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Revision 0

Electric Ground Support Equipment Advanced Battery Technology Demonstration Project at the Ontario Airport

July 2013

Idaho National Laboratory

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ACRONYMS

BIM	battery identifier module
BMS	battery management system
CAN	controller area network
eGSE	electric ground support equipment
FLA	flooded lead-acid
GSE	ground support equipment
MS SQL	Microsoft Structured Query Language
ONT	Ontario International Airport
SWA	Southwest Airlines
TUG	Tug Technologies Corporation
V	volt
VCU	vehicle control unit

Electric Ground Support Equipment Advanced Battery Technology Demonstration Project at the Ontario Airport

1. INTRODUCTION

The intent of the electric Ground Support Equipment (eGSE) demonstration is to evaluate the day-to-day vehicle performance of electric baggage tractors using two advanced battery technologies to demonstrate possible replacements for the flooded lead-acid (FLA) batteries utilized throughout the industry. These advanced battery technologies have the potential to resolve barriers to the widespread adoption of eGSE deployment. Validation testing previously had not been performed within fleet operations to determine if the performance of current advanced batteries is sufficient to withstand the duty cycle of electric baggage tractors.

This report summarizes the work performed and data accumulated during this demonstration in an effort to validate the capabilities of advanced battery technologies. The demonstration project also established a relationship with Southwest Airlines (SWA), our demonstration partner at Ontario International Airport (ONT), located in Ontario, California. The results of this study have encouraged a proposal for a future demonstration project with SWA.

2. OVERVIEW

2.1 Demonstration Partner

To complete the objective of this demonstration, baggage tractors equipped with advanced battery technologies had to be routinely operated within an airport baggage tractor fleet. A demonstration partnership was established with SWA, allowing for utilization of four of SWA's airport baggage tractors within one airport operations fleet. SWA has operations in 76 cities within the United States and manages a large fleet of eGSE, including, but not limited to, electric baggage tractors and electric pushback tractors. The airport operation selected for this demonstration was ONT located in Ontario, California. ONT was selected due to SWA having previous experience with eGSE at this airport with an all-electric baggage tractor fleet. SWA also has been involved in similar projects with integration of advanced battery chemistries into eGSE. The temperate weather of Southern California also was considered favorable in that it would not impose harsh conditions on the test batteries. All coordination for demonstration-related items was with John Salter, Reliability Analyst for GSE at SWA, and Tony DiLuccia, Lead GSE Technician for SWA operations at ONT. No alterations to the fleet operations were made for the baggage tractors under test in order to allow for comparison with other GSE fleets.

3. ADVANCED BATTERY TECHNOLOGIES

The eGSE demonstration originally was intended to be performed with four baggage tractors powered by advanced battery technologies, two with an advanced lead-carbon battery developed by East Penn Manufacturing and two with a lithium-based battery developed from a battery manufacturer with current funding, in part, by a U.S. Department of Energy battery manufacturing contract. East Penn Manufacturing provided two Advanced Valve Regulated Lead Acid batteries for inclusion in the demonstration at ECOtality's request in July 2011. Unfortunately, due to the extensive delays in obtaining functional lithium-based batteries at the onset of this project, East Penn Manufacturing decided to focus its resources on more active projects and withdrew their batteries from participation in the project.Because of a lack of previously accumulated comparable data for FLA batteries, the lead-carbon chemistry intended for the demonstration was substituted with relatively new EnerSys DesertHog FLA batteries (see Figure 1). Data from the EnerSys batteries provide a baseline for the current battery chemistry, which will allow for more informative comparisons between current and future battery chemistries, including the lithium-based chemistry in this demonstration.

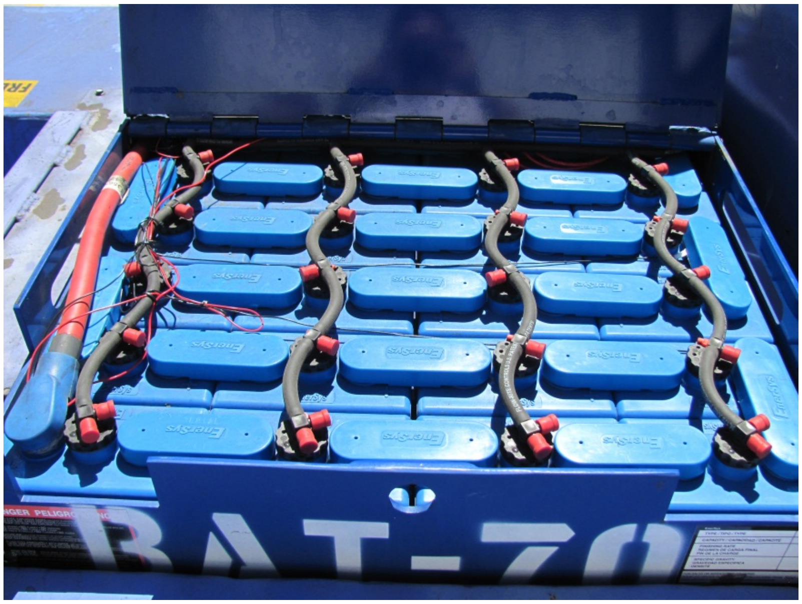

Figure 1. EnerSys DesertHog flooded lead-acid battery pack.

A request for proposal was created and sent to lithium-based chemistry battery manufacturers and integrators who expressed interest in this demonstration. The RFP also was posted online to allow for any qualified organization to submit a proposal. All submittals were subject to the same selection criteria, including, but not limited to, the following:

- Product availability
- Compatibility
- Cost
- Available technical support
- Current or future business interest in eGSE applications.

From these criteria, Corvus Energy Limited (Corvus) was chosen to supply the lithium-based battery pack. Corvus is a battery manufacturer that incorporates cells into packaged modules and engineers a battery management system (BMS) to safely control the batteries during discharge and charging. Corvus configured Dow Kokam's lithium-polymer pouch cells within a self-managed, heavy-duty battery module that can be configured to create a variety of pack voltages and energy capacities. Their modules are designed to meet automotive and other heavy-duty use applications. For this demonstration in an eGSE baggage tractor, Corvus created a prototype battery pack configured with three battery modules in parallel with a junction box and vehicle control unit (VCU). Each module contained 24 series-connected cells in order to allow for a similar voltage range as currently used within the baggage tractors. The three modules and junction box were placed in a structure that was specifically designed to fit the battery cavity of an airport baggage tractor (see Figure 2).

On August 10, 2011, Dow Kokam was awarded a grant of $4.9 million by the U.S. Department of Energy to assist in manufacturing and development of the large-format lithium-ion cells. This award fulfills this demonstration's requirement of using a lithium-based battery developed by a manufacturer with current funding by a U.S. Department of Energy battery manufacturing contract.

The specifications of the two study battery pack types are shown in Table 1. The differences in nominal specifications are due to the differences in the battery technology. The FLA battery suffers from the Peukert effect (also known as Peukert's Law), which states that as the rate of discharge increases, the available capacity decreases. In contrast, lithium battery chemistries have a negligible capacity loss with an increased discharge rate. This difference also is why the available capacity for the FLA battery is indicated at a 6-hour rate, while no such rate is specified for the lithium battery. Because of this key difference between the battery chemistries, the rated capacity and energy of the lithium battery pack can be lowered to approximately half of the rated capacity and energy of the FLA battery pack. Note that the FLA pack is five times heavier than the lithium pack due to the amount of lead utilized in the FLA chemistry. In the case of eGSE, however, less weight is not strictly an advantage because the baggage tractor design requires a designated weight to perform its daily operations. The weight difference was compensated through additional ballast for the lithium battery pack.

Figure 2. Corvus lithium battery pack, with a specifically designed container for airport baggage tractors.

Table 1. Specifications by Battery Chemistry.

Specification	Flooded Lead-Acid Battery Pack	Lithium Battery Pack
Battery Cell Manufacturer	EnerSys	Dow Kokam
Battery Pack Integrator	EnerSys	Corvus Energy Ltd
Battery Pack Model	DesertHog E125D-9	Prototype based on AT6500-125-96VSM modules
Cell Chemistry	Flooded lead-acid	Lithium NMC
Pack Manufactured Date(s)	October 2011 and April 2012	March 2012
Rated Pack Capacity (Ah)	500 at C_6	225
Rated Pack Energy (kWh)[a]	40 at C_6	19.5
Pack Configuration	40 cells in series	24 series cells connected in three parallel strings
Approximate Pack Weight	3,225 lb	500 lb

a. The discharge current rate for the Corvus lithium battery is not listed due to the minimal Peukert effect on the capacity of lithium-ion based batteries. In contrast, the discharge current rate is shown for the FLA batteries due to the apparent Peukert effect on their capacity.

4. CHARGER AND DATA RECORDING

4.1 Charger

Current eGSE batteries are ‘fast’ or ‘opportunity[a]’ charged to allow for the maximum amount of run time. They typically are off-board chargers that can output between 5 to 20 kilowatts of direct current power to directly charge the battery onboard the baggage tractor. For this demonstration, a charger of this type also had to include the capability of logging charge data and being network capable for remote access and data download. Commercially available eGSE chargers with these capabilities did not exist at the start of the project and had to be developed specifically for this demonstration.

The decision was made to upgrade a Minit-Charger GSE 250DP/hf (shown in Figure 3), with a new charger control card that would allow for the desired network and data logging capabilities while still maintaining its original functionality. To accomplish this upgrade, a new printed circuit-board was designed with greater non-volatile flash memory in the form of a secure digital card and Ethernet communication, in addition to any hardware and software previously needed for controlling and monitoring safety while charging. Use of a secure digital card to increase flash memory allowed for greater data storage capacity with easier accessibility. Ethernet communication protocol is the standard for interconnection of electronic devices and its inclusion allowed for direct and remote access to the charger control software. It provided a means to download data to a secure offsite Microsoft Structured Query Language (MS SQL) server through a cellular router. A cellular router was selected in place of a hard line or local wireless communication protocol in order to maintain a secure and independent network from airport communications. The cellular router used for the study was a Digi Transport WR44 enclosed in a NEMA outdoor-rated enclosure (shown in Figure 4). This cellular router contains an internal, four-port Ethernet switch, which provided a single solution to connect all four charging ports to one unit.

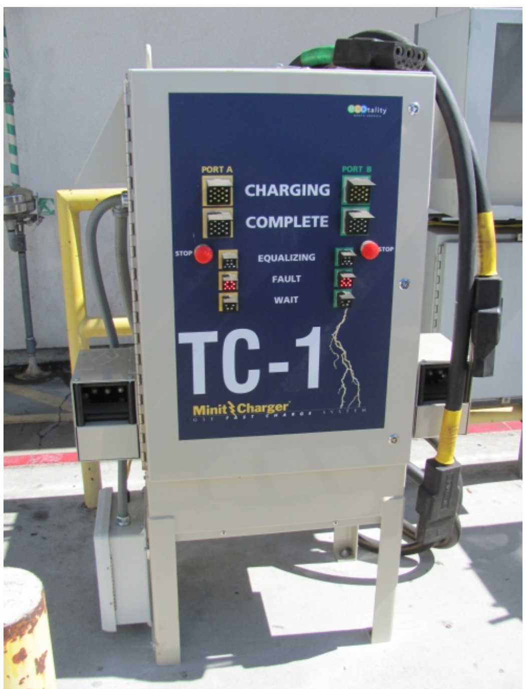

Figure 3. Minit-Charger GSE 250DP/hf with updated charger-controlled board.

a. An opportunity charge is any charge where the battery is only partially charged from the total rated capacity due to minimal baggage tractor down time and charger availability.

Figure 4. Digi Transport WR44 inside NEMA outdoor-rated enclosure.

Ultimately, two Minit-Charger GSE 250DP/hf units, with upgraded charge control cards, were allocated for this demonstration. Each unit contained two individual charging ports controlled by separate charge control circuit boards. This allowed for each port to be capable of independently and simultaneously delivering a maximum charge power up to 15 kilowatts or a maximum current of 250 amps within a voltage operating range of 18 to 120 volts direct current. For data collection and communications purposes, each of these ports were considered an individual charger because each charge control board collects unique charging data that were separately communicated to the data collection server. These four charge ports were referred to by a simple label of 'C0000001' to 'C0000004.'

4.2 Battery Identifier Module

The Battery Identifier Module (BIM) (Figure 5) was developed to help accomplish the main objective of this demonstration by containing hardware and software to perform the following four tasks:

1. Communicate with the charger.
2. Create a unique identifier for each battery in the study.
3. Collect high-level battery usage data while the baggage tractor is operating (both while charging and while supplying traction power).
4. Interface with the Corvus lithium BMS for proper battery pack charging.

A means to uniquely identify each battery during charging was needed for distinguishing one battery from another for data collection purposes, but also was needed due to the difference in charging algorithms required for the two battery chemistries. FLA battery charging has been well established within the GSE industry, and the standard charging algorithm for FLA batteries was built into the chargers used for the study. A BIM with FLA batteries is still needed to communicate specific battery parameters to the charger (such as battery type, capacity, number of cells, and target voltages) for proper charging of the specific battery packs used. Charger-to-BIM communication was performed using a control-area network (CAN) bus, using a CAN open stack that was compliant with the CIA 418 device profile for battery modules. Lithium batteries, on the other hand, have not been established in the GSE industry; therefore, a different charge algorithm monitored by a BMS is needed. For this demonstration, the Corvus battery modules each contain a BMS that communicates with a master vehicle control unit/display, which is an off-the-shelf VeeCAN module with custom programming (referred to as a VCU module). The VCU, in turn, oversees specific parameters from each of the modules in a pack to control charging of the pack as a whole. The VCU module can direct the charger to pause charging (generally for cell balancing purposes), start/stop charging, and change the current magnitude of the charge. This direction comes by way of a CAN protocol, unique to Corvus, connecting each battery module within the pack, the VCU module, and a secondary CAN bus on the BIM. The BIM had to be designed with this secondary CAN bus and programmed to recognize specific messages from the VCU module to perform the charging tasks requested by the Corvus battery pack in order to offer the best life and performance of the battery pack.

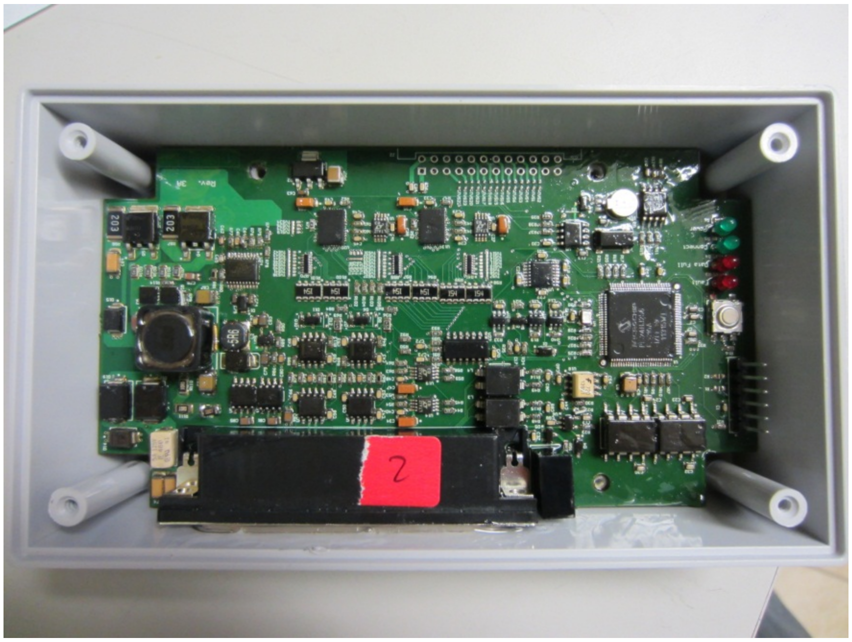

Figure 5. Battery identifier module.

Minute-by-minute logs[b] of battery usage information were collected for each battery over the duration of the demonstration to gain a better understanding of how the different battery chemistries handle the duty cycle of a ground support baggage tractor. To accomplish this, the BIM needed to have a means for monitoring, recording, and communicating to the ECOtality data server. It was determined that the desired information to be communicated was cell voltages, pack voltage, pack current, and pack temperature. For the FLA battery packs, this meant that the BIM hardware would contain the proper circuitry and software to monitor and record:

- 20 high-voltage leads placed on the positive terminal of every other cell of a 40-cell, 80-volt (V) nominal pack in order to record intermediate cell voltages and full battery pack voltage
- Pack charge and discharge current via a bus bar, connecting two battery cells and acting as a shunt
- Battery temperature with a thermistor placed on the pack.

For the Corvus battery packs, each module was sealed without a means to connect the BIM analog circuitry to the modules. However, the Corvus BMS internal to each module communicated analog data for maximum and minimum cell voltages, module voltage, module current, module temperature, and module state-of-charge via the BMS CAN bus. Because the BIM also had to be connected to the Corvus

b. Minute-by-minute logs were made up of the minimum, maximum, and average values of data sampled at 1 Hz for 1 minute.

CAN bus for charging, all analog data were taken from each module's BMS using a secondary CAN bus on the BIM.

Other common functions needed on the BIM for both battery chemistries include the following:

- Extended non-volatile memory to retain all data accumulated during all operations
- Ability to be powered through the entire voltage range supplied by either battery chemistry
- Contain circuitry for interfacing with the charger pilot line to signal a connected tractor
- Adequate processing power to monitor and record information while performing all tasks at any given time
- Software for integrating all hardware, communications, and desired functionality.

4.3 User Interface Tool

A user interface tool was developed to communicate with both the BIM and the charge control card used within this demonstration. The user interface communicated with the BIM through the charger for display of real-time information and also was able to configure the parameters associated with the battery. In addition, it communicated with the charger to download the different logs and set the real-time clock. The tool was used to configure the network settings of the server so that it would properly communicate with the chargers and the database.

4.4 Central Data Server

The ECOtality central data server acted as a data parser in communication with all chargers in the demonstration and the MS SQL server. It listened on the network for connected chargers to pass up the required data. Once the server received these data, it was able to reformat the data to communicate with the MS SQL server for upload. In addition to being able to handle all data, the server confirmed the firmware versions of the BIMs and charger control boards and was able to remotely upgrade them as needed.

4.5 Isaac Data Logger

To gain a more in-depth understanding of the usage of the baggage tractors during the study, an Isaac Instruments (Isaac) DRU-908 data logger was added to each of the four test baggage tractors. Data were collected for a 1-month period from December 12, 2012, to January 12, 2013. This particular timeframe was selected due to the high volume of air travelers and increased number of flights at this time of the year.

The Isaac DRU-908 allowed for continuous logging at a 1-second sample rate of battery voltage, battery current, and vehicle speed. Battery voltage was measured with an analog direct current voltage sensor (Isaac part number SENVD1-501), which is capable of measuring ±500 V at an accuracy of 1% of the full scale. Battery current was measured with an analog direct current Hall effect current sensor (Isaac part number SENADC-501), which is capable of measuring ±500 A at an accuracy of better than 1% of the full scale. Vehicle speed was measured with a global positioning system device (Isaac part number COMGPS-G18-1HZ-DR8), which has a 1 hertz position and measurement update rate and has a position accuracy of better than 3 m.

5. BATTERY INTEGRATION WITH BAGGAGE TRACTORS

5.1 Original Baggage Tractor Configurations

The eGSE baggage tractors currently in use by SWA at ONT are Tug Technologies Corporation (TUG) brand MX4 model tractors. This model tractor contains a Ballard Power Systems (Ballard) electric drive system consisting of a Ballard electric motor-integrated rear axle and a Ballard motor controller assembly (Figure 6). The MX4 tractors with FLA batteries (BT-4 and BT-5) used the complete (i.e., unmodified) Ballard system. Because this tractor model previously had been used with lead-acid batteries for an extended period of time without complication, it was decided that no further proof of operation was needed.

One tractor in use at ONT was an MX4 model tractor containing a Ballard motor-integrated rear axle and a Curtis motor controller assembly. This unit was developed through a collaborative effort between TUG and SWA in an attempt to use currently available parts from the TUG MZ model tractors with the MX4 model and part configurations. More specifically, the desire was to have the Curtis alternating current induction motor controller (Curtis model number: 1238-6501) replace the original, obsolete Ballard Ecostar 80 Vac motor controllers without having to purchase new electric drive systems or entire vehicles. This modified baggage tractor (BT-1) was used for one of the Corvus lithium battery packs. The second MX4 tractor equipped with Corvus batteries (BT-3) was originally intended to include the unmodified Ballard system. It was desired to use both drive systems with the Corvus packs to ensure the advanced batteries could operate with both systems.

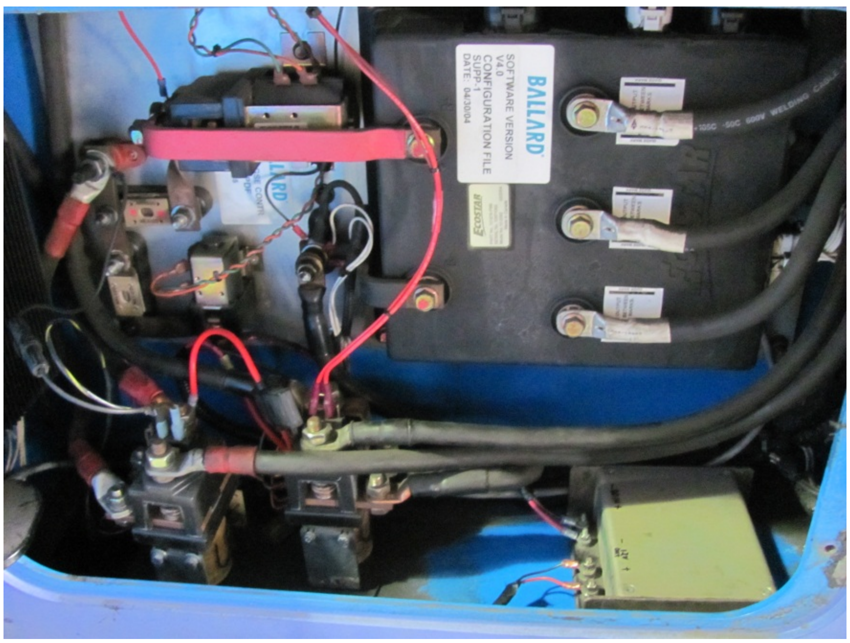

Figure 6. Ballard motor controller assembly.

5.2 Ballard Motor Controller Voltage Compatibility Issue

Although all specifications and programmable parameters shown in the Ballard documentation state that the motor controller can operate with battery voltages up to 100 V (maximum voltage of the Corvus lithium pack is 98.4 V), it was found that the controller will produce a non-drivable fault for any battery voltage above 96 V. This parameter was found in the ‘Pinpoint Tests’ section pertaining to a ‘Hardware Over-Voltage Fault’ of the latest version available of the *Ballard Ecostar 80 VAC GSE Powertrain System Service Manual and Diagnostics Procedures* documentation provided by SWA. Because of this parameter, the Corvus lithium battery pack, as configured for this demonstration, could not be operated with a baggage tractor using the Ballard Ecostar motor drive controller. This does not mean that all lithium battery packs cannot be used to power a tractor with the Ballard Ecostar motor drive controller. All indications are that this system could be used with any battery, as long as the battery voltage maximum and/or minimum do not exceed the actual voltage limits of the motor drive controller (approximately 96 V). In fact, the low internal resistance associated with lithium batteries could be better suited for use with this controller because of the smaller voltage fluctuations with respect to increasing current magnitudes typically found in lithium batteries.

Because the Corvus battery pack voltages were set prior to finding the hardware over-voltage fault with the Ballard system, the demonstration had to move forward by finding a replacement motor controller that could still be used in an MX4 and allow for the full usable voltage range of the Corvus pack. Fortunately, the Curtis motor controller is capable of operating with a total input battery voltage range of 50.4 to 120 V and was proven to be capable of operating an MX4. As previously mentioned, BT-1 was previously retrofitted with a Curtis motor controller; therefore, this tractor was the first to be configured with a Corvus battery pack. Some tuning had to be completed to the programmable battery parameters of the Curtis motor controller in order for the Corvus battery pack to operate correctly. Table 2 lists the battery parameters for each battery technology and denotes which ones were modified. This tuning caused an offset in the start time of data collection between this tractor and the FLA-powered tractors. The official start date of this demonstration was July 23, 2012.

Table 2. Curtis motor controller parameters for each battery technology.

Curtis Parameter	Value for FLA Battery	Value for Corvus Battery
Nominal Voltage (Pack)	80.0 V	80.0 V
Under Voltage (per Cell)	2.0 V	2.1 V
User Over Voltage	125%	126%
User Under Voltage	70%	80%
Reset Voltage per Cell	2.090 V	2.400 V
Full Voltage per Cell	2.040 V	2.460 V
Empty Voltage per Cell	1.730 V	2.088 V
BDI (Battery Discharge Indicator) Reset	90%	100%

5.3 Second Lithium Baggage Tractor Integration

The second baggage tractor to be integrated with a Corvus battery pack (BT-3) had to be reconfigured with the parts needed for the Curtis motor controller. These retrofit parts are listed in Appendix A, and several of the parts were sourced from the TUG MZ, which is the next generation of TUG eGSE baggage tractors. The MZ contains a Harlan Global Manufacturing (Harlan) designed, motor-integrated rear axle and Curtis alternating current induction motor controller assembly (see Figure 7). The process of determining the parts needed and ordering, receiving, and integrating them forced this second tractor to be delayed by 2 months, starting fleet operation on August 27, 2012. BT-3 is shown in Figure 8.

After approximately a week and a half into the fleet tractor operation, the tractor began to act erratically, exhibiting jerky movements with no accelerator input. After substantial troubleshooting, an issue with the mechanical tone wheel within the Harlan motor axle assembly was found. The cause was determined as a misalignment with the speed encoder, thus causing the motor drive controller to falsely measure vehicle movement at rest. The motor controller would then attempt to correct the movement by applying a torque on the motor in the opposite direction of the request. This behavior was not found to be correlated to the lithium battery integration. The solution to this issue was to install a remanufactured Ballard integrated rear axle assembly into the tractor. The process of troubleshooting and rectifying this issue caused BT-3 to be inoperable for an additional 2 months; it re-entered the fleet on October 29, 2012.

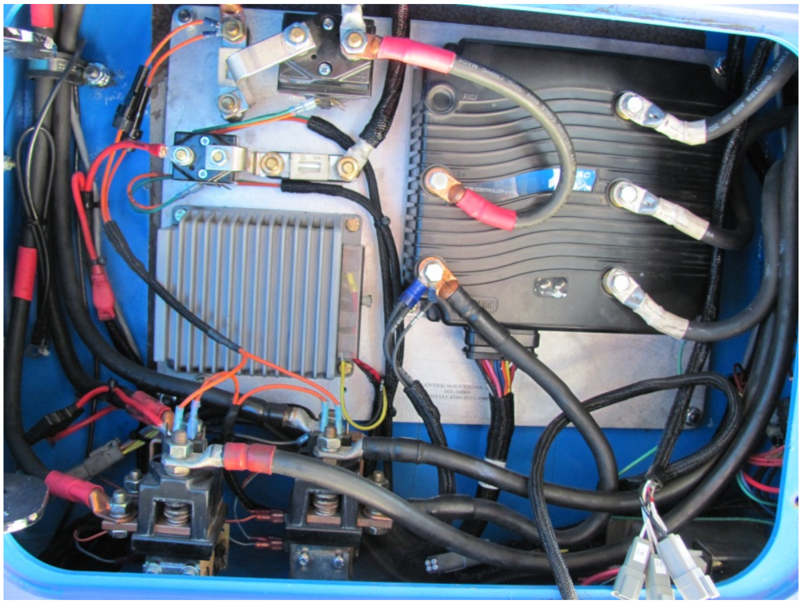

Figure 7. Curtis motor controller assembly designed for a TUG MZ, retrofitted and installed in a TUG MX4 (BT-3).

Figure 8. Airport baggage tractor BT-3 integrated with Corvus battery pack.

5.4 Corvus Battery Weight Issue

The Corvus lithium battery pack weighs 500 lb, which is approximately 2,700 lb less than the EnerSys FLA battery. This weight difference in typical vehicle applications is considered to be an advantage due to less power needed to propel the vehicle. However, for the MX4, the additional battery weight is used to achieve drawbar tow ratings. The baggage tractor manufacturer, TUG, was consulted to determine if the baggage tractor would still operate correctly without the designed battery weight. It was concluded that the designed weight must be present on the tractor to meet the design specifications. The particular vehicles used in the study previously had been subject to a previous drivetrain conversion, with a large steel plate welded to the rear of the tractor for ballast. The approximate weight of that plate was 700 lb. A decision was made by the team to add in 2,000 lb of ballast in addition to the 700 lb of steel plate to simulate the FLA battery weight increase of 2,700 lb. The ballast consisted of 40 steel shot bags weighing 50 lb each (Figure 9), which were placed under and around the Corvus battery pack within the battery compartment of the baggage tractors.[c] The tractor with the ballast included is shown in Figure 10.

5.5 Charger/VCU Interference Issue

It was found that the display screen on the VCU module, which is used by the Corvus system to control the charging-related CAN messages and display battery state of charge to the driver, would intermittently cease to update or freeze during charging and continue to be inoperable after charging. The frozen battery state-of-charge indication would cause the driver to become unaware of the actual state if charge of the battery, and, on a few occasions, cause the battery to be discharged to the point where the BMS would disconnect modules to protect against over-discharge. The modules would have to be individually charged to a voltage level within 2% of each other before each module BMS would allow for parallel connection.[d] This caused the tractors to be inoperable for an extended period, thereby affecting fleet operation during the study. Corvus has since completed a software update to correct this behavior when the VCU is used with their modules.

Figure 9. Steel shot bags loaded to ballast tractors with lithium batteries.

c. Steel shot-filled bags were chosen as the ballast in order to not permanently alter the demonstration vehicles, which are owned by SWA. A more sophisticated approach to ballast addition could be designed by a GSE manufacturer, if desired.

d. While the demonstration was ongoing, Corvus released new software for the BMS that would allow each additional module to connect into the system automatically when the voltage level was within 2% during a charge. The software was not implemented to keep consistency throughout testing.

Figure 10. Corvus battery integrated into baggage tractor with additional ballast weight.

After closely monitoring the BMS/VCU CAN bus and battery pack voltage while charging, it was determined that electrical noise on the power lines was affecting the CAN communication and VCU module power source. The first attempt to correct this issue was to add filters to both the high-voltage and 12-V power lines to attenuate the noise on the charging circuit and VCU power circuit. The filters did attenuate the noise and lowered the frequency with which the display freezing occurred, but it did not eliminate it. Therefore, to resolve this issue, a connection scheme was implemented that would power the VCU module only when the tractor's drive or charge contactors closed. This allowed the VCU module to reboot between a charge and a drive cycle so that the display would not freeze. Once this was corrected, there were no accounts of the tractor being driven to the point where the Corvus BMS had to disconnect the batteries.

6. RESULTS

The intent of this study was to demonstrate that advanced battery technologies can operate within the normal duty cycle of an eGSE application. In order to minimize the number of variables that could affect battery performance (such as temperature and elevation), ONT in California was selected to perform this study. ONT does not experience extreme ambient temperatures, which could have prevented the demonstration of new battery technology. Over the course of 6 months, battery usage and charging data were collected from four eGSE baggage tractors. This section presents the accumulated data.

Figure 11 and Figure 12 show the charge capacity versus the total charge time for both of the FLA battery baggage tractors, while Figure 13 and Figure 14 show the same data for the two lithium battery baggage tractors. The red line in each graph shows the maximum possible charge capacity that the charger can deliver due to current limitations. The lithium battery data lie on or slightly below this line, while the FLA battery data only partially lie along this line. The interpretation is that the lithium battery packs can accept a full charge current for the majority of a full charge, while the FLA battery packs can only accept full charge current for approximately the first hour of a full charge. After the first hour, or in the case of an opportunity charge, the charge current for the FLA battery drops in order to maintain a charge voltage limitation. An FLA battery charge also can end in an equalization stage, where a fraction of the rated charger current flows into the battery to equalize the individual battery cells that make up the pack. As seen in Figure 11 and Figure 12, an FLA charge equalization may take several hours to finish under normal circumstances, even with a healthy battery pack. The equalization stage would not occur on every charge event, regardless if the battery were allowed to remain on charge for a period long enough to complete the equalization process. No equalization stage is needed for lithium battery packs due to the BMS handling of all cell balancing.

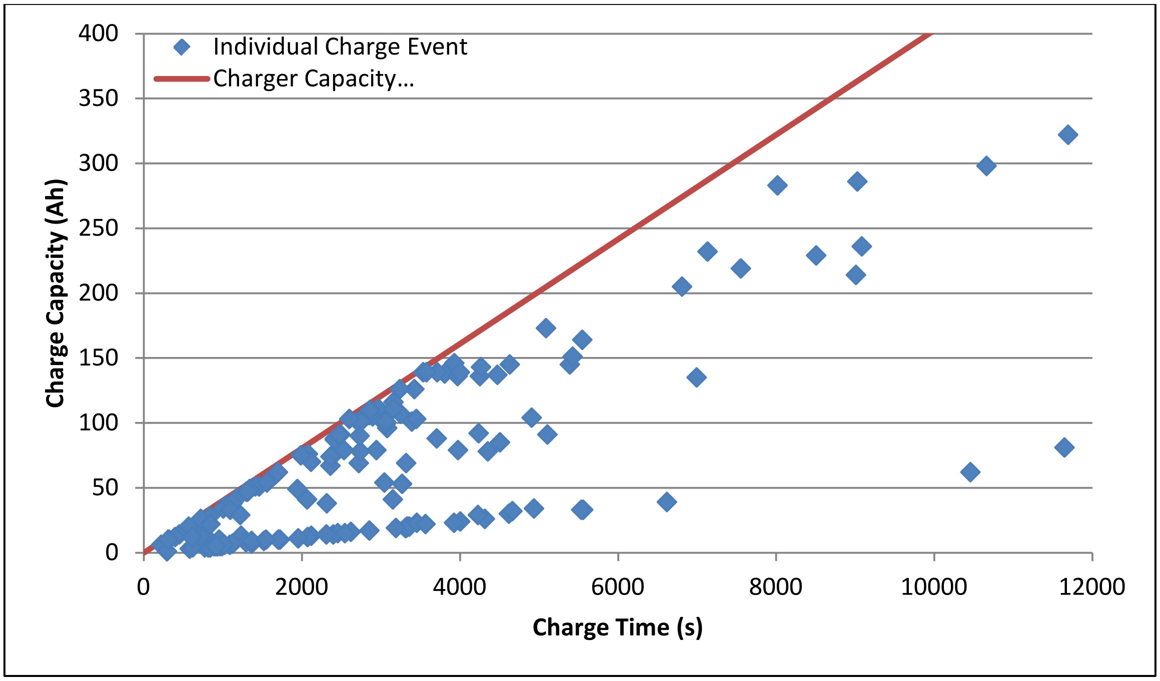

Figure 11. Individual charge event capacity charged versus total charge time for flooded lead-acid baggage tractor BT-4.

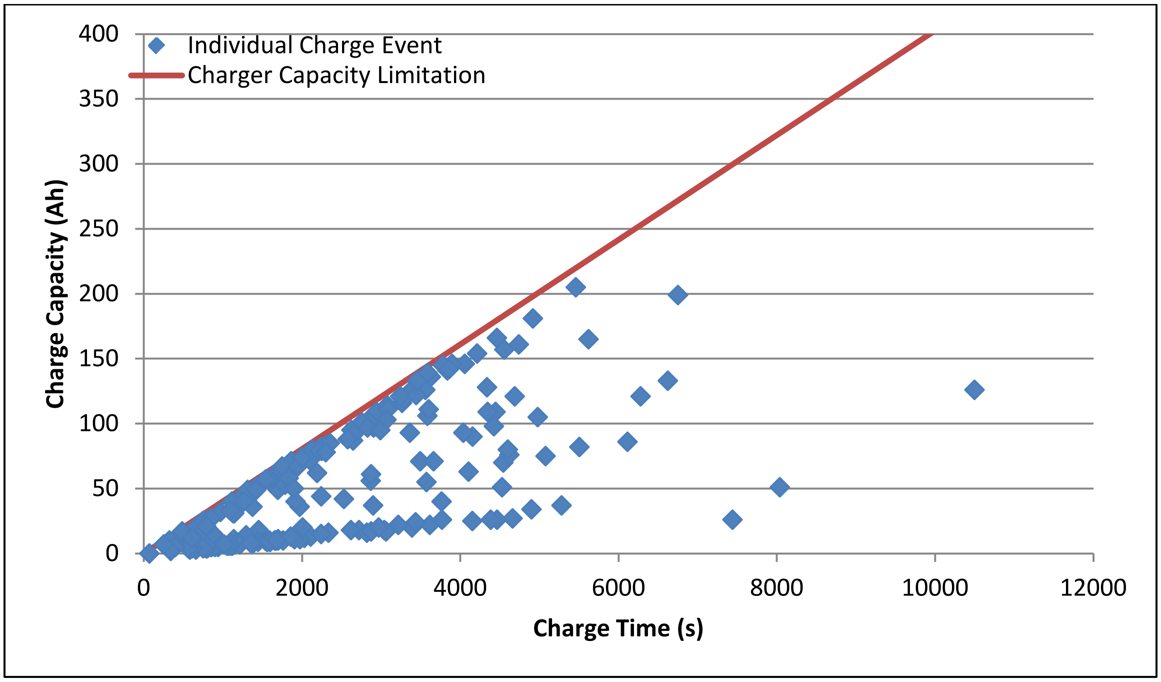

Figure 12. Individual charge event capacity charged versus total charge time for flooded lead-acid baggage tractor BT-5.

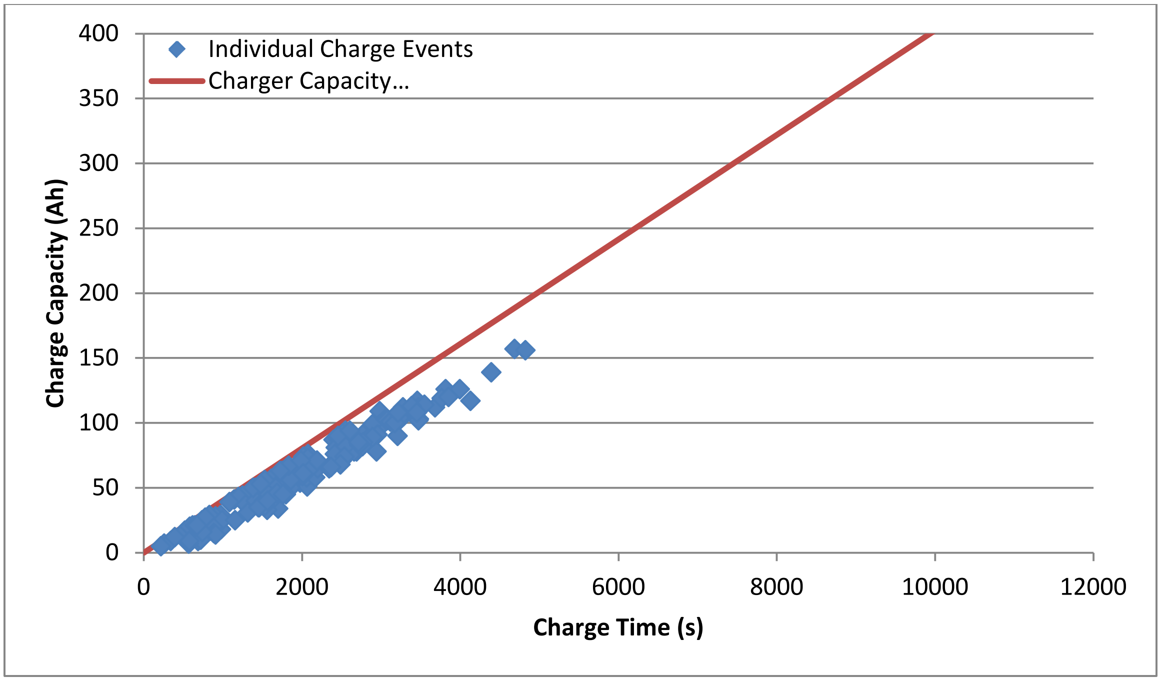

Figure 13. Individual charge event capacity charged versus total charge time for lithium baggage tractor BT-1.

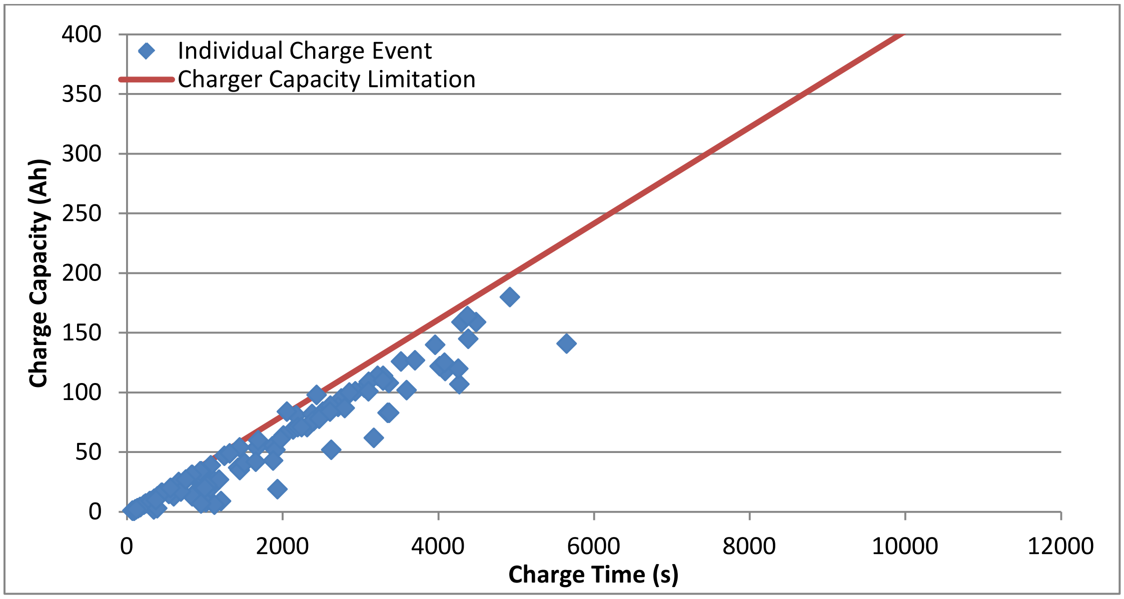

Figure 14. Individual charge event capacity charged versus total charge time for lithium baggage tractor BT-3.

A summary of the charge events over the duration of the fleet data accumulation period is presented in Table 3. The lithium batteries had less time required for charging, resulting in less charge events. The lithium batteries were able to be charged more rapidly, with essentially an equal capacity added during the charge.

Table 3. Breakdown of charge events over the duration of the fleet data accumulation period.

Baggage Tractor	Total Charge Capacity (Ah)	Total Charge Time (hr)	Number of Charge Events	Maximum Single Charge Capacity (Ah)	Maximum Single Charge Time (hr)	Average Capacity per Charge Event (Ah)	Average Time per Charge Event (min)
BT-4 (FLA)	11,733	149.6	184	322	3.35	63.8	48.8
BT-5 (FLA)	11,614	158.1	216	205	3.42	53.8	43.9
BT-1 (lithium)	9,706	76.4	154	157	1.34	63.0	29.8
BT-3 (lithium)	6,339	58.0	118	180	1.57	53.7	29.5

Figure 15 through Figure 18 shows the voltage and current profiles for each baggage tractor for the time period of December 12, 2012, to January 12, 2013. Comparing these graphs shows that the tractors with lithium batteries were used in a manner similar to the baggage tractors with FLA batteries. Notable differences between the lithium battery tractors and the FLA battery tractors include an increased regenerative braking current magnitude (300-A peak versus 200-A peak) and a significantly more stable battery voltage under load for the lithium battery tractors.

Figure 19 and Figure 20 illustrate the current for approximately a full charge for both battery chemistries. Note that the overall charge duration of the lithium battery is half that needed for the FLA battery. The transients shown for the FLA battery are a part of the Minit-Charger fast charge algorithm and are used to determine the charging batteries' internal resistance.

A summary of the drive and charge events for the period from December 12, 2012, to January 12, 2013, is presented in Table 4. These data show that the average charge time of the lithium baggage tractors was nearly half the average charge time needed by the FLA battery tractors, while the average drive time was comparable. The lithium batteries had a more consistent discharge to charge capacity efficiency at 85.0% and 86.7%, compared to the FLA batteries at 60.6% and 87.2%. When comparing the amount of time spent driving the baggage tractors versus charging, there is a clear advantage to the lithium battery vehicles, with more time available for driving than required for charging. The FLA battery vehicles remained inefficient, with the vehicles undergoing more hours of charging than they could be driven due to the longer charges and battery equalization cycles required for the FLA batteries. By taking the available drive time and dividing by the charge time, the FLA batteries are represented at less than 100%, while the lithium battery vehicles are reflected as greater than 100% due to the quick charge times.

Table 4. Breakdown of data accumulated from December 12, 2012, to January 12, 2013, recorded by the Isaac data loggers.

Baggage Tractor	Number of Charges	Total Discharge Capacity (Ah)	Total Charge Capacity (Ah)	Discharge to Charge Capacity Efficiency (%)	Drive Time (hr)	Charge Time (hr)	Vehicle Utilization (%)
BT-4 (FLA)	22	1,928	3,184	60.6	21.4	28.7	74.6
BT-5 (FLA)	45	3,604	4,134	87.2	33.5	48.0	69.8
BT-1 (lithium)	33	1,785	2,100	85.0	23.4	19.7	118.8
BT-3 (lithium)	29	1,861	2,147	86.7	28.0	21.2	132.1

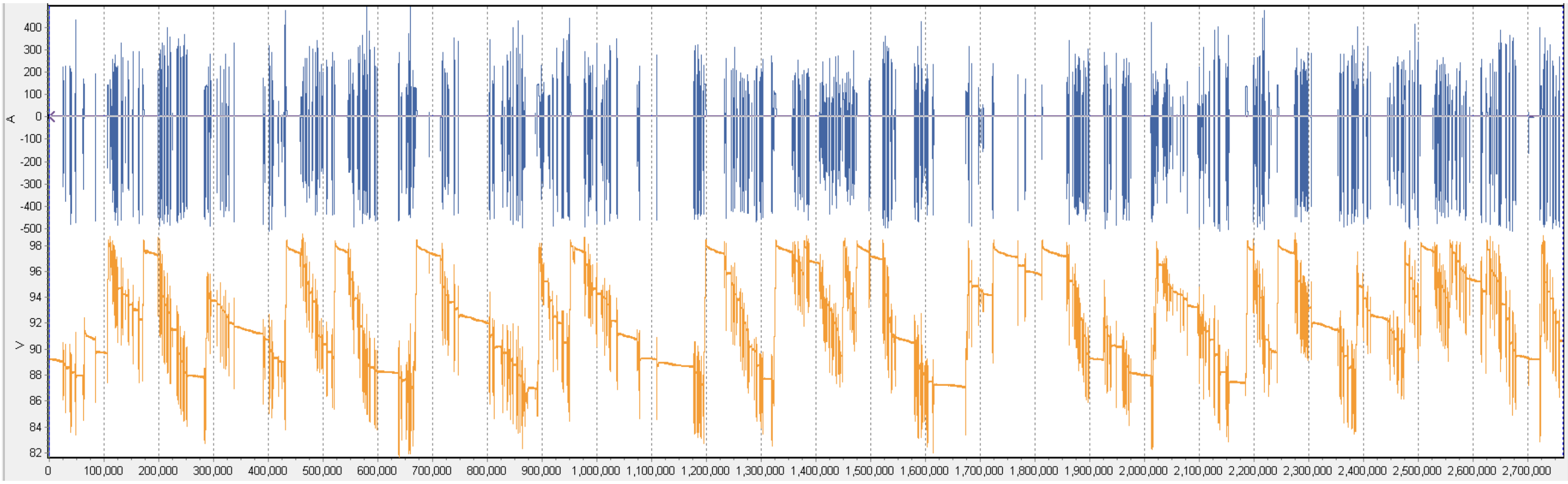

Figure 15. BT-1 (lithium) battery current (blue) and voltage (yellow) data over the duration of the Isaac data logging period.

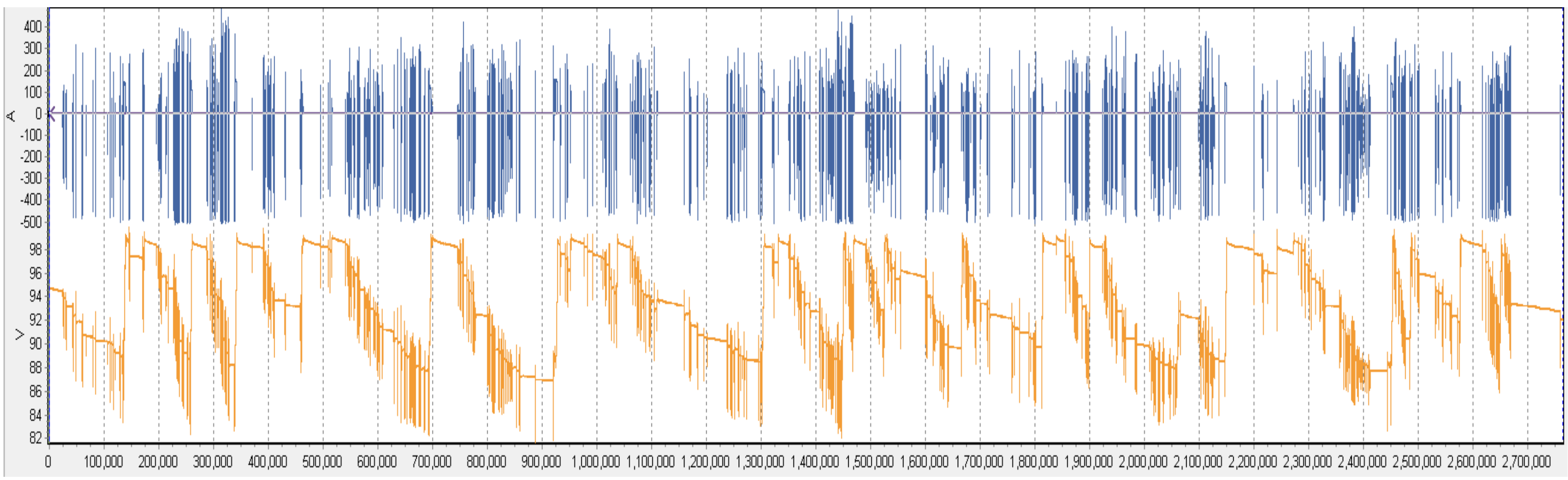

Figure 16. BT-3 (lithium) battery current (blue) and voltage (yellow) data over the duration of the Isaac data logging period.

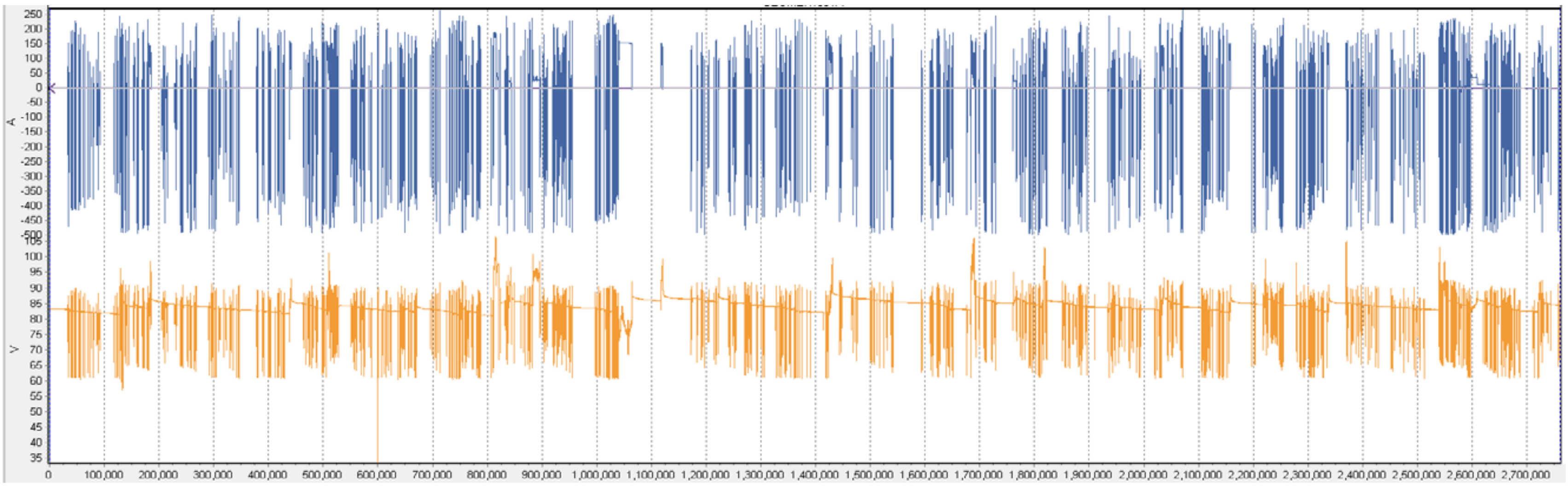

Figure 17. BT-4 (flooded lead-acid) battery current (blue) and voltage (yellow) data over the duration of the Isaac data logging period.

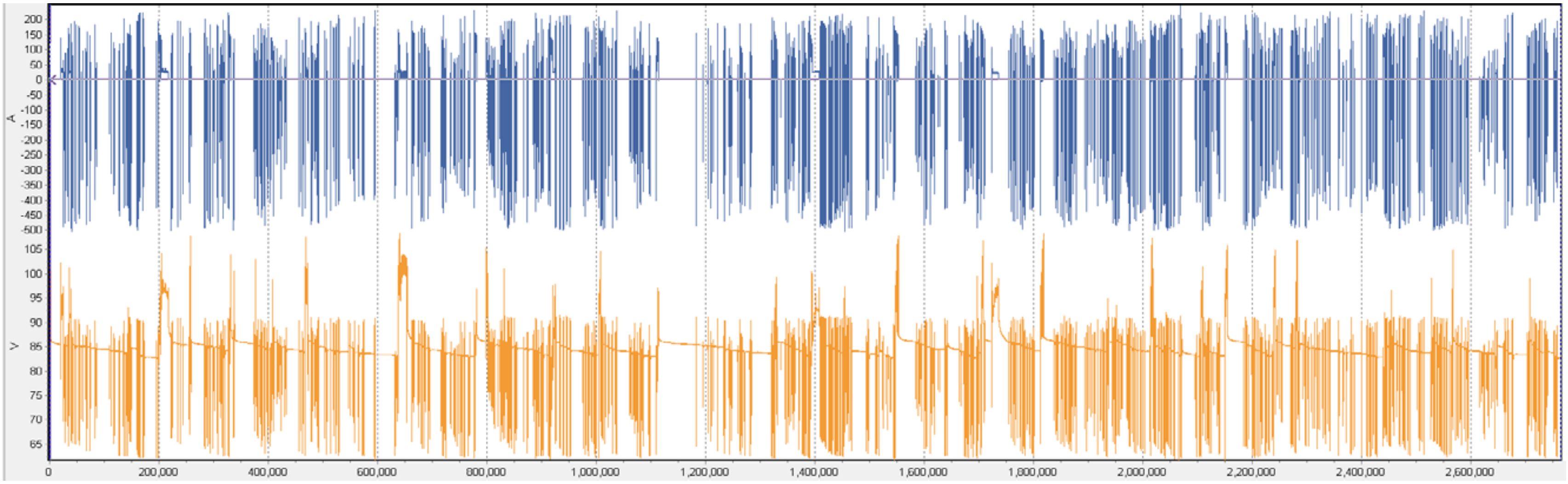

Figure 18. BT-5 (flooded lead-acid) battery current (blue) and voltage (yellow) data over the duration of the Isaac data logging period.

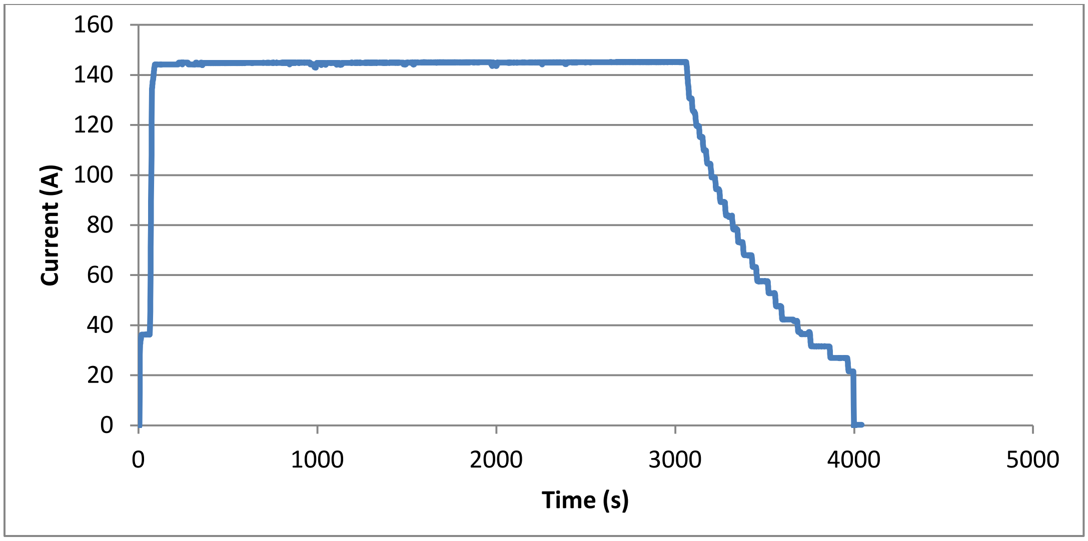

Figure 19. Example of a full charge for a lithium baggage tractor.

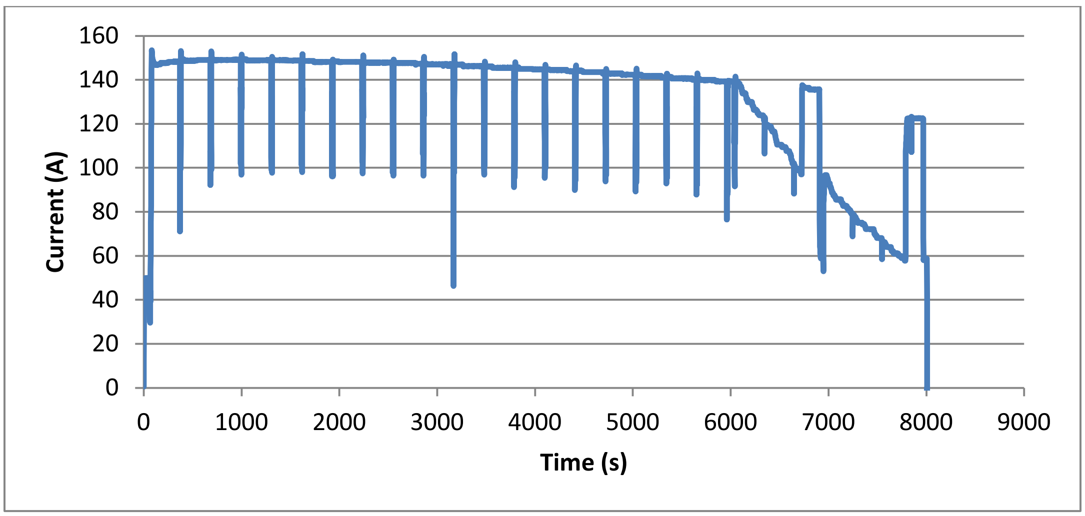

Figure 20. Example of a full charge for a flooded lead-acid baggage tractor.

7. CONCLUSION

The intent of the eGSE demonstration was to evaluate the day-to-day vehicle performance of electric baggage tractors using two advanced battery chemistries in an effort to demonstrate possible replacements for the FLA battery currently used across eGSE. The two chemistries to be tested were the lithium-ion based and advanced lead-carbon based. The advanced lead-carbon battery was to be supplied by East Penn Manufacturing; however, development limitations for this particular battery chemistry caused it to be unavailable for the start of testing. There were no alternative battery manufacturers that were able to provide a lead-carbon battery, which was well-suited for the intended application at the start of testing. Therefore, without available lead-carbon batteries and a lack of previously accumulated comparable data for FLA batteries, the decision was made to test an industry standard FLA battery in place of the advanced lead-carbon chemistry. The lithium-ion based battery chemistry was supplied by Corvus Energy, which utilizes Dow Kokam manufactured battery cells.

The Corvus prototype lithium battery pack was designed to be a ‘drop-in’ replacement of the FLA battery by using the same battery cavity within the tractor, the same connection to power the tractor, and be charged while installed in the tractor. However, the Ballard Ecostar motor drive controller was found to have a hardware over-voltage fault set at 96 V on the battery input. With the Corvus battery having a top-end voltage of 98.4 V, the motor drive controller was replaced with a Curtis motor controller. This motor drive voltage limitation is worth noting due to lithium-ion batteries typically having higher nominal cell voltages than FLA batteries. Future lithium integration with FLA-designed controllers could have similar concerns. Although the Ballard Ecostar drive system is now obsolete, a large number of existing electric baggage tractors still use this motor controller. Therefore, the type of motor drive controller installed in a particular tractor and the number of series-connected cells within a pack will need to be considered for widespread adoption of lithium-ion batteries in baggage tractor applications.

Another key point for implementation of lithium-ion batteries into baggage tractors or any material handling application is the battery weight. The Corvus lithium battery pack is approximately one-fifth lighter than that of the current industry standard FLA battery pack at 2,500 lb. In passenger vehicles, additional battery weight is typically considered a disadvantage, and a reason for using lithium batteries for propulsion, but in baggage tractors, the extra weight is used as ballast for towing purposes; therefore, it is an advantage. For this study, the difference in weight was compensated by using steel shot bags in the tractor battery cavity. This ballast was not permanently affixed to the tractor. Therefore, using a lithium-ion chemistry battery with existing tractors designed specifically for FLA battery packs will require an engineered solution from the manufacturer that accounts for the weight difference. Further testing will need to be performed at reduced weights in an attempt to characterize the actual weight needed to meet the performance specifications. At the start of the project, reduced weight performance data were not available from TUG that could have allowed less ballast. There are very few production tractors specifically designed for the lithium-ion chemistry batteries that are currently available. One example of a baggage tractor designed with lithium batteries is the NMC Wollard Model 40e Tow Tractor, which also utilizes a similar Corvus battery pack.

A large factor in the ability of any new technology to be adopted into new or different applications is the acceptance of that technology by the end user. In this case, the baggage tractor drivers and operations support have to be educated about the lithium battery and believe that it is capable of handling the application. The similar use of the baggage tractors in this study suggests that the drivers trusted the lithium battery vehicles to perform the same work as the FLA vehicles. In an effort to confirm this assumption, drivers were asked to fill out an optional survey to provide their opinions of each tractor. These surveys are shown in Appendix B. Unfortunately, only one survey was returned, but it was very positive with regard to the lithium battery vehicles, even asking to ‘bring them back’ as an additional comment. This survey corroborates the feedback from Tony DiLuccia, SWA Lead GSE Technician at ONT, that the lithium tractor was found to be a reliable choice and often preferred by the ramp personnel over the FLA due to the run time and consistent operation.

While there are some implementation issues that will need to be addressed in order for lithium-ion batteries to be widely adopted into material-handling applications, the battery is capable of handling the duty cycle. As shown in Figure 15 through Figure 18, baggage tractors with the Corvus lithium battery were utilized in a similar manner as the baggage tractors with FLA batteries. The maximum output current for each tractor was identical at approximately 500 A, but the FLA batteries can maintain that maximum output for a longer duration. This is due to the FLA batteries’ inherent high internal resistance causing voltage to sag down to around the minimum voltage allowed. Therefore, for the battery to supply enough power to the tractor to operate correctly, the FLA-powered tractors must have a higher average output current. The lithium batteries have a very low internal resistance, which causes the voltage to have smaller transients and stay stable with respect to variation in load. This also was evident in the maximum current magnitude during regenerative braking. The lithium battery reached approximately 300 A of regent current, while the FLA maximum was approximately 200 A.

Of primary importance are the large reductions in recharge time needed for the lithium baggage tractors versus the FLA baggage tractors for similar output performance. The difference in charge time between the two battery types is demonstrated by the vehicle utilization times for the lithium batteries at 118.8% and 132.1%, while the utilization time for the FLA batteries was at 69.8% and 74.6% (see Table 4). This indicates that even though the lithium batteries have a smaller rated discharge capacity, the reduction in charging time allows for the tractor to maintain similar drive-time capability as the current FLA batteries.

Along with being shorter in duration, recharging the lithium batteries was more consistently linear with respect to energy input. This is due to the difference in energy acceptance for differing charge rates and it allows for a tractor with a lithium battery to have a more predictable system utilization time. The predictability in charging and discharging of the lithium battery is shown in the stability of the voltage in Figure 15 and Figure 16, and the nearly identical performance metrics shown in Table 4. With the ability to better predict drive and recharge times, fleet managers could increase the efficiency of a single tractor and ultimately need fewer tractors to perform the same tasks.

The cost savings due to a decrease in fleet tractors, along with the maintenance and additional spare batteries associated with FLA tractors, could be enough to offset the higher cost of lithium-ion batteries. Periodic maintenance is required to keep the FLA batteries sustained with the proper water levels and also periodic cleaning of the batteries and baggage tractors due to leaks. The lithium batteries do not require periodic maintenance. In addition, there is increased safety due to eliminating hydrogen out-gassing that can occur with the FLA batteries during charging. Indoor or enclosed applications would benefit greatly from the use of sealed lithium battery packs in baggage tractors.

Further testing is needed in order to evaluate the lithium-ion battery life in this application and how this compares to the life of current battery chemistries. However, an approximation can be calculated by using the charge capacities (i.e., 2,100 Ah and 2,147 Ah) for one month of testing (see Table 4) and dividing by the rated capacity of the lithium-ion battery (i.e., 225 Ah). Dow Kokam states that their cell is capable of 1,400 cycles at 100% depth-of-discharge; however, Corvus limits the depth-of-discharge available to the eGSE with their BMS to enhance battery cycle life. Then assuming the cycle life is 1,700 cycles, each module could last roughly 15 years.[e] Cycle life is dependent on the lithium cell construction, chemistry, and manufacturer.

Lithium-ion-based battery chemistries (such as those offered by Corvus) are fully capable of handling the duty cycle of material handling applications; however, in order for these batteries to have widespread adoption, the designed tractor battery weight integration issue must be considered by the GSE manufacturer. Because of the number of functionally capable tractors already deployed, integration solutions will need to be capable of retrofitting existing tractors, while maintaining current performance capabilities. If a safe and cost-effective solution is found and if the cost of lithium-ion batteries decreases, then lithium-ion batteries will be a competitive alternative to the industry standard FLA batteries. There also is an increased benefit to the operator in battery maintenance reductions, along with increased safety due to eliminating hydrogen out-gassing that can occur with the FLA batteries during charging. Depending on facility requirements, lithium battery packs might be the only candidate for fleets requiring long-term durability and safety.

Because of this study, further evaluations of using lithium-ion chemistries within the eGSE industry are being discussed. These future evaluations will be performed with the intent of expanding on the data collected within this study by using baggage tractors with batteries directly installed by the battery manufacturer and by testing in a location with temperatures regularly exceeding 100°F.

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e. Calculations are estimates with the data available and are not intended to reflect real-world, life–cycle or calendar life performance.

Appendix A, Ballard-to-Curtis Controller Conversion Parts for Tug MX4

Table A-1. List of parts needed to convert a TUG MX to a Curtis motor controller.

TUG Part Number	Description	Quantity
MX4-20010	Assy. Controller Panel	1
MX4-20012	Encoder Assembly	1
MZ-10016	Switch Toggle DPST, Sealed	1
BLE-1-2624	Assembly, Light Switch	1
MZ-10029	Terminal Board, 20 Amp, 4 Point	2
67486	Gauge, Battery Discharge Indicator	1
MZ-10007	Harness, Body 12 V	1
HRN-MZ-80V-112	Harness, Main MZ 80V	1
HRN-MZ-80V-111	Harness, Speed Sensor – Controller	1
660-4-0741-5	Circuit Breaker 20 Amp	4
T6-7013-209	Relay, Horn	1

Appendix B, Driver Survey(s)

PDF Complete

e Tractor Survey at Ontario Airport

ECOtality is conducting a study to investigate new battery technologies for electric ground support equipment. Two baggage tractors, BT-1 and BT-3, have been retrofitted with a new battery technology and we would like the drivers' feedback on their use and performance.

If you have questions, please contact Tyler Gray at tgray@ecotality.com. Completed forms can be faxed to 602-443-9007, ATTN: Tyler Gray or sent via email to tgray@ecotality.com with Subject: eGSE SURVEY.

Thank you for your support and assistance.

Baggage Tractor # (BT-1 or BT-3): Both **Date:** 4-1-13

Name (Optional): John [illegible] **Title:** Ramp Agent

1. BT-1 and BT-3 General Use:
[ ] Transport personnel [ ] Assigned to a specific ramp [X] Cart baggage only

Please provide any additional information on its use:

2. Vehicle location (where is the vehicle parked at night)?
[X] At a specific ramp [ ] Charger [ ] Other

Specific vehicle overnight parking location: CHARGERS G3

3. On a typical day, how many times do you drive BT-1 or BT-3?
[ ] 0 times [ ] 1-2 times [ ] 3-4 times [ ] 5-6 times [X] >6 times

4. When in use, how many people are typically on board?
[X] 1 person [ ] 2 people

5. On average, how many baggage carts are in tow?
[ ] 0 carts [ ] 1 cart [ ] 2 carts [X] 3 carts [ ] 4+ carts

6. How many people have access and regularly use BT-1 or BT-3?
[ ] 1 assigned [ ] 2 people [ ] 3-4 people [ ] 5-7 people [X] >7 people

7. Is this vehicle used during specific hours or at any time during the day?
[ ] Daytime only [ ] Evenings only [X] Any time

Please provide specific hours, i.e. (6 AM-11 AM. 3PM-5 PM, etc):

drive in comparison to other baggage tractors?

Charge seemed to last longer & seemed quicker charge

9. Do you have to charge BT-1 and/or BT-3 more or less often than the other baggage tractors?

Less

10. What do you like more about BT-1 and/or BT-3 versus the other baggage tractors?

Same As Above

11. What do you like less about BT-1 and/or BT-3 versus the other baggage tractors?

Nothing, The big box was hard for shorter Agents

12. Please add any additional comments:

Bring them back