Demonstration of Advanced Battery-Electric School Bus at Napa Valley Unified School District

ICAT FY01/02

Sacramento, CA

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Santa Barbara Electric Bus Works

SMUD
SACRAMENTO MUNICIPAL UTILITY DISTRICT
The Power To Do More.℠

Project Objectives

- Apply Santa Barbara electric-bus experience toward the design and development of a suitable electric propulsion system for school bus industry
  - 11 years of electric-bus service
  - 250,000 hours of operation on most diverse fleet
  - 30,000 driving cycles
  - 1,200,000 miles driven
  - 10 million passengers carried
  - Significant redesign, retrofit, and rebuild activities
- Design from operator's perspective

Propulsion System Design Objectives

- Safety
- Reliability
  - robust, field-proven components
  - designed or modified for transportation application
  - systems integration
- Performance
- Serviceability
  - compatible with mechanic's skills
- Affordability
  - acquisition cost
  - life-cycle costs

Battery Options

- Lead-Acid
  - Lowest specific energy
  - Sealed variants intolerant of abuse (overcharge & overdischarge)
  - Failure mechanism requires high level of preventive maintenance
- Nickel-Metal Hydride
  - Expensive (~$2,000/kWh)
  - Uncertain durability in bus applications
  - Unproven in parallel interconnections
- Nickel-Cadmium
  - Affordable in flooded variants (watering req'd; electrolyte spillage)
- Sodium-Nickel Chloride (Zebra)
  - Highest specific energy, energy density
  - Field-proven in Europe (developed by Daimler Benz)

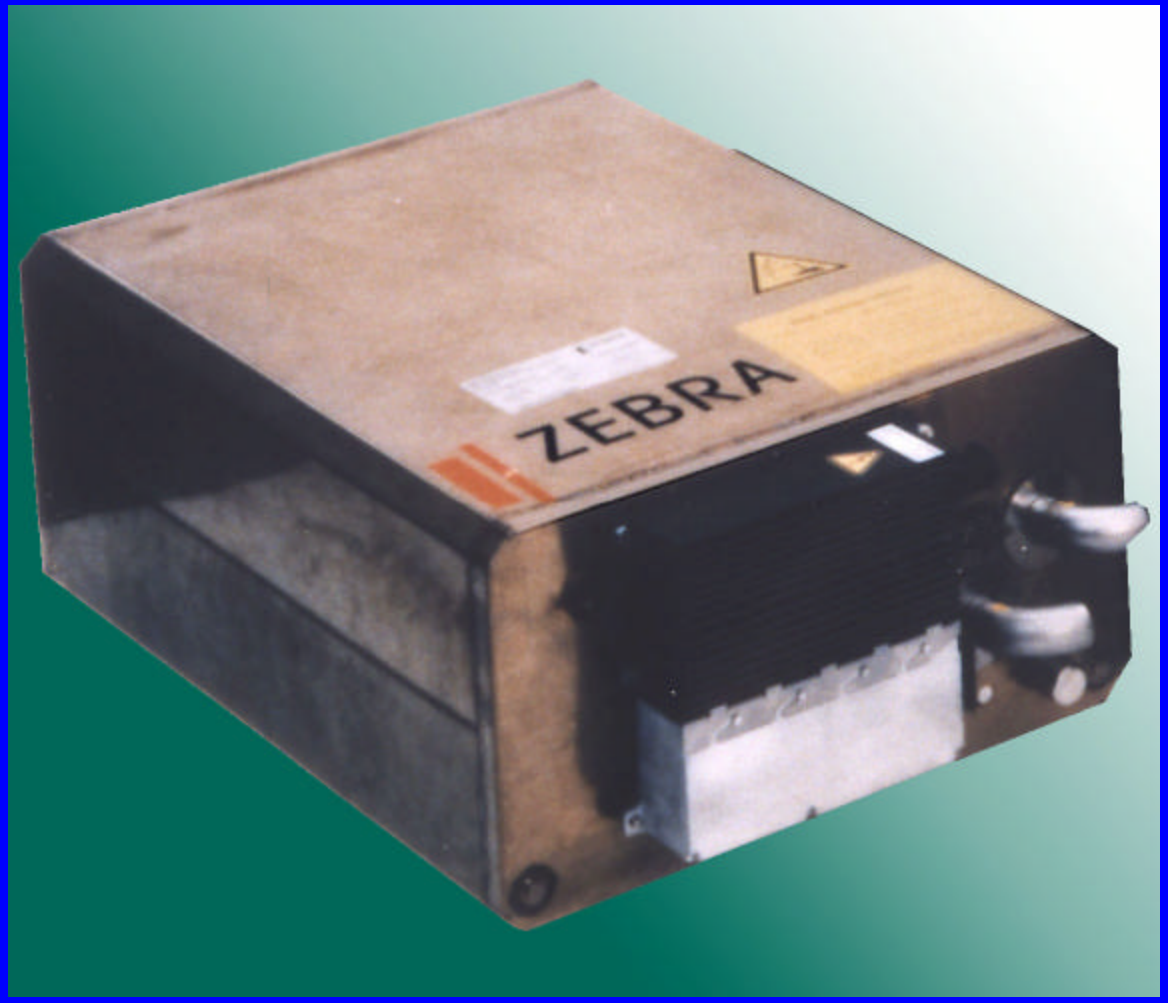
GNB, Ni-Cd, and Zebra Comparisons

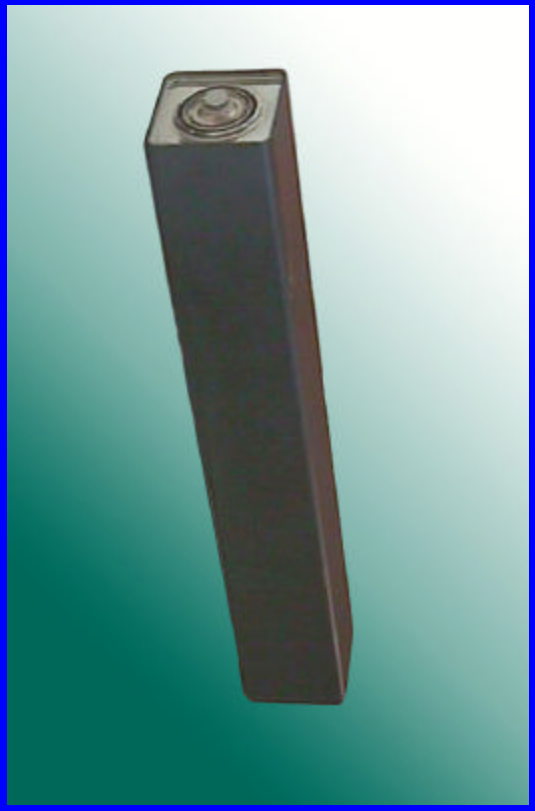
Criterion	GNB	Ni-Cd	Zebra
Specific Energy (system)	~30 Wh/kg	38 Wh/kg	89 Wh/kg
Energy Density (system)	~90 Wh/L	57 Wh/L	148 Wh/L
Number of modules	112	170	6
Nominal Voltage	336	510	557
Number of Elect. Conn.'s	224	340	12
Number of Watering Conn.'s	0	340	0
# of Thermal Mngmnt. Conn.'s	(air?)	900	24
Rated System Energy	132 kWh	119 kWh	107 kWh
Practical Discharge Depth	70%	75%	90%
Accessible Energy	92 kWh	89 kWh	96 kWh
Battery System Mass	7,392 lbs.	5,380 lbs.	2,640 lbs.

GNB, Ni-Cd, and Zebra Comparisons (continued)

Criterion	GNB	Ni-Cd	Zebra
$E_{thermal}$ Avail. For Heat/Defrost?	no	no	yes
Range b/w Chgs (@1.2 kWh/mi)	77 miles	74 miles	80 miles
Charge Management System	not incl.	not incl.	part. incl.
Sensitivity to Cold Ambient T?	less range	less range	none
Sensitivity to Hot Ambient T?	reduced life	reduced life	none
Warranty	90 day	400 cycles	1 year
Life Expectancy (nameplate cycles)	300 cycles	1,000 cycles	>1,200
Maintenance Requirements	testing; insp.	water; insp.	none
Battery Cost (per kWh)	?	$670	Now:$600 2005: $550
Meets USABC Mid-Term Goals?	no	no	yes

Zebra Z5C Battery Module
32.5”L x 20.9”W x 11.5”H, 396 lbs, 17.8 kWh





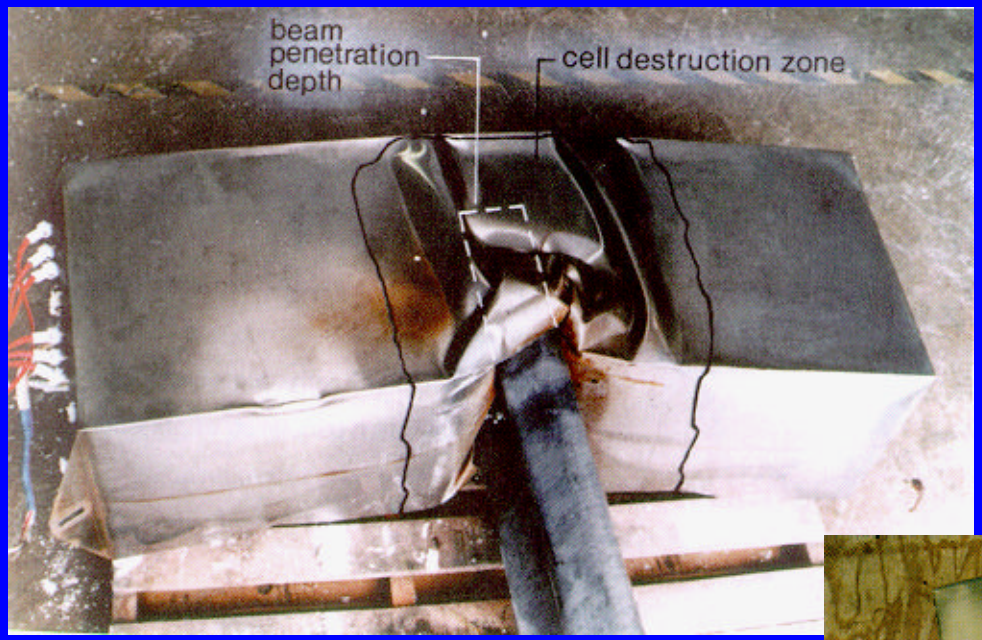
2.57V Cell

Zebra Battery Safety

- National Renewable Energy Laboratory (NREL) Study[1]
  - Internal failures
  - Externally inflicted influences (shock and crushing/deformation, piercing, gasoline fire, exposure to aqueous fire extinguishing media, orientation changes, water immersion, loss of thermal management or insulation, thermal shock, short circuit)
  - Day-to-day abuses (overcharge, overdischarge, thermal cycling, ambient temperature extremes, polarity reversal on charge, dust/moisture, inadequate maintenance, tampering, vibration)
  - Conclusion: “. . . the Zebra System appears, from the available information, to be relatively safe with respect to severe influences of the kind normally associated with vehicle collisions or accidents.”

[1]Current Status of Health and Safety Issues of Sodium/Metal Chloride (Zebra) Batteries, NREL/TP-460-25553, November 1998

Zebra Battery Safety (continued)

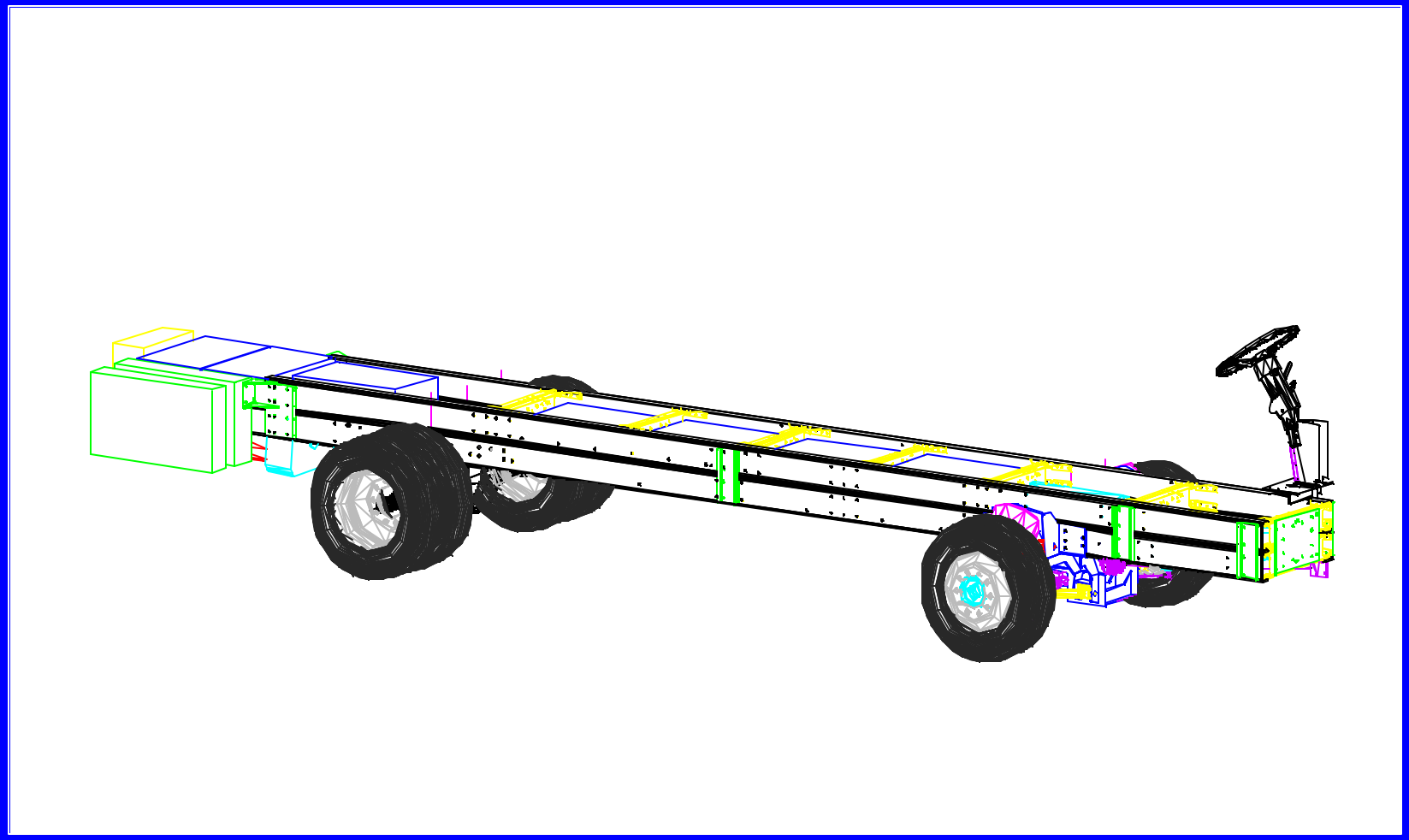


Crash Simulations

Zebra Battery Safety (continued)

- Elevated Temperature
  - Internal operating temperature range 270°C to 330°C
  - Vacuum insulation system yields near-ambient case temperatures
- Placement between frame rails reduces collision hazard
  - High energy density
  - True maintenance-free design
- No exposed conductors, internal contactors
  - Eliminates potential for current “tracking” between terminals

Potential Purpose-Built Chassis Configuration



Zebra Field Experience (Buses)
~500 modules in EV's worldwide

Delivery Van: Deutsche Post (German Post Office)

Motor/Controller Options

- AC-Based System
  - Superior efficiency
  - Superior robustness
  - Smaller size and lower weight
  - Maintenance-free motor design
- System Voltage
  - 300V systems historically used in North America because of cost
  - 600V systems commonly used in heavy industrial drives, as well as traction drives of electric trams, trolley buses, and trains
  - European electric buses already use 600V systems because of reduced size and weight, increased efficiencies, reduced cooling requirements, and availability of lower cost off-the-shelf 650V DC / 440V AC components

Motor/Controller Options (continued)

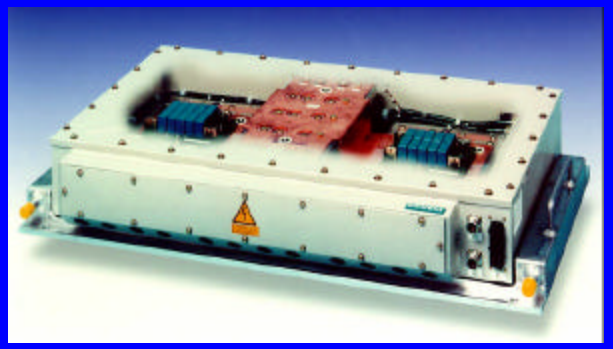
- Manufacturers Considered
  - Solectria
  - Enova (US Electricar)
  - AC Propulsion
  - ISE Research
  - Soleq Corporation
  - Adtranz
  - Siemens (several divisions)
  - Satcon (formerly Northrup Grumman)
  - General Electric
  - Lockheed Martin
- Concerns
  - Some systems cost prohibitive
  - Some systems more appropriate for car market
  - Some use industrial drive components not modified for the environmental, shock & vibration environment encountered in buses
  - Some developed by small companies
  - Some products not field-proven

Motor/Controller Options (continued)

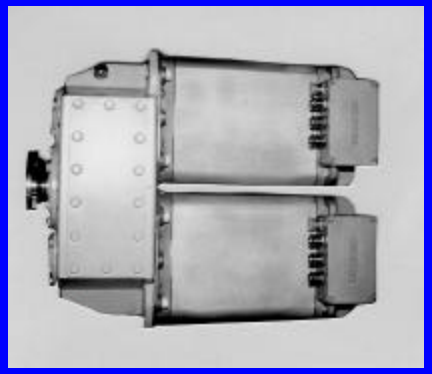
- Siemens Transportation Systems
  - Presently offers best mix of price, quality, robustness, & track record (~200 buses in revenue service in Europe, ~1,000,000 total miles)
  - Drive components used in the Mercedes Cito bus, the Iveco Europolis, BredaMenarinibus, and in MAN buses
  - Product line also used in the Ford Ranger and Ford Ecostar, and is based on products made for the trolley bus market
  - Series-production nature of products yields a relatively low price and a high degree of confidence in product suitability and long-term availability
  - Novel application of on-board inverter as battery charger

Siemens ELFA System Deployments

Siemens ELFA System Components

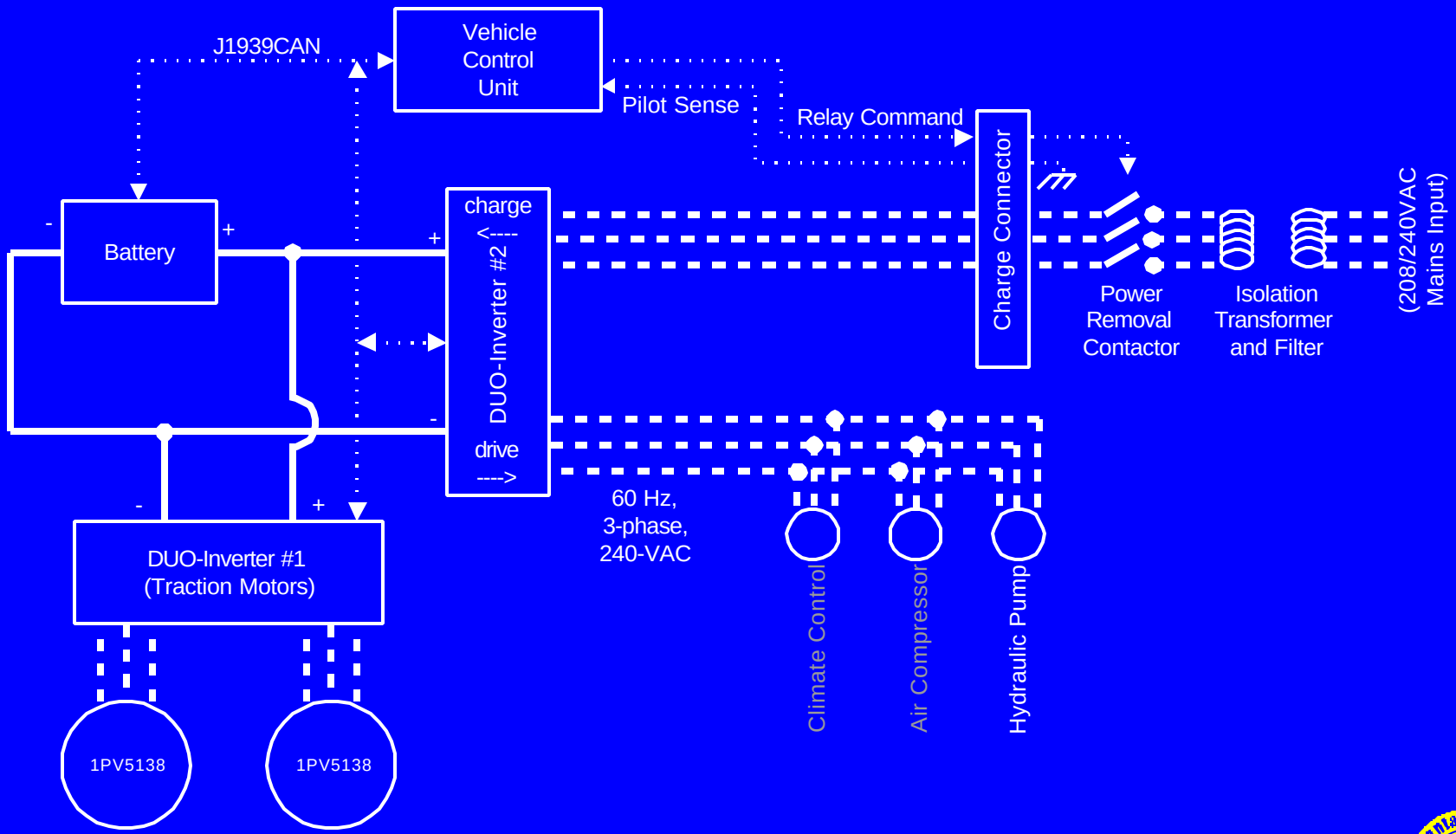


Inverter / Motor Controller

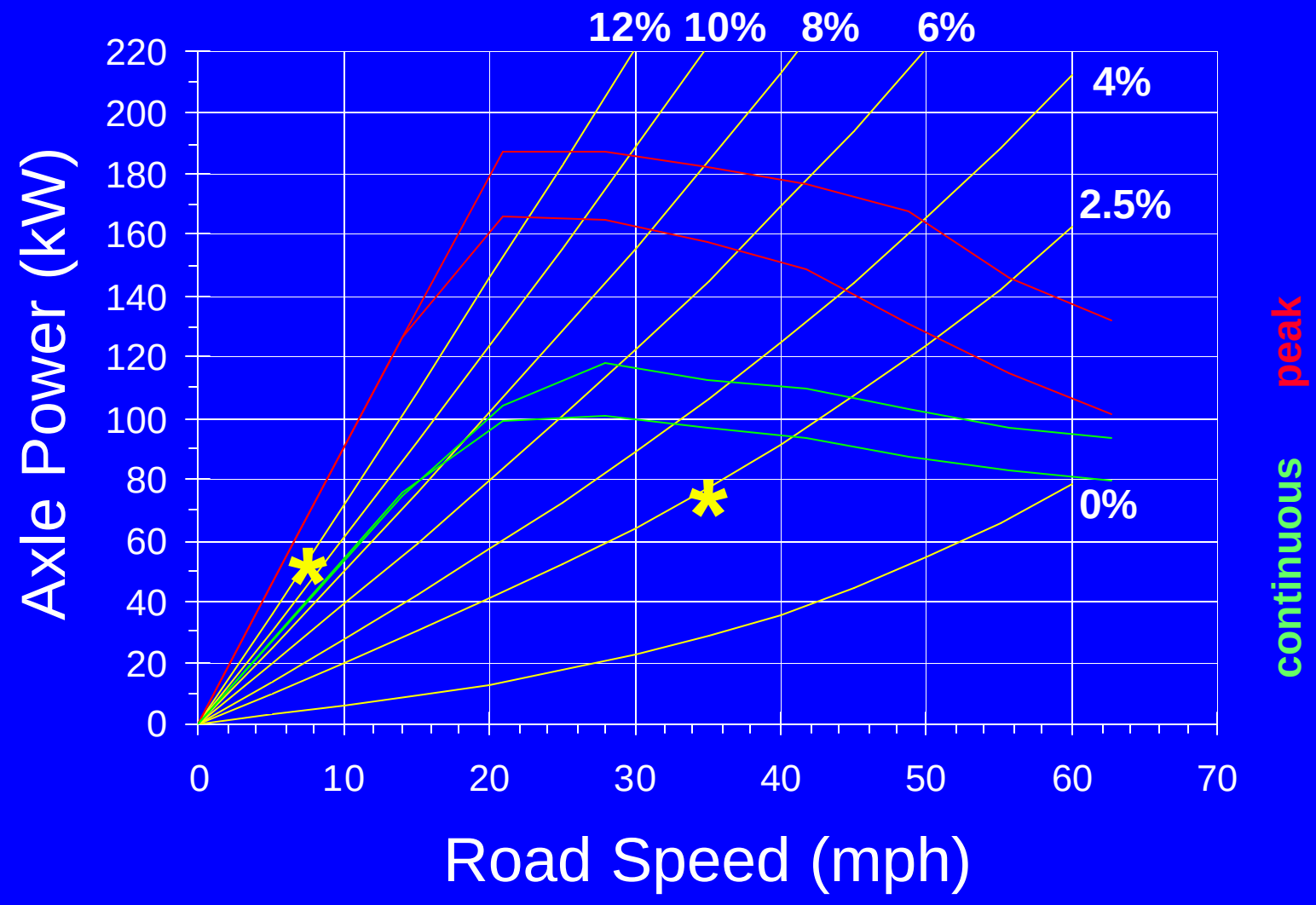


Traction Motors,
Summation Gearbox

Propulsion System Block Diagram



Required/Available Axle Power vs. Road Speed (28,000 lbs.)



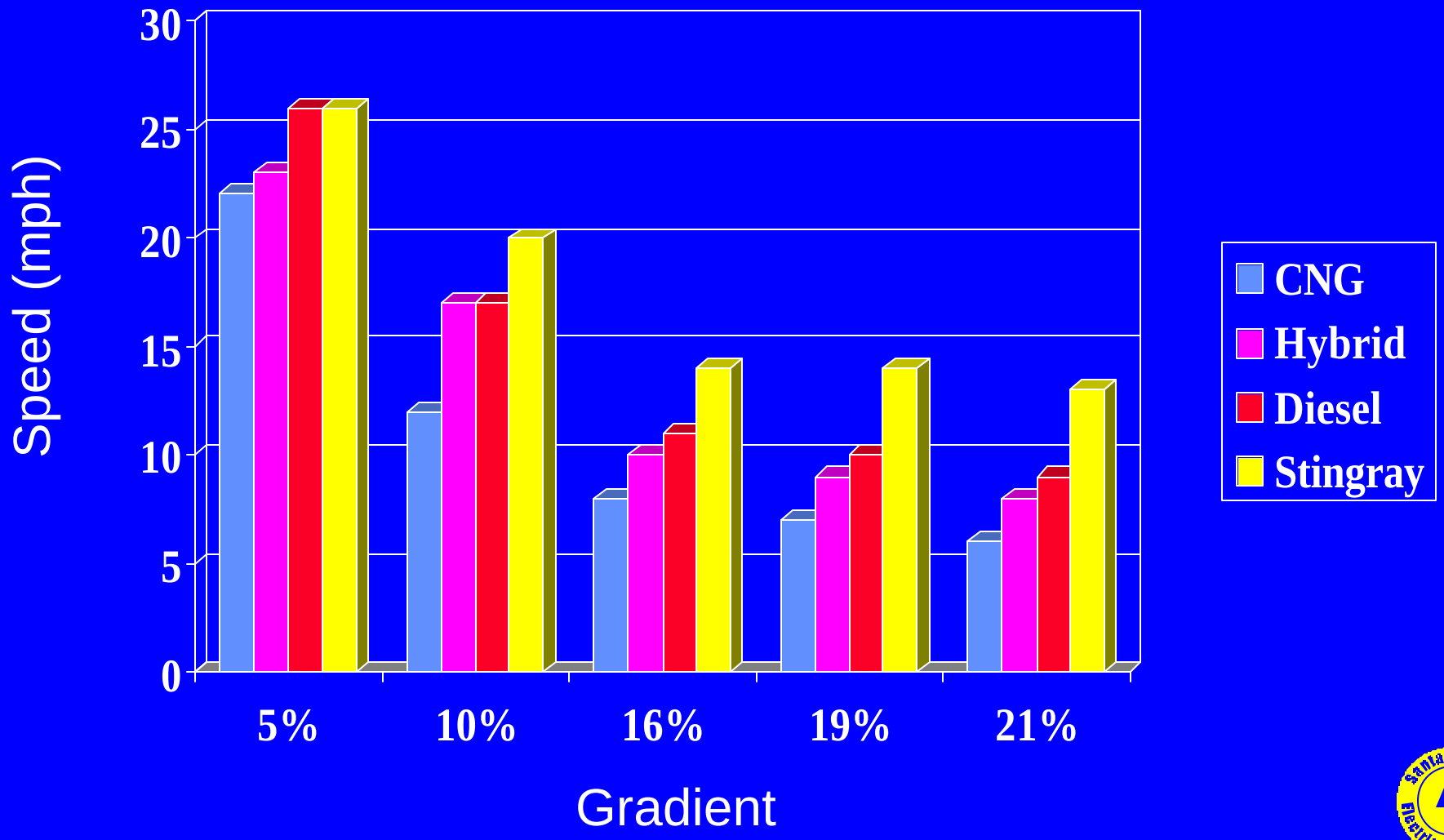
30-foot Santa Barbara Electric Transit Bus

30-foot Electric Transit Bus (Battery Compartment)

Performance Results – Speed on Grade At Full-Capacity Load (mph)

Gradient	CNG	Hybrid	Diesel	Stingray
5%	22	23	26	**26**
10%	12	17	17	**20**
16%	8	10	11	**14**
19%	7	9	10	**14**
21%	6	8	9	**13**

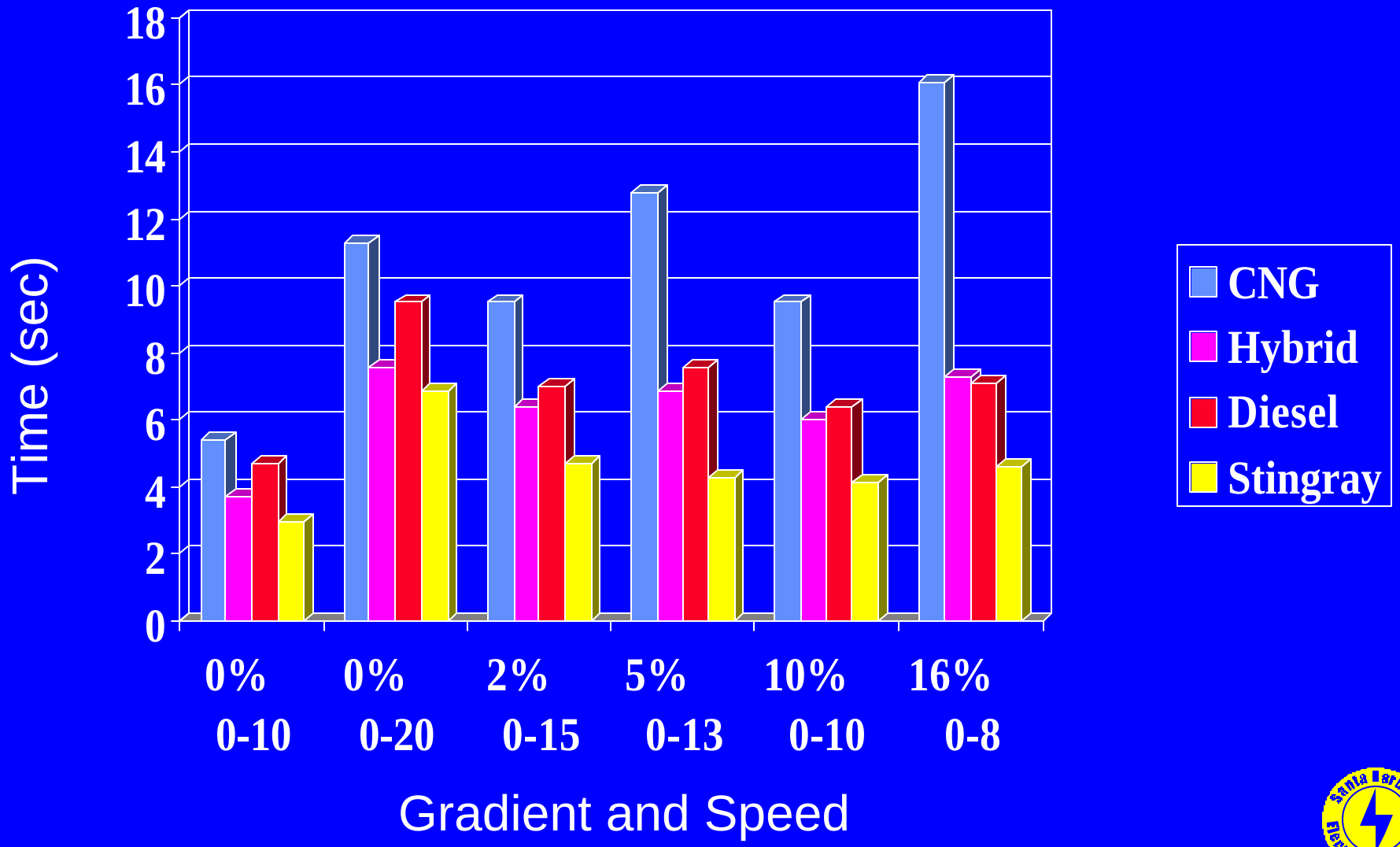
Speed on Grade at Full-Capacity Load (mph)



Performance Results – Acceleration on Grade At Full-Capacity Load (sec)

Gradient	Speed	CNG	Hybrid	Diesel	Stingray
0%	0-10 mph	5.4	3.7	4.7	**2.9**
0%	0-20 mph	11.3	7.6	9.5	**6.9**
2%	0-15 mph	9.5	6.4	7.0	**4.7**
5%	0-13 mph	12.8	6.9	7.6	**4.3**
10%	0-10 mph	9.5	6.0	6.4	**4.1**
16%	0-8 mph	16.1	7.3	7.1	**4.6**

Acceleration on Grade at Full-Capacity Load (sec)



Blue Bird Electric School Bus – TCEV 7200

Mechanical Integration by Bus Manufacturing USA

Blue Bird Electric School Bus TCEV 7200

Parameter	Pb-Acid (Sonnenshein)	As modified (ZEBRA)
Chassis/Body Wt. (w/o EPS)	13,370 lbs.	13,370 lbs.
Electric Propulsion System Wt.	10,080 lbs.	5,990 lbs.
Curb Weight	23,450 lbs.	19,360 lbs.
Payload (driver + 72 passngrs.)	8,790 lbs.	8,790 lbs.
Operating Weight	32,240 lbs.	28,150 lbs.
Battery Specific Energy (system)	27 Wh/kg	89 Wh/kg
Battery System Wt. (measured)	8,720 lbs.	2,640 lbs.
Rated System Energy	108 kWh	107 kWh
Practical Discharge Depth	60% - 80%	90%
Accessible Energy	65 kWh - 86 kWh	96 kWh
Range/Charge (1.2 DC kWh/mi)	54 mi - 72 mi	80 mi

12-year Lifecycle Cost Comparison

Acquisition Cost, Maintenance Costs, Fuel Costs, Driver Costs

(4-hr, 80-mi/day, 200 days/yr, 2.5% ann. inflation rate, 3.0% cost of capital)

Criterion	Diesel	ZEBRA	Ni-Cd
Investment ($ per mile)	$0.63	$1.30	$1.41
Maint., incl. batt. replcmnt ($/mi)	$0.35	$0.61	$1.07
Fuel ($ per mile)	$0.38	$0.13	$0.15
Driver ($ per mile)	$0.85	$0.85	$0.85
TOTALS ($ per mile)	$2.21	$2.90	$3.48
TOTALS (normalized to diesel)	100%	131%	158%

ZEBRA: [($600/kWh x 21.2 kWh) / (1,200 cyc. X 21.2 kWh/cyc.)] x 1.2 kWh/mi = $0.60/mile

Ni-Cd: [($670/kWh x 0.952 kWh) / (990 cyc. X 0.952 kWh/cyc.)] x 1.2 kWh/mi = $0.81/mile

Accomplishment of Design Objectives

- **Safety**
  - Each module electrically isolated by internal contactors
  - Interlocks on all high-voltage access doors
  - Hermetically-sealed battery, no gassing
  - No exposed electrical terminals
  - No battery maintenance
- **Reliability**
  - Robust, field-proven components, suitable to application
    - motor: -30C to 70C (-22F to 158F) IP65 (dust tight, water-jet protected)
    - controller: -25C to 70C (-13F to 158F) IP54 (dust, water-splash protected)
    - battery: -40C to 70C (-40F to 158F) IP54 (dust, water-splash protected)
  - Abuse-resistant battery
  - Integrated BMI, microprocessor monitoring/control of battery performance
  - Accurate SOC meter
  - Remote monitoring of propulsion system status

Accomplishment of Design Objectives (continued)

- **Performance**
  - 30-ft. school bus: 80-mile range between recharges
  - 1-mile range extension per minute fast charged
  - Excellent acceleration and hill climbing capabilities
- **Serviceability**
  - On-board diagnostics via CAN-bus
  - Absolutely no battery maintenance, maintenance-free motor and controller
  - No frame corrosion
- **Affordability**
  - Low-cost powertrain due to series production
  - Use of on-board power electronics for charging functions
  - Long-life battery (1,500 cycles @ 80% DOD)
  - Low-maintenance components
  - Forklifts, battery trucks, load banks not required
  - Mechanic training minimized
  - Fuel costs ~50% lower than for diesel bus

Advancements to Electric Propulsion System from Generation 1 to Generation 2

- Battery System Energy
  - 19% increase in energy capacity
  - No increase in battery weight or volume
- Propulsion System Weight
  - 1800 lb. weight reduction (30% for 6-module bus)
- Off-Board Charge Equipment
  - Box size reduced from 40”x40”x40” to 16”x14”x6”
  - Box weight reduced from 1 ton to 30 lbs.
- Propulsion System Cost
  - Cost of EPS components reduced by $26k
  - Installation simplified
- Serviceability and data tracking
  - Integrated phone modem option will allow for remote diagnostics & monitoring

Future Projects

- Retrofit Additional Electric School Buses with Bus Works' EPS
  - ~100 BlueBird TCEV 7200's delivered across US
- Other EV Retrofit Project
- Modification of EPS for 22-ft. Bus Applications
  - Transit bus and shuttle bus configurations
- Modification/Application of EPS to other vehicle platforms

The Bus Works.