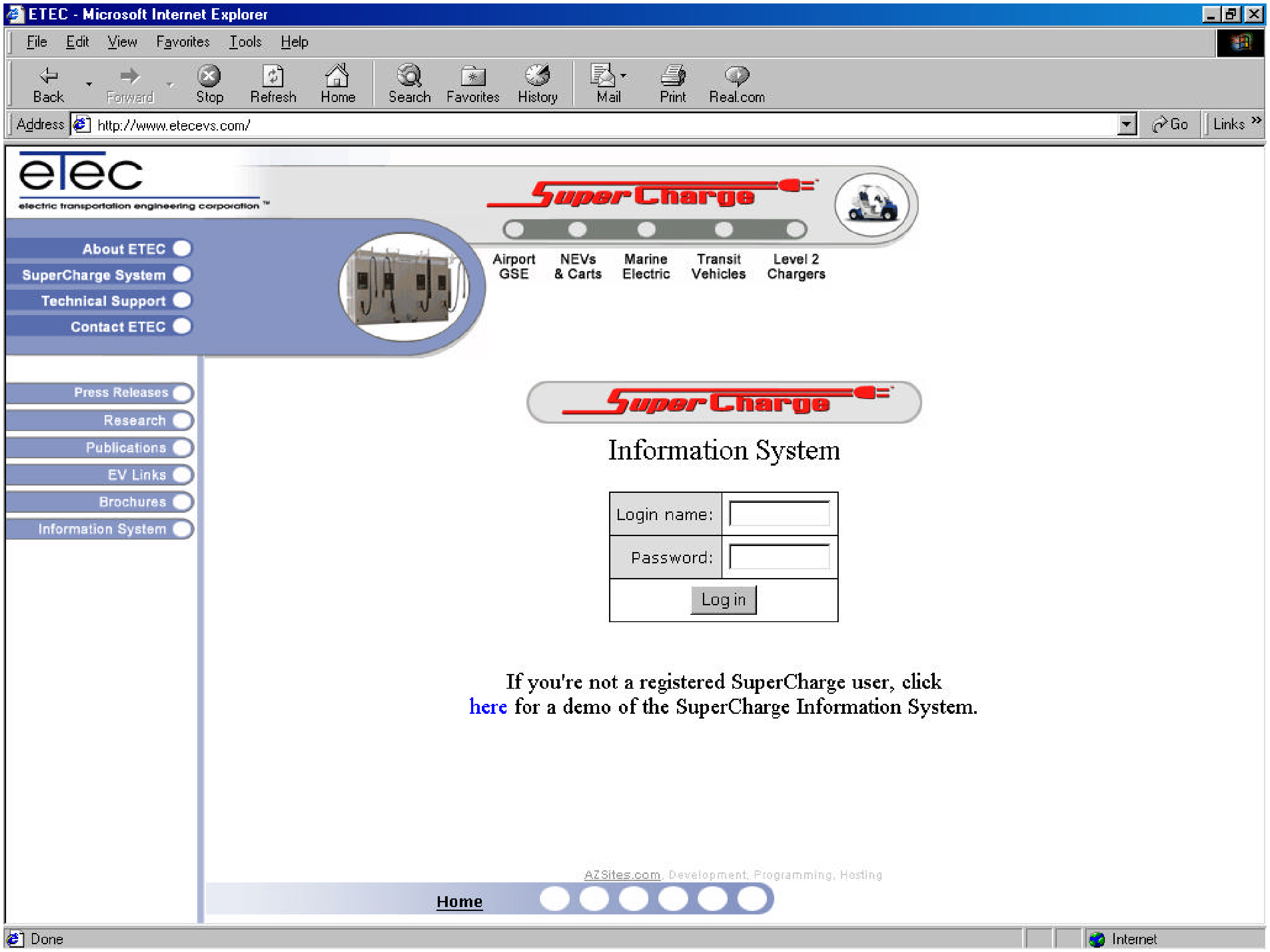
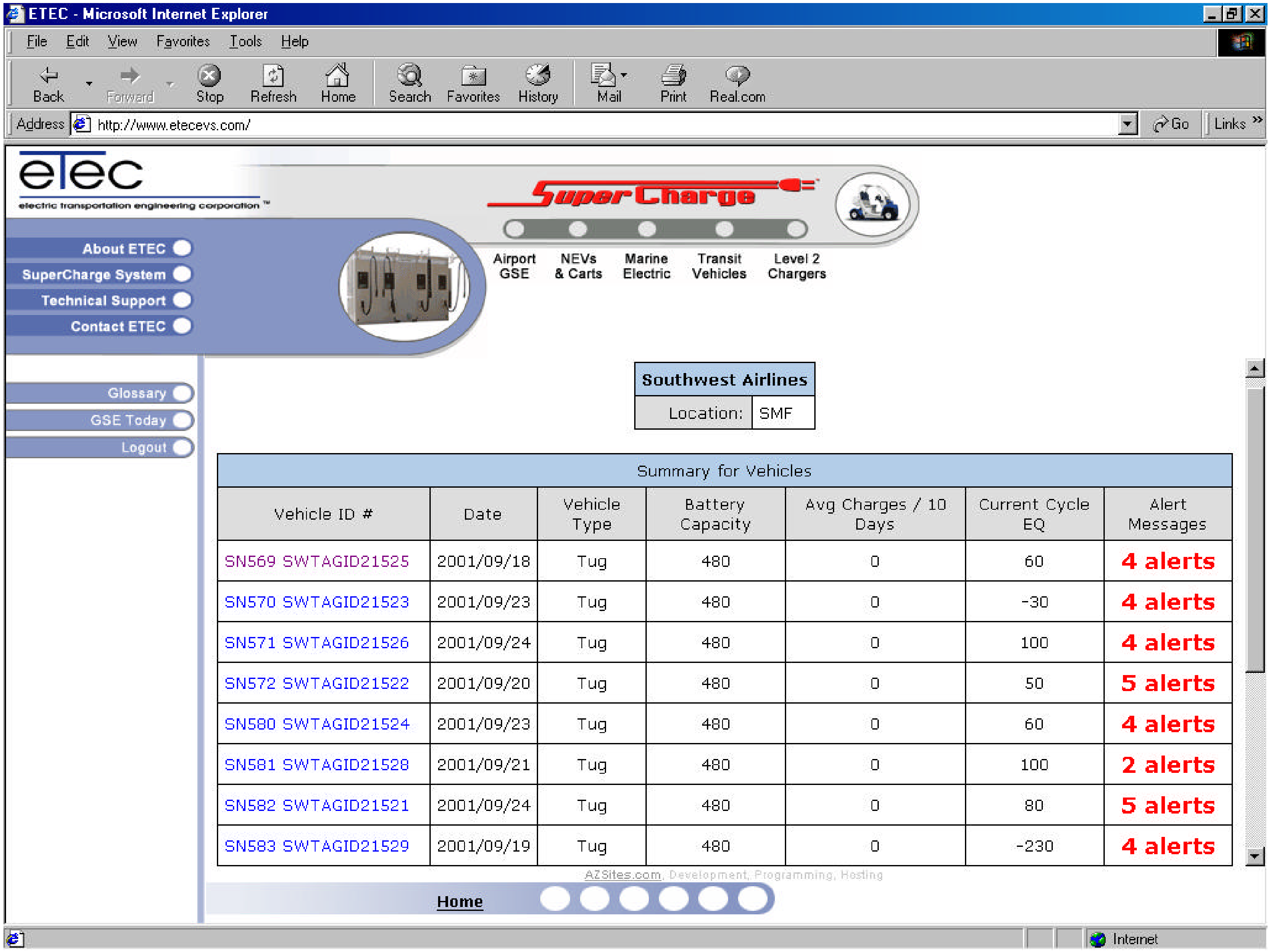
APPENDIX F

MANAGEMENT INFORMATION SYSTEM (MIS) SAMPLE WEB PAGES

Logon Screen

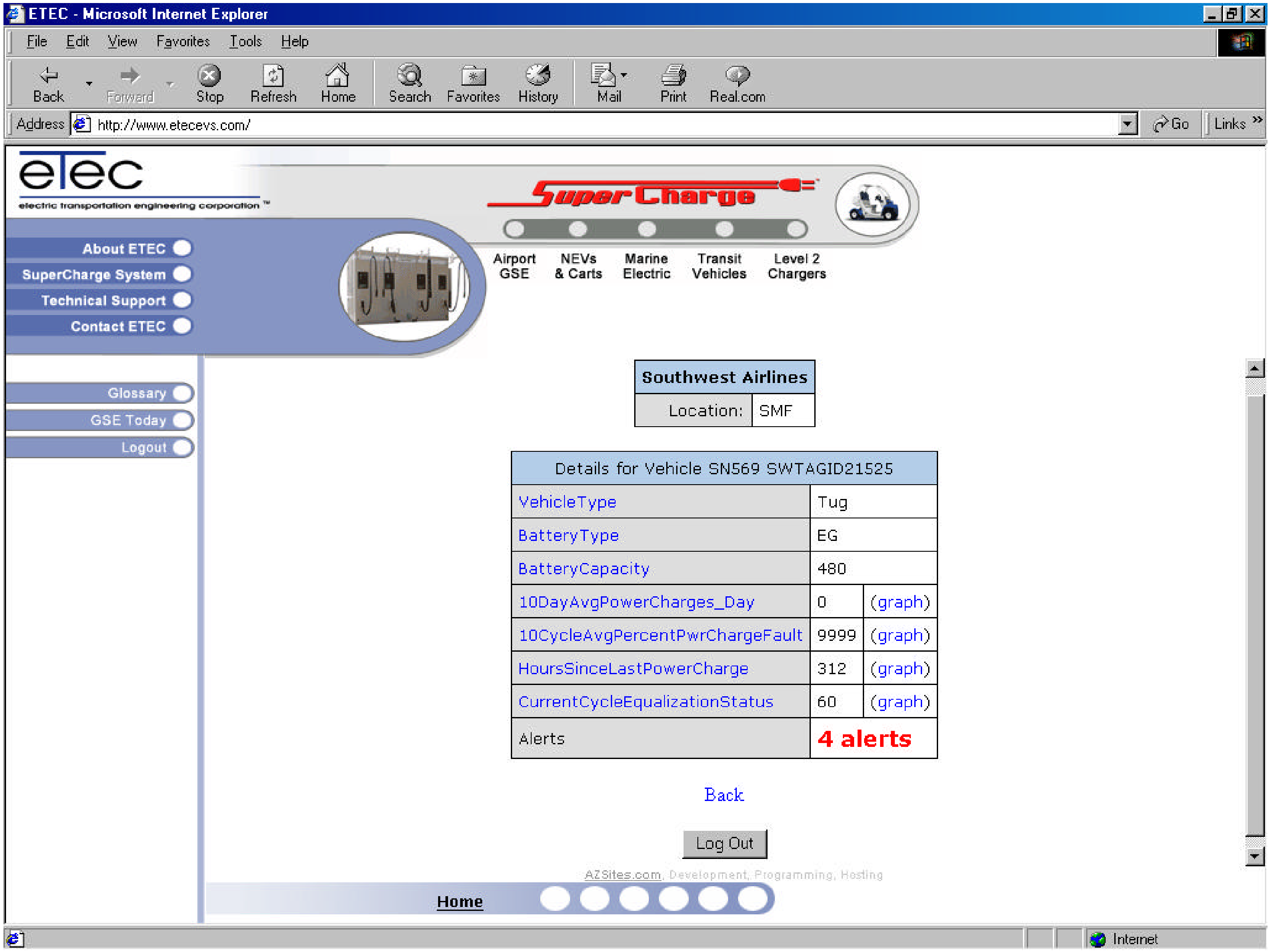


Level 1 Tractor Directory Screen

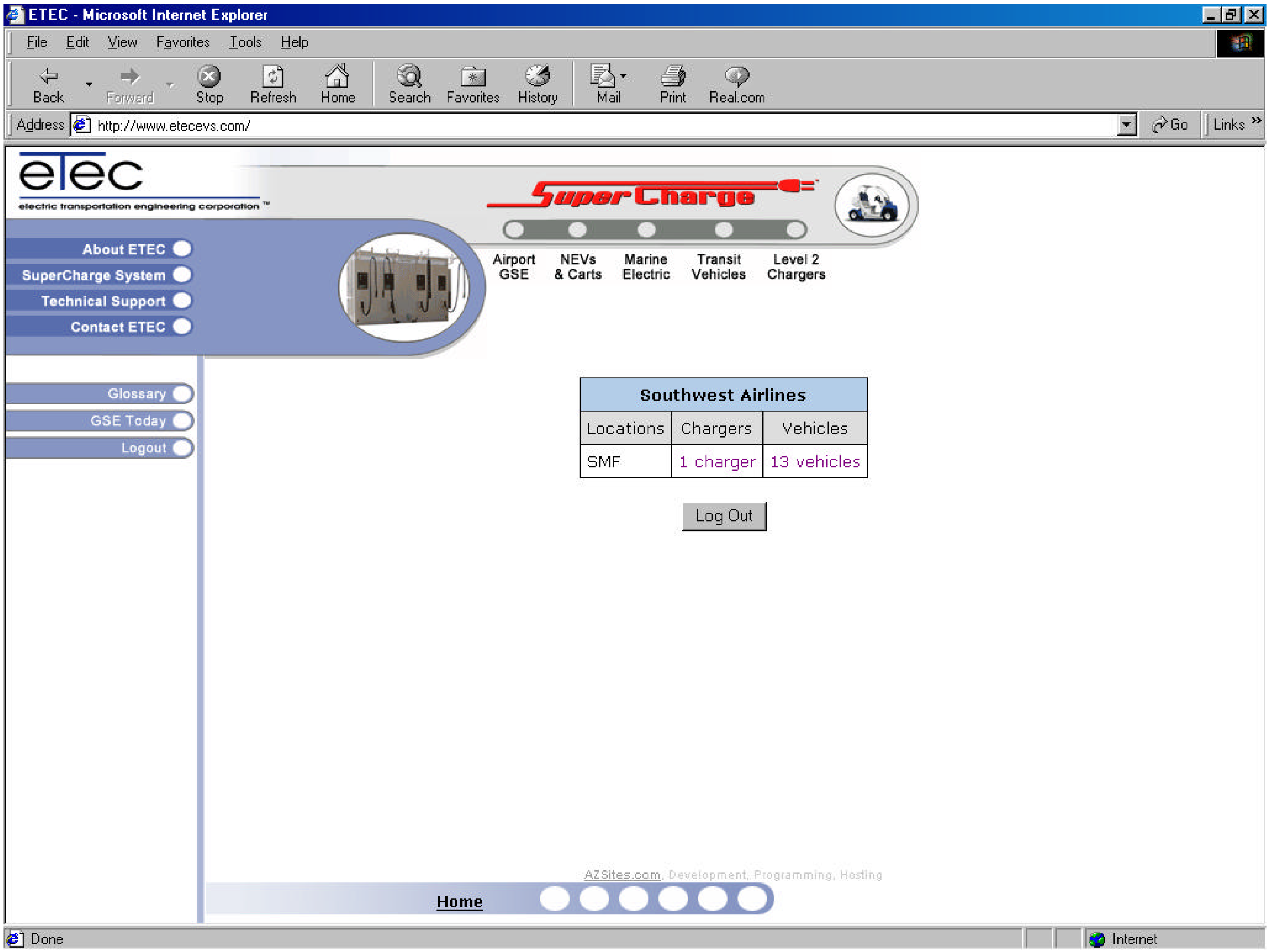


Vehicle ID #	Date	Vehicle Type	Battery Capacity	Avg Charges / 10 Days	Current Cycle EQ	Alert Messages
SN569 SWTAGID21525	2001/09/18	Tug	480	0	60	4 alerts
SN570 SWTAGID21523	2001/09/23	Tug	480	0	-30	4 alerts
SN571 SWTAGID21526	2001/09/24	Tug	480	0	100	4 alerts
SN572 SWTAGID21522	2001/09/20	Tug	480	0	50	5 alerts
SN580 SWTAGID21524	2001/09/23	Tug	480	0	60	4 alerts
SN581 SWTAGID21528	2001/09/21	Tug	480	0	100	2 alerts
SN582 SWTAGID21521	2001/09/24	Tug	480	0	80	5 alerts
SN583 SWTAGID21529	2001/09/19	Tug	480	0	-230	4 alerts

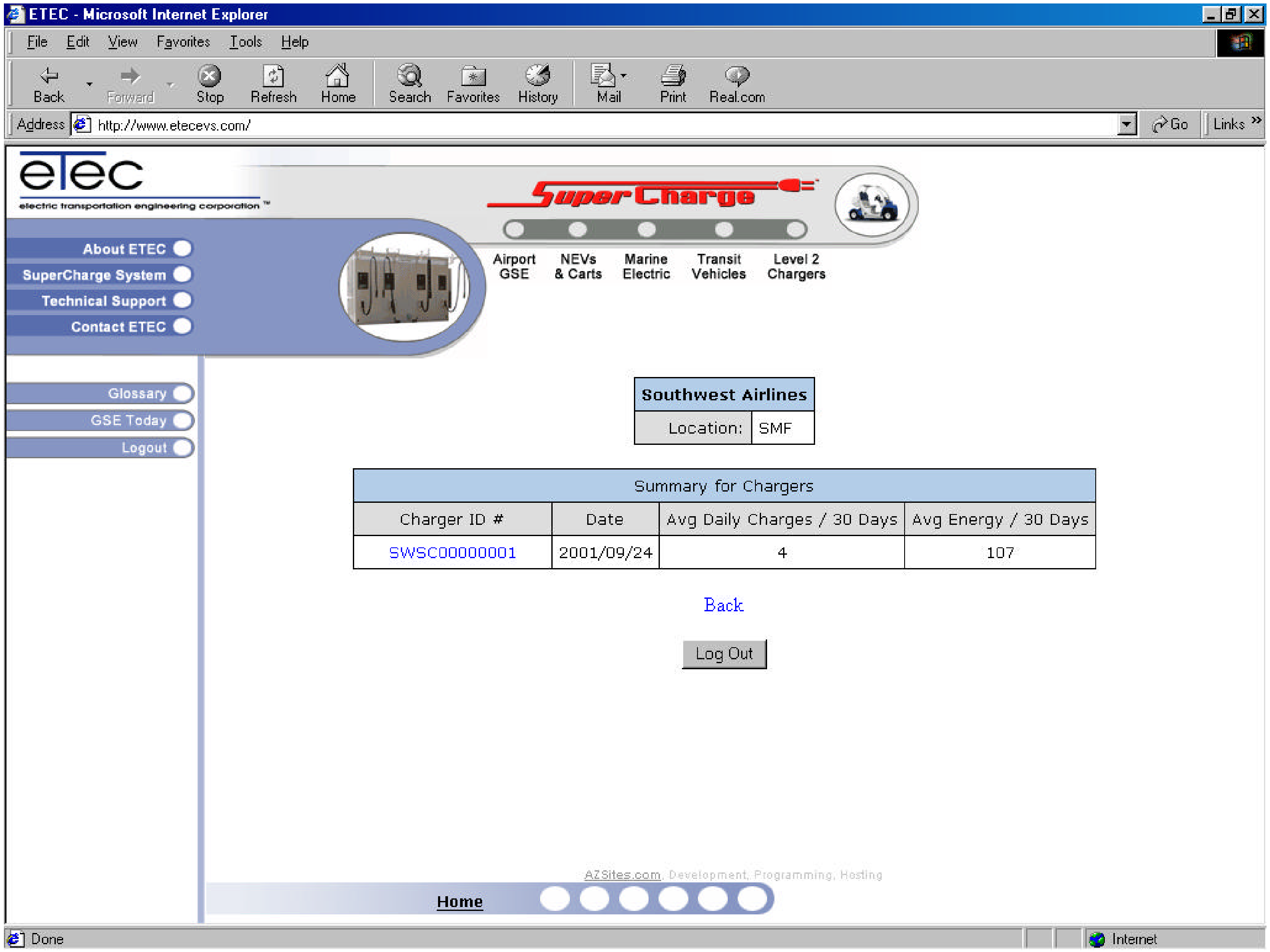
Level 1 Tractor Screen



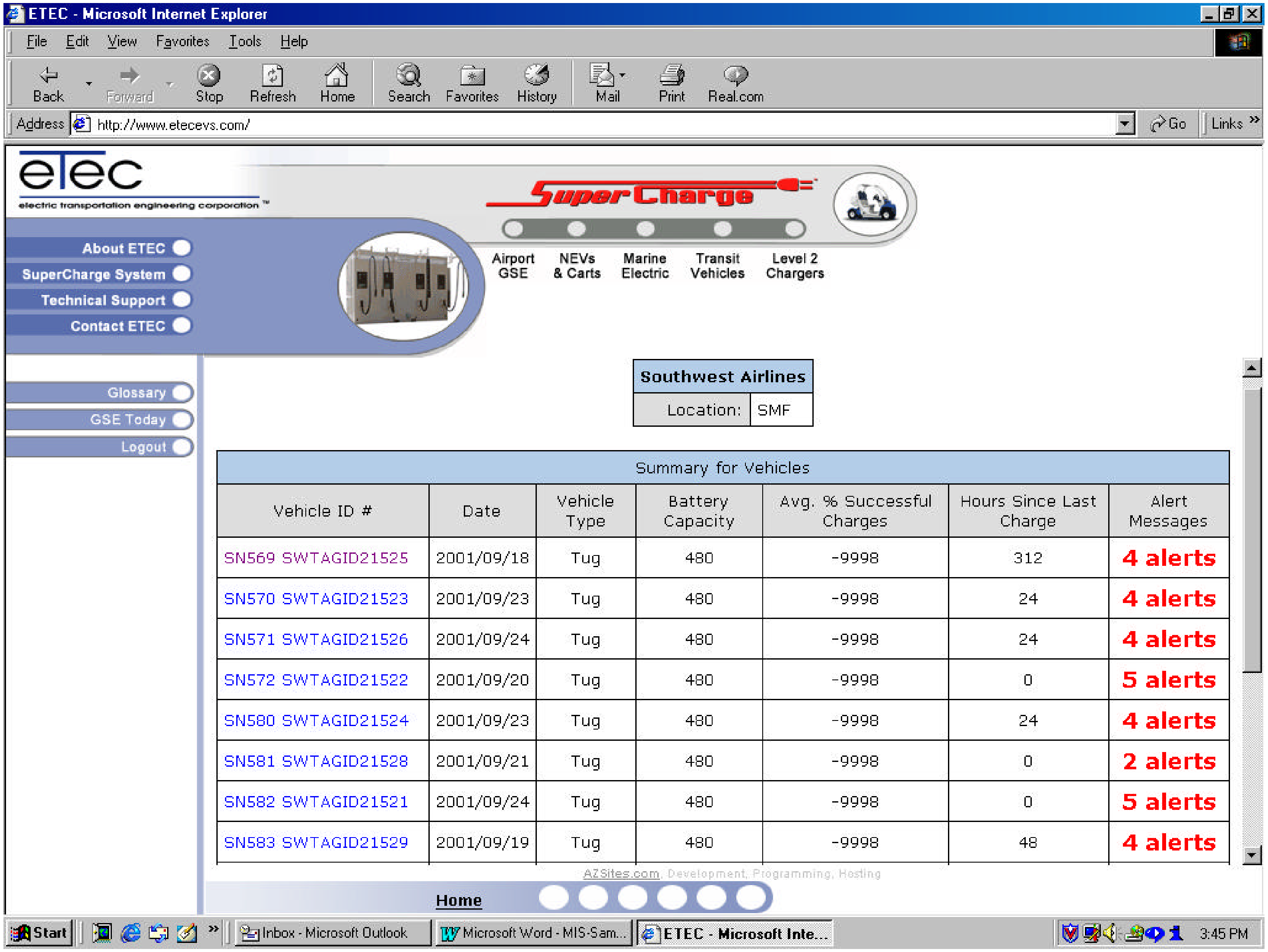
Level 2 Selection Screen



Level 2 Charger Selection Screen



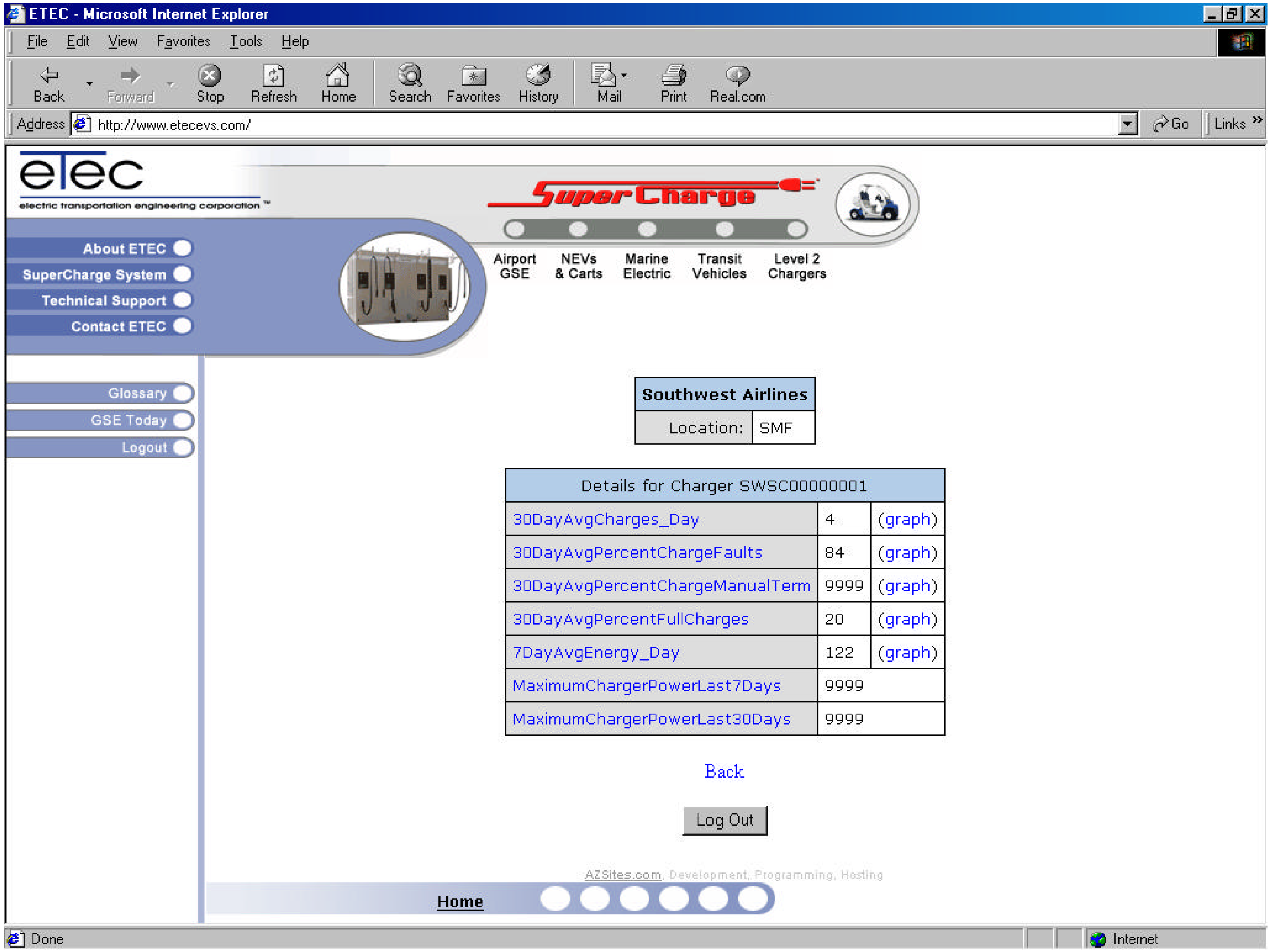
Level 2 Tractor Selection Screen



Summary for Vehicles

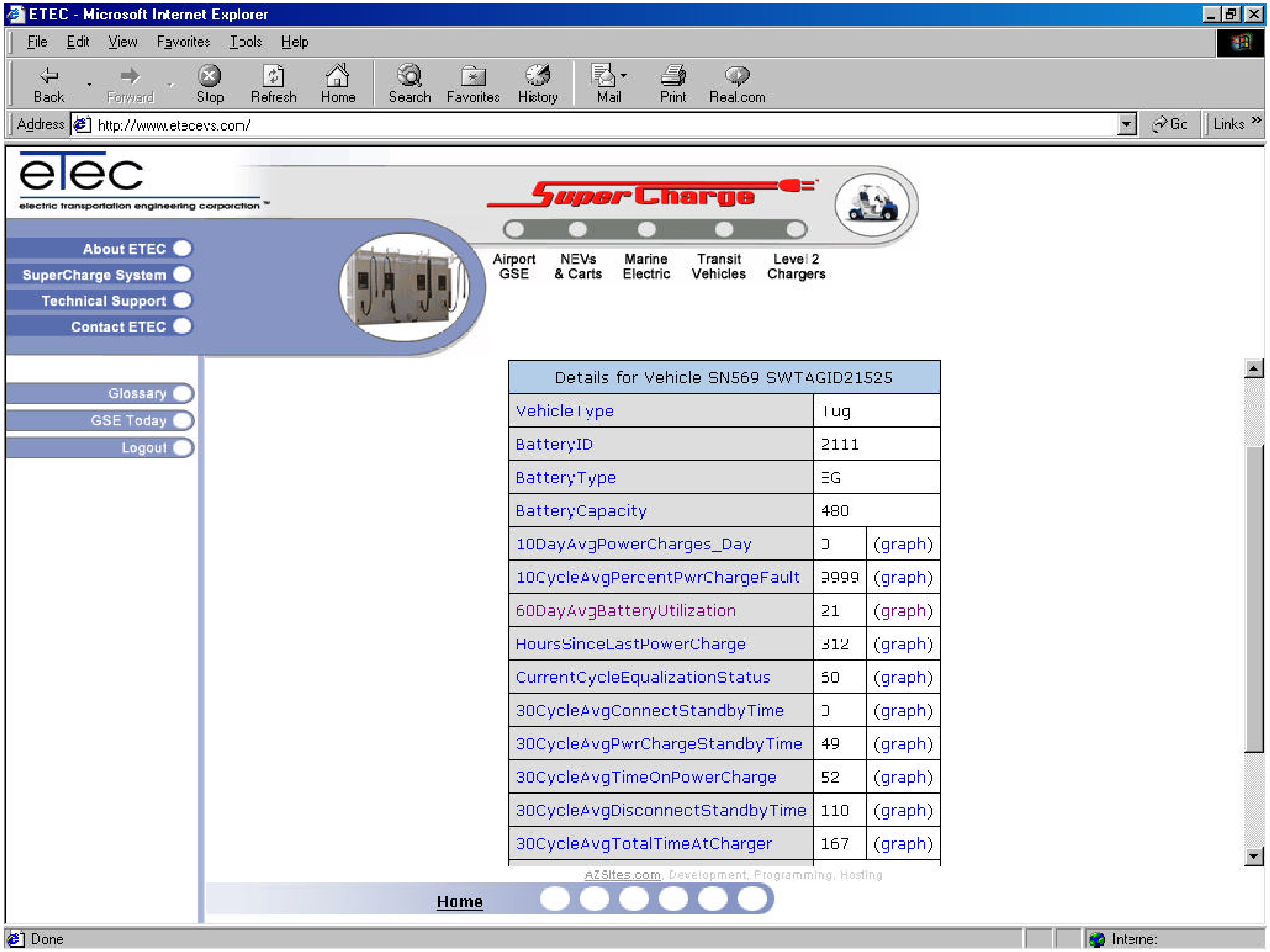
Vehicle ID #	Date	Vehicle Type	Battery Capacity	Avg. % Successful Charges	Hours Since Last Charge	Alert Messages
SN569 SWTAGID21525	2001/09/18	Tug	480	-9998	312	4 alerts
SN570 SWTAGID21523	2001/09/23	Tug	480	-9998	24	4 alerts
SN571 SWTAGID21526	2001/09/24	Tug	480	-9998	24	4 alerts
SN572 SWTAGID21522	2001/09/20	Tug	480	-9998	0	5 alerts
SN580 SWTAGID21524	2001/09/23	Tug	480	-9998	24	4 alerts
SN581 SWTAGID21528	2001/09/21	Tug	480	-9998	0	2 alerts
SN582 SWTAGID21521	2001/09/24	Tug	480	-9998	0	5 alerts
SN583 SWTAGID21529	2001/09/19	Tug	480	-9998	48	4 alerts

Level 2 Charger Data Screen



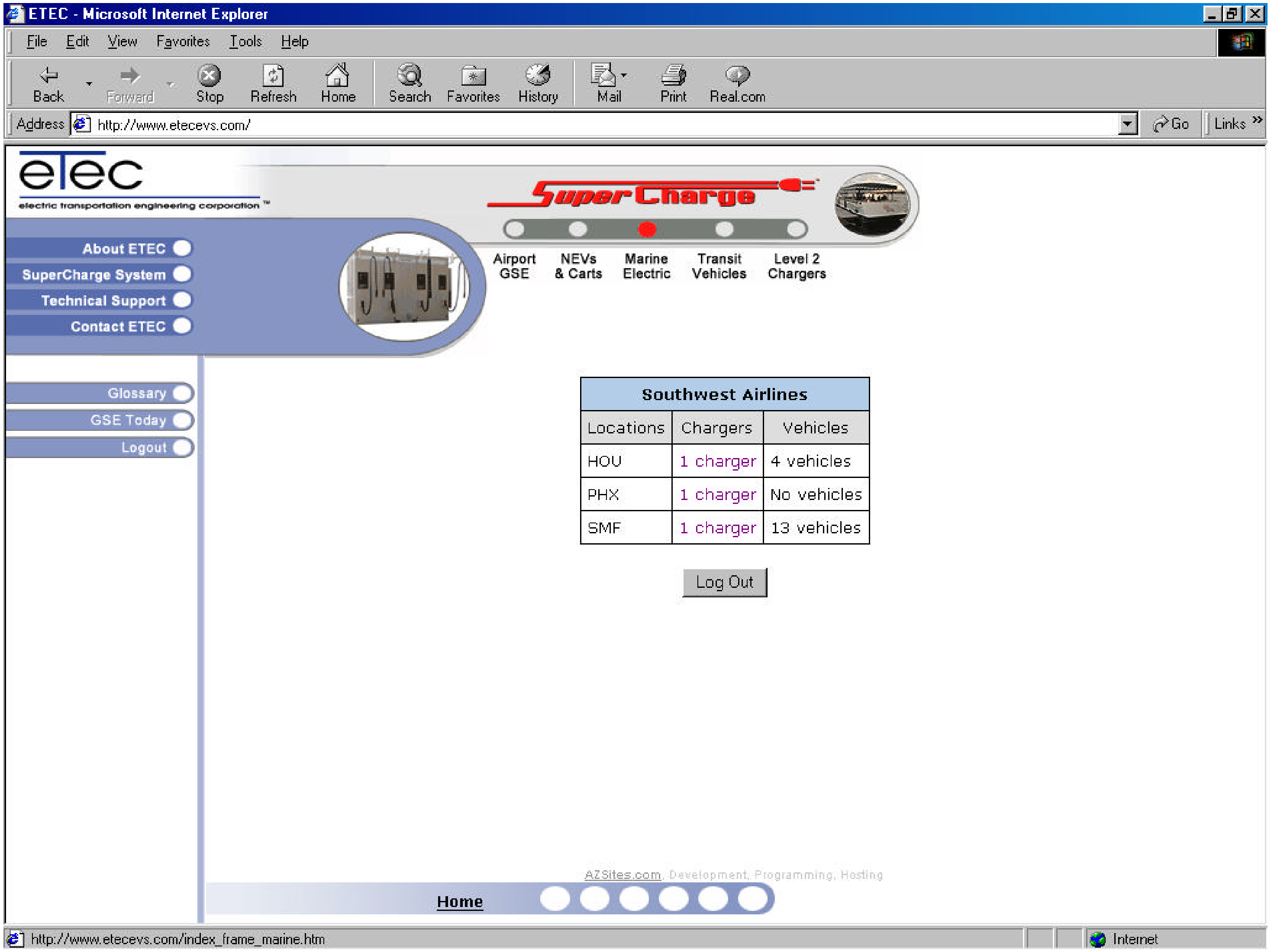
Details for Charger SWSC00000001		
30DayAvgCharges_Day	4	(graph)
30DayAvgPercentChargeFaults	84	(graph)
30DayAvgPercentChargeManualTerm	9999	(graph)
30DayAvgPercentFullCharges	20	(graph)
7DayAvgEnergy_Day	122	(graph)
MaximumChargerPowerLast7Days	9999	
MaximumChargerPowerLast30Days	9999	

Level 2 Tractor Data Screen

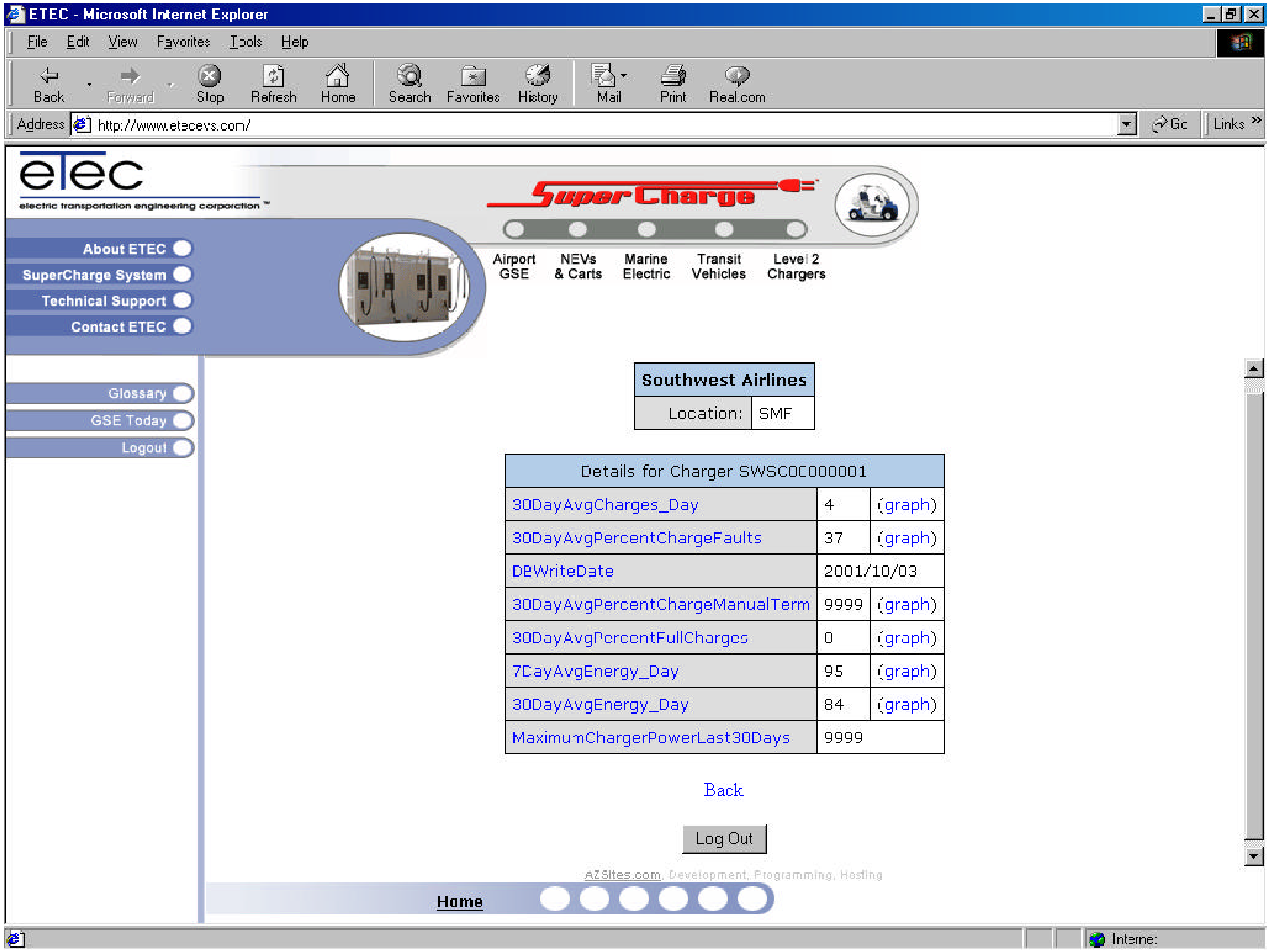


Details for Vehicle SN569 SWTAGID21525		
VehicleType	Tug	
BatteryID	2111	
BatteryType	EG	
BatteryCapacity	480	
10DayAvgPowerCharges_Day	0	(graph)
10CycleAvgPercentPwrChargeFault	9999	(graph)
60DayAvgBatteryUtilization	21	(graph)
HoursSinceLastPowerCharge	312	(graph)
CurrentCycleEqualizationStatus	60	(graph)
30CycleAvgConnectStandbyTime	0	(graph)
30CycleAvgPwrChargeStandbyTime	49	(graph)
30CycleAvgTimeOnPowerCharge	52	(graph)
30CycleAvgDisconnectStandbyTime	110	(graph)
30CycleAvgTotalTimeAtCharger	167	(graph)

Level 3 Selection Screen



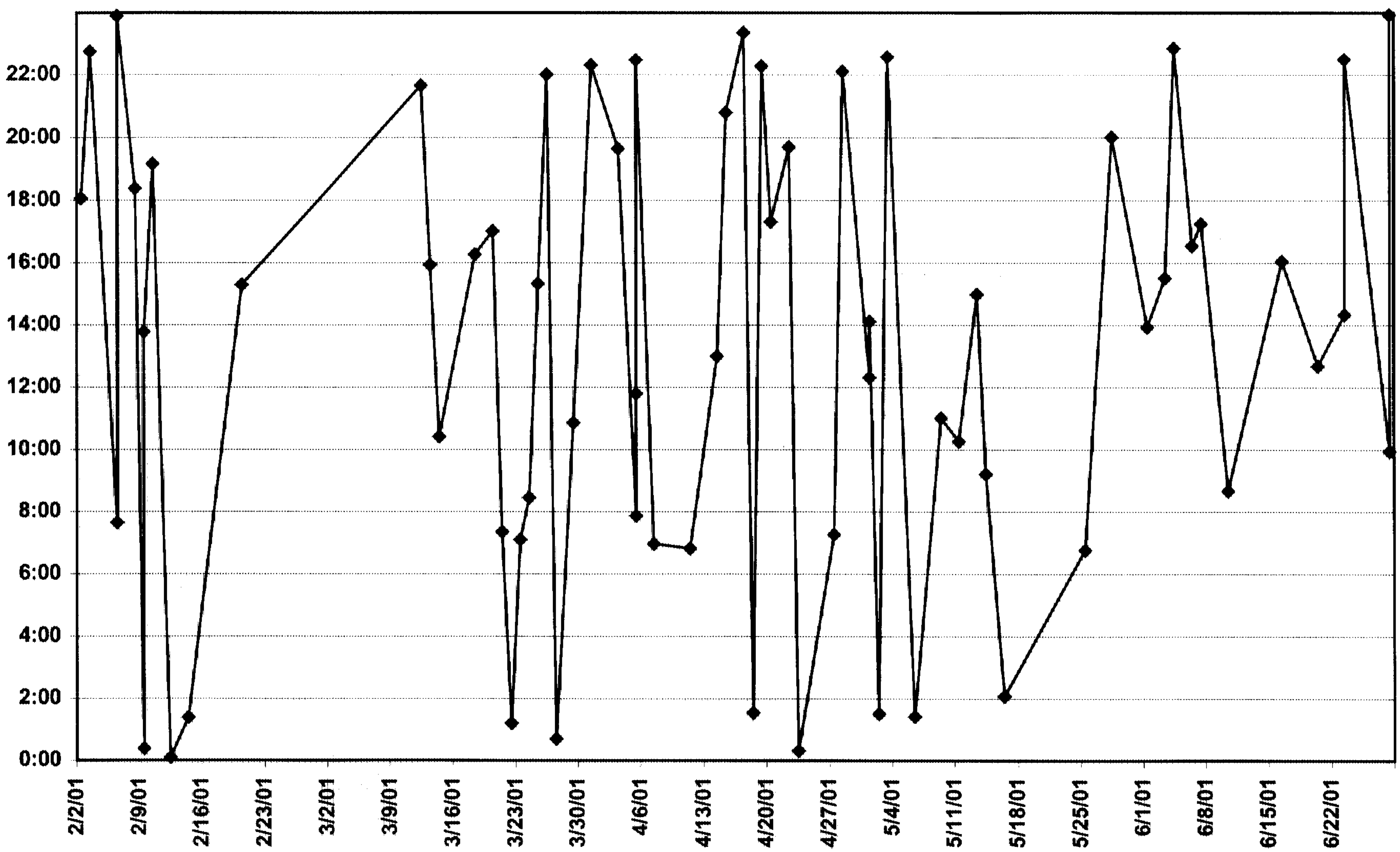
Level 3 Charger Screen



APPENDIX G

TECHNOLOGY ACCEPTANCE: TIME OF DAY CHARGE EVENTS

Time of Day Charge Start - Vehicle BTE-04



APPENDIX H

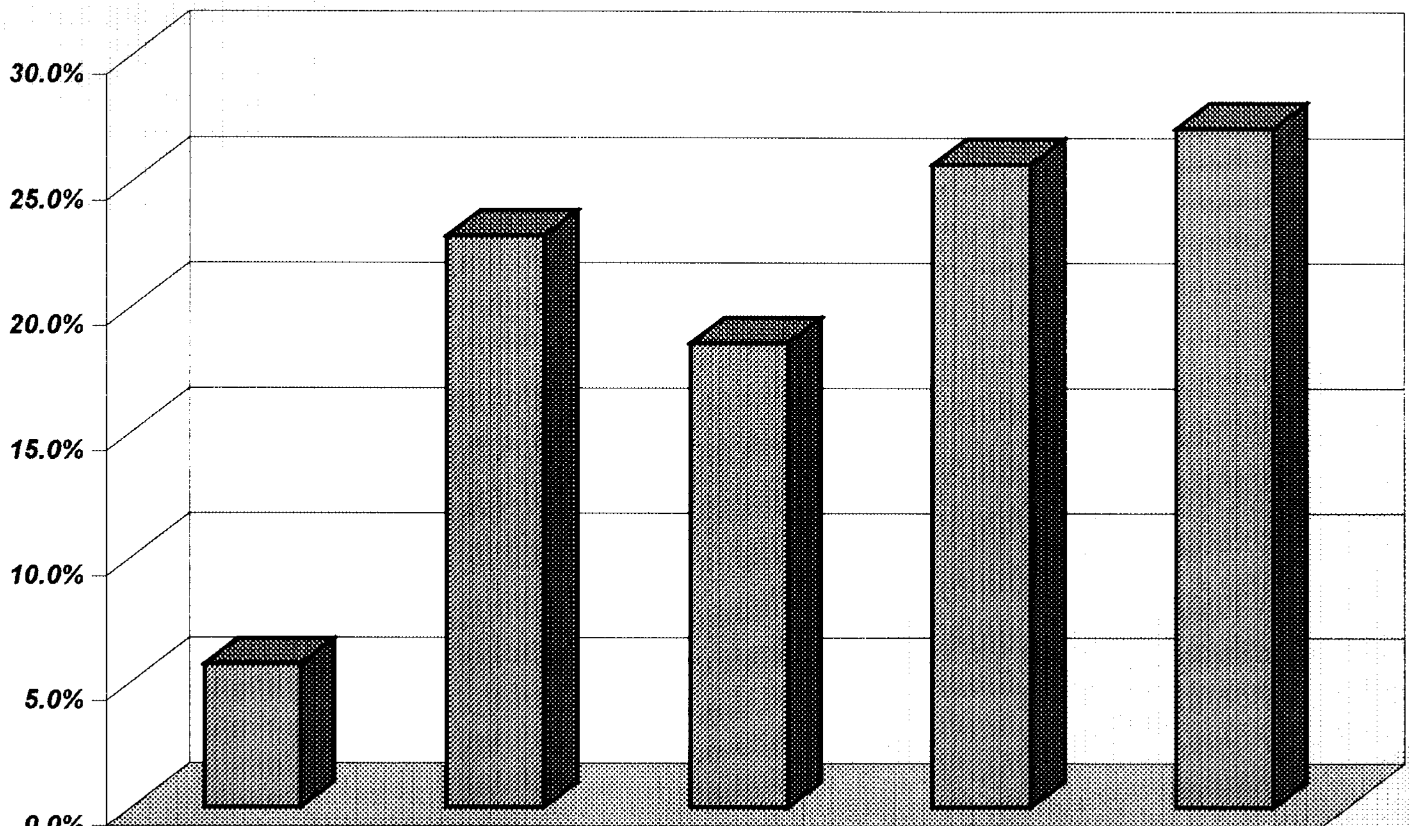
TECHNOLOGY ACCEPTANCE: SURVEY RESULTS

QUESTION

	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
The electric tractors are easy to use	4	16	13	18	19
The charging station is easy to use	14	19	10	16	11
Waiting for a tractor to charge has not kept me from doing my job	21	17	18	6	8
I have enough time to charge a tractor between work assignments	20	19	21	6	4
I prefer using the electric tractors	34	10	16	4	6
I prefer using the gasoline tractors	3	5	13	10	39
I prefer using the diesel tractors	9	5	24	9	23
I do not charge the vehicle until the red "Charge Now" light comes on	9	10	25	12	14

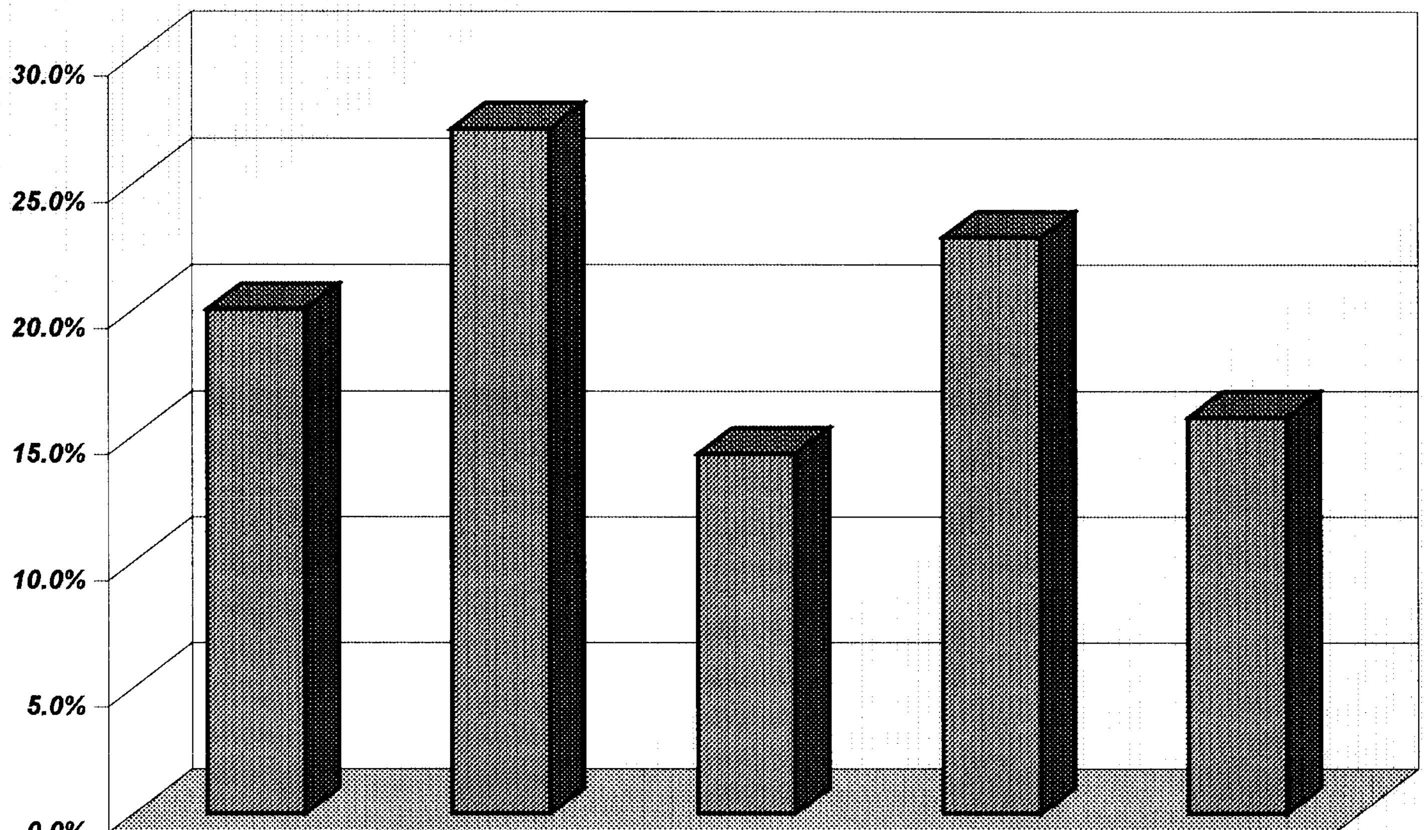
	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
The electric tractors are easy to use.	**5.7%**	**22.9%**	**18.6%**	**25.7%**	**27.1%**
The charging station is easy to use.	**20.0%**	**27.1%**	**14.3%**	**22.9%**	**15.7%**
Waiting for a tractor to charge has not kept me from doing my job	**30.0%**	**24.3%**	**25.7%**	**8.6%**	**11.4%**
I have enough time to charge a tractor between work assignments	**28.6%**	**27.1%**	**30.0%**	**8.6%**	**5.7%**
I prefer using the electric tractors	**48.6%**	**14.3%**	**22.9%**	**5.7%**	**8.6%**
I prefer using the gasoline tractors	**4.3%**	**7.1%**	**18.6%**	**14.3%**	**55.7%**
I prefer using the diesel tractors	**12.9%**	**7.1%**	**34.3%**	**12.9%**	**32.9%**
I do not charge the vehicle until the red "Charge Now" light comes on	**12.9%**	**14.3%**	**35.7%**	**17.1%**	**20.0%**

The electric tractors are easy to use.



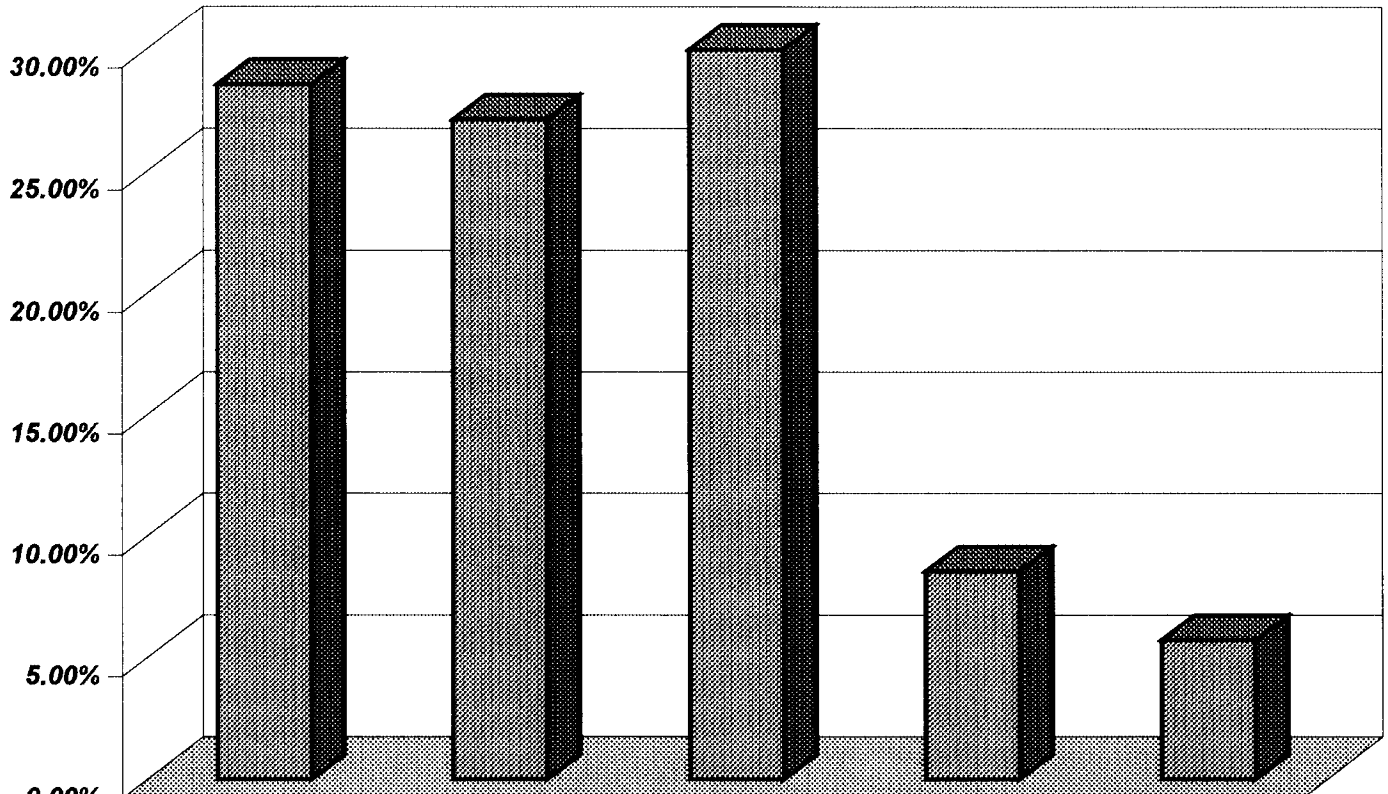
	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
The electric tractors are easy to use.	5.7%	22.9%	18.6%	25.7%	27.1%

The charging station is easy to use.



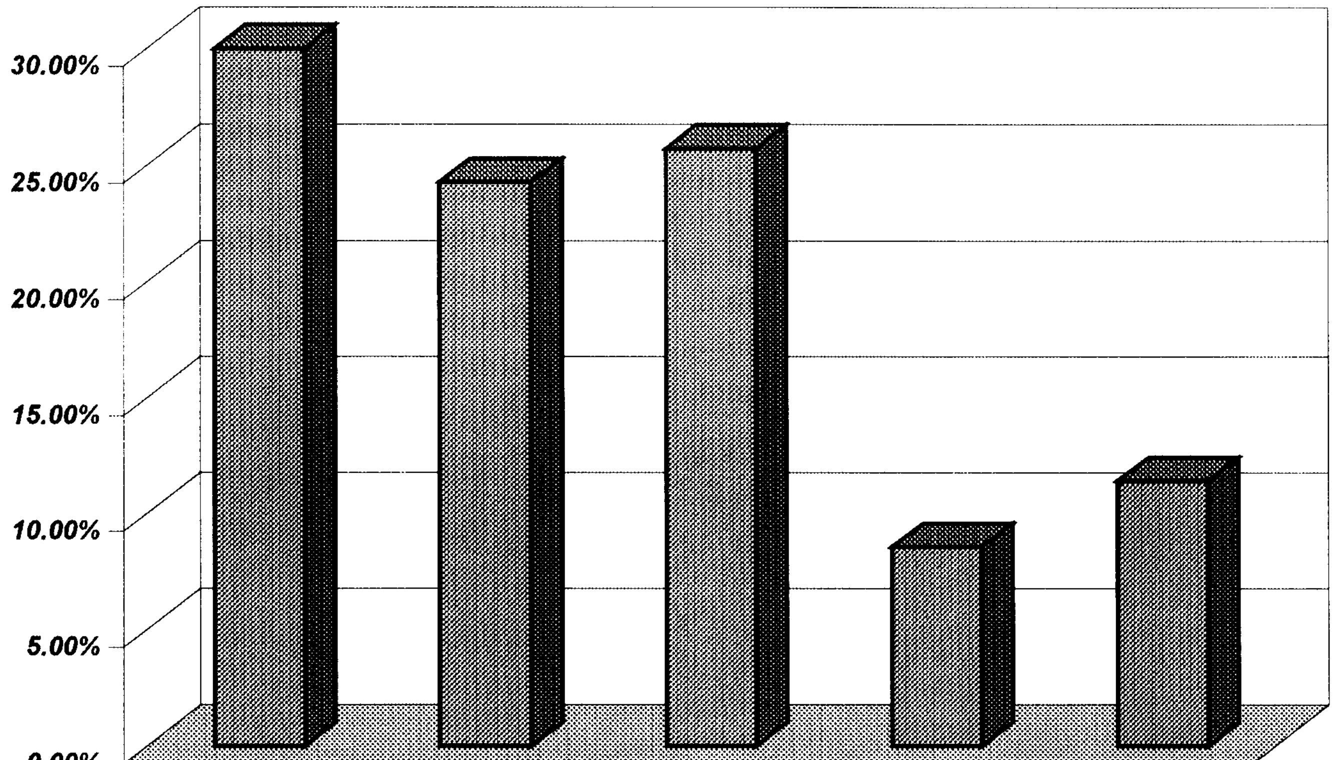
	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
The charging station is easy to use.	*20.0%*	*27.1%*	*14.3%*	*22.9%*	*15.7%*

I have enough time to charge a tractor between work assignments

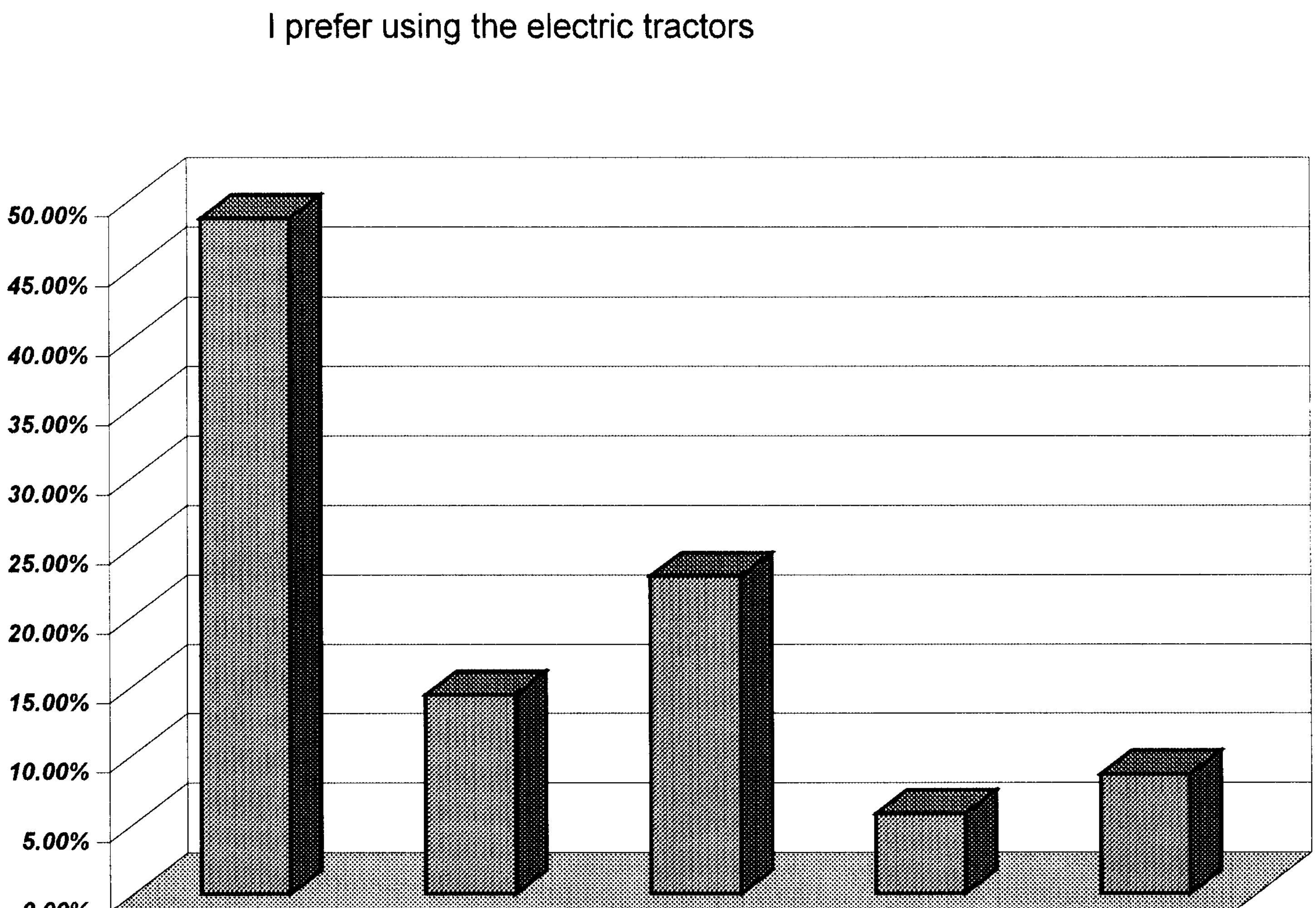


	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I have enough time to charge a tractor between work assignments	28.57%	27.14%	30.00%	8.57%	5.71%

Waiting for a tractor to charge has not kept me from doing my job

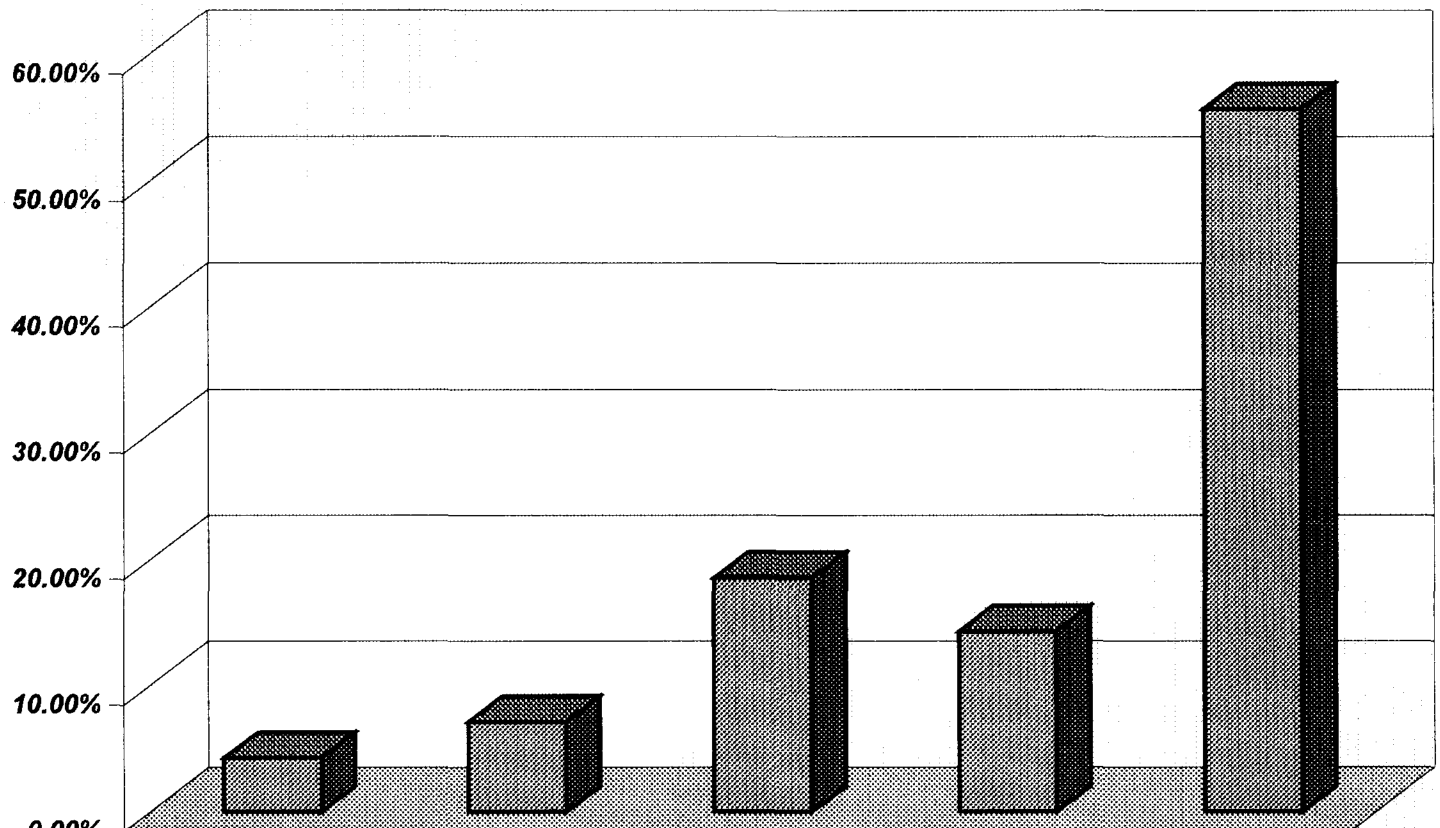


	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
Waiting for a tractor to charge has not kept me from doing my job	30.00%	24.29%	25.71%	8.57%	11.43%



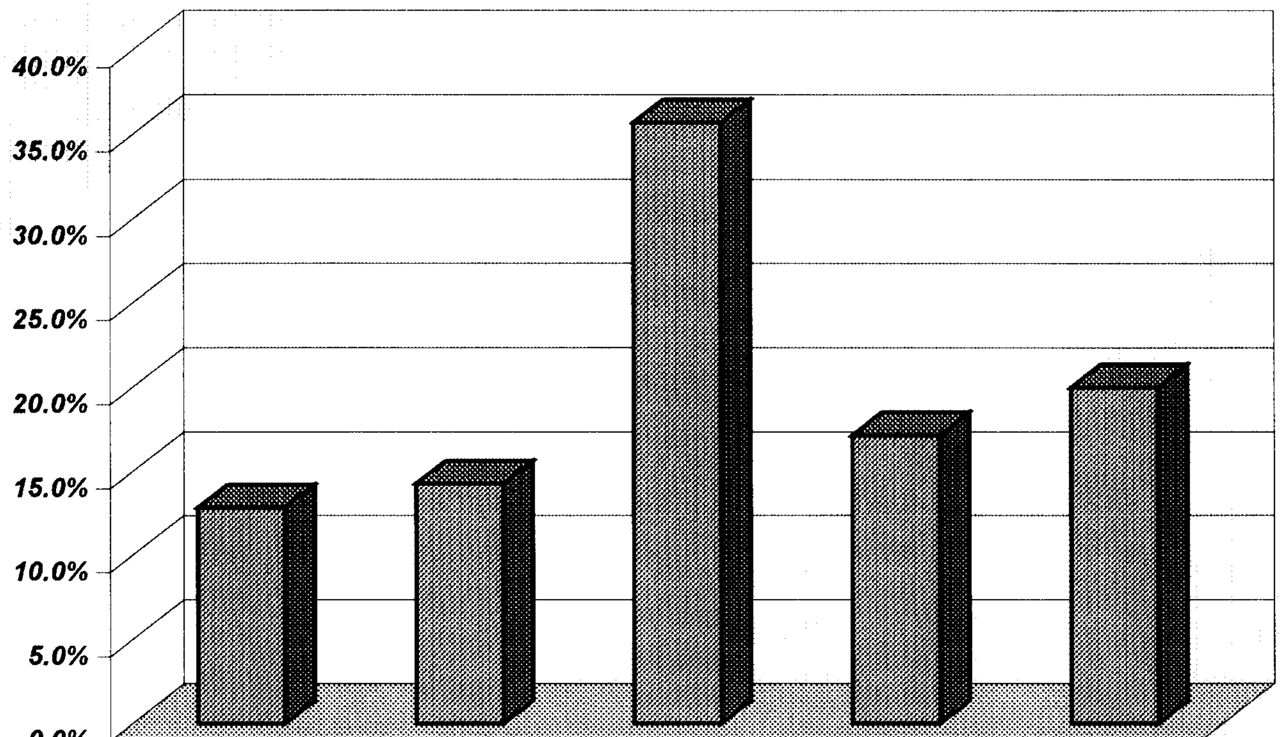
	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I prefer using the electric tractors	48.57%	14.29%	22.86%	5.71%	8.57%

I prefer using the gasoline tractors



	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I prefer using the gasoline tractors	*4.29%*	*7.14%*	*18.57%*	*14.29%*	*55.71%*

I do not charge the vehicle until the red "Charge Now" light comes on.

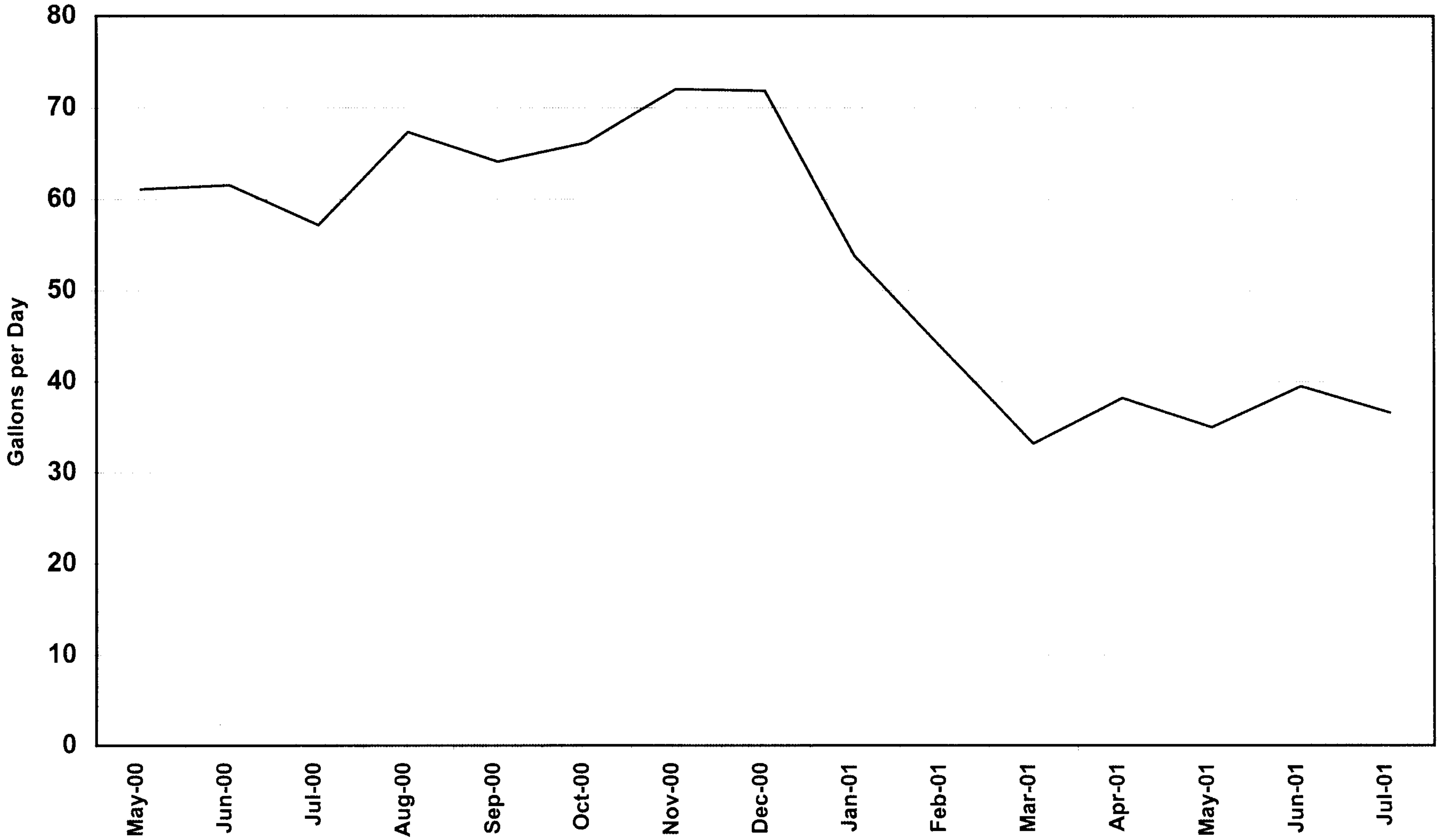


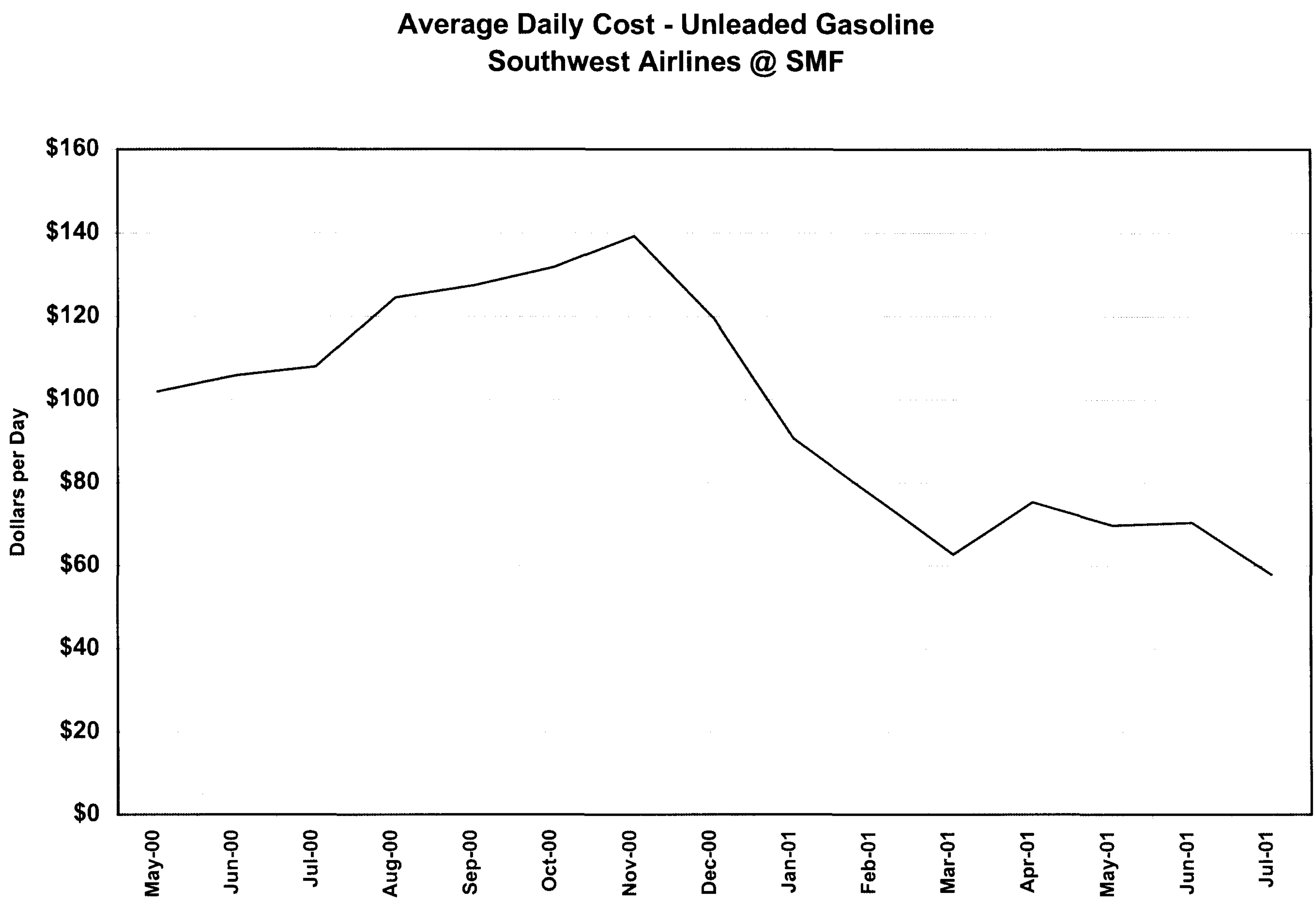
	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I do not charge the vehicle until the red "Charge Now" light comes on	12.9%	14.3%	35.7%	17.1%	20.0%

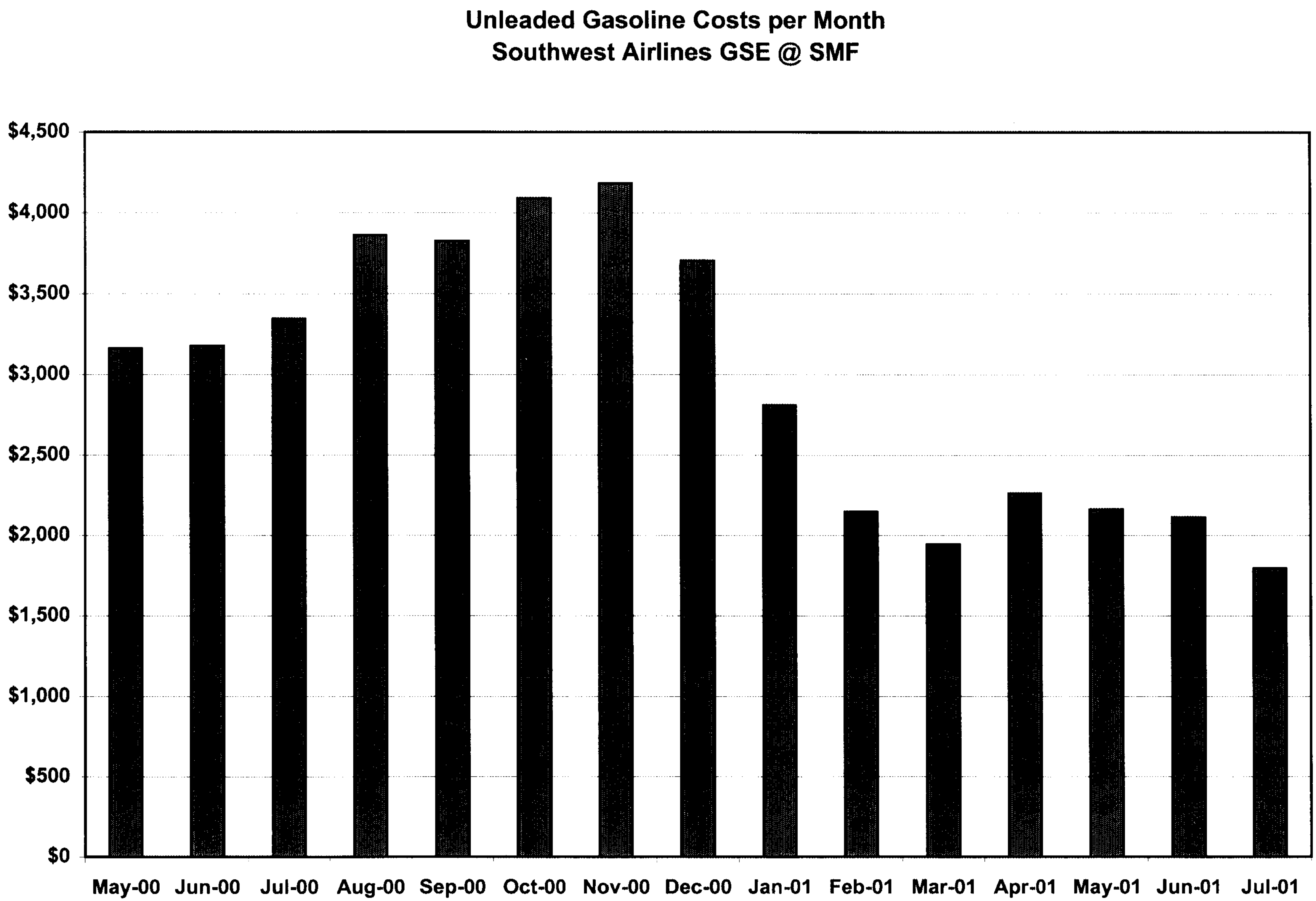
APPENDIX I

GASOLINE CONSUMPTION DATA

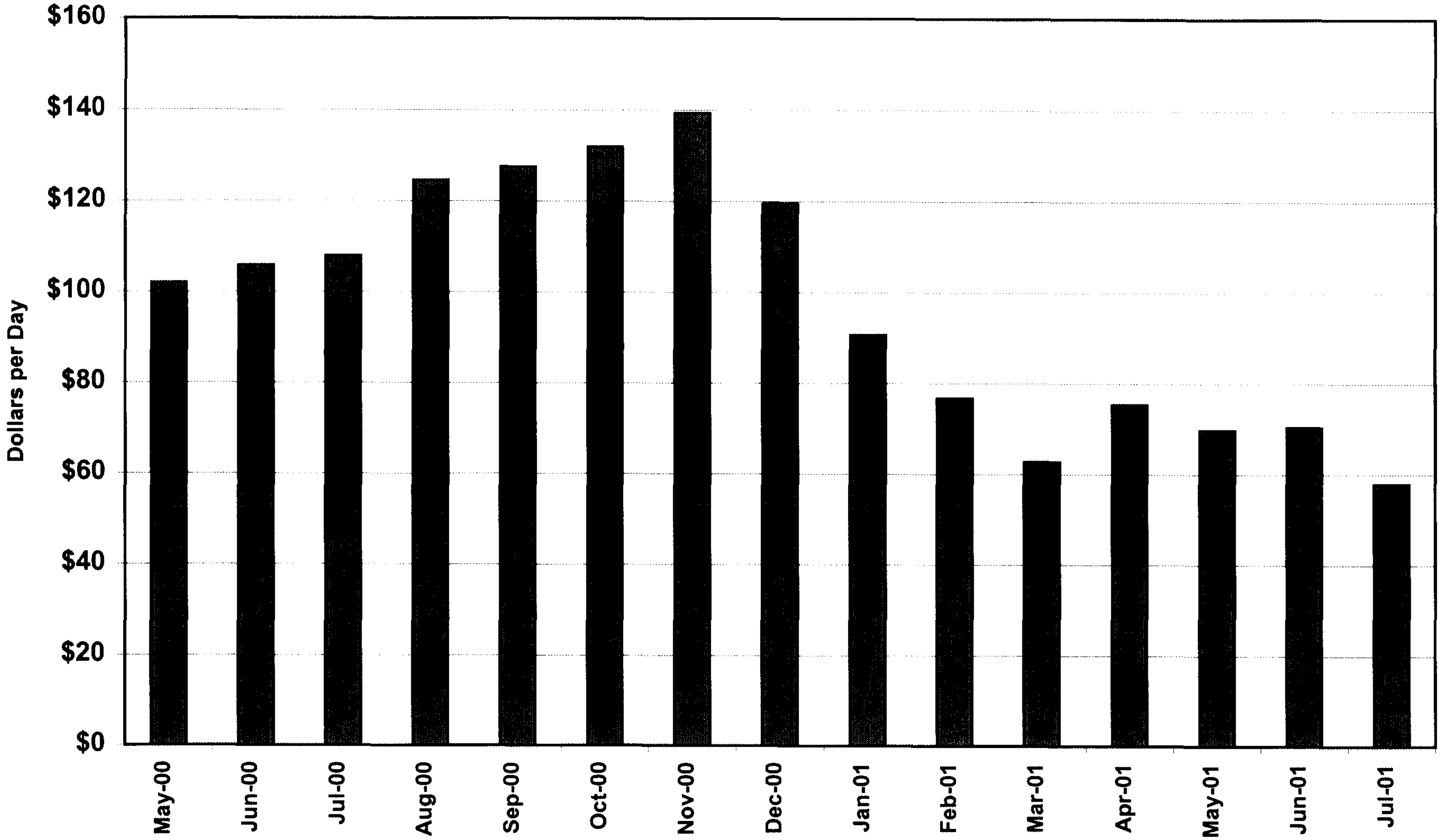
Consumption of Unleaded Gasoline - Gallons per Day
Southwest Airlines @ SMF




Average Daily Cost - Unleaded Gasoline
Southwest Airlines @ SMF
Dollars per Day
$160
$140
$120
$100
$80
$60
$40
$20
$0
May-00
Jun-00
Jul-00
Aug-00
Sep-00
Oct-00
Nov-00
Dec-00
Jan-01
Feb-01
Mar-01
Apr-01
May-01
Jun-01
Jul-01


Unleaded Gasoline Costs per Month
Southwest Airlines GSE @ SMF
$4,500
$4,000
$3,500
$3,000
$2,500
$2,000
$1,500
$1,000
$500
$0
May-00
Jun-00
Jul-00
Aug-00
Sep-00
Oct-00
Nov-00
Dec-00
Jan-01
Feb-01
Mar-01
Apr-01
May-01
Jun-01
Jul-01

Average Daily Cost - Unleaded Gasoline
Southwest Airlines @ SMF



APPENDIX J

Battery Pack Optimization Study

PERFORMANCE OF VALVE-REGULATED LEAD-ACID 6-VOLT MONOBLOCK BATTERIES UNDER ELECTRIC VEHICLE GROUND-SUPPORT EQUIPMENT CONDITIONS.

AUGUST 2001

CONTENTS

Page No.

1. EXECUTIVE SUMMARY

Electric Transportation Engineering Corporation (ETEC) has been developing infrastructure for the operation of electric vehicles for over 10 years. They have developed partial-state-of-charge (PSOC)/fast-charge strategies for a variety of lead-acid battery powered electric vehicles (EVs). This type of duty has been shown to decrease charge times to 10-30 min, while retaining, if not improving, battery cycle life. Recent developments have included vehicles and operating systems for electrically powered ground support equipment (GSE) at airports.

The valve-regulated lead-acid (VRLA) batteries currently used for GSE vehicles are expensive and have a high internal resistance. This leads to significant heating of the batteries during charging and extended charge times (up to 1 h). ETEC has developed a simulated GSE operating strategy based on actual data from the field and has used this strategy to evaluate the performance of an alternative VRLA battery that has both a lower internal resistance and cost to that previously used. The battery is manufactured by Sonnenschien and is called a Dryfit. The battery has completed 570 cycles between 30-80% state-of-charge, with each cycle representing one day of GSE service. After 510 cycles, the capacity of the battery had decreased to ~ 80% of the initial value. A full recharge returned the battery to almost 100% capacity. Unfortunately, battery performance slowly decreased again when GSE duty was recommenced. This gradual drop-off in performance is attributed to insufficient charge return, rather than actual degradation of the battery. The problem is exacerbated by a decrease in charging efficiency as the batteries 'age'. It is predicted that optimization of the operating strategy has the potential to extend cycle life to over 800 cycles.

2. INTRODUCTION AND BACKGROUND

Until recently, the battery systems used in the GSE EVs have comprised 2-V, tubular-plate gelled-electrolyte batteries (500 Ah at the C/20 rate) arranged in one series string (nominal 80 volts). While the tubular plates should be well suited to heavy cycling applications, the batteries have a high profile (i.e., tall, narrow plates) and, as a consequence, have a high internal resistance. This results in unnecessary heating of the batteries during fast-charge, and limits charging times to close to 1 h. Further, the batteries are expensive and the performance of the batteries under GSE service in terms of $/lifetime-Ahs requires improvement.

The aim of this project is to evaluate the performance of an alternative design of VRLA battery under simulated GSE conditions. This battery is called a Dryfit and is manufactured by Sonnenschien. It has a lower internal resistance, is considerably less expensive on a $/lifetime-Ahrs basis, and has a higher energy density than the tubular-plate variants currently used. Details of the new battery are given below:

- VRLA design (gelled-electrolyte)
- flat-plate design
- 6-V monobloc
- 180 Ah Nominal Capacity (C_6 rate)
- 110 Ah Useable Capacity (C_1 rate, 1.6 V/cell cut-off)
- 30 kg
- 22 Wh/kg (1C rate)

GSE vehicles fitted with these batteries would have 28 modules configured in two parallel strings, thereby providing a system voltage of 84 V and a nominal capacity of 360 Ah.

3. WORK AREAS

The present program comprises two work areas.

Work Area 1. Formulation of a simulated PSOC/fast-charge strategy for GSE duty.

The first part of the project involves the formulation of a suitable, simulated GSE operating strategy. The ideal strategy mimics closely the conditions experienced in the field and provides a high charge/discharge throughput.

Work Area 2. Battery performance under simulated GSE duty

The second part of this project involves the evaluation of the alternative battery under the simulated, GSE operating strategy. The batteries will be operated until they no longer provide what corresponds to an acceptable range.

4. TEST ENVIRONMENT

The following conditions have been observed for all battery cycling.

(i) batteries sit on a foam pad, but are exposed to atmosphere on all sides and top;

(ii) ambient temperature 22 ^{o}C ± 2 ^{o}C;

(iii) battery temperature is measured at the base of a middle cell (probe is lodged between the battery base and the foam mat);

(iv) current measurement accurate to 1% of maximum charge rate;

(v) voltage measurement accurate to 1% of measured value;

5. WORK PROGRESS

5.1. Background: Basic PSOC 0peration

PSOC/fast-charge operating strategies generally comprise the following three regimes:

Regime 1: a discharge (usually to 20-30% SOC);
Regime 2: a fast charge (usually to 70-90% SOC);
Regime 3: a regular conditioning charge.

One pass through Regimes 1 and 2 is called a PSOC cycle. Regimes 1 and 2 are repeated sequentially until a preset number of PSOC cycles have been completed. A conditioning charge (Regime 3) is then applied. This latter procedure usually comprises a constant voltage/constant current charge applied using resistance-free voltage techniques. The preset number of PSOC cycles completed between each conditioning charge, and the composition of the conditioning charge generally require fine-tuning for each specific type of duty in order to achieve optimum battery life.

5.2. Work Area 1: Formulation of a simulated PSOC/fast-charge strategy for GSE duty.

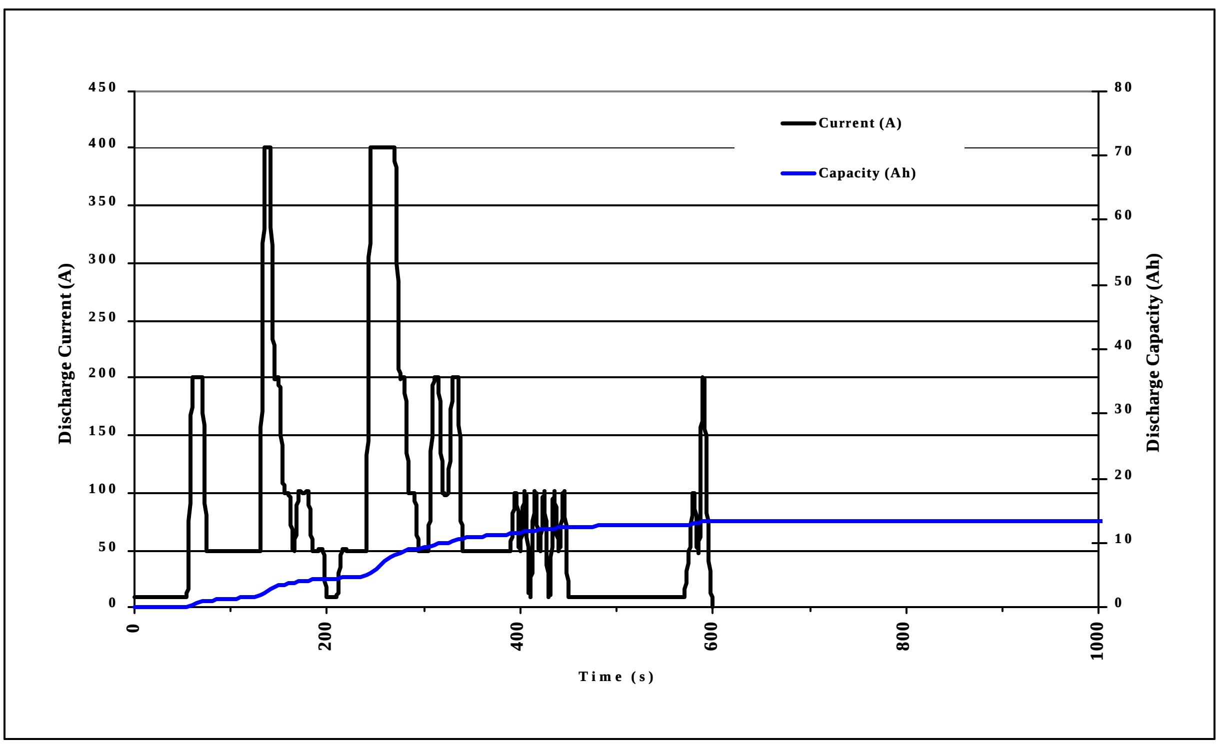
The simulated GSE operating strategy derived in this study is based on the basic PSOC/fast-charge strategy described in Section 5.1. Regime 1 has been derived from field data obtained by monitoring GSE vehicles at various airports and is based on a 70% depth-of-discharge (DOD), i.e., 30% SOC. Regime 2 is based on a fast-charge current of 300 A (150 A per battery string). Regime 3 involves a full conditioning charge every six PSOC cycles. The frequency and intensity of this charge has been based on knowledge gained from previous PSOC/fast-charge studies. The derivation of the GSE operating strategy is described in more detail in the following sections.

5.2.1. Regime 1: Discharge.

ETEC has operated a variety of GSE EVs at airports and monitored the charge and discharge currents experienced by the batteries under such duty. The data collected has been reviewed and a typical discharge profile has been selected. The profile is shown schematically in Fig. 1. (note, the current and energy values are for two parallel strings — currents for individual batteries will be half the values displayed). The profile removes 6.7 Ah and is repeated until the desired battery SOC is reached (~70% DOD).

It is well understood that the capacity of lead-acid batteries varies with the discharge rate. As the GSE schedule used in this project involves a complex combination of discharge rates, the first requirement was to determine the battery capacity under such GSE duty. Hence, two batteries, connected in series, were discharged according to the GSE discharge profile (see Fig 1). The profile was repeated until the battery voltage reached 1.5 V/cell. After a full recharge, the battery was then subjected to another full discharge to 1.5 V/cell under the GSE schedule. The capacities obtained for the two discharges were 137 and 138 Ah. Based on the voltage response during discharge, it was estimated that a voltage of 1.83 V/cell under maximum load (200 A per string) would correspond to the target DOD of 70%. Hence, this value was designated as the voltage limit for discharge during Regime 1 of the GSE schedule.

Fig. 1: GSE discharge cycle



5.2.2. Regimes 2 and 3: Charge and conditioning.

An objective of the project is to obtain a satisfactory cycle life, whilst charging the batteries as quickly as practical. The maximum current available from the fast-chargers currently installed at the relevant airports is 400 A, i.e., 200 A for each of the two parallel strings that comprise the GSE battery banks. This charge current (~ 2C) is considered excessive for the Sonnenschien batteries, as it may result in melting of the top lead in the battery. Consultation with Sonnenschien engineers revealed that the maximum recommended charge current is 150 A (~ 1.5C). This rate is expected to provide a charge time of ~ 30 min for a 30-80% PSOC window. The conditioning procedure is based on previous PSOC/fast-charge work. The complete PSOC/fast-charge operating protocol employed to operate the batteries under GSE duty is as follows.

(i) discharge using repeats of the GSE discharge profile until battery voltage reaches 1.83 V/cell (i.e., discharge from 100% to ~ 30% SOC);

(ii) charge at 150 A until 2.35 V/cell (resistance-free voltage control and temperature compensation), then continue to charge battery until the charge current has decreased to 75 A;

(iii) discharge using repeats of the GSE discharge profile until battery voltage reaches 1.83 V/cell (i.e., discharge from 80% to ~ 30% SOC). This discharge step only commences if battery temperature is < 40 ^{o}C;

(iv) repeat (ii)-(iii) until step (iii) has been performed five times (i.e., six discharges in total);

(v) charge at 150 A until 2.35 V/cell (resistance-free voltage control and temperature compensation), then continue to charge battery until the charge current has decreased to 75 A;

(vi) charge at 25 A until the voltage reaches 2.35 V/cell;

(vii) charge at 9 A for 1 h;

(viii) repeat steps (i)-(vii) until the capacity recorded during step (i) is less than 80% of the nominal value.

The completion of consecutive discharge and charge steps is called a PSOC cycle (see Section 5.1). The completion of 6 such PSOC cycles (steps (i)-(iii)) followed by the conditioning procedure (steps (v)-(vii)), is referred to as a master cycle (note, one PSOC cycle is equivalent to one day of GSE service).

5.3 Work Area 2: Battery performance under simulated GSE duty.

5.3.1. Battery performance during initial capacity testing.

The batteries were first weighed (see Table 1) and then subjected to the following procedure:

(i) charge at 30 A for 4 h charge with a TOCV (top-of-charge voltage) of 2.67 V/cell;
(ii) discharge at 110 A to 1.75 V/cell;
(iii) charged at 50 A with a TOCV of 2.55 V/cell until 106% of the previous discharge has been returned.
(iv) repeat (ii)-(iii) a total of five times

The capacity of the batteries during the cycling are shown in Table 1.

Table 1. Initial capacity (1C) and weight of Dryfit batteries

Cycle	Capacity (Ah)	
Number	**Battery 1 (31.5440 kg)**	**Battery 2 (31.472 kg)**
1	102.3	105.6
2	98.9	102.5
3	98.2	101.9
4	97.2	100.5
5	98.4	100.8
Average	**98.9**	**102.3**

The average capacities obtained are ~ 10% lower than the nominal value (i.e., 110 Ah). It is likely that the batteries are not yet fully formed, and battery capacity is expected to improve gradually during preliminary cycling.

5.3.2. Battery performance during GSE cycling.

Two Dryfit batteries, connected in series, were operated under GSE duty for several months. They were cycled according to the schedule described in Section 5.2.2 and have completed 570 PSOC cycles between 30-80% SOC. The time required to recharge the batteries from 30 to 80% SOC has varied between 25 to 30 min — this meets the target charge-time of 30 min.

Figure 2 shows the total Ahs delivered by the batteries during each set of six consecutive PSOC cycles (termed 'master-cycle capacity'), the total Ahs received by the batteries during each master cycle (termed 'master-cycle charge-return'), and the master-cycle charge-return divided by the master-cycle capacity (termed 'overcharge'). During the first 10 master cycles, the master-cycle capacity decreased gradually from ~ 380 to 330 Ah, whereas the overcharge increased from 101 to 103%. This drop in capacity suggests that an overcharge factor of 103% is not sufficient to maintain battery capacity during GSE service.

In order to increase the level of overcharge, the constant current component of the conditioning procedure performed at the end of each six PSOC cycles (step (vii), Section 5.2.2) was changed from 9 A for 1 h, to 12 A for 1.5 h. This modification increased the charge delivered during each master cycle by 9 Ah. This resulted in an increase in capacity, and after the completion of 20 master cycles, the master-cycle capacity had increased to ~ 420 Ah.

Between master cycles 20 and 40, a software problem in the battery cycler resulted in a significant reduction in the Ahs delivered during the conditioning procedure (steps (v)-(vii), Section 5.2.2). This caused a drop in both the master-cycle capacity and the master-cycle charge-return. Once, this problem was rectified (36 master cycles), the master-cycle capacity increased quickly to 425 Ah, and the overcharge stabilized at ~ 103%. Between master cycles 38 to 85, however, the master-cycle capacity decreased gradually from 425 to 320 Ah. At this stage the master-cycle capacity was considered too low for practical GSE operation, so the batteries were removed from duty and charged at 50 A with a TOCV of 2.45 vpc for 14 h, followed by a 2 A charge for 4 h. Following this recovery procedure, the batteries were subjected to two 1C discharge/charge cycles (see Section 5.3.1 above, for conditions). The average capacity of the batteries was found to be ~ 104 Ah (see Table 2), which is slightly higher than that obtained when the batteries were new (i.e., 100.6 Ah). This behavior indicates that the 85 master cycles completed (i.e., 510 PSOC cycles) has not affected the capacity of the batteries.

Table 2. Capacity of Dryfit batteries after 510 PSOC cycles (1C rate)

First Cycle	Second Cycle	Average Capacity	Average Capacity (initial)
103.4	104.5	104	100.6

The batteries were then returned to GSE duty. The first master-cycle capacity after the full recharge was ~ 370 Ah (Fig. 2), which confirms that the batteries were still in a very good condition. During subsequent service, however, the master-cycle capacity began to decrease and after the completion of 95 master cycles, the master-cycle capacity was below 330 Ah. As the battery is obviously still in good condition, the decrease in capacity during GSE duty is attributed to insufficient overcharge during each master cycle (note, the overcharge delivered between master cycles 85 and 95 varied between 102 to 103%).

The Ahs delivered and returned to the batteries during both the first (Fig. 3) and sixth PSOC cycle (Fig. 4) of each master cycle have also been monitored. The evolution of both these values during GSE cycling follows the same trend as that observed for both the master-cycle capacities and master-cycle charge-returns (Fig. 2). The capacity delivered during the first PSOC cycle (~ 70-90 Ah) is considerably larger than that obtained during the sixth PSOC cycle (~40-60 Ah). This is be expected as the first and the sixth discharges of each master cycle commence with the battery at a nominal capacity of 100 and 80% SOC, respectively.

In general, the existing algorithm delivers up to 103% overcharge during GSE duty (Fig. 2). It appears that this is not sufficient to maintain battery capacity. Further, it is thought that the charging efficiency of the batteries is decreasing with cycling, which is further exacerbating the problem of insufficient charge return. This drop in charging efficiency is attributed to electrolyte dryout as a result of both oxygen loss from the battery and positive-grid corrosion. This behavior causes the fissures in the gelled-electrolyte to increase in both number and size, thereby increasing the rate of oxygen transfer from the positive to the negative plates. This, in turn, increases the recombination rate, which reduces the overall charging efficiency of the battery.

Fine tuning of the GSE operating algorithm to increase the level of overcharge and also compensate for changes in charging efficiency are expected to overcome the problems outlined above. It is expected that such an optimization process will provide a cycle life of in excess of 800 PSOC cycles. With two battery strings per GSE vehicle, 800 PSOC cycles (assuming an average of 60 Ah per 80-30% discharge) will provide a lifetime Ah throughout of ~ 94 000 Ah.

Fig. 2. Master-cycle capacity, master-cycle charge-return and overcharge of Dryfit batteries during GSE cycling

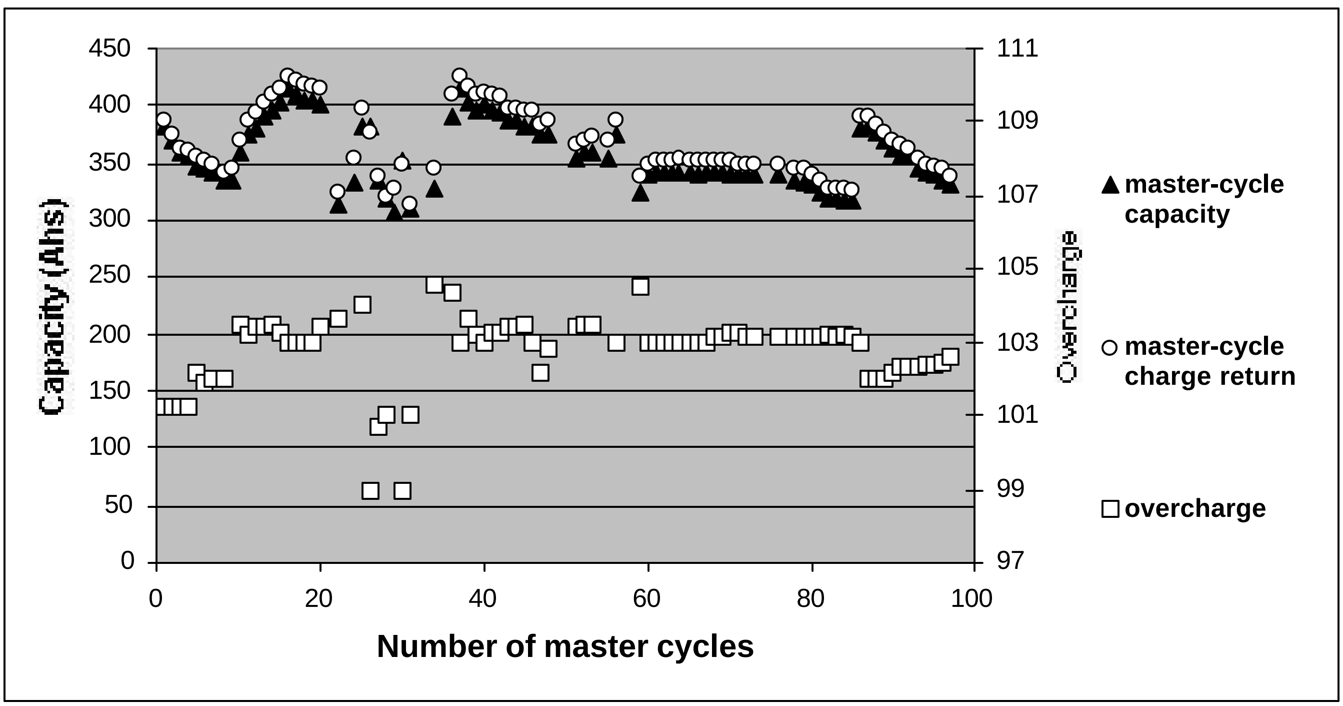


Fig. 3. Capacity and charge return of Dryfit batteries during the first PSOC cycle of each master cycle of Dryfit batteries during GSE cycling

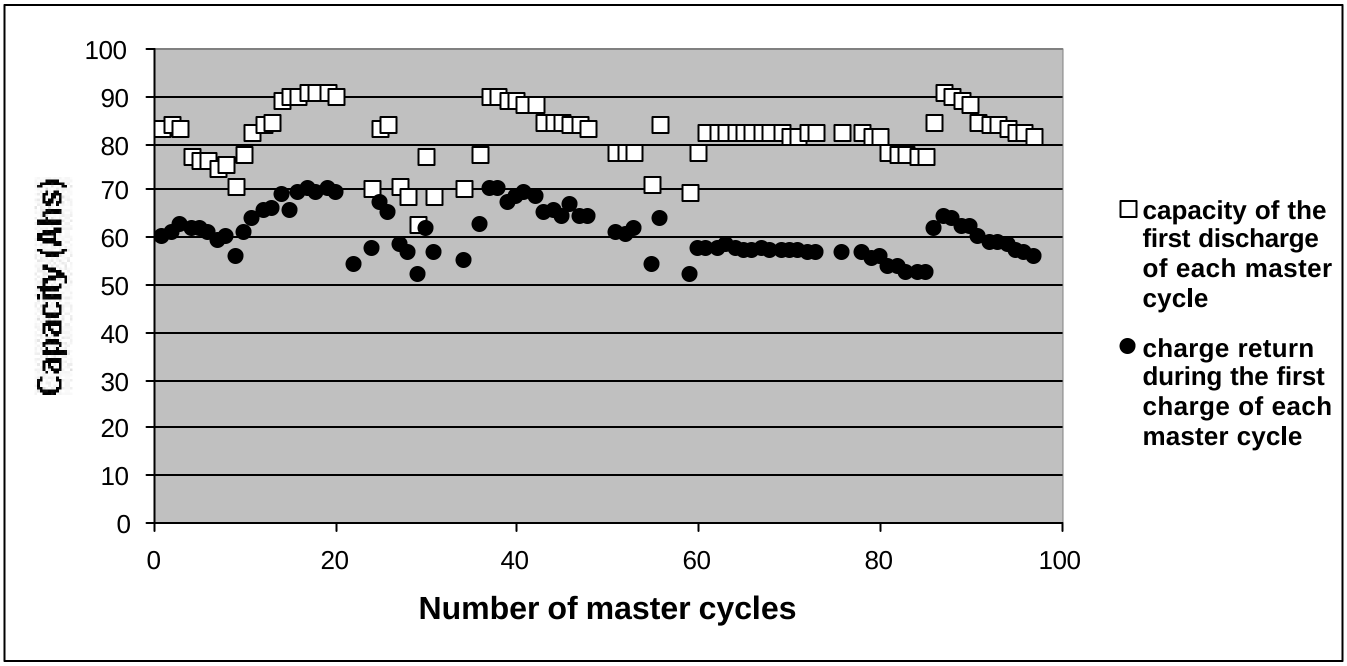
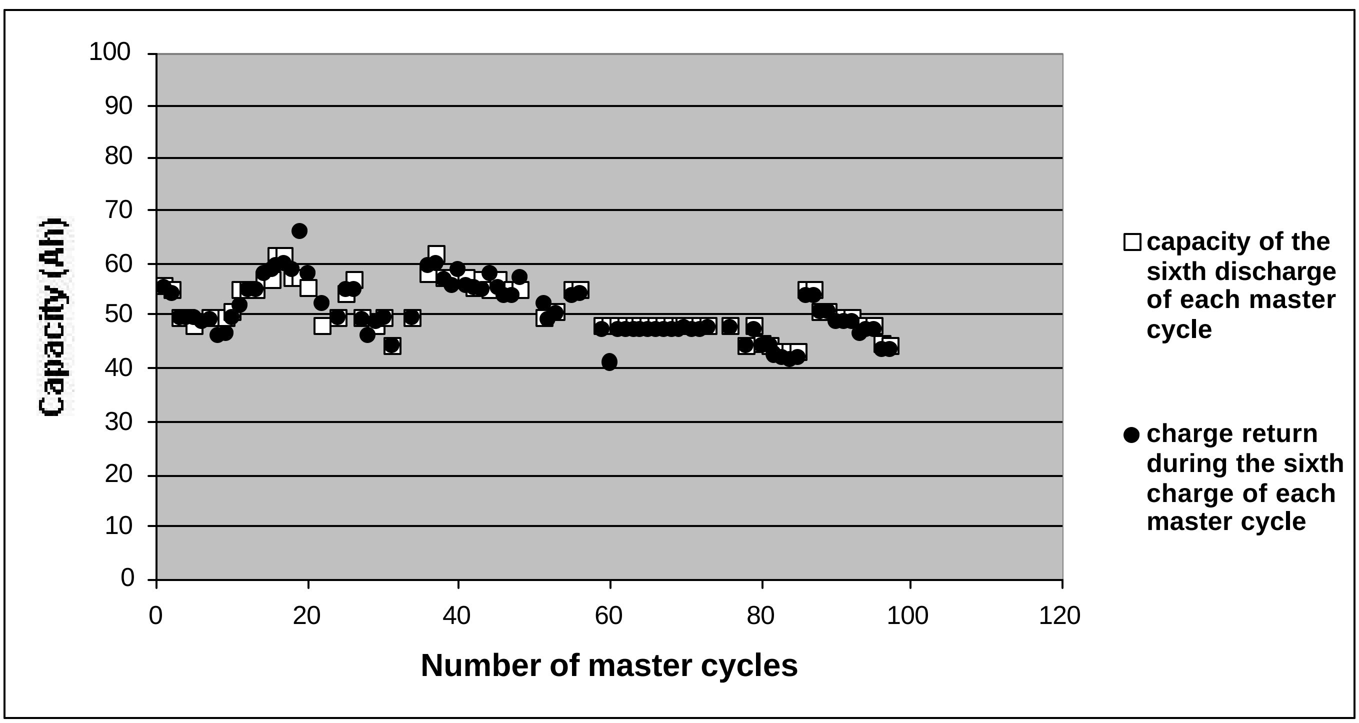


Fig. 4. Capacity and charge return of Dryfit batteries during the sixth PSOC cycle of each master cycle of Dryfit batteries during GSE cycling



6. CONCLUSIONS

- Sonnenschien Dryfit batteries have provided 570 days of simulated GSE service with minimal degradation in capacity.

- The current algorithms do not provide sufficient charge return and additional charging is required to maintain capacity during GSE service.

- The charge efficiency appears to decrease with cycling. It is expected that overcharge will need to be increased as the batteries age.

- Fine-tuning of the algorithms, in terms of conditioning and overcharge, are expected to provide a service life in excess of 800 days under GSE service.

APPENDIX K

Battery Leakage Current Study

BATTERY LEAKAGE CURRENT IMPROVEMENT FOR ELECTRIC GROUND SUPPORT EQUIPMENT APPLICATIONS

INTRODUCTION

Unlike the grounded 12 volt accessory system in an internal combustion powered automobile, the battery packs in electric vehicles are isolated from the vehicle chassis for personnel protection. The higher voltages of electric vehicle battery packs dictate that both a supply and a return conductor be used rather than relying on the vehicle chassis as a return. As a result, the battery can tolerate one of either the positive or the negative side of the battery being shorted to the vehicle chassis. Unlike with a grounded 12 volt system, if only one side of the electric vehicle battery is shorted to the chassis, there is no return path for the current to flow in and, therefore, no short circuit. This allows a mechanic to drop a wrench between the battery and chassis or touch the battery while touching the chassis without getting shocked or creating an arc.

Unfortunately, the battery is never perfectly isolated from the vehicle chassis. Ground leakage current occurs when the electrical isolation of the battery pack is not perfect. Dirt, grime, water and other contaminants often provide a leakage path from the battery positive and negative terminals to the vehicle chassis. Poor vehicle design and poor battery design can also provide leakage paths. Current flows from the positive terminal of the battery, through the contamination to the vehicle chassis, then through more contaminants back to the negative terminal of the battery. Some ground leakage current will always be present as the isolation is, in fact, never perfect. However, problems arise if the ground leakage current becomes too great.

High ground leakage current indicates poor isolation (or low electrical resistance) between the battery and the vehicle chassis. Often this is the result of a chaffed wire connecting directly to the vehicle chassis. This is a very dangerous condition, because battery isolation is lost and a return path to the battery is present if a mechanic touches the battery and the vehicle chassis or drops a wrench across the battery terminal and chassis. While the voltages currently present on ground support equipment (GSE) would not typically provide a lethal shock, people often fall, or hit elbows on hard objects when recoiling from an electric shock. The injury from the recoil, or startle reaction, can often be serious.

Unfortunately, ground leakage current is often not just the result of solid connections between the battery and vehicle chassis due to chaffed wires. It may be the result of dirty batteries, or wet conditions caused by rain, snow or fog. The ground leakage current from these factors is typically less than from a chaffed wire, but is often enough to create a significant startle reaction. Generally flooded batteries are a major source of ground leakage paths due to the acid and corrosion from flooded batteries providing excellent leakage current paths. Open connectors such as the widely used SB350 made by Anderson Power Products can also be a source of leakage current paths.

It is important to limit the ground leakage current (or loss of electrical isolation) from all sources in order to ensure the safety of airline personnel. To ensure that excessive ground leakage currents are detected and repaired, Underwriter's Laboratories requires that a leakage current monitor be installed in electric vehicle chargers to prevent charging of any vehicle that has "significant" ground leakage paths. With electric ground support equipment, the trick is to set the allowable level high enough to prevent nuisance trips of the charger during rain storms, but low enough to ensure personnel protection. Industry standards and experience on the ramp provide some insight into the appropriate setting.

Both the electric vehicle and electric construction industries have found that it is important to limit the allowable ground leakage current to ensure good battery isolation (a high electrical resistance). Each industry has established standards regulating the allowable ground leakage current. Typical ground leakage currents allowed by the standards range from 5 milliamperes (5/1000th of an ampere) to 20 milliamperes (20/1000th of an ampere). It is not clear which standards, if any, may apply to ground support equipment. Underwriters Laboratories is currently preparing a GSE specific charging standard that will address allowable ground leakage current. Unfortunately, this standard will not be available until well into 2002.

Experience on the ramp is varied, depending strongly on the type of batteries used. Flooded batteries are notorious for high leakage current. Measurements taken by Electric Transportation Engineering Corporation (ETEC) personnel in conjunction with providing charge infrastructure support have measured the following typical values for the leakage currents in GSE battery packs.

Battery Condition	Isolation Resistance	Leakage Current [1]
Flooded Pack Clean & Dry	>100 kilo-ohms	<1 milliamperes
Flooded Pack Dirty & Dry	>2 kilo-ohms	<40 milliamperes
Flooded Pack Wet	0.2 kilo-ohms	400 milliamperes
Sealed Pack Clean & Dry	>100 kilo-ohms	<1 milliamperes
Sealed Pack Wet	1 kilo-ohms	80 milliamperes

(1) Based upon an 80 volt battery pack

Sealed batteries typically show lower leakage current as they do not suffer from the presence of highly conductive acid residue found on the tops of flooded batteries. However, both batteries show high leakage currents when the tops of the batteries are wet, such as is possible in a violent rain storm. Current battery pack and GSE vehicle designs include numerous openings through which water can contact energized portions of the vehicle drive system. The water provides a conductive path to the vehicle chassis and, therefore, increases the magnitude of leakage current. This wide range of leakage currents makes it difficult to protect against "excessive" leakage current. The ETEC SuperCharge electric GSE fast charge system is equipped with high leakage current protection trip. As a result, ETEC has gained significant field experience with determining the best protection setting for currently available GSE battery packs and vehicles.

ETEC has found that a leakage current trip of 20 milliamperes, the highest of the values contained in industry standards, is adequate for sealed batteries in all but the most extreme environmental conditions. ETEC has tested the SuperCharge System with this setting installed at Sky Harbor International Airport in Phoenix, Arizona. The testing included water testing a bag tractor on charge to determine how much water and in what places was required to increase ground leakage current (reduce battery isolation resistance) to the point that the charger tripped. ETEC found that even with extensive amounts of water placed directly on connectors and generally over the tractor, the charger did not trip with the 20 milliampere setting. However, if water were placed directly on the battery top, the charger tripped with leakage currents rising to values approaching 100 milliamperes. This required that water be directed to the positive or negative terminals of the battery in very large quantities. Obviously, this would be a highly unusual situation and one in which a charger trip is appropriate.

Unfortunately protecting flooded batteries from “excessive” leakage current is much more problematic. In a very clean condition a flooded pack has very low leakage current, approaching that of a sealed pack. However, with gassing typical of a flooded pack, the leakage very quickly increases far in excess of the 20 milliampere protection setting used for sealed batteries. With moisture present on the battery tops the leakage increases to very significant levels. These high leakage currents limit the level of protection possible with flooded packs to the detection of a solid short circuit between battery and vehicle chassis.

BATTERY PACK DESIGN

Design of the battery pack offers many opportunities for reduction of leakage currents. The design aspects that present the greatest opportunity for improvement are;

1. Battery interconnection links
2. Battery box vent holes
3. Battery power connectors

For the first prototype battery pack constructed ETEC utilized fabricated cable interconnects as shown in Figure 1. The battery was fully covered with a “top hat” cover as shown in Figure 2. Anderson Power Products SB 350_x connectors were utilized for the battery pack to vehicle connection. As the Anderson Power Products $SB350_x$ connector is a known source of leakage current, the cable end of the connector for prototype battery pack 1 was sealed using a silicon sealing caulk. This pack was tested for leakage current in both dry and wet conditions. The results are presented in Table 1.

Table 1; Leakage Current results For Prototype Battery Pack 1

Battery Condition	Isolation Resistance	Leakage Current [1]
Dry With Cover	>100 kilo-ohms	<1 milliamperes
Wet With Cover	>100 kilo-ohms	<1 milliamperes

(1) Based upon an 80 volt battery pack

Figure 1; Prototype Battery Pack 1 Interconnection Links

Figure 2; Prototype Battery Pack 1 Cover

While the results achieved for the prototype pack were very good, there was a concern that moisture could condense on the battery tops (under the “top hat” cover, increasing leakage current. Therefore, the battery pack was tested without the cover on using a water spray to generously wet the batteries. The results of this test are presented in Table 2.

Table 2; Leakage Current Results For Prototype Battery Pack 1 With Cover Off

Battery Condition	Isolation Resistance	Leakage Current [(1)]
Wet Without Cover	20 kilo-ohms	4 milliamperes

(1) Based upon an 80 volt battery pack

The high leakage current was the result of water contacting the battery posts under the rubber boots used for protective insulation. The rubber boot insulation system does not provide a water tight seal. To prevent high leakage currents when the battery tops are wet, a European style interconnect system was used to construct a second prototype battery pack. The European style interconnect system uses a bolted connection as shown in Figure 4. This system is fully insulated and water tight. It is available on the Sonnenschein 6V180 modules as an optional connection method. This style of connection is, unfortunately, not offered on any US manufactured batteries at this time. Prototype battery pack 2 was water spray tested using a test facility designed for testing cabinets to Underwriters Laboratories outdoor requirements. The leakage currents measured during the water spray test are presented in Table 3.

Figure 4; Prototype Battery Pack 1 Interconnection Links

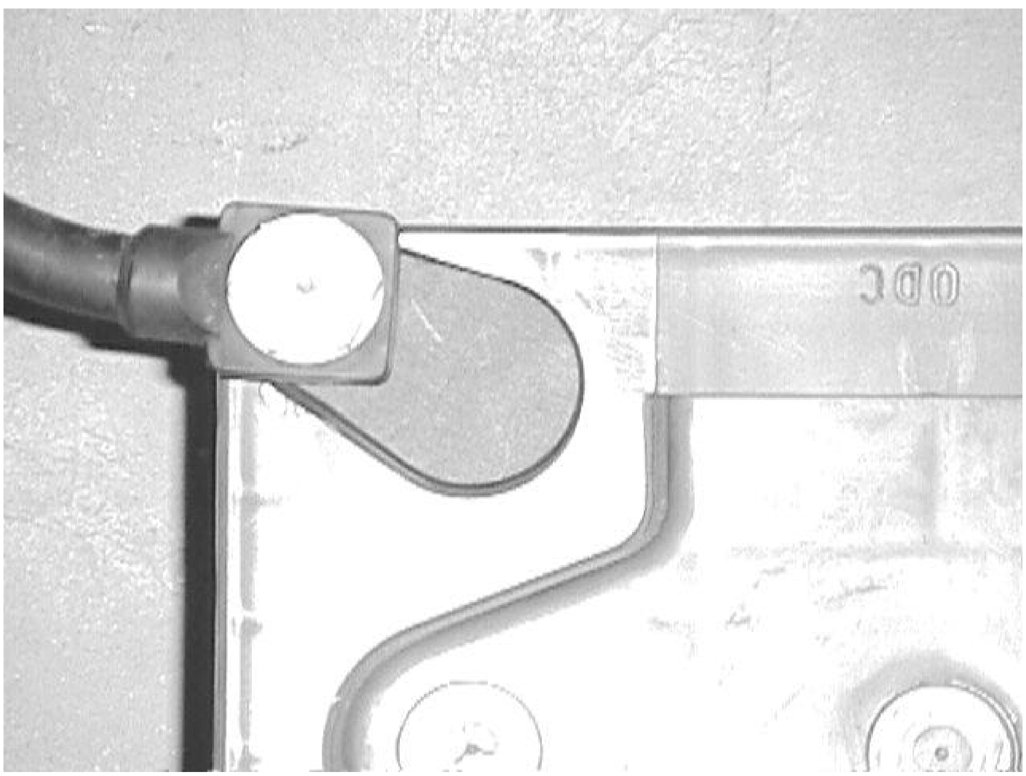


Table 3; Leakage Current results For Prototype Battery Pack 2

Battery Condition	Isolation Resistance	Leakage Current [1]
Wet Without Cover	>100 kilo-ohms	<1 milliamperes

[1] Based upon an 80 volt battery pack

CONCLUSIONS

Prototype battery pack 2 achieved very satisfactory results from the water spray test and will be used as the pack design for the battery pack to be tested at Sacramento International Airport. The availability of fully sealed European style connectors provides an extra measure of value to the six volt golf cart size monoblocks used for this test.

APPENDIX L

Prototype Battery Cycle Testing

PERFORMANCE OF VALVE-REGULATED LEAD-ACID BATTERIES UNDER ELECTRIC VEHICLE GROUND-SUPPORT EQUIPMENT CONDITIONS. PACK CYCLING OF SONNENSCHIEN GEL BATTERIES.

DECEMBER 2001

CONTENTS

1. EXECUTIVE SUMMARY

Electric Transportation Engineering Corp. (eTec) has been developing infrastructure for the operation of electric vehicles for over 10 years. They have developed partial-state-of-charge (PSOC)/fast-charge strategies for a variety of lead-acid battery powered electric vehicles (EVs). This type of duty has been shown to decrease charge times while retaining if not improving battery cycle life. Recent developments have included vehicles and operating systems for electrically powered ground-support equipment (GSE) at airports.

The gelled-electrolyte valve-regulated lead-acid (VRLA) batteries currently used for GSE vehicles are expensive and have a high internal resistance. This leads to unecessary heating of the batteries during charging and extended charge times. eTec has evaluated the performance of an alternative technology manufactured by Sonnenschien that has both a reduced cost and a lower internal resistance. The batteries, called Dryfit, are a 6-V monobloc with a 1C capacity of 110 Ah.

This report describes the evaluation of two GSE vehicle battery packs that comprise 28, Dryfit modules, configured in two, 84-V strings, under simulated GSE service. Both a brand new pack, and a pack retrieved from the field have been tested. The latter had been in service at the Phoenix airport for over 18 months and had performed an estimated 350 GSE cycles. The new and old packs were subjected to 204 and 24 days of simulated GSE service, respectively. The performance of both packs during these cycling periods was excellent. Indeed, the capacity provided by the old pack matched that of the new. The excellent condition of the old pack was confirmed by a series of standard 1C discharge/charge cycles — the capacity obtained during these experiments was at least equal to that of the nominal value. Given the service life already provided by the old pack (see above), it is considered conservative to predict a lifetime in the field of over three years.

2. INTRODUCTION AND BACKGROUND

Until recently, the battery systems used in the GSE EVs have comprised 2-V, tubular-plate gelled-electrolyte batteries (500 Ah at the C/20 rate) arranged in a single string (nominal 80 volts). Whilst the tubular plates should be well suited to heavy cycling applications, the batteries have a high profile (i.e., tall, narrow plates) and, as a consequence, have a high internal resistance. This results in significant heating of the batteries during fast-charge, and limits charging times to close to 1 h. Further, the batteries are expensive and the performance of the batteries under GSE service in terms of lifetime-Ahs/dollar requires improvement.

The aim of this project is to evaluate the performance of an alternative design of VRLA battery under simulated GSE conditions. This battery is called a Dryfit and is manufactured by Sonnenschien. It has a lower internal resistance, is considerably less expensive and has a higher energy density than the tubular-plate variants currently used. GSE vehicles fitted with these batteries have 28 modules configured in two parallel strings, thereby providing a system voltage of 84V. Details of the new battery are given below:

- VRLA design (gelled-electrolyte)
- flat-plate design
- 6-V monobloc
- 110 Ah (1C rate, 1.6 V/cell cut-off)
- 30 kg
- 22 Wh/kg (1C rate)

Initial Task 4 work involved a comprehensive study of the performance of pairs of 6-V modules (connected in series) under simulated GSE duty in the laboratory. This report describes an investigation of the performance of two, complete battery packs under simulated GSE duty. Each pack comprises two, 84-V strings of Dryfit batteries. One pack has been assembled from brand new modules, whilst the second has been removed from a bag tractor that has been operating successfully in the field for over 18 months.

3. WORK AREAS

The work performed in this report comprises three work areas.

Work Area 1. Construction of battery test facility.

Work Area 2. Development of real-time GSE operating strategy.

Work Area 3. Pack performance under real-time GSE conditions.

4. TEST ENVIRONMENT

The following conditions have been observed for all pack cycling.

- Batteries are mounted in a three-tier, fabricated steel structure (i.e., identical configuration to that used in the GSE vehicles).
- Battery structure rests on a wooden pallet and is exposed to atmosphere on all sides and top.
- Battery pack is located inside a covered building with no climate control.
- Ambient temperature range; 4 °C to 49 °C.
- Battery temperature is measured in between the mating faces of two adjacent battery modules; three temperatures measurement are made and averaged.
- Current measurement accurate to 1% of maximum charge and discharge rate.
- Voltage measurement accurate to 1% of measured value.

5. WORK PROGRESS

5.1. Work Area 1: Construction of battery test facility

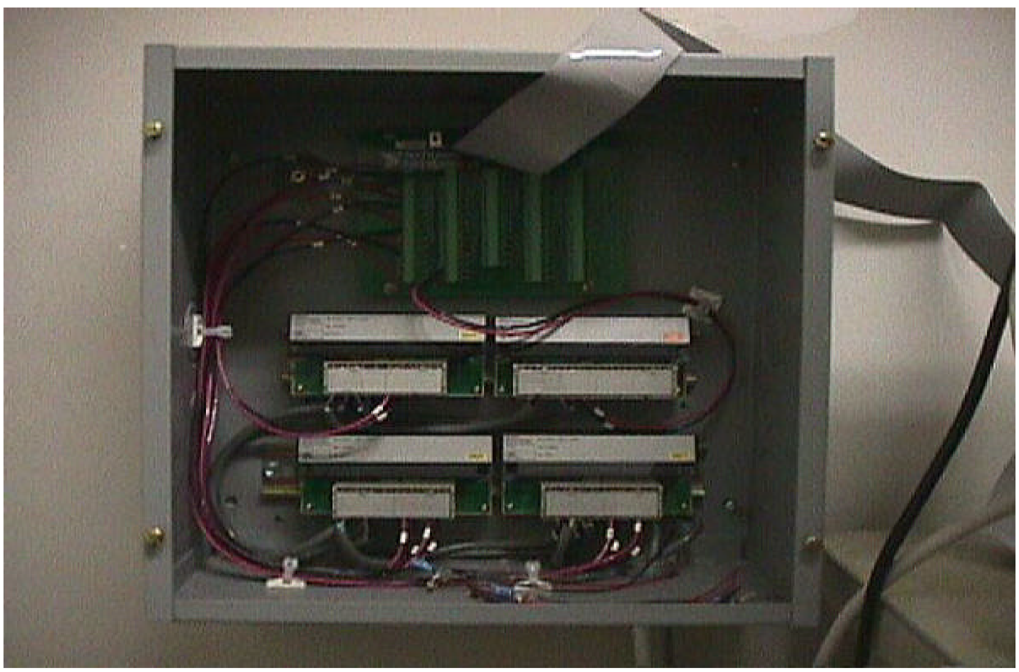
The first part of the current work has been to construct a test facility that can discharge battery packs under GSE duty while providing a recharge that is identical to that supplied by the chargers at the airports. This has been achieved by combining a commercially available eTec fast-charging system with a ABC 150 battery test facility manufactured by AeroVironment (note, it is difficult to program commercial cycling equipment so that it mimics all the idiosyncrasies of large, field-based fast-charge units. Hence, combining the actual field charging unit with a simulated load, ensures that the conditions experienced by the packs in the laboratory are as close as practical to those experienced in the field).

The ABC150 is a programmable power supply/power sink that can be used to deliver power and/or sink current from the battery. For the current work, the ABC150 was employed to discharge current from the battery pack according to the GSE discharge profile developed in Section 5.2 (see below).

The charger used in the experiments was a 33 kW eTec SuperCharge fast-charging system (see Fig. 1). It is identical in design to that being used to recharge GSE vehicles in the field. There was, however, no natural control interface between this device and the ABC150 control system (Aerovironment Remote Operating System--ROS). To enable both automated and unattended cycling, a special software set was written for the SuperCharge system to allow for external control by the ROS. This control was accomplished by using a National Instruments

NIDAQ card, which provided analog input and output signals controlled by the ROS (see Fig. 2).

Fig. 1. eTec SuperCharge fast-charging system (33 kW) used in pack cycling.
Fig. 2. National Instruments NIDAQ card for providing analog input and output signals during



GSE operation.

The SuperCharge control system was configured to deliver a charge to the battery only when the appropriate analog signals were transmitted by the ROS. Similarly, the ROS was programmed to discharge the battery only when the appropriate signal was received from the SuperCharge control system. In this manner, safety interlocks were provided to prevent the charger and the ABC150 from operating at the same time. The ROS was then programmed to be the master controller of the system. A script was written to discharge and recharge the battery using a PSOC strategy.

The batteries were configured in an identical manner to that used in actual vehicles. Two parallel strings of 14 modules (28 in total) were assembled into a standard 84-V GSE battery pack (see Fig. 3).

Fig. 3. Battery configuration during pack testing.

The battery pack was instrumented to record several module voltages and temperatures, ambient temperature and the current in one of the two parallel module strings. Module voltages, temperatures and ambient temperature were measured and transmitted using an Aerovironment SmartGuard system. Four Smart Guard modules were installed such as to record the voltage for four modules on each parallel string (each SmartGuard module measures the voltage across two series modules). The SmartGuard module also uses a thermistor to measure temperature. These thermistors were inserted between the case walls of two adjacent battery modules (see Fig. 4).

During operation, the battery pack was first discharged using the GSE discharge profile (see Section 5.2, below) and recharged with the SuperCharge algorithm. After six such PSOC cycles, the ABC150 automatically delivered an equalizing charge to the battery pack. Using the temperature signal from the Smart Guard modules, the ROS continually monitored the average module temperature of the battery pack. If this average value exceeded 50°C, the ROS was programmed to delay charging until the average module temperature fell below 45°C. The ROS was programmed to save charge and discharge data (including terminal voltage, discharge current, ampere-hours discharged and returned as well as data from the Smart Guard system and the NIDAQ card) to a file.

Fig. 4. Position of temperature thermistors.

5.2. Work Area 2: Development of real-time GSE operating strategy

Fast-charge operating strategies for use in GSE vehicles generally comprise the following three regimes:

Regime 1: a discharge (usually to 10-30% SOC);
Regime 2: a fast charge (usually to 70-90% SOC);
Regime 3: a regular conditioning charge.

One pass through Regimes 1 and 2 is called a PSOC cycle. Regimes 1 and 2 are repeated sequentially until a preset number of PSOC cycles have been completed. A conditioning charge (Regime 3) is then applied. This latter procedure usually comprises a constant voltage/constant current charge applied using resistance-free voltage techniques. The preset number of PSOC cycles completed between each conditioning charge, and the composition of the conditioning charge generally require fine-tuning for each specific type of duty in order to achieve optimum battery life.

Regime 1: the discharge. It is well known that the capacity of lead-acid batteries varies with the discharge rate. As GSE duty involves a complex combination of discharge rates, the actual battery capacity of the Dryfit units under GSE duty needs to be established. Hence, two batteries, connected in series, were subjected to a discharge according to repeats of a typical GSE discharge profile [1] (see Fig. 5) until the battery voltage reached 1.5 V/cell. After a full recharge, the batteries were then subjected to another full discharge to 1.5 V/cell. The capacities obtained for the two discharges were 137 and 138 Ah (note, two batteries connected in parallel have a GSE capacity of ~ 274 Ah). Based on the voltage response during discharge, it was estimated that a voltage of 1.75 V/cell under maximum load (200 A per string) would correspond to an SOC of 10%, which was the target for these experiments.

It is appropriate at this point to mention that a cut off voltage of 1.83 V/cell (SOC 30%) was used in the laboratory cycling of 12-V battery sets [1]. It was decided to use a lower cutoff voltage during the pack cycling (i.e., 1.75 V/cell; SOC 10%) to simulate the worst possible conditions that could occur in the field.

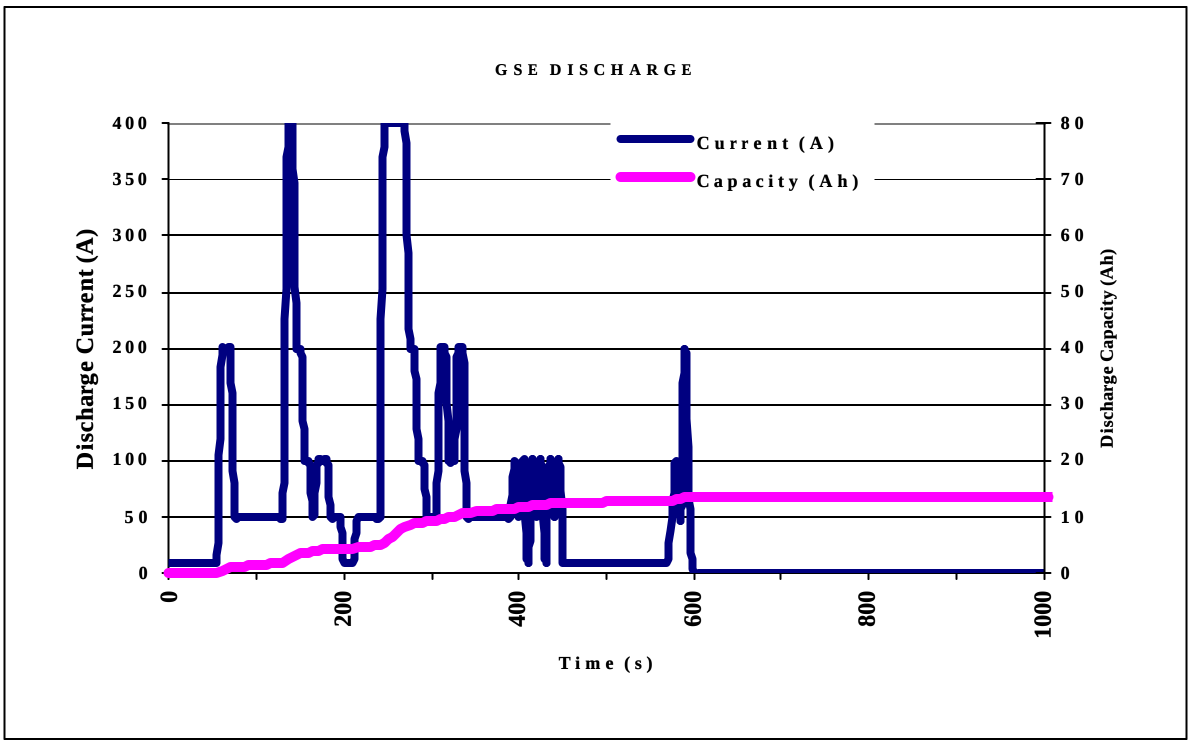


Fig. 5. GSE discharge component.

Regimes 2 and 3: the charge and conditioning. The charge current available from the fast-chargers currently installed at the relevant airports is 400 A, i.e., 200 A for each of the two parallel strings that comprise the GSE battery banks. This charge current (~ 2C) is considered excessive for the Sonnenschien batteries, as it may result in failure of the battery top lead. Consultation with Sonnenschien engineers revealed that the maximum recommended charge current is 150 A (~ 1.5C). Hence, the lower value has been used in the field and also in the laboratory pack cycling.

The full GSE operating strategy, complete with the conditioning procedure (based on previous PSOC/fast-charge work) is as follows:

(i) discharge using repeats of the GSE discharge profile until battery voltage reaches 1.75 V/cell (i.e., discharge from 100% to 10% SOC);

(ii) charge at 300 A until 2.35 V/cell (resistance-free voltage control and temperature compensation), then continue to charge battery until the charge current has decreased to 100 A (i.e., charge from 10% to 90% SOC. Note, a cutoff current of 150 A was used in the laboratory experiments [1]).

(iii) discharge using repeats of the GSE discharge profile until battery voltage reaches 1.75 V/cell (i.e., discharge from 90% to 10% SOC). This discharge step only commences if battery temperature is $< 40\,^{o}$C;

(iv) repeat (ii)-(iii) until step (iii) has been performed five times (i.e., six discharges in total);

(v) charge at 300 A until 2.35 V/cell (resistance-free voltage control and temperature compensation), then continue to charge battery until the charge current has decreased to 100 A;

(vi) charge at 50 A until the voltage reaches 2.35 V/cell;

(vii) charge at 24 A for 4,050 seconds (67.5 minutes);

The completion of consecutive discharge and charge steps is called a PSOC cycle (see above). The completion of 6 such PSOC cycles (steps (i)-(iii)) followed by the conditioning procedure (steps (v)-(vii)), is referred to as a master cycle (note, one PSOC cycle simulates one day of GSE service).

5.3 Work Area 3. Pack performance under real-time GSE conditions

In these experiments, a new GSE battery pack and a pack that has operated in a GSE vehicle in the field for over 18 months (estimated 350 days of GSE service, based on a 65% duty cycle), have been operated under simulated GSE duty. The results of these experiments are described in Sections 5.3.1 and 5.3.4, below.

It should be noted that it was originally planned to operate one new battery pack under simulated GSE duty for over 400 GSE cycles (i.e., ~ 200 days of simulated service). Once operation had commenced, however, it became apparent that there would be insufficient time to perform the required number of cycles, given the complexity of the simulated profile and equipment. In order to obtain a fair comparison between new and used batteries, it was decided to evaluate a second battery pack that had been recalled from field service.

5.3.1. Capacity

The total Ahs delivered by both packs during each master cycle (termed master-cycle capacity) are shown in Fig. 6. The master-cycle capacity of the new pack increased from ~800 Ah to over 1100 Ah during the first six master cycles. During the next five master cycles, the master cycle capacity decreased to ~ 640 Ah as a result of a hardware fault that terminated discharge prematurely. Once the problem was rectified, the capacity increased and reached ~ 1000 Ah after 12 master cycles. After the 18th master cycle, the level of overcharge was increased slightly to ensure that the pack was being returned to 100% SOC at the end of each master cycle. This resulted in a further increase in performance, and after the 27th master cycle the capacity reached ~ 1300 Ah. The performance of the pack then remained relatively stable until it was removed from service after 34 master cycles (204 days of simulated GSE service).

It was decided to operate the old pack "as returned from the field", i.e., without a full recharge, as this would provide direct information on how the pack was performing in the field prior to removal. The capacity obtained during the first master cycle was 1071 Ah, which is only ~ 130 Ah lower than the best value recorded for the new pack. The old pack was then subjected to five 1C discharge/charge cycles (220 A discharge to 1.75vpc; 40 A charge to 2.45 V with 110% overcharge) to determine the actual capacity of the pack under standard conditions (note, 105% overcharge is normally sufficient. An additional 5% was provided to ensure that the batteries attained full SOC). The capacities delivered during this procedure are given in Table 1, and it can be seen that they are comparable with the nominal value, i.e., 220 Ah). Obviously, the GSE duty performed by the pack to date, has had no effect on the absolute capacity of the batteries.

Table 1. Capacity (1C) of old pack after first master cycle.

	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle
Capacity (Ah)	209	214	233	239	240

After the completion of the standard 1C testing, the pack was subjected to an additional 3 master cycles. The master-cycle capacities during this period of operation were 1071,1209, 1207 and 1213 Ah, respectively, which is similar to the highest delivered by the new pack. This result confirms that 18 months of GSE duty has had a minimal effect on the performance of the batteries.

It is important that GSE vehicles provide an acceptable range and, thereby, avoid the need for more than one fast-charge per day. If multiple charges are required, 'vehicle queing' may occur which decreases the efficiency of GSE fleets. Hence, it is important that the capacity of GSE battery packs should be maintained at a reasonable level throughout each master cycle. The Ahs delivered by the packs during both the first and the sixth discharge of each master cycle are shown in Fig. 7. It can be seen that the capacity obtained from the first discharge is generally higher than that delivered during the sixth. This is to be expected, as the SOC of the pack prior to the first discharge is 100%, whereas it is 90% at the commencement of the sixth.

The lowest capacity delivered by either pack during any discharge throughout GSE cycling was 117 Ahs. This was recorded by the new pack during the first discharge of the third master cycle. The low value was a result of a hardware fault, which resulted in the SOC of the pack being well below 100% at the commencement of discharge. Considerably higher values were obtained from both packs (180-200 Ah) when the cycling equipment was operating normally. As the lower capacity (i.e., 117 Ah) is still well above the lowest level considered for acceptable GSE range (i.e., 84 Ah, see reference [1]), the current operating strategy is considered adequate for battery packs in good condition. As batteries age, however, it is likely that the charging efficiency of the packs will decrease as a result of partial electrolyte dryout. When this occurs, an interactive algorithm that varies the amount of overcharge would extend the cycle life of the battery packs.

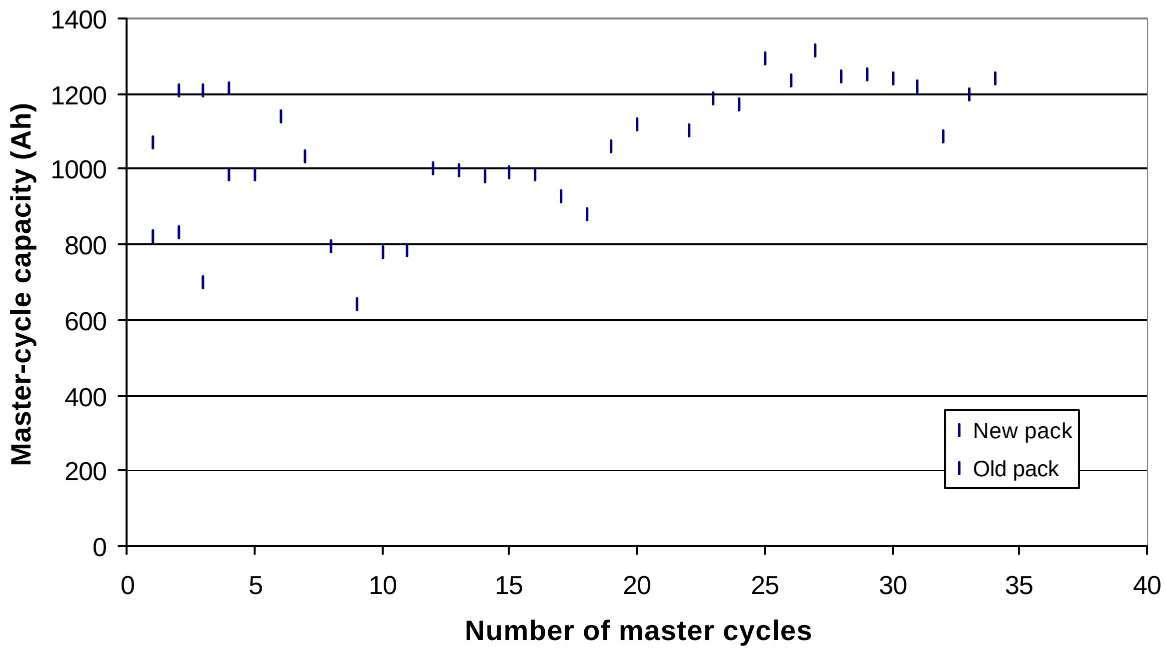


Fig. 6. Master-cycle capacity of new and old packs during GSE cycling.

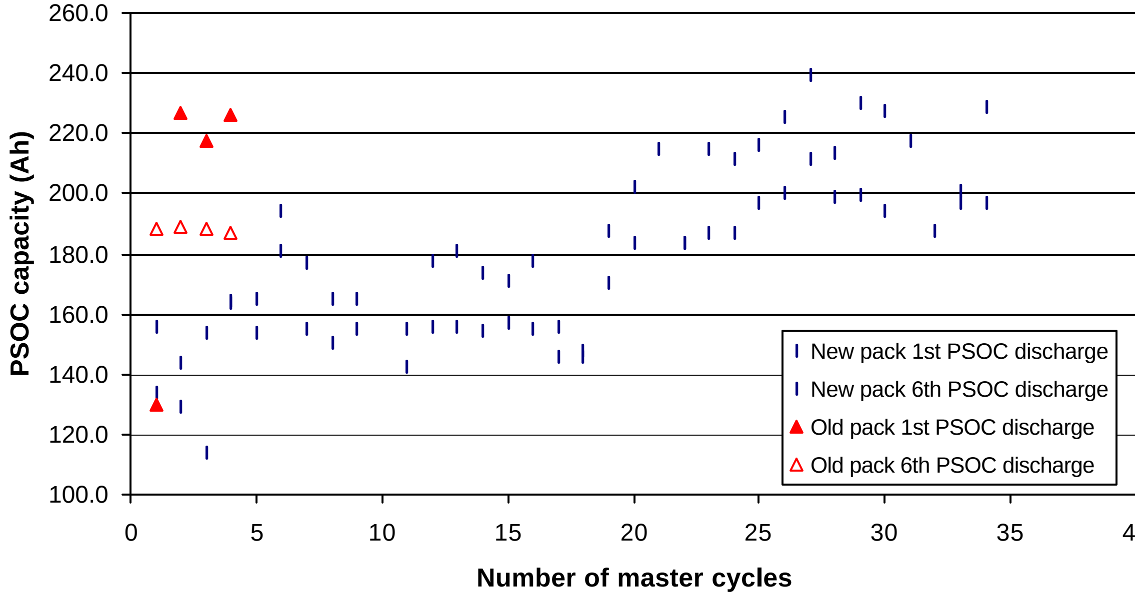


Fig. 7. Capacity during 1st and 6th PSOC cycle of each master cycle for new and old packs during GSE cycling.

In Fig. 8, the GSE performance of the old and new packs is compared with that obtained for two, 6-V Dryfit modules operated in the laboratory [1]. The SOC operating windows used for the old/new packs and the 12-V set were 10-90% SOC and 30-80% SOC, respectively (note, the more conservative window was chosen for use in the laboratory as it was of interest to determine the absolute maximum number of cycles available from the Dryfit technology. The more 'abusive' 10-90% SOC window was used in the pack cycling as it allows us to determine the performance of the batteries under 'worst case conditions').

The laboratory pack operated for almost 100 master cycles, i.e., 600 days of simulated GSE service before the capacity during the sixth discharge decreased to an unacceptable level. The 1C of the battery after a recovery charge, however, was close to 100% of the nominal value, and it was considered that optimisation of the charging algorithm should provide well over 800 days of simulated GSE service. The new and old packs delivered 204 days of simulated GSE duty and ~ 370 days of field and simulated service (~350 in field, and 24 in laboratory), respectively, and still maintained a capacity at or above the nominal value. Based on these results, it seems conservative to predict that packs of Dryfit batteries should provide over three years of service in GSE vehicles in the field.

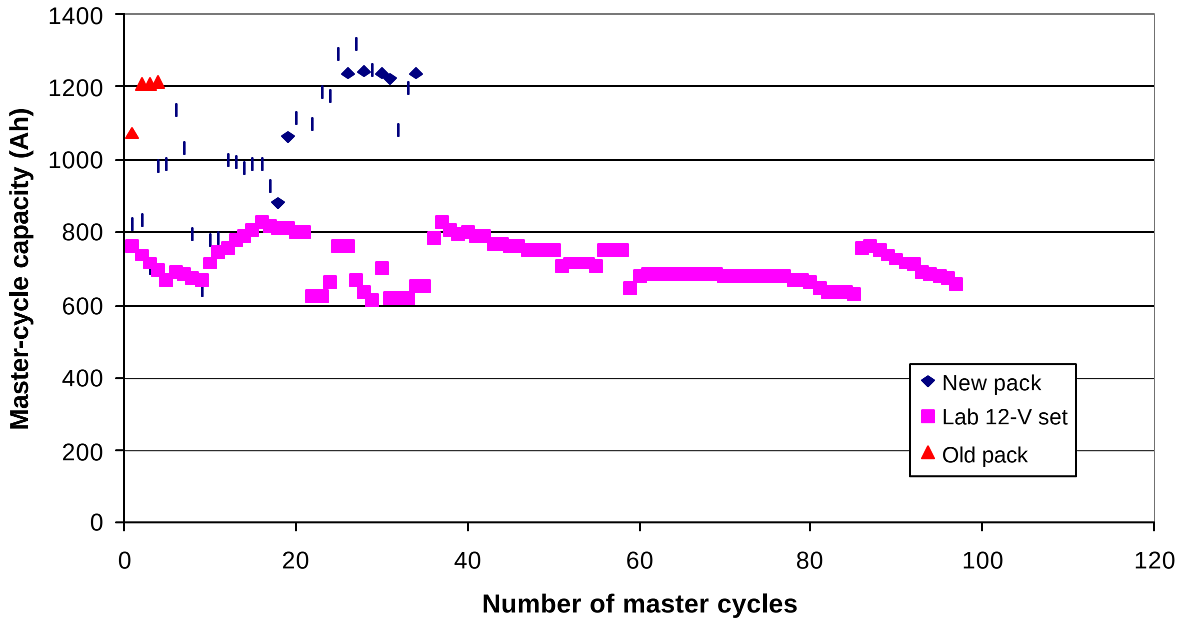


Fig. 8. Master-cycle capacity of new and old packs, and laboratory 12-V set during GSE cycling.

In addition to the laboratory work, the 78V battery pack in service at SMF was tested at the completion of the project. In order to minimize the disruption to normal operations, the discharge test was conducted in the field using the discharge capabilities of the charging equipment. With the vehicle connected to the charger, the battery was first recharged to 100% SOC. The charger was then reconfigured to discharge the battery with the vehicle still connected. Due to an operator error, the battery was discharged at 247 amps, slightly higher than the C1 rate of 220A (110A per parallel string). The charger has a built-in over-discharge protection such that the battery cannot be discharged below 1.9 vpc. The data logging equipment already in-place on the vehicle was used to record voltage for each of the 26 modules in addition to the current in each parallel string.

The discharge was completed at 1.9 vpc and lasted 1867 seconds, removing 128 Ah from the two strings. To determine the full capacity of the battery, the field data were compared to 5 laboratory C1 discharge tests of the 18-month old pack (see above). Dividing the average Ahr capacity at 1.9 vpc by the average Ah capacity at 1.75 vpc, a ratio of the two discharge levels was calculated. This ratio was used to estimate the full C1 capacity of the 78V field pack. This calculation resulted in an estimated capacity of 209.4 Ahr. As a check, the Peukert's equation was used to estimate the full capacity at a discharge rate of 247A (123.5A per parallel string). This calculation resulted in a capacity of 210.6 Ahr which strongly supports the 209.4 Ah estimation.

While the 209.4 Ah capacity is somewhat lower than the 220Ah C1 manufacturer's rating, it compares well to the 208.5 Ah capacity delivered by the 18-month old pack (see above) during its first discharge test. This pack eventually delivered 240.4 Ah after four charge/discharge cycles. Therefore, we expect that the 78V pack at SMF would show a similar increase in capacity after only a few charge/discharge cycles.

5.3.2. Charge time.

It is important that the time required to recharge batteries during GSE duty is maintained at an acceptable level throughout the life of the battery pack. Hence, the time required to recharge both battery packs was carefully monitored during GSE duty. The charge time during the sixth PSOC cycle of each master cycle is shown in Fig. 9, and varies between 31 minutes and 50 minutes. Such charge times are considered acceptable, given that the 'target time' for a recharge from 30-80% is 30 minutes (charge return of 137 Ah), and the charge return associated with these charge times was 125 and 216 Ah, respectively (see Fig. 7).

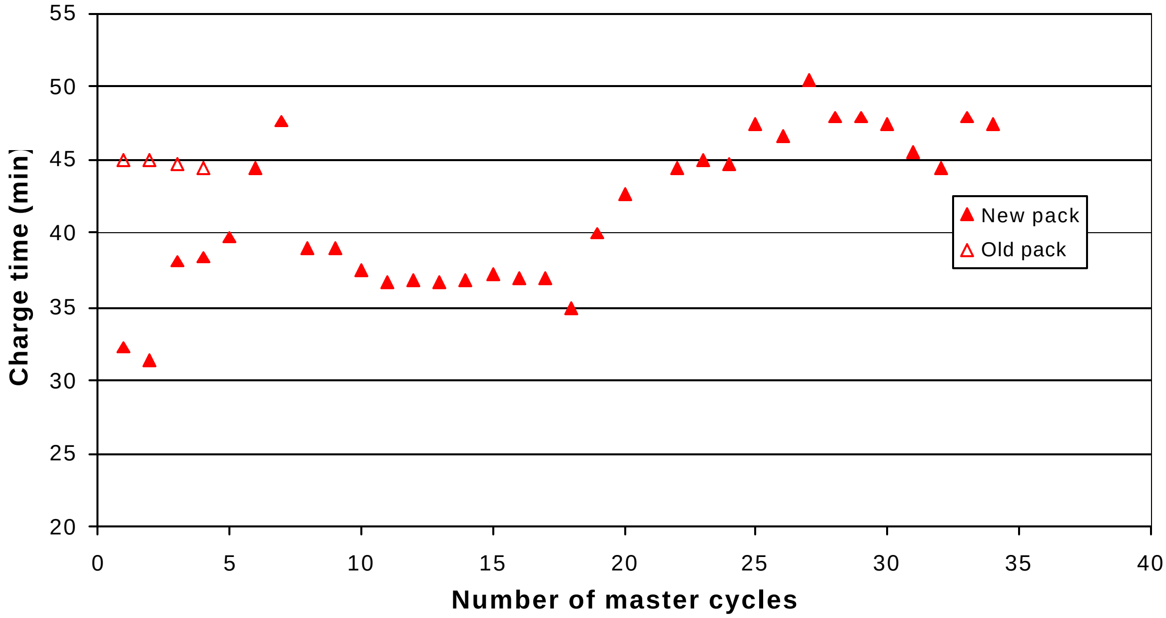


Fig. 9. Charge time during the sixth PSOC cycle of each master cycle for both packs.

5.3.3. Battery temperature during charging.

GSE vehicles are required to operate in a wide variety of conditions. They can experience both hot and sub-zero temperatures. Obviously, appropriate thermal management of the battery packs in such vehicles is of significant importance.

The ambient temperature and the temperature of three modules within both the new and the field battery packs were measured throughout simulated GSE service. The difference between the average module temperature and the ambient temperature during a typical master cycle is shown in Fig. 10. The temperature of both battery packs increased by ~ 10 ^{o}C during the first charging period. It then remained relatively stable during the following drive cycle, before increasing a further 10 ^{o}C during the second charging period. This trend continued until after the fourth charge of the old pack and the fifth charge of the new pack, at which time the ambient temperature began to decrease quickly as a result of nightfall. Given that battery packs in the field experience typically experience only one charge each day, the battery pack has over 23 h to cool back to the ambient level. Hence, pack temperature in the field should not rise by more than 10 ^{o}C above the ambient temperature. This degree of temperature increase is considered acceptable and is not expected to significantly affect the performance of the battery pack.

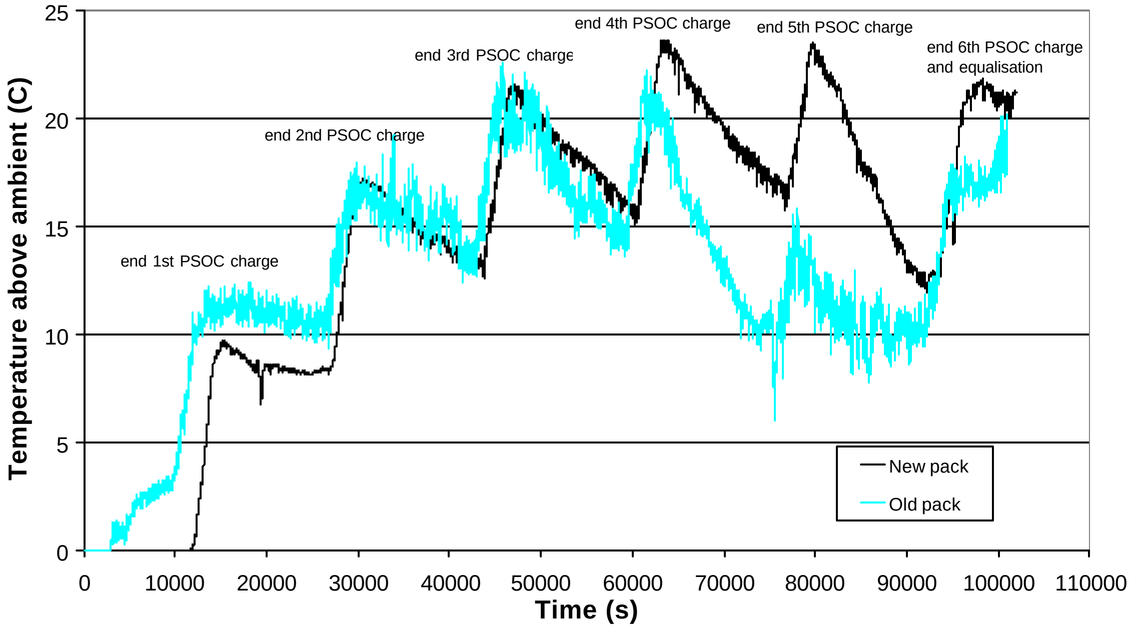


Fig. 10. Temperature above ambient of old and new battery packs during a master cycle (average of three modules).

5.3.4. Current distribution between battery strings.

It is well known that parallel strings of VRLA batteries can experience uneven current sharing during charge/discharge operation. Such behavior occurs when differences in internal resistance develop between the strings. In extreme cases, this can lead to premature failure of the battery pack. The current delivered and accepted by the individual strings of both the new and old packs has been monitored throughout simulated GSE cycling. It was found that there was no discernible difference in current sharing within either pack. This result suggests that the operating algorithm installed in the eTec SuperCharge fast-charging system is maintaining individual strings within GSE battery packs in an even condition.

6. CONCLUSIONS

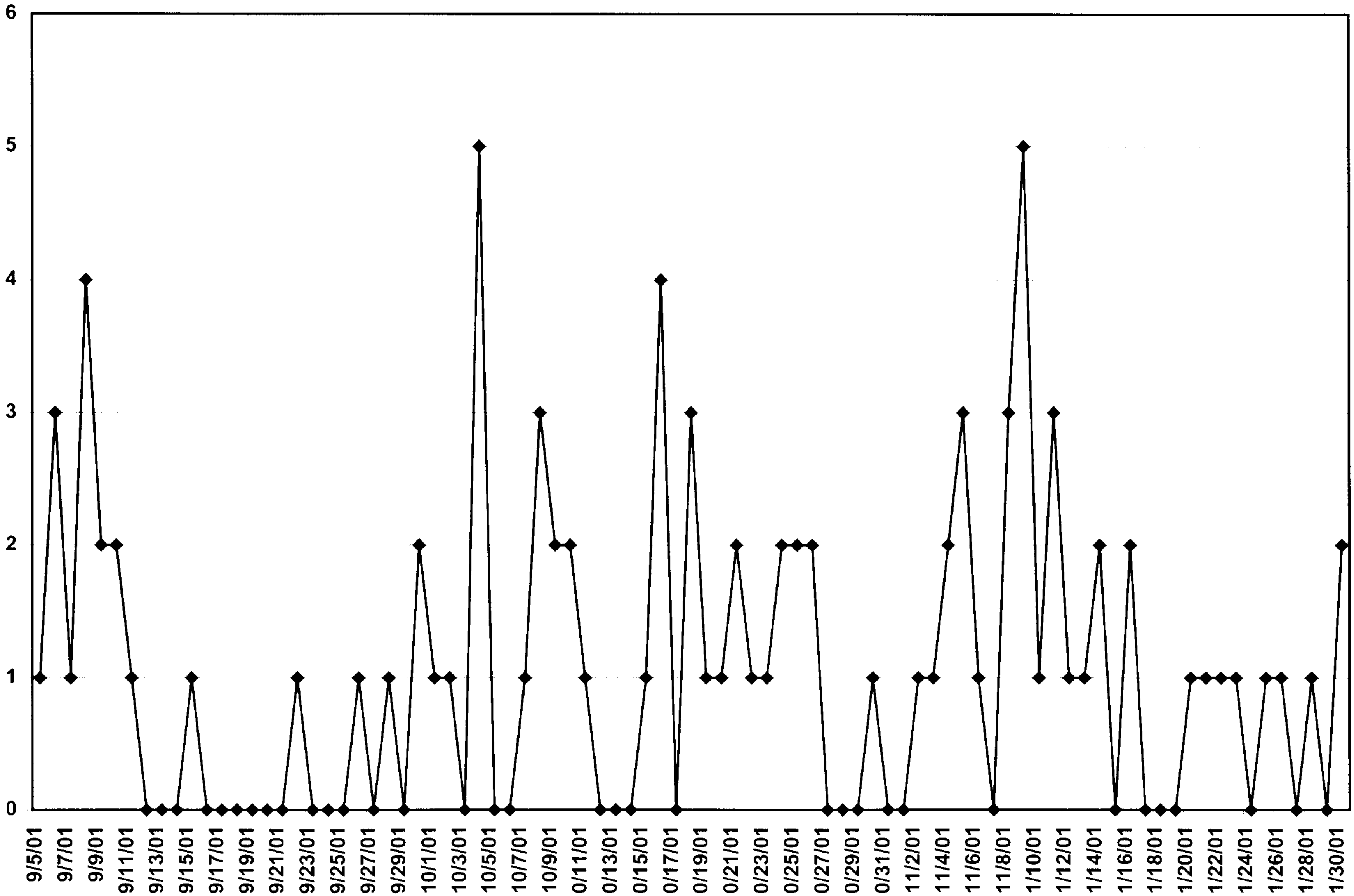
- A new and an old pack of Dryfit batteries delivered 204 days of simulated GSE duty and ~ 370 days of field and simulated service (~350 in field, and 24 in laboratory), respectively, and still maintained a capacity at or above the nominal value. Based on these results, it seems conservative to predict that packs of Dryfit batteries should provide over three years of field service in GSE vehicles.
- The charge time of GSE battery packs varied between 31 and 50 min. This is considered acceptable for normal GSE duty.
- The battery packs operated in this study typically experienced a rise of 10 ^{o}C when charged from 10-90% SOC with an eTec SuperCharge fast-charging system.

- GSE battery packs that comprise two parallel strings, and are charged with an eTec SuperCharge fast-charging system do not experience uneven current sharing.

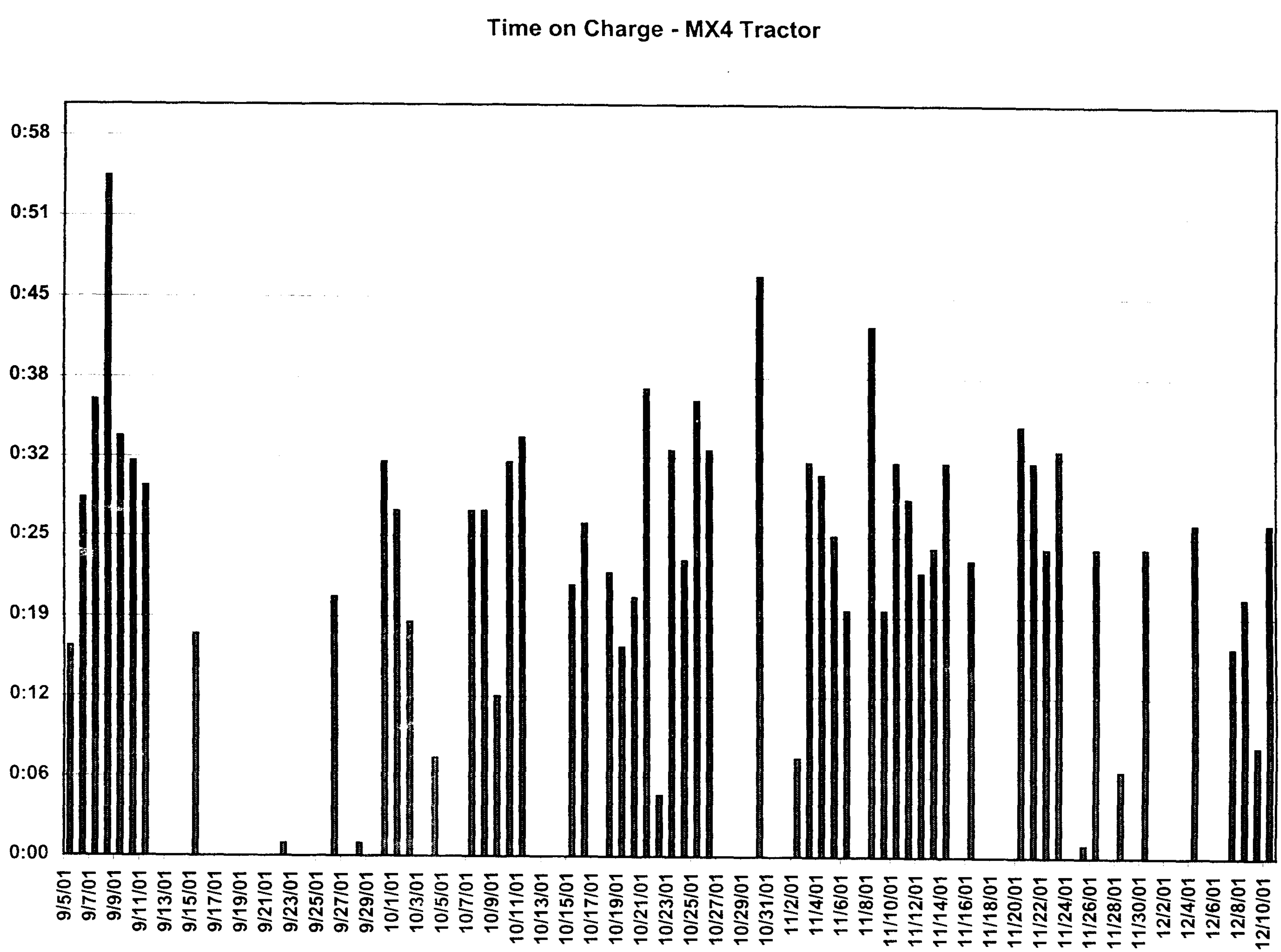
APPENDIX M

MX4 Charge Data

Total Charges per Day - MX4 Tractor



Task 4 - MX4 Tractor at SMF


Time on Charge - MX4 Tractor
0:58
0:51
0:45
0:38
0:32
0:25
0:19
0:12
0:06
0:00
9/5/01
9/7/01
9/9/01
9/11/01
9/13/01
9/15/01
9/17/01
9/19/01
9/21/01
9/23/01
9/25/01
9/27/01
9/29/01
10/1/01
10/3/01
10/5/01
10/7/01
10/9/01
10/11/01
10/13/01
10/15/01
10/17/01
10/19/01
10/21/01
10/23/01
10/25/01
10/27/01
10/29/01
10/31/01
11/2/01
11/4/01
11/6/01
11/8/01
11/10/01
11/12/01
11/14/01
11/16/01
11/18/01
11/20/01
11/22/01
11/24/01
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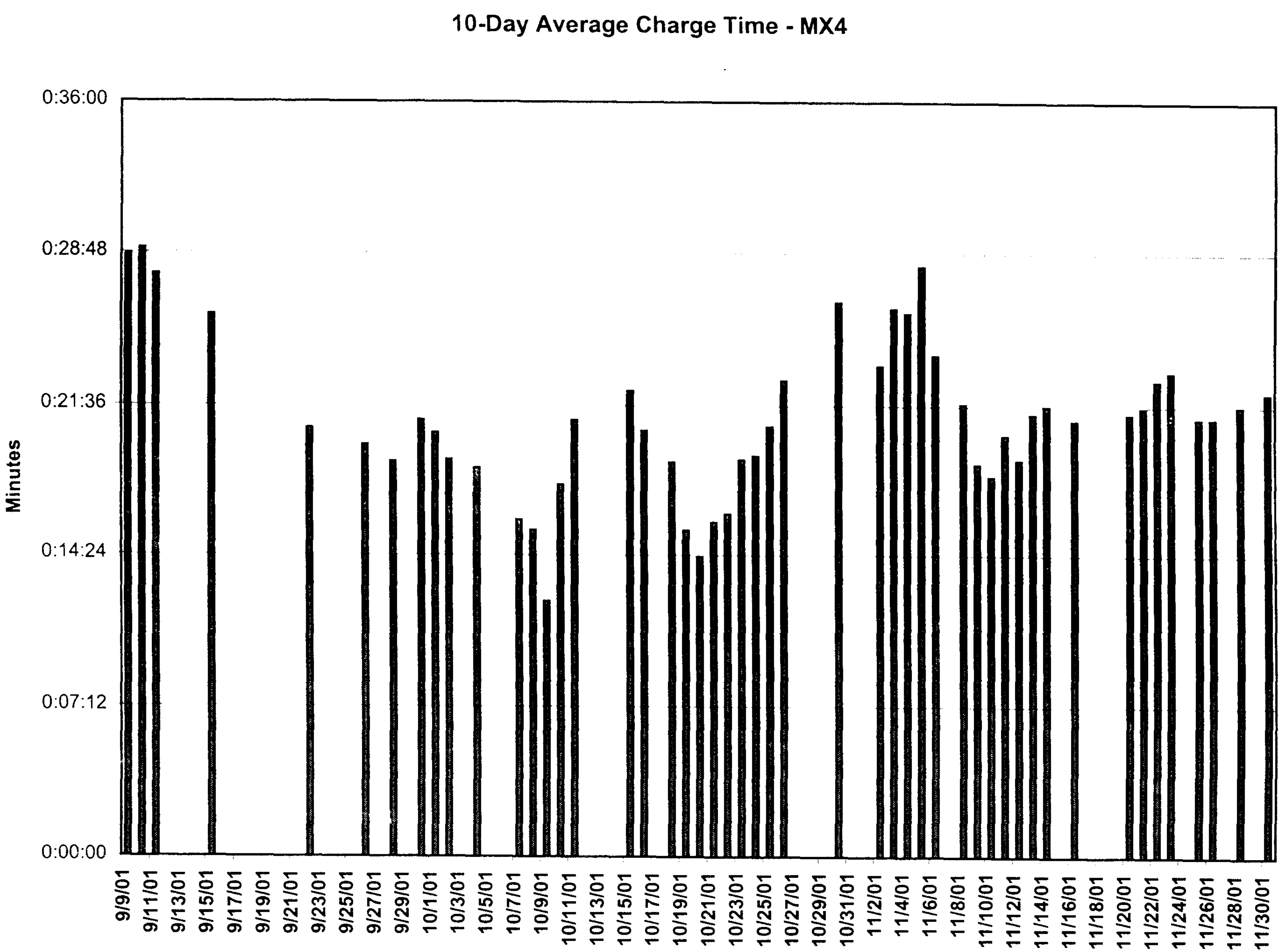
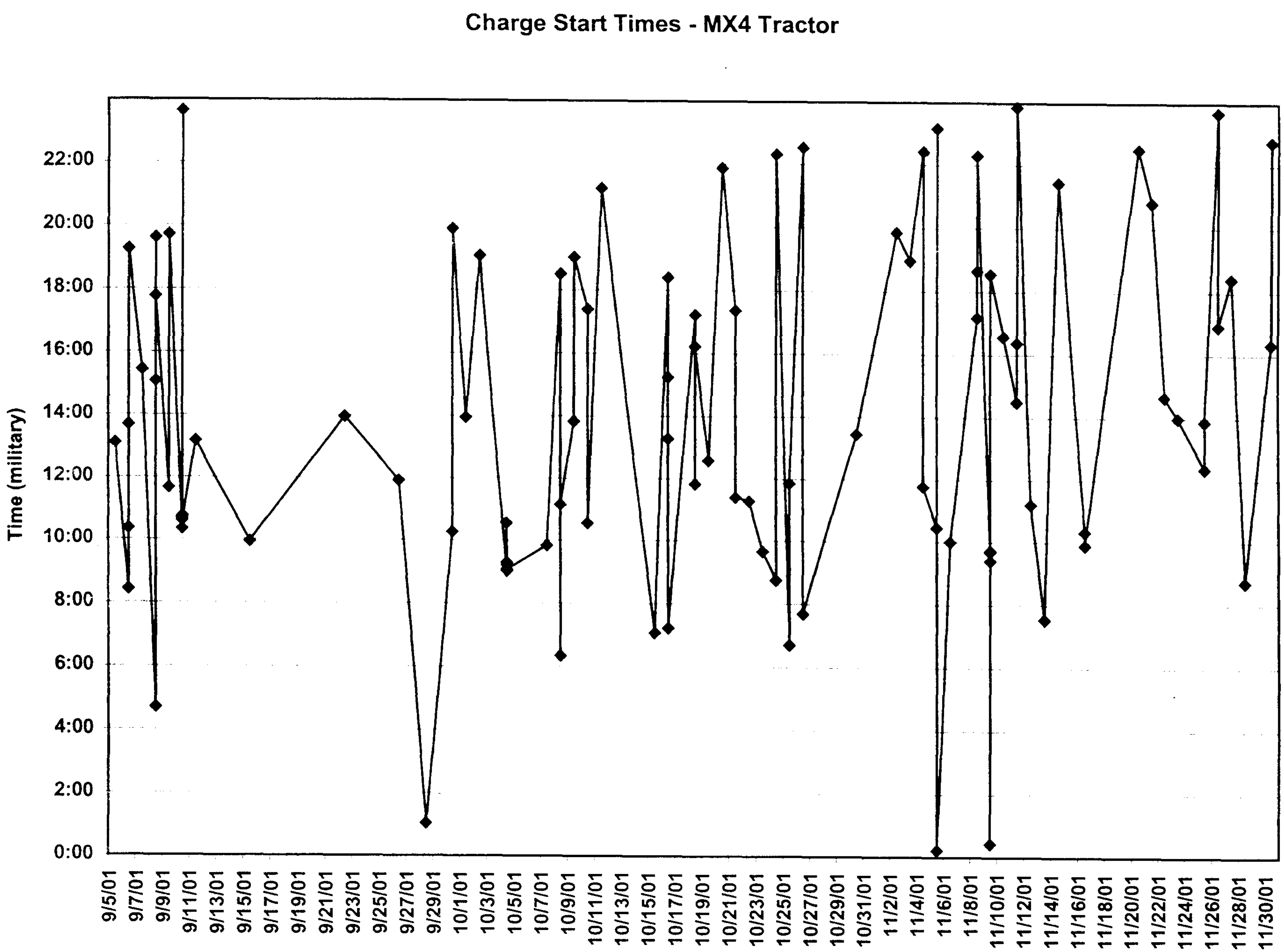
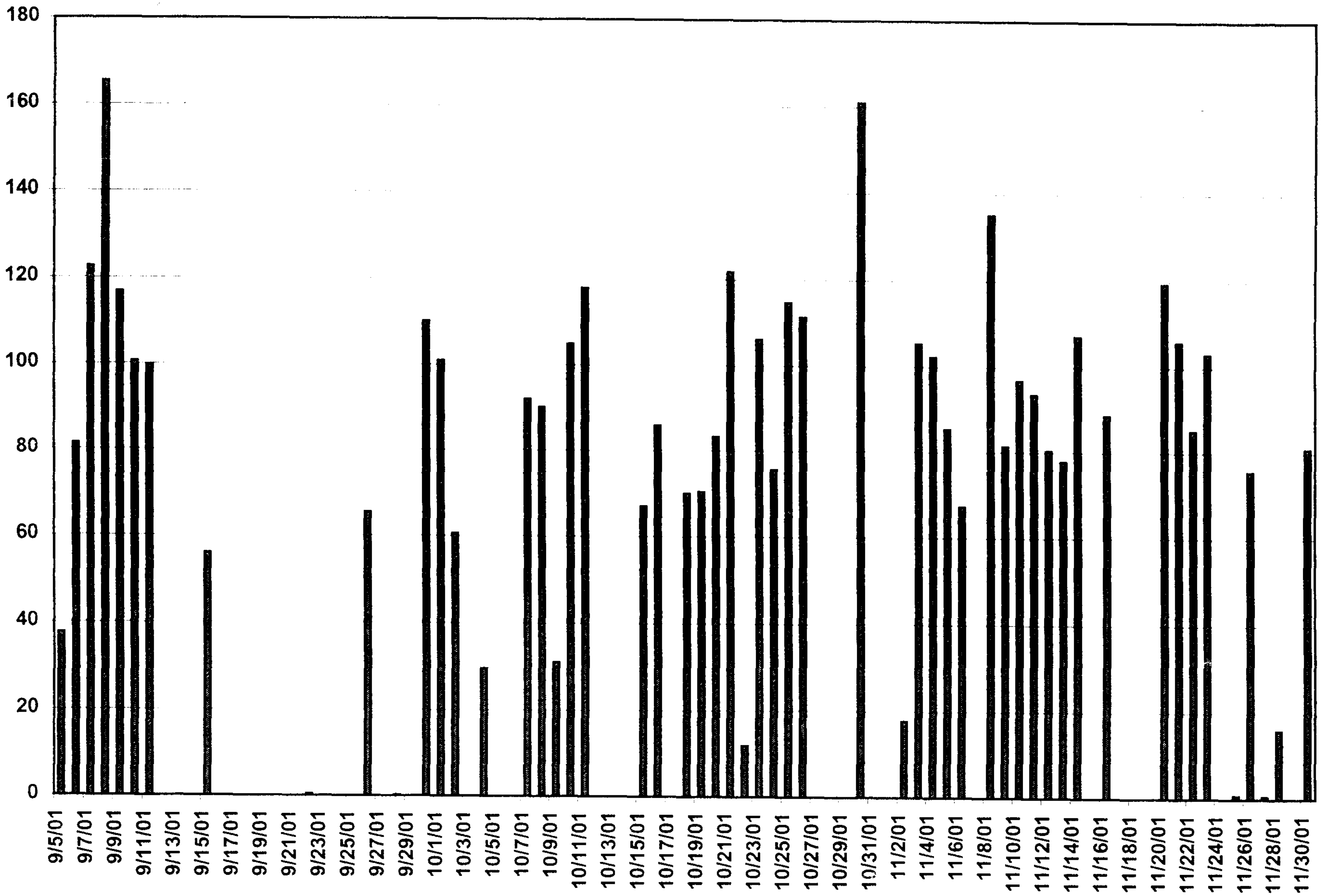
12/4/01
12/6/01
12/8/01
12/10/01



Task 4 - MX4 Tractor at SMF


Charge Start Times - MX4 Tractor
Time (military)
0:00
2:00
4:00
6:00
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
9/5/01
9/7/01
9/9/01
9/11/01
9/13/01
9/15/01
9/17/01
9/19/01
9/21/01
9/23/01
9/25/01
9/27/01
9/29/01
10/1/01
10/3/01
10/5/01
10/7/01
10/9/01
10/11/01
10/13/01
10/15/01
10/17/01
10/19/01
10/21/01
10/23/01
10/25/01
10/27/01
10/29/01
10/31/01
11/2/01
11/4/01
11/6/01
11/8/01
11/10/01
11/12/01
11/14/01
11/16/01
11/18/01
11/20/01
11/22/01
11/24/01
11/26/01
11/28/01
11/30/01

Ampere-Hours Returned per Charge - MX4

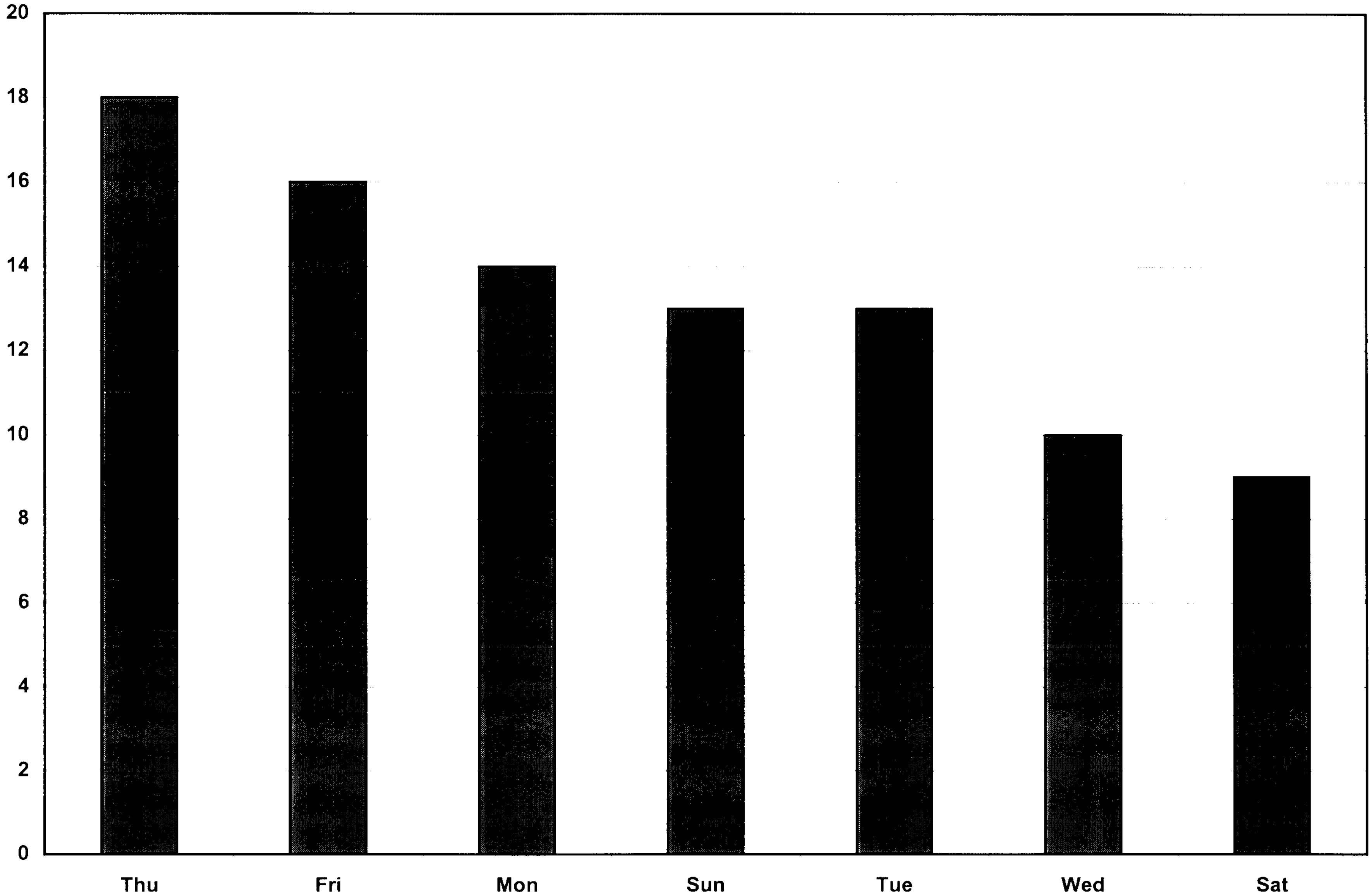


Task 4 - MX4 Tractor at SMF

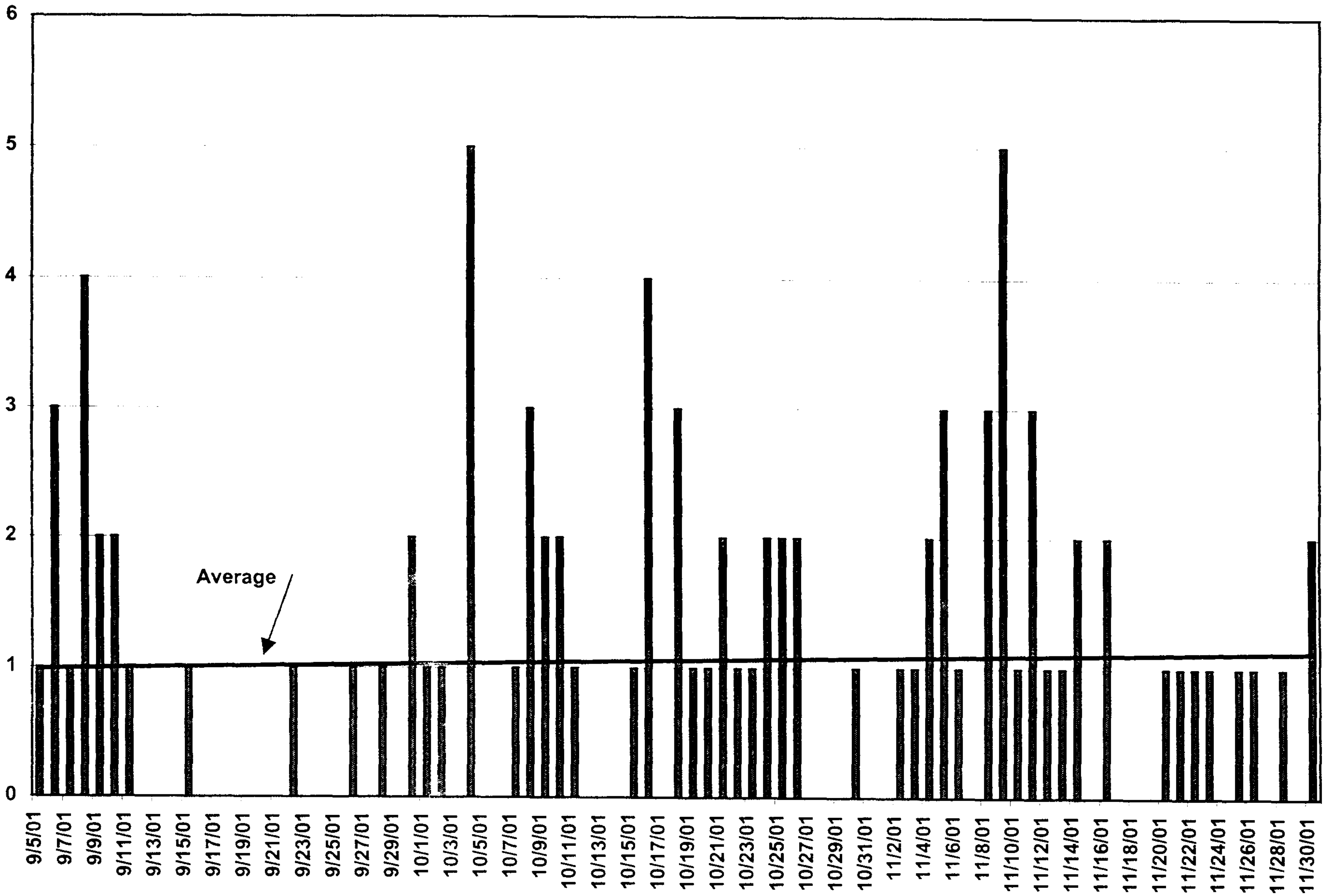
APPENDIX N

SuperCharge™ Data

Frequency of Charges per Day - MX4 Tractor

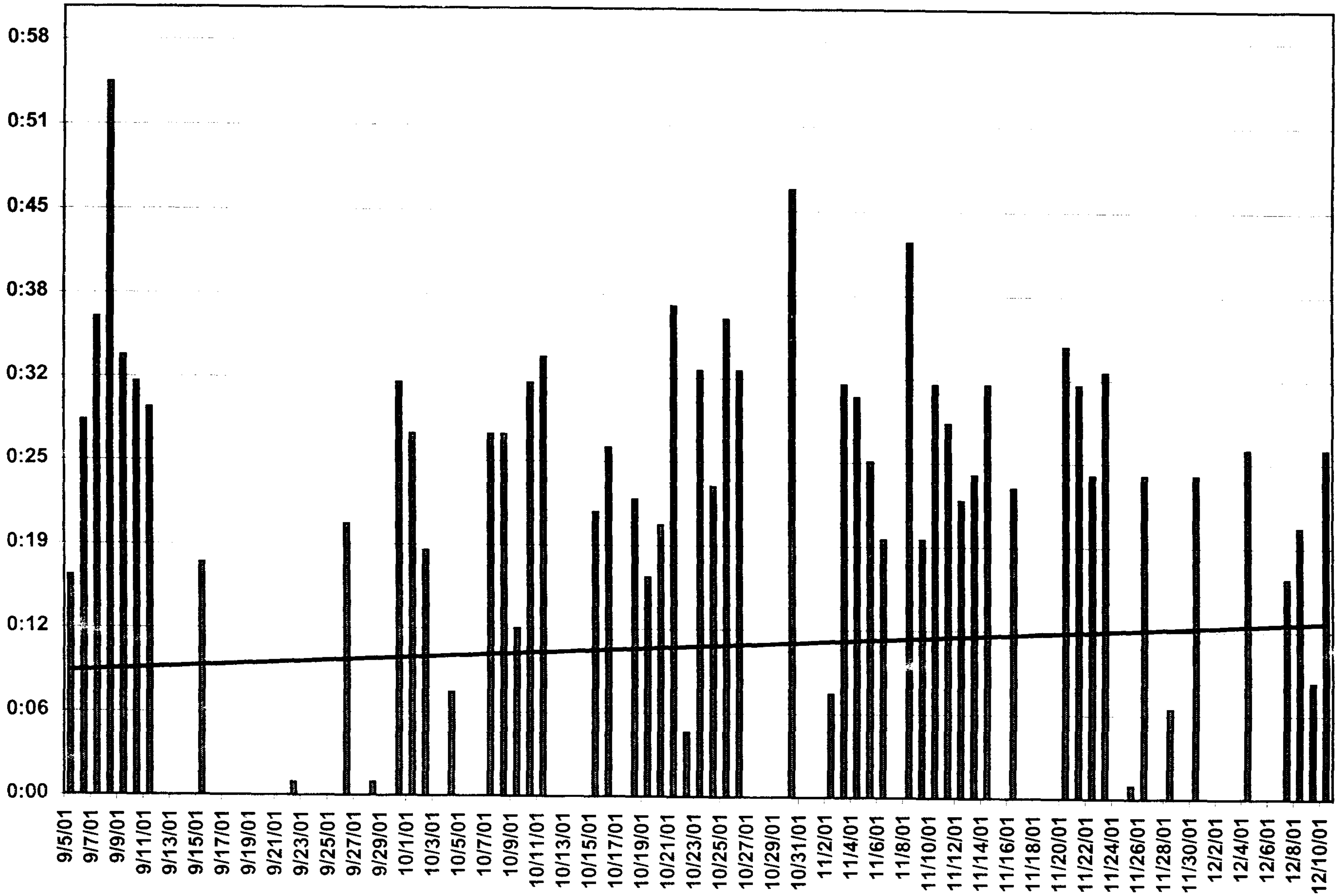


Charges per Day - MX4 Tractor



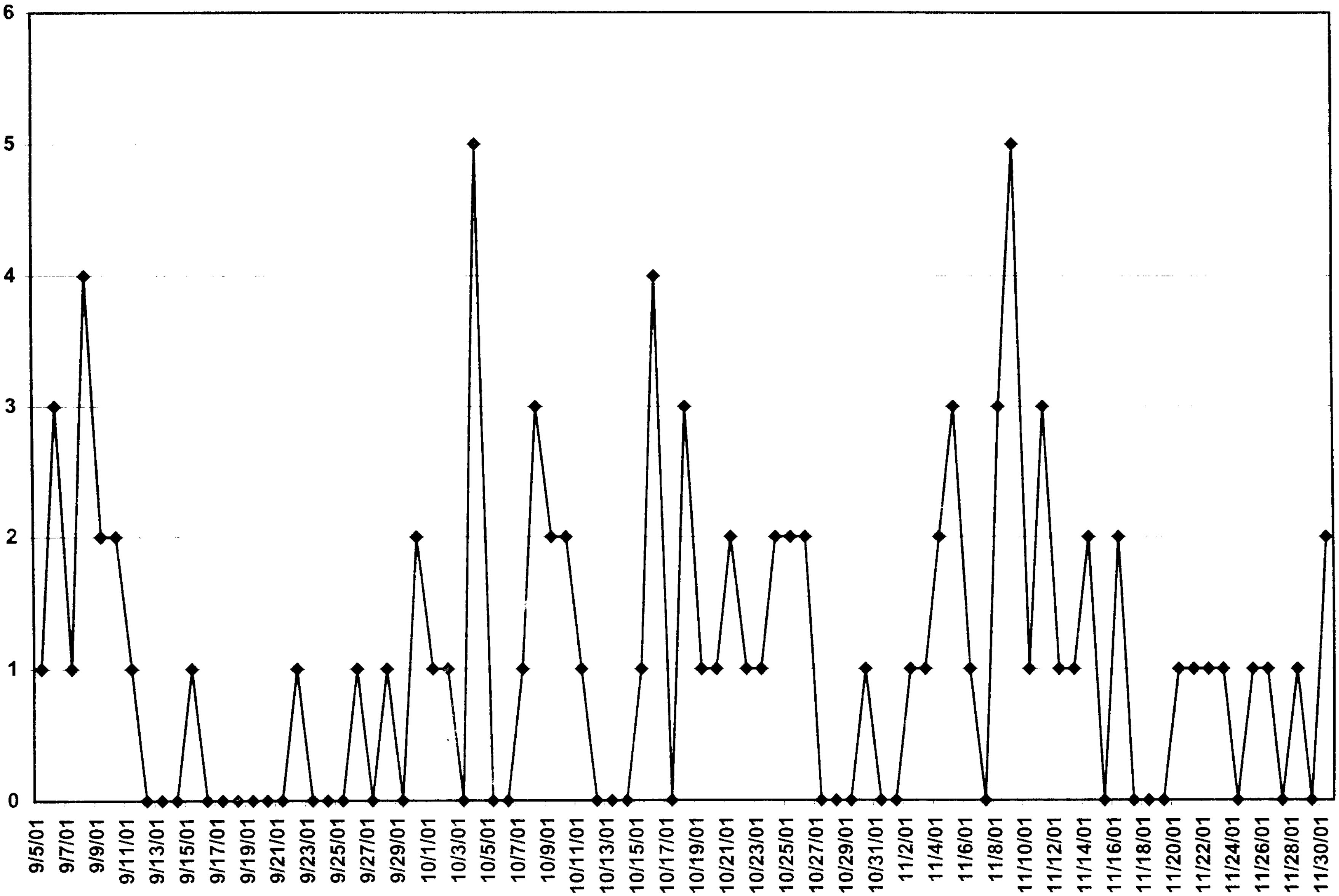
Task 4 - MX4 Tractor at SMF

Time on Charge - MX4 Tractor

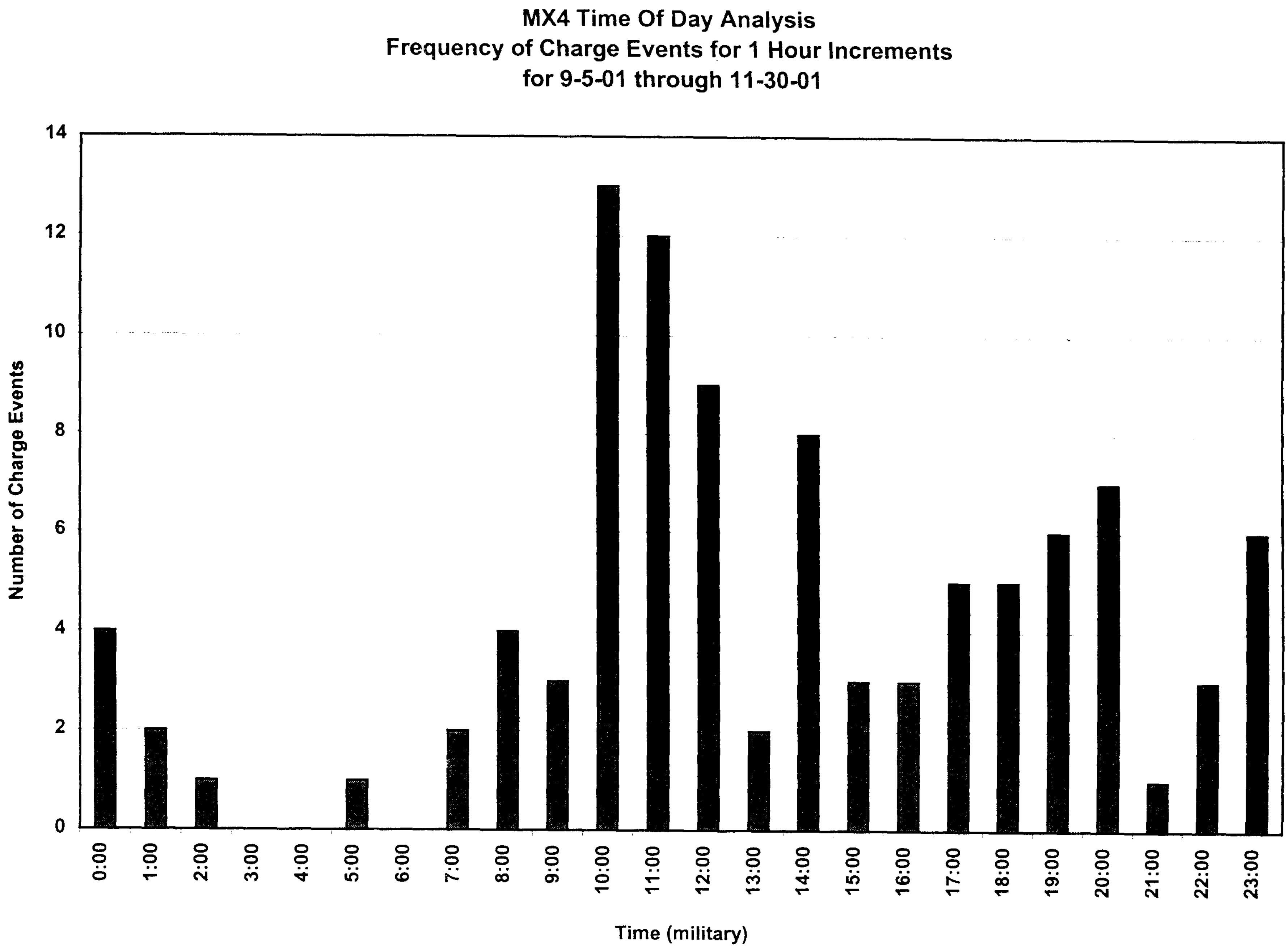


Task 4 - MX4 Tractor at SMF

Charges per Day - MX4 Tractor

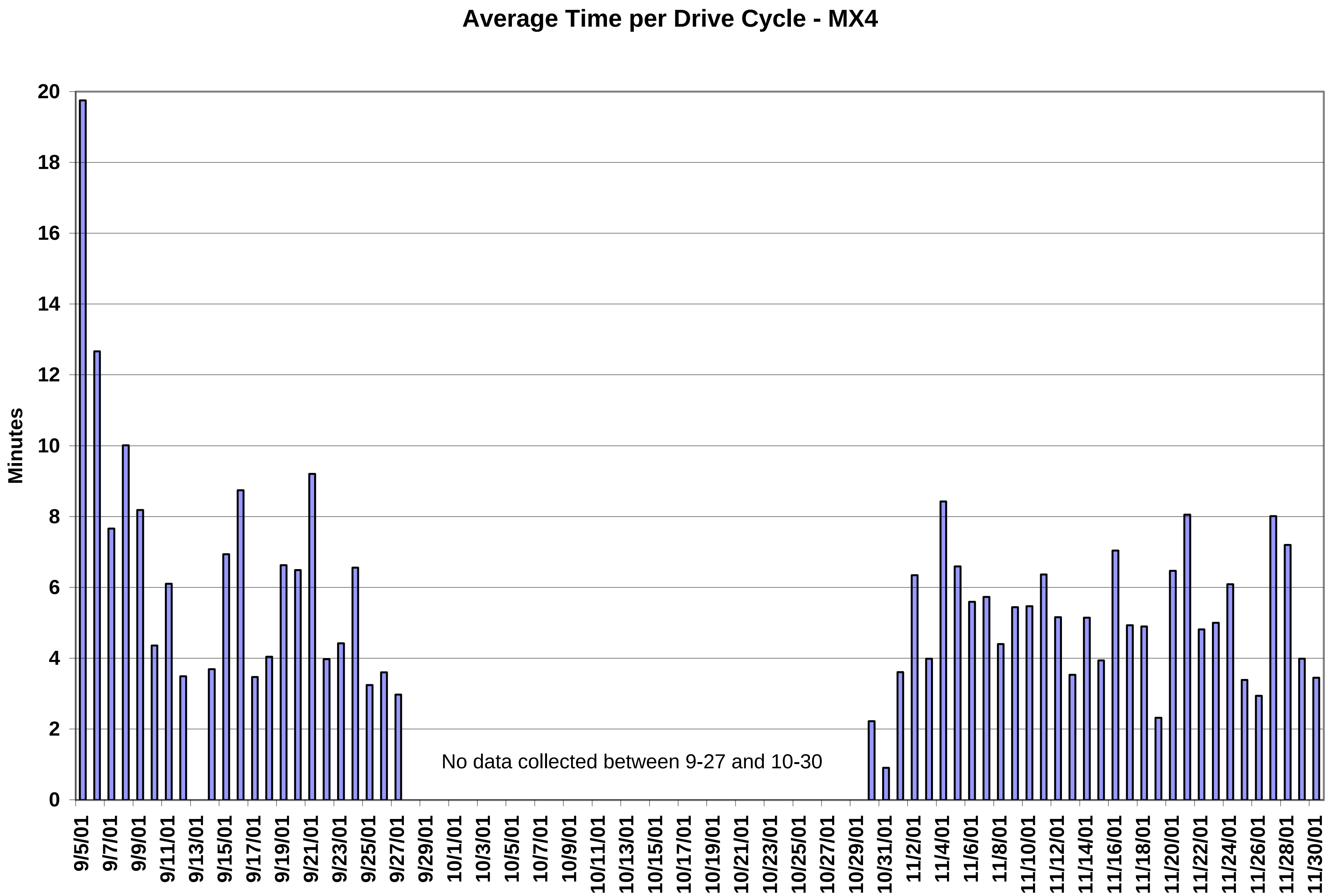


Task 4 - MX4 Tractor at SMF


MX4 Time Of Day Analysis
Frequency of Charge Events for 1 Hour Increments
for 9-5-01 through 11-30-01
Number of Charge Events
0
2
4
6
8
10
12
14
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time (military)

APPENDIX O

Tractor Energy Usage



Average Time per Drive Cycle - MX4
Minutes
20
18
16
14
12
10
8
6
4
2
0
No data collected between 9-27 and 10-30
9/5/01
9/7/01
9/9/01
9/11/01
9/13/01
9/15/01
9/17/01
9/19/01
9/21/01
9/23/01
9/25/01
9/27/01
9/29/01
10/1/01
10/3/01
10/5/01
10/7/01
10/9/01
10/11/01
10/13/01
10/15/01
10/17/01
10/19/01
10/21/01
10/23/01
10/25/01
10/27/01
10/29/01
10/31/01
11/2/01
11/4/01
11/6/01
11/8/01
11/10/01
11/12/01
11/14/01
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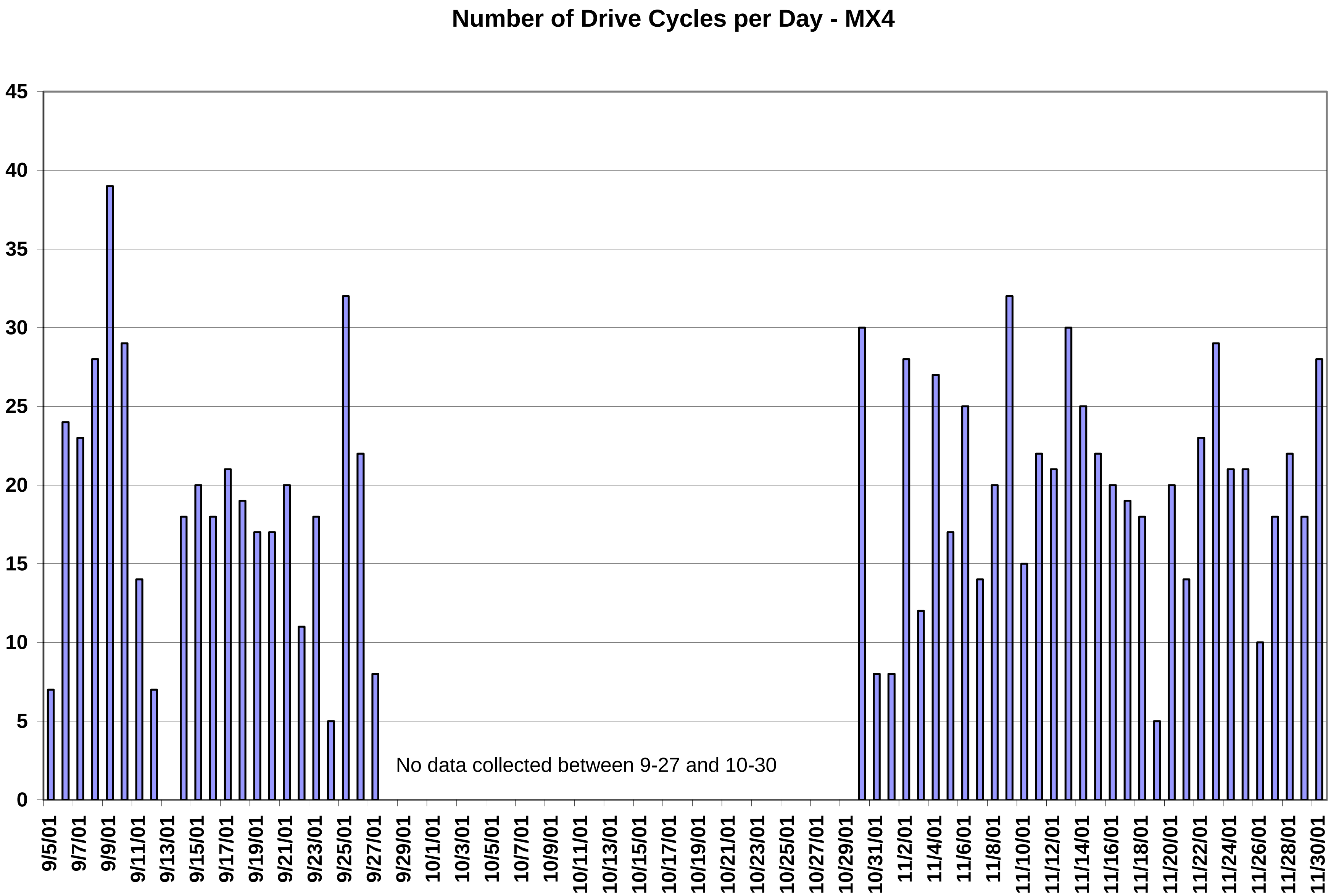
11/26/01
11/28/01
11/30/01


Number of Drive Cycles per Day - MX4
45
40
35
30
25
20
15
10
5
0
No data collected between 9-27 and 10-30
9/5/01
9/7/01
9/9/01
9/11/01
9/13/01
9/15/01
9/17/01
9/19/01
9/21/01
9/23/01
9/25/01
9/27/01
9/29/01
10/1/01
10/3/01
10/5/01
10/7/01
10/9/01
10/11/01
10/13/01
10/15/01
10/17/01
10/19/01
10/21/01
10/23/01
10/25/01
10/27/01
10/29/01
10/31/01
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11/4/01
11/6/01
11/8/01
11/10/01
11/12/01
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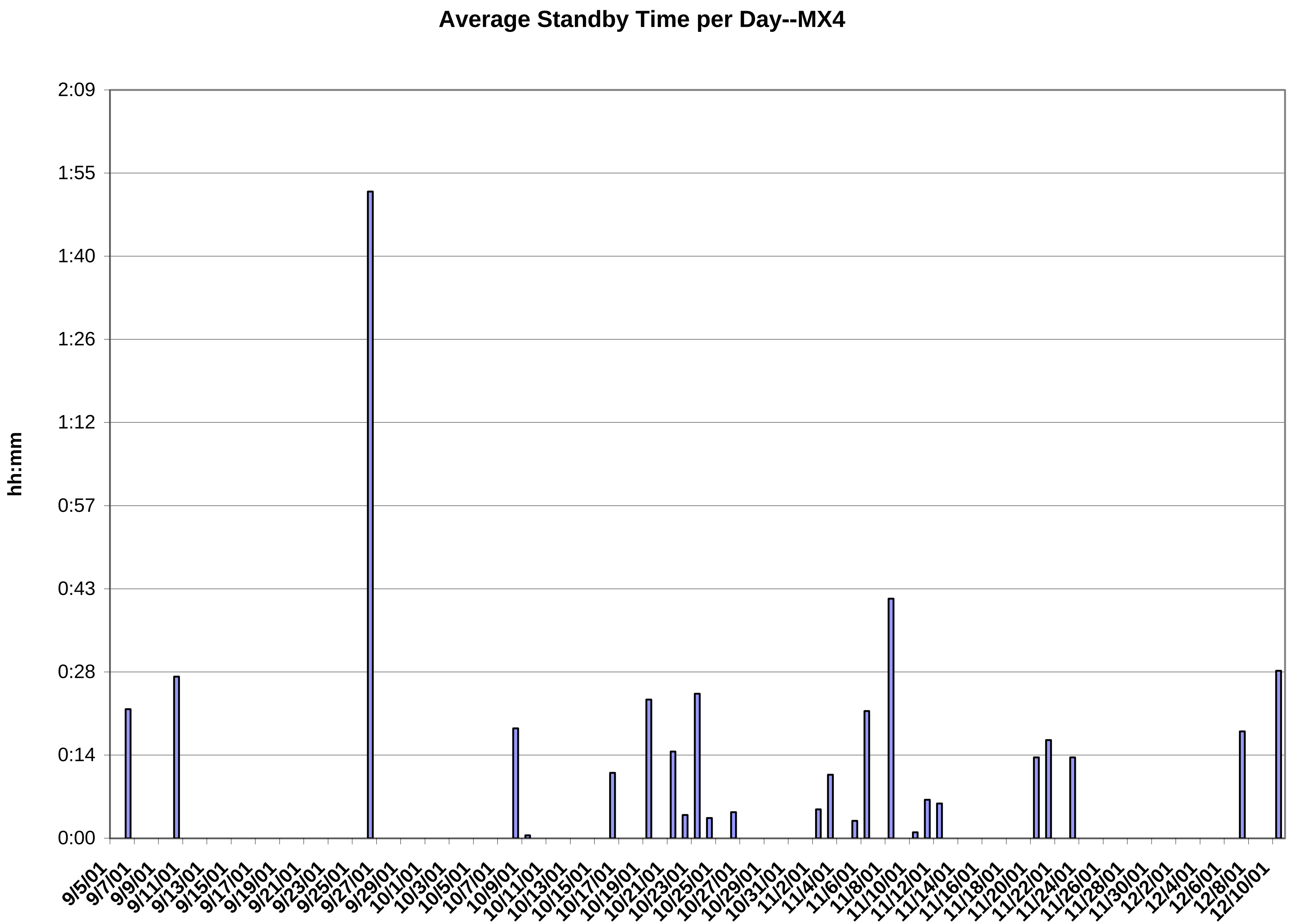
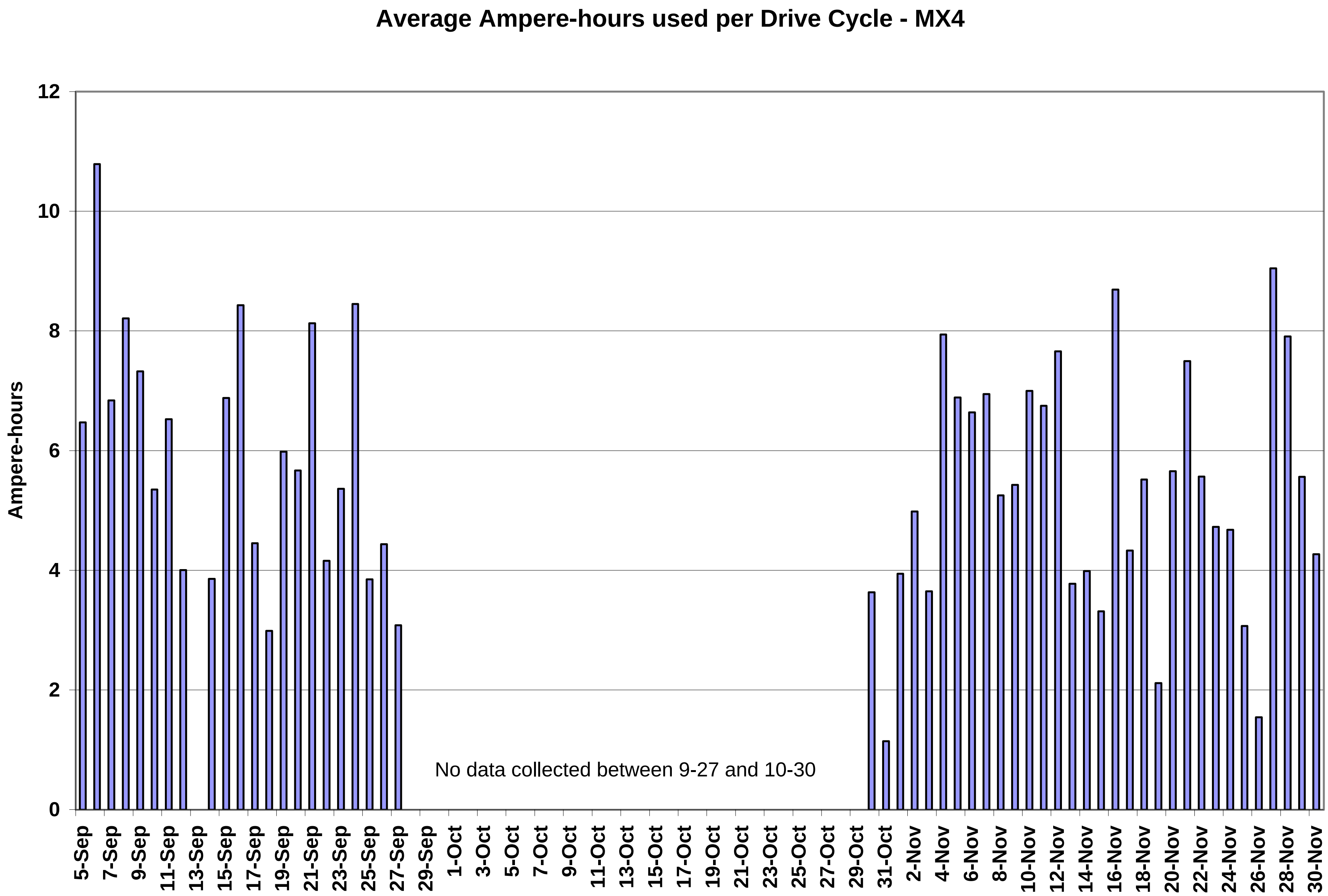
11/28/01
11/30/01



Task 4 - MX4 Tractor at SMF



Task 4 - MX4 Tractor at SMF

APPENDIX P

Detailed Tractor Report

SPECIFIC CHARGE AND DISCHARGE DATA FROM THE ON-BOARD DATA COLLECITON SYSTEM INSTALLED ON MX4 TRACTOR

DATA ANALYSIS

TIME PERIOD OF DATA COLLECTED

Data collection began on August 31 at 10:46 am and ended on September 25 at 10:40 am. Sampling rate was one (1) sample every two (2) seconds (0.5Hz).

FILES DOWNLOADED

During this 26-day period, data files were automatically saved into the on-board computer once each four hours. Approximately once each two weeks the files were downloaded and transmitted to eTec for reduction and analysis. Files were DAQSTANDARD formatted files; using the DAQSTANDARD software, each file was converted into an Excel format. The three data files for each day were then merged into a single file in order to obtain one 24 – hour data file. Each file contained the following information:

- date stamp
- time stamp
- cell voltages for 24 cells
- bi-directional battery current – string I
- bi-directional battery current – string II
- battery temperature
- ambient temperature

A date and time stamp on each file was used to create daily files with charge/discharge data. Time stamps along with a sampling rate of 1 sample each two seconds was used to graph voltages, currents, or temperatures for that the day. Sampling rate and current column for each string was used to calculate the battery pack capacity. Cell voltage data were used to monitor the behavior of individual cells and variations in total battery pack voltage during the charge/discharge cycles.

GRAPHICAL REPRESENTATION OF TYPICAL ONE DAY DATA

Sampling rate of 1 sample per 2 seconds provided each 24 hours data file with an Excel file with over 43,000 rows of data. This large number of datum made it impossible to graph an entire 24 hours period of data in a single graph.

To provide a proper perspective on the data collected, a typical day of operation was selected. The day selected was September 07, 2001. This day was representative of the normal operation and service requirements for all of the electric bag tractors utilized during this project. A typical 16 hours of data are presented in Figures 1 through 4.

Figure 1 shows that in the morning of September 07, 2001, there were 7 - 8 drive cycles (indicated by the negative and positive current values). Following these drive cycles, the vehicle was placed on charge. Following the charge cycle the vehicle completed a number of drive cycles (>15). The duration's of these drive cycles can be measured in minutes. Following these drive cycles the vehicle was placed on charge again. The corresponding variations in battery pack voltage are shown in Figure 2.

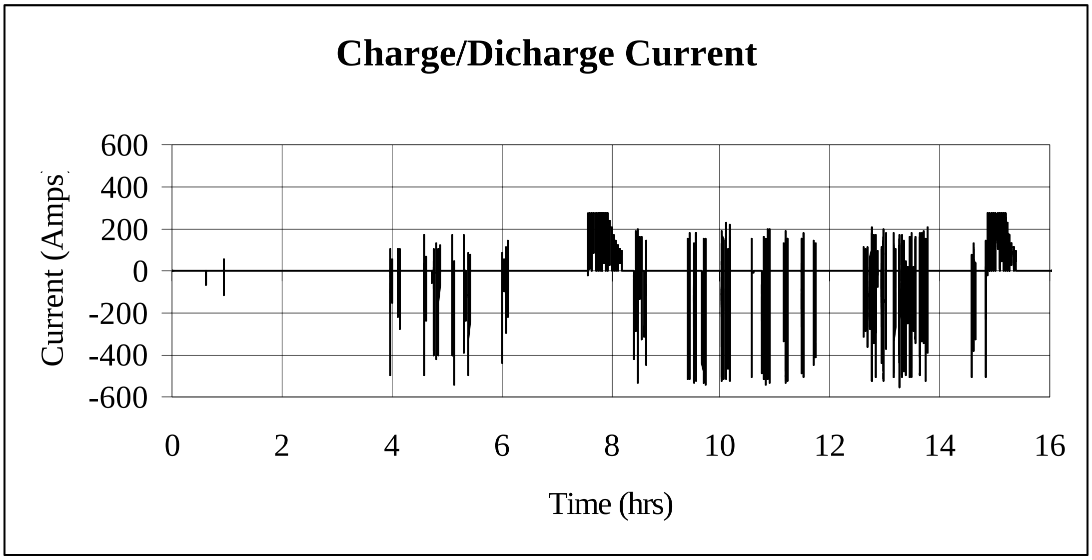


Figure 1. Drive cycle and charge currents recorded on September 07, 2001

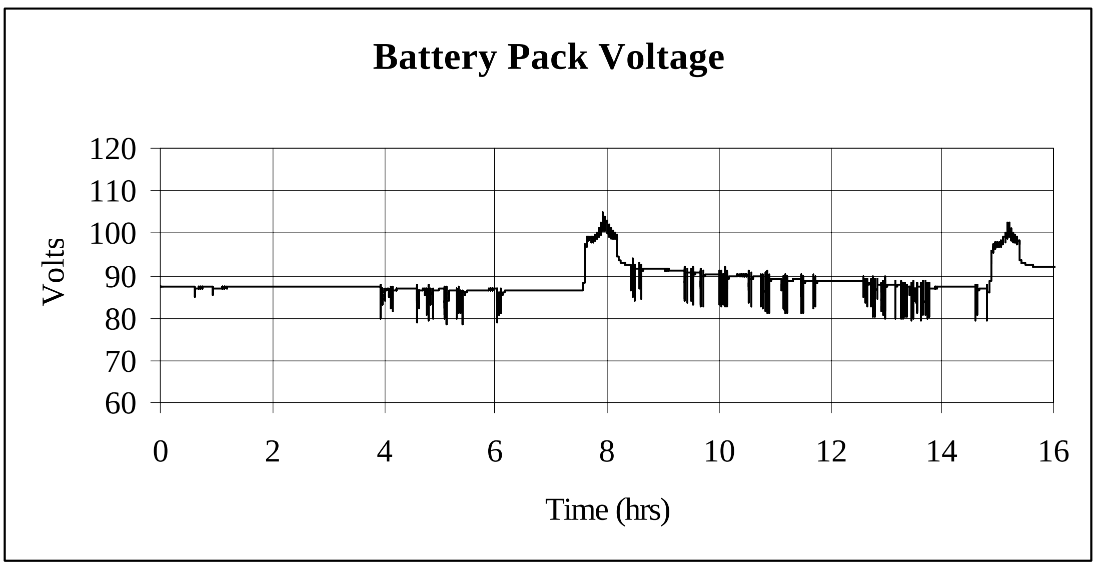


Figure 2. Battery pack voltage recorded on September 07, 2001

During the charge cycle the battery pack voltage increased from about 80V to over 100V. After the vehicle was taken off charge and placed back into service, battery pack voltage immediately decreased, and then gradually dropped as the number of drive cycles increased.

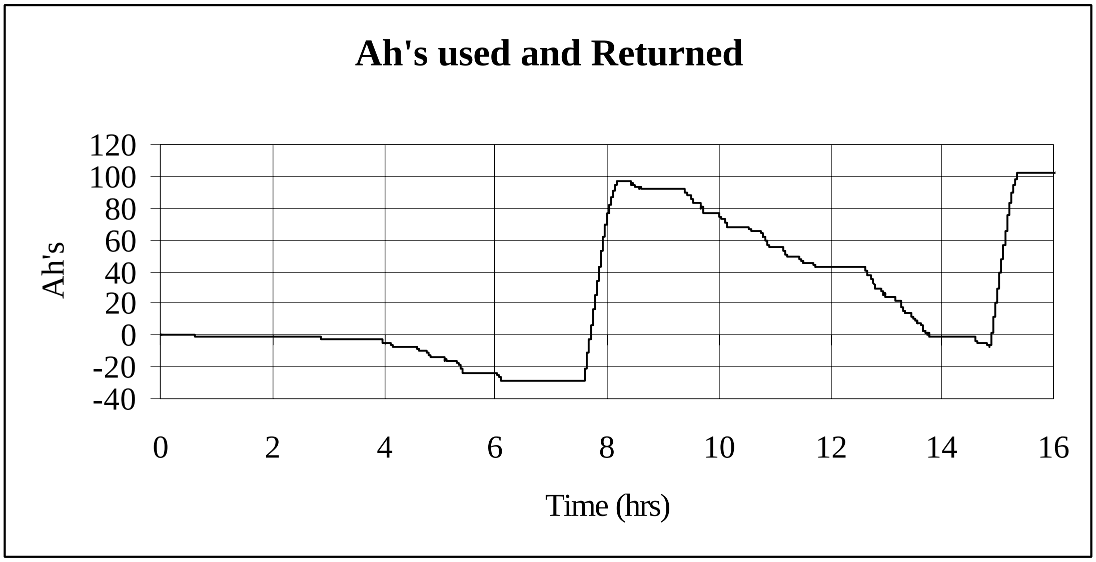


Figure 3. Battery pack Ah's recorded on September 07, 2001

Figure 3 shows that they were two charge cycles with total of 67 minutes of charging. During these two charging cycles, ~ 240 Ah of energy were returned to the battery. With each ensuing drive cycle, the energy returned was consumed. After the first charge cycle 100 Ah of battery energy was consumed. After the second charge cycle 30 Ah of battery energy was consumed by the end of the day of September 07.

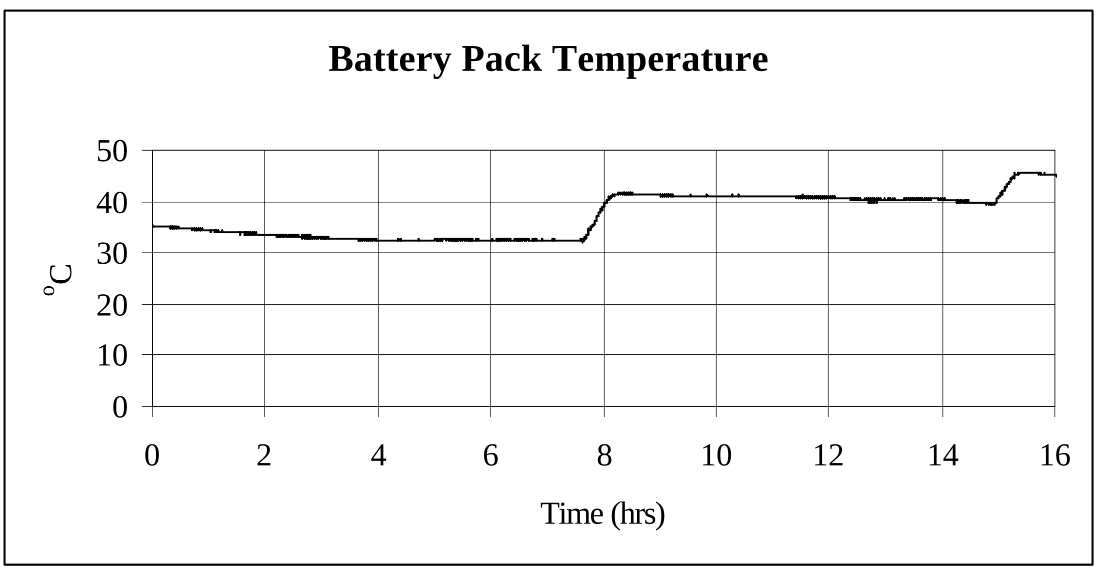


Figure 4. Battery pack temperature recorded on September 07, 2001

Figure 4 shows that battery temperature increased during each charge cycle, which is expected.

Calculated Parameters for One Day's Data

The following parameters were calculated from data collected for September 07, 2001:

- Number of drive cycles,
- Duration of each drive cycle in minutes,
- Ampere-hours used during each drive cycle for string 1,
- Ampere-hours restored during each drive cycle for string 1,
- Ampere-hours used during each drive cycle for string 2,
- Ampere-hours restored during each drive cycle for string 2,
- Total Ampere-hours used during each drive cycle,
- Ampere-hours restored during each drive cycle,
- Average current during each drive cycle in Amps for string 1,
- Average current during each drive cycle in Amps for string 2,
- Total Average current during each drive cycle in Amps,
- Total Maximum current during each drive cycle in Amps,
- Standard deviation of total current during each drive cycle in Amps,
- Average time between two drive cycles in minutes,
- Number of charge cycles,
- Duration of each charge cycle in minutes,
- Ampere-hours restored into the battery pack during the charge cycle,
- Average charge current in Amps during the charge cycle,
- Maximum charge current in Amps during the charge cycle,

Calculated discharge cycle data from the file for September 07, 2001 are presented in Table 1.

TABLE 1

	TOTAL DATA					RETURNED DATA					USED DATA				
N	t	Ah	I_{max}	I_{avg}	STD	t	Ah	I_{max}	I_{avg}	STD	t	Ah	I_{max}	I_{avg}	STD
	min	Ah	Amps	Amps	Amps	min	Ah	Amps	Amps	Amps	min	Ah	Amps	Amps	Amps
1	18.8	0.6	119.0	2.3	8.0	0.1	0.0	56.0	31.5	34.6	18.7	0.7	119.0	2.2	7.7
2	2.5	2.3	496.0	65.2	80.7	0.3	0.2	109.0	39.4	36.4	2.2	2.5	496.0	68.3	84.1
3	3.8	2.7	274.0	51.8	64.1	0.4	0.3	104.0	49.9	43.1	3.5	3.0	274.0	52.0	66.1
4	9.5	6.6	498.0	52.7	85.8	0.9	0.9	162.0	58.9	47.6	8.6	7.5	498.0	52.0	88.8
5	2.1	2.6	534.0	96.1	132.2	0.4	0.4	162.0	56.4	53.1	1.7	3.0	534.0	105.4	143.5
6	6.8	7.0	491.0	71.0	76.7	0.6	0.6	165.0	56.7	45.2	6.2	7.5	491.0	72.4	79.0
7	16.0	4.5	440.0	20.9	52.3	0.6	0.6	142.0	56.7	41.6	15.4	5.0	440.0	19.6	52.2
8	4.8	5.7	535.0	99.8	113.3	0.7	1.1	194.0	98.4	57.5	4.1	6.9	535.0	100.0	120.4
9	5.3	8.9	529.0	133.3	149.0	0.9	1.5	176.0	97.1	62.4	4.4	10.3	529.0	140.7	160.3
10	3.5	5.8	532.0	131.3	155.4	0.6	0.9	154.0	94.4	43.5	2.9	6.7	532.0	139.0	168.8
11	6.2	8.1	527.0	108.3	133.0	1.0	1.6	228.0	94.2	63.7	5.2	9.7	527.0	111.0	142.5
12	2.0	2.5	500.0	103.2	135.2	0.6	0.5	152.0	51.1	43.0	1.4	3.0	500.0	125.0	154.0
13	7.5	10.6	535.0	118.5	139.6	1.4	2.1	191.0	92.7	56.6	6.2	12.8	535.0	124.2	151.6
14	4.8	6.6	535.0	111.9	133.8	0.9	1.2	182.0	78.8	56.6	3.9	7.8	535.0	119.9	145.4
15	2.2	2.8	502.0	102.9	128.3	0.3	0.5	174.0	94.5	59.4	1.9	3.3	502.0	104.4	137.2
16	2.3	2.7	446.0	101.5	107.0	0.4	0.5	138.0	75.5	46.0	1.8	3.3	446.0	107.7	116.4
17	17.1	18.7	526.0	86.8	108.9	2.4	3.0	202.0	76.8	56.4	14.8	21.8	526.0	88.4	115.0
18	19.1	24.5	547.0	106.1	130.3	2.8	4.6	197.0	97.9	54.2	16.2	29.1	547.0	107.6	139.4
19	3.2	4.1	506.0	99.2	113.3	0.5	0.6	129.0	71.5	46.4	2.7	4.7	506.0	104.3	121.2
20	2.3	1.7	503.0	50.1	100.1	0.2	0.1	134.0	47.4	57.9	2.1	1.8	503.0	50.3	103.0
21	6.0	4.3	259.0	51.2	71.3	0.4	0.4	113.0	53.5	35.7	5.6	4.7	259.0	51.0	73.4
22	17.9	17.0	542.0	75.9	109.7	2.1	2.8	238.0	78.6	56.9	15.7	19.8	542.0	75.5	115.1
23	12.4	7.0	492.0	40.9	82.6	1.1	0.7	112.0	39.8	39.6	11.3	7.7	492.0	41.0	85.6

Table 2 show an example of drive cycles summary data calculated for September 07, 2001

TABLE 2

Drive Cycles		
Total Number of Drives Cycles	-	23
Average Duration of Drive Cycle	min	7.66
Average Ah's used per Drive Cycle	Ah	7.94
Average Ah's Returned per Drive Cycle	Ah	1.10
Average Maximum Drive Cycle Current in Used Mode	Amps	472.52
Average Maximum Drive Cycle Current in Returned Mode	Amps	157.13
Average Drive Cycle Current in Used Mode	Amps	85.29
Average Drive Cycle Current in Returned Mode	Amps	69.20
Total Time in Current Used	min	156.6
Total Time in Returned Mode	min	19.60
Total Drive Time	min	176.1

Table 3 shows the charge cycle summary data calculated for September 07, 2001

TABLE 3

Charge Cycles	**I**	**II**
Date	**9/07**	**9/07**
Charge Time (min)	36.60	30.87
Ah Returned String I (Ah)	63.82	55.34
Ah Returned String II (Ah)	62.83	53.65
Ah Returned Net (Ah)	126.65	108.99
Average Charge Current String I (Amps)	104.62	107.57
Average Charge Current String II (Amps)	102.99	104.29
Average Charge Current Net (Amps)	207.62	207.62
Initial Pack Voltage (Volts)	86.60	86.72
Final Pack Voltage (Volts)	98.77	97.87
Voltage Increase (Volts)	12.17	11.15
Initial Pack Temperature (^oC)	32.40	39.60
Final Pack Temperature (^oC)	41.50	45.70

Criteria For Identifying Drive (Discharge) Cycle

To determine the use patterns of the bag tractor, it was necessary to establish certain Criteria. These were stated in the following questions:

- What constitutes a Drive Cycle?
- How will the duration of the Drive Cycle be determined?
- How will the number of Drive Cycles be determined?

Figure 1 shows that a drive cycle duration is normally short. The start and the end of the drive cycle are determined based on the discharge current value. The beginning of a Drive Cycle was ascertained to coincide with battery current becoming negative. The end of drive cycle occurred when the battery current dropped to zero. The time between those two events was stipulated to be a Drive Cycle.

The more difficult task was to determine the number of drive cycles within a single day. In order to determine this, it was necessary to establish the end of each of the Drive Cycles relative to the beginning of the next discharge sequence. [Otherwise stated, how much wait-time needed to pass before the next drive cycle began.] After reviewing all the data and observing Ramp Operations, it was decided that five (5) minutes would be the threshold. Wait times less than five minutes would be considered the same drive cycle; wait times greater than five minutes would establish a new drive cycle.

CHARGE DATA SUMMARY

During the period between August 31 and September 25 were 31 charge cycles recorded. Table 4 shows the summary of charge data.

TABLE 4

	Time	Ah String I	Ah String II	Ah Net	Amps String I	Amps String II	Net Amps	Initial Volts	Final Volts	Volts Change	Initial Temp	Final Temp	Temp Change
	min	Ah	Ah	Ah	Amps	Amps	Amps	Volts	Volts	Volts	^oC	^oC	^oC
31-Aug	16.3	26.8	24.0	50.9	98.7	88.5	187.2	88.5	96.5	8.0	n/a	n/a	n/a
5-Sep	16.9	19.3	19.5	38.8	69.7	69.4	138.1	87.0	101.8	14.9	24.3	26.9	2.6
6-Sep	17.5	19.5	20.3	39.8	67.2	69.8	137.0	87.0	101.9	14.9	25.9	28.2	2.3
6-Sep	27.9	37.3	37.8	75.1	80.3	81.4	161.6	86.8	100.3	13.5	29.3	34.6	5.3
6-Sep	24.1	33.6	33.3	66.9	83.8	83.2	167.0	88.3	99.4	11.1	35.0	39.3	4.3
6-Sep	26.2	42.2	41.7	83.9	96.5	95.4	191.9	88.0	97.7	9.7	39.6	44.6	5.0
7-Sep	36.6	63.8	62.8	126.7	104.6	103.0	207.6	86.6	98.8	12.2	32.4	41.5	9.1
7-Sep	30.9	55.3	53.7	109.0	107.6	104.3	207.6	86.7	97.9	11.2	39.6	45.7	6.1
8-Sep	29.6	59.9	58.2	118.1	121.2	117.8	239.1	86.0	100.2	14.2	33.3	40.4	7.1
8-Sep	15.6	20.1	20.1	40.2	77.1	77.2	154.3	89.5	99.1	9.6	40.3	42.2	1.9
8-Sep	8.6	11.4	11.3	22.7	79.3	78.3	157.6	90.2	99.2	9.0	41.9	42.5	0.6
8-Sep	15.2	24.4	23.8	48.1	95.9	93.7	189.7	88.6	99.0	10.4	42.2	44.4	2.2
9-Sep	27.3	49.3	47.4	96.7	108.1	104.1	212.2	86.8	100.2	13.5	30.8	36.9	6.1
9-Sep	33.9	60.8	59.7	120.4	107.5	105.6	213.0	86.6	98.6	12.1	35.7	42.3	6.6
10-Sep	34.0	48.2	46.9	95.1	84.8	82.7	167.5	86.5	100.9	14.3	28.8	34.7	5.9
10-Sep	30.9	51.8	51.9	103.7	100.5	100.6	201.1	88.8	100.2	11.4	31.3	37.4	6.1
11-Sep	29.1	51.9	51.1	103.0	107.1	105.4	212.5	86.8	100.3	13.5	30.2	36.7	6.5
12-Sep	22.5	33.1	33.4	66.5	88.2	88.9	177.0	87.2	101.8	14.6	23.8	27.7	3.9
14-Sep	2.5	2.5	2.6	5.0	57.7	59.7	117.4	89.7	101.8	12.1	24.1	24.1	0.0
14-Sep	24.2	35.7	36.8	72.6	88.6	91.3	179.9	88.2	100.4	12.2	27.2	31.5	4.3
15-Sep	17.6	29.0	28.8	57.8	98.5	98.2	196.6	87.3	100.6	13.3	28.2	31.5	3.3
15-Sep	29.8	47.2	47.5	94.7	96.1	95.6	190.7	86.3	101.6	15.3	25.8	31.8	6.0
16-Sep	25.5	41.7	40.9	82.6	97.9	96.2	194.1	87.3	100.8	13.4	31.1	35.9	4.8
16-Sep	27.8	46.5	45.9	92.4	100.2	98.8	199.0	87.9	98.8	10.8	36.2	41.2	5.0
18-Sep	43.3	77.6	79.4	157.0	107.6	110.0	217.6	85.7	99.2	13.5	26.7	36.9	10.2
20-Sep	39.1	69.6	71.4	141.0	106.7	109.4	216.0	85.5	100.7	14.5	24.5	33.7	9.2
21-Sep	26.6	46.2	45.5	91.7	104.0	102.4	206.4	87.8	101.3	13.5	27.9	33.2	5.3
21-Sep	28.9	49.5	49.2	98.6	102.6	102.0	204.5	87.2	99.0	11.8	33.3	38.9	5.6
22-Sep	29.9	51.6	51.7	103.3	103.5	103.8	207.3	87.3	100.2	12.9	30.1	36.2	6.1
23-Sep	31.3	48.4	49.0	97.4	92.6	93.8	186.4	88.2	101.8	13.6	28.6	34.2	5.6
24-Sep	12.9	20.4	20.7	41.1	95.1	96.2	191.3	88.6	102.0	13.4	26.6	28.7	2.1

Table 4 shows that net Ampere-hours returned during the observed period was a minimum of 5.01 Ah and maximum of 157 Ah. Figure 5 presents the variation of energy returned to the battery pack capacity during this period.

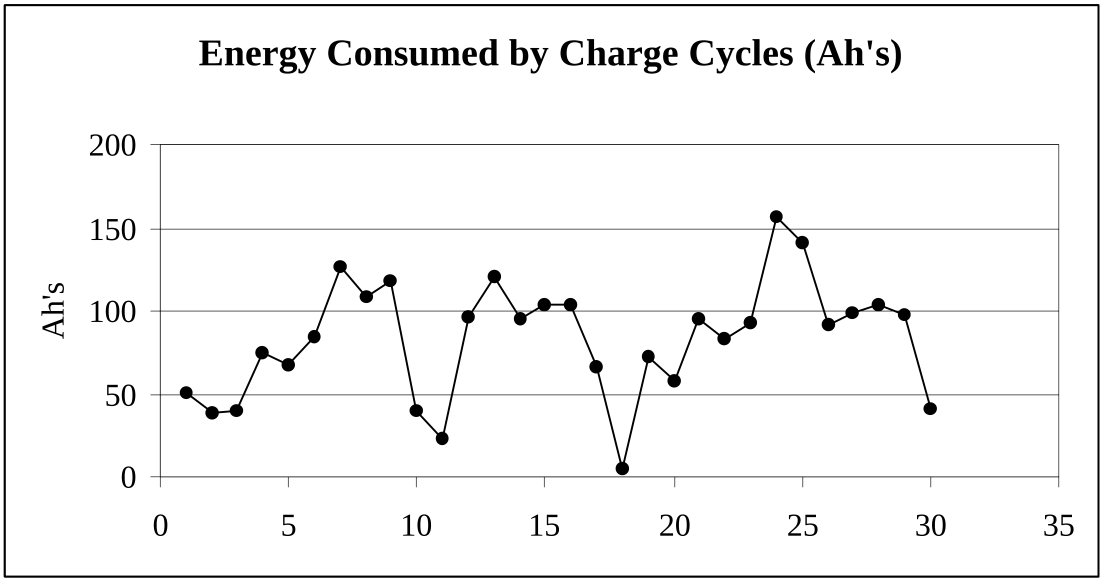


Figure 5. Variation of Recharged Capacity and Charge Cycles

When a trend line is applied it shows that energy returned during the Project's Duration increased at the rate of ~ 1.1 Ah per charge cycle. The Trend Line is shown in Figure 6.

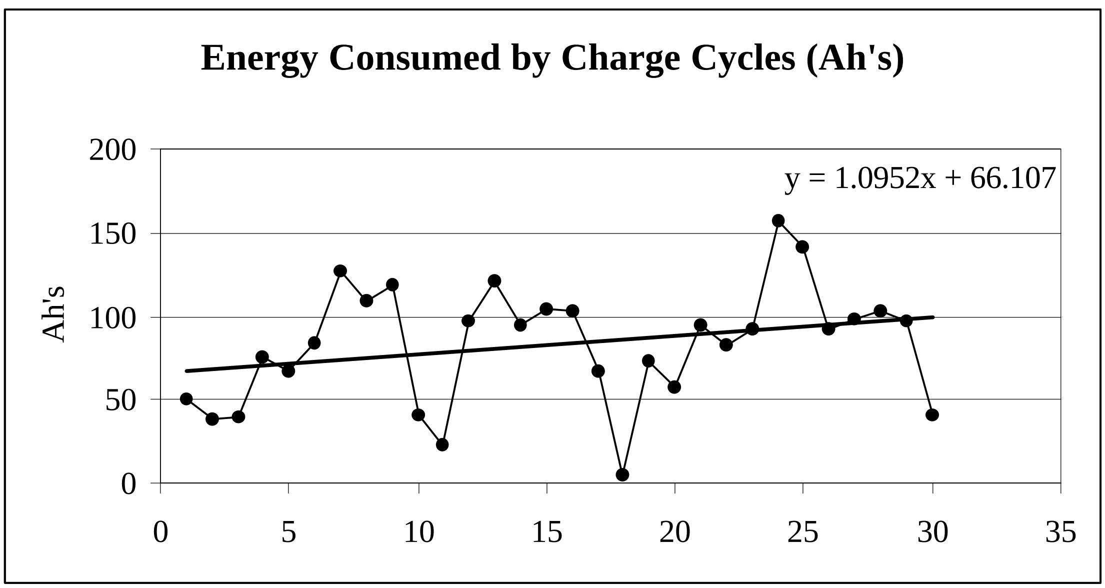


Figure 6. Trend Line for Recharge Capacity

A Histogram for energy returned was developed and is shown in Figure 7. This Figure shows that most of the time energy returned was between 100 Ah and 120 Ah. In only three occasions the energy returned greater than 120 Ah and the rest of the times it was less then 120 Ah.

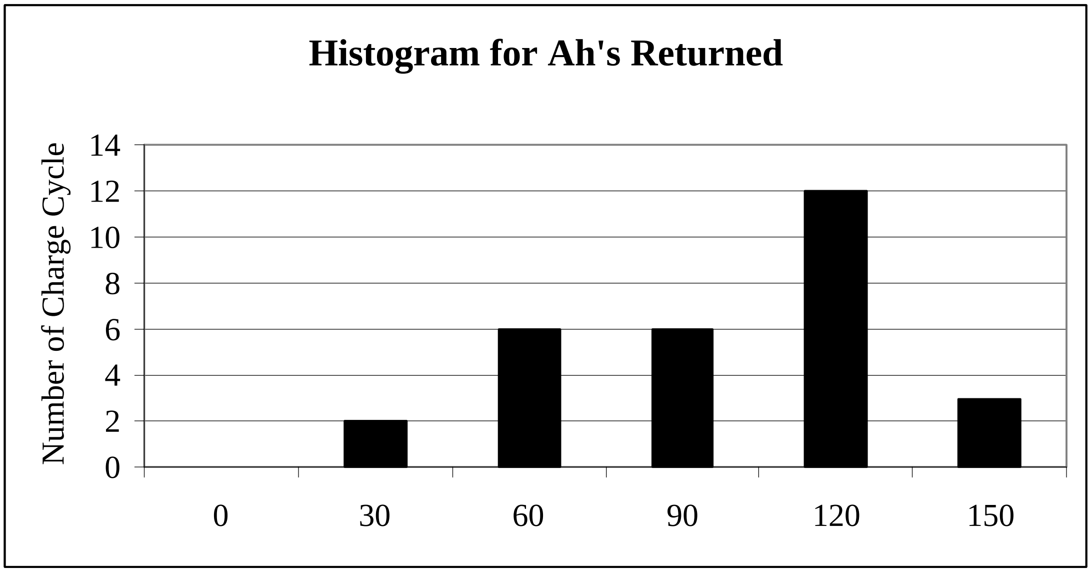


Figure 7. Histogram for Recharge Capacity

Table 4 shows that recharge time during the observed period was a minimum of 2.53 minutes and maximum of 43.27 minutes. Figure 8 shows the variations in recharge times during the sampling period.

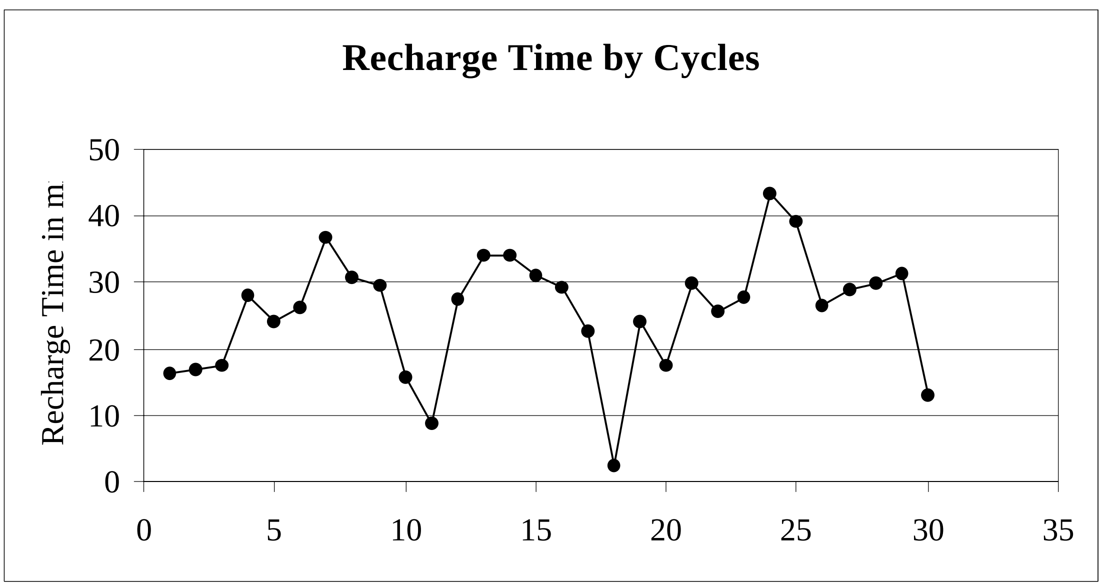


Figure 8. Variation of Recharge Time and Charge Cycles

When a trend line is applied, it indicates that during the sampling period recharge times increased at the rate of ~ 0.2 minutes per charge cycle. See Figure 9.

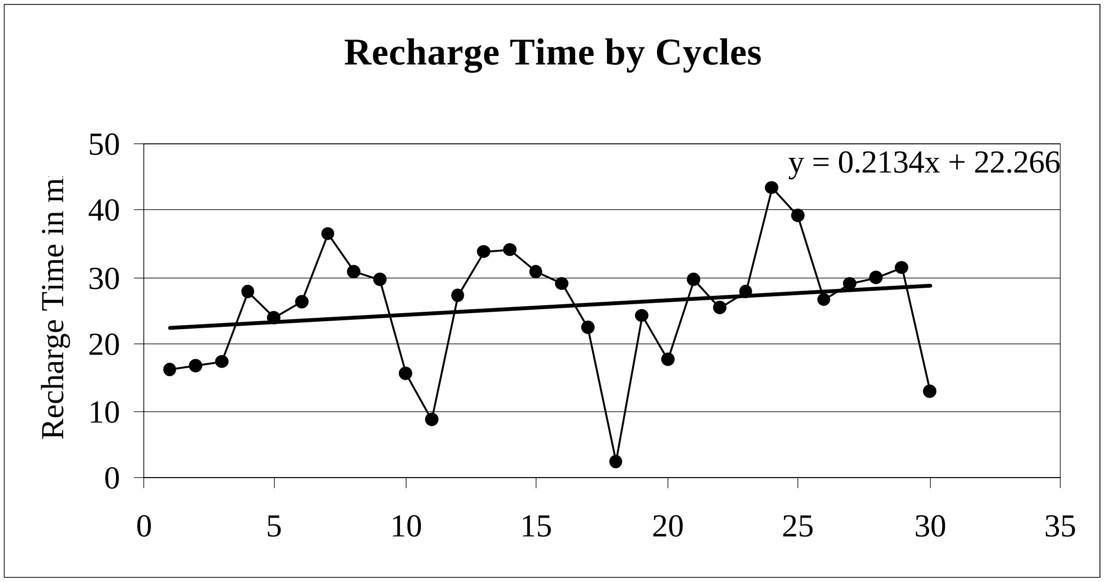


Figure 9. Trend Line for Recharge Time

A Histogram for recharge times shows that the typical recharge time was between 25 and 35 minutes. See Figure 10.

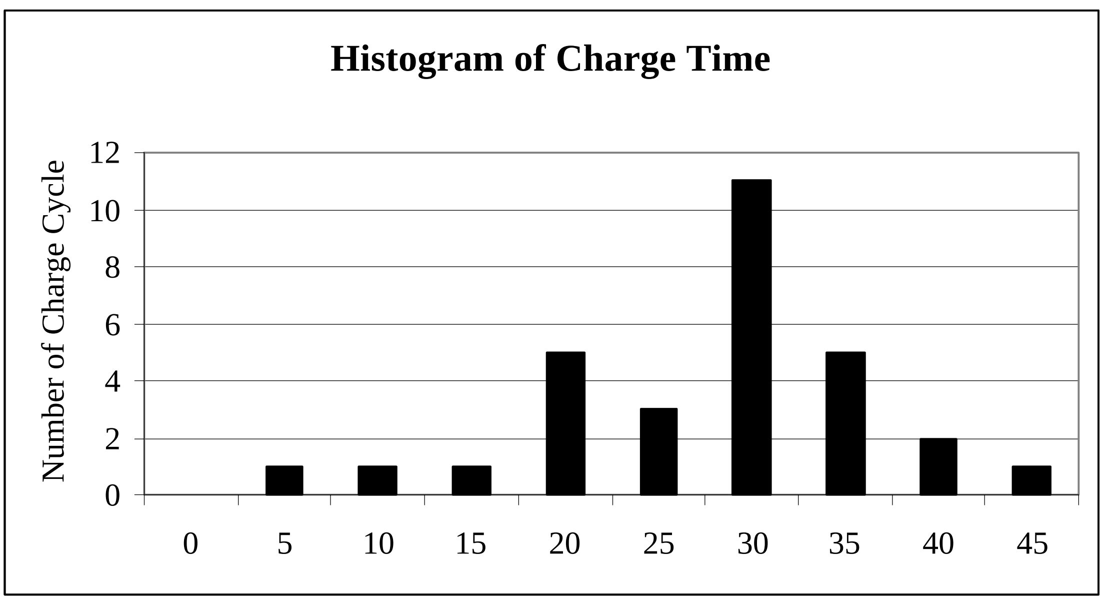


Figure 10. Histogram for Recharge Time

Histograms for recharge current and pre-charge battery pack voltage[1] are given in Figures 11 and 12. Figure 11 shows recharge current. Figure 12 shows the pre-charge battery voltage.

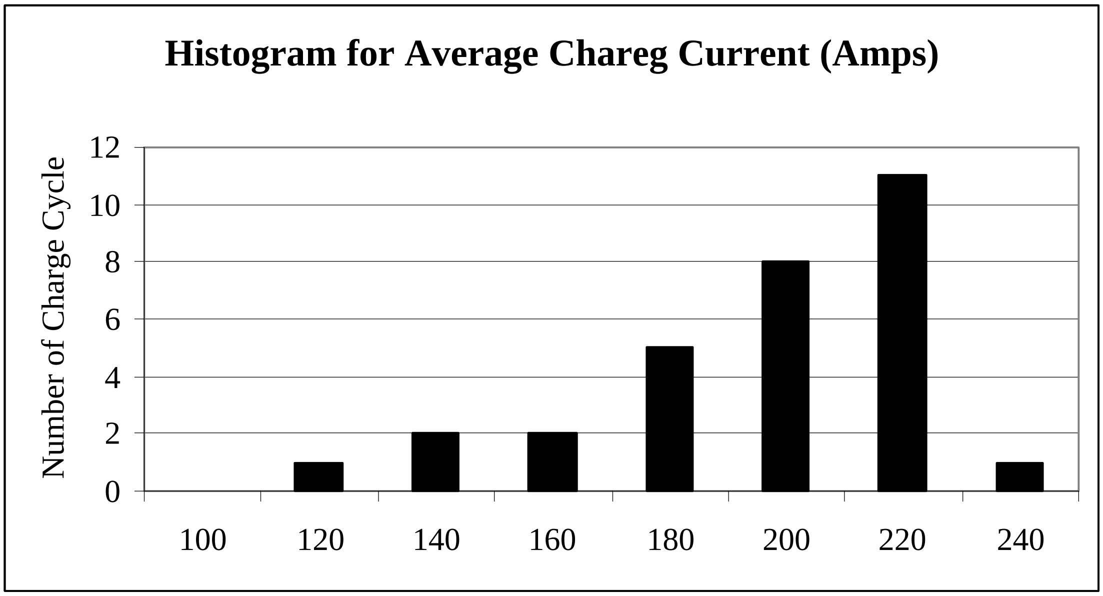


Figure 11. Histogram for Recharge Current

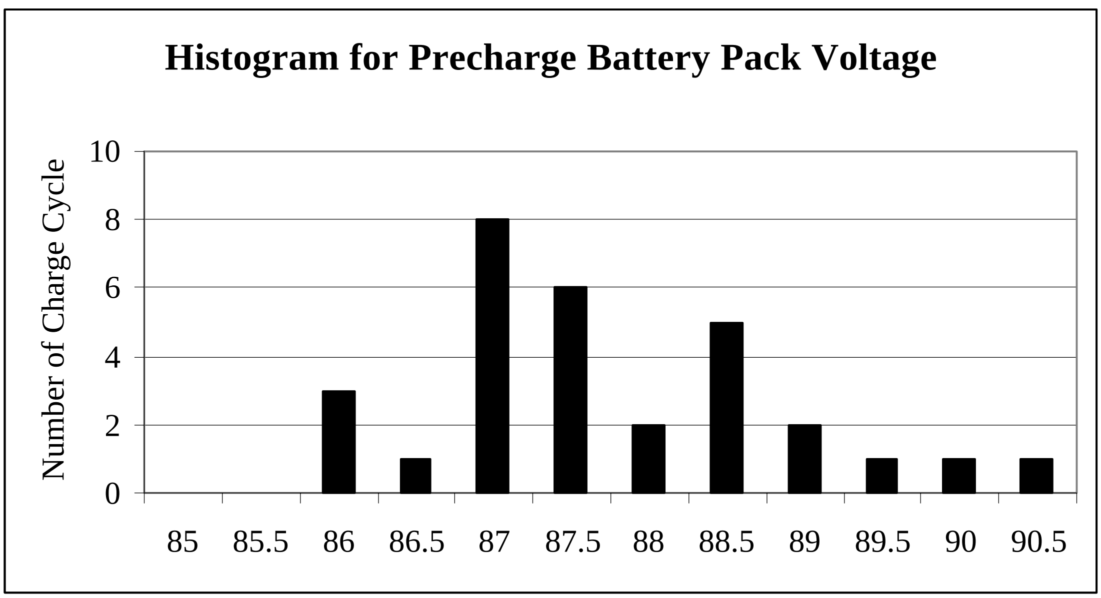


Figure 12. Histogram for Pre-charge Battery Pack Voltage

[1] Pre-charge battery pack voltage is the battery voltage seen by the charger immediately prior to the commencement of charging current flow.

DISCHARGE SUMMARY DATA

During the observed period there was large number of drive cycles every day. For each day the average data were calculated. Rows with n/a indicate no data were collected that day. These data are presented in Table 5.

TABLE 5

Date	# of Cycles	Cycle Duration (min)	Ah's USED Ah	Ah's RET Ah	Ah's NET Ah	I_{max} USED Amps	I_{max} RET Amps	I_{max} NET Amps	I_{avg} USED Amps	I_{avg} RET Amps	I_{avg} NET Amps	Time Between (min)
1-Sep	1	9.0	14.4	1.1	13.3	400.0	238.0	400.0	105.7	72.6	102.5	1431.0
5-Sep	7	19.7	7.8	1.4	6.5	366.9	150.4	366.9	20.6	58.1	21.9	184.0
6-Sep	24	12.7	13.1	2.3	10.8	476.2	212.8	476.2	82.2	91.5	81.3	42.9
7-Sep	25	7.1	7.9	1.1	6.8	472.5	157.1	472.5	78.8	85.3	81.8	47.8
8-Sep	28	10.0	9.6	1.4	8.2	511.0	169.0	511.0	79.0	76.0	78.0	39.0
9-Sep	39	8.2	8.5	1.2	7.3	498.0	162.3	498.0	91.0	75.3	88.0	27.2
10-Sep	29	4.4	6.2	0.8	5.4	452.1	161.9	452.3	95.2	82.4	93.2	43.1
11-Sep	14	6.1	7.2	0.7	6.5	518.2	153.6	518.2	105.1	78.5	99.8	94.7
12-Sep	7	3.5	4.471	0.5	4.0	435.7	137.7	435.7	82.61	72.06	81.2	199.0
13-Sep	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14-Sep	18	3.7	4.5	0.6	3.9	424.7	130.8	424.7	86.7	58.6	81.6	74.8
15-Sep	20	6.9	7.7	0.9	6.9	451.3	166.3	451.3	88.2	69.2	84.9	62.7
16-Sep	18	8.7	9.8	1.5	8.4	485.2	182.2	490.3	99.2	90.4	99.9	68.3
17-Sep	21	3.5	5.1	0.7	4.5	468.5	156.4	468.5	111.4	79.0	104.8	65.1
18-Sep	19	4.0	3.2	0.2	3.0	362.0	96.2	369.7	53.5	45.9	55.5	69.5
19-Sep	17	6.6	6.9	0.9	6.0	526.2	157.5	526.2	101.0	79.2	97.4	78.5
20-Sep	17	6.5	6.4	0.7	5.7	456.9	122.9	456.9	93.0	59.1	88.3	75.9
21-Sep	20	9.2	9.6	1.5	8.1	498.4	157.1	503.6	100.9	82.4	96.3	60.0
22-Sep	11	4.0	4.6	0.5	4.2	448.0	139.7	454.1	85.2	69.7	79.3	124.2
23-Sep	18	4.4	3.8	0.9	5.4	6.2	156.2	454.4	444.7	75.8	94.9	73.8
24-Sep	5	6.6	9.1	0.9	8.4	427.0	142.0	444.8	80.1	82.3	92.2	278.9

****

Table 5 shows that during the observed time interval, there were few days with no data collected (sep 1, 2, 3, 4). For every other day, data on the table are average values. The second column in Table 5 contains the number of drive cycles for that day. The number of drive cycles per day varies from 1 cycle to 39 cycles, which is shown graphically in Figure 13. The graph shows that number of drive cycles over the observed period stays almost constant.

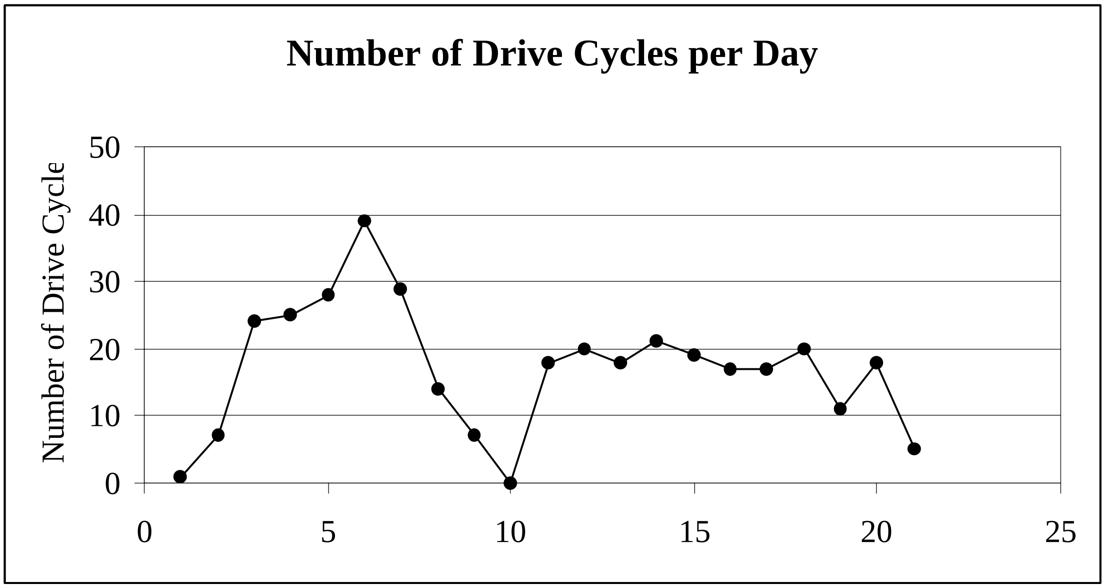


Figure 13. Number of Drive Cycles over the Observed Period

Drive Cycles per Day

Figure 14 shows that the number of drive cycles decreased at the rate of ~ 0.2 drive cycles per day. Trend line also shows that over the data collection period, the average number of drive cycles was decreased, from 19 drive cycles per day at the beginning to 16 drive cycles per day.

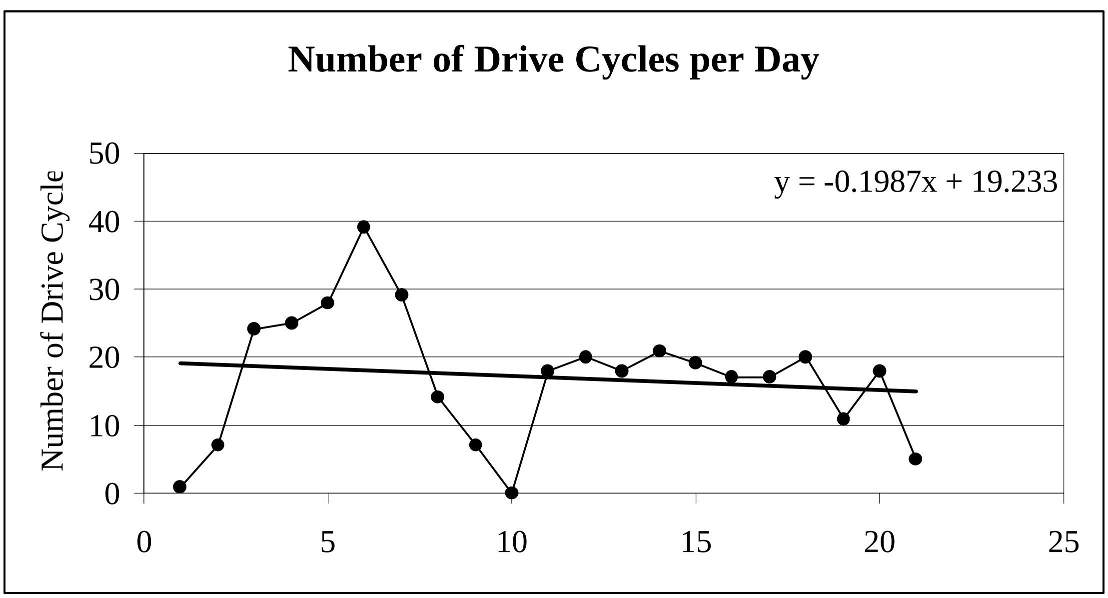


Figure 14. Trend Line for the Number of Drive Cycles

Figure 15 contains a Histogram showing the distribution of the number of drive cycles per day. These data shows that in eight days there was 20 drive cycles.

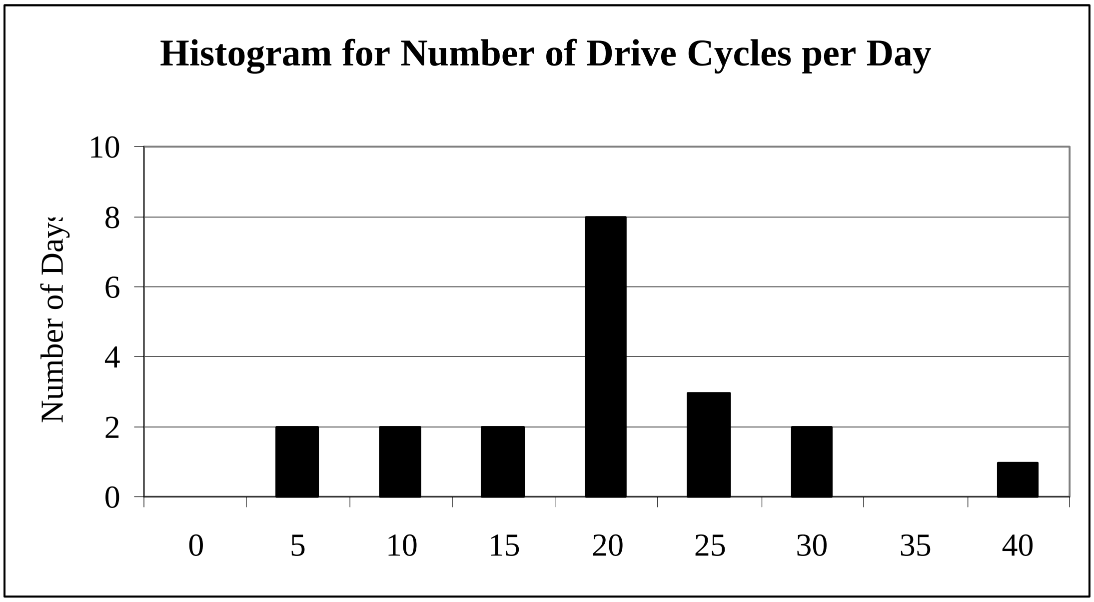


Figure 15. Histogram for the Number of Drive Cycles per Day

Average Drive Cycle Duration

The third column in Table 5 shows the average duration of drive cycles per day. This average varies from a low of 3.5 minutes to a high of 19.7 minutes, and is shown graphically in Figure 16. Graph shows a gradual decrease in the number of drive cycles over the observed period. Figure 17 shows that the number of drive cycles decreased at the rate of 0.3 minutes per day. A trend line shows that the average duration of daily drive cycles decreased for over 50 % for the observed period: from just under 10 minutes per drive cycle at the beginning to under 4 minutes per drive cycles by the end of observed period.

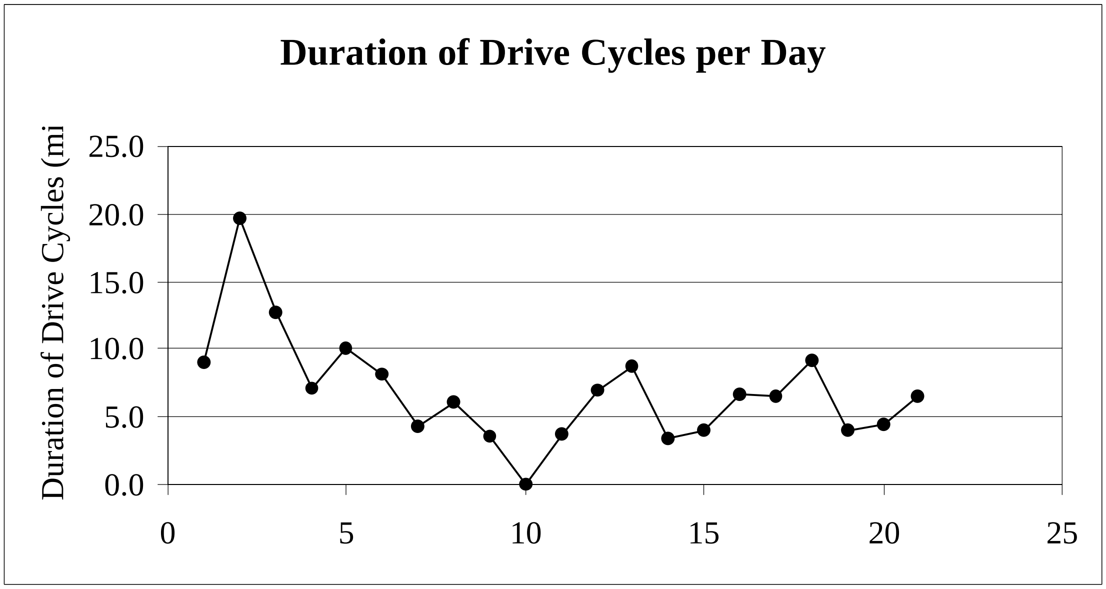


Figure 16. Average Duration of Drive Cycles per Day

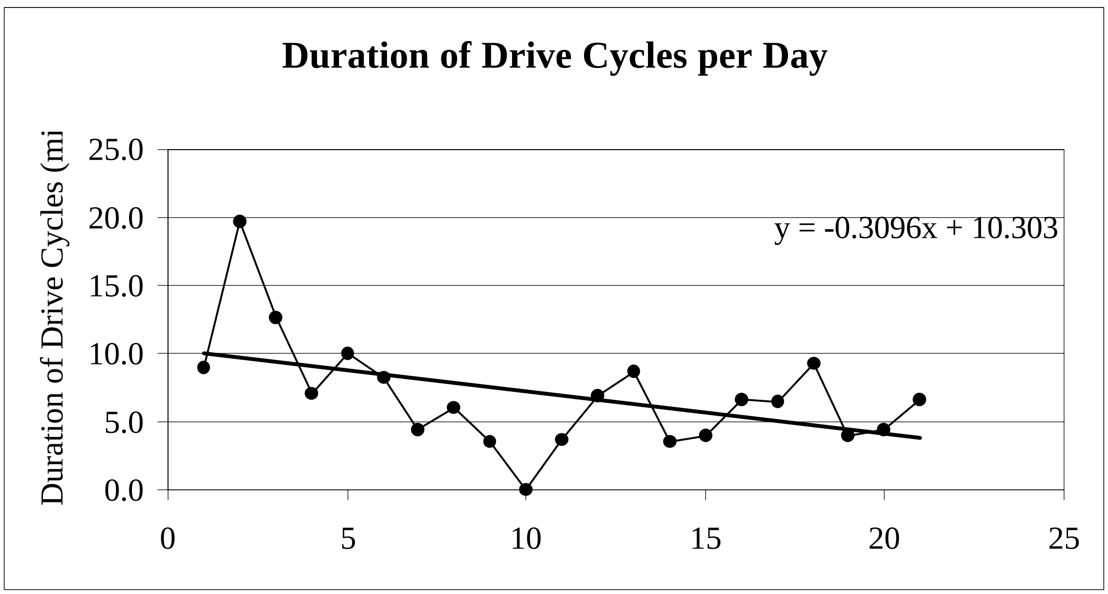


Figure 17. Trend line for Average Duration of Drive Cycles per Day

A Histogram for Drive Cycle duration shows that while most drive cycles were between 2 and 7 minutes in duration, the majority of drive cycles had a duration of 4 minutes.

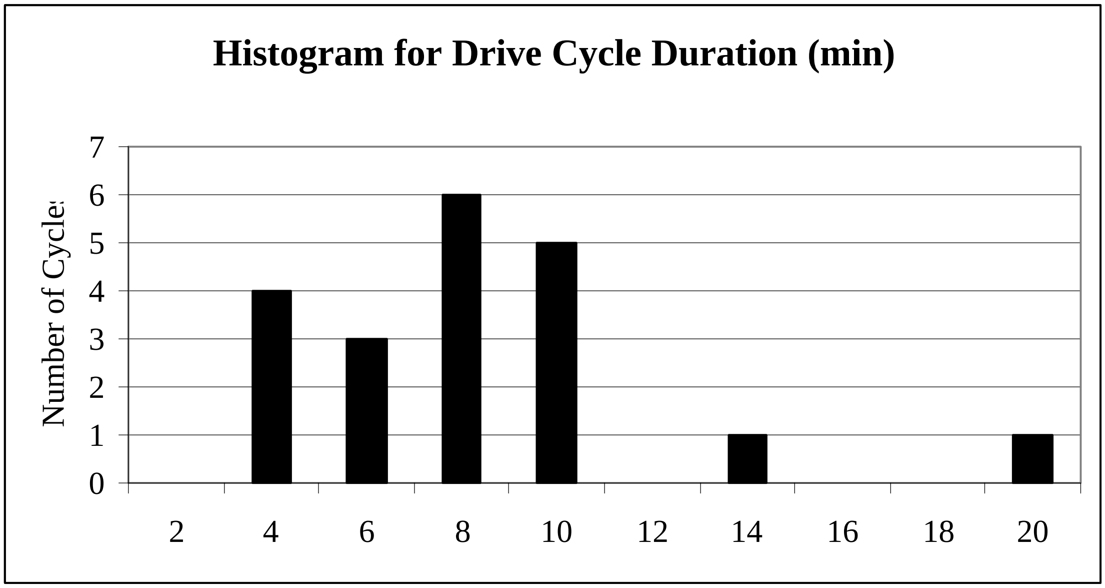


Figure 18. Histogram for Drive Cycle Duration

The last column in the Table 5 shows the average time between drive cycles each day. The averages, which vary from a low of 27.2 minutes to a maximum of 1431 minutes, are given in Figure 19. The graph shows a gradual decrease in the average number of drive cycles over the observed period. This is mostly due to the first data point in the range that is large out of order.

To better evaluate the data without the deleterious effects of skewing from one extremely large data point, the point was removed from the data set, and the graph recast. The results are contained in Figures 21 and 22.

Average Time Between Drive Cycles – Unmodified

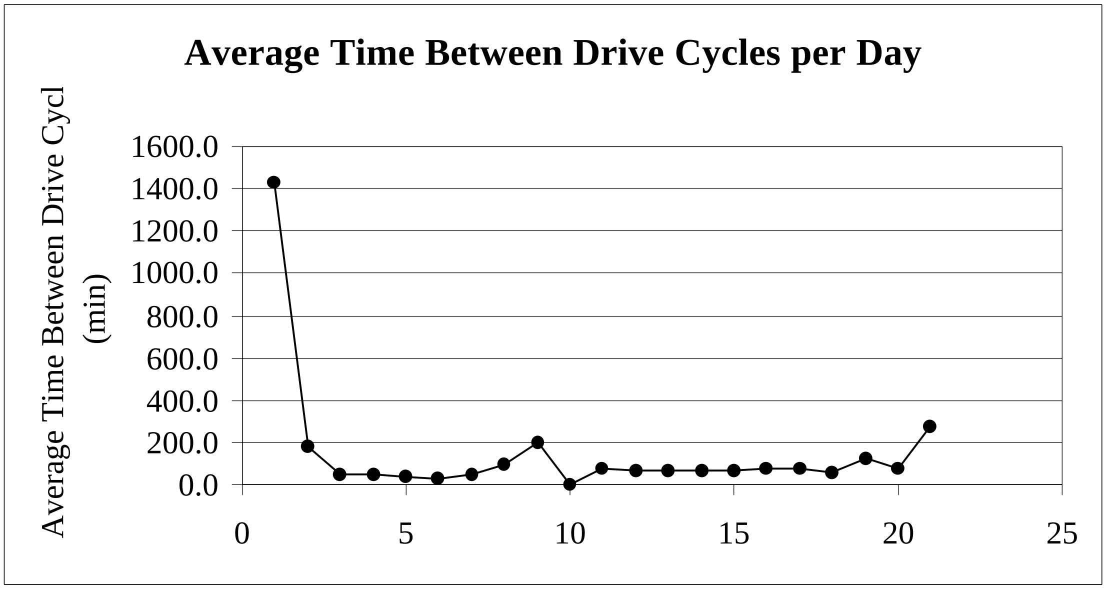


Figure 19. Average time between drive cycles per day over the observed period

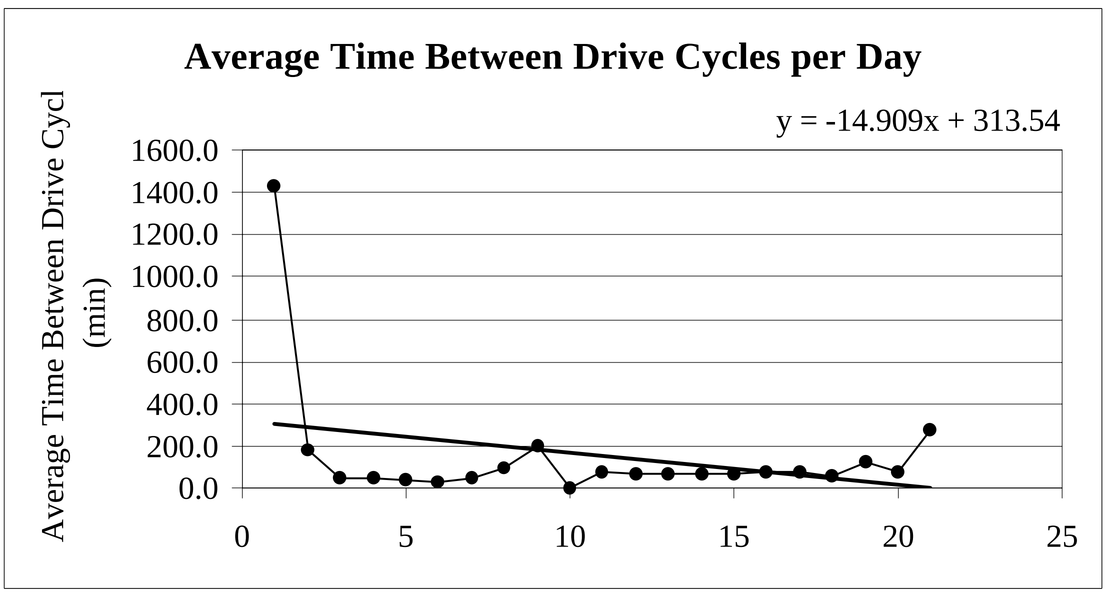


Figure 20. Trend line for average time between drive cycles per day

Modified Average Drive Cycles

When the first point is ignored, the trend line for time between two drive cycles is given on Figure 21. Same data along with a trend line are shown in Figure 22.

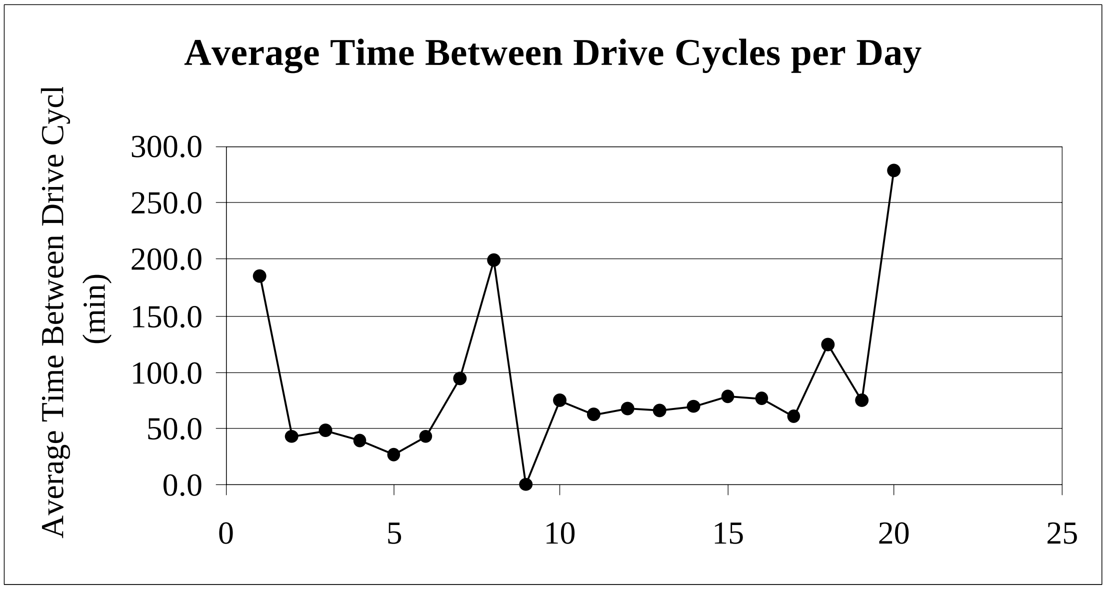


Figure 21. Trend Line for Time Between Drive cycles

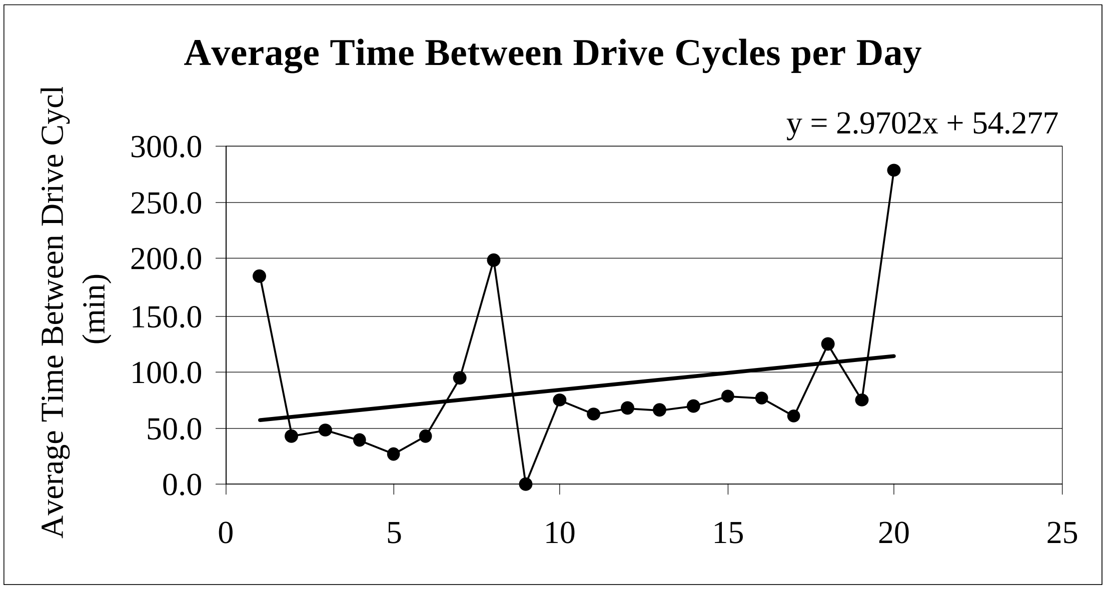


Figure 22. Trend Line for Time Between Drive cycles

Trend line on Figure 22 shows that average time between two drive cycles increases at the rate of 3 minutes per day. This can be attributed to the fact of decreased number of drive cycles during the observed period.

A histogram for the time between two drive cycles, shown in Figure 23, indicates that the majority of time, the time between drive cycles was between 60 minutes and 100 minutes.

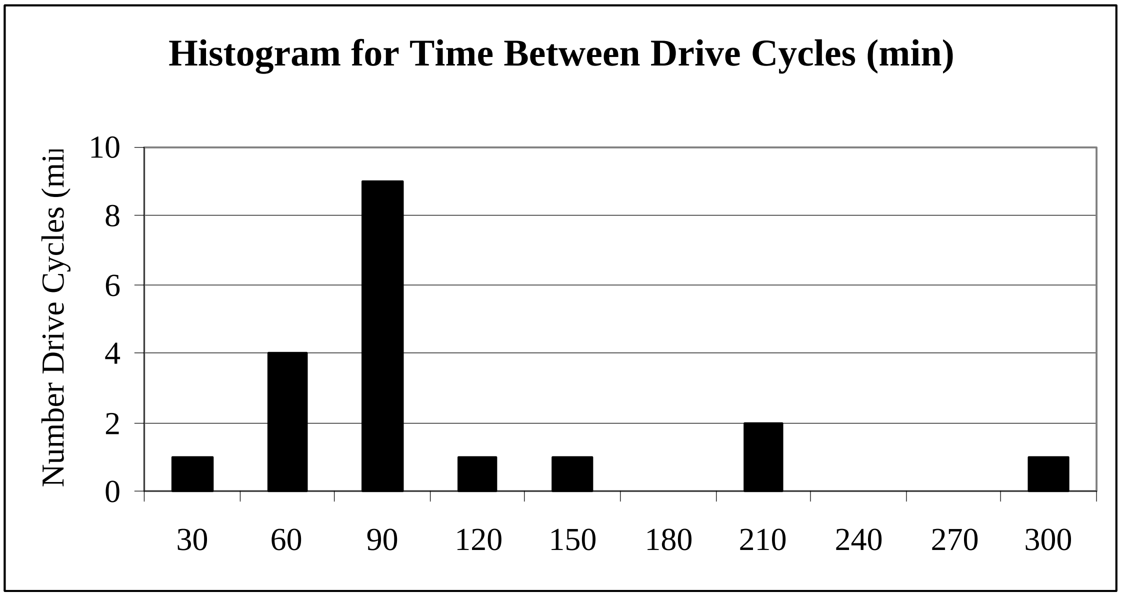


Figure 23. Histogram for Time Between two Drive Cycles

Ampere-Hours (Ah) per Drive Cycle

The sixth column in the Table 5 gives the net average Ah's used in a drive cycles per day. The average varied from a low of 3.0 Ah to a maximum of 19.7 Ah and is shown in Figure 24. The graph shows a gradual decrease in Ah's used per cycle per day over the observed period. Figure 25 shows that the average Ah's used decreased at the rate of ~ 0.16 Ah per drive cycle per day. A trend line also shows that the average Ah used per drive cycle decreased from 8 Ah to under 5 Ah.

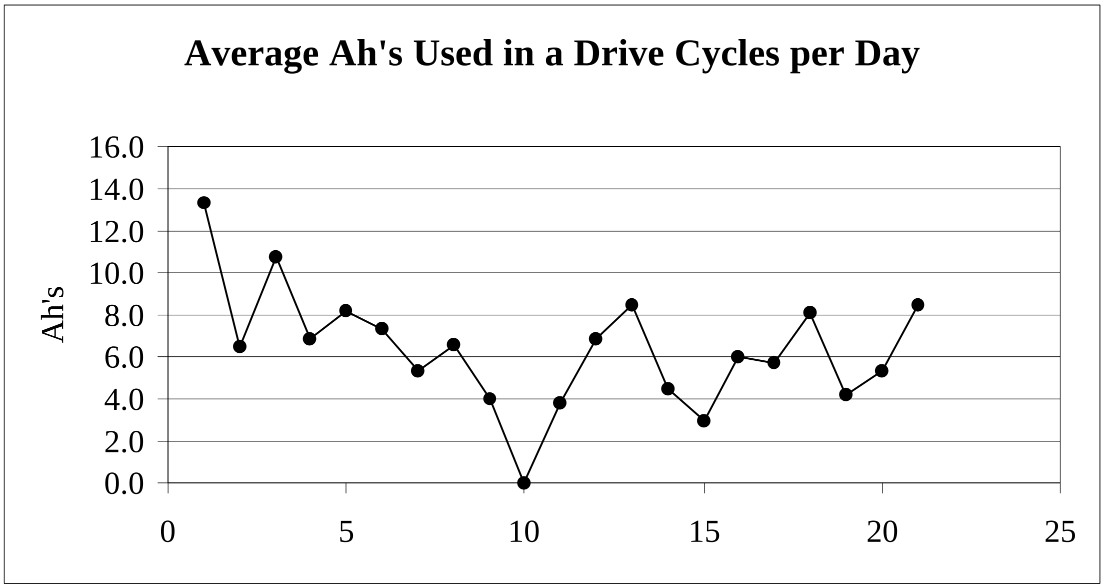


Figure 24. Average Ah's Used in a Drive Cycle per Day

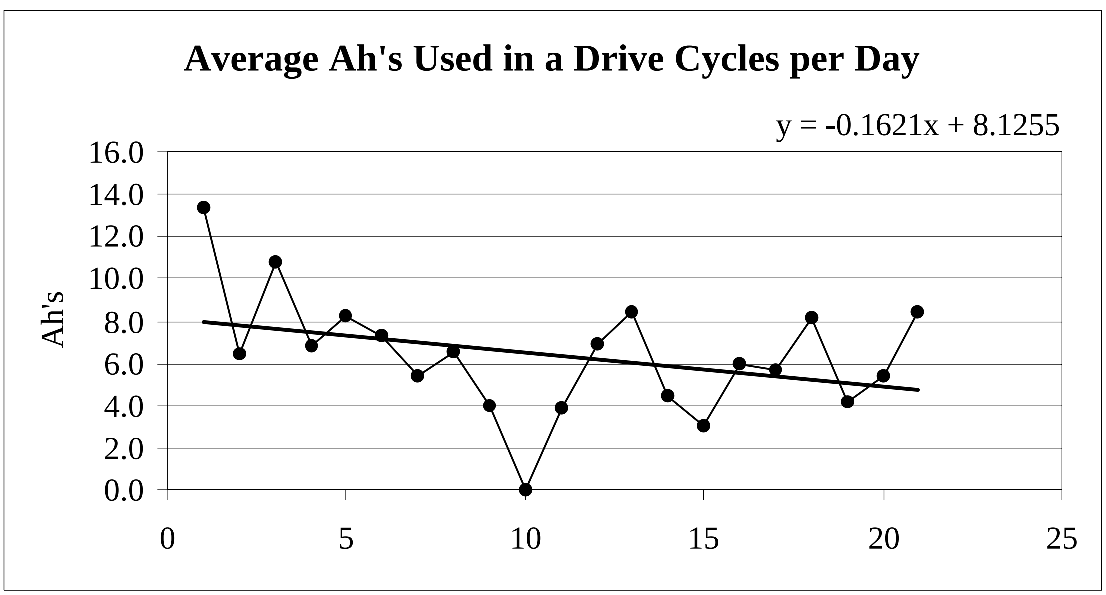


Figure 25. Trend Line for Average Ah's Used in a Drive Cycle per Day

Figure 26 is a Histogram for Ah's used per drive cycle, and shows that the typical drive cycle used between 6 Ah and 8 Ah.

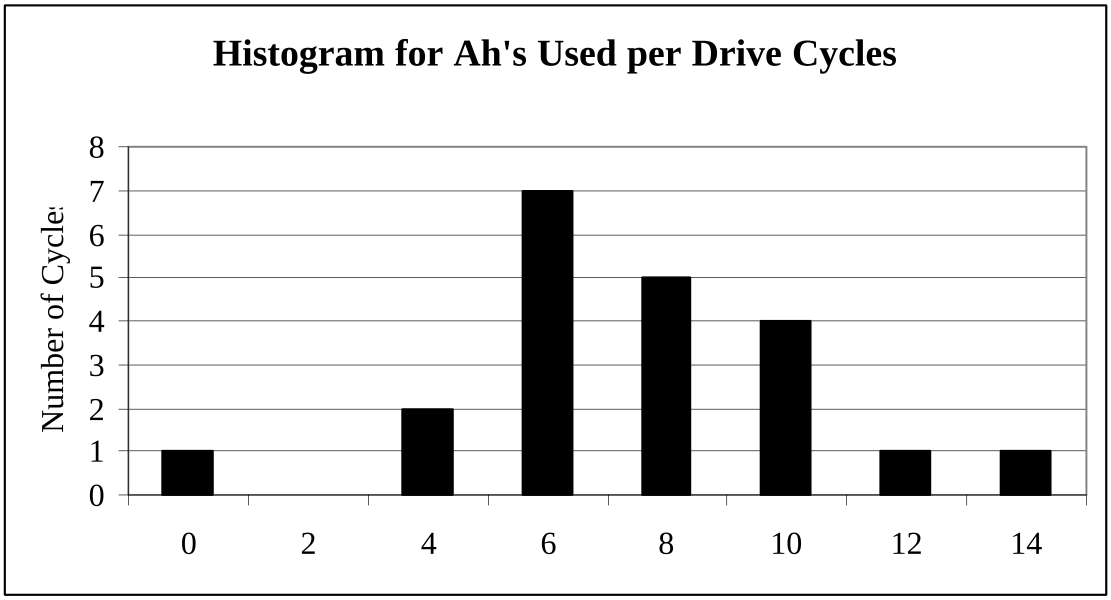


Figure 26. Histogram for Ah's Used

AVERAGE CHARGE AND DISCHARGE DATA FOR SEPTEMBER

The average values for the charge and discharge cycles were determined for the entire observed period. Table 6 shows average charge data, while Table 7 shows average discharge data.

TABLE 6

Charge Time	Average Current	Capacity In	$V_{INITIAL}$	V_{FINAL}	$V_{INITIAL} - V_{FINAL}$	$T_{INITIAL}$	T_{FINAL}	$T_{INITIAL} - T_{FINAL}$
min	Amps	Ah	Volts	Volts	Volts	^oC	^oC	^oC
25.57	187.98	83.08	87.47	100.10	11.60	30.78	35.84	5.07

TABLE 7

Average Number of Cycles per Day	Average Duration of Cycle	Average Ampere-hours used per Cycle	Average Time Between Cycles	Average Current for Cycle
	minutes	Ah	minutes	Amps
18	7.2	6.7	90.0	85.1

CONCLUSION

Based upon these averages, the average tractor can expect a normal discharge per day of approximately 101 Ah, or approximately 28% of it's available battery capacity. The vehicles used in this project were outfitted with discharge limit devices to prevent discharging the battery below 30% of nominal capacity. Therefore, the tractor will consume approximately 40% of its rated capacity per day. However, the SuperCharge only charges the battery to ~80% State of Charge. This reduces the available energy to 50% (80% of nominal capacity – 30% lower SOC lower Limit). If the tractor consumes ~101 Ah per day, this equates to ~56% available capacity per day. This means the tractor could theoretically operate for almost two full days between charges.

APPENDIX Q

MX4 Energy Usage Monthly Summaries

MX4 DRIVE CYCLE DATA - SEPTEMBER 2001

DRIVE CYCLES		NET ENERGY OUT (Gross-Regen)				ENERGY RETURNED BY REGEN				GROSS ENERGY OUT			
Date	Cycles	Duration	Ah	Imax	Iavg	Duration	Ah	Imax	Iavg	Duration	Ah	Imax	Iavg
		min	Ah	Amps	Amps	min	Ah	Amps	Amps	min	Ah	Amps	Amps
1-Sep-01	1	9.03	13.34	400.00	102.52	0.87	1.05	238.00	72.58	8.17	14.39	400.00	105.70
2-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
3-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
4-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
5-Sep-01	7	19.75	6.47	366.86	21.92	0.83	1.37	150.43	58.07	18.92	7.83	366.86	20.60
6-Sep-01	24	12.67	10.79	476.24	81.29	1.19	2.32	212.84	91.49	11.48	13.11	476.24	82.18
7-Sep-01	23	7.66	6.84	472.52	81.78	0.85	1.10	157.13	69.20	6.81	7.94	472.52	85.29
8-Sep-01	28	10.01	8.21	511.00	77.99	1.05	1.36	169.00	75.98	8.96	9.58	511.00	79.02
9-Sep-01	39	8.18	7.33	498.03	87.96	0.94	1.19	162.26	75.26	7.24	8.52	498.03	91.01
10-Sep-01	29	4.36	5.35	452.28	93.24	0.55	0.80	161.86	82.44	3.80	6.15	452.14	95.15
11-Sep-01	14	6.10	6.52	518.21	99.83	0.55	0.65	153.64	78.46	5.55	7.18	518.21	105.05
12-Sep-01	7	3.49	4.00	435.71	81.25	0.35	0.47	137.71	72.06	3.13	4.47	435.71	82.61
13-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
14-Sep-01	18	3.69	3.86	424.72	81.59	0.56	0.65	130.83	58.61	3.13	4.50	424.72	86.74
15-Sep-01	20	6.93	6.88	451.30	84.93	0.72	0.87	166.30	69.21	6.22	7.74	451.30	88.18
16-Sep-01	18	8.74	8.43	490.28	99.93	1.00	1.47	182.22	90.38	7.74	9.85	485.22	99.21
17-Sep-01	21	3.47	4.45	468.48	104.81	0.51	0.69	156.38	78.99	2.96	5.14	468.48	111.38
18-Sep-01	19	4.04	2.99	369.68	55.55	0.30	0.23	96.21	45.88	3.74	3.18	362.00	53.50
19-Sep-01	17	6.63	5.98	526.18	97.40	0.64	0.90	157.47	79.21	5.99	6.88	526.18	100.98
20-Sep-01	17	6.49	5.67	456.88	88.34	0.66	0.72	122.88	59.15	5.83	6.39	456.88	92.96
21-Sep-01	20	9.21	8.13	503.60	96.26	1.08	1.52	157.10	82.40	8.12	9.56	498.35	100.93
22-Sep-01	11	3.97	4.16	454.09	79.30	0.38	0.48	139.73	69.70	3.58	4.63	448.00	85.16
23-Sep-01	18	4.42	5.36	454.39	94.86	0.65	0.89	156.22	75.81	3.76	6.15	444.67	94.47
24-Sep-01	5	6.55	8.45	444.80	92.23	0.66	0.93	142.00	82.29	5.89	9.11	427.00	80.15
25-Sep-01	32	3.24	3.85	388.32	82.23	0.38	0.53	123.65	66.17	2.86	4.38	388.32	85.05
26-Sep-01	22	3.60	4.43	462.14	93.15	0.46	0.56	147.71	68.28	3.14	5.00	462.14	99.88
27-Sep-01	8	2.97	3.08	505.71	97.77	0.40	0.50	137.43	79.91	2.57	3.58	505.71	103.21
28-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
29-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
30-Sep-01	0	-	-	-	-	-	-	-	-	-	-	-	-
Total Cycles	**418**												
Cycle Averages		**6.75**	**6.29**	**457.89**	**85.92**	**0.68**	**0.92**	**154.74**	**73.11**	**6.07**	**7.19**	**455.64**	**88.19**

MX4 DRIVE CYCLE DATA - SEPTEMBER 2001

DRIVE CYCLES		NET ENERGY OUT (Gross-Regen)				ENERGY RETURNED BY REGEN				GROSS ENERGY OUT			
Date	Cycles	Duration	Ah	Imax	Iavg	Duration	Ah	Imax	Iavg	Duration	Ah	Imax	Iavg
		min	Ah	Amps	Amps	min	Ah	Amps	Amps	min	Ah	Amps	Amps
30-Oct-01	30	2.22	3.63	514.50	130.15	0.29	0.43	164.77	95.14	1.93	4.06	514.50	137.10
31-Oct-01	8	0.90	1.14	316.25	89.65	0.10	0.11	72.50	50.78	0.80	1.25	314.63	96.29
1-Nov-01	8	3.60	3.94	396.75	80.32	0.29	0.30	106.00	43.70	3.31	4.24	396.75	83.88
2-Nov-01	28	6.35	4.98	434.07	81.88	0.68	0.99	153.75	76.72	5.67	5.97	434.07	82.87
3-Nov-01	12	3.99	3.65	406.08	71.43	0.39	0.32	123.92	56.08	3.60	3.97	406.08	73.82
4-Nov-01	27	8.42	7.94	491.11	97.83	0.85	1.12	156.96	77.13	7.50	9.06	491.11	101.31
5-Nov-01	17	6.59	6.89	397.41	74.84	0.88	1.15	141.00	66.56	5.72	7.69	389.12	70.62
6-Nov-01	25	5.59	6.64	503.52	103.90	0.57	0.83	161.00	84.82	5.02	7.47	503.52	106.93
7-Nov-01	14	5.73	6.94	364.71	62.65	0.56	0.63	91.36	43.00	5.17	7.57	364.71	65.61
8-Nov-01	20	4.40	5.25	342.10	65.29	0.35	0.35	93.35	42.95	4.04	5.60	338.90	65.90
9-Nov-01	32	5.44	5.42	427.28	76.54	0.52	0.65	121.19	58.34	4.92	6.07	427.28	79.49
10-Nov-01	15	5.47	6.998	488.67	105.00	0.70	0.83	150.73	69.32	4.77	7.83	488.67	111.12
11-Nov-01	22	6.36	6.75	453.36	88.40	0.66	0.74	150.27	69.63	5.70	7.49	453.36	91.62
12-Nov-01	21	5.16	7.66	478.00	106.55	0.52	0.74	159.76	80.36	4.63	8.40	478.00	109.49
13-Nov-01	30	3.53	3.77	476.37	93.57	0.41	0.47	133.63	65.86	3.12	4.24	476.37	99.10
14-Nov-01	25	5.14	3.99	417.36	84.51	0.47	0.55	112.56	62.46	4.67	4.53	417.36	88.35
15-Nov-01	22	3.94	3.31	282.55	64.26	0.43	0.38	87.23	42.13	3.51	3.70	282.55	68.22
16-Nov-01	20	7.04	8.69	480.45	108.33	0.94	1.30	177.65	83.63	6.10	9.99	480.45	112.87
17-Nov-01	19	4.93	4.33	432.00	86.49	0.31	0.37	102.79	58.22	4.62	4.70	432.00	89.95
18-Nov-01	18	4.90	5.52	472.06	94.33	0.62	0.77	151.78	69.23	4.28	6.29	472.06	98.41
19-Nov-01	5	2.32	2.11	292.80	57.17	0.31	0.26	60.60	33.95	2.01	2.04	271.40	43.60
20-Nov-01	20	6.47	5.66	358.65	67.68	0.51	0.48	99.05	46.03	5.95	6.09	354.15	66.50
21-Nov-01	14	8.05	7.50	455.36	85.36	0.59	0.67	138.93	65.90	7.46	8.17	455.36	87.70
22-Nov-01	23	4.81	5.57	471.65	99.98	0.67	0.93	150.48	79.42	4.14	6.49	471.65	103.64
23-Nov-01	29	5.00	4.72	440.93	80.94	0.40	0.40	119.62	56.88	4.60	5.13	440.93	84.01
24-Nov-01	21	6.09	4.68	404.00	66.24	0.41	0.46	116.52	53.19	5.68	5.14	404.00	68.08
25-Nov-01	21	3.39	3.07	355.81	71.99	0.33	0.42	106.71	59.39	3.05	3.35	346.67	66.47
26-Nov-01	10	2.94	1.54	309.90	71.63	0.20	0.20	73.20	44.01	2.74	1.47	290.30	60.12
27-Nov-01	18	8.01	9.04	464.67	90.40	0.80	0.96	154.39	66.86	7.21	9.93	459.72	89.55
28-Nov-01	22	7.20	7.91	506.68	92.38	0.94	1.57	159.05	77.50	6.26	8.75	506.68	94.86
29-Nov-01	18	3.98	5.56	475.17	106.00	0.50	0.66	136.22	71.87	3.48	6.23	473.72	111.23
30-Nov-01	28	3.45	4.27	491.68	98.26	0.44	0.56	145.82	79.82	3.01	4.83	491.68	102.25
Total Cycles	**642**												
Cycle Averages		**5.04**	**5.28**	**425.06**	**86.06**	**0.52**	**0.64**	**127.27**	**63.47**	**4.52**	**5.87**	**422.74**	**87.84**