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ELECTRIC/HYBRID SUPER CAR DESIGNS USING ULTRACAPACITORS

Andrew F. Burke
Institute of Transportation Studies
University of California, Davis
Davis, California 95616

ABSTRACT

Advanced passenger car designs utilizing electric/hybrid drivelines with an engine/generator or fuel cell to generate electricity on-board the vehicle and electrical energy storage (a pulse power unit, such as an ultracapacitor) to load level the engine/generator or fuel cell and to recover energy during vehicle braking are evaluated. All the cars have good acceleration performance (0–96 km/h in 9–10 seconds) and gradeability (96 km/h on a 6% grade). Computer simulation results on the Federal City and Highway driving cycles for the hybrid vehicles show that driveline and vehicle design technology have a large effect on both fuel economy and emissions of the vehicles. The results indicate that using the hybrid/electric drivelines in steel body, engine/generator powered vehicles, fuel economies of 50–70 mpg are achievable and that composite body, fuel cell powered vehicles can have fuel economies of 150–200 mpg gasoline equivalent. Intermediate fuel economies can be achieved using other combinations of vehicle material and driveline technologies. All the cars are projected to have emissions well below the California ULEV emissions standards. The ultracapacitors used in the hybrid drivelines has an energy density of 10 Wh/kg and stored 300–500 Wh of energy. Combined with on-off operation of the engine/generator or fuel cell, the ultracapacitors were maintained within 60–90% of their rated voltage by regenerative braking and on-board electricity generation.

INTRODUCTION

There has been considerable study in recent years concerning how much the fuel economy of passenger cars could be increased if the auto companies were to utilize the best known advanced driveline and materials technologies. In most cases, the studies (National Academy Press, 1992; DeCicco and Ross, 1994; DeCicco, 1992) considered incremental changes in technology resulting in relatively small increases in fuel economy (15–35%). A few studies (Lovins, 1995; Lovins et.al., 1995) have considered the possibility of very large increases in fuel economy resulting in passenger cars having fuel economies in excess of 100 miles per gallon for full-size cars and 200–300 miles per gallon for small two passenger cars. These very high fuel economy cars are often refered to as "super cars" or "hypercars". In addition to very high fuel economy, these cars would have very low emissions–well below the California ULEV standards approaching those of battery powered electric cars charged with electricity from the South Coast Air Basin.

It is generally agreed that these super cars would utilize electric/hybrid drivelines with the capability (engine/generator or fuel cell) of generating electricity on-board the vehicle from a chemical fuel and some form of electrical energy storage (a pulse power unit) to load level the engine/generator or fuel cell and to recover energy during vehicle braking. This paper is concerned with the design and projected performance and fuel economy of super cars using ultracapacitors as the pulse power unit. Ultracapacitors are well-suited for this application because of their very high specific power (kw/kg), long cycle life under deep discharge conditions, and high round-trip efficiency (Burke, 1992; Burke, 1994a; Burke, 1994b). The energy density (Wh/kg) of ultracapacitors is modest (10–20 Wh/kg) compared to batteries, so it is important to limit the energy stored in them to that required for load leveling the engine/generator or fuel cell and for braking energy recovery. As will be discussed in a later section of the paper, the engine/generator or fuel cell is sized to provide the steady power for high speed cruise and gradeability. The results given in the paper are based on detailed sec-by-sec simulations of vehicle operation obtained using the SIMPLEV program (Cole, 1993) and where possible, component characteristics based on test data. The vehicle characteristics (weight and road load) are not based on detailed vehicle designs, but are selected as being attainable based on the characteristics of present cars and information in the literature (Gjostein, 1995) on what reductions in drag, rolling resistance, and weight appear to be feasible.

VEHICLE DESIGN

In order to maximize the fuel economy of a vehicle, it is necessary to make the vehicle as light and the road load as low as possible consistent with its interior size and utility and safety and handling considerations. Presently there is considerable uncertainity concerning both the minimum practical weight and aerodynamic drag (CdA) of various size cars. The vehicle design parameters used in this study are based primarily on those given in Gjostein, 1995 and are felt to be relatively conservative. Much more aggressive weight and aerodynamic drag reductions are assumed in References (Lovins, 1995; Lovins et.al., 1995) and as a result, the projected fuel economy values are much higher than those obtained in this paper.

Following Reference (Gjostein, 1995), the vehicle weight was divided into four parts – body, chassis, powertrain, and fuel/fluids. For a future super car, the body and chassis weights were reduced by 50% to reflect the design targets given in Reference (Gjostein, 1995). The powertrain weight for the hybrid/electric driveline was calculated based on the weights of the various components (motor, electronics, ultracapacitors, engine/generator or fuel cell) as discussed in later sections of the paper. The weight breakdowns for cars using 1995 body/chassis design approaches and 2005 super cars of various sizes (small, mid–size, and full) using light–weight materials are summarized in Table 1.

The road load of the various size vehicles is specified using their drag coefficient, frontal area, and tire rolling resistance. The road load parameters are summarized in Table 2. The same frontal area was used for the 1995 and 2005 cars, but the drag coefficient and rolling resistance were reduced for the 2005 vehicles within practical ranges. The same acceleration and gradeability performance specifications are used for all the vehicles – 0–96 km/h acceleration in 9–10 seconds and a gradeability of 96km/h on a 6% grade. The power ratings of the various components are shown in Table 2. The top speed of the vehicles is in excess of 120 km/h (75mph). The fuel economy and emissions of the vehicles will be evaluated on the Federal Urban and Highway driving cycles. The ultracapacitors are sized such that they store sufficient energy (Wh) that they can load level the engine/generator or fuel cell on the Federal Cycles without being discharged below about 60% of their rated voltage. This energy storage is sufficient for several repeated vehicle accelerations to 96 km/h.

DRIVELINE COMPONENTS AND CONTROL STRATEGIES

Both series and parallel hybrid drivelines are considered. In the case of the series hybrid driveline configurations (Figure 1), the electric motor is placed on the rear axle in a single–shaft arrangement as used by Ford/GE (Sims et.al., 1992) with the engine/generator or fuel cell in the front under the hood of the vehicle. For the parallel hybrid configurations (Figure 2), the engine, motor, and transmission would be placed under the hood of the vehicle with the components connected as in the driveline of the University of California, Davis hybrid vehicle (Bye et.al., 1995). In all cases, the ultracapacitor unit and its interface electronics are placed under the vehicle. There should be sufficient space available in all the vehicles for the driveline components without sacrificing vehicle utility.

DRIVELINE COMPONENTS

Motors and electronics

All the vehicles studied utilized the AC induction motor and DC–AC inverter electronics developed by General Electric on the United States Department of Energy (DOE) Modular Electric Vehicle Program (MEVP). The characteristics of the MEVP driveline components are discussed in detail in King et. al.,, 1992. The specific power of the motor and electronics is 1.2 kg/kW. An efficiency map for the MEVP motor/electronics combination as a function of torque and speed was obtained from General Electric for use in SIMPLEV. The efficiency data from General Electric was for a 56 kW system. Maps for higher and lower power systems are obtained from that data by normalizing the torque with the maximum value for the 56 kW system and utilizing the efficiency data in terms of speed and normalized torque for 45 to 90 kW systems.

Ultracapacitors

As stated earlier in the paper, the ultracapacitors are sized (Wh) to load level the engine/generator or fuel cell. Computer simulations of hybrid vehicle operation on urban and highway driving cycles (Burke and Dowgiallo, 1990; Burke et.al., 1990)) have shown that this requires an energy storage capacity of 300–700 Wh depending on vehicle size and weight. The weight of the ultracapacitors is calculated using an energy density of 10 Wh/kg. In order to control the rate of charge and discharge of the capacitors as they load level the engine/generator or fuel cell, interface electronics is needed between the capacitor unit, engine/generator or fuel cell, and the motor controller. The weight of that electronics is estimated to be .35 kg/kw (DeDoncker et.al., 1993).

In the simulations of the hybrid vehicles, the ultracapacitors are modeled like batteries whose open–circuit voltage and state–of–charge 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. The capacitors are characterized by the specific capacitance (F/cm2), specific resistance (ohm–cm2), rated voltage, and energy density (Wh/kg) of the cells, determined from laboratory tests of small devices. The characteristics used in this study are those for the carbon–based Maxwell cells using an organic electrolyte (Burke, 1994a). The cell values are:

.75 F/cm2, 1 Ohm–cm2, 3V, 10 Wh/kg

A 336 V, 400 Wh ultracapacitor unit would weigh 40 kg and consist of one–hundred twelve 3V cells. Each cell stores a charge of 2.4 Ah and has a resistance of .02 milliohms. The 400 Wh unit has a round–trip efficiency of 93% at a power of 60 kW.

The energy storage capacity (Wh) 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 ultracapacitor cells as 1/Ah when the cell capacity is changed from the input reference value. Modeling the ultracapacitors in this way includes the effect of resistance on capacitor voltage

Engine/generators

In the series hybrid drivelines, the engine/generator is load leveled using ultracapacitors. It is sized (kW) such that the vehicle has a gradeability of 96 km/h on a 6% grade. The weight of the engine/generator is calculated using a specific power of 1.5 kg/kW for the engine and 1.2 kg/kW for the generator and its electronics based on data given in Burke, 1992; Burke 1993. The engine characteristics are input into SIMPLEV as brake specific fuel consumption (bsfc) and emission maps as a function of power fraction. The engine operating line selected was that which resulted in the minimum bsfc at each power fraction. Bsfc is given as gm gasoline/kWh and the engine out emissions are given as gm HC,CO, NOx/kWh. The engine inputs (Table 3) used in this study are based on data for a modern (stock) fuel injected, 4 cylinder, 4–stroke engine. The maximum efficiency of the engine is 32%. It is assumed that the same engine maps apply regardless of the maximium power of the engine even for engines as small as 10 kW. The engine exhaust is connected to a three–way catalyst with a specified conversion efficiency (90–95%) for each of the pollutants. It is assumed that the catalyst is electrically heated for all the simulations. SIMPLEV has the capability for including thermal warm–up of the catalyst and engine stop/start emissions, but those effects were not considered.

For the series hybrid drivelines, the power output of the engine is input to a generator having a constant efficiency of 90%. For the parallel hybrid drivelines, the engine output is either used to power the vehicle directly at the wheels or to recharge the batteries using the electric motor as a generator.

Fuel Cells

One of the objectives of the study was to compare the fuel economy of hybrid vehicles using proton exchange membrane (PEM) fuel cells with those using an engine/generator for on–board electricity generation keeping the remainder of the vehicle technolgy the same. The fuel cell is load– leveled with the ultracapacitor so it is sized (kW) in the same way as the engine/generator. The powertrain weight for the fuel cell–powered vehicles is calculated assuming the specific power of the PEM fuel cell is 4.25 kg/kW. This includes the stack and support/accessory equipment needed to operate the stack.

The operating characteristics of the fuel cell are modeled similar to that of an engine in that the fuel use is given as gm gasoline equivalent /kWh electricity output as a function of power fraction. The fuel use is calculated based on the steady–state efficiency data for a PEM fuel cell given in Sn et.al., 1994. The tests of the PEM fuel cell were run using hydrogen and air. The operating line (pressure and stoichiometry) selected for the fuel cell was that which resulted in the maximum efficiency at each power fraction. The gasoline equivalent bsfc map used for the fuel cell is given in Table 4. The efficiency 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 loads. In addition, since the fuel cell tests were run on hydrogen, the fuel map in Table 4 does not include any reformer losses. In this study, it is assumed that hydrogen is stored on–board the vehicle. The weight of the fuel cell–powered vehicles is calculated assuming a 4% (by weight) hydrogen storage system and a range of 300 miles.

DRIVELINE CONTROL STRATEGIES

Series Hybrid Vehicles

In the series hybrid vehicle, the electric motor provides all the power to the wheels. The control strategy is concerned with setting the power that comes from the ultracapacitor and the operating power of the engine/generator or fuel cell such that the capacitor is maintained at 60– 90% of its rated voltage. The power setting of the engine/generator or fuel cell changes rather slowly as the vehicle power requirement is averaged over a period of 75 seconds. A minimum power setting for the engine/generator is specified so that the engine is not forced to operate at a power point at which the bsfc is significantly higher than its minimum. Setting a minimum power is not necessary for the fuel cell, because it operates most efficiently at low power. When the ultracapacitor voltage reaches 90% of its rated value, the engine/fuel cell is turned–off and it is restarted when the voltage falls to 60% of its rated value. Nearly all the energy to operate the vehicle passes through the ultracapacitor and its SOC varies continuously over a wide range (see Figure 3).

Parallel Hybrid Vehicles

In a parallel hybrid vehicle, both the electric motor and the engine can provide power directly to the wheels either separately or together. The control strategy is then concerned with the power split between the motor and the engine to drive the vehicle and the recharging of the ultracapacitors if their voltage falls below 60% of their rated voltage. The control strategy used in the present study utilized the electric motor as the primary drive for vehicle speeds below 32 km/h (20 mph) and the engine as the primary drive at higher speeds. The transition speed was selected such that on the FUDS cycle, the energy recovered from regenerative braking is sufficient to keep the ultracapacitor voltage in the desired range with minimum input from the engine driving the motor as a generator. When the voltage falls outside the desired range, the engine power is increased in order to charge the ultracapacitors. Using this strategy, the engine is turned off and on a number of times during the FUDS driving cycle. Such a strategy was implemented successfully in a previous DOE hybrid vehicle program in 1980 (Burke et.al., 1984).

FUEL ECONOMY AND EMISSIONS

Series Hybrid Vehicles

SIMPLEV simulations for each of the vehicle designs given in Tables 1 and 2 were run for the Federal City and Highway Cycles. The results for the fuel economy (miles/gal gasoline) and emissions (gm/mi) are shown in Table 5. For the fuel cell–powered vehicles, the hydrogen use (kg H2/mile) is given by 1/mpg gasoline – for example, 100 mpg gasoline equivalent corresponds to 0.01kg H2/mi. It was verified using the simulations that all the vehicles had an acceleration performance of 0–96 km/h in 9–10 seconds and a gradeability of 96 km/h on a 6% grade.

The results in Table 5 show the large effect of driveline and vehicle design technology on both fuel economy and emissions For each vehicle size class, the projected fuel economy increases markedly as the vehicle weight and road load are reduced and the energy conversion efficiency (fuel to electricity) is increased by the use of a fuel cell. The simulation results indicate that using hybrid/electric drivelines in steel body, engine–powered vehicles, fuel economies of 50–70 mpg are achievable and that composite body, fuel cell–powered vehicles can have fuel economies of 150–200 mpg gasoline equivalent. Intermediate fuel economies can be achieved using other combinations of vehicle materials and driveline technologies. All of the hybrid vehicles are projected to have emissions well below the California ULEV emission standards.

The effect of the use of the series hybrid driveline alone can be seen in Table 6 in which the fuel economy of hybrid vehicles having the same weight and road load as 1995 stock passenger cars are compared with the published fuel economy (1994 Gas Mileage Guide) of those cars. The calculated hybrid vehicle fuel economies were degraded by 20% for the city cycle and 10% for the highway cycle as is done by EPA for the stock cars. The improvements obtained with the series hybrid drivelines are in general the greatest for the city cycle (40–60%) and for the larger cars (50–60%). The highway and composite cycle fuel economy improvements are 30–40% for all size cars. Energy recovery during regenerative braking is an important contributor to the large improvement in fuel economy in city driving.

Parallel Hybrid Vehicles

A few simulations were done of hybrid vehicles using a parallel driveline configuration. SIMPLEV in its current form is not well–suited for simulating parallel hybrid systems, because the engine maps are input as a single operating line rather than general tables having the complete range of engine torque and RPM. This approach is realistic for series hybrids, but not for parallel hybrids in which engine speed can not be set independent of vehicle speed. As a result, SIMPLEV simulations will overestimate the fuel economy of parallel hybrids relative to series hybrid. A summary of the parallel hybrid results compared with the corresponding series hybrid results for the engine systems are given in Table 7. As expected, the simulations for the parallel hybrid vehicles yielded higher fuel economy. The same electric driveline components were used in the parallel and series drivelines even though the electric motor could have been downsized in the parallel driveline without sacrificing acceleration performance. In other words, the parallel driveline was not optimized to take advantage of the simultaneous operation of the electric motor and engine during periods of maximum power demand. The most important result of the parallel hybrid simulations is that the same size ultracapacitors (300–500 Wh) used in the series hybrid vehicles designs can be used in the parallel hybrid vehicles with the electric motor being used as a generator during periods in which the engine is the primary power source for the vehicle. In the parallel hybrid driveline, the ultracapacitors are recharged both from the engine and during periods of regenerative braking. The electrical energy stored in the ultracapacitors is used to power the hybrid vehicle as an electric vehicle on both the city and highway cycles for speeds less than 32 km/h (20 mph). The results given in Table 7 indicate this mode of operation yields a vehicle with attractive fuel economy. Additional work investigating the use of ultracapacitors in parallel hybrid drivelines should be done.

STATUS OF HYBRID VEHICLE TECHNOLOGY AND R&D NEEDS

The hybrid vehicle simulations presented in this paper indicate that the use of hybrid/electric drivelines is an attractive approach for greatly improving fuel economy and reducing emissions in high performance passenger cars. These improvements were achieved using ultracapacitors and modes of engine and system operation very different from that customarily used in conventional engine–powered passenger cars. Specifically, the engine/generator was operated in an on–off mode based on the state– of–charge of the ultracapacitors and the power demand of the vehicle. The control strategies used in the simulations involved detailed management (second–by–second) of the energy flow to and from the vehicle, ultracapacitors, and engine/generator or fuel cell. On–board electrical energy was generated as needed and recovered during regenerative braking when it was available. This approach offers the opportunity for more efficient vehicle operation than has been possible in the past using mechanical drivelines (engines and transmissions).

As noted previously, the results given in Table 6 are based on steady–state bsfc and emissions maps for the engines and do not include possible effects on fuel consumption and emissions of transient, on–off operation of the engine/generator. The magnitudes of these effects are not thought to be large based on the limited data available (Burke, 1993), but they do represent a significant uncertainty. It should also be noted that the engine maps used in the present study are for a stock 4– stroke engine that has not been optimized for hybrid applications in which the range of engine operating parameters is much more limited than in conventional vehicles and the response time of the engine is much less important (series hybrids). In addition, the control strategy for operating the hybrid driveline was not optimized and the effect of control strategy on fuel economy can be significant. Hence, much additional work is needed to refine the fuel economy projections given in Table 6 and 7 and to develop and test the vehicle hardware and software needed to implement the driveline control strategies. This work should include considerable laboratory testing of engine/generators operated in on–off modes and optimization of engines to be used in that way.

The ultracapacitor is a key component in the hybrid drivelines studied in this paper. Development of ultracapacitors for electric/hybrid vehicles has been underway with support from the United States Department of Energy (DOE) since 1991. The ultracapacitor characteristics used in the simulations are based on tests of small (20 cm2) devices designed and fabricated by Maxwell Laboratories in the DOE program. Much additional development and scale–up to large devices for use in hybrid and electric vehicles are needed (Burke, 1994b) before hybrid vehicle designs such as those invisioned in this paper become a reality. In addition, continued materials research (Burke and Murphy, 1995) is needed to improve the energy density of ultracapacitors from the present values of 8–10 Wh/kg to 20 Wh/kg or even higher without sacrificing power density or cycle life.

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TABLE 1: WEIGHT BREAKDOWN SUMMARIES FOR HYBRID VEHICLE DESIGNS

Vehicle	Total[(1)] Weight	Body	Chassis	Fuel/ Fluids	Prop. System	Motor/ Electronics	Capacitor/ Electronics	Engine or Fuel Cell	Generator Electronic
Compact-size									
95 Eng/gen	1095	358	348	41	208	78	57	41	32
05 Eng/gen	677	179	174	28	156	54	43	33	26
95 FC[(2)]	1171	358	348	75	250	78	57	115	–
05 FC	734	179	174	50	191	54	43	94	–
Mid-size									
95 Eng/gen	1343	446	433	51	273	96	69	60	48
05 Eng/gen	814	223	217	34	200	67	57	42	34
95 FC	1454	446	433	100	335	96	69	170	–
05 FC	889	223	217	66	243	67	57	119	–
Full-size									
95 Eng/gen	1644	605	526	62	311	108	81	68	54
05 Eng/gen	978	303	263	41	231	78	66	48	39
95 FC	1763	605	526	112	380	108	81	191	–
05 FC	1061	303	263	75	280	78	66	136	–

(1)All weights are in Kg. Total weight includes 140 kg payload.

(2)FC - Fuel Cell Powered.

TABLE 2: ROAD LOAD PARAMETER AND POWER TRAIN SUMMARIES FOR THE HYBRID VEHICLE DESIGNS

Vehicle	Total Weight (kg)	C_D	Frontal Area (m^2)	Rolling Resistance	Max Motor Power (kw)	Generator/ Fuel Cell (kw)	Capacitors wh
Compact-size							
95 Eng/gen	1095	.25	1.85	.006	65	27	340
05 Eng/gen	677	.20	1.85	.005	45	22	270
95 FC	1171	.25	1.85	.006	65	27	340
05 FC	734	.20	1.85	.005	45	22	270
Mid-size							
95 Eng/gen	1343	.27	2.0	.006	80	40	410
05 Eng/gen	814	.22	2.0	.005	56	28	370
95 FC	1454	.27	2.0	.006	80	40	410
05 FC	889	.22	2.0	.005	56	28	370
Full-size							
95 Eng/gen	1644	.27	2.1	.006	90	45	485
05 Eng/gen	978	.22	2.1	.005	65	32	430
95 FC	1763	.27	2.1	.006	90	45	485
05 FC	1061	.22	2.1	.005	65	32	430

TABLE 3: ENGINE FUEL CONSUMPTION AND EMISSION CHARACTERISTICS

Power Fraction	bsfc (gm/kwh)(1)	Emissions (gm/kwh)		
		HC	CO	NO_x
0	277	1.5	1.75	6.5
.11	277	1.5	1.75	6.5
.22	256	1.3	1.80	10.0
.33	238	1.2	1.90	9.0
.44	238	1.1	2.1	10.0
.55	243	1.0	2.2	11.0
.67	260	1.15	2.5	6.0
.78	290	1.4	2.75	5.0
.89	297	1.5	2.90	5.0
1.0	308	1.5	3.0	5.0

(1) Fuel-gasoline, maximum engine efficiency - 32.5%

TABLE 4: PEM FUEL CELL - FUEL CONSUMPTION AND EFFICIENCY CHARACTERISTICS

Power Fraction	Specific Fuel Consumption(gm/kwh) Gasoline Equivalent[1]	Efficiency (%)
0	118	66
.166	118	66
.33	126	62
.50	133	58
.67	141	55
.833	150	52
1.0	171	45

[1] Based on tests using hydrogen and air. (Swan et.al, 1994)

TABLE 5: SUMMARY OF THE FUEL ECONOMY AND EMISSIONS SIMULATION RESULTS FOR THE HYBRID VEHICLE DESI

Vehicle	Total Weight (kg)	Fuel Economy (mpg-gasoline)		Emissions (gm/mi) City Cycle		
		City	Highway	HC	CO	NO_x
Compact-size						
95 Eng/gen	1095	68	70	.01	.016	.077
05 Eng/gen	677	110	101	.006	.01	.048
95 FC	1171	135	138	–	–	–
05 FC	734	196	186	–	–	–
Mid-size						
95 Eng/gen	1343	53	57	.013	.020	.101
05 Eng/gen	814	87	82	.008	.012	.060
95 FC	1454	101	112	–	–	–
05 FC	889	188	177	–	–	–
Full-size						
95 Eng/gen	1644	42	50	.016	.024	.125
05 Eng/gen	978	76	77	.009	.014	.068
95 FC	1763	93	108	–	–	–
05 FC	1061	156	165	–	–	–

TABLE 6: COMPARISON OF THE FUEL ECONOMY FOR HYBRID/ELECTRIC AND STOCK CARS OF VARIOUS SIZES.

Vehicle	City(3)	Highway(3)
Compact Size		
95 Eng/gen(1)	58 (48.3)	58 (52.7)
95 Stock(2)	34	40
%Improvement of the Hybrid	42	32
Mid-size		
95 Eng/gen(1)	46.5(38.8)	47 (42.7)
95 Stock(2)	25	31
%Improvement of the Hybrid	55	38
Full-size		
95 Eng/gen(1)	38(31.7)	41 (37.3)
95 Stock(2)	20	28
%Improvement of the Hybrid	59	33

(1)95 Eng/gen Hybrid simulations used the C_dA and rolling resistance for 95 Stock passenger cars

(2)Fuel economy taken from the EPA/DOE Mileage Guide for either M5 or L4 transmissions and popular models

(3)The calculated fuel economies were reduced using the EPA factors: city by 20% and highway by 10%

TABLE 7: COMPARISON OF SIMULATION RESULTS FOR SERIES AND PARALLEL HYBRID VEHICLES

Vehicle	City	Highway
Full-size		
95 Eng/gen series	42	50
95 Parallel(1)	59	62
05 Eng/gen series	76	77
95 Parallel(1)	102	93

(1)Engine operating at best bsfc conditions at all powers; fuel economy using a complete engine map would be lower.

FIGURE 1: SERIES HYBRID DRIVELINE SCHEMATIC

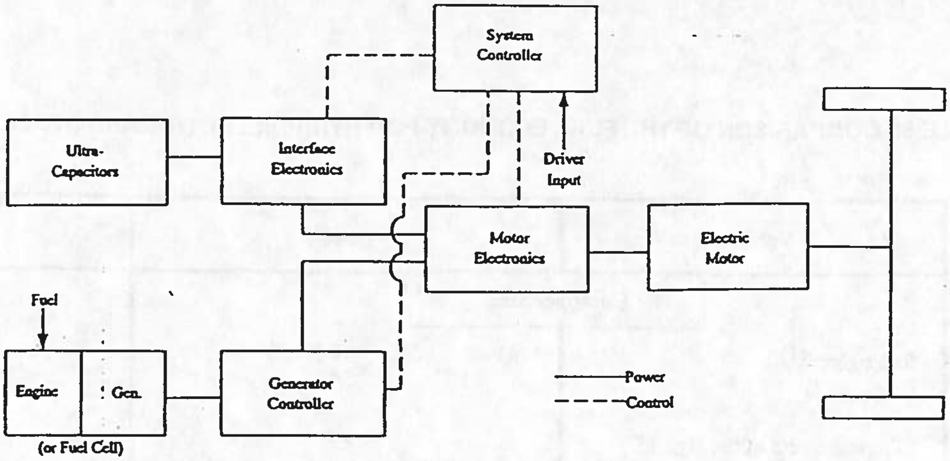
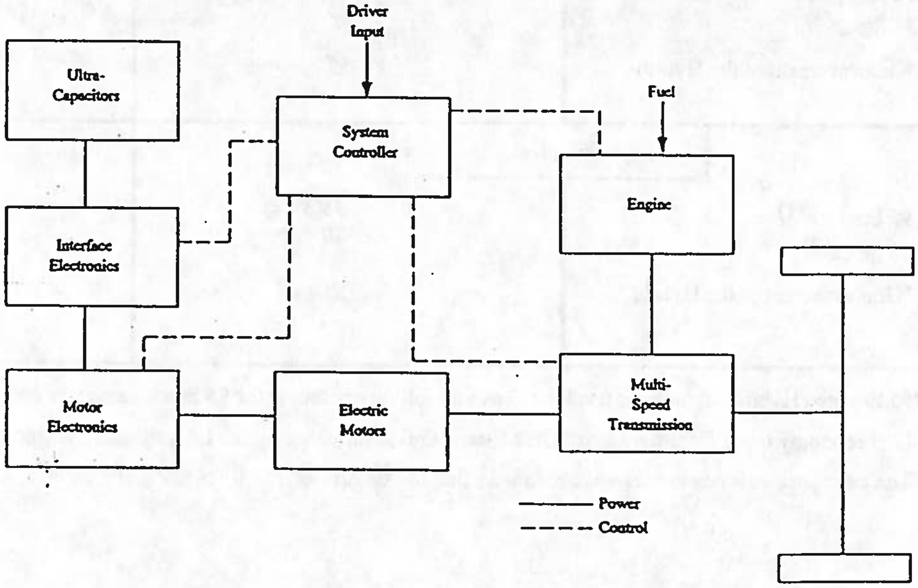


FIGURE 2: PARALLEL HYBRID DRIVELINE SCHEMATIC



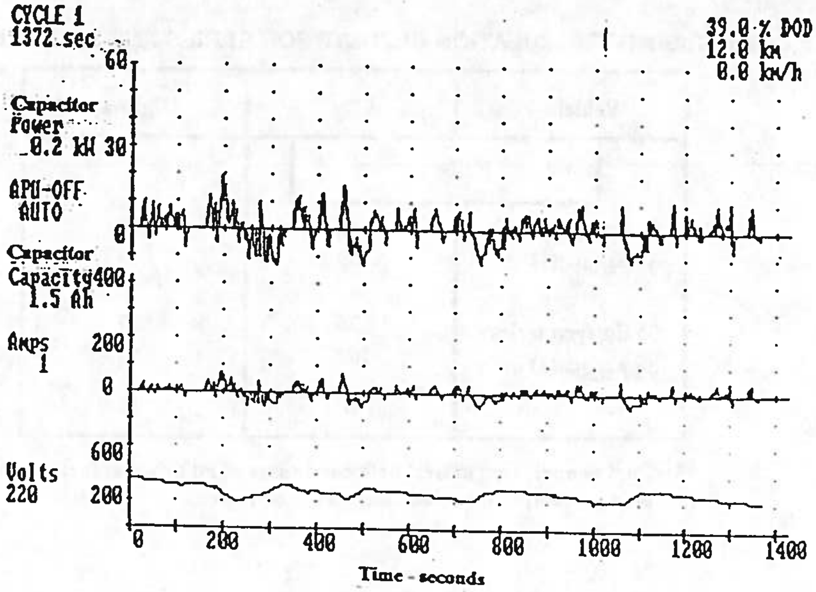


Figure 3: Discharge/charge of the ultracapacitor on the Federal City Driving Cycle