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ELECTRIC/HYBRID TRANSIT BUSES USING ULTRACAPACITORS

by

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ABSTRACT

The use of electrochemical capacitors (ultracapacitors) in the electric driveline of full– size electric and hybrid transit buses was studied for buses with performance comparable to standard diesel –powered buses (0–20 mph acceleration times of 6–8 seconds). The capacitors were used in conjunction with or instead of batteries. For the hybrid buses, a turbo–diesel generator or fuel cell was used for on–board generation of electricity. It was found that the diesel generator or fuel cell could be load leveled on the CBD15 driving cycle with an ultracapacitor storing 2.5–3.0 kWh of energy. Using the energy density (6–10 Wh/kg) of state–of–the–art, small (20 cm^2) ultracapacitors, the weight of the ultracapacitor unit would be 300–400 kg, which is much less than a battery pack to provide the same power (200 kW). Simulations of the 14500 kg hybrid buses on the CBD 15 cycle using ultracapacitors indicated a fuel economy of 4.4 miles/gallon diesel fuel with the turbo–diesel generator and 7.5 miles/gallon diesel fuel equivalent with a fuel cell. The projected emissions of the bus using the diesel generator were .7 gm/mi HC, 3.4 gm/mi CO, and 14.1 Gm/mi NOx. The low resistance and high round–trip efficiency of the ultracapacitors resulted in significantly higher (10–30%) fuel economy using the ultracapacitors instead of batteries in the hybrid/electric driveline. Quantitative conclusions concerning the improvements to be expected in the fuel economy and emissions from utilizing an electric/hybrid driveline in transit buses must await the availability of chassis dynamometer data for hybrid and standard diesel–powered buses on the same urban driving cycles.

INTRODUCTION

There are a number of approaches for reducing exhaust emissions from transit buses that operate in the urban areas of large cities. These include the use of engine–powered buses using alternative fuels (methanol, ethanol, and natural gas), battery–powered electric buses that are charged from the utility grid, and hybrid/electric buses having an engine/generator or fuel cell for on–board generation of electricity. The latter two options, which involve buses using an electric driveline, are the subject of this paper.

To date, nearly all the buses using electric drivelines have used batteries for on–board storage of electricity. In the case of battery–powered buses, the batteries are sized to provide the desired range of the bus and they also provide the power required to accelerate the bus and recover energy from regenerative braking. In the case of hybrid/electric buses, batteries are used to load–level the engine/generator or fuel cell. They are sized by the power required to accelerate the bus. Batteries sized in this way can also be used to recover energy from regenerative braking. For a fuel cell bus using hydrogen, a battery is not required if the power rating of the fuel cell is sufficiently high to meet the power requirement of the bus during accelerations. In this case, the bus would not, however, have the capability to recover energy during braking.

This paper is concerned with the use of electrochemical capacitors (ultracapacitors) inconjunction with or instead of batteries in electric drivelines for buses. Ultracapacitors have significantly lower energy density (Wh/kg) than batteries, but they have much higher peak power density (W/kg) in both discharge and charge modes and much longer life for applications in which a very high number of discharge/charge cycles are encountered. The use of ultracapacitors in various electric and hybrid drivelines is evaluated for buses operating on driving cycles appropriate for urban routes. The requirements for ultracapacitors for these applications are determined and compared with the present state–of–the–art of ultracapacitors and with projected future developments. The acceleration, gradeability, all–electric range, energy consumption and fuel economy, and emissions of electric and hybrid buses using ultracapacitors with or instead of batteries are presented based on computer simulation results obtained using a vehicle simulation program – SIMPLEV.

ELECTRIC AND HYBRID DRIVELINE DESIGNS FOR TRANSIT BUSES

Component Sizing

There are a number of options for utilizing electric drivelines in transit buses. Several of driveline configurations are shown in Figure 1. In all the configurations shown, the torque and power to the wheels are applied by an electric motor(s). The electrical energy required by the motor is provided by batteries, ultracapacitors, an engine/generator or fuel cell, or some combination of them. In the latter case a control strategy is required to determine the power split between the various energy sources as a function of bus speed, power demand, and state–of–charge of the battery and/or ultracapacitor.

Sizing the components (electric motor, engine/generator, battery, ultracapacitor, etc.) in the drivelines depends critically on the characteristics of the bus (operating weight, frontal area, drag coefficient, and tire rolling resistance), the desired performance (acceleration times, gradeability, top speed, range if it is an all–electric bus), and the driving cycle on which the bus will operate. The performance targets for the present study are based on the UMTA "White Book" Baseline Advanced Design Transit Coach Specifications, which are summarized in Table 1. The key specifications are the 0–32 km/hr (20 mph) acceleration time and gradeability at speed (11 km/hr on a 16% grade and 71 km/hr on a 2.5% grade). Following Reference (1), the acceleration performance selected was 0–32 km/hr in 6–8 seconds, which results in electric/hybrid bus performance comparable to diesel–powered buses.

A number of computer runs were made using SIMPLEV (Reference 2) for buses with operating weights between 9500 and 17000 kg. The road load parameters for the buses are C_D =0.6, A_F=6.9 m^2, and a rolling resistance coefficient of .015. The results of the SIMPLEV calculations are summarized in Table 2. As shown in Table 3, the results for the different weight buses can be normalized by the weight of the bus to obtain values of specific power (kW–motor/kg–vehicle) for estimating the power requirement (kW) of the electric motor needed to meet the acceleration time and gradeability specifications for the bus. Note in the table that for a 0–32 km/hr acceleration time of 6 seconds, the vehicle specific power is 0.013 kW/kg and for an acceleration time of 8 seconds, the specific power is 0.010. The power requirement to meet the high speed (71 km/hr) gradeability is also 0.010 kW/kg. The low speed (11 km/hr) gradeability specific power requirement is 0.0065 kW/kg. This specific power yields a speed of 48 km/hr on the 2.5% grade. In the electric/ hybrid bus designs discussed in this paper, the engine/generator or fuel cell are sized to meet the continuous low speed gradeability requirement (11 km/hr on a 16% grade) and not the high speed gradeability (71 km/hr on a 2.5% grade).

The battery pack in the battery–powered buses is sized by the desired electric range of the bus, which depends on its energy consumption (Wh/mi) and the energy density (Wh/kg) of the batteries. Energy consumption values for the different weight buses at various steady speeds and on several driving cycles are given in Table 2. Energy consumptions, normalized by vehicle weight (Wh/mi/kg–vehicle), are given in Table 3. These values are useful for estimating range and battery pack weight. The specific energy consumption for urban driving cycles is about .15 Wh/mi/kg–vehicle. Hence for a 14000 kg, battery–powered bus with a range of 80 km (50 miles), the energy storage requirement is 105 kWh. For an electric/hybrid bus, the primary role of the battery or ultracapacitor is to load–level the engine/generator or fuel cell by providing the high power required during vehicle accelerations. In the case of a battery pack, it is sized such that its peak power density (W/kg) is not exceeded when the electric motor is operating at its maximum power. The peak power density for most batteries is 100–200 W/kg. Ultracapacitors are sized by the energy (kWh) required to load–level the engine/generator or fuel cell in the bus during urban driving. As discussed in Reference (3), this requires a minimum of 2–3 kWh for a 10000–15000 kg bus. For capacitors with an energy density of 10–15 Wh/kg, this results in a weight of 200–300 kg. Since the peak power density of capacitors is 1–2 kW/kg, they will have little difficulty providing the maximum power to the electric motor even in a high performance bus. The same ultracapacitor unit that would be used in the electric/hybrid bus to load–level the engine/generator or fuel cell can be used to load–level the battery pack in a battery–powered bus (see Figure 1b). Load–leveling the battery pack will extend battery cycle life and permit the design of batteries with higher energy density and lower cost (Reference 4).

Electric and Hybrid Transit Bus Designs

The normalized relationships discussed in the previous section have been applied to the design of a number of transit buses with electric and hybrid drivelines. These buses utilize various combinations of batteries, ultracapacitors, engine/generators, and fuel cells. The various designs are summarized in Table 4. All the buses have an operating weight (curb weight plus passengers) of about 15000 kg with a maximum electric driveline output power of 200 kW. The electric driveline consists of an AC induction motor(s) and three–phase inverter(s) developed by General Electric under contract with the United States Department of Energy (Reference 5). The application of the General Electric driveline for bus applications is discussed in Reference 1. The efficiency maps of the electric driveline used in the SIMPLEV simulations are based on laboratory test data taken by General Electric during the DOE program.

The engine/generators and fuel cells in the hybrid buses have a maximum power of 100 kW. The batteries used in the buses are either nickel–cadmium or sealed lead–acid. In both cases, the battery characteristics (Table 5) are based on laboratory tests of modules (References 6,7). A turbo–charged diesel engine is used in the buses to drive the generator. The bsfc and emission characteristics assumed for the engine are given in Table 6. The bsfc values as a function of power fraction were taken from Reference 8. The emissions values were taken from Reference 9 and are for an automotive turbo–charged diesl engine built by Volkswagen in the early 1980s. This was done because engine maps for heavy–duty turbo–charged diesel engines for buses do not seem to be available in the open literature.

The operating characteristics of the fuel cell are modeled similar to that of the diesel engine in that the fuel use is given as gm diesel fuel equivalent/kWh electricity output as a function of power fraction. The equivalent bsfc map for the fuel cell was calculated based on the steady– state efficiency data for a PEM fuel cell given in Reference 10. In those tests, a 3 kW fuel cell was run using hydrogen and air. The operating line (pressure and stoichiometry) selected for use in the simulations was that which resulted in the maximum efficiency of the fuel cell at each power fraction. The bsfc map for the fuel cell is given in Table 7. The efficiency of the fuel cell ranges from 66% at very low loads to 45% at maximum load. These efficiencies include the energy needed for compression of the air, but do not include pump and fan accessory power. In addition, since the fuel cell tests were run on hydrogen, the fuel map in Table 7 does not include any reformer losses. Since the fuel cell is assumed to operate on hydrogen, the emissions from the fuel cell are taken to be zero.

The control strategies used for engine and fuel cell operation and for splitting the power between the various energy storage devices and power sources in the bus simulations are the same as used previously in SIMPLEV studies of electric/hybrid light–duty vehicles (References 11,12). Most of the calculations in this study were done for the New York Center Business District (CBD15) driving cycle, for which there is dynamometer emissions test data (gm/mi) for a few buses (Reference 13) for comparison with the simulation results.

ULTRACAPACITOR TECHNOLOGY

Ultracapacitor Basics (How they work)

Energy is stored in an electrochemical capacitor (ultracapacitor) by charge separation within the micropores of a very high surface area electrode material (see Figure 2). The charge separation is distributed throughout the volume of the electrode material in the double–layer formed at the liquid–solid interfaces between the solid electrode material and the liquid electrolyte with which the electrode is impregnated. As shown in Figure 2, the internal construction of an electrochemical capacitor is much like that of a battery in that it has two electrodes, a separator, and an electrolyte for ion transfer in the cell. In most cases, the two electrodes in the electrochemical capacitor are identical unlike a battery where the electrodes are made of the different materials that form the electrochemical couple of the battery. A double–layer forms at the solid–liquid interfaces in all electrochemical systems and is discussed in all texts on electrochemistry and electrochemical engineering (Reference 14). The current (electronic or ionic) at any electrode must be accounted for either by Faradaic reactions, surface charge–transfer, or charging of the double–layer. In a battery, the Faradaic reactions are dominant and the electrode material takes part in the reaction with the effect of the double–layer being minor. In the case of the simplest electrochemical capacitors, usually termed double–layer capacitors, all the current to or from the electrode is due to charging or discharging the double–layer. In the double–layer capacitor, the ions from the electrolyte approach the electrode material but do not react with it or are not adsorbed into it. The Faradaic current is zero in the case of the double–layer capacitor. A more complex situation arises in the double–layer if some or most of the ions that enter the double–layer are adsorbed into the surface of the electrode (charge transfer) or are intercalated into the material matrix of the electrode. In this case, the double–layer can store much more charge than in the simple case of double–layer capacitance (pure charge separation) and the additional capacitance is referred to as psuedo–capacitance. Even in this case, the electrode material itself does not take part in the interface reactions and all the ions being transferred are from the electrolyte. For vehicle applications, the simple double–layer devices are the most attractive as they are expected to have the highest power capability and the longest cycle life. However, it is expected that devices that utilize psuedo–capacitance will have higher energy density.

The capacitance (C) of the double–layer capacitor can be expressed as

$$C=dQ/dV$$

where Q is the charge stored and V is the voltage of the capacitor. The energy stored is

$$E = C\int d(V^2/2)$$

In general, C is a function of voltage. If C is a constant,

$$Q= CV$$

$$E=1/2\, C\, V^2$$

These are the equations used most frequently to describe the performance of ultracapacitors.

<u>The DOE Ultracapacitor Development Program</u>

In 1991, the United States Department of Energy (DOE) initiated a program to evaluate and develop electrochemical capacitors (ultracapacitors) for potential use in electric and hybrid vehicles. The goals of the program are summarized in Table 8. Since from the beginning it has been assumed that power density would not be a problem, the key specification for the capacitors is energy density (Wh/kg and Wh/liter) and the major thrust of the DOE program has been to increase the energy density of the prototype devices being fabricated. The initial goal of the program was to achieve 5 Wh/kg along with a useable peak power density of 500 W/kg. In the last several years, a number of promising material technologies (Reference 15) have been identified for use in the electrodes of high energy density ultracapacitors. These material technologies are the following:

1. Carbon/metal fiber composites
2. Foamed (aerogel) carbons
3. Monolithic cellulose–derived carbon foams
4. Doped conducting polymers
5. Mixed metal oxides

Ultracapacitor devices have been fabricated and tested using all these material technologies as part of the DOE program. Most of the devices have been small (20 cm^2 or less), but they have exhibited the charge/discharge characteristics expected of capacitors–that is a linear charge vs.voltage curve, low resistance, and high peak power density (1–2 kW/kg). Test data for laboratory evaluations of the various ultracapacitor technologies are given in References (15–18).

Present Status of the Maxwell Ultracapacitor Technology

A summary of the present status of ultracapacitor technology is given in Table 9. As indicated in the table, the most advanced of the technologies is that being developed for DOE by Maxwell Laboratories. Maxwell met the initial DOE goal of 5Wh/kg and 500 W/kg in 1994 with carbon/aluminum composite electrodes and an organic electrolyte resulting in a cell voltage of 3V. The ultracapacitors being developed by Maxwell Laboratories on their DOE contract are bipolar in configuration meaning that the current flows normal to the electrodes through the devices in multi– cell series stacks. Test data for sealed 3 and 8 cell bipolar stacks are shown in Figures 3 and 4. These units have energy densities of 6 Wh/kg and 9 Wh/liter and have been discharged at power densities up to 2.6 Wh/kg. The cell resistance is 1.1 ohm–cm^2 for the 20 cm^2 cells. Work has started to scale up the bipolar devices to 200 cm^2.

In addition to the work on bipolar stacks on the DOE program, Maxwell Laboratories has designed and fabricated a 3V, 2500 F device (see Figure 5) consisting of 50 cells connected in parallel. As shown in Figure 6, the cells are placed in a clam–shell shaped, aluminum enclosure using a gasket seal. The 2500 F device stores 2.6 Wh of energy and has energy densities of 5.6 Wh/kg and 8.7 Wh/liter. These energy densities are more than double that of the commercially available Panasonic capacitors, which have been extensively tested at the Idaho National Engineering Laboratory (References 18,19). Charge/discharge data at 100A for the 2500 F Maxwell capacitor are shown in Figure 7. AC impedance data indicates a resistance of .55 mohm corresponding to a normalized resistance of 1.8 ohm–cm^2 for the 3V, 2500 F device. As indicated in Figure 8, the 3V clamshell devices can be connected in series to make–up high voltage units for use in cars or buses. At their present state–of– development, a 3kWh capacitor unit would weigh about 500 kg and have a volume of 345 liters. For a bus requiring a maximum power of 200 kW, the working power density of the capacitor would be only 400 W/kg, which is much below its maximum power density capability of 2500 W/kg. Further development of the Maxwell capacitors is expected to increase their energy density to at least 10 Wh/kg.

Modeling of Ultracapacitors

In the simulations of the electric/hybrid buses, the ultracapacitors are modeled like batteries whose open circuit voltage (V) and state–of–charge (SOC) are related as in an ideal capacitor – SOC = V/Vrated, where the state–of–charge is based on the net charge (Ah) taken from the capacitor. The capacitor resistance is taken to be constant independent of SOC (see Table 10) . The capacitors are characterized by the specific capacitance (F/cm^2), specific resistance (ohm– cm^2), rated voltage, and energy density (Wh/kg) of the cells based on laboratory tests of small devices. The characteristics used in this study are those for the carbon–based Maxwell cells using an organic electrolyte. The cell values used in this study are:

.75 F/cm^2, 1 ohm–cm^2, 3V, 10 Wh/kg

A 240 V, 3 kWh ultracapacitor unit would weigh 300 kg and consist of eighty 3 V cells. Each cell would store a charge of 15 Ah and have a resistance of .042 milliohms. The 3 kWh unit would have a round–trip efficiency of 93% at a power of 200kW.

The energy storage capacity (kWh) of the ultracapacitor unit is proportional to the Ah capacity of the cells for a fixed system voltage. As is done for batteries, SIMPLEV scales the resistance of the ultracapacitor cells as 1/Ah when the cell capacity is changed from the input reference value. This is consistent with a constant value of specific resistance (ohm–cm^2) for the capacitor designs. Modeling of the ultracapacitors in this way includes the effect of resistance on capacitor voltage and system losses for both charge and discharge.

ELECTRIC/HYBRID TRANSIT BUS PERFORMANCE USING ULTRACAPACITORS

Battery–powered (electric) Transit Buses

Simulations were run of battery–powered transit buses with and without ultracapacitors to load level the batteries. The characteristics of the electric buses are given in Table 4. The buses have an operating weight of 16100 kg and are equipped with a 200kW electric driveline and 2480 kg of sealed lead–acid (Electrosource–Horizon) batteries. The ultracapacitors stored 3.5 kWh of energy and could provide up to 200 kw of power for acceleration or regenerative braking . The SIMPLEV calculations indicate the buses accelerated from 0 –32 km/h in 6 seconds and 0–64 km/h in 19 seconds. The maximum battery power during the maximum effort acceleration was 240 kW (96 W/kg) without ultracapacitors and 60 kW (24 W/kg) with the ultracapacitors. The state–of– charge of the capacitors was 70% at 72 km/h (45 mph) during the acceleration.

The ranges of the electric buses are 30 miles on the CBD15 driving cycle and 33 miles on the SAE C–cycle. The range on the urban driving cycles was increased by 10% by using ultracapacitors. The range of the bus at a constant speed of 40 km/h (25 mph) is 52 miles. The maximum battery power during accelerations on the CBD15 cycle without ultracapacitors was 250 kW and with capacitors, it was 60 kW. The energy consumption of the bus on the CBD15 cycle was 3.287 kWh/mi using an accessory load of 9 kW. It was assumed in the simulations that 60% of braking force was applied by regenerative braking. On the CBD15 cycle, this resulted in a maximum regenerative braking power of 124 kW to the capacitors and an energy recovery of 14.3% from regenerative braking.

The simulation results discussed in the previous paragraph indicate the advantages of the use of ultracapacitors to load–level the batteries in an electric transit bus. First, the maximum power that must be provided by the batteries is reduced from about 100 W/kg to less than 25 W/kg. Even though some electric vehicle batteries can provide a power density of 100 W/kg , it results in significantlly shorter cycle life than if the batteries are discharged at the average constant power of the driving cycle (Reference 19). Second, high regenerative braking power can be ultilized to recovery energy during bus decelerations without subjecting the batteries to high charging rates and possible thermal problems. The ultracapacitors can be charged efficiently at very high charging rates (up to 2 kW/kg) resulting in energy recovery of about 15% on typical urban driving cycles. Third, for ultracapacitors with energy densities of 10–15 Wh/kg, the improvement in range predicted from load leveling the batteries permits the battery weight to be reduced to compensate for the weight of the capacitors without increasing the bus operating weight or reducing the range of the bus. It is expected that batteries designed to a lower peak power density specification than is required at the present time will have higher energy density, lower cost, and longer cycle life than presently available batteries (Reference 4). In that case, the use of ultracapacitors would result in a lower bus operating weight and/or longer range and lower battery life cycle costs.

Electric/hybrid Transit Buses using Ultracapacitors

Simulations of transit buses using various electric/hybrid drivelines were run on SIMPLEV. Electricity is generated on–board the bus using either a turbo–diesel generator or a fuel cell which is load–leveled by batteries or ultracapacitors. The batteries are not recharged at any time using electricity supplied from the utility grid and thus the energy use/fuel economy of the bus is expressed in terms of miles/gallon diesel fuel equivalent even for the fuel cell–powered buses that use hydrogen as the fuel. The characteristics of the buses, whose operation is simulated, are given in Table 4. All the buses utilize a 200 kW motor(s) to power the wheels and have acceleration performance comparable or better than standard diesel–powered buses (0–32 km/h in 6 seconds). The on–board electricity generating capacity of 100 kW is sized to provide good gradeability – 11 km/h (7mph) on a 16% grade and 48 km/h (30 mph) on a 2.5% grade. Better high speed gradeability on short grades can be achieved using the batteries or ultracapacitors to augment the output of the turbo–diesel generator or fuel cell up to the 200 kW capacity of the electric motor.

One of the objectives of the hybrid bus study was to compare the fuel economy and emissions of the buses using batteries with those using ultracapacitors as the energy storage unit. The battery packs used in the hybrid buses were about one–half the size used in the battery–powered buses, because the range of the bus on battery–stored electricity was not a consideration for the hybrid bus. This does mean, however, that the maximum power density experienced by the batteries in the hybrid buses is about twice that of the batteries in the battery–powered buses. The effect of these high power densities (150–200 W/kg) on battery life is somewhat mitigated in that the control strategy of the driveline in the hybrid buses maintains the state–of–charge of the batteries in a narrow range. For the simulations run in this study, the batteries are maintained near 70% state–of–charge. The control strategy for the hybrid buses using ultracapacitors maintained the capacitors between 90% and 50% state–of–charge with the power density being 500–1000 W/kg. For the CBD15 driving cycle, the turbo–diesel generator or fuel cell in the 15000 kg buses operated at about 60 kW most of the time.

The fuel economy and emissions simulation results for the buses using the various driveline combinations are summarized in Table 11. As would be expected, the fuel consumption of the buses using fuel cells is considerably lower (about 40%) than the buses using a turbo–diesel generator for on–board generation of electricity. What was not expected was the significant effect of the energy storage unit on the fuel use. Note that the fuel use with ultracapacitors was 10% less than using the sealed lead–acid batteries and 32% less than using nickel–cadmium batteries. These differences are due to the high round–trip efficiency of the capacitors compared to that of the batteries (see the last column in Table 11). The resistances of the three energy storage units are shown in Table 12. The resistance of the nickel–cadmium battery pack is more than forty times that of the ultracapacitor unit and the resistance of the lead–acid battery pack is more than ten that of the ultracapacitors. The increased fuel use using the batteries also results in higher projected HC and NOx emissions from the engine than when ultracapacitors are used. The emissions given in Table 11 are engine out emissions as there was no catalytic converter in the engine exhaust system.

It is difficult to make a direct comparison of the fuel economy and emissions of the electric/hybrid buses with those of the standard diesel engine–powered buses, because of there is little published data for standard diesel buses tested on a chassis dynamometer for specified driving cycles. For the data that is available (Reference 13), there is considerable scatter for buses of the same test weight and engine model. Ranges of the emissions data taken from Reference 13 are indicated in Table 11 for comparison with the simulation results for the hybrid buses. The approximate range of fuel economy for diesel–powered buses is based on information from Reference 20.

Quantitative conclusions concerning the improvements to be expected in the fuel economy and emissions from utilizing an electric/hybrid driveline in transit buses must await the availability of chassis dynamometer data for electric/hybrid and standard diesel–powered buses tested on the same driving cycles. At the very least, it is necessary to have availabe for use in the simulations detailed engine maps for heavy duty diesel engines. The simulation results shown in Table 11 do, however, indicate that the use of low loss energy storage units, such as ultracapacitors, will result in significantly larger improvements for hybrid buses using either fuel cells and turbo–diesel generators for on–board generation of electricity.

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Table 1: Baseline Advanced Design Transit Bus Specifications
(Source: UMTA White Book)

Top Speed (level road)	93.6 km/hr (58 mph)
Gradeability	11.3 km/hr (7 mph) on a 16% grade 71 km/hr (44 mph) on a 2.5% grade
Acceleration	0-32 km/hr (20 mph) in 6-8 seconds
Design-Driving Cycle	CBD 15

Table 2: Summary of Simulation Results for Electric Buses

Weight (kg)	9870	13962	17144
C_DA (m^2)	4.18	4.18	4.18
f_r (kg/kg)	.015	.015	.015
Access Power (kW)	0	0	0
Max Motor Power (kW)	106	171	223
Specific Power (kW/kg)	.0107	.0122	.013
Acceleration Times (sec.)			
0-32 km/hr	7.5	6.6	6.2
0-56 km/hr	19.0	16.1	.5
Energy use at the battery		(Wh/mi)	
Constant Speeds			
32	900	1222	1476
48	970	1277	1517
64	1150	1463	1698
80	1366	1670	1903
Driving Cycles			
SAE-C-Cycle	1520	2073	2514
CBD 15	1705	2429	2961
Power on grade		Motor(kW)	
71 Km/hr on 2.5%	99	146	174
11 Km/hr on 16%	66	94	115

Table 3: Weight Normalized Bus Simulation Results

Acceleration	Times (seconds) kW/kg motor .010	.013
0-32 km/hr	8	6.2
0-48 km/hr	15	11.6
0-64 km/hr	26	20
0-80 km/hr	50	35

Energy use	Wh/mi/kg-vehicle
48 km/hr (speed)	.090
80 km/hr (speed)	.120
SAE C-cycle	.145
CBD 15	.173

Motor Power on Grade	(kW/kg) motor
71 km/hr on 2.5%	.010
11 km/hr on 16%	.0067

Table 4: Summary of Bus Design Characteristics

Driveline Configuration	Operating Weight(kg)	Energy Storage (kg) Batteries	Capacitors	Electricity Generation (kW) Turbo-Diesel	Fuel Cell
Electric, Batteries	16087	2481			
Electric, Batteries, Capacitors	16087	2481	350 (3V cells)		
Hybrid, Batteries, Engine	14847	1160 (Pb-Acid) 1040 (NiCd)		100	
Hybrid, Batteries, Fuel Cell	14849	1160 (Pb-Acid) 1040 (NiCd)			100
Hybrid, Capacitors, Engine	14889		295 (3V cells)	100	
Hybrid, Capacitors, Fuel Cell	14380		295 (3V cells)		100

All designs: 200 kW electric motor
C_DA = 4.18 m^2, f_r = .015, Access. Power = 9kW
ultracapacitor - 10 wh/kg

Table 5: Battery Characteristics

Sealed Lead-Acid
6 Cells per module
14.5 kg/module
45 Ah at C/3 rate

DOD	V/cell	Resistance/cell (ohms)
0	2.12	.000833
0.1	2.105	.000833
0.2	2.087	.000833
0.3	2.067	.000833
0.4	2.050	.000850
0.5	2.030	.000875
0.6	2.010	.000900
0.7	1.990	.000950
0.8	1.965	.001000
0.9	1.935	.001100
1	1.890	.001166

Nickel-Cadmium (flooded)
5 cells per module
18.2 kg/module
140 Ah at the C/3 rate

DOD	V/cell	Resistance/cell (ohms)
0	1.33	.0006
.1	1.315	.0006
.2	1.302	.0006
.3	1.288	.0006
.4	1.275	.0006
.5	1.262	.0006
.6	1.249	.0006
.7	1.235	.0006
.8	1.220	.0006
.9	1.202	.0007
1.0	1.176	.0014

Table 6: Fuel Consumption and Emission Characteristics of the Heavy-Duty Turbo-Charged Diesel Engine

Power fraction	gm fuel / kWh	HC (gm/kWh)	CO (gm/kWh)	NO_x (gm/kWh)
0	240	.266	3.00	2.40
.16	22	.206	2.00	2.50
.5	213	.133	1.46	3.00
.6	210	.173	1.46	3.60
.75	232	.266	.700	5.33
.9	235	.302	.543	5.33
1.0	240	.340	.453	4.11

diesel fuel: 820 $\frac{gm}{liter}$, 9805 wh/liter

Table 7: Fuel Consumption and Efficiency Characteristics of the PEM Fuel Cell

Power Fractions	Specific Fuel Consumption (gm/kWh) Diesel Fuel Equivalent	Efficiency (%)
0	127	66
1.66	127	66
.33	135	62
.50	144	58
.67	152	55
.833	161	52
1.0	186	45

Diesel fuel: 820 gm/liter, 9805 wh/liter

Table 8: Goals of the DOE Ultracapacitor Development Program

	Near-term	Advanced
Energy Density		
wh/kg	5	15
wh/liter	10	25
Power Density		
W/kg	500	1600
Round-trip Efficiency (%)	>90	>90
Cycle Life	>100,000	>100,000
Cost ($/wh)	.5-1	.5-1

Table 9: Summary of the Status (1995) of Ultracapacitor Technology

Developer	Electrode/Electrolyte Material	W-h/kg*	W-h/L	W/kg	Voltage
Panasonic	Carbon/Organic	2.2	2.9	400	3V
Pinnacle Research Institute	Mixed Metal Oxides/Aqueous	0.8	3	500	28V
Maxwell Laboratories	Carbon/Organic	6	9	2,500	24V
Maxwell Laboratories	Carbon/Organic	7	9	2,000	3V
Livermore National Lab	Aerogel Carbon/Aqueous	2	1.5	2,000	1V
Sandia National Lab	Synthetic Carbon/Aqueous	<2	1.7	1,000	1V
Los Alamos National Lab	Polymer/Aqueous	<2	–	>500	0.75V

*Weight based on cell, including current collector, active material, separator, and electrolyte

Table 10: Ultracapacitor Characteristics

<u>Carbon-based, Organic Electrolyte Cells</u>

1 cell per module

.408 kg/module

2.77 Ah capacity

DOD	V/cell	Resistance/cell (ohms)
0	3.0	.000206
.1	2.7	.000206
.2	2.4	.000206
.3	2.1	.000206
.4	1.8	.000206
.5	1.5	.000206
.6	1.2	.000206
.7	0.9	.000206
.8	0.6	.000206
.9	0.3	.000206
1.0	0	.000206

Table 11: Summary of Hybrid Bus Simulation Results on the CBD 15 Driving Cycle

Driveline Configuration	Operating Weight (kg)	Fuel Economy mpg	Emissions (gm/mi) HC	CO	NOx	Battery/Capacitor Round-trip Efficiency
Standard Diesel-Engine	14500	2.2 - 4.0	1.5 - 2.5	8 - 13	18 - 28	–
Diesel generator, Capacitors	14377	4.35	.69	3.4	14.1	99
Diesel generator, Lead-Acid Batteries	14847	3.87	.89	2.6	17.9	92
Diesel generator, NiCd batteries	14727	2.90	1.20	3.5	24.2	71
Fuel Cell, Capacitors	14378	7.45	0	0	0	99
Fuel Cell, Lead-Acid Batteries	14849	6.7	0	0	0	92
Fuel Cell, NiCd batteries	14727	5.0	0	0	0	71

Table 12: Resistance of the Energy Storage Units (240 V)

Unit	Cell Voltage	Ah	Cell Resistance (mohm)	No. of cells	Unit Resistance (mohm)
Ultra Capacitors	3	25	.022	80	1.76
Lead-Acid Batteries	2	180	.208	120	25
Nickel-Cadmium Batteries	1.2	200	.42	200	84

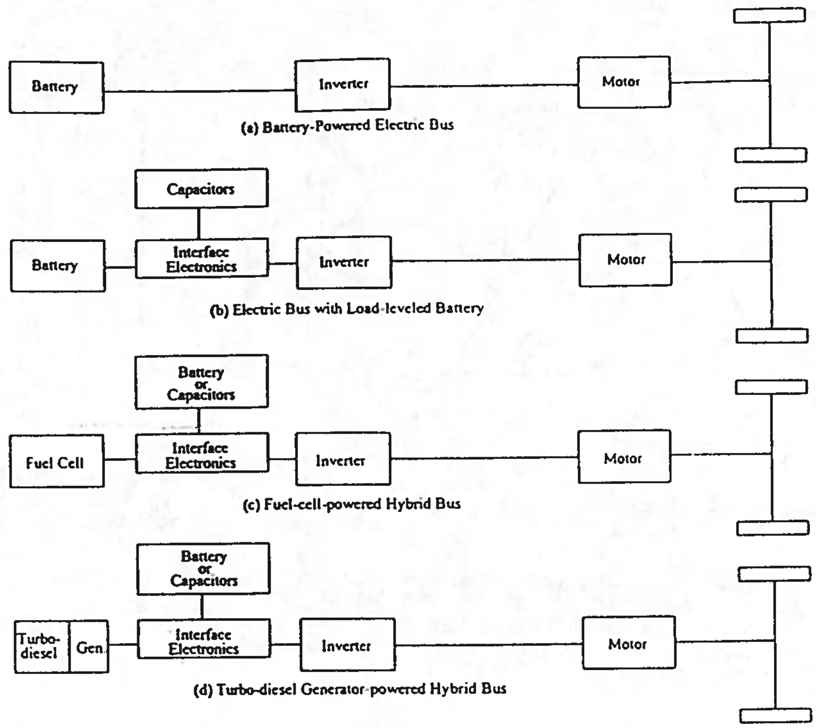


Figure 1: Electric/Hybrid Bus Driveline Options

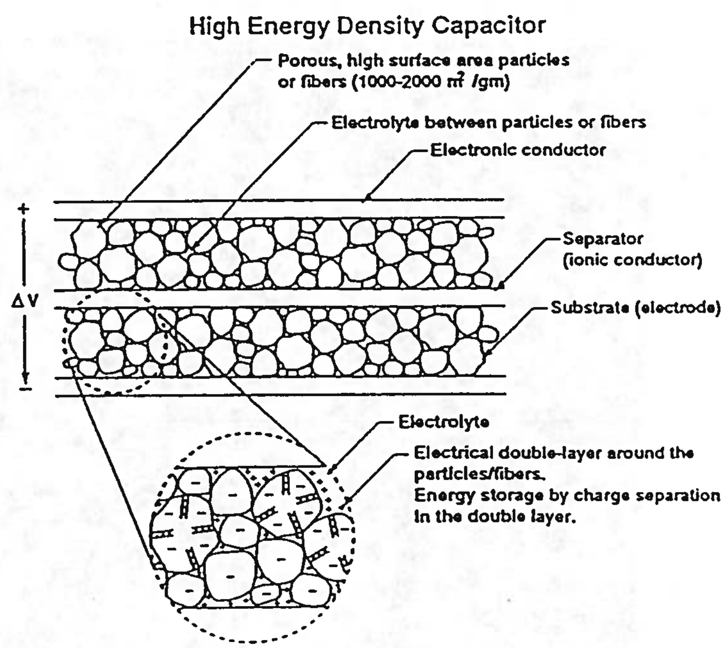
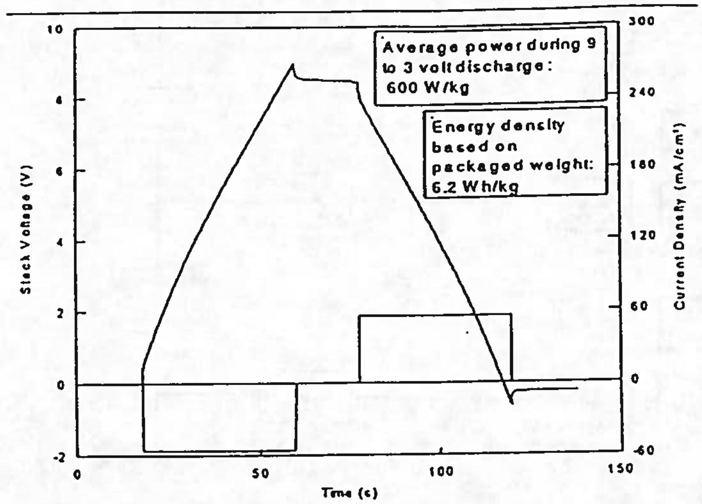
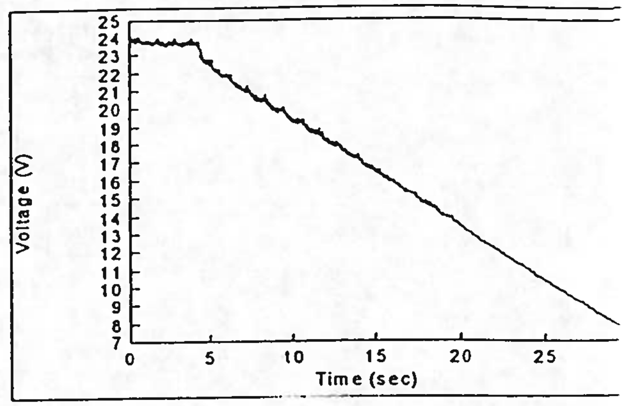


Figure 2: Bipolar UltraCapacitor Schematic



Constant current charge/discharge curve of a packaged three-cell, 9 V, organic electrochemical capacitor. Active area and height of the stack were 17.8 cm² and 0.33 cm. The total packaged weight of the device was 9.56 g. The discharge rate shown represents an average power of 600 W/kg during a 9 to 3 volt discharge. At this rate the capacitance was measured to be 5.2 F (15.6 F/cell).

Figure 3: Constant Current (1A) Charge/Discharge of a Three-cell, 9V Maxwell Capacitor



Constant current discharge curve of eight-cell, 24 V, bipolar stack. The sta
active cross-sectional surface area of 17.8 cm², and a height of 0.8 cm. Tl
at 56 mA/cm² shows a capacitance of 1.7 F. This translates to a energy de
9.5 Wh/l.

Figure 4: Constant Current (1A) Discha of an Eight-cell, 24V Maxwell Capacito

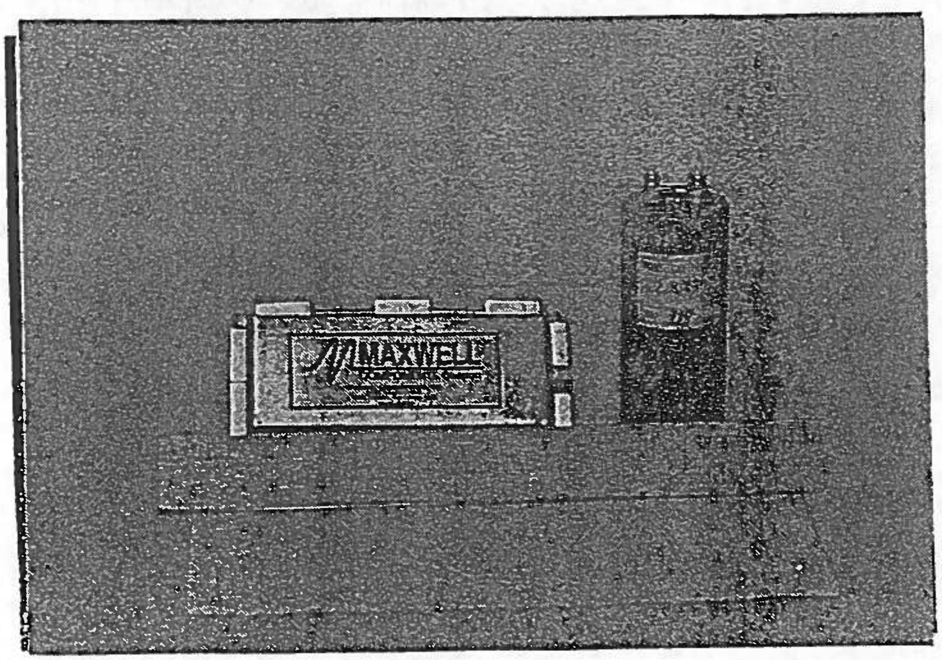
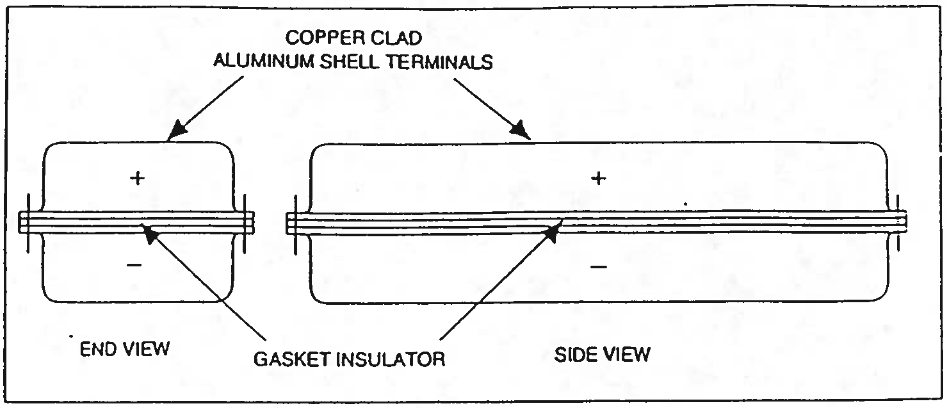


Figure 5: The Maxwell Package 2500F, 3V Capacitor



Basic capacitor cell (3 volts, 2.6 Whr).Size is approximately 4 cm high x 5 cm wide x 15 cm long.

Figure 6: Drawing of the External Enclosure of the Maxwell 2500F, 3V Capacitor

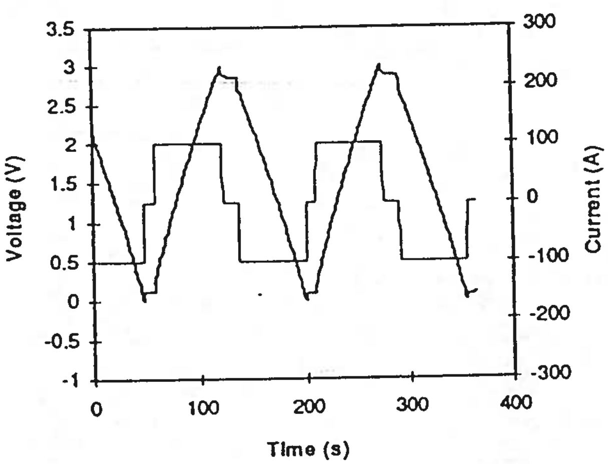


Figure 7: Constant Current (100A) Charge/Discharge of theMaxwell 2500F Capacitor

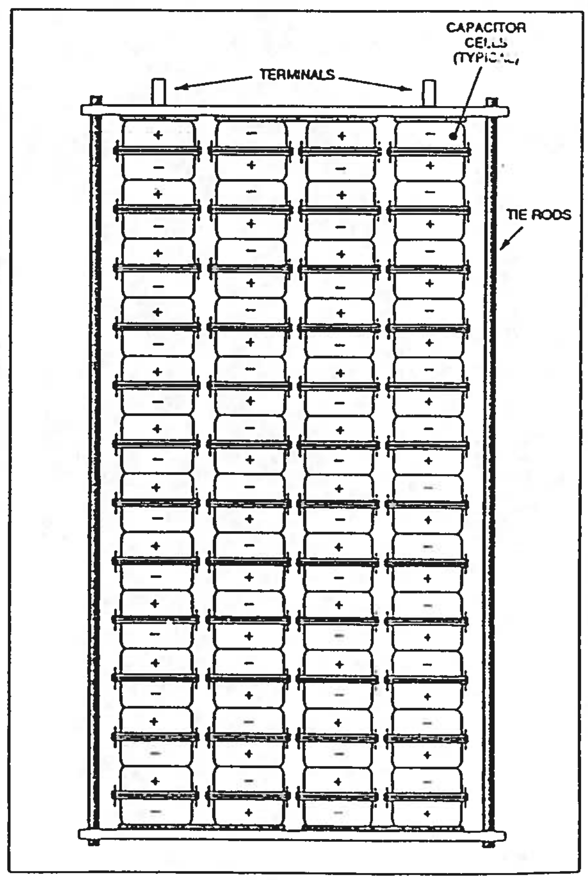


Figure 8: Schematic of a Maxwell 144V, 52F Capacitor Unit (125 wh)