California Air Resources Board
ICAT Grant #01-1

Electric School Bus with ZEBRA Battery and Integrated Fast Charge

FINAL TECHNICAL REPORT

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Submitted By:

Sacramento Municipal Utility District
Electric Transportation Department

Final Technical Report:

Electric School Bus with ZEBRA Battery And Integrated Fast Charge

Abstract:

The ZEBRA Electric School Bus Project was accomplished with funding from the California Air Resources Board under ICAT Grant 01-1, in addition to funding from other project partners. This project shows how a currently available battery and drive system technology is being used to reliably provide school bus service. As of the writing of this report, the bus has been fielded now for 14 months and 9936 miles. The bus has provided regular service, completing both a morning trip and an afternoon trip picking up and delivering students to Napa Valley Unified School District.

The bus utilizes a Sodium Nickel Chloride ZEBRA battery, advanced Siemens Drive System, and modern CAN Bus linked microprocessor control for a very high level of integration. The possibilities for cost reduction and performance improvements with this control scheme have only begun to be realized. This bus addresses all of the market barriers encountered by early BlueBird TCEV 2000 electric school busses originally fitted with lead acid batteries and Northrup Grumman drive systems.

This final report describes the technologies, reliability, costs, and performance of the bus. The design of subsystems and their assembly into the bus is discussed. Actual performance of the bus shows how this vehicle system is ideally suited for school bus service. Lessons learned and prospects for the future service of this bus are also described.

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<u>**Final Technical Report:**</u>

Electric School Bus with ZEBRA Battery And Integrated Fast Charge

1.0 Executive Summary

This Final Report summarizes work accomplished with funding from the California Air Resources Board and from project participants Santa Barbara Electric Bus Works, U.S. Department of Transportation, Research and Special Projects Administration, and the Sacramento Municipal Utility District. In this project, an advanced battery system and an advanced drive were integrated into an existing 1997 BlueBird electric school bus. The installed system addressed the performance, range, reliability, and cost barriers that limited the market place success of earlier efforts to field electric busses. This report shows why this battery and drive system were chosen. A review of battery technology available today is provided. Operations, maintenance, and costs of this technology have improved to a level that should encourage additional efforts to deploy this technology. Finally, actual performance of the bus during the first 14 months of service is described, including energy consumption, fast charge capability, battery behavior, adequacy of energy storage, and other performance measures.

This ZEBRA Electric School bus achieves energy consumption of better than 15 miles per diesel-equivalent gallon, compared to 6 miles per gallon for a conventional diesel school bus, or 4 miles per gallon equivalent compressed natural gas. A school bus is a great application for electric drives, because of the repetitive trips and frequent return to the bus yard after morning and afternoon routes, when the bus can be recharged. While recent regulations promulgated by the California Air Resources Board prohibit idling of diesel school busses, *electric busses provide for total elimination of diesel exhaust from areas frequented by our children*.

2.0 Introduction and Background

In 1997 the Blue Bird Bus Company produced and sold 15 electric school Busses based on their 37 and 35 foot California School Bus model to support state initiatives at replacing older diesel school busses with clean zero-emission alternatives. Electric school busses, operating on the clean California electricity grid can be 93 % cleaner than diesel busses when considering NOx emissions. In fact, a CO2 emissions comparison between electric busses and other technologies as shown in Figure 1 indicates a strong motivation to develop electric bus technology.

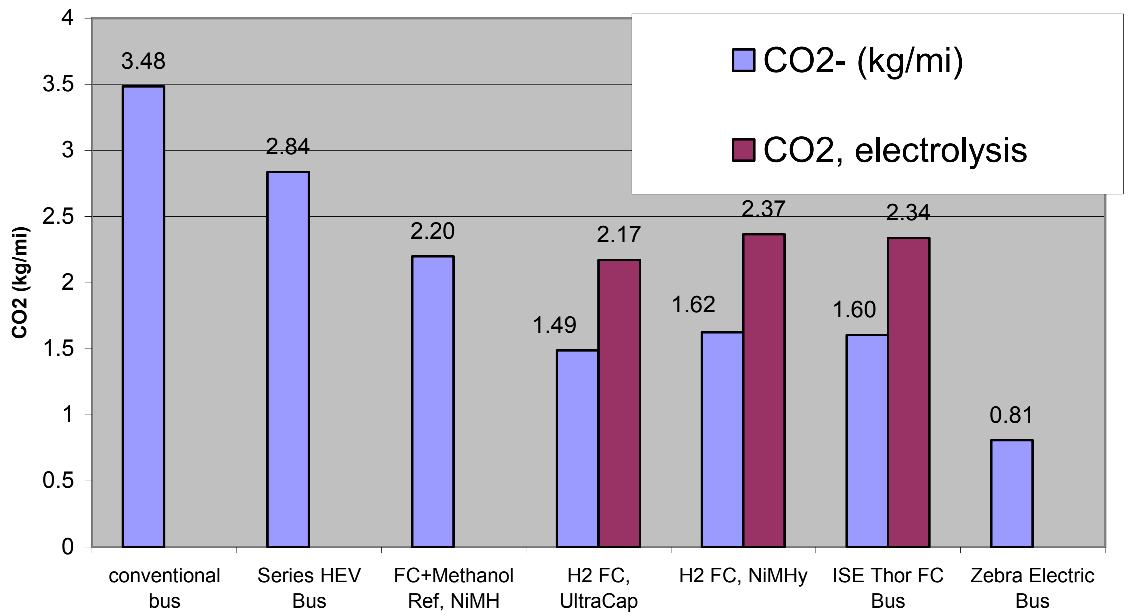

Figure 1: Electric Busses emit significantly less CO2 than diesel, hybrids, or fuel cell busses when powered by combined cycle natural gas electricity generation. [1]

Figure 1 also shows the difference in CO2 emissions for hydrogen powered vehicles, depending on whether the hydrogen is produced by electrolytic splitting of water, also called electrolysis, or by reformation of natural gas, using a combination of catalyzed partial oxidation reforming and steam reforming. Reforming natural gas is the most prevalent commercial method for hydrogen production today. Less common now, but commercially available electrolysis will likely be used to produce hydrogen using renewable energy options, such as hydrostatic, solar and wind power.

The original fifteen Blue Bird Electric Busses used GNB lead acid batteries, an Enerpro Fast Charger and a Northrup Grumman Drive System (Northrup Grumman sold this division to Satcon). The initial 15 Busses operated adequately at first, but problems started to show up after approximately 6 months due to premature battery system failures. The original planned life for the battery packs and warranty was two years. Troubleshooting on the original bus battery systems uncovered many shortfalls in the battery pack design and the battery charging system interaction.

The original lead acid battery pack design stacked two layers of batteries in a steel structure, one layer on top of the other and housed them in fiberglass protective covers. This design was fraught with problems. First this design connected four parallel strings of 28 modules per string in parallel with no means to assure current flow was balanced through each of the four parallel strings. In a high voltage battery pack, it is important to keep each individual battery cell at the same state of charge and capacity. When the cells are different and the pack is discharged, the weaker ones reach a complete discharge earlier, limiting range, and possibly incurring damage due to over discharge. During recharge, the stronger cells are prone to being damaged due to their reaching a full state before the other cells.

With four parallel current paths or strings of batteries it was impossible to keep the battery state of charge balanced within the strings and between 112 batteries that made up the packs. Within the battery pack assembly, the state of charge and health of individual cells diverged, and the range of the bus quickly decreased as the busses were driven. The driver had no means to determine remaining range other than a voltmeter, and over discharge of the batteries was common. The battery system did not provide for cooling which let the batteries constantly get hot thus decreasing battery life. This condition was further exacerbated by the warm California climate and because the battery resistance increased with over-discharging. In an effort to improve cooling many school bus maintenance organizations added cooling holes in the fiberglass cover to allow more cooling, but this did not help much.

The stacked battery module layout accidentally provided a large voltage potential pathway from the top stack to the bottom stack in one corner of the pack. This problem led to one of the busses experiencing a high voltage discharge when one of the top battery module cases cracked and allowed acid to drip onto the bottom stack creating a high voltage short circuit.

Additional problems were associated with the lack of a battery management charging system having adequate instrumentation to effectively monitor and control battery charging operations. This caused repeated over-charge and discharge of individual batteries in the subpack causing them to fail prematurely. (One of the four battery series strings of 28 battery modules is referred to as a subpack.) This problem was compounded by the battery system design that connected the four subpacks in parallel that made it impossible to control charge or discharge current to any individual subpack.

SMUD conducted its own diagnostics on the original Blue Bird Bus design in 1998 and confirmed that improved instrumentation and an active battery charge management system could improve battery life by providing charge equalization for each module [2]. Equalization is one strategy used in short series strings of lead acid batteries to even up the cells state of charge through a mild overcharge. Periodic battery equalization has been proven to improve battery life by bringing each module up to the same state of charge so one subpack does not have to work harder than another subpack, thus avoiding premature life degradation. The original Blue Bird Bus individual lead acid battery recharge voltages were diverging over time due to lack of an active management system, over charge or over discharge of individual modules, and resulting changes in module internal resistance. The undamaged batteries had to do all the work, and thus some modules were providing higher than intended currents and discharging more quickly. High resistance batteries in the string also diverted recharge current to the relatively more healthy strings, exacerbating the divergence in subpack state of charge and module voltages.

In spite of these problems, the school busses were quite popular with students and bus drivers. Several projects have been undertaken to deploy advanced battery technology to resurrect these Bluebird busses. Notably, this effort has included a number of busses (including ZEV3 at Napa) retrofitted with Solectria drive systems and advanced lead acid batteries. In addition, one of the busses at the Napa Valley Unified School District (ZEV-5) was fitted with Ovonic Nickel metal Hydride batteries, in combination with an AeroVironment Posicharger. The Bay Area Air Quality Management District funded the Napa Solectria bus, and the Ovonic bus was funded by the US Department of Transportation –

Research and Special Projects Administration- Advanced Vehicle Program.

For the present project, a high voltage (557 V) sodium nickel chloride battery is combined with Siemens power electronics and Santa Barbara Electric Bus Works software and know-how to resurrect one of the Bluebird busses. This report describes the design, operation, costs, and performance of this bus. A review of presently available battery technologies is provided to help the reader place the technical significance of this bus in context.

3.0 Battery Technology

Battery technology is seen as one of the key limiting factors in meeting the cost, reliability, and performance goals of electric drive technologies. This project shows one battery technology that addresses this technical and cost barrier.

Several promising battery types have emerged and become more technically and economically viable as a result of intensive work on storage batteries for electric vehicles and other technologies over the past decade. Although lead acid technology essentially achieved a current performance benchmark in the mid 1990's, improvements in manufacturing processes appeared to have made advanced lead acid batteries more suitable for assembly into high voltage battery packs, since the variability between modules has for certain manufacturers become minimal. While Lead acid batteries are the heaviest per unit energy storage (energy density), they are still the lowest cost battery.

Nickel Metal Hydride batteries were used extensively in EV's fielded in 1998. These batteries were shown to provide more than 100,000 Ampere hours of throughput, and last more than 100,000 miles and more than 4 years in EV service [3]. Several manufacturers advanced NiMH technology to the point of being market ready, including VARTA, Saft, Panasonic, and Texaco - Ovonic Battery Company. These batteries remain relatively expensive, but because of their long life, may provide viable life cycle cost applications, depending on the degree of integration and robustness of the host system and host vehicle.

Lithium Ion batteries are a more recent entrant in the advanced battery technology market. They offer very high specific power and specific energy. While Li-ion batteries are common in computers and consumer electronics, cells large enough for bus applications are still in the prototype stage. Li-ion technology would reduce the battery mass while enabling higher power. Li-ion batteries also have a high cell voltage, and would therefore decrease the system complexity by decreasing the number of series connections in the battery pack.

The Sodium Nickel Chloride battery was marketed extensively by AEG ZEBRA Marketing in Germany, and was used extensively in the German EV demonstration program at Ruegen Island in the early 1990s. In 1998 MES-DEA SA of Stabio Switzerland acquired the battery design and tooling, and began limited production and marketing of ZEBRA batteries. Since that time, MES-DEA invested 100 million Swiss Francs in production tooling and achieved significant cost reductions and technical advancements. By arranging 216 cells in series in their Z5C sealed package, a 557 nominal voltage battery that is ideal for high power (150 kW+) drive systems is created. This battery is completely sealed, and includes internal contactors and a battery management system capable of CAN bus communication. Data on the ZEBRA battery is included in Appendix 1. This data includes a price quote of $220/ kW-h for 30,000 module assemblies per year. If this volume were achieved, the ZEBRA battery would become more cost competitive than advanced lead acid batteries on a cost per unit energy throughput.

Current battery technologies are summarized in Table 1. In this table a battery pack mass, volume, and cost are calculated based on achieving a 107 kW-h battery pack, as used in the ZEBRA school bus. For completeness, Nickel Cadmium batteries are included in the table. The table shows that the ZEBRA battery offers the lowest weight battery with sufficient energy storage to comfortably meet the school bus trip mission, as we currently perceive it.

Battery	ZEBRA	Saft NiCd	Ni-M-Hy	Saft Li Ion	Pb-Acid
Specific Power W/kg	178	200	180	262	200
Specific Energy W-h/kg	100	55	70	126	35
Energy Density W-h/l	154	88	145	197	90
Cycle Life	1250	2000	2500	2000	500
Cell Voltage	2.57	1.2	1.2	3.8	2.2
Mass of a 107 kW-h pack- (kg)	1070	1945	1529	849	3057
Volume of a 107 kW-h pack (liters)	695	1216	738	543	1189
Peak power of 107 kW-h pack (W)	190	389	275	222	611
number of cells for 557 V	216	464	464	147	253
Cost in 2003	$53,500	$42,800	$80,250	$321,000	$16,050

Table 1: **Battery Technology Comparison**

Costs in Table 1 assume modest production volumes, not the high volume scenario mentioned above. The cost figure listed for the ZEBRA is $500/ kW-h, representing the 2003 price. In 2002 the price paid for the batteries was $656/kW-h, and the 2004 price appears to be $467 in low volumes.

Figure 2 shows a comparison of the mass and volume of the different battery technologies given the energy storage capacity used in these busses, as shown in Table 1. Figure 3 provides a battery price trend.

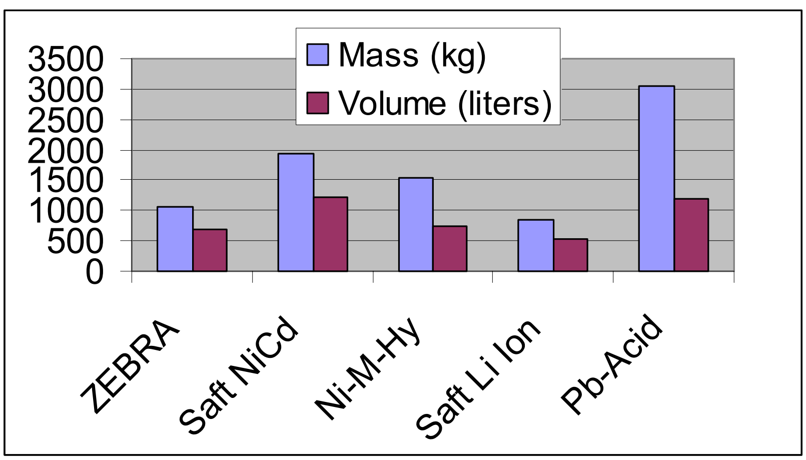

Figure 2: The ZEBRA battery provides a good compromise in pack mass and volume

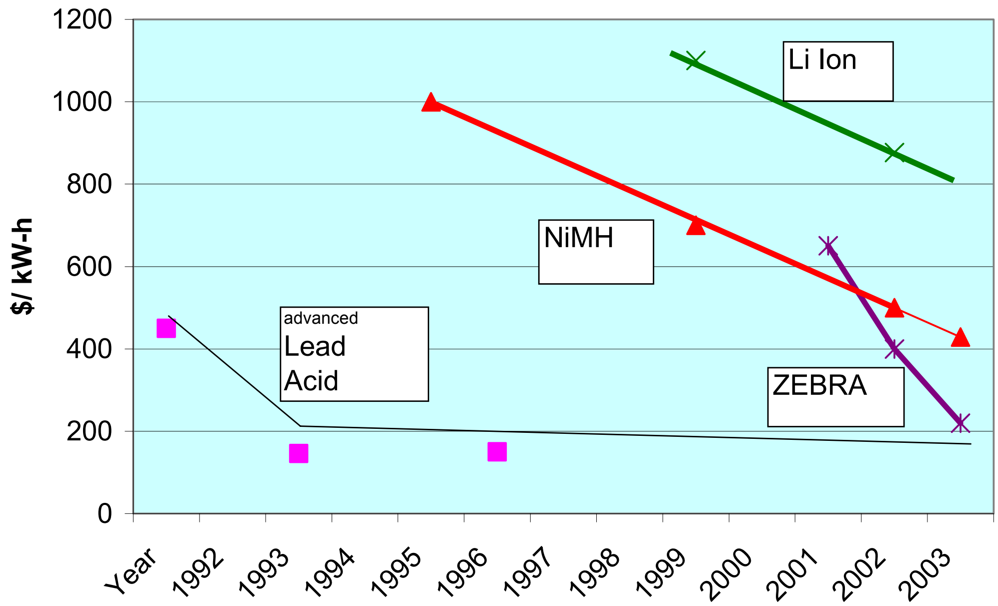

Figure 3: MES-DEA is driving down the cost of the ZEBRA Battery, especially in relation to other technologies

4.0 Design of the ZEBRA Bus

The propulsion system design was completed in the fourth quarter, 2001. The design effort focused on integrating the ZEBRA battery with Siemens power electronics and controls. The Siemens drive system is an advanced induction motor system driven by microprocessor controlled power electronics. The Siemens motors and controllers were developed specifically for vehicle use. Microprocessors in each subsystem can communicate with those in other systems utilizing a Control Area Network (CAN) network cable in which encoded messages are sent and received by the various components on the network. The design also used on of the power inverters on the bus as a high powered “fast” battery charger, input power being provided by an off board power conversion system that connects to the power inverter with three phase power cables similar to those on the motor side of the drive inverter.

The advantages of the Siemens system are that it is in limited production now, it is modular, and it is well developed and robust.

The Siemens drive system relied on the Drive Input Control Unit (DICO) to translate J-1939 CAN bus commands for the DUO Drive Inverters. One of the key challenges of this design was to design and program an electric vehicle control unit (EVCU) and a battery interface for the battery system that could communicate with the DICO. Because standard software driven Siemens systems were acquired, the main work for this project was software design. Application software development was required because the drive system must take into account vehicle specific characteristics, such as mass, rotating mass, in addition to the communication needs of the various subsystems, which had not before been combined in this fashion.

One design accomplishment in this area focused on design revisions to the Electric Vehicle Control Unit (EVCU). The EVCU is the “brain” of the propulsion system and its proper function is essential to bus safety and reliability. Among the many functions of the EVCU is to translate between the various CAN-protocols used by propulsion system components. A new CAN-protocol translation unit was integrated into the EVCU in order to achieve the high reliability required of this critical system. Reprogramming of some of the propulsion system software (i.e., motor drive interface, battery management system, and EVCU) was accomplished, and bench testing was completed.

Another interesting and significant accomplishment was to make the DICO drive controller recognize the battery management system control messages. This allowed the battery manager to communicate the results of its polling of the six 557- volt battery modules and determine the control limits (voltage and current) for the limiting module. These limits are operative during driving (discharging) and during charging. The ability to control in this manner means that as the battery ages and begins to lose cells or capacity, the system will compensate and continue to charge and to manage discharge correctly. One feature of the ZEBRA battery is the fact that when cells within the battery module fail, they fail short circuit. This allows the battery to continue to function, albeit at a lower voltage. Santa Barbara Electric Bus Works engineers have indicated that they believe the battery system will continue to function with 5% cell loss, and have projected bus operations for another 5 to 6 years based on current performance.

Charging power is provided to Siemens Duo Inverter number two from an off board power supply. This power supply converts 480 three-phase power to 330V three-phase power at up to 93 kW to the inverter. The inverter then converts the power to direct current, and onto the high voltage battery Buss.

During charging, the Battery Management Interface must communicate with each battery to determine what the limit or clamp voltage is for the main high rate charge phase. [1] Charged to this clamp voltage, the batteries are approximately 80% charged. The clamp voltage limit is communicated to the Charge inverter via the DICO. Once the limit is reached, the inverter stops charging. A brief discharge pulse is accomplished to remove the surface charge from each of the batteries, and a new set of charge voltage limits is requested from the set of six modules. At this point the Battery Management Interface may elect to charge one of the six modules to some voltage-limited state of charge. It may then select another battery, and similarly advance it's state of charge. As the six different modules diverge in health and cell count, the time needed to complete a full charge is stretched out, but because of the high power charger the 80% state of charge is reached in about an hour after a typical bus route.   Since the pack is conservatively designed relative to its duty cycle, reaching 100% state of charge every cycle is not required.   This is discussed further in the Performance section of this Final Technical Report.

For more information on the design of the system please see the Santa Barbara Electric Bus Works Final Report in Appendix 2. Descriptions of the design process and a detailed Battery Integration Report as delivered by Santa Barbara Electric Bus Works provide more details about the design, and are provided in Appendix 3. Design of safety features of the Bus taking into account SAE Surface Vehicle Information Report J-2344 Guidelines for Electric Vehicle Safety is covered in a design document included in Appendix 4.

[1] Interested readers can refer to Linden; Handbook of Batteries and Fuel Cells for battery technology information and terminology.

5.0 Review of Costs

This section provides a review of component costs for the prototype bus, and then additionally an estimate of life cycle cost for operating this electric school bus. The lifecycle cost estimate provides a basis for comparison of this electric school bus design with compressed natural gas (CNG) or diesel school busses.

5.1 Review of Component Costs

One of the primary goals of this project was to show that this electric bus technology was cost effective and might have commercial potential. It should be remembered that this bus was a one of a kind prototype fabricated on an existing bus platform. A large amount of effort is involved in producing one-off components for each part of the vehicle system, and significant cost reduction will be possible even in volumes of 10 to 20 vehicles. Component costs for this first one-off unit are listed in table 2.

Quantity	Components	Cost
6	ZEBRA battery	$70,062
1	Battery Server	$938
2	Drive Motors	$12,000
1	Flanders Gear Box	$9,500
2	DUO Inverter	$22,000
1	Drive Input Control Unit	$3,000
1	Cable Set	$2,753
1	Electric Vehicle Control Unit	$12,880
1	On Board Power Eq. Package	$23,890
1	Off Board Power Unit	$15,760
		$172,783

Table 2: Component Costs for the Prototype Bus

In moderate volume production, this bus drive system would cost $80,000 dollars or so, which would amount to an incremental cost of about $70,000 over a conventional diesel bus without 2007 engine technology or emission controls, catalysts, or special fuel. (2007 represents the next step function in diesel engine emission control technology, as driven by EPA and CARB emissions regulations.) It appears that this bus design therefore has commercial potential, if the benefits of clean quiet, diesel particulate free operation are taken into account. A more optimistic assessment of the future cost potential is provided in Appendix 5, in which a more rigorous comparison of diesel, fuel cell, hybrid, and electric busses is undertaken. In this (Appendix 5) analysis, the incremental cost of this electric bus is reduced to less than $25,000, assuming that manufacturing of drive components reaches greater than 10,000 per year levels. It is noted that the energy consumption figures in this Appendix 5 report appear to be rather pessimistic, as the actual energy consumption discussed in the performance section below is quite a bit better than the analytical model.

5.2 Life Cycle Costs

To provide a comparison to school busses commonly used today to provide pupil transport, cost data was obtained from Elk Grove School District. Elk Grove operates 41 diesel and 26 CNG school busses. The diesels are 1989 to 1992 models, and the CNG's are 1992 – 2004 models. Using actual energy and operating costs from Elk Grove, and values derived from this project, the following comparison of life cycle cost elements is possible.

Table 3 provides the input data for the life cycle cost comparison. The Elk Grove busses are driven about 18,000 to 19,000 miles per year, while the Napa ZEBRA bus is expected to complete around 13,000 miles based on present routes. The original lead acid bus is included to indicate the progress that has been made in electric school busses. It is noted that the battery replacement labor and battery cost is included in the maintenance line in the table, because yearly effort to maintain

Life Cycle Cost Analysis	Diesel	CNG	ZEBRA Electric	lead acid orig.bus
Acquisition cost	$105,000	$140,000	$200,000	$230,000
Fuel cost $/mi	0.17	0.22	0.20	0.22
Maintenance cost: ($/mi)	0.36	0.25	0.16	1.50
Battery replacement- 6 years	na	na	$51,000	Yearly

Table 3: Life Cycle Cost Input Data

batteries was required with the lead acid battery pack design. The energy costs used were $1.03 per gallon of diesel, $0.813 per Therm

(100,000 BTU) of natural gas, and $0.10 per kW-h. School districts as government entities are exempt from fuel taxes on diesel, and may get lower prices on natural gas and electricity than other commercial activities.

For comparison on an annualized cost basis, an annual mileage of 15,000 miles and a 10-year life are assumed. The ZEBRA batteries are assumed to have a 6-year life, which matches their performance warranty and the current usage. An interest rate of 5% was assumed. Table 4 shows the resulting annualized cost comparison. These figures are shown graphically in Figure 4. The prototype ZEBRA bus project has shown how utilizing an advanced battery and drive system reduces the cost of an electric school bus.

Life Cycle Cost Analysis	Diesel	CNG	ZEBRA Electric	Lead acid orig.bus
Vehicle life, years	10	10	10	10
Annualized purchase cost	$13,597.98	$18,130.64	$25,900.91	$29,786.05
Battery life, years			6	1
Annualized battery cost			$4,928.55	
Annualized fuel cost	$2,505.00	$3,225.00	$2,998.25	$3,277.97
Annualized maintenance cost	$5,445.00	$3,750.00	$2,400.00	$22,500.00
Total annualized cost	$21,547.98	$25,105.64	$36,227.72	$55,564.02
Cost per mile	$1.44	$1.67	$2.42	$3.70

Table 4: Annualized and Per-Mile life cycle costs [4]

It should be emphasized that the costs considered here do not include the health care and long term costs of exposure of school children to Diesel Exhaust. More cost reduction and effort to deploy and utilize electric drive technologies in school busses is warranted

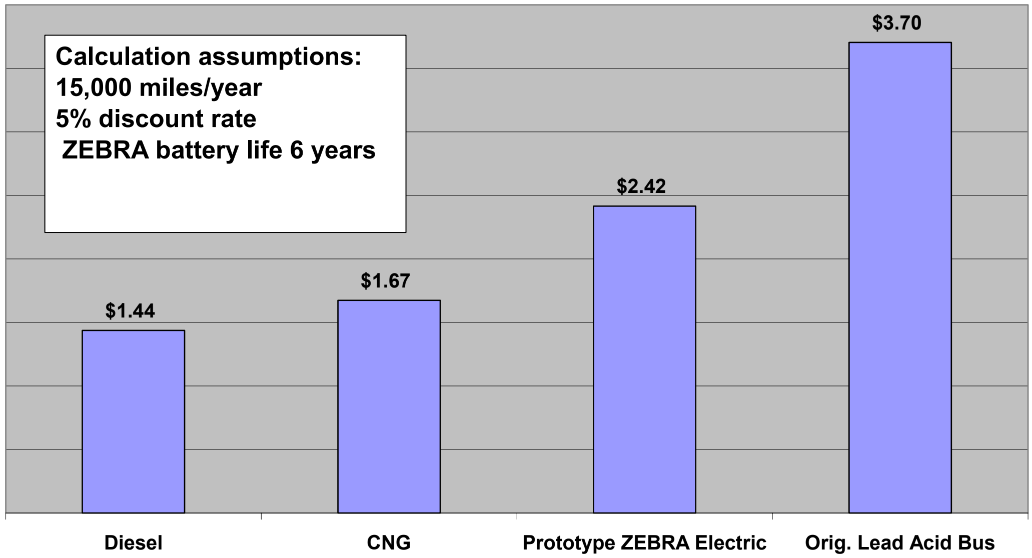

Figure 4: Cost Comparison of the Prototype ZEBRA shows that the cost premium for an electric bus is greatly reduced.

6.0 Operating and Maintenance considerations

Operation of the bus is essentially identical to driving a normal school bus. The drive system in the bus behaves just like an automatic transmission bus, and no clutching or shifting is required. The driver has a forward – reverse switch to select driving direction. A touch screen provides status information, including state of charge and system temperatures.

One feature that is an improvement over conventional busses takes a little getting used to - starting the bus on a grade. In conventional school busses, the driver would execute a “heal and toe” maneuver - operating the brake and accelerator at the same time to start on a hill without roll back. The ZEBRA school bus however, utilizes a programmed creep value in the drive system that wants to creep the bus forward at a very low speed, unless the brake pedal is pushed. When placed in drive, the driver need only lift his foot from the brake pedal, at which time the bus will creep forward at the set speed regardless of slope up to the grade ability limit. Application of the accelerator increases the speed of the bus above the set creep speed value.

This bus has a number of legacies from the original 1997 Blue Bird design, and some other issues because it is a prototype bus. These are not worth enumerating here, as they are expected in a prototype bus, especially one built on an older platform. The ZEBRA Bus has completed 9936 miles as of April 2004, and has been available 69% of school days since its deployment. This amounts to 159 days of service out of 230 school days from March 2003 to April 1, 2004. This availability is considered very good for the first prototype of a vehicle type, in any vehicle industry. The bus continues to accumulate about 1000 miles per month.

Often trouble shooting and maintenance requires a CAN interface equipped computer or laptop with serial cable to access and diagnose the various systems. It is certain that training maintenance personnel and gaining experience in trouble shooting these systems would be an important element of any program to field electric busses, since the skill set and procedures are different from those required for conventional busses.

It should be recognizing that many high voltage battery packs are assemblies of 12-volt modules, wired together in series to realize high voltages. The original Blue Bird busses used 28 each 12 Volt modules to provide 336 volts. Maintenance of batteries in an electric bus constructed with conventional lead-acid 12-volt battery modules frequently requires maintenance personnel to work on high voltage wiring within the pack. Since the ZEBRA battery is self-contained it represents a safer option for maintenance personnel since the internal contactors are opened unless the system is given a pilot signal, and senses an allowed load on the output of the battery. With a ZEBRA battery, replacement can be accomplished without working on high voltage wiring. Santa Barbara Electric Bus Works provided detailed operating and maintenance manuals, which are included in Appendix 6.

7.0 Performance of the Bus During the Demonstration Period

The bus was placed into service during the first quarter of 2003. This milestone was delayed due to resource constraints of the bus fabrication subcontractor. Upon vehicle construction completion but before the batteries could be brought up to operating temperature, the off board charger had to be installed at Napa Valley Unified School District, and the bus transported to that location. Once in operation, Santa Barbara Electric Bus Works completed a detailed safety checkout. The completed Safety Check List and procedure is included in Appendix 7.

A safety inspection of the charge system wiring and OBCU installation was made and the system was declared safe for battery heating and charging. Battery charging was initiated and initial software checkout of the batteries was accomplished at Napa in January 2003.

Safety testing of the drive-system wiring was repeated and initial driving tests were completed in early February 2003. The drive system was not fully functional due to a lack of feedback signal from one motor. Close examination of the control wiring revealed that a motor control cable had been incorrectly assembled at the factory. The wiring errors were corrected and driving tests were initiated. System response to driver inputs was evaluated and minor changes were made to the accelerator and brake calibrations.

Regenerative braking was found to be nonfunctional at this time. A close examination identified software parameters as the cause. Correct parameters were entered into the inverter controls and testing was continued without further interruption.

Testing showed that the expected performance levels were realized. Top speed of 62 mph and grade-ability of 15% at over 15 mph was achieved. Operation at full power of 170 kW was realized but the traffic and terrain in the Napa rarely allow for or require operation at this power level. Starting on grade was accomplished on all hills that were attempted. Response to driver controls and feedback through the driver display were evaluated and found to be without fault.

Initial performance testing and driver training showed energy consumption of from 1.4 to 1.6 kilowatt-hours per mile, which is equivalent to diesel fuel economy of about 20 miles per gallon. Traction energy consumption was about 1.8 kWh/mi and regenerative braking returned from 0.2 to 0.4 kWh/mi to the batteries depending on the route and driving style. Un-recharged range of the bus from 100% state-of-charge to 15% SOC in route service is estimated to be from 60 to 70 miles, depending on driver skills, average speeds and gradients, and passenger loads.

Maintenance personnel were familiarized with the bus systems. Driver training and maintenance manuals were furnished to the school district and the Transportation Director trained the bus's driver while continuing testing. A range test at freeway speeds to Yuba City revealed a minor component-overheating problem that was later corrected. A round trip of 55 miles was accomplished with a finishing state-of-charge of 20%.

Late in the first quarter 2003, the bus was put into route service. The superiority of the ZEBRA battery system design was demonstrated by an event on the last school day of March 2003. One battery automatically went offline. Examination of the battery's fault logs early in the second quarter 2003 revealed an internal fault that was ultimately traced to a faulty battery management interface unit. The bus remained in service, as its assigned duty-cycle did not require the full complement of batteries to achieve the needed range.

During the second quarter 2003, initial performance of the bus was monitored closely while performing normal bus routes. The bus averaged 52 miles per day, completing both a morning and an afternoon route. The battery management interface (BMI) unit that had been identified as faulty during the previous quarter was replaced in early June. As of the end of the second quarter the bus was functioning again on all six battery modules. A Roadworthiness Test Report Was prepared during this time, and is attached in Appendix 8.

In September 2003 the bus began to experience problems while charging unattended at night. The 24-volt lead acid batteries that are used to operate auxiliary systems, including compressed air and power steering would be discharged to below 20 volts in the morning by the time the driver attempted to start the bus and the ZEBRA battery state-of-charge would only be 95%. The bus would not start and it was necessary to charge the 24-volt batteries with an external portable charger. The charging system and 24-volt batteries were thoroughly evaluated without the identification of a problem. Diagnosis of the problem via telephoned reports was both slow and irresolute. Onsite visits by Bus Works personnel eventually confirmed the immediate cause of the problem. It was determined that the problem of discharged 24-

volt batteries and incomplete charging were closely related. The 24-volt batteries were not being adequately charged and charging of the traction battery was prematurely discontinued at 95% state-of-charge. New battery-management software was loaded into the battery-management interfaces and the multi-battery server (MBS).

However, the new software did not solve the problem of charge termination before all ZEBRA batteries reached a full state-of-charge, and subsequent discharge of the 24-volt battery. Further investigation revealed that one ZEBRA battery at 70% SOC was not connecting to the high-voltage system although its battery-management interface unit was reporting that it was connected. Near the conclusion of the charge process, the other ZEBRA batteries would reach a full state-of-charge and the charge inverter would abort the charge after encountering open-circuit conditions while the battery server indicated a battery online. The abort mode also turned off the auxiliary inverter that powered the on-board 24-volt charger. Inspection of the faulty battery's wiring failed to reveal any problems. The next diagnostic step of removing the battery management interface from the suspect battery was not undertaken in order to allow the bus to participate in the Michelin Challenge Bibendum at Sonoma the following day. The suspect battery was taken off-line in order to allow normal charge completion.

While bus range was slightly degraded by having one ZEBRA battery offline, the bus successfully competed in the Michelin event. Further diagnosis of the battery problem revealed a faulty connector in the Battery Management Interface. This connector was replaced in October 2003, bringing the battery back on line.

In spite of operating on five of six ZEBRA battery modules, the ZEBRA Electric School Bus earned two gold medals and two silver medals at the Michelin Challenge Bibendum September 23, 24, and 25, 2003. During these tests the bus was loaded with bags of cement to rated load. Driving performance during the noise test was great. The bus was able to accelerate to 30 mph in the same distance as most of the cars.

The ZEBRA school bus also performed well during the fuel economy tests, driving on 18% & 24% grades while lapping the Sears Point circuit and lapping at a high enough speed to be in an early lead. Stop signs were installed on the circuit during the tests to simulate stop and go driving. After stopping on a 24% grade, the bus could not pull away from the sign. The bus was backed down only 20 to 25 feet and then was able to get over the top. After that first stop no one was required to make the stop on the 24% grade. The time lost during stopping and backing up on the 24% grade allowed the fuel cell busses to pass the ZEBRA bus. Before the 6th lap around the course the ZEBRA bus passed the fuel cell busses and returned to its leading position, ahead of the fuel cell busses. Those busses were so much slower up the hills that the ZEBRA bus could overtake them. Acceleration testing also went very well. The bus was able to accelerate to 41.6mph in the ¼ mile. A summary of testing is included in the following Table 3. The ZEBRA School Bus is listed here as the 1997 Blue Bird.

		Acceleration	Emissions	Energy Efficiency	Noise	Range	Totals
2003 E Bus Vintage Trolley	Battery-Electric	1	4	NS	3	NS	8
2001 Gillig Standard Floor, 40'	Diesel Hybrid	3	NS	4	NS	1	8
1998 Mercedes-Benz Citaro	Fuel Cell	2	4	4	4	2	16
1997 Blue Bird Electric School Bus	Battery-Electric	3	4	4	3	1	15
2001 ISE Fast Track Fuel Cell Bus	Fuel cell Battery	2	4	4	2	2	14

Table 3: Michelin Bibendum Challenge Results for Busses (Higher number is higher score; NS means no score)

Performance tests on the bus have shown that it has a wide margin of safety on its energy storage system compared to the energy required to complete driving routes. Figure 4 shows that 1/5 to 1/3 of the battery's capacity is being used for normal routes. It will be interesting to see how many cycles the bus completes with this shallow discharge.

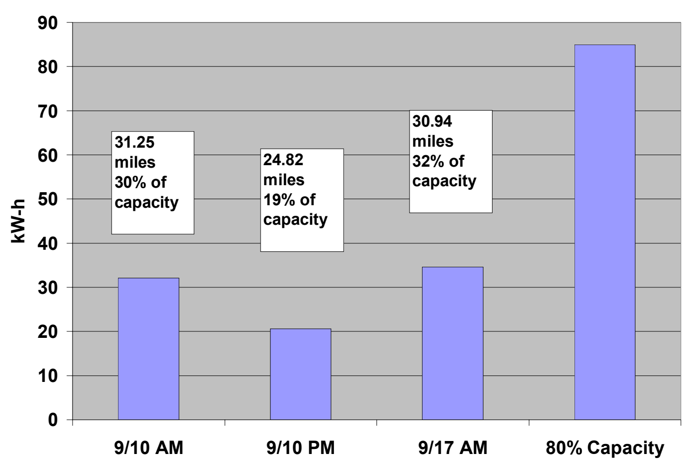

Figure 4: The ZEBRA Bus has a comfortable battery capacity margin

This is a definite improvement over the lead acid battery busses, which were frequently over-discharged to complete a 30-mile route.

Charging to 80% state of charge after the morning route is normally completed about one hour after plugging in. Figure 5 shows a full charge being completed in less than an hour after the afternoon run on September 10, 2003. Note also how surface charge is removed from the battery by a discharge pulse (positive current is charging).

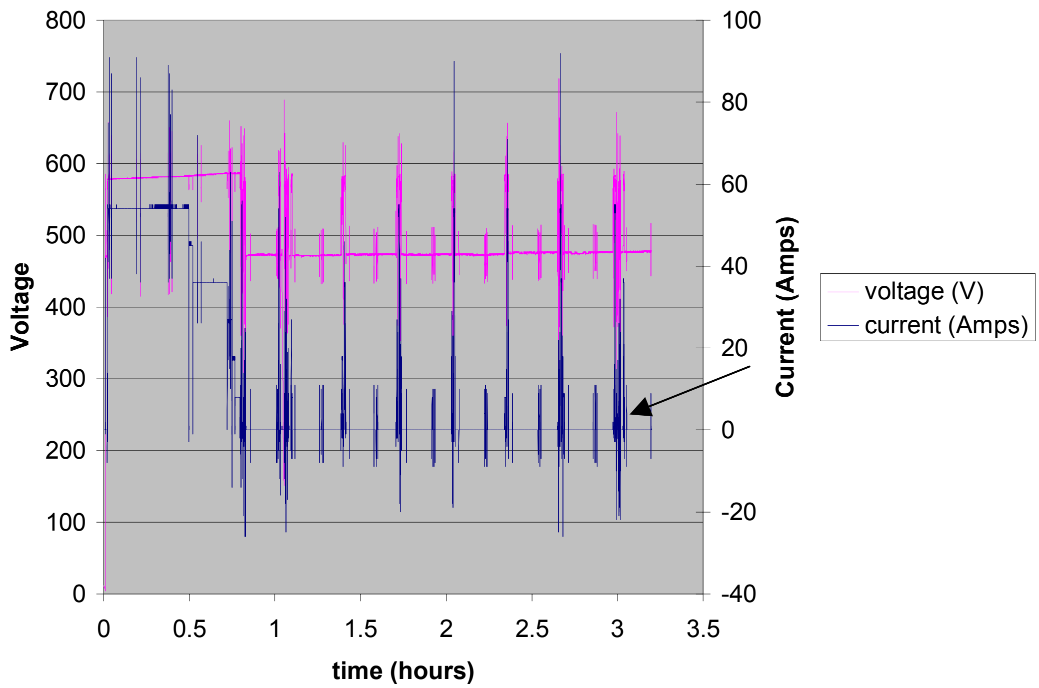

Figure 5: Recharge from 25-mile trip in less than one hour

7.1 Modeling versus Measured Performance:

Energy consumption of the 557 Volt ZEBRA bus is lower than modeled, the actual value being around 1000 DC W-h per mile. Before the bus was completed, Professor Andrew Burke of UC Davis applied his extensive experience and using a SIMPLEV modeling program performed modeling of the busses to predict performance. The modeling effort is described in the report included in Appendix 5. The ZEBRA bus also has lower energy consumption than the 317 Volt Ovonic Nickel Metal Hydride Battery bus which normally consumes around 1400 W-h/mile. We attribute these differences mainly to higher efficiency of the high voltage drive, which was probably not adequately taken into account in the modeling efforts. Figure 6 shows the difference in modeled versus actual energy consumption for the two busses. The GT-50 and CBD values are from modeling, while actual was measured during driving tests. One other source of this variation could be due to driving cycle differences.

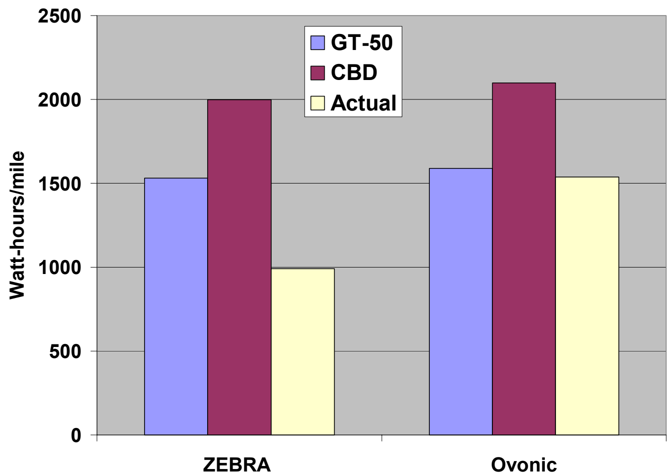

Figure 6: ZEBRA Bus Energy Consumption is lower than predicted by modeling

The drive system is correctly sized. Drivers use the full 170 kW drive system for acceleration, and utilize up to 140 kW for braking, as shown in Figure 7.

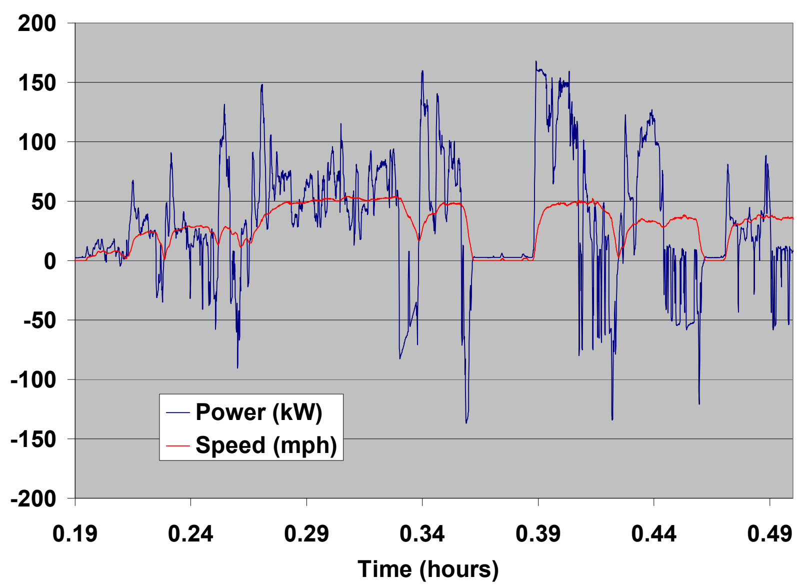

Figure 7: Sample of power and speed levels from a driving test

Santa Barbara Electric Bus works has been monitoring performance of the bus since it was commissioned early in the year. A comparison of data taken shortly after commissioning and later this fall shows that the apparent battery efficiency (power in/ power out) has dropped from 85% to 78%. This could be due to cooler temperatures and additional heating of batteries, or it could be due to more energy used to recharge batteries that are less balanced. This change is so far not fully understood. This data is shown in the In Service Test Report attached in Appendix 9.

The in-service test report also discusses the energy required to keep the ZEBRA batteries at 270 C internal temperature. The batteries are enclosed in a stainless steel case, as shown in Figure 8. Although about 100 W might be consumed to keep each of the six batteries hot internally, the outside surface of the battery case is only warm to the touch. The batteries are kept warm by power from the off board grid connected power supply while the bus is stationary, and heated by their own power while driving. The energy consumption to keep the batteries hot appears to be about 40W-h/mile per battery, or 240 W-h/mile total. External power is required around the clock to prevent cooling of the batteries, and this bus must be plugged in when not being driven. The batteries do have a lot of thermal inertia, and there is no danger of losing battery heating unless the bus is left unplugged for an extended period, over a day for instance.

Figure 8: The ZEBRA Battery is enclosed in a stainless steel case

8.0 Conclusions and Recommendations

Operation of the ZEBRA bus had been reliable and economical. Energy consumption has been better than 15 miles per diesel-equivalent gallon, and maintenance costs have been lower than expected for a first of a kind development prototype. Most of the problems encountered with the original bus design have been addressed through three main elements that are:

- Improved System Integration through microprocessor control and CAN Bus Communication
- High Performance, High Efficiency, Software Driven drive and charging system
- Improved Battery Technology with integrated battery management and control

The performance of this bus should be monitored in the future to verify the actual life and aging characteristics of the system. As of this writing, the bus appears to perform its mission with ease. During extended service of this bus, opportunities to document maintenance experiences and procedures could prove extremely valuable for future training of maintenance personnel. In addition, these records would be invaluable in assessing the actual life cycle cost of this bus system. It is noted that cycle life of 2500 cycles was listed in Table 1 for Ni-MH batteries. This exceeds the expectation for those batteries derived from early experience. Will the ZEBRA bus exceed the guarantee? What effect will the shallow discharge cycles have on the batteries ultimate life? Continued operation will answer these questions. It is our hope that efforts to maintain the bus and find these answers continue at Napa Valley Unified School District.

Electric Busses have a tremendous potential to improve energy efficiency and to provide the cleanest possible transportation for our children. Additional effort to develop this technology and to educate industry and policy makers is warranted. Figure 9 shows the bus as deployed in the Napa Valley Unified School District last spring.

Figure 9: ZEBRA Bus deployed in the Napa Valley Wine Country

9.0 Commercialization

Santa Barbara Electric Bus Works continues to market these electric bus systems. The potential for the ZEBRA battery combined with the Siemens drive system is large, however, school districts have limited budgets and additional public will to implement zero emissions busses must be developed. A Commercialization Report from Santa Barbara Electric Bus Works is attached as Appendix 10.

Meanwhile, MES-DEA in Switzerland continues to develop new markets for the ZEBRA battery. One notable example is the batteries use in submersible watercraft. MES-DEA has also pioneered a battery-leasing program that helps customers manage the first cost of these batteries by spreading battery payments out over the battery warranty period, and by assuring the residual value of the battery is realized by placing it in a less demanding application once its capacity has been reduced below that needed for vehicle service.

10.0 Key Personnel:

PROJECT PARTICIPANTS

Following is a list of project participants, including key contacts:

William R. Warf, Project Manager, Sacramento Electric Transportation Consortium
Sacramento Municipal Utility District
Electric Transportation Department
6301 S Street - MS A351
Sacramento, CA 95817-1899
Tel: (916) 732-6976
Email: bwarf@smud.org

Paul Griffith, President, Santa Barbara Electric Bus Works
Technical Lead for the ZEBRA Battery Electric School Bus Project
Santa Barbara Electric Bus Works (SBEBW)
PO Box 727
Santa Barbara, CA 93102
Tel: (805) 895-6949
Email: paulgriffith@direcway.com

Ralph Knight, Supervisor of Transportation
Napa Valley Unified School District
1340 Menlo Avenue
Napa, CA 94558
Tel: (707) 253-3455
Email: Elecbus5@aol.com

List of References:

[1] Analysis by SMUD Project Manager William R. Warf, P.E. (author of this report); similar calculations are described in Appendix 5.

[2]Executive Summary from the Bluebird Electric School Bus: Test Report, William R. Warf, Pacific Electric Vehicles on contract to the Sacramento Municipal Utility District, June 30,1998

[3] An Assessment of Advanced Battery Technologies for Plug-In Hybrid Electric and Battery Electric Vehicles, EPRI Report 1001577, February 2003, Dr. Mark Duvall, et al.

[4]Data on Diesel and CNG busses furnished by Gary Dodson of Elk Grove School District, personal conversation with author; analysis of electrolysis and CNG reformer performance by author, based on SMUD research projects “Multifuel Reformer project” and Electrolysis data from Dr. Paul Scott, formerly of Stuart

Appendix 1

ZEBRA Battery data and Information

Appendix 2

Santa Barbara Electric Bus Works Final Technical Report

DEMONSTRATION OF ADVANCED BATTERY-ELECTRIC SCHOOL BUS AT NAPA VALLEY UNIFIED SCHOOL DISTRICT

Appendix 3

Design Report: Demonstration of Electric School Bus with ZEBRA Battery and Integrated Fast Charge

Note: This document contains data that is proprietary to Santa Barbara Electric Bus Works. It has therefore been omitted from this Final Report to satisfy ARB's policy related to confidential data in ICAT reports.
For a copy of the document please contact:

Santa Barbara Electric Bus Works
PO Box 727
Santa Barbara, CA 93102

Appendix 4

Compliance with SAE j2344 Safety Guidelines

Note: This document contains data that is proprietary to Santa Barbara Electric Bus Works. It has therefore been omitted from this Final Report to satisfy ARB's policy related to confidential data in ICAT reports.
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Santa Barbara Electric Bus Works
PO Box 727
Santa Barbara, CA 93102

Appendix 5

Modeling and Simulation Comparisons of Advanced Propulsion Systems in 30’ and 40’ Bus Platforms

Appendix 6

Operating and Maintenance Manuals for the ZEBRA School Bus

Appendix 7

Electric Propulsion System Safety Checkout Procedure

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Appendix 8

Roadworthiness Test Report

Appendix 9

In Service Test Report

Appendix 10.

Commercialization of Advanced Battery-Electric Drive Technology for Electric Busses

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