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Data Acquisition System for Electric- and Hybrid-Electric Buses

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Abstract

Electric- and hybrid-electric bus deployments have sometimes failed because the operating agencies did not have a clear understanding of how the performance capabilities of any particular bus match up with the requirements of the operational duty cycle. Batteries are frequently subjected to over-discharge and over- or under-charge and other operational conditions that progressively degrade the performance and durability of the battery. The Data Acquisition System (DAS) developed by the Center for Energy, Transportation and the Environment (CETE) at the University of Tennessee at Chattanooga (UTC) permits operating agencies to understand, in real time, the impact that an operator and/or service requirement has on the entire electric- or hybrid-electric propulsion system and, more specifically, the batteries. It can be used to increase the utility and successful implementation of a electric- or hybrid-electric bus fleet by providing data on driving techniques, energy consumption versus road/load conditions and the energy requirements of existing and potential routes. In essence, this operational mode of the DAS system performs the functions of a digital storage oscilloscope, thereby enabling sophisticated evaluation and diagnosis. Three prototype DAS units were developed, fabricated, and installed on battery-electric buses operating in Santa Barbara, California, and Emory University in Atlanta, Georgia, and on a hybrid-electric bus operating in Sevierville, Tennessee. The results of these installations will be presented.

Keywords: data acquisition, BEV, HEV

1 Introduction

Electric- and hybrid-electric bus deployments have sometimes failed because the operating agency did not have a clear understanding of how the performance capabilities of any particular bus match up with the requirements of the operational duty cycle. Batteries are frequently subjected to over-discharge and over- or under-charge and other operational conditions that progressively degrade the performance and durability of the battery. In response to these issues, the Center for Energy, Transportation and the Environment (CETE) at the University of Tennessee at Chattanooga (UTC) developed and deployed a Data Acquisition System (DAS) that permits operating agencies to understand, in real time, the impact that an operator and/or service requirement has on the entire electric- or hybrid-electric propulsion system and batteries. The DAS can be an effective tool in increasing the utility and successful implementation of an electric or hybrid-

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electric bus fleet. DAS allows for driving techniques to be monitored and studied; energy consumption versus road/load conditions to be scrutinized; the energy requirements of existing and potential routes to be analyzed; and battery recharge profiles to be monitored and subsequently submitted to the appropriate battery manufacturer to ensure compliance with recommended practices which can address potential warranty disputes. In essence, the operational mode of DAS performs the functions of a digital storage oscilloscope, thereby enabling sophisticated evaluation and diagnosis.

The DAS is comprised of a "black-box flight recorder" or Central Processing Unit (CPU) designed for installation in an area of the bus inaccessible to passengers and drivers, and an input/output module located in the interior of the bus to allow for real-time monitoring and stored data downloads. Data files recorded and stored by the input/output module are easily downloadable using the provided storage media for transfer to a customer-provided personal computer (PC) for subsequent post-processing using DAS software. A list of DAS features is shown in Table 1.

Table 1: DAS Features

A) Simple hardware installation
B) Easy set-up and calibration
C) Use of laptop not required for data downloads
D) Download charge profiles of interest "after-the-fact" (no need to connect extraneous equipment prior to collecting real-time data)
E) Evaluate energy-flow events leading up to low-power events "after-the-fact"
F) Sufficient memory capacity for storing approximately two (2) weeks of data between downloads
G) Ability to download data records for all buses in a fleet in a single short time period
H) Low incidence of system crashes
I) No high-voltage signals to areas accessible to passengers and drivers

The DAS has been designed to automate and maximize the yield of information of interest to the operating agency, while simultaneously minimizing intrusion upon the bus system (for example, a relatively simple wiring arrangement is employed). The CPU samples and stores the vehicle data shown in Table 2 at a rate of 2.0 samples/sec.

Table 2: Data Stored and Sampled by DAS CPU

A) 2 Separate channels of Battery Current - Range: -400 to +400 Amps - Resolution: 0.2 Amps - Typical maximum Error: 1%
B) 2 Separate channels of Traction Battery Potential - Range: 30 to 475 Volts - Resolution: 0.2 Volt - Typical maximum Error: 1%
C) 2 Separate channels of Ambient Temperature - Range: +5 to +255 deg. Fahrenheit - Resolution: 1.0 deg. Fahrenheit - Typical maximum Error: +/- 5 deg. Fahrenheit
D) Vehicle Axle Pulse Counts – from existing or new sensor - Allows precise velocity and distance calculations - Easy calibration using provided Pocket PC Auto-Calibration Function by driving vehicle a known distance (i.e., 100 ft)
E) Genset Current (Uses 500Amp/50mV current shunt in negative line) - Range: -400 to +400 Amps - Resolution: 0.2 Amps - Typical maximum Error: 1%
F) Genset Voltage - Range: 30 to 475 Volts - Resolution: 0.2 Volt - Typical maximum Error: 1%

2 DAS Development Process

Following the identification of the specific type of vehicle data system required to accomplish the objectives of the project, work began in June 2007 on technical specifications and supporting

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documentation required for the procurement process to solicit bids on the vehicle data acquisition system equipment. A Request for Proposals (RFP) was released publicly through UTC in August of 2007 to notify a wide range of potential vendors about the DAS procurement. After a thorough review by a CETE evaluation committee and the completion of a cost analysis by CETE staff, it was determined that the proposal from Stone Electronics, a company based in Gig Harbor, Washington, USA met the evaluation criteria and procurement requirements. Subsequently, UTC issued a purchase order in October of 2007 to Stone Electronics for the design, development and installation of a vehicle data acquisition system specified in the RFP. Once the procurement process was completed, work began on the DAS conceptual design, a preliminary firmware logic flow diagram, an interconnection drawing, the hardware design and other associated tasks required at the initial stage of the project. During this stage of the project, the owner/engineer of Stone Electronics met on-site at UTC in December of 2007 with the CETE project team to complete the design review process.

Following the design review process meeting, work began on developing the DAS prototype unit #1 for installation at Santa Barbara Metropolitan Transit District (MTD). Project work included completion of the circuit board design, fabrication of boards, and procurement of parts. Additionally, the core firmware was developed along with code entry (over 1800 lines of code) and design was completed on a surge suppressor for high voltage input lines intended to protect inputs from brief surges up to 1000V. Next, work was completed on the assembly and testing of prototype unit #1 and the acquisition of IPAQ HX 2495 Pocket PCs and parts for assembly of units 2-4 (unit #4 was retained by Stone Electronics for product support).

Following this work, development and installation of Visual Studio 2008 for IPAQ real-time code was completed along with the real-time firmware code for the CPU microcontroller (with approximately 2,000 total CPU lines of code). Work was also performed on an end-to-end communication test between the CPU and the IPAQ Pocket PC (RS-232) and the development of IPAQ real-time software and the desktop post processing code. Following these activities, the DAS Installation Guide was completed to provide step-by-step instructions on installing the DAS units in buses.

Installation of the DAS CPU involves three connectors used for data collection and delivery. There is a 19-pin high voltage connector, a 16-pin low voltage connector, and a USB connector. All connections use threaded connectors to seal the contacts against moisture and debris.

The 19-pin circular connector leads to battery pack 1, battery pack 2, and the genset. The positive voltage lead uses a 1-amp fuse to protect the DAS CPU. The positive ampere lead is connected to a high voltage shunt. Both negative leads are wired to the same ring terminal. The final wire lead is a chassis ground for the DAS CPU. The 16-pin circular low voltage connector carries the 12-24 VDC to power the DAS CPU. The power is protected using a 3-amp fuse. The two temperature sensors, the axle pulse sensor, and the LED status lamp also share this connector. The temperature sensors are used to log the temperature of each battery bank. The axle pulse sensor uses a magnetic pulse generator on the driveshaft to determine vehicle speed. The LED status lamp and USB connector are mounted in the interior of the bus for easy access data retrieval.

The final preparations for the installation of prototype DAS unit #1 at Santa Barbara included the completion of the real-time and post-processing software packages, assembly of the custom wiring harness assembly per Santa Barbara MTD requirements and completion of an integrated bench testing of all DAS system elements including hardware, firmware and software.

With the completion of the pre-installation activities at Santa Barbara MTD, work proceeded to install DAS unit #1 in a 1999 model battery electric bus (Bus EV19 manufactured by Ebus, Inc.) in April of 2008. CETE staff and the owner/engineer from Stone Electronics were on-site for the DAS installation performed by the maintenance personnel with Santa Barbara MTD. The UTC DAS system was tested on a variety of bus routes in Santa Barbara and performed satisfactorily during the initial tests.

Following the installation of the first prototype at Santa Barbara, Stone Electronics completed the assembly of UTC DAS CPU module circuit boards for prototype units #2 and #3 and continuing

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refinement and upgrades to post-processing software. Additionally, fabrication of DAS units #2 and #3 and the custom wiring harnesses for the Emory University and City of Sevierville installations were completed.

Following the successful DAS installation at Santa Barbara MTD, DAS unit #2 was installed on battery electric Bus #802 at Emory University in July of 2008 and DAS unit #3 was installed on hybrid electric antique replica trolley #954 in Sevierville, Tennessee in August of 2008. The systems at Emory and Sevierville both performed as expected and data collection was closely monitored on all three DAS units for several weeks.

3 DAS Data Analysis

Following the installation of the DAS units, a comparative analysis was completed for the battery strings on the Santa Barbara MTD and Emory University buses. The DAS system allows for monitoring a number of parameters such as voltage, current, distance traveled, and battery temperature (and derivative parameters such as power, energy, and vehicle speed) during motoring and recharge. This data assessment compares and contrasts data collected on these two buses operated at different sites.

3.1 Battery String Balance

An analysis of data for Santa Barbara MTD bus EV19 shows that the batteries appear to be out of balance. On average, String 1 (packs A, B, C) provides 65% of the energy used during the overall driving cycle. This ratio is even higher during the first six hours of driving before String 1 runs very low on energy, at which time String 2 becomes dominant. This phenomenon is illustrated in Table 3.

Table 3: EV19, 7/10/08, Bus Route #20-Carpinteria

Interval	Ah – String 1	Ah – String 2
0-2 hrs	33.78	2.67
2-4 hrs	35.35	8.77
4-6 hrs	23.79	12.30
6-8 hrs	14.59	21.54
8-10 hrs	5.05	10.75
Total	*112.56*	*56.03*

Plots of voltage and current for this driving cycle are depicted in Figure 1. It may be noted that because the battery strings are bussed together during driving the string voltages are essentially equal (the voltage spikes on String 2 will be addressed later in this report). However, these plots corroborate the finding that String 1 provides more current during the initial portion of the driving cycle before fading, at which point String 2 becomes the dominant string.

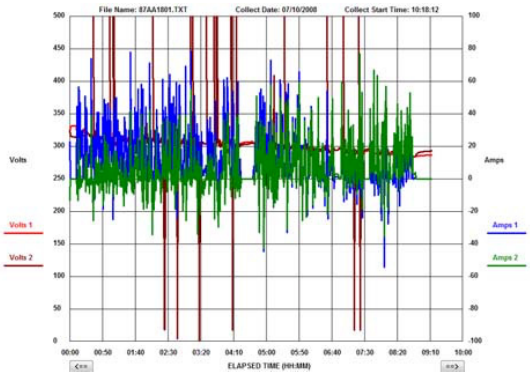

Figure1: EV19, 7/10/08, Bus Route #20-Carpinteria

In contrast, Emory Bus #802 exhibits better load sharing and balance, as illustrated in Table 4. (Note: the Emory buses typically receive a midday recharge after the first 90 minutes of driving, as is reflected by the 1.5-hour gap in the interval column.)

Table 4: Emory #802, 7/11/08

Interval	Ah – String 1	Ah – String 2
0-1 hrs	16.07	13.59
1-1.4 hrs	7.31	6.42
1.4-1.5 hrs	0.87	0.77
3-5 hrs	35.28	27.18
5-5.6 hrs	9.30	10.30
5.6-5.7 hrs	0.20	0.19
Total	*69.03*	*58.45*

3.2 Charge Profiles and Charge Coefficients

The charge profile for the recharge event after EV19's 7/20/08 Bus Route #20-Carpinteria deployment is shown in Figure 2. As would be expected, the charge of String 2 is of shorter duration than that of String 1.

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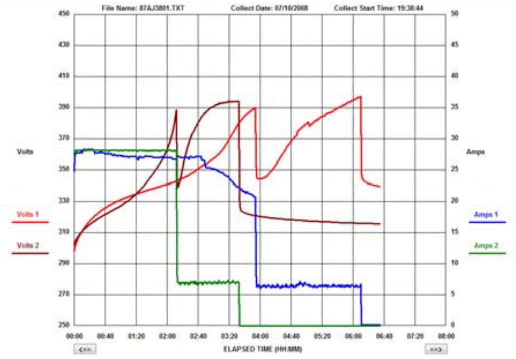

Figure 2: EV19 Recharge Profile

In comparison, a typical charge profile for the Emory buses is depicted in Figure 3. (Because the Emory buses are recharged immediately after they are returned from service, the charge profiles are included in the same file as the drive cycles and current is therefore plotted as negative values.)

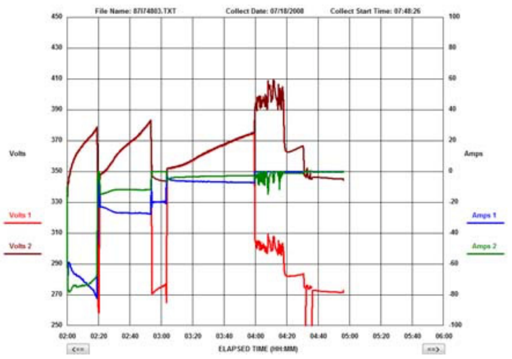

Figure 3: Emory #802 Charge Profile

Review of the above charge profiles indicates that Santa Barbara MTD's EV19 charger delivers a recharge profile that more closely reproduces that specified by Saft, the battery manufacturer. (This is indicative of the many hours of effort that the MTD maintenance department has devoted to this task.) The profile delivered by the charger that recharges Emory's #802 bus, however, does not approximate that specified by Saft, the battery manufacturer, and is worthy of further attention.

Average charge coefficients for the two buses are shown in Table 5. Saft recommends a charge coefficient of 1.15 for these batteries. Therefore, the only battery string that is significantly out of bounds with respect to this parameter is String 2 on Santa Barbara MTD's EV19.

Table 5: Charge Coefficients

Bus	String 1	String 2
Santa Barbara MTD EV19	1.07	1.32
Emory #802	1.10	1.09

3.3 Voltage Spikes

Santa Barbara MTD's EV19 has shown evidence of voltage spikes on String 2 during the driving mode but not during the charge mode. A representative depiction of this phenomenon over a relatively short time span is shown in Figure 4.

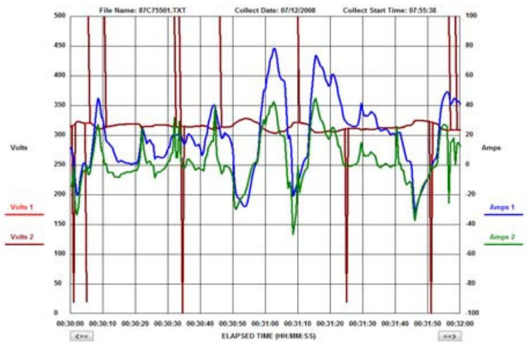

Figure 4: Voltage Spikes on String 2, EV19: 2-minute window

A brief assessment of a random sampling of EV19 driving cycles suggests that these spikes may occur more frequently when the amperage of String 2 drops to zero or goes negative (i.e., drawing a charge from String 1 or regen) while String 1 is still in a discharge state.

For comparison, a driving cycle from Emory #802 is presented in Figure 5.

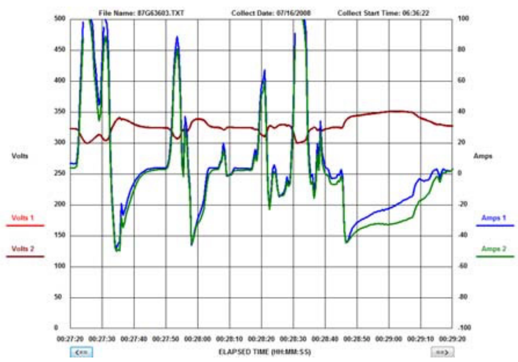

Figure 5: Driving Profile, Emory #802; 2-minute window

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Santa Barbara MTD EV19 recently had its battery system swapped out. A non-service driving profile (i.e., across the bus depot facility parking area) collected with the replacement battery set is depicted in Figure 6.

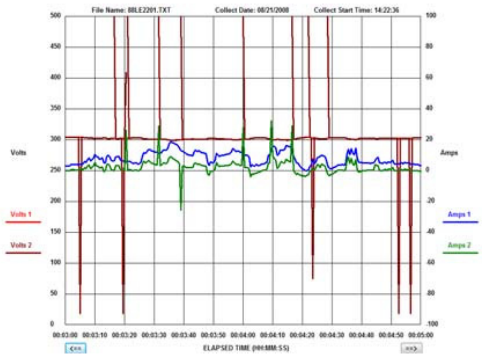

Figure 6: Voltage Spikes on String 2, EV19: Replacement Battery Set

Although the magnitude of the current draw was not as great during this cycle as compared with an operational cycle, the voltage spikes on String 2 persist with the replacement battery set.

The comparative data analysis between the two buses at Santa Barbara MTD and Emory University is an excellent example of the value of the DAS in evaluating the performance of buses. This level of specificity in performance data is necessary to ensure transit agencies can manage their electric- and hybrid-electric bus fleet at an optimal level.

4 Conclusion

In summary, the DAS project met the original project objectives of developing and demonstrating a system that allowed for the analysis of the performance capabilities of a particular bus with the requirements of the operational duty cycle. The DAS was successfully installed and demonstrated on battery electric buses at Santa Barbara MTD and Emory University and on a hybrid electric bus at the City of Sevierville. Data analysis of all three systems show the DAS is operating as intended, and as can be seen from the comparative analysis report in Section 3, the DAS unit provides specific data that can isolate problems such as the out-of-balance battery strings on the Santa Barbara bus. This type of report is representative of the useful data that can be used to diagnose problems and allow for well-defined solutions for electric and hybrid-electric buses.

CETE will continue to monitor the performance and data generation of the DAS units at all three sites in order to ensure continued optimal operation. Additionally, the results of this project and other pertinent information related to DAS will be disseminated to other stakeholders with a need for this type of system to address performance and durability issues with electric and hybrid-electric buses.

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