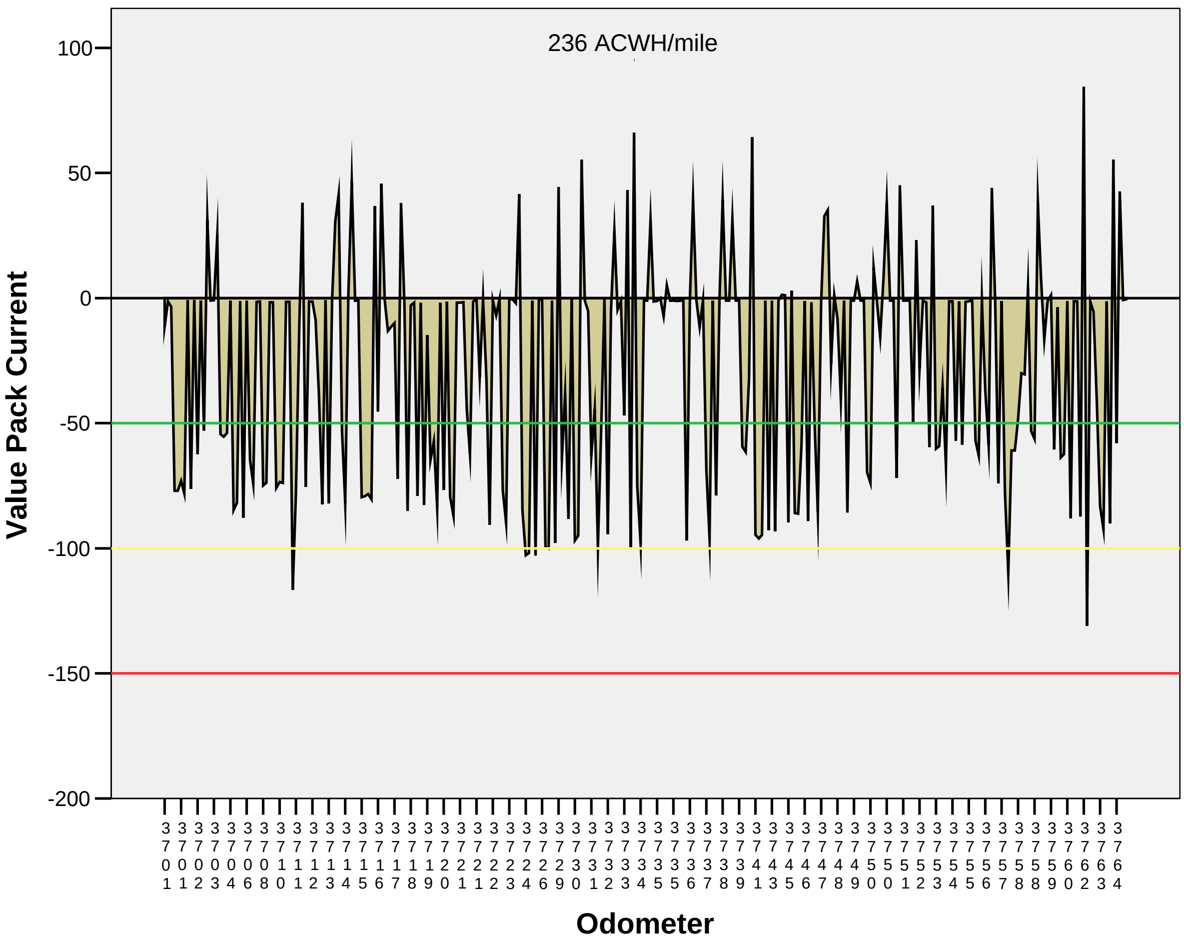


FIGURE B-36 EV-1 Pack Currents for July 13-14, 2005

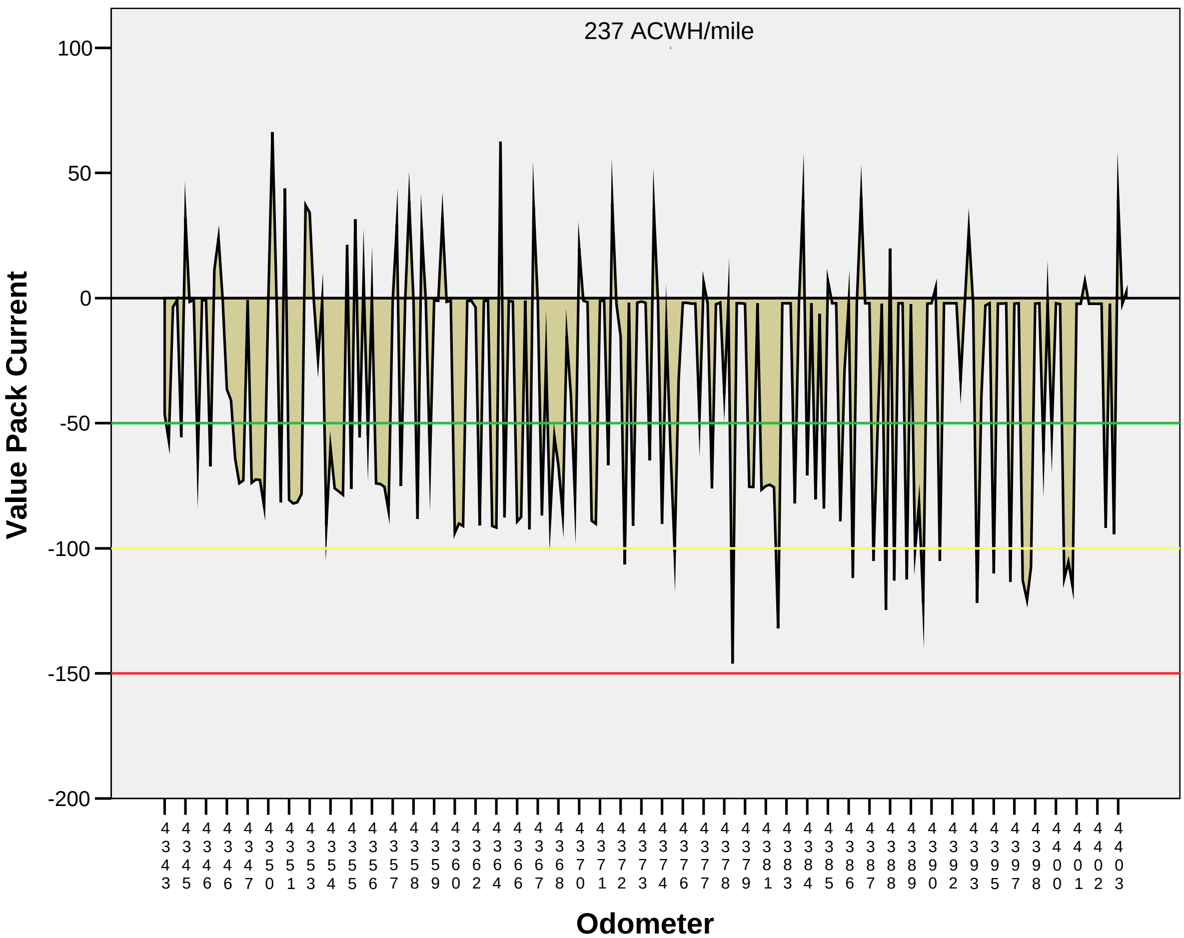


FIGURE B-37 EV-1 Pack Currents for July 14-18, 2005

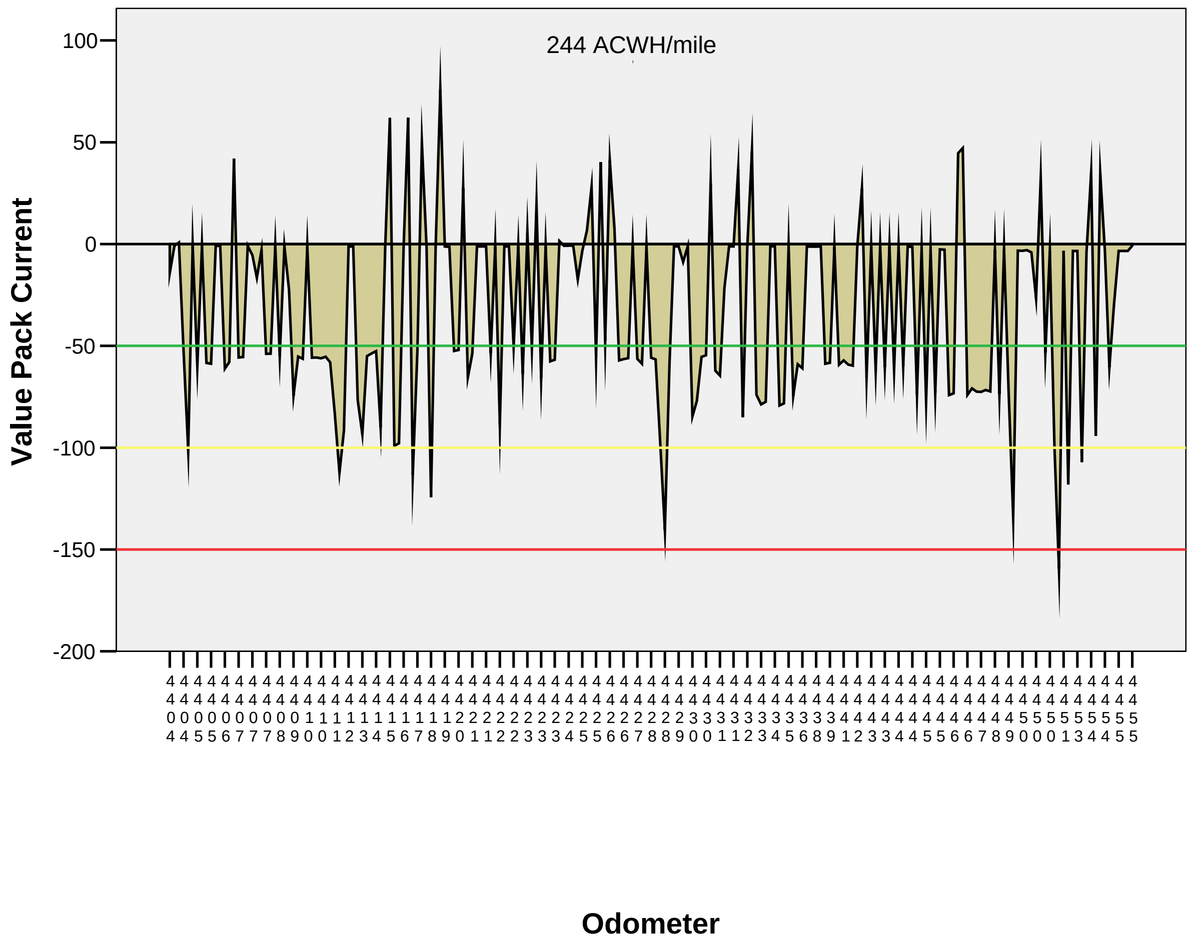


FIGURE B-38 EV-1 Pack Currents for April 7-12, 2006

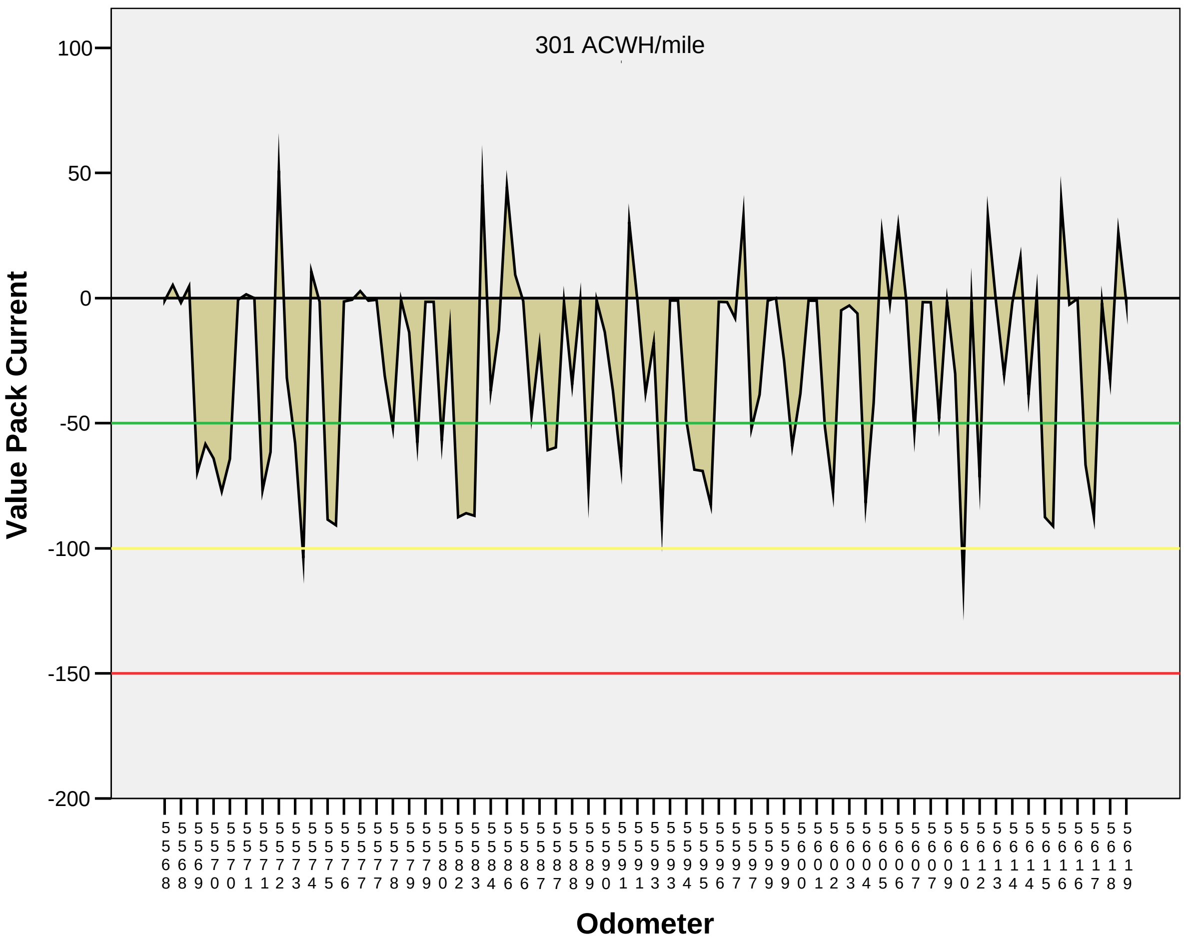


FIGURE B-39 EV-1 Pack Currents for April 12-13, 2006

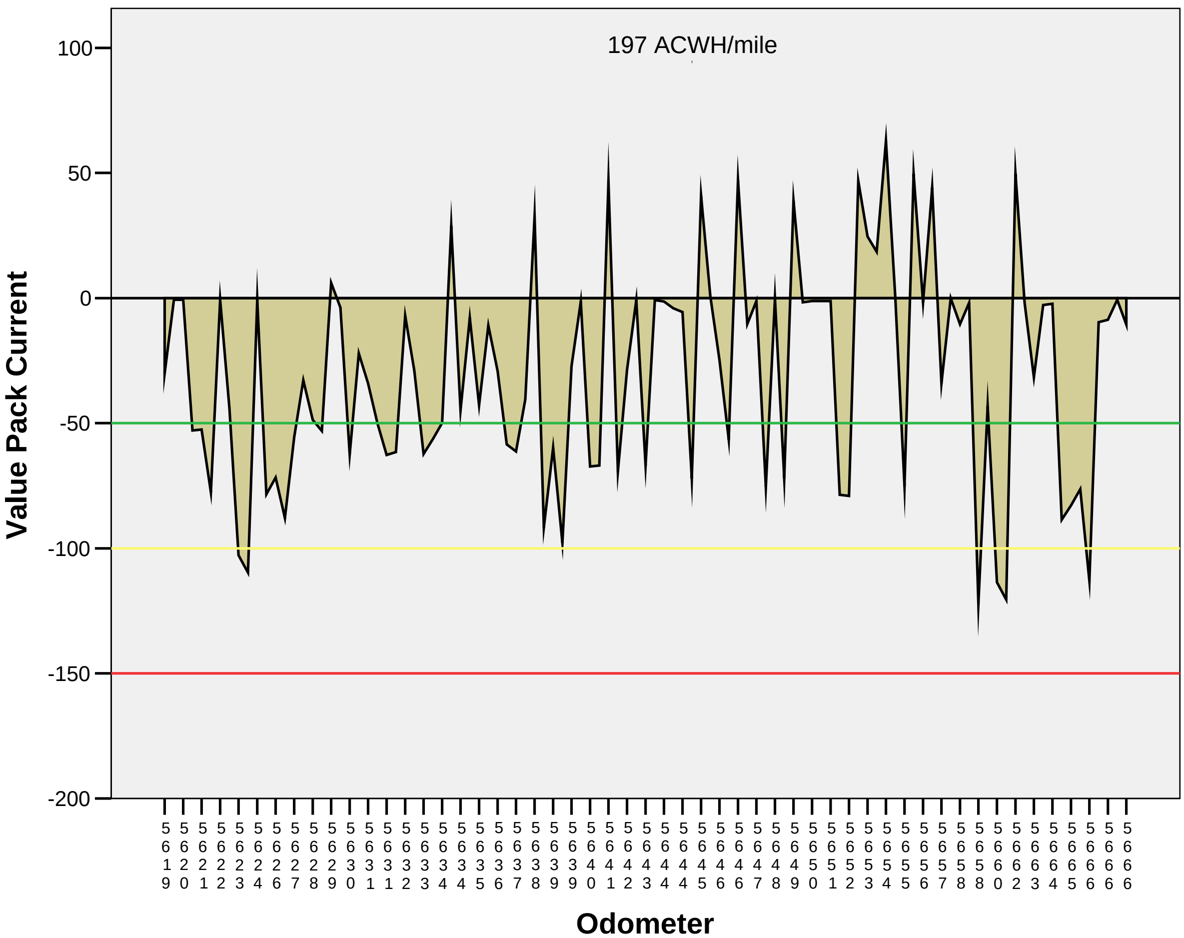


FIGURE B-40 EV-1 Pack Currents for April 13-17, 2006

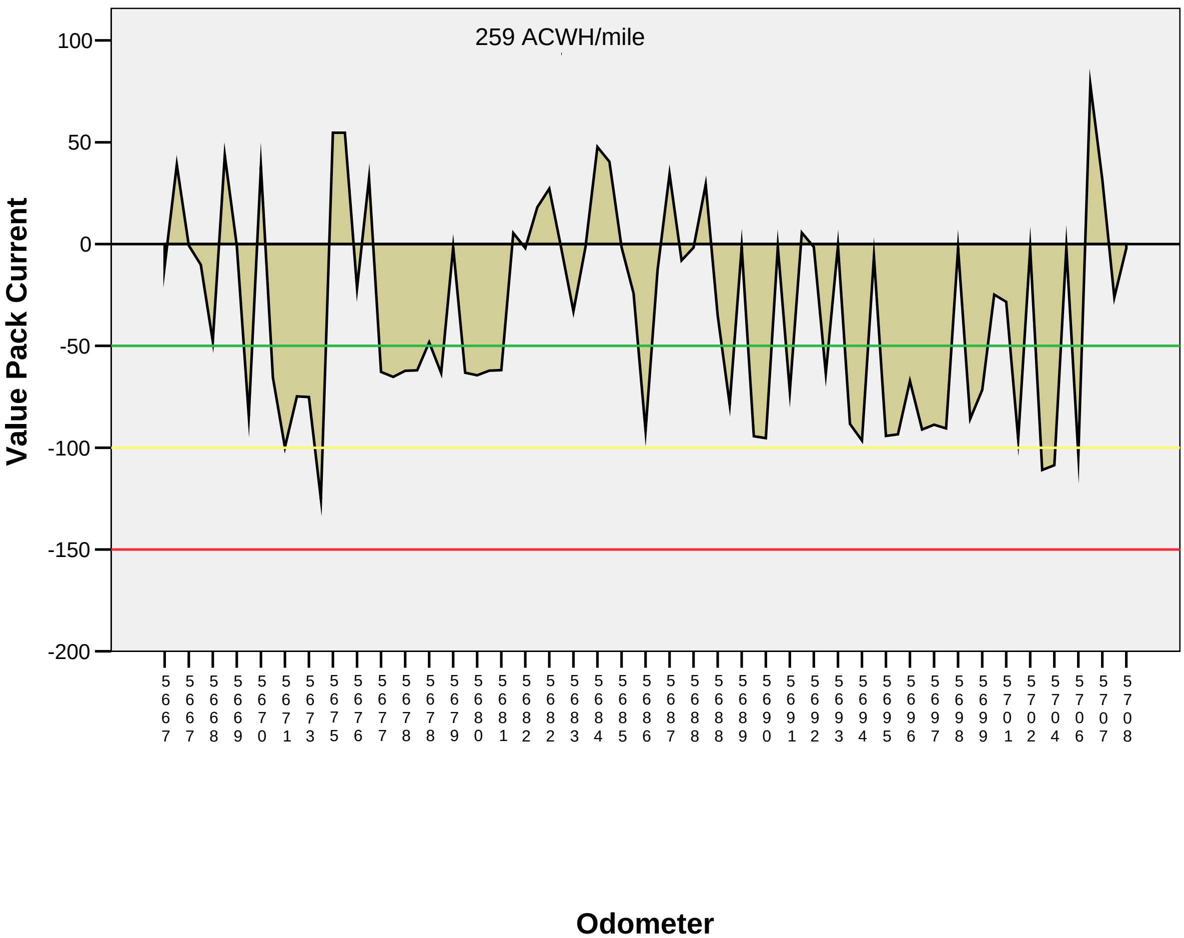
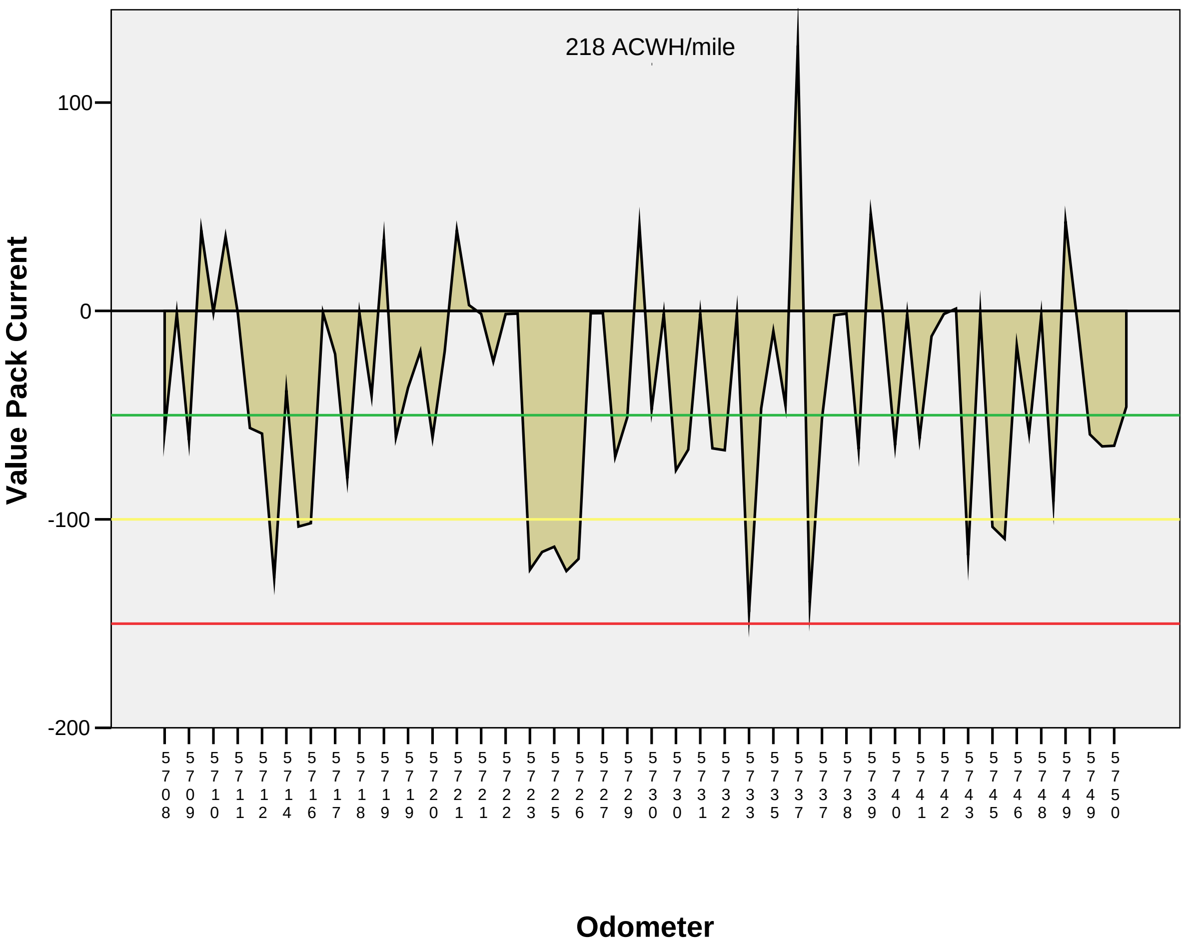


FIGURE B-41 EV-1 Pack Currents for April 17-18, 2006



Graph

FIGURE B-42 EV-1 Pack Currents for April 18-19, 2006

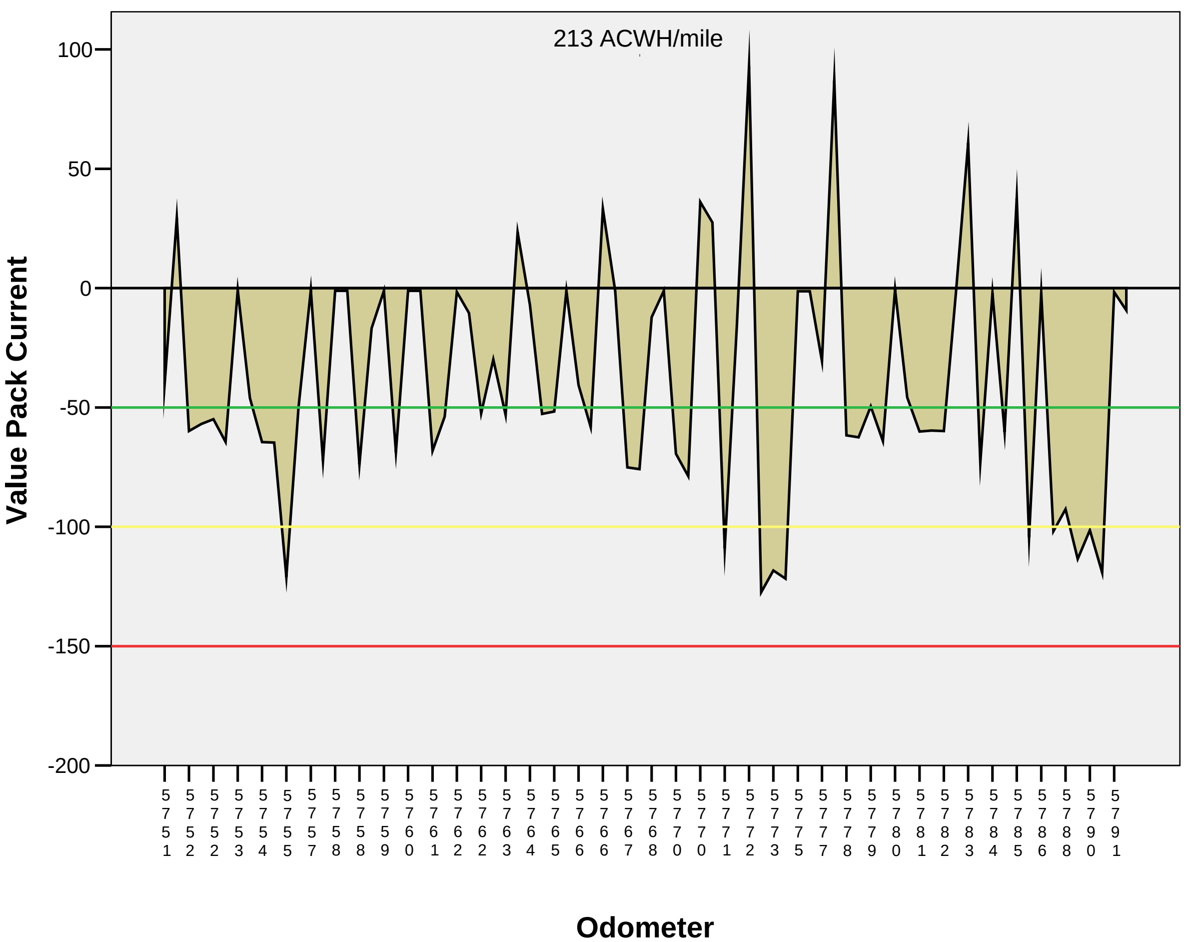


FIGURE B-43 EV-1 Pack Currents for April 19-20, 2006

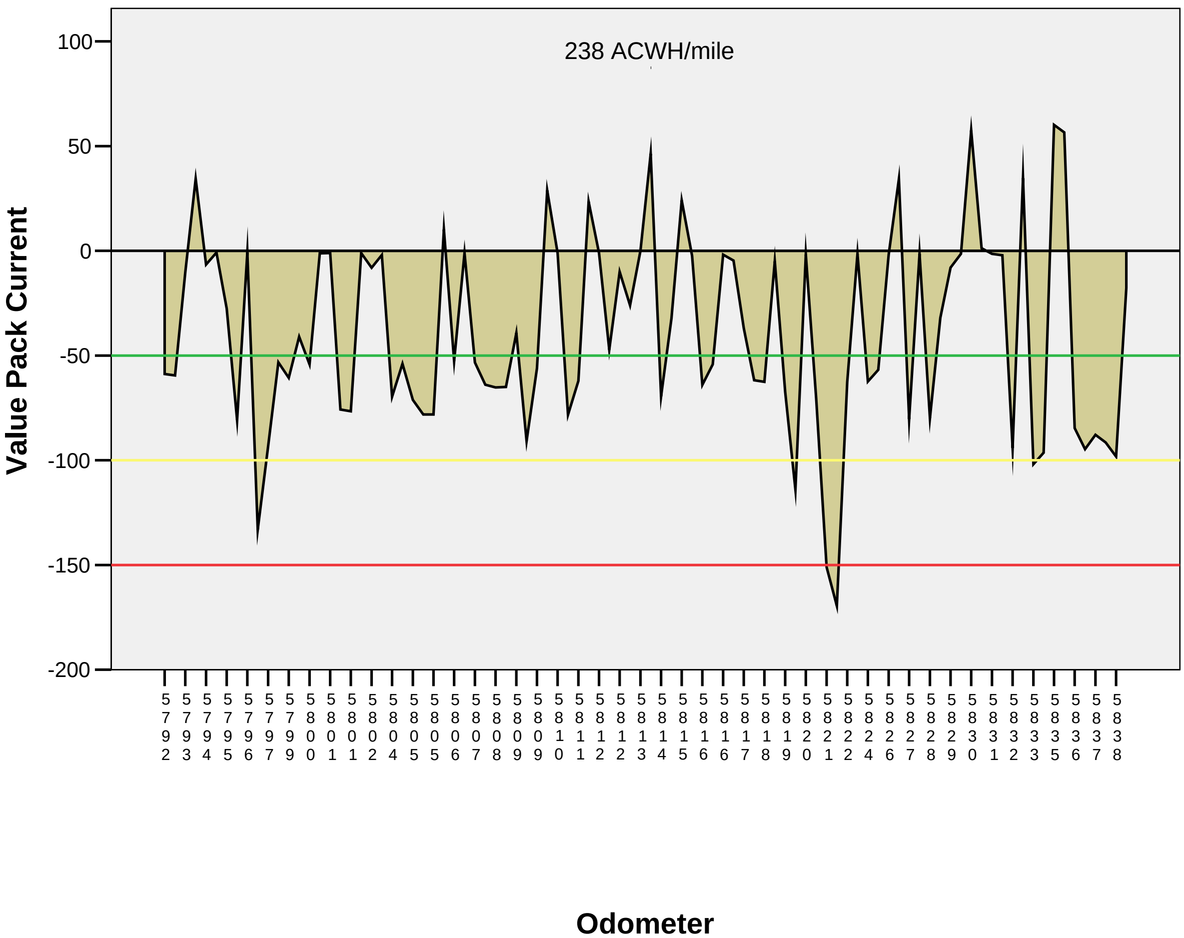
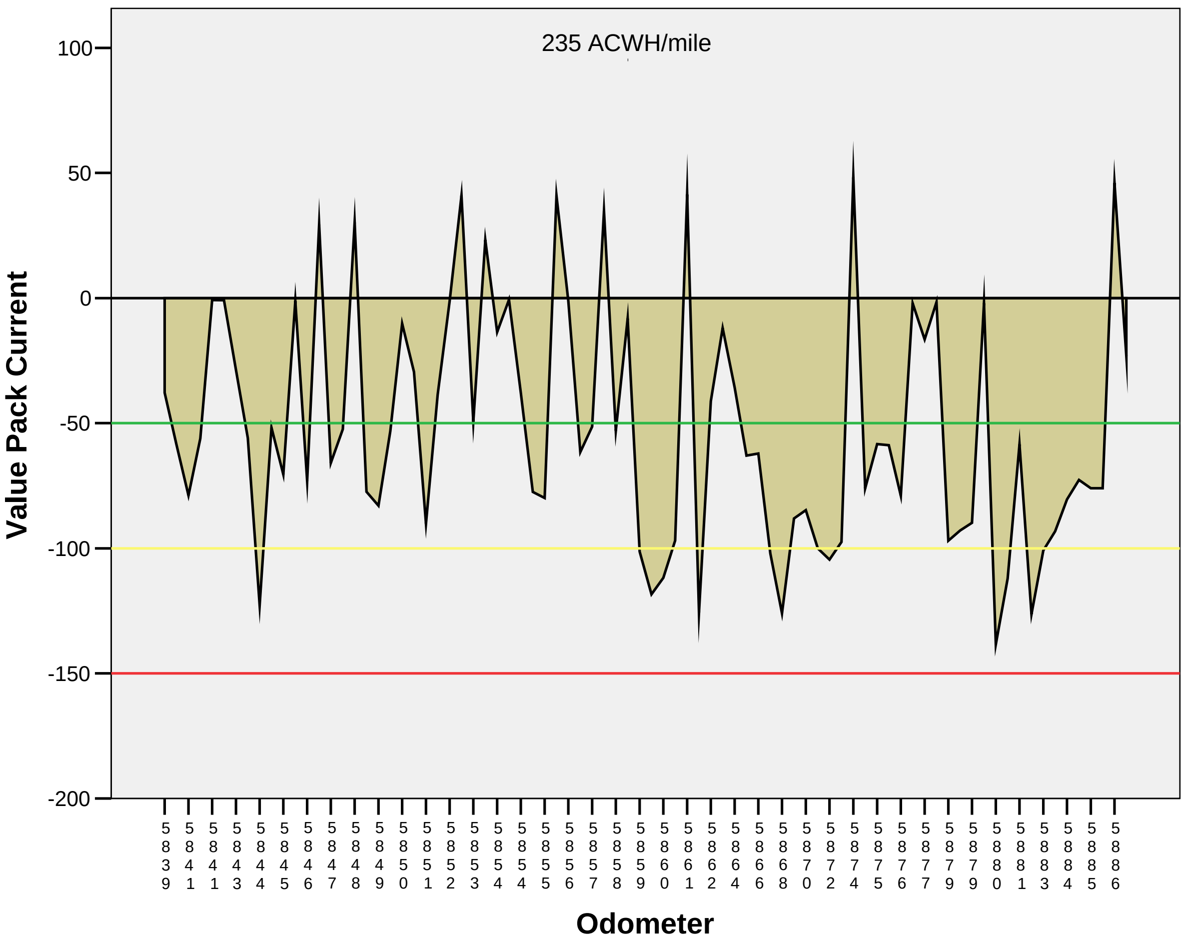


FIGURE B-44 EV-1 Pack Currents for April 20-21, 2006



APPENDIX C

Additional Photos
Of BEV Subcompact
Cars in Phase 2

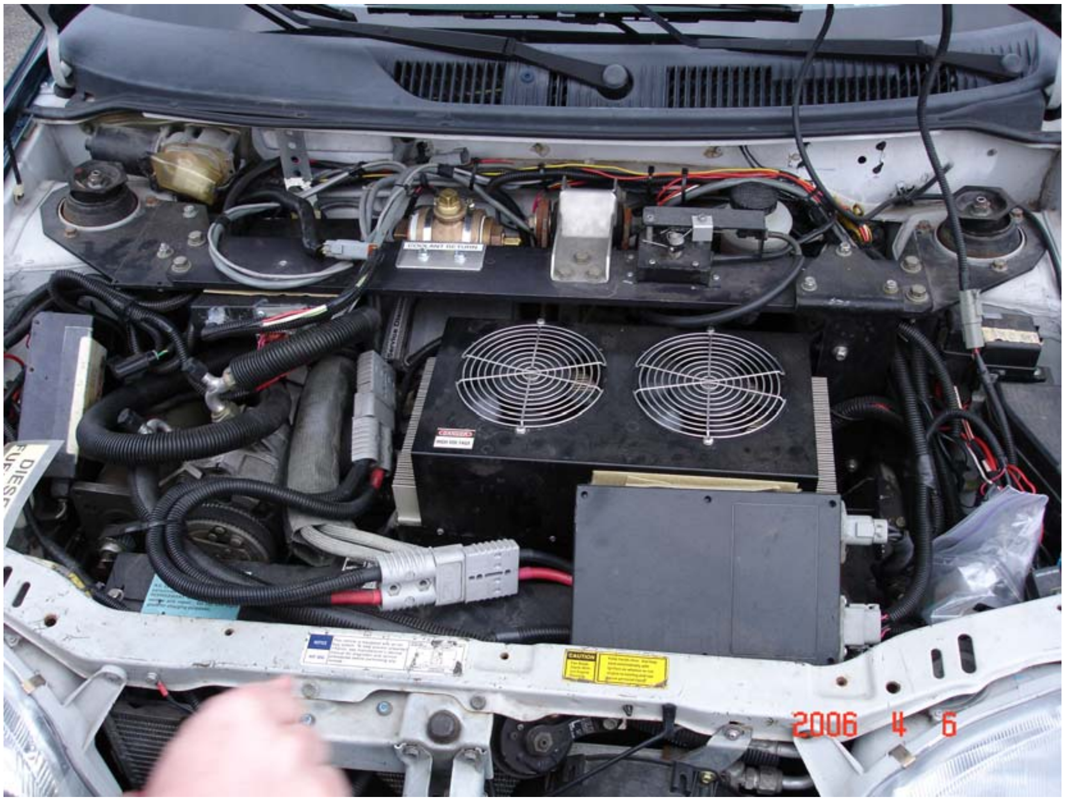


FIGURE C-1 Under the hood of one of the Phase 2 electric vehicles, EV-1.

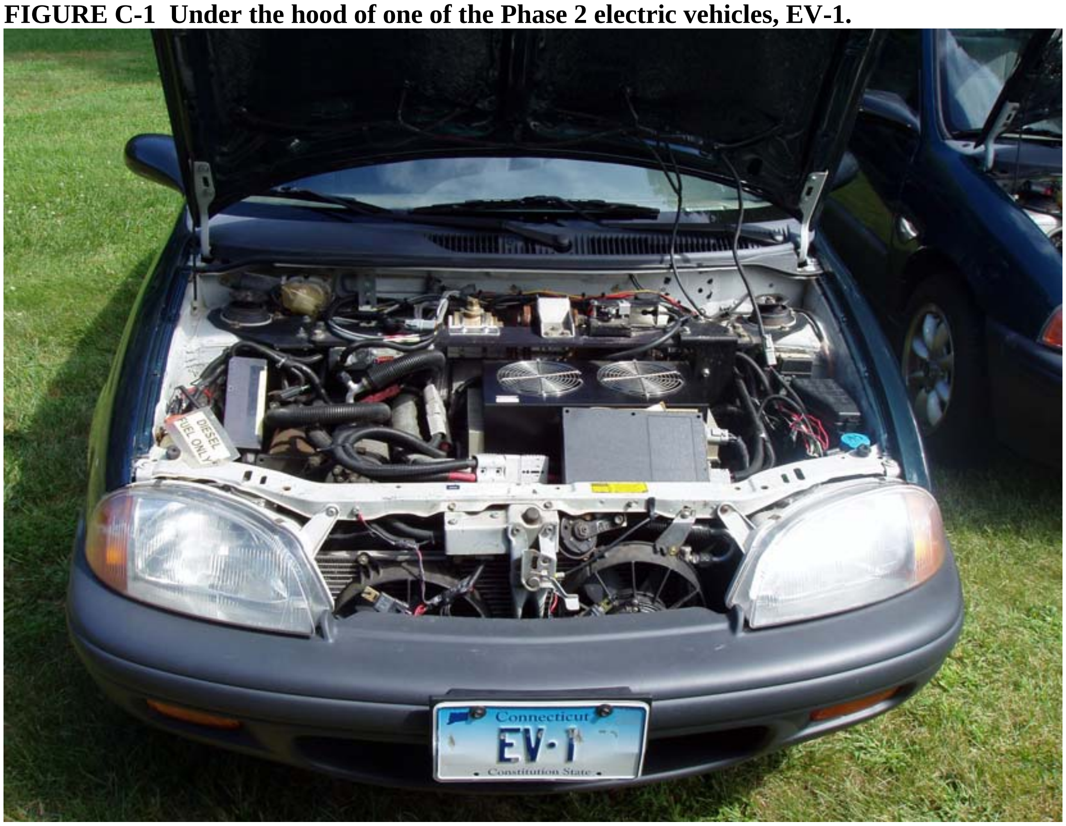


FIGURE C-2 Under the hood of one of the Phase 2 electric vehicles, EV-1.

FIGURE C-3 Phase 2 BEV parked with hood up.

FIGURE C-4 Inside the trunk of Phase 2 BEV.

FIGURE C-5 Interior of Phase 2 BEV.

FIGURE C-6 The three Phase 2 BEVs.