Assessment of the Greenhouse Gas Emission Reduction Potential of Ultra-Clean Hybrid-Electric Vehicles

UCD-ITS-RR-97-24

December 1997

by

Andrew F. Burke
Marshall Miller

Institute of Transportation Studies
One Shields Avenue
University of California, Davis
Davis, California 95616
Tel. 530/752-0247 Fax 530/752-6572
http://www.engr.ucdavis.edu/~its/
e-mail: itspublications@ucdavis.edu

Institute of Transportation Studies
University of California, Davis
One Shields Avenue
Davis, California 95616-8762

Assessment of the Greenhouse Gas Emission Reduction Potential of Ultra-Clean Hybrid-Electric Vehicles

A.F. Burke
M. Miller

December 1997

Phone 530-752-6548 • Fax 530-752-6572 • http://www.engr.ucdavis.edu/~its/events/index.html

TABLE OF CONTENTS

APPENDICES (In Separate Volume)

LIST OF TABLES

LIST OF FIGURES

Acknowledgments

This report resulted from an integrated study of hybrid/electric vehicle technology supported by several agencies - the California Air Resources Board (CARB)via a contract with the California Energy Commission (CEC) via a contract with the United States Environmental Agency (USEPA), the National Renewable Energy Laboratory (NREL), and the University of California Transportation Center (UCTC). The primary technical monitor of this study was Dr. James Lerner of CARB. His patience and that of the other agencies were essential to the successful completion of the work, because the scope of the study and the time it took to complete it was much greater than was originally planned in the workstatements for the contracts.

The contribution of David Friedman in the development of the Advanced Vehicle Tecnology Evaluator (AVTE) simulation program was key to the evaluation of parallel hybrid vehicles in the study. Important data on driving cycles and upstream emissions were recieved from CARB and CEC. The cooperation of all these collaborators is greatly appreciated.

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

Assessment of the Greenhouse Gas Emission Reduction Potential of Ultra-Clean Hybrid-Electric Vehicles

A. F. Burke
M. Miller

Abstract

The study focused on the emission reduction and fuel economy benefits of the application of hybrid/electric powertrain technology to light-duty vehicles (mid-size and compact passenger cars). The approach taken was to calculate the exhaust emissions (gm/mi) and energy use (Wh/mi and mpg) for a wide range of vehicle designs (steel and light-weight materials), engines, energy storage devices, control strategies, and driving cycles using two vehicle simulation programs (SIMPLEV and AVTE). The full fuel cycle total emissions were then calculated for each of the hybrid designs using an EXCEL macro, which used as inputs the vehicle simulation results and upstream emissions to account for the vehicle evaporative and refueling emissions and the production and distribution of the fuel and electricity used by the vehicles. The total emissions calculations included the effects of the vehicle use-pattern.

The key conclusions drawn from the results of the study were the following: (1) light-duty vehicles using an engine-powered hybrid driveline can have up to double the fuel economy and thus one-half the total CO2 emissions of conventional ICE vehicles of the same weight and road load, (2) Vehicles using a load-leveled fuel cell fueled with compressed hydrogen can have about one-third the total CO2 emissions of a conventional vehicle using gasoline, (3) the calculated total emissions of mid-size, battery-powered vehicles in the LA Basin are close to or less than the CARB EZEV standards, (4) hybrid vehicles with an all-electric range of 50 miles or more have total emissions close to those of an electric vehicle for a use-pattern of 10,000 miles per year, (5) regulated emissions and CAFE standards for light-duty vehicles should be set in terms of total full fuel cycle emissions for NMOG, CO, NOx, and CO2 rather than exhaust emissions and mpg as is current practice, and (6) the marketing of advanced hybrid vehicles, including fuel cell powered vehicles, will be driven by CAFE or other vehicle efficiency standards and not regulated emission standards, because the ultra-clean emission standards can also be met using advanced engine technologies in conventional engine drivelines with catalytic exhaust after-treatment without large retooling investments by the auto industry.

1. Introduction

The contribution of transportation in general and light duty vehicles (passenger cars and small trucks) in particular to greenhouse gas emissions (primarily carbon dioxide) has been the subject of a number of conferences, reports, and papers (References 1-4) in recent years. In nearly all the references, hybrid/electric vehicle technology is cited as one of the most promising approaches to reducing vehicle emissions (exhaust and upstream emissions) and fuel consumption (and thus CO2 emissions) regardless of the fuel used. A hybrid-electric vehicle is a vehicle that utilizes both an electric motor and an engine in its driveline and electricity and a chemical fuel for propulsion.

This study focuses on the emission reduction and fuel economy benefits of the application of hybrid/electric vehicle technology to light-duty vehicles. The emissions of interest are the regulated exhaust pollutants - non-methane organic gases (NMOG), carbon monoxide (CO), nitrogen oxides (NOx), and particulates (PM10 and PM 2.5) - and the greenhouse gases - carbon dioxide (CO2), methane (CH4), and Nitrous Oxide (N2O). Since the emission rate (gm/mi) of the primary greenhouse gas (CO2) is directly related to the energy consumption (miles per gallon or Wh per mile) of a vehicle, calculation of the fuel usage of the hybrid/electric vehicles is a central issue in this investigation.

Methodology

The approach taken in this study is to calculate the exhaust emissions (gm/mi) and energy use (Wh/mi and mpg) for a wide range of vehicle designs, driveline technologies, and driving cycles using the SIMPLEV and AVTE vehicle simulation programs (References 5-7). For calculating emissions from hybrid vehicles which can operate in an all-electric mode --that is powered exclusively by batteries charged from the wall-plug -- it is important to define typical use patterns in order to estimate the extent to which these vehicles are likely to be used in their all-electric mode. The use-pattern of the vehicles is described in terms of distance to work, annual mileage, and daily travel statistics. The annual tailpipe emissions and energy useage (electricity and fuel) of the various hybrid vehicle designs are calculated using vehicle simulation results and the use-pattern statistics. Emissions other than tailpipe emissions (often refered to as upstream emissions) -- including evaporative and refueling, fuel distribution, powerplant and refinery emissions -- are calculated for each vehicle design and use-pattern. The total annual full fuel cycle emissions (gm/mi) are then calculated using an EXCEL spreadsheet that combines the tailpipe and upstream emissions for each vehicle design and use-pattern. The spreadsheet results are then compared with the various emission standards for conventional engine-powered vehicles using gasoline and the benefits of the hybrid vehicle technologies and alternative fuels assessed. Most emissions standards for light duty vehicles have been set in terms of tailpipe exhaust emissions with the upstream emissions being determined by other regulations for evaporative and refueling emissions and emissions from oil refineries and electrical powerplants. In this study, the emission comparisons, including CO2 emissions, are based on the full fuel cycle emissions of the conventional and hybrid vehicles and not only on the exhaust emissions as has been often done in past studies.

Discussion of Policy Implications

The last section of the report includes an assessment of regulatory changes that could facilitate the commercialization of hybrid-electric vehicles. The vehicle technologies discussed in this report are based on electric driveline and energy storage components that are very different from those currently used by the automobile industry. Making the transition to these new technologies would be both disruptive and expensive for the auto industry. Hence, even if the auto industry should conclude that it is not possible to achieve large reductions in energy usage and CO2 emissions from evolutionary improvements in the current technologies, it would likely take the industry many years to make the changes to hybrid vehicle technology unless there are special incentives through new emissions or fuel economy regulations or tax credits for the first companies or consumers that produce or purchase vehicles using the new hybrid vehicle technologies.

2.0 Hybrid Vehicle Design Considerations

Before discussing in detail the various hybrid-electric vehicle technologies, it is useful to consider in more general qualitative terms, various aspects of hybrid vehicle design, because as discussed in References 8,9 there are several types of hybrid vehicles that can be designed depending on the primary objective of the design process. In addition, even for a particular design objective and type of hybrid vehicle, there is a wide variety of components that are available for use in the driveline of the vehicle. Hybrid-electric vehicles can be designed to minimze total energy use (energy efficiency and thus CO2 emissions) or to minimize total annual emissions of regulated gases, primarily those directly related to vehicle operations. Minimizing these emissions likely requires maximum annual operation in an all-electric mode and significant recharging from the wall-plug. This type of hybrid would incorporate large on-board electrical energy storage and have a fairly long all-electric range. It is often referred to as a "California Hybrid" as it could qualify for a significant ZEV credit under terms of proposals previously considered by the California Air Resources Board (Reference 10). Minimizing total energy use requires minimum vehicle weight and size and thus minimum on-board energy storage consistent with efficient operation of the driveline in urban driving. A hybrid-electric vehicle designed to maximize fuel economy in the hybrid mode would have essentially zero all-electric range and thus be operated in a hybrid mode at all times. The regulated emissions from this type of vehicle would be essentially independent of use-pattern much like conventional, gasoline fueled vehicles and would be designed to meet specific exhaust emissions regulations, probably ULEV or lower. This is the approach being taken in the Partnership for a New Generation Vehicle program (PNGV).

After deciding whether the primary intent of the design is to minimize annual full fuel cycle emissions or to minimize total energy useage, the next major design decision is whether to utilize a series or parallel driveline. In a series driveline, all the torque to drive the vehicle is applied to the wheels by the electric motor and the fuel is converted to electricity on-board the vehicles by an engine/generator or a fuel cell. In a parallel driveline, torque is applied to the wheels by the electric motor or engine (or both if required) and the most of the fuel is used directly to power the vehicle when the engine is operating. Either approach can be optimized to meet emissions or energy useage objectives, but it is likely that it will be easier to minimize tailpipe emissions using the series driveline and to maximize hybrid mode fuel economy using the parallel driveline. Driveline designs that can be operated in a combined series/parallel mode have been conceived and built (Reference 11), but such designs are necessarily more complex, more difficult to control, and more expensive than either a series or parallel driveline. In this study, both series and parallel drivelines are analyzed and compared.

Selection of an engine for a hybrid-electric vehicle is influenced by whether the driveline is to be a series or parallel design. The major difference is that for a parallel design the engine must be capable of fast response (turn-on and turn-off) as the driver changes power demand and the vehicle changes speed. Engines for series hybrid vehicles can be turned on and off as required at a time and rate that is optimum for clean and efficient operation of the driveline system independent of driver power demand. For these reasons, parallel hybrid vehicles will likely utilize internal combustion engines (spark or compression ignition) and series hybrids can utilize either internal or external combustion engines, such as the gas turbine or Stirling engines, or fuel cells. Engines in a parallel hybrid also must operate clean and efficient over wider RPM and power (torque) ranges than engines in a series hybrid, because in a parallel hybrid, the engine is directly connected to the wheels of the vehicle and much of the time provides all the power. Small engine size is important for all hybrid-electric vehicles, but is probably more important for the parallel hybrid in which the engine must be positioned near the electric motor and transaxle under the hood of the vehicle. Hence it appears that the engine requirements for parallel hybrid vehicles are more demanding than for series hybrids and the engines types that are applicable are fewer.

The next consideration in the design of the hybrid driveline is selection of the energy storage unit. The energy density (Wh/kg) and power density (W/kg) requirements for this unit depend primarily on the all-electric range of the vehicle and the maximum power (kW) rating of its electric motor/electronics. The requirements will be essentially the same for series and parallel drivelines. The key parameter is the power density (W/kg), especially for vehicles with a short all-electric range. In those cases, the energy stored (kWh) is small and the storage unit is sized by the power requirement unless its power density is greater than 1-2 kW/kg. Hence, except for hybrid vehicles having relatively long all-electric ranges (> 25 miles), the energy storage unit must be a pulse power device, such as a thin-film battery, ultracapacitor, or flywheel.

3.0 Fuels, Energy Usage, and Greenhouse Gas Emissions

Hybrid-electric vehicles can be fueled using reformulated gasoline, diesel fuel, methanol, natural gas, or hydrogen. For hybrid vehicles having energy storage units charged with elctricity from the wall-plug, the electricity can be generated using coal, oil, natural gas, nuclear, or hydro. The CO2 emissions for a particular vehicle design depend on the heating value and the carbon/hydrogen characteristics of the fuel used in the vehicle and powerplant and the energy usage (mpg and Wh/mi) of the vehicle.

For vehicles fueled with compressed natural gas (CNG), the hydrocarbon tailpipe emissions contain primarily unburnt methane (CH4), which on a molecular basis is a more active greenhouse gas than CO2 by a factor of 20-30. On a mass basis, 1 gm CH4 has the effect of about 70 gmCO2. This is not a serious problem for natural gas fueled vehicles, because the gm CH4/mi emissions are very small (less than 0.05 %) compared to gmCO2/mi that result from burning the fuel in the engine. For a fuel of the chemical formula CxHyOz , the CO2gm/mi emissions from the engine can be expressed as

$$\mathrm{gmCO2/mi}=(\mathrm{FF})*1/(\mathrm{mpg})_{\mathrm{gasolineequiv.}}*120{,}600/(\mathrm{kJ/gm})_{\mathrm{fuel\text{-}LHV}}$$

The factor FF = 44*x/ (12*x +y +16*z) follows from the stoichiometric combusion of the fuel to CO2 and H2O. The gmCO2/mi emissions corresponding to a fuel economy of 27.5 mpg gasoline equivalent are given in Table 1. The values range from 308 and 321 gmCO2/mi for gasoline and diesel fuel to 268 and 265 gmCO2/mi for natural gas and methanol. Hence vehicles fueled with natural gas have about a 20% CO2 emissions advantage over those fueled with gasoline and diesel fuel for the same fuel energy efficiency. Fuel cells fueled with hydrogen, of course, have zero tailpipe CO2 emissions, but as shown in Table 1, the fuel cycle CO2 emissions using hydrogen can be high if the hydrogen is produced by reforming natural gas (Reference 27) . Hence both the fuel used and the equivalent gasoline mpg combine to determine the greenhouse emissions of the hybrid vehicle.

For hybrid vehicles that are charged from the wall-plug, it is necessary to include the CO2 emissions from the powerplant. The wall-plug electricity needed depends on the net electrical energy from the battery (kWh/mi) and the battery and charger efficiencies. The energy needed at the powerplant to supply the wall-plug electricity depends on the efficiencies of the powerplant and the electrical distributions system. The resulting CO2 emissions are given by

$$\mathrm{gmCO2/mi} = 3600*(\mathrm{FF})*(\mathrm{kWh/mi})_{\mathrm{bat}} / (\mathrm{comb.\ effic.} * (\mathrm{kJ/gm})_{\mathrm{fuel}})$$

The combined efficiency from primary energy at the powerplant to the battery terminals is only about 21% for a 33% efficient powerplant, so that the CO2 emissions due to the use of electricity in a hybrid-electric vehicle can be significant. A summary of information on CO2 emissions for various powerplant technologies is given in Reference 12. Selected results calculated using the above equation for gmCO2/mi are summarized in Table 2. Note from the table the large difference in the CO2 emissions from conventional coal and natural gas fueled steam powerplants and the projected improvements in the efficiency and CO2 emissions from advanced technology gas-fired powerplants in future years.

The total CO2 emissions for a hybrid vehicle are the sum of the tailpipe and powerplant emissions.

$$\text{gmCO2/mi} = (\text{gmCO2/mi})\ \text{burnt fuel} + (\text{gmCO2/mi})\text{elec.pp.} + 65^{*}\ (\text{gmCH4/mi})$$

The tailpipe CH4 emissions are typically ten times the non-methane hydrocarbon emissions for the vehicle. However, the resultant effective contribution to the greenhouse gases of the CH4 tailpipe emissions from a natural gas fueled vehicle is only a few percent.

4. Assessment and Characterization of Technologies for Hybrid-electric Vehicles

The first part of this study was an assessment of advanced technologies for hybrid-electric vehicles, including small, energy efficient internal combustion engines and gas turbines, fuel cells, pulse power batteries and ultracapacitors, and electric driveline components. In order to perform computer simulations of hybrid/electric vehicles, it is necessary to assemble detailed information on each of the components in their driveline. This information is used to prepare the inputs for the simulation programs (SIMPLEV and AVTE (References 5,7)), which are used to calculate the energy consumption and emissions of each of the vehicle designs. Characterizations of the various driveline components are discussed in the following sections,. The formats for the component information presented in this report are similar to that given previously in References 13,14.

4.1 Engines and Emission Control

The key characteristics of an engine are its size and weight for a maximum specified power rating and its fuel consumption and emission maps as a function of torque and RPM. These characteristics vary over wide ranges for the different types of engines, which can be considered for use in hybrid vehicles. Cost and fuel requirements are also important in assessing engines for hybrid vehicle applications. The engines that could be considered for use in hybrid vehicles are listed in Table 3a along with a qualitative assessment of their relative advantages and disadvantages for use in series and parallel hybrid vehicles. As discussed previously in Section 2, the external combustion engines (gas turbine and Stirling) are best suited for series hybrids for which fast engine response is not essential. The internal combustion engines can be used in both series and parallel drivelines and the continued improvements in these engines for use in conventional vehicles will benefit hybrid vehicles as well. Research and development on gas turbine and Stirling engines for automobile applications has been in progress for over twenty years (References 15-18). More recent work has begun to emphasize the development of these engines for hybrid vehicles. Quantitative comparisions of the various engines are given in Table 3b.

In the vehicle simulations, the fuel useage and engine-out emissions are calculated over a specified driving cycle from fuel consumption and emissons maps by summing the sec-by-sec fuel use and emissions as the power demand varies over the cycle. The engine- out emissions are then passed through a catalyst to convert the pollutants to CO2, H2O, and nitrogen. Detailed engine map data (assuming steady-state operation) are needed for these calculations (see Appendix 1 for typical engine maps). More extensive engine data are needed to simulate parallel hybrid vehicles than series hybrids, because the engine in a parallel hybrid operates over a much wider range of power and RPM. For series hybrids, the fuel consumption and emission characteristics (gm/kWh) are needed only along an operating line as a function of power. The operating line is selected to give the best combination of engine efficiency and low emissions. For most of the simulation calculations, an electrically heated catalyst is assumed with the catalyst operating at maximum efficiency at all times. The catalyst efficiencies were varied according to engine type. Three-way catalyst systems for engines that operate very close to stoichiometric air fuel ratio are very well developed and have conversion efficiencies for all the regulated pollutants in excess of 95%. Catalysts for lean burn engines, like the diesel, are not well developed and conversion efficiencies, especially for NOx, are much lower. The catalyst efficiencies used in this study are given in Appendix 1. It should be noted that the emissions calculated in the simulations do not include the effects of engine warm-up and power transients. These effects can be minimized more easily for series that for parallel hybrid vehicles. Much further analysis and testing is needed to assess the effect of system warm-up and transients on the fuel economy and emissions of hybrid vehicles.

As might be expected, no single engine has characteristics that make it the clear choice for use in hybrid vehicles. In general, the smallest and lighest engines (two stroke and rotary engines) are not the most efficient and the cleanest (lowest emissions) and the most efficient (diesels) are not the cleanest. The response of the different engines to sudden changes in power demand varies considerably making some more suitable for series hybrids than for parallel hybrids and for use with control strategies involving on/off engine operation. Hence engine choice requires a complex set of trade-offs, which are highly dependent on detailed engineering information and data which are often not completely available. Even within a given engine type, designs can be optimized to favor efficiency, emissions, or size/weight with special attention being given to the particular operating mode (torque and RPM range) of series or parallel hybrid vehicles. Unfortunately, not much work has been done as yet to optimize engines for hybrid vehicle applications.

Much of the available information for automotive engines is for larger, higher power engines than would be used in hybrid vehicles, which for most powertrain designs require significantly smaller engines than conventional cars. Also, due to the proprietary nature of new engine development and the reluctance of the automobile companies to release emissions data for their systems intended to meet the various California low emissions standards, very limited engine map data are available for most of the engine types of primary interest in the present study and when available, the data are generaic in character rather than for specific engines. The best source of engine data found was Reference 19, which contains fuel consumption and emissions maps for both gasoline and diesel fueled engines and discussions of advanced exhaust emission treatment for those engines. Nevertheless, there is considerable uncertainty regarding the engine emission characteristics given in Appendix 1 even for gasoline and diesel engines. For alternative engines, such as gas turbine and Stirling, the availability of data is even more limited and the uncertainity of emissions for those engines is even greater at the present time. The uncertainty of the fuel consumption (bsfc) maps is much less than for emissions, but more accuracy is required for the bsfc maps because the fuel economies of the various vehicle designs are expected to vary over a much narrower range than for the emissions. Little hybrid vehicle test data for fuel economy or emissions are available with which to assess the validity of the simulation results.

4.2 Fuel Cells

Fuel cells can be utilitized in electric-hybrid vehicles as the means of converting chemical fuel to electricity on-board. Rapid progress (References 20-22) has been made in the development of fuel cells, especially Proton Exchange Membrane (PEM) fuel cells, for transportation applications. This progress (see Table 4) has resulted in a large reduction in the size and weight of the fuel cell stack and as a result, there is now little doubt that a fuel cell of the required power (20-50 kW) can be packaged under the hood of a passenger car. The primary question regarding fuel cells in light duty vehicles is presently how they will be fueled. The simplest approach is to use high pressure hydrogen as has been done in the most successful bus demonstrations to date (References 23,24). This approach is satisfactory for small test and demonstration programs, but since the development of the infrastructure for using hydrogen as a fuel in transportation is likely to be many years in the future, considerable work (References 25,26) is underway to develop fuel processors (reformers) to generate hydrogen on-board the vehicle from various chemical fuels (ex. methanol or hydrocarbon distillates). Most of the hydrogen used for industrial and transportation applications is presently generated by reforming natural gas using a well developed technolgy (Reference27). A promising approach to fuel processing to hydrogen on-board the vehicle is direct oxidation of methanol within the fuel cell stack itself (References 28,29). When the technology for the efficient, direct conversion of a liquid fuel to hydrogen within the PEM fuel cell is developed, the commercialization of fuel cells in light duty vehicles is likely to occur rapidly.

If the engine/generator in the series hybrid vehicle is replaced by a PEM fuel cell using hydrogen as the fuel, the regulated exhaust emissions (HC,CO,NOx) would be essentially zero. If the hydrogen were generated from solar energy or biomass, the CO2 emissions would be only those due to the hydrogen distribution and its compression into storage tanks on-board the vehicle. If the fuel cell is fueled with hydrogen produced from natural gas, the full fuel cycle emissions would include those generated by the production of the hydrogen at the natural gas reforming plant and the distribution and compression of the hydrogen. If the fuel cell is fueled using an on-board reformer and a petroleum-based fuel, the exhaust and CO2 emissions would be non-zero and possibly more comparable to the case of hybrid vehicles using engines. However, to evaluate the emissions for this case requires an in-depth analysis of fuel reformers, which was not part of the present study. Hence in this study, only vehicles utilizing fuel cells fueled with hydrogen produced from natural gas, solar PV, and biomass are considered. A summary of CO2 emissions for these processes for producing hydrogen is given in Table 5 based on information taken from References 30 and 31. Note that the CO2 emissions depend markedly on the source of the hydrogen.

For the hybrid vehicle simulations, the fuel cell can be modeled like either a battery or an engine. In the case of modeling like a battery, the fuel cell is described in terms of an open-circuit voltage and a resistance - both being independent of state-of-charge. This approach is used to determine the detailed current- voltage response of the fuel cell much like is done for batteries or ultracapacitors. When modeled as an engine, the efficiency of the fuel cell is determined as a function of power fraction from test data (Reference 32) for a fuel cell stack. The efficiency values are then used to calculate the brake specific fuel consumption (gm fuel/ kWh) as a function of power fraction for hydrogen or its gasoline equivalent. The effects of the auxilary loads for air compression and humidification/cooling pumps are included by using an efficiency factor that is power fraction dependent. The auxilary loads have the largest effect on the system efficiency at low net power from the fuel cell, because the auxilary load can not be reduced proportional to current at the small currents. For example, there is a minimum airflow that can be supplied by the blower or compressor regardless of the air required by the fuel cell at stoichiometry ratios (SR) near to 1. The efficiency/fuel consumption and efficiency factor inputs used for the PEM fuel cell simulations in this study are given in Table 6. These inputs are used to calculate the fuel economy (mpg equivalent) of the fuel cell-powered hybrid vehicles discussed in later sections of the report. For the fuel cell powered vehicles, it is assumed that the exhaust emissions are zero using hydrogen as the fuel. The upstream CO2 emissions are then determined from the calculated fuel useage for different sources of the hydrogen fuel (see Table 5). The fuel cell powered vehicle designs considered in this study all utilize a battery to load level the fuel cell and control strategies that permit the fuel cell to operate at above a minimum power fraction (at least 20%) at all times. This approach maximizes system efficiency and thus the fuel economy (mpg gasoline equivalent) of the hybrid vehicle. In addition, it permits effective use of regenerative braking.

4.3 Pulse Power Energy Storage

For the successful development of electric-hybrid vehicle drivelines with mimimal all-electric range, the availability of electrical energy storage components having high power peak power capability (W/kg) and high round-trip energy efficiency is critical. The primary role of the energy storage unit in such a hybrid vehicle is to provide high power during vehicle accelerations and to recover energy during regenerative braking. The unit needs to store a modest amount of energy (usually less than 1 kWh) and provide high power (50-100 kW). As shown in Figure 1, this results in peak power requirements for hybrid vehicles that are much higher than for energy storage devices for electric vehicles. Pulse batteries, ultracapacitors, and flywheels are currently being developed to meet these performance requirements. Projected characteristics of such devices are shown in Table 7. In the case of batteries and ultracapacitors, considerable test data are available for laboratory devices and it appears likely that energy storage units meeting the performance requirements for hybrid vehicles can be developed. For flywheels, the energy is stored as mechanical energy in a high-speed rotor and electrical energy is put into and taken out of the rotor through a motor/generator integral to the rotor shaft. This results in a rather complex system (Figure 2) for which the energy and peak power densities of the system are much less than that of the rotor alone. The projection of the flywheel system characteristics are further complicated by the need for a containment structure that can withstand possible failure of the rotor (Reference 33,34). For these reasons, projections of the energy and peak power densities of flywheels are considerably more uncertain than those of pulse batteries and ultracapacitors. The primary uncertainties for pulse batteries and ultracapacitors are their calendar and cycle lifes. Little test data are yet available for life cycle testing of these devices. The life of flywheels is much less uncertain with the primary uncertainty being fatigue weakening of the composite rotor material. Cost issues are important for all three types of pulse power devices with carbon material costs being the key factor for both ultracapacitors and flywheels.

Modeling of the energy storage components for hybrid vehicle simulations is relatively straightforward as all three devices can be treated in terms of an effective open-circuit voltage (Voc) and a series resistance (R). At any state-of-charge (SOC), the voltage at the terminals of the energy storage unit can be expressed as

$$V = Voc - I * R \qquad (1)$$

where I is the electrical current from the unit. For the pulse batteries, the open-circuit voltage and resistance are determined directly from pulsed discharge and charge tests of the batteries. The battery size is specified and scaled in terms of the cell Ah rating. For the ultracapacitors, the open-circuit voltage is linearly related to state-of-charge (V/Vo = SOC where Vo is the maximum operating voltage of the capacitor) since the charge on the ultracapacitor is given as Q0 = C* V0 = Ah where C is the capacitance of the device. The energy stored is given by Eo = 1/2*Ah*Vo. The resistance of the ultracapacitor is determined from constant current tests (Reference 35) of the device. As in the case of the batteries, the resistance of the ultracapacitor will scale as 1/Ah.

The flywheel is often referred to as an "electromechanical battery", but in terms of modeling, it behaves more like an ultracapacitor than a battery with its RPM tracking its SOC like voltage does for an ultracapacitor. The moment of inertia (Ifw) of the rotor acts like the capacitance of the ultracapacitor. The energy stored in the flywheel can be expressed as Eo = 1/2*(Ifw * RPMo)*RPMo where RPMo is the maximum operating RPM of the rotor. Comparing the energy expressions for the flywheel and ultracapacitor, the angular momentum (Ifw * RPM) is equivalent to the charge Qo on the ultracapacitor. Hence the RPM of the flywheel corresponds to the voltage and the torque of the flywheel corresponds to the electrical current of the ultracapacitor. Most of the losses in the flywheel system occur in the motor/generator and the associated electronics so they can be expressed in terms of an effective resistance (R fw,eff) related to the maximum efficiency and power of the system.

$$\mathrm{Rfw,eff} = ((1-\mathrm{eff,max})/2*\mathrm{Vmax2})/\mathrm{Pmax} \qquad (2)$$

where eff,max is the round-trip efficiency of the flywheel system at maximum power (Pmax) and Vmax is the maximum output voltage of the system. The resistance calculated from Eq. (2) is used in Eq.(1) to model the electrical characteristics of the flywheel system. The resultant efficiency is a maximum at high power and high RPM and decreases at low powers and rotor speeds (flywheel system voltages). Measurements of the efficiency of a protype flywheel system at Lawrence Livermore National Laboratory are available in Reference 34.

The characteristics (open-circuit voltage and resistance as a function of state-of-charge) of the pulse power devices are given in Tables 8-10. Characteristics are given for modules of each type of device and the pulse power unit would consist of a number of modules in series to attain the required operating voltage for the driveline. The modules are sized (Ah) to yield the energy storage (Wh or kWh) needed in the unit. For the flywheel, a single module is used with the required system voltage and equivalent Ah to store the required energy. The round-trip efficiency (energy out divided by energy in) of the devices is dependent on their resistance. Hence resistance becomes a key device characteristic for hybrid vehicle applications.

4.4 Electric Driveline Components

The drivelines for the electric-hybrid vehicles incorporate most of the same components as electric vehicles. These include the motor, inverter, and control electronics and for hybrids having a significant all-electric range, conventional electric vehicle batteries and an on-board battery charger. In the case of a series hybrid, the driveline would also include a generator (and its control electronics), which is driven by an engine. All of these components are being developed for electric vehicles and their characteristics are well established. The physical characteristics (size and weight) of the electric motor and electronics are given in Table 11 in terms of specific volume and weight (liter/kW and kg/kW). It can be anticipated that the size and weight of motor and electronic components for a given maximum (pulse) power rating (kW) will continue to decrease with further development. This will make it less difficult to package the hybrid driveline under the hood of the vehicle. Even using presently available electrical components, the combined volume and weight of the motor and inverter are less than that of an engine of the same peak power. The efficiency of the motor, electronics, and generator are important in determining the electrical energy useage and fuel economy of the hybrid vehicles. The efficiency characteristics of these components are input into the simulations using maps of efficiency as a function of output torque or power and rotational speed (RPM). These maps, which are given in Appendix 2, are based on test data received from the manufacturers. Each of the efficiency maps is for an existing unit having a specified power rating and maximum RPM. For drivelines requiring different power ratings and RPM, the maps are scaled in terms of power (or torque) and speed fractions.

For hybrid vehicles with significant all-electric range (greater than 30 miles), the battery pack can likely be sized to provide both the energy (kWh) for the range and the peak power (kW) for acceleration. Hence, both the energy density (Wh/kg) and the peak power density (W/kg) of the batteries used will have an important effect on the weight and volume of battery pack. Depending on these characteristics and the vehicle performance specifications, the battery pack will be sized by either the energy or the power requirement. For many hybrid designs, the power requirement will be the controlling factor. For hybrid vehicles with a short all-electric range (less than 20 miles), special high power density batteries will be required to meet the vehicle power requirements.

The battery types considered in this study are sealed lead-acid, nickel metal hydride, and lithium-ion. The energy density and power characteristics of these batteries are shown in Table 12. The performance characteristics of these batteries are now reseasonably well-established. What is much less certain are the cost and cycle life of the batteries. This is especially true for battery designs and test cycles appropriate for hybrid vehcle applications, which require a large number (several thousand) of partial discharge cycles at high average power. For the hybrid vehicle simulations, the energy storage batteries are modeled in the same manner as the pulse power devices - that is in terms of the open-circuit voltage and resistance as a function of state-of-charge. The inputs (Voc and R vs. SOC) for the batteries used in the present study are given in Appendix 3. The battery pack of specified voltage and energy storage (kWh) is configured using a series string of modules having the required cell Ah capacity. The simulation program automatically scales the module weight and cell resistance to reflect the difference in Ah capacity between the required value and that of the module in the battery input data table. The uncertainty in the characteristics of presently available energy storage batteries is relatively small. It can be expected that the performance of batteries will continue to show modest improvement in the next few years with further development.

5.0 Design of Hybrid Vehicles

5.1 Design Specifications

The quantitative assessment of the energy usage and emissions of electric-hybrid vehicles requires that simulations be performed for specific vehicle designs. These designs will encompass a wide range of technologies for both the driveline and vehicle chassis and vehicle all-electric range. This study is primarily concerned with determining the effect of vehicle size, engine selection, and all-electric range on the full fuel cycle emissions of hybrid vehicles. The acceleration, top speed, and gradeability of all the vehicles considered were essentially the same - (1) acceleration from 0-100 km/h in 12-13 seconds, (2) top speed of at least 120 km/h, and (3) a gradeability of 96 km/h on a 6% grade. The driveline components in all the designs were sized to meet these vehicle performance requirements. The key vehicle design parameter is all-electric range since it has a large influence on the fraction of annual miles for which the hybrid vehicle would be used in the all-electric and hybrid engine operating modes. Vehicle designs having essentially zero all-electric range using ultracapacitors as the pulse power unit on one extreme and those having an all-electric range of 125 km (75 miles) on the other extreme were analyzed. The effect of vehicle weight on the energy use and emissions was studied by comparing the simulation results for designs using conventional steel and lightweight materials for the body and chassis. All the vehicles used high efficiency, alternating current (ac) components in the driveline. The efficiencies of the motor and electronics are typical of state-of-the-art components used in electric vehicles currently being demonstrated by the large auto manufacturers in the United States, Europe, and Japan. Designs were prepared using both gasoline and diesel engines in otherwise identical vehicles in order to compare results with only the engines being different.

5.2 Driveline Configurations

A number of electric-hybrid drive configurations were considered in this study. The two main categories are series and parallel (see Figure 3). Both configurations can be designed to have a significant all-electric range. In those cases, it is assumed that the energy battery is charged from the wall-plug almost daily. For a parallel hybrid vehicle having a significant all-electric range and the same acceleration capability in the all-electric and hybrid modes, the electric motor must have the same power rating as that in the comparable series hybrid. If maximum acceleration performance is achieved only in the hybrid mode using both the engine and motor for torque, the electric motor in a parallel hybrid can be smaller. For the series hybrid vehicles, electricity is generated on-board the vehicle using either an engine/generator or a fuel cell.

5.3 Vehicle Designs Selected

Two vehicle types were considered in this study. One was a mid-size passenger car (ex. Ford Taurus) built using 1995 steel body/chassis technology and the other a compact passenger car (ex. Honda Civic) built using a light-weight aluminum or composite body/chassis. These vehicle types represent two extremes in vehicle design and the fuel economy and emissions projections for them can be considered limiting cases for the various driveline technologies. The weight breakdowns for the vehicles were taken from Reference 36, where a set of hybrid vehicles that included the two vehicle designs considered in this study were analyzed.

Simulation runs were made for both vehicle types using sealed lead-acid, nickel metal hydride, and lithium-ion batteries and carbon/organic electrolyte ultracapacitors. The batteries were sized to yield all-electric ranges between 32 km and 125 km to 75% depth-of-discharge. The vehicles utilizing ultracapacitors were assumed to have zero all-electric range for purposes of evaluating energy useage and emissions. It was verified using simulations that all the vehicle designs of both types had 0-96 km/h acceleration times of 12-13 seconds and gradeability of 96 km/h on a 6% grade.

Table 13 describes the vehicle characteristics and the driveline configuration and component ratings for each of the vehicles. Each vehicle and battery combination was evaluated for at least two engine types and a fuel cell. The appropriate fuel is used for each engine and the fuel cell. Some designs using ultracapacitors as the pulse power units have also been evaluated. Simulations were run for each of the vehicle designs for a number of driving cycles and driveline control strategies. The power and energy storage requirements for the different driving cycles vary significantly and the component characteristics given in Table 13 permit the vehicles to operate over the most demanding of the cycles. The control strategies (to be discussed in Section 6.2) are such that they can be adapted to the various vehicle designs and driving cycles.

6.0 Vehicle Simulations

6.1 Approach and Simulation Programs

The hybrid vehicle simulation results are the basic inputs used to calculate the energy use and full fuel cycle emissions of the vehicles. Hence it is important that those results be as realistic as possible and reflect systematic changes in vehicle design and component operating characteristics as well as the effects of different control strategies and driving cyles. Two hybrid vehicle simulation programs - SIMPLEV and AVTE - were used in this study. The SIMPLEV program (Reference 5), which was developed at the Idaho National Engineering Laboratory in the early 1990s, has been used over the last several years to perform simulations of electric and hybrid vehicles that incorporate advanced vehicle and driveline technologies (References 37,38). The results from SIMPLEV for electric vehicles have been well validated using dynamometer test data for a number of vehicles and driveline technologies (References 39-41). There has not been appropriate test data available to validate the SIMPLEV results for hybrid vehicles. The AVTE program is a relatively new simulation program whose development was started at the National Renewable Energy Laboratory (NREL) in 1994 as the ADVISOR program. Modification and further development of the ADVISOR program has taken place at the University of California, Davis (UCD) over the last year as part of a contract with NREL to model driveline components for hybrid vehicles (Reference 42). The UCD version of the ADVISOR program (referred to as AVTE) was used in this study.

Results for electric vehicles obtained using the AVTE program at UCD have been found to agree well (within a few percent) with those obtained using SIMPLEV and with dynamometer test data. Results for hybrid vehicles obtained using AVTE have also compared well with calcuated results from SIMPLEV and test data for the UCD AfterShock and Future Car hybrid vehicles (Reference 43). The component modeling and generaic control strategies are much the same for the two simulation programs. The primary difference between the two programs is that the AVTE program uses complete engine maps (gm/kWh vs. torque and speed), while SIMPLEV describes the engines in terms of an operating line (gm/kWh vs. power fraction). The simpler SIMPLEV approach is reasonable for series hybrids, but not for parallel hybrids. A second important advantage of the AVTE program in the present study is that it is written using MATLAB/SIMULINK software and the program can be easily altered to reflect new technologies and more complete understandings of hybrid vehicle operation. The source code for SIMPLEV was not available to UCD and hence, changes could not be made to that program as desired.

In the present study, most of the results presented for series hybrid vehicles were obtained using SIMPLEV and those for parallel hybrids were obtained using AVTE. This was done for several reasons. First, the AVTE program is still under development and as yet, is not as user friendly as SIMPLEV. Second, the SIMPLEV program files include a wider range of driving cycles at the present time. In the case of parallel hybrids, however, it was found during the course of the study that the AVTE program was fundamentally more accurate than SIMPLEV for parallel driveline configurations. It is anticipated that for future hybrid vehicle studies at UCD, the AVTE program will become the principal simulation tool as more and more features are added to it that are not available in SIMPLEV.

6.2 Driving Cycles

It is well-known that the energy useage and emissions of conventional ICE and electric-hybrid vehicles are strongly dependent on how the vehicles are driven (speed, acceleration, stop-start frequency, grades, etc.). These effects can be evaluated for various vehicle designs by performing the simulations for different driving cycles. Most simulations to date have been done for the Federal Urban Driving Schedule (FUDS) and Federal Highway Driving Schedule (FHWDS). The Federal and California emissions standards and Corporate Average Fuel Economy (CAFE) standards are set using these driving cycles. It has been recognized by both the Environmetal Protection Agency (EPA) and the California Air Resources Board (CARB) that those driving cycles do not adequately represent the manner in which light duty vehicles (passenger cars and trucks) are actually driven in urban areas. Hence there has been considerable work (References 44-46) done to develop additional driving cycles, which better represent actual use of the vehicles. Information on driving cycles was recieved from CARB (Reference 46) for use in this study. A summary of the various driving cycles is given in Table 14. Speed vs. time plots of several of the cycles are shown in Fgure 4. These cycles are based on following actual cars in traffic on the freeways and arterials in California. None of the new cycles is in official use as yet to set emissions and fuel economy standards, but they do represent the current thinking at CARB relative to real world use of vehicles under various driving conditions.

The driving cycles shown in Table 14 have been input into SIMPLEV and simulations run for a number of the electric-hybrid vehicle designs. Since the average speed and maximum power requirements of the different cycles vary widely, it can be expected that energy useage and emissions calculated for the various cycles will also show significant variation. The simulation results and the full fuel cycle emissions for the different driving cycles will be compared with those using the conventional FUDS and FHWDS cycles in later sections of the report.

6.3 Control Strategies

6.3.1 Control Strategies for Series Hybrid Vehicles

In general, the intent of the control strategy is to maintain the state-of-charge of the energy storage unit within a prescribed range regardless of the driving cycle and the resultant power demand on the driveline. This should be done such that the on-board electrical generator (engine/generator or fuel cell) is operated at high efficiency and low emissions. This is done more easily when the energy storage capacity is reasonably large as with a battery than when it is small as using ultracapacitors. The strategy used for vehicles having a significant all-electric range is to discharge the battery to a prescribed state-of-charge (20-30%) and then to turn-on the engine to maintain the battery within 10-20% of that condition. Electrical energy is generated at a rate slightly greater than the average power demand of the vehicle to account for losses associated with storing the energy. In the case of an engine/generator, a minimum power level is set such that the engine never is operated below it. Proper selection of this minimum power can have an important effect on fuel economy. When the battery charge reaches the maximum permitted, the engine is turned off and it remains off until the battery state-of-charge falls to the engine turn on state-of-charge. When the series hybrid is operated in this mode, it is termed a charge depleting hybrid. If the battery is maintained at a high state-of-charge (80%), it is termed a charge sustaining hybrid and the battery is seldom recharged from the wall-plug.

The average power requirement is calculated by time-averaging the electrical power to the electric driveline. The time period for the power averaging is a system design parameter, which is usually set between 30 and 120 seconds. Selection of the time averaging parameter is not critical for systems with large energy storage. It is more critical for systems using ultracapacitors or flywheels, because in those cases, if the state-of-charge of the pulse power unit falls below a critical value, the maximum power of the system must be reduced and the vehicle might not be able to follow the driving cycle. For driving cycles having periods of high peak power, averaging times of less than 30 seconds may be needed to keep the pulse power unit at an acceptable state-of-charge. For series hybrids, the engine and generator output power can be changed relatively slowly without compromising vehicle performance and driveability. This permits the engine to be turned-on and off in an optimum manner that minimizes emissions and wasted fuel. Hence the control strategies for series hybrid vehicles are relatively simple and can be expected to have a minor effect on vehicle driveability.

6.3.2 Control Strategies for Parallel Hybrid Vehicles

The control strategies for parallel hybrid vehicles are more complicated than those for series hybrids primarily because they are dependent on both vehicle speed and energy storage unit state-of-charge and should include a criteria for splitting the driveline torque between the engine and the electric motor. In general, the intent of the strategy is to permit the electric motor to provide the torque if it can at vehicle speeds below a prescribed value and permit the engine to provide the torque at higher speeds. If the vehicle is operating in the all-electric mode, the motor provides the torque and the engine is not turned on regardless of the torque demand or vehicle speed. Since the all-electric range of a hybrid vehicle is usually less than 80 km, operation of the vehicle should change sutomatically to the hybrid mode when the all-electric range is exceeded. The control strategy in the hybrid mode can be either charge sustaining or charge depleting. In the case of charge sustaining, the battery state-of-charge is maintained at a near constant value by a control strategy using electrical energy produced by the engine and the motor acting as a generator and consequently little eleectrical energy is used from the wall-plug. For the charge depleting case, the control strategy permits the battery state-of-charge to decrease as the vehicle is driven and the battery is then recharged from the wall-plug at night. Parallel hybrids usually have a multi-speed transmission so the control strategy must also include a gear shifting algorithm that depends on whether the motor or engine or both are producing torque. A continuously varable transmission (CVT) would be particularly attractive for use in a parallel hybrid drivelline (Reference 47).

In order to achieve high fuel economy with a parallel hybrid, it is necessary to minimize engine operation below some minimum engine torque (or effective throttle setting) where the engine bsfc is relatively high and to manage engine turn on and off carefully to minimize emissions and wasted fuel. In urban driving (such as on the Federal Urban Driving Schedule), the control strategies often result in the engine being turned on and off frequently as the vehicle speed and power demand vary rapidly in stop-and-go driving. The effects of this on-off engine operation on fuel usage and emissions for the parallel hybrids are neglected in the present simulations, so further analysis and vehicle testing is needed to determine whether the high fuel economy and low emissions projected for parallel hybrids can be attained in practice for actual vehicles having good driveability. The control strategies for parallel hybrids are necessarily more complex than those for series hybrids and the uncertainty in the simulation results for parallel hybrids are greater.

6.4 Simulation Results

6.4.1 Summary Tables

A large number of simulation runs were performed for the vehicles shown in Table 13. Runs were made for all the vehicles on the FUDS and FHWDS and for some of the vehicles on the other driving cycles (Table 14). Runs were made for most of the electric-hybrid vehicles in both the all-electric and hybrid operating modes. For vehicle designs having no significant all-electric range, such as those using ultracapacitors, simulations were made for only the hybrid operating mode. Simulations were also run for several pure electric vehicles (battery only - no on-board electricity generation) to obtain electrical energy use values for the calculation of ZEV full fuel cycle emissions. Most of the hybrid vehicles simulated utilized a series driveline configuration, but some runs were made for vehicles using a parallel configuration for purposes of comparing vehicles with series and parallel hybrid drivelines. Most of the simulations were done using engine/generators, but some runs were done with hydrogen-fueled fuel cells for on-board electricity generation for comparison with the engine-powered hybrid vehicles. In all cases, comparisons involving different driveline technologies were made for the same basic vehicle designs (weight and road load). The fuels used for each simulation were those appropriate for the engine or fuel cell utilized in the driveline of the vehicle. The major effects of the different fuels were on the upstream emissions resulting from the consumption, distribution, and production of the fuel. Data on the effect of fuel type on the engine maps were not available. For example, the detailed maps using natural gas as the fuel in spark ignition engines were not available for comparison with maps for similar engines using gasoline as the fuel.

A summary of the simulation results for the mid-size (5-passenger) car designs using steel construction and for the small (4-passenger) cars using light-weight materials is given in Appendix 4. For each design, the electrical energy use (Wh/mi) and range (mi) to 75% depth-of-discharge (DOD) for all-electric operation and the fuel economy (miles per gallon) and HC, CO, and NOx emissions (gm/mi) for hybrid operation with an engine/generator or fuel cell are given. Appendix 4 contains the vehicle inputs on which the emissions and energy use calculations discussed in subsequent sections are based.

6.4.2 Comparison of Simulation Results for Conventional, Electric, and Hybrid Vehicles

Mid-size (5/6 passenger) Cars

Selected simulation results for mid-size hybrid cars (5-passengers) using port injected gasoline engines are given in Table 15. This is the size car that is being developed in the PNGV program. The weight of the hybrid vehicles analyzed was only slightly less than that of stock passenger cars of that class in 1997, but the aerodynamic drag coefficient and tire rolling resistance were significantly reduced. The fuel economy results for the hybrid vehicles indicate that large improvements in fuel economy and thus also CO2 emissions can be attained with series hybrid drivelines even using gasoline engines for on-board electricity generation. This improvement is due both to the hybrid driveline and reductions in weight and road load. Hence, it is of interest to determine the improvement due to the hybrid driveline alone. In order do this, hybrid vehicle simulation runs were made using the same weight and road load characteristics as found in the 1997 passenger cars. The fuel economies of the conventional ICE passenger cars for 1997 are published in the EPA Fuel Economy Guide (Reference 48). Note that the measured fuel economy for each of the vehicles listed in the EPA Guide was decreased by 10% for the FUDS cycle and 22% for the highway cycle to make the published values agree more closely with real world driving . Hence for comparison with the calculated hybrid vehicle fuel economies, the published EPA fuel economy values have been corrected back to the measured values (Table 16). Comparisons between the hybrid and conventional vehicle fuel economies are shown in Table 17. For the FUDS cycle, the series hybrid vehicle with the gasoline engine has 50% higher fuel economy than the 1997 mid-size car of the same weight and road load. For the Federal Highway cycle, the hybrid car has only about 10% higher fuel economy than the 1997 mid-size car. The exhaust emissions of 1997 passenger cars meet the California TLEV (Transitional Low Emission Vehicle) standards - .125 gm/mi NMOG, 3.4 gm/mi CO, .4 gm/mi NOx. The simulation results (Table 15) for the exhaust emissions in the hybrid mode for the series hybrids using gasoline engines indicate that it should be possible to meet the ULEV emission standards of .04 gm/mi NMOG and 1.7 gm/mi CO, but that meeting the NOx standard of .2 gm/mi with the three-way catalyst will be more difficult (require a very high conversion efficiency catalyst), because the smaller engines used in the hybrid vehicle operate much of the time at high power fractions.

The exhaust emissions in the all-electric mode are, of course, zero, but there are CO2 emissions generated at the electrical powerplant. The powerplant emissions - gmCO2/ kWh depend on the technology and fuel used at the powerplant. The electrical energy use at the wall-plug depends on the energy use of the car (kWh/mi) and the battery and charger efficiencies. The battery efficiencies depend on the type of battery used in the car and the average depth of discharge at which charging is started. The energy use and CO2 emissions for the mid-size vehicle design in the all-electric mode using several battery types are given in Tables 18. The CO2 emission calculations were done assuming an average powerplant emission of 505 gmCO2/kWh. The all-electric FUDSWay emissions vary from about 110 gm CO2/mi for lithum ion batteries to 150 gmCO2/mi for lead acid, and 210 gmCO2/mi for nickel metal hydride batteries. The primary reason for the differences in the CO2 emissions of the various batteries are differences in their overcharge characteristics. The corresponding CO2 emissions for mid-size ICE passenger cars in 1997 are 380 gmCO2/mi on the FUDS cycle and 235 gmCO2/mi on the Federal Highway cycle.

Compact (4-passenger) Cars

Selected simulation results for compact (4-passenger) hybrid cars using port injected gasoline engines are given in Table 19. These are relatively small cars having a test weight of 800 kg (1760 lbs) using either aluminum or composites in the vehicle structure and body panels to reduce the weight. The corresponding conventional cars with similar weight in 1997 are subcompacts like the Geo Metro. The 1997 subcompact cars have a higher drag coefficient and rolling resistance than used for the hybrid, but the hybrid has a larger frontal area because it is a larger, compact vehicle. The fuel economy of the 1997 Geo Metro are shown in Table 17 for comparison with the corresponding values for the small, light-weight hybrid vehicles using a gasoline engine. The small hybrid car has a fuel economy of 74 mpg and CO2 emissions of 114 gm/mi. The fuel economy improvement is 65-75% on the FUDS cycle and 35-55% on the HiWay cycle. The CO2 emissions are corresponding lower for the hybrid vehicle. The calculated values of the regulated exhaust emissions of the small hybrid car with the gasoline engine are well below ULEV indicating it should be possible to meet the ULEV standards with a three-way catalyst. The CO2 emissions for the small vehicle as a 100 mile range, battery-powered EV are shown in Table 20 for powerplant emissions of 500 gmCO2/kWh. For lithium-ion batteries, the CO2 emissions are 70 gm/mi for the FUDS and Highway cycles. For lead-acid and nickel metal hydride, the CO2 emissions are 100 and 130 gmCO2/mi, respectively. The corresponding CO2 emissions for the conventional subcompact passenger cars in 1997 are 220 gmCO2/mi on the FUDS cycle and 170 gmCO2/mi on the Highway cycle.

Comparison of Series and Parallel Hybrid Vehicles

Calculations were made with the AVTE simulation program to compare the fuel economy of the mid-size and compact hybrid cars using series and parallel hybrid drivelines. Simulations were run for each vehicle type on the FUDS and Highway cycles using the same weight, road load parameters, and driveline components (electric motor/electronics, batteries, and engine).

Calculations were done for the gasoline engine. Charge sustaining and charge depleting control strategies were utilized for the parallel hybrids and only charge sustaining for the series hybrids. The results of the calculations for fuel economy (miles per gallon gasoline equivalent) are given in Table 21. For the charge depleting hybrids, the energy use is expressed as gasoline equivalent fuel economy at the powerplant, which is calculated from the sum of the gasoline used by the engine/generator and the gasoline (source energy) that would be needed at the powerplant to generate the electricity required to recharge the battery. The fuel economy results shown in Table 21 indicate that the charge depleting parallel hybrids are 12-15% more efficient than the charge sustaining series hybrids for combined city and highway driving using the gasoline engine, but the difference is only 2-3% for vehicles using the swirl chamber diesel engine. The differences between the parallel and series hybrid cases are essentially the same for the city and highway driving cycles. For the parallel hybrids, the fuel economy of the charge depleting hybrid was only 1-2 % greater than that of the charge sustaining hybrid. Hence the effect of the driveline configuration (parallel vs. series) was larger than the effect of control strategy (charge depletion vs. charge depleting). It should be noted that these conclusions are to some extent dependent on powerplant efficiency and the battery and charger efficiences. The values of these parameters used for the present calculations are shown in Table 21.

Comparisons of Hybrid Vehicles using Batteries and Ultracapacitors

The effect of the characteristics of the energy storage unit on the fuel economy and thus the CO2 emissions of a series hybrid was investigated by performing SIMPLEV simulations of hybrid vehicles using batteries and ultracapacitors to load level the engine/generator. Simulations were run for the FUDS and Highway cycles as well as several of the more demanding other driving cycles being considered by EPA and CARB. Runs were made for vehicles using 48 and 24 Ah/cell nickel metal hydride batteries and 3V, 2400 F ultracapacitors. The all-electric range of the vehicles using the batteries were 60 miles and 30 miles, respectively. Comparisions of the fuel economies of the various vehicles are given in Table 22. For the same driving cycle, the vehicles using ultracapacitors have consistently higher fuel economy than those using batteries. Part of this improved fuel economy with ultracapacitors is due to the lighter weight of the vehicles with the ultracapacitors, but most of the improvement is due to the lower resistance and thus, the lower losses associated with storing and extracting energy from the ultracapacitors. The differences in fuel economy are greatest for demanding driving cycles such as the UC-92 and the ART 14. In addition, the advantage of the ultracapacitors becomes most significant when compared with the designs using the small 15 Ah battery which has the highest resistance. In those cases, the fuel economy advantage of the vehicles using ultracapacitor ranges from 17% for the FUDS to 32% for the UC-92 cycle. On the Highway cycle, the fuel economy differences are less than 5%. These results (Table 22) indicate that fuel economy in hybrid vehices can be significantly influenced by the losses (resistance) of the energy storage devices used in the driveline.

7.0 Vehicle Use-Patterns

7.1 Types of Driving

In the real world, passenger cars are driven for a variety of reasons and between many starting and final destinations. This driving is done in the city and the suburbs on arterials and freeways and between cities and towns on two-lane and four-lane inter-state highways. The length of the trips involved vary from a few miles or less to hundreds of miles in a day. The average speed and the way in which the speed changes with time for the different types of trips vary markedly. This means that a single or even two driving cycles are inadequate to describe the general use-pattern of cars. Various cycles (speed vs. time) that have been proposed to account for different types of driving have been discussed previously in Section 6.2. Hence, to realistically assess the average annual energy use and emissions from electric-hybrid vehicles is not a simple matter and the variations in the use of the vehicles must be taken into account in a systematic manner to make meaningful comparisons of the full fuel cycle emissions of various electric-hybrid vehicle designs.

In terms of vehicle use-patterns, the primary focus in this study has been on city and suburban driving and not on long distance inter-city travel. It is for those areas that the operation of electric-hybrid vehicles is highly use-pattern dependent for a particular design. Operation of hybrid vehicles for inter-city trips will be primarily on the engine/generator or fuel cell and the energy use (mpg) is primarily dependent on average speed and can be described in terms of a simple, nearly constant speed driving cycle. In addition, except for CO2, emissions are of much less importance for inter-city travel than for city driving.

For urban driving, it is convenient to divide the total miles driven into travel to and from work and that for all other purposes. The work travel for a particular car owner varies little from day to day while the all-purpose travel tends to be random varying significantly from day to day. Information on daily individual travel to and from work and random all-purpose travel can best be described in terms of statistics. Data from which these statistics can be derived have been collected for California to a limited extend by State (References 49,50) and for the United States by the US Department of Transportation (References 51,52). General methods for using these statistics to analyze the use-patterns of electric and hybrid vehicles are presented in Reference 53,54. Discussions of the application of these methods in the present study are given in the following sections.

7.2 Annual Mileage

A key consideration in determining the use-pattern of a particular car is the annual mileage that the vehicle is driven annually. Of particular interest is the annual miles driven in the urban area - that is in the city and suburbs. The total urban miles driven are the sum of the work travel and all-purpose trip travel. The work travel miles can be determined simply from the distance that the car owner lives from his/her place of employment. All-purpose travel miles vary greatly for different car owners and is in fact a key distinquishing factor determining the effect of use-pattern on annual emissions and energy use of electric-hybrid vehicles. As discussed in the next section, the all-purpose travel miles are assumed to be driven in a random manner and lead to well defined daily travel statistics.

7.3 Daily Travel Statistics

The random daily (all-purpose) travel statistics of a particular car owner can be presented in terms of the cumulative probability distributions shown in Figures 5 and 6. The probability distributions indicate the fraction of the days that the car owner travels a total of "x" miles or less and the fraction of the annual random miles traveled on days on which he/she travels "x" miles or less. Note that the distributions shown are strong functions of annual mileage. In principle, these distributions should be determined from data obtained from detailed surveys of large numbers of car owners concerning how they use their cars. Unfortunately, such data do not currently exist and it is necessary to determine the distributions by calculation based on trip number and trip length statistics for which there are some data. The procedures for calculating the distributions shown in Figures 5 and 6 are given in detail in References (53,54).

7.4 Calculation of the Use-Pattern

In order to utilize the simulation results given in Section 6.4 to determine the energy useage and the full fuel cycle emissions of the electric-hybrid vehicles, it is necessary to calculate the miles per year that the vehicle is operated in the all-electric and hybrid modes. The calculation requires as inputs the all-electric range (EVR) of the vehicle, the distance (RTWD) that the owner travels to/from work each day, and the total annual random mileage (ANRM) in urban driving. The calculation procedure is as follows: (1) determine the maximum random daily travel (MXRT) for which the vehicle can be operated in the all-electric mode, MXRT = EVR - RTWD, (2) using the annual random mileage (ANRM), enter Figures 5 and 6 for MXRT and find the fraction of days (Df) and fraction of miles (Mf) for which random daily travel is less than MXRT, (3) the days per year for all-electric operation is Df*365 and the random miles traveled on those days is Mf*ANRM, (4) partial all-electric operation will occurs on (1-Df)*365 days up to a range of MXRT for a mileage of (1-Df)*365*MXRT, (5) the work travel is all-electric if the range is greater than RTWD for a mileage of 5*52*RTWD, (6) the total mileage for all-electric operation (TEOP) is then TEOP = Mf*ANRM + (1-Df)*365*MXRT + 5*52*RTWD, (7) the mileage in hybrid operation (THOP) is THOP = AMRM - TEOP.

An EXCEL spreadsheet was written that implements the calculation procedure outlined above for the calculation of the electric and hybrid mode mileages. As inputs to that spreadsheet, the cumulative probability curves for Df and Mf were curvefit for annual mileages of 4300, 7500, and 10400 miles. Results obtained using the spreadsheet are shown in Table 23 for the three annual mileagesof random driving and associated roundtrip work travel distances.

8.0 Energy Use and Exhaust Emissions

8.1 Energy Use (Fuel and Electricity)

In general, an electric-hybrid vehicle uses both a chemical fuel (gasoline, diesel oil, natural gas or hydrogen) and electricity from the wall-plug. Hybrid vehicles can be designed and/or operated such that they use only a chemical fuel. In that case, the state-of-charge of the energy storage unit is maintained in a relatively narrow range using electricity generated on-board the vehicle and it is never recharged from the wall-plug. This mode of operation is termed - charge sustaining and nearly all hybrid designs can be operated in that mode with the proper choice of system control strategy. However, for hybrid vehicle designs with a significant all-electric range, the total energy use (fuel plus electricity) can be less in a charge depleting mode, in which wall-plug electricity is used to recharge the battery, than in the charge sustaining mode in which the battery is recharged on-board the vehicle using fuel. Whether or not this is the case depends on the efficiencies of the battery charger and the battery (charge/discharge) and the efficiency of the powerplant at which the electricity is generated as well as the average efficiency of the engine. The exhaust emissions of the charge depleting hybrid are expected to be lower on an annual basis than those of the charge sustaining hybrid, because a significant fraction of the driving is done using wall-plug electricity rather than fuel. It is for this reason that the California Air Resources Board prefers hybrid designs having a significant all-electric range and operation of the vehicle in the charge depleting mode.

The fuel and electricity use are calculated from the fuel economy (mpg), electrical energy consumption (Wh/mi), and the miles per year that the vehicle is driven in the all-electric and hybrid modes. These calculations have been implemented in a series of EXCEL spreadsheets using the vehicle simulation results given in Appendix 4 as inputs. Calculations for charge sustaining and charge depleting operation of the hybrid vehicle designs can be made using the spreadsheet by simply setting a flag in the input.

8.2 Exhaust Emissions

The annual average exhaust emissions are those vehicle emissions (HC, CO, and NOx) resulting from the operation of the engine and are directly proportional to the miles driven in the hybrid mode. These emissions, termed "running emissions", are calculated directly from the vehicle simulation results (gm/mi). The hybrid vehicles have zero exhaust emission when driven in the all-electric mode. The evaporative and refueling emissions are included separately as "upstream emissions" along with the emissions from the generation of the electricity at the powerplant. The "total" fuel cycle emissions, including CO2, can also be calculated for each of the vehicle designs using the EXCEL spreadsheet.

8.3 Energy Use and "Running" Emissions for the Various Hybrid Vehicle Designs

The annual fuel and wall-plug electricity use and the "running" emissions for a number of mid-size electric-hybrid vehicle designs using various engines are shown in Tables 15, 25-29 for different driving cycles, use-patterns, and control strategies. A complete set of spreadsheet runs for all the vehicle designs is given in Appendix 5. The code for identifying the vehicle type (first column in the Tables 25-30) is given in Table 24. The spreadsheet "macro" has the capability to select a subset of the many possible cases based on user designated values in the code (see the "selection criteria" in the tables).

The large effect of all-electric range on the fuel use and annual average running (exhaust) emissions of charge depleting hybrid vehicles (those charged from the wall-plug) is evident in the Tables 15, 26-28. For the base case (7500 miles random travel and 15 miles work travel), the average HC, CO, and NOX exhaust emissions (gm/mi) decrease rapidly as the all-electric range is increased from 30 miles to 60 mile. For all-electric ranges greater than fifty miles, the annual average exhaust emissions can be much less than the ULEV standards even for vehicles having hybrid mode emissions that are above the ULEV standard, if the vehicle is consistently used in the charge depleting mode with the battery being charged from the wall-plug. The large differences between the exhaust emissions from hybrid vehicles in the charge sustaining and charge depleting modes are evident from comparing Table 15 with 27 and Table 25 with 26. In the charge sustaining mode, the engine is operating a large fraction of the time and the exhaust emissions are much higher unless the vehicle meets ULEV or lower standards when operating in the hybrid mode. Designs using a gasoline engine have relatively low emissions (Table 27) because of the high conversion efficiency (>95%) of the three-way catalyst for all three regulated pollutants. The advanced engines (Tables 25,26 and 28) have higher NOx emissions than the gasoline engines. All the engines have low HC and CO emissions and can be designed to meet very low HC and CO emissions if required by the regulations. The major advantage of the advanced engines is that they are more efficient and vehicles using them have higher fuel economy. In other respects, the port injected gasoline engine is a good choice for hybrid vehicles.

CO2 emission values for the hybrid vehicles are meaningful only if they include both the chemical fuel used and the electricity used to recharge the battery. Hence the low exhaust CO2 emissions of hybrid vehicles with long all-electric range are not meaningful and comparisons of charge sustaining and charge depleting hybrids must be done in terms of total emissions including both the exhaust (running) emissions and the upstream powerplant emissions. This is done in a later section.

8.4 Off-cycle Emissions

The exhaust emission and fuel economy standards for light duty vehicles are given in terms of the Federal Urban (FUDS) and Highway (FHWDS) driving schedules. Hence most of the results discussed in previous studies of hybrid vehicles have considered only those driving cycles. Considering only results for the two Federal Driving Cycles does not show the complete picture of hybrid vehicles as it is well known that a significant fraction of vehicle operation occurs at conditions not included on those cycles and that the exhaust emissions are higher and the fuel economy is lower on other driving cycles which may be a better representation of how cars are operated in the real world.

In driving the FUDS and FHWDS cycles on the dynamometer, the engine in the vehicle operates over only a portion of its total range of torque and RPM and does not experience all of the transient conditions that it will experience in actual on-the-road driving. The vehicle systems (engines, transmissions, and exhaust control systems) are designed and calibrated such that the vehicles meet the emission standards for the regulated emissions on the FUDS cycle and little attention is given to emissions at conditions that are not experienced on the cycle. As discussed in References (55-57), there are engine/vehicle operating conditions that are experienced relatively frequently in real driving that can result in high emissions that are not accounted for in the emission standards. These operating conditions generally occur at high speed and high power during more rapid accelerations and decelerations than are required on the FUDS cycle. Time spent in these operating conditions is often short (several seconds), but the emissions (gm/sec) can be very high resulting in a significant contribution to the actual emissions from the vehicle in actual use. These emissions are often referred to as "off-cycle emissions", because they do not occur at operating conditions that need to be controlled to meet emissions measured on the FUDS cycle. As noted previously, one of the reasons for the development of the various new cycles (Table 14) by EPA and CARB was to force engine operation and thus emissions control at higher power levels and speeds than on the FUDS cycle.

This study was not concerned with "off -cycle" emissions by the conventional definition (References 55-57), but simulations were made using driving cycles other than the two Federal cycles. As shown in Table 25-30, the fuel economy and emissions on several of the other driving cycles were less favorable (fuel economy lower and emissions higher) than on the standard Federal driving cycles. This is especially true for the ART14, UC-92, and US06 driving cycles that can result in NOx emissions two to three times higher than the FUDS and fuel economy reductions of over fifty percent from the FUDS values. Simulations were not made of conventional ICE vehicles on these same cycles, but without doubt the conventional vehicles would also have higher emissions and lower fuel economy on those cycles. The magnitude of the effect of the driving cycle on emissions and fuel economy would be greater for the conventional vehicles, because in most instances of high power demand, the additional power in the case of the electric-hybrid vehicles is provided by the electric drive portion of the system, which is more efficient and certainly cleaner than the engine operating at high power in the conventional car. In addition, especially in series hybrid vehicles, engine and catalyst transients can be minimzed in the hybrid vehicle and it is during these periods of engine operation that "off-cycle" emissions are highest. Confirmation of these effects would require study of the modal emissions of conventional and electric-hybrid vehicles. These types of analysis are discussed in References (58,59).

9.0 Upstream Emission Calculations

By upstream emissions are meant those emissions which occur prior to the energy (fuel and electricity) being used in the hybrid vehicle. These include emissions due to the production of the fuel at the refinery, the distribution of the fuel to the service station, the refueling of the vehicle at the service station, and evaporative emissions from the storage/operation of the vehicle that are not recycled for use in the vehicle. The fuel-related emissions vary significantly for the different fuels. A second type of upstream emissions are those generated at the electrical powerplant, primarily those resulting from the production of the electricity, and the distribution of the electricity used to recharge the battery from the wall-plug. The fuel-related emissions are proportional to the volume (gallons or Scf) of fuel used and the powerplant emissions are proportional to the kWh taken from the wall-plug. In recent years, there have been number of studies of fuel-related and powerplant emissions (References 60-62) as various federal and state agencies have considered the environmental impact of alternative energy use in the transportation sector. The results of those studies were used as the basis for the upstream emissions calculations performed in this study. Additional information (Reference 63) was received from th California Energy Commission (CEC) and the California Air Resources Board (CARB) during the course of the study.

When calculating the upstream emissions, it is necessary to designate where the vehicle is being refueled or the batteries charged, because some or even most of the emissions resulting from the refueling or recharging can occur in a region different from that where the refueling and recharging takes place. This is particularly true of emissions at a refinery or electrical power plant. The designations used in this study for the emissions due to the hybrid vehicles are expressed as **LA basin, LA state, and LA total**. These designations mean that the refueling/recharging takes place in Los Angeles (**LA**) and that the emissions are those that occur in the South Coast Air **basin**, the **State** of California, or anywhere in the United States (**total**). Note that the **State** emissions include the **basin** emissions and that the **total** emissions include the **State** emissions. In other words, the emissions are accumulative from the smaller to the larger regions and the emissions (gm/mi) as given can be used to calculate the contribution of vehicles to the emissions inventory in the **basin, state, and the USA**. The incremental emissions in each of the regions from refueling/recharging in LA can be determined by simply subtracting the emissions (gm/mi) from the next smaller region.

9.1 Fuel-related emissions

Vehicle fuels of current interest are reformulated gasoline, diesel oil, methanol, natural gas (CNG), and hydrogen. As noted above, the fuel-related emissions include those from the production of the fuel at the refinery, but not the extraction of the crude oil or natural gas at the wells. The fuel-related upstream emission factors (gm/gal for liquid fuels and gm/100 scf for natural gas) used in subsequent calculations of full fuel emissions are given in Table 30. Emission factors are listed for each of the pollutants (CO, NOx, NMOG, PM (particulate matter), SOx, and CO2). When information was available for the different geographic regions (**LA Basin, state of California, and the USA**), individual emission factors are given for each of the regions. It should be noted that there is considerable uncertainty concerning these factors and that the values given in the various references can be significantly different (References 60-63). The values of the emission factors given in Table 30 for gasoline, diesel fuel, and natural gas were taken from Reference 61, which is a recent study done by Acurex for CARB for the La basin. The values used were for the Year 2005, not those for the present (1992). The emission factors (gm/gal) for refueling and evaporative emissions were obtained from CARB. A refueling factor of .21 gm/gal was used for gasoline.The evaporative emissions factors are use-pattern dependent as they depend on trips and miles per day, which makes their application in the spreadsheet somewhat arbitary as one must use average values for the trips and miles per day. The emission factors for hydrogen (gm/gallon gasoline equivalent) were calculated from emission values given in Reference 62 for production of hydrogen from natural gas. No technical details were given in Reference 62 to describe the natural gas reforming processes, so it was not possible to assess the potential for reducing the relatively high emissions for hydrogen production.

9.2 Powerplant Emissions

Electric and hybrid vehicles can be recharged from the wall-plug using electricity generated remote from the region in which the vehicle is operated. This means that a fraction of the resultant powerplant emissions will occur in regions other than where the vehicle is operated. The emission factors applicable to a particular region should reflect where the electricity for that region was generated. This is especially important for the LA basin, for which a considerable fraction of its electricity is generated outside the basin. A second complication in determining the emission factors for electrical power generation is that powerplants use different fuels and pollution control technologies and as a result, the emission factors vary considerably between powerplants and regions. For this study, emission factors (gm/kwh) were obtained from the California Energy Commission (CEC) for the various regions in California (Reference 63). The emission factors (Table 31) are based on detailed information on the powerplants in California and several different scenarios for recharging the batteries. The emission factors are for electricity used in the LA region and are not applicable for electricity used in the state of California or the USA as a whole. Emission factors must be determined separately for each region of vehicle use. The change in the emission factors from region to region in Table 32 indicate the accumulation of emissions in the regions with the differences indicating the fraction of the emissions occurring outside the basin. For example, 48% of the NMOG and 86% of the NOx emissions for electricity used to recharge batteries in the LA basin are generated outside the basin.

10.0 Full Fuel Cycle Emissions of Electric and Hybrid Vehicles

10.1 Electric Vehicles

The full fuel cycle emissions for electric vehicles using lead-acid, nickel metal hydride, and lithium-ion batteries have been calculated for recharging in the LA basin. The results are given in Tables 18, 32, 33 for the LA basin, LA state, and LA total regions. It is of considerable interest to note that the NMOG and NOx emission results on the FUDS/Highway cycle in the LA Basin for the mid-size car are close to the CARB EZEV standards of .004 gm/mi NMOG and .02 gm/mi

NOx. There are, however, significant variations in the emissions due to vehicle range, battery type and driving cycle. The CO emissions are well below the EZEV standard of .17 gm/mi for all the cases considered. The calculated NMOG and NOx emissions for the small car (Appendix 5) are well below the EZEV standard, because the energy consumption of the small car is 120 Wh/mi compared to 200 Wh/mi for the mid-size car. Both vehicles show higher emissions in the LA Basin for the more demanding driving cycles, such as the UC-92 and US06 cycles. The regulated emissions for recharging the electric vehicles are considerably higher if all the emissions produced in the state of California are included in the calculations. In that case, the emissions of the electric vehicles are approximately .005-.008 gm/mi NMOG and .03-.04 gm/mi NOx for the mid-size car and .003-.005 gm/mi NMOG and .015-.025 gm/mi NMOG for the small car. Including the NOx emissions outside the state of California, the total NOx emissions on the FUDSWay cycle can be as high as .1-.2 gm/mi for the mid-size electric car. All the emissions are lowest for electric vehicles using lithium-ion batteries and highest for those using nickel metal hydride batteries. The differences are due primarily to the more efficient charging characteristics of the lithium-ion batteries.

The CO2 emissions of the electric vehicles were also calculated (see Tables 18, 32,33). As with the regulated emissions, the CO2 emissions occur at the powerplant and thus depend on the characteristics of the powerplant (efficiency and fuel used). The results shown in the tables are for electric vehicles operating in Los Angeles (LA). Since CO2 is a global pollutant, the CO2 emissions include all the CO2 emitted regardless of where the electricity is generated. The CO2 emissions (gm/mi) vary significantly with vehicle range, battery type, and driving cycle, because of differences in energy consumption (Wh/mi) on the various cycles and battery charging efficiency. The battery charging efficiency is higher for vehicles with shorter range, because of the lower average state-of-charge at the start of battery charging. For the FUDSWay cycle, the CO2 emissions for the mid-size electric cars vary from about 110 to 210 gm/mi with the lowest CO2 emissions being for vehicles using lithium-ion batteries and the highest for vehicles using nickel metal hydride batteries. The CO2 emission results show a strong dependence on vehicle design (weight and range) and driving cycle making it difficult to state a single value for the CO2 emissions of electric vehicles. Values as low as 65 gmCO2/mi and as high as 275 gmCO2/mi were calculated.

10.2 Conventional Low Emission ICE Vehicles

The emissions of conventional ICE vehicles are usually discussed in terms of the exhaust emission standards effective during the year of their sale. The hydrocarbon emissions resulting from refueling and fuel evaporation in the ICE cars are significant, and their key importance should not be overlooked in discussions of emissions from electric and hybrid vehicles. Since the refueling and evaporative emissions depend on the quantity of fuel handled, the full fuel cycle emissions (gm/mi) are a function of the fuel economy (mpg) of the vehicle. Spreadsheet model results for the total full fuel cycle emissions of a mid-size car meeting the ULEV exhaust emission standards are shown in Table 34 for fuel economies between 27.5 and 50 mpg using gasoline as the fuel. Results are shown with and without evaporative emissions. In the case of the hydrocarbon emissions, the full fuel cycle emissions are much higher than the exhaust emissions with the evaporative emissions being the largest contributor. The total emissions (gm/mi) decrease slightly as the fuel economy increases. The full fuel cycle hydrocarbon emissions of the ULEV car are .07-.09 gm/mi excluding the evaporative emission and nearly .20 gm/mi including the evaporative emissions. Near elimination of the refueling and evaporative emissions appears to be a requirement if liquid fuels are to be used in hybrid vehicles intended to meet SULEV and EZEV standards. The contribution of the refinery emissions to the full fuel cycle NOx emissions is also significant and could present problems for hybrid vehicles having near EZEV exhaust emissions. These results indicate the full fuel cycle emissions of present gasoline-fueled vehicles meeting the ULEV exhaust emission standards are much greater relative to those of electric vehicles than would be the case if one considered only exhaust and powerplant emissions. Comparing the CO2 emissions of conventional and electric mid-size vehicles (Tables 35) indicates that most electric vehicles will have significantly lower CO2 emissions even if the conventional ICE vehicle had a fuel economy of 42 mpg. This advantage of the electric vehicle will increase as the efficiency of electrical powerplants increases from the present value of about 33% to close to 40% in future years (Reference 12).

Recent progress by the auto industry on natural gas fueled passenger cars indicates that those vehicles can have very low exhaust emissions. Emission data on a natural gas fueled Honda Civic (Reference 64) indicates it meets the EZEV exhaust emissions standards at 100,000 miles. Since there are no refueling or evaporative emissions using natural gas, because the fuel is stored at high pressure and the fuel system must be sealed, the CNG Honda Civic appears to be an EZEV vehicle independent of its use-pattern and region of operation. The gasoline equivalent fuel economy of the CNG Civic on the FUDS is given by Honda in Reference 64 to be 30.5 mpg compared to 32.4 mpg for the 1997 gasoline fueled Civic. The corresponding CO2 emissions are 261 gm/mi for the gasoline fueled Civic and 242 gm/mi for the CNG fueled Civic. These recent advances by Honda seem to indicate that using natural gas as the fuel, ICE vehicles can be designed that meet the EZEV standards including full fuel cycle emissions. The CO2 emissions of the CNG fueled vehicles can be expected to be slightly lower (5-10%) than similar gasoline fueled vehicles.

10.3 Mid-size Hybrid Vehicles

Full fuel cycle emissions have been calculated using the spreadsheet model for the mid-size hybrid vehicle designs described in Table 13. Calculations have been made for gasoline, diesel, and Stirling engines driving a generator in a series hybrid driveline. The methods of analysis have been discussed in detail in previous sections of the report. The calculations were done for three regions - LA Basin, LA state, and LA total- for the regulated emissions (NMOG, CO, and NOx). Since CO2 is a global pollutant, the same total CO2 emission value is given regardless of the region being considered for the regulated pollutants. Representative results for the full fuel cycle emissions and energy use of selected hybrid vehicle designs and use-patterns are presented in Tables 36-45. Additional results are given in Appendix 5. The vehicle identification code used in the tables was given previously in Table 24. Exhaust (running) emissions for the various vehicle designs have been previousl discussed (Tables 15, 25-29), so this section will focus on the full fuel cycle emissions, which, of course, include the contribution of the running emissions.

On each table, the use-pattern assumed for that set of calculations is given in terms of the total miles driven per year, the round trip distance to work, and the random miles driven. The use-pattern is intended to describe city/suburban use of the vehicle - that is all use except long distance intercity travel of over 100 miles. The table also indicates the region (origin) of the pollution included in the calculations. Note that the emissions for each region include those from the previous smaller regions (i.e. emissions are accumulated from region to region). All the results given in Tables 36-42 are for zero evaporative emissions. A flag (0 or 1) indicates whether the hybrid vehicle is operated in the charge depleting or charge sustaining mode. Charge depleting means that the vehicle is recharged each day from the wall plug and the user maximizes the use of electricity. This is the optimum mode to mimimize running emissions. Charge sustaining means that the hybrid vehicle is operated using the engine/generator to keep the battery at a near fixed state-of-charge and the battery is never recharged from the wall-plug. This mode of operation results in unlimited range without recharging the battery, but it maximizes annual running emissions and fuel consumption.

In the following paragraphs, selected important aspects of the results are discussed for different engines, energy storage technologies, and use-patterns. Computer runs were made for many more combinations of technologies, use-patterns, and regions than can be discussed in the report. Computer outputs for additional cases are given in Appendix 5 as reference material for further consideration by the reader.

Hybrid Vehicles using Port Injected Gasoline Engines

Total emissions results for hybrids using nickel metal hydride batteries and a 3-cylinder, port injected gasoline engine are given in Tables 36-38 for 4300, 7500, and 10,500 annual miles of random travel. The base case is 7500 miles random travel and an all-electric range of 34 miles. In this case, there is in a high fraction of all-electric miles (charge depleting), but significant driving using the engine. The full fuel cycle emissions (Table 37) in the LA basin for this case excluding evaporative emissions are relatively low being less than one-half ULEV for NMOG (42%) and NOx (24%) for charge depleting operation on the FUDS driving cycle. For charge sustaining operation (all miles in the hybrid mode), the total full fuel cycle emissions excluding evaporative emissions (Table 39) are significantly higher being 45% above the ULEV standard for NMOG and 33% below the ULEV standard for NOx. The CO2 emissions are 180 gmCO2/mi in the charge depleting mode, which is about one-half that of present ICE cars, and 260 gmCO2/mi in the charge sustaining mode. If the total annual mileage of this vehicle is increased from 10,000 miles to 15,000 miles (see Table 38), the NMOG and NOx emissions of the vehicle in the charge depleting mode increase by nearly 50% and the CO2 emission increase by about 10% bringing them closer to the ULEV standard and CO2 emissions for a conventional ICE vehicle. In the charge sustaining mode, the emissions are independent of annual mileage as the vehicle operates in the hybrid mode at all times. For the case of a 10 mile round-trip to work and 4300 random miles per year (Table 36), the hybrid vehicle would be used essentially as an electric vehicle for urban/suburban travel and be used in the hybrid mode for intercity highway travel only. For this use-pattern, an all-electric range of 34 miles would be sufficient to achieve near EZEV emission levels.

Next consider a hybrid vehicle design with an all-electric range of 56 miles on the FUDS driving cycle. For charge depleting operation (recharge from the wall-plug) and 7500 mile random travel (10,000 total miles), the NMOG and NOx emissions (gm/mi) are reduced by 50% and 65%, respectively, from that of the vehicle having a 34 mile all-electric range. The resultant emissions are close to, but still above the EZEV standard. The CO2 emissions are essentially uneffected by the increased all-electric range. For a vehicle traveling 15000 total miles, increasing the all-electric range to 56 miles, reduces the NMOG and NOx emissions by 60% resulting in emissions that are still well above the EZEV standard. Hence whether increasing the all-electric range to about 60 miles results in a hybrid vehicle having annual average emissions near EZEV depends on the use-pattern of the vehicle. The CO2 emissions are only slightly effected by the all-electric range, but in general, are reduced by increasing the fraction of the miles that the vehicle is driven on wall-plug electricity. This is the case for the LA Basin and state of California where most of the electricity used is not generated using coal.

Next consider the effect of the driving cycle on total full fuel cycle emissions for the base use-pattern (15 miles round-trip to work and 7500 random miles per year). Simulation results are given in Tables 37 and 39 for charge depleting and charge sustaining operation in the LA Basin. The effect of the driving cycle on total emissions is much greater for charge depleting than for charge sustaining operation (compare Tables 37 and Table 39), because of the significant effect that the driving cycle has on the all-electric range of a particular vehicle design. For charge sustaining operation, the most demanding driving cycles (FW70 and US06) have significantly higher NOx and CO2 emissions than the FUDS cycle, but the differences in the NMOG and CO emissions are not as significant. The CO2 emissions for the different vehicle designs, control strategies, and driving cycles vary by almost a factor of two. In the case of the charge depleting strategy, the CO2 emissions vary from 162 to 299 gmCO2/mi and for charge sustaining hybrids, they vary from 206 to 389 gmCO2/mi.

The large effect of evaporative emissions on the total emissions is shown in Tables 40 and 41 for charge depleting and charge sustaining operation in the LA basin. For low exhaust emission vehicles, it is clear that evaporative emissions much be reduced to near zero values before it is possible for their total emissions to be near EZEV.

Hybrid Vehicles using Advanced Engines

Simulation results for the total emissions of mid-size hybrid vehicles using advanced engines are given in Tables 41 - 44. The advanced engines include swirl chamber and direct injection diesel, direct injection gasoline, and Stirling engines. The emissions given in the tables are for the baseline use-pattern with vehicle operation in the LA basin with zero evaporative emissions. Results are given for both the charge depleting and charge sustaining control strategies.

The emission results for the charge depleting hybrids given in Table 42 indicate that the total NMOG and CO emissions using the advanced gasoline and diesel engines are essentially the same as using the conventional port injected gasoline engine with the vehicles meeting the EZEV standard if the all-electric range of the vehicle is 50 miles or greater. The NMOG and CO exhaust emissions can be reduced to almost any non-zero level using an oxidizing catalyst as is the case for the conventional gasoline engine. The total NMOG and CO emissions for the charge sustaining hybrids (Table 44) are well below the present ULEV standards, but well above the EZEV standards for most of the driving cycles and vehicle designs. The exhaust (running) NMOG and CO emissions (Table 25) of the charge sustaining hybrids using the direct injection engines are well above the EZEV and new SULEV (.008 GM/MI) standards. NMOG and CO exhaust emissions from the vehicles using the Stirling engine are very low (less than EZEV) even without a catalyst (Table 29).

The primary challenge with the direct injection diesel and direct injection gasoline engines is that reduction of the exhaust NOx emissions to .1 gm/mi and lower requires a very high efficiency (>95%) NOx catalyst that functions in the exhaust stream from the lean burn direct injection engines. A recent presentation (Reference 65) by CARB indicates they are considering lowering the ULEV NOx emission standard to .05 gm/mi and establishing a new SULEV emission category with a NOx standard of .02 gm/mi, which is the same as the EZEV standard. Without a lean-burn NOx catalyst with a conversion efficiency comparable to the 3-way catalysts currently being used in port injected gasoline engines with oxygen sensors, it does not seem likely the advanced engines will be able to meet the new ULEV or SULEV NOx standards even in the charge depleting mode unless the engine is operated very infrequently in city driving. This will require an all-electric range in excess of 60 miles. The hybrid vehicles using Stirling engines have lower NOx emissions than those using the other advanced engines, but without a catalyst with a reasonably high NOx conversion efficiency (>75%), charge sustaining hybrid vehicles with Stirling engines will not meet the EZEV or SULEV NOx standard (.02 gm/mi). Meeting the low NOx standards becomes more difficult for the driving cycles that are more demanding than the FUDSWay cycle.

The CO2 emissions for the various hybrid designs using the advanced engines are also given in Tables 42 -44. The hybrid cars with direct injection diesel and Stirling engines have the lowest CO2 emissions being 160 gmCO2/mi and 175 gmCO2/mi on the FUDSWay cycle, respectively. The CO2 emissions for the direct injection gasoline engine are 180 gmCO2/mi. The reason that the CO2 emissions of vehicles using the direct injection diesel and gasoine engines do not differ by a greater percentage is that the diesel fuel has a higher energy content per gallon (15%) and a higher carbon content (6%) than gasoline, which significantly reduces (by about 20%) the fuel economy advantage of the diesel engines. The advanced engines have CO2 exhaust emissions corresponding to 55-60 mpg gasoline equivalent. Hence in the mid-size car, they represent about a 25% reduction in total CO2 emissions compared with hybrid vehicles using the conventional port injected gasoline engines.

Hybrid Vehicles using Fuel Cells

Simulations were also run using a fuel cell in the mid-size vehicle to generate electricity on-board the vehicle. The fuel cell powered hybrids were always operated in the charge sustaining mode with the battery used to load level the fuel cell. As noted previously in the report, only the cases of fuel cells fueled with hydrogen stored on-board have been considered and further it has been assumed the hydrogen was produced by reforming natural gas. Since the use of a reformer to produce the hydrogen on-board the vehicle was not considered in this study, the running (exhaust) emissions are zero as for an electric vehicle. Hence, the total emissions are those due to the production of hydrogen from natural gas and the distribution and storage of the hydrogen for use in the hybrid vehicle. Total emissions for the fuel cell powered hybrid vehicles considered in this study are given in Table 45 for various driving cycles. For hydrogen produced from natural gas, the total emissions are well above the EZEV standard for both NMOG or NOx. The CO2 emissions are 115-120 gmCO2/mi for the mid-size car on the FUDSWay cycle. These CO2 emissions are significantly lower than those obtained for the mid-sized hybrid using the advanced engines. The CO2 emissions are also much lower than would be expected if natural gas had been used in place of gasoline or diesel fuel in the engine. If the hydrogen had been produced from solar energy rather than natural gas, both the exhaust and total emissions of the fuel cell powered vehicle would be near zero.

10.4 Compact size (Light-Weight) Hybrid Vehicles

Full fuel cycle emissions have also been calculated using the spreadsheet model for compact (light-weight) hybrid vehicles described in Table 13. The results for selected designs and operating conditions are given in Tables 46-49. Additional results are given in Appendix 5. Much of the discussion given in the previous section for the mid-size hybrid vehicles is applicable to the smaller, lighter weight hybrids. Hence this section will be much briefer than the previous section and will only highlight the differences between the emissions and fuel use characteristics of the two types of hybrid vehicles. The smaller hybrid vehicles (4-passengers) weigh only about 800 kg compared to about 1550 kg for the mid-size hybrids due primary to the use of light-weight materials in the chassis and body of the smaller vehicle. It was assumed that the use-patterns and driving cycles for the two types of vehicles would be the same, so there can be a direct comparison of their exhaust (running) and total emissions. As would be expected the energy use and emissions of the small, light-weight hybrids are considerably lower than that of the larger mid-size car (compare Tables 39 and 47 for the baseline gasoline engine). As in the case of the mid-size car, the emissions for the charge depleting hybrids are lower than that of the charge sustaining hybrids. In the charge depleting mode, the NMOG and CO emissions of the smaller car can be reduced to the EZEV standards with a simple two-way catalyst. This is true for both the port injected gasoline engine and the advanced engines (see Tables 46 and 48). Reducing the NOx emissions for the smaller vehicle to meet the SULEV and EZEV standards will be less difficult than for the larger car as the engine out emissions are lower. The total CO2 emissions of the small car in the charge sustaining mode on the FUDSWay cycle are 130 gmCO2/mi using the port injected gasoline engine, 110 gmCO2/mi for the direct injected gasoline engine, and 100 gmCO2/mi for the direct injected diesel and Stirling engines. The improvement in CO2 emissions by using the advanced engines in the small car is only 15-20%, which is somewhat less than in the mid-size car. The use of the fuel cell in the small car decreases the CO2 emission to 60-70 gmCO2/mi even when the hydrogen is produced by reforming natural gas. This is much lower than the CO2 emissions (96 gmCO2/mi) that would be expected if the natural gas was used in an advanced engine in the hybrid. The NOx emissions of the fuel cell powered small car are relatively high at .11 gm/mi. Further study is needed to determine if the NMOG and NOx emissions from the hydrogen production from natural gas can be greatly reduced. There does not seem to be much information on the emissions from the natural gas reforming processes in the literature.

11. Regulatory Considerations for Electric-Hybrid Vehicles

Simulation results presented in previous sections of the report show that with existing technology and that currently being developed, electric-hybrid vehicles can be designed that have emissions considerably below ULEV and significantly higher fuel economy (and thus lower greenhouse gas emissions) than passenger cars presently available for sale. It seems highly desirable to get such vehicles into the market in a timely manner in order to reduce smog and greenhouse gas emissions and to reduce US oil imports. In this section of the report, various approaches to promote the commercialization of the new hybrid vehicle technologies in the near-term are discussed and the emissions and fuel economy standards that these vehicles could meet are identified.

11.1 Approaches for Early Commercialization of Hybrid Vehicles

Most auto industry experts in the United States are very doubtful that market forces alone will cause the early commercialization of hybrid vehicles solely because of the attractiveness of their higher fuel economy to potential new car buyers. The principal reason for this opinion is that the introductory price of the hybrid vehicles would likely be considerably higher than that of the conventional ICE cars curently being sold to offset the development cost of the new technologies and the investment in equipment and factories required to produce the hybrid driveline components and vehicles in large quantities. Hence a key consideration is how to induce the automobile companies in the US and abroad to make the investment in engineering resources and capital necessary to develop and manufacture hybrid vehicles when the market for such vehicles is at best uncertain.

There are two basic approaches. One approach is offer monetary incentives to the companies and consumers that are early producers and purchasers of hybrid vehicles that meet emissions and fuel economy standards that are much cleaner and efficient than vehicles presently available - that is total emissions approaching EZEV and fuel economy much above (say twice) that of present vehicles of the same size. This approach is currently being used by some states and the Federal government to promote the lease of electric vehicles. For example, the capital value of a Honda EV Plus leased in California is reduced by a $4000 Federal Tax credit and a $5000 Air Quality District Allowance, but since the base vehicle price is very high ($53999), the monetary incentives have little bearing on the leased payment of the vehicle. It is only when the monetary incentives are a significant fraction of the difference in price between the new technology vehicle and the conventional vehicle that the incentives have a large bearing on consumer purchasing decisions. This was the case in the 1970's for solar water heating units in California where incentives effectively drove the market. When the incentives were eliminated, the market collapsed. Detailed studies of monetary incentives as applied to the development and marketing of advanced, energy efficient vehicles are given in References 66-68. The approaches suggested in the references are largely untested for cars, but have been found to work reasonably well for electrical appliances like refrigerators. The monetary incentive approach will not be considered further in this report.

A second approach would be to set emissions and fuel economy standards for future years that would require the auto industry to significantly improve their products before they could be sold. These future emissions standards would be well below ULEV (maybe the proposed SULEV) and the CAFE (Corporate Average Fuel Economy) standard would be systematically increased from the present value of 27.5 mpg to about 50 mpg over a period of years. This approach would force all auto companies to produce cars that meet the stricter standards and are attractive in features and price to new car buyers in order to remain profitable. There has been considerable experience with this second approach through the successively stricter emission standards of California and EPA since 1970 and the CAFE standards for fuel economy instituted in 1978. History has shown that over the years since 1970 the emissions of cars has been reduced by a least 95% and that their fuel economy has increased by at least 50% with essentially no decrease in vehicle performance, comfort, or safety (Reference 51). The price of cars has increased, but car sales have remained high. Whether the "standards" approach was the best in terms of economic efficiency is debatable, but the improvement in the emissions and fuel economy of passenger cars over the last 20-25 years is a matter of record. It is doubtful that these improvements, which almost every one agrees have benefited society, would have occurred without the emissions and fuel economy standards of the past twenty five years (References 69,70).

Looking at more recent history, consider the reaction of the automobile industry to the California EV Mandate, which initially required 2% electric vehicles in 1998 and 10% electric vehicles in 2003. Along with the EV Mandate, a series of increasingly strict HC,CO, and NOx standards were imposed on the exhaust emissions of conventional ICE cars. Since their imposition in 1990 the auto industry has developed technology to meet all the new standards usually well ahead of the mandatory schedule. It is doubtful whether the auto industry would have been willing to spend the very large resources necessary to meet the tightening emissions standards for conventional vehicles in California if they had not had the incentive to attempt to show that conventional engine powered vehicles could be made almost as clean as electric vehicles when the powerplant emissions were included.

This brief review of history indicates that the "standards" approach is a powerful way of forcing technology change in the auto industry especially if technical information available at the time the standards are set indicates that at least one technical approach is known that will allow the industry to meet the new standards. Cost and time considerations regarding the development for market of the new technologies always will be debated between the industry and the public agencies, but that is to be expected and in the long term heathy. It is best to set the new future standards without specifying the technology to be used and allow each company to develop the technologies that best suit their situation. In the present case of standards for significantly improving the efficiency of light-duty vehicles and thus reducing greenhouse gas emissions, this means setting total emission standards, including CO2, that are vehicle and fuel technology neutral and letting the auto industry select and develop the technologies required to meet the standards. This could result in the development and marketing of hybrid-electric vehicles or it could result in development of other technologies, such as engine-powered vehicles using hydrogen or bio-fuels. The work presented in this report indicates that hybrid vehicle technology is one approach to the development of vehicles with greatly reduced CO2 emissions. The results obtained in this study can be used as a guide to setting future emissions standards for light-duty vehicles.

11.2 Emission Standard Considerations

Current emission and fuel economy standards are expressed in terms of gm/mi for exhaust emissions and and miles per gallon (mpg) for fuel economy. The emissions are measured on the Federal Urban Driving Schedule (FUDS) and the fuel economy is for a composite of driving on the FUDS and FHWS (Federal Highway Schedule) cycles. This approach for specifying the standards is satisfactory when exhaust emissions are the dominant source of emissions from cars and all or nearly all vehicles use a single fuel - gasoline -from a pump at a service station. This is not the case for the vehicles considered in this study that can utililze electricity from the wall plug and one or more liquid or gaseous fuels. In addition, the fraction of each energy source used depends on the use-pattern of the vehicle. Further, one of the primary emission gases of interest is CO2, which is emitted in connection with both the electricity and fuel. For these reasons, consideration should be given to restructuring the way in which the emission standards are set and how they are applied to different types of vehicles.

The primary changes that should be considered are that all emissions (NMOG, CO, NOx, and CO2) should be specified as the total emissions (gm/mi) generated in connection with the electricity and fuel used by the vehicle and that instead of fuel economy (mpg), the efficiency of the vehicle should be expressed in terms of the total gmCO2/mi. Emissions and vehicle efficiency given in this way can be applied to electric, hybrid, and conventional engine powered vehicles using various liquid and gaseous fuels and electricity generated using different fuels and technologies. The CO2 emissions could be interpreted as mpg - gasoline equivalent, if that is needed to inform the public of the relative fuel economy of the different vehicles. Unlike the present fuel economy standard, which is set in terms of the corporate (fleet) average (CAFE), it seems reasonable to set the CO2 standard for each separate class of car based on the interior volume for passengers and luggage. In this way, the standard can insure the same efficiency for each class of cars and not favor manufacturers that market mostly small cars. All manufacturers would be required to utilize equivalent levels of new technology regardless of the average vehicle size.

In the case of electric cars, the efficiency standard should be specified in terms of kWh/mi at the wall-plug. In a given region, this would insure that the total emissions for all EVs of the same interior volume would be the same regardless of vehicle design. The actual total emissions in a particular region are dependent on where and how the electricity is generated for that region.

It will probably be necessary to specify an average daily use of the vehicle since battery charging efficiency depends on battery state-of-charge at the initiation of the charging. There is a wide variation in electric usage of electric vehicles, much like electrical appliances, and setting the CO2 standard will force manufacturers to design energy efficient electric vehicles.

Setting the standards for hybrid vehicles is more complex than for electric vehicles, because they use both electricity and chemical fuels with the fraction of each energy source used depending on the control strategy for the vehicle and its use-pattern. As discussed in Section 10, the emissions of a hybrid vehicle can be determined if its characteristics in the all-electric and hybrid operating modes are known and the use-pattern is specified. The emission standards (gm/mi) could be set for one or more specified use-patterns (annual miles and travel statistics). The government agency (EPA or CARB) would specify the test and calculation procedures for determining the total emissions of hybrid vehicles for each of the use-patterns. The manufacturers would demonstrate that their vehicles meet the standards when operated as intended. The test and calculation procedures would include a standard set of upstream emission factors that would be used by all manufacturers. A standard set of vehicle dynamometer tests would be required and the application of the data to the set of use-patterns could be performed on a computer(PC) using government furnished software.

The emission and efficiency standards for conventional engine-powered vehicles would be closely related to those for hybrid vehicles that have only a hybrid operating mode (that is zero all-electric range). The emissions of these vehicles would be essentially independent of use-pattern with only the refueling and evaporative emissions being dependent on annual mileage. The total emissions would be calculated using the same upstream emission factors as used for the hybrid vehicles. These factors would apply to all liquid and gaseous fuels.

11.3 Discussion of Emission Standards for Advanced Vehicles

This discussion of emission standards for advanced vehicles will be based on simulation results for compact and mid-size cars using the same driveline technologies included in the hybrid-electric vehicles considered in Sections 8-10. The weight of the vehicles (1320 kg for the mid-size and 1000 kg for the compact cars) are somewhat lighter than 1996 vehicle designs, but not as extreme as the advanced lightweight compact car previously considered (Table 13). A summary of the vehicle inputs to the EXCEL spreadsheet for these additional vehicles is given in Table 50. All the vehicle simulation results are for the FUDSWay driving cycle . Spreadsheet runs were made for these vehicles using evaporative and refueling emissions that were equal to, one-third of, and one-tenth of the baseline upstream emissions given in Tables 30. All runs were made for the baseline use-pattern of 7500 miles per year random travel and a 15 mile round-trip to work. Emissions were calculated for the **LA State** region as representative of a large region of national interest. Comparisons have been made (see Table 51) between the total NMOG and NOx emissions for the hybrid vehicles operating in the charge depleting and sustaining modes with those of conventional vehicles meeting various exhaust emission standards (ULEV and SULEV) and electric vehicles using nickel-metal-hydride and lithium ion batteries. The comparisons are made for the the three levels of evaporative and refueling emissions noted above. The CO2 emissions of the different vehicle designs are also compared.

The first comparisons (Table 51) are made for vehicles using port injected gasoline engines because that is the engine technology in use today. All the NMOG and NOx emissions shown in Table 51 are relatively low compared with the exhaust emissions standards in effect before CARB set its Low Emissions Standards in 1990 (TLEV, LEV,ULEV, ZEV). However, the total NMOG emissions shown in the table for the hybrid vehicle are much higher than the exhaust emissions for the vehicle and in the case of the charge sustaining mode of operation, much greater than the ULEV standard (.04 gm/mi). Hence,in the case of NMOG emissions, there is little relationship between the exhaust emissions of a vehicles and its total emissions. The total NMOG emissions are higher than the exhaust emissions by factors 10 to 15. This is the case for the NMOG emissions, because the upstream emissions (evaporative, refueling, and refinery) are many times greater than the exhaust emissions. Hence continued tightening of the NMOG exhaust emissions of passenger cars does little to reduce their total NMOG emissions. The total NOx emissions of the hybrid vehicles in the charge sustaining mode are below the ULEV standard (.2 gm/mi) and only slightly above the exhaust emissions for the vehicles. The upstream NOx emissions are not dominate as is the case of NMOG emissions. The total NMOG and NOx emissions of the hybrid vehicles (all-electric range of about 50 miles) in the charge depleting mode are much below ULEV, being dominated by the upstream electrical powerplant emissions, but as shown in Table 51, there is still a significant effect of evaporative and refueling emissions on the NMOG emissions. Also shown in Table 51 are the total emissions of conventional ICE cars meeting the ULEV and SULEV standards. As would be expected based on the discussion of hybrid vehicle emissions, the upstream NMOG emissions for the gasoline fueled conventional vehicle dominate the exhaust emissions and the total NOx emissions are only slightly higher than the exhaust NOx emissions (see Table 52 for the total emissions of conventional cars meeting the ULEV and SULEV standards with present refueling and evaporative emissions).

The results shown in Table 51 indicate that setting emissions standards for advanced clean vehicles in terms of exhaust emissions makes little sense and that for these vehicles all standards should be set in terms of the total emissions, including all upstream emissions at least including the refinery and powerplant. Total emissions for electric vehicles are also given in Table 51 for both the **LA Basin** and **LA State** regions. Note that the emission values for the **LA Basin** are close to the EZEV standard and that those for the **LA State** region are in most cases above the EZEV standard. In all cases, the total emissions of the electric vehicles are below those of the hybrid vehicles, but only slightly below for hybrid vehicles operating in the charge depleting mode. Setting emission standards in terms of total emissions would make comparisons of the emissions from all types of advanced vehicles possible on a consistent basis. That is not possible using exhaust emissions as the standard. For example, consider the case of fuel cell powered vehicles using compressed hydrogen from reformed natural gas (Table 53). The exhaust emissions from such a vehicle are zero, but the upstream NMOG and NOx emissions are only slightly below ULEV, certainly not near the EZEV standard as is often claimed.

Vehicle efficiency is presently measured by the Corporate Average Fuel Economy (CAFE) for each vehicle manufacturer. The standard is currently 27.5 mpg for gasoline fueled vehicles. It is difficult to apply this type of standard to advance vehicles that use different fuels and electricity. Vehicle efficiency is directly related to CO2 emissions and fossil fuel useage. Hence expressing the fuel economy standard in terms of the total CO2 emissions (gmCO2/mi) rather than miles per gallon would be a more unified approach as well as a direct method of stating the reductions in greenhouse gases resulting from changes in vehicle efficiency standards. For the combustion engines, the exhaust CO2 emissions represent the major fraction of the total CO2 emission as the upstream CO2 emissions are relatively small (about 12%). Hence the CO2 emissions from engines are dependent primarily on the engine fuel economy and fuel type. For fuel cells, the key consideration is how the hydrogen is produced either onboard (reformer) or offboard (stored, compressed gas) the vehicle. In this study, only onboard storage of compressed hydrogen is considered and all the emissions, including CO2, are upstream emissions. The fuel economy and total CO2 emissions of the vehicles being discussed in this section are shown in Tables 54-57. Both the fuel economy and CO2 emissions vary significantly for the different vehicle types and engines being considered. All the fuel economy values are well above the present standard of 27.5 mpg and the CO2 emission values are well below the value of 350 gmCO2/mi corresponding to a gasoline fueled vehicle meeting the 27.5 mpg standard. This indicates there are many options for reducing the CO2 emissions from passenger cars. The hybrid vehicles using diesel engines have lower CO2 emissions than those using the gasoline engines, but not by as wide a margin as might be expected. This is because the CO2 emissions from a diesel engine powered vehicle are 20% higher than from a gasoline engine powered vehicle having the same fuel economy (mpg). Hence direct use of "mpg" as a measure of CO2 emissions for diesel and gasoline engine and fuel cell powered vehicles can be misleading and should be avoided. However, it seems appropriate to recognize the inherently higher fuel economy and lower CO2 emissions of smaller vehicles (less interior volume) and set different CO2 emission standards or targets for different size vehicle. These differences are apparent in Tables 54-57.

11.4 Technology Feasible Emission Standards

It is recognized that vehicle emission and efficiency standards are set based on political and economic considerations as well as technical feasibility. The discussions of emission standards in this section of the report are based solely on the technical results presented in previous sections and how, whether, or when these standards could/should be implemented is not addressed. The key considerations are that the emission standards should be set in terms of total emissions (exhaust plus upstream emissions) and in order to relate directly to greenhouse gas emissions, the vehicle efficiency standards should set in terms of CO2 emissions. At the present time, knowledge of and test procedures for exhaust emissions are well-established, because for the most part, vehicle emissions have been regulated in terms of exhaust emissions. Information on upstream emissions, including refueling and evaporative emissions, is much less available and well defined. There are in place evaporative emission standards and test procedures, but the consequences of these standards on the NMOG emissions (gm/mi) of cars in actual use are much less certain. As indicated in Table 30 the evaporative emission standards are event oriented for the most part, which makes the calculation of the emissions (gm/mi) from them difficult and uncertain for a particular use-pattern and vehicle operating strategy. As shown in Tables 58, the contribution of the refueling and evaporative emissions to the total emissions for the advanced clean vehicles is very large being at least 70% of the total NMOG emissions at the present time. Hence it seems necessary to virtually eliminate the refueling and evaporative emissions of vehicles using liquid fuels if such vehicles are going to have total emissions as low as battery-powered electric, natural gas fueled, and fuel cell (hydrogen from non-fossil sources) powered vehicles. The total NMOG emissions of these vehicles can be expected to be less than .005 gm/mi. Hence the liquid fueled vehicles must have a closed pressurized fuel system and be refueled using a rigid connection between the car and the fuel dispensing pump (from an emissions point-of-view, equivalent to the fuel system in natural gas fueled vehicles). The exhaust NMOG emissions from hybrid vehicles and possibly from conventional, advanced engine-powered vehicles (see Reference 71 for information on the Honda ZLEV engine that has exhaust emissions less than the CARB EZEV standard) can be reduced to below .005 gm/mi using high (>98%) conversion efficiency catalysts. The total CO emissions standard can be set below .5 gm/mi and rather easily met if the engine start up exhaust emissions are well managed. The largest uncertainties concerning the total emissions of liquid fueled vehicles are the upstream emissions from the refinery (fuel processing) and fuel distribution to service stations. At the present time, these NMOG emissions are thought to be much greater (.02-.03 gm/mi) than the .005 gm.mi standard desired based on emissions from powerplants. It seems clear that for advanced clean vehicles (conventional or hybrids), the exhaust emissions are small compared with the upstream emissions, which must be greatly reduced if liquid fueled vehicles are have emissions comparable to electric vehicles. These problems are much less difficult for charge depleting hybrids that would use much less liquid fuel than a charge sustaining hybrid (see Tables 54 and 56).

Consideration of NOx emission standards are more complex than for NMOG standards for at least two reasons. First, it is difficult using the most efficient engines (see Table 50) to reduce the exhaust NOx emissions from the vehicle to low levels (<.10 gm/mi) even with catalytic converters. Thus there is likely to be a trade-off between the NOx standard and vehicle efficiency. Second, since the powerplant NOx emissions for recharging the batteries in an electric vehicle are the basis for setting the NOx standard for other vehicles, the dependence of these emissions on powerplant technology and location make it difficult to determine a single value of NOx emissions for elecdtric vehicles. For example, the proposed EZEV NOx standard (.02 gm/mi) is based on NOx emissions from powerplants in the LA basin for recharging EV batteries in the LA basin. If the total NOx emissions outside the LA basin are included, the total NOx emissions for the electric vehicle would be about .1 gm/mi. For liquid fueled vehicles, the effect of upstream emission on their total NOx emissions is small and their exhaust emissions are a good measure of their total NOx emissions. Projected NOx emissions of hybrid vehicles using various engines for charge depleting and charge sustaining operation are given in Tables 54-57. The exhaust NOx emissions in the charge sustaining mode (no battery charging from the wall plug) vary between .023 gm/mi for the Stirling engine and .3 gm/mi for the direct injection diesel. The emissions for the gasoline engines are .05-.09 gm/mi. For the 50 mile all-elctric hybrid vehicles in the charge depleting mode, the NOx emissions approach those of the powerplant for the region of interest. Hence setting a total NOx standard less than .05 gm NOx/mi would be difficult to meet even with a mid-size electric vehicle unless one only considers emissions into the LA basin. The direct injection gasoline engine seems to offer the best choice in terms of low NOx and high fuel economy (low CO2 emissions). The most efficient engine is the direct injection diesel, but it has a high NOx emissions (.3 gm/mi) and would require a very high efficiency catalyst for meet the .05 gm standard. The simulation results for the mid-size car indicate meeting the SULEV NOx standard (.02 gm/mi) in the charge sustaining mode will be difficult except possibly with the Stirling engine. The prospects of meeting the .02 gm/mi NOx standard are better for the compact car. This study did not consider particulate emissions, but that could evolve into a very important issue for the diesel engines and possibly even for the direct injection gasoline engine. This should be carefully investigated in a future study.

The approach most often discussed for reducing greenhouse gases (CO2) from light duty vehicles is to increase the CAFE standard from 27.5 mpg to a higher value over a period of five to ten years. A more direct approach is to set a CO2 standard (gmCO2/mi) that is lower than the total CO2 emissions from vehicles presently being sold in compliance with the CAFE standard of 27.5 mpg. Including the upstream CO2 emissions, a gasoline-fueled, mid-size conventional car with a FUDSWay fuel economy of 27.5 mpg generates 350 gmCO2/mi. The total CO2 emissions have been calculated for all the various electric and hybrid vehicle designs considered in this study using the EXCEL spreadsheet. Of particular interest in this section are the compact and mid-size vehicles listed in Table 50. These vehicles have weights and road load characteristics achievable in the relatively near term (production in 5-10 years) and thus can be used to project technically feasible CO2 emission standards for that period. The lowest CO2 emissions can be achieved for electric vehicles and hybrid vehicles with an all-electric range of 40-50 miles in the charge depleting mode. The CO2 emissions of these vehicles are 100-120 gmCO2/mi for the compact car and 155-180 gmCO2/mi for the mid-size car. The CO2 emissions of the hybrids in the charge sustaining mode vary significantly with engine type and are generally higher than for the charge depleting mode. For gasoline engines in a hybrid, compact car, the CO2 emissions are 160-180 gmCO2/mi using gasoline engines and 130-160 gmCO2/mi for diesel engines. For gasoline engines in mid-size cars, the CO2 emissions are 190-220 gmCO2/mi and for diesel engines, the CO2 emissions are 170-195 gmCO2/mi.

The vehicle efficiency results using the various hybrid vehicle technologies support an initial reduction of total CO2 emissions for the mid-size car to 220 gmCO2, which corresponds to a fuel economy of about 45 mpg (gasoline). This can be done using the port injected gasoline engine technology. Introduction of the direct injected gasoline or Stirling engines could lead to a further reduction in CO2 emissions to 180-190 gmCO2/mi and with diesel engines to 170-195 gmCO2/mi. For equivalent engine technology, the CO2 emissions for the compact cars are about 25% less than that of the mid-size hybrid vehicles. These CO2 emission targets represent a 40-50% reduction from present levels. Using gasoline engines and three-way catalysts, these reductions in CO2 are achievable with near EZEV exhaust emissions. The total emissions of the vehicles would critically depend on the evaporative and refueling systems incorporated into the advanced hybrid vehicles.

The simulations indicate that the lowest CO2 emissions can be achieved using fuel cells and compressed hydrogen. The values calculated are 100 gmCO2/mi for the mid-size car and 85 gmCO2/mi for the compact car. These represent CO2 reductions of 70-75% from present levels. Using hydrogen from natural gas, the total NMOG emissions would be .04 gm/mi and the NOx emissions would be .18 gm/mi, which are only slightly below the ULEV standards. The efficiency and emissions of fuel cell powered vehicles are critically dependent on how the hydrogen required by the fuel cell stack is produced. Production of hydrogen from solar energy is clearly the best approach in terms of minimizing total emissions and on-board reforming of a hydrocarbon fuel is the least attractive approach for fueling a fuel cell from the total emissions point-of-view. The results of this study clearly show the great potential for fuel cells to reduce CO2 emissions, but a detailed investigation of the refueling issues for fuel cells is needed to better define the potential reductions of CO2 emissions and the total NMOG and NOx emissions to be expected.

Summary and Conclusions

This study focused on the emission reduction and fuel economy benefits of the application of hybrid/electric powertrain technology to light-duty vehicles (mid-size and compact passenger cars). The approach taken was to calculate the exhaust emissions (gm/mi) and energy use (Wh/mi and mpg) for a wide range of vehicle designs (steel and light-weight materials), driveline technologies, control strategies, and driving cycles using two vehicle simulation programs (SIMPLEV and AVTE). The vehicle designs utilized various engines (injected gasoline, diesel, and Stirling) and PEM fuel cells for on-board generation of electricity. Both series and parallel hybrid driveline configurations were analyzed. Batteries (lead-acid,nickel metal hydride, and lithium-ion) and ultracapacitors were considered as the energy storage units. The annual full fuel cycle total emissions were then calculated for each of the hybrid vehicle designs, as well as for electric (battery-powered) and ICE vehicle designs, using an EXCEL (macro) spreadsheet, which used as inputs the simulation results from SIMPLEV and AVTE and upstream emissions to account for vehicle evaporative and refueling emissions and the production and distribution of the fuel and electricity used by the vehicles. The total emissions calculations included the effect of the vehicle use-patterns. The baseline use-pattern was 7500 miles random use per year and a 15 mile round-trip to work.

The following major conculsions were drawn based on the results of the study:

1. Light-duty vehicles using an engine-powered hybrid driveline can have up to double the fuel economy and thus one-half the CO2 emissions of conventional ICE vehicles of the same weight and road load.
2. Vehicle using a load-leveled PEM fuel cell fueled with compressed hydrogen produced by reforming natural gas can have about one-third the total full fuel cycle CO2 emissions of a conventional vehicle using an gasoline ICE engine.
3. The exhaust emissions of all vehicles (hybrid and conventional) can be reduced to sub-ULEV levels using advanced electrically heated catalyst systems and computer engine control.
4. The full fuel cycle emissions of all advanced light-duty vehicles (hybrid and ICE powered) are primarily dependent on upstream emissions and the emissions of these vehicles will not be close to EZEV levels unless their evaporative and refueling emissions are essentially zero and the deterioration with use is minimal.
5. The calculated total emissions of electric (battery-powered vehicles) are dependent on the recharge characteristics of the batteries used and the relevant powerplant emissions. For the LA Basin, the calculated values for mid-size EVs emissions are close or less than the CARB EZEV standards.
6. When operated in the charge depleting mode (batteries recharged from the wall-plug), hybrid vehicles with a 50 mile or greater all-electric range have total full fuel cycle emissions close to that of an electric vehicle for the baseline use-pattern (10,000 miles per year).
7. The total CO2 emissions on the FUDS/Highway driving cycle (charge sustaining operation) of a parallel hybrid vehicle are 12-15% lower than that of a series hybrid vehicle using the same port

injected gasoline engine. The difference in the CO2 emissions of the series and parallel hybrid vehicles is only 2-3% using a swirl chamber diesel engine.

8. It would be technically more rational to regulate emissions and the CAFE standards for light-duty vehicles in terms of total full fuel cycle emissions for NMOG, CO, NOx, and CO2 rather than regulate exhaust emissions and miles per gallon (mpg) as is current practice. This approach would place ICE, electric, and hybrid vehicles using various fuels on an equal footing.

9. Given continued rapid improvements in ICE vehicle emissions, the introduction into the market of advanced hybrid vehicles, including fuel cell powered vehicles, will be driven by CAFE or other vehicle efficiency and/or greenhouse gas standards and not by regulated emission standards even if those standards are for total full fuel cycle emissions.

References

1. Greene, D.L. and Santini, D.J., Transportation and Global Climate Change, published by the American Council for an Energy-Efficient Economy, Washington, D.C., 1992
2. Sperling, D. and Shaheen, S., Transportation and Energy, published by the American Council for an Energy-Efficient Economy, Washington, D.C., 1995
3. Choosing an Alternative Transportation Fuel (Air Pollution and Greenhouse Gas Impacts), Organization for Economic Co-Operation and Development, Paris, 1993
4. Deluchi, M.A., Emissions of Greenhouse Gases from the Use of Transportation and Electricity Volume 1 and Appendices), Argonne National Laboratory Report ANL/ESD/TM-22, November 1991
5. Cole, G.H., SIMPLEV: A Simple Electric Vehicle Simulation Program - Version 1.0, Idaho National Engineering Laboratory Report DOE/ID-1023, June 1991
6. Cole, G.H., SIMPLEV: A Simple Electric Vehicle Simulation Program - Version 2.0 (Hybrid Vehicles), Idaho National Engineering Laboratory Report DOE/ID-10293-2, April 1993
7. Friedman, D., Currier, B., Burke, A.F., Development and Validation of the AVTE (Advanced Vehicle Technology Evaluation) Simulation Program at UC Davis (A User's Manual), ITS-Davis Report written for the National Renewable Energy Laboratory, January 1997
8. Kalberlah, A., Electric Hybrid Drive Systems for Passenger Cars and Taxis, SAE Paper 910247, February 1991
9. Burke, A.F., Hybrid Vehicles, Chapter in the "Encyclopedia of Energy technology and the Environment", pg 1709-1724, John Wiley and Sons, 1995
10. Proposed Amendments to the Low-Emission Vehicle Regulations to Add an Equivalent Zero-Emissions Vehicle Standard, California Air Resources Board Staff Report (draft), June 11, 1996
11. Mc Cosh, D., 70 mpg Hybrids, Popular Science, July 1997, pg 66-69
12. Bentley, J.M., etals, The Impact of Electric Vehicles on CO2 Emissions, Idaho National Engineering Laboratory Report EGG-EP-10296, May 1992
13. Burke, A.F., Hybrid/Electric Vehicle Design Options and Evaluations, SAE Paper 920447, February 1992
14. Burke, A.F., On-off Engine Operation for Hybrid/Electric Vehicles, SAE Paper 930042, February 1993
15. Craig, P., The Capstone Turbogenerator as an Alternative Power Source, SAE Paper 970292, February 1997
16. Nakazawa, N, etals, Status of the Automotive Ceramic Gas Turbine Development Programs - Seven Years Progress, Paper 97-GT-383, paper presented at the ASME Internationa Gas Turbine & Aeroengine Congress, Orlando, Florida, June 1997
17. Dowdy, M., etals, Automotive Technology Status and Projections (Volume II, Assessment Report), JPL Publication 78-71, July 1978
18. Johansson, L. and Rose, T., A Stirling Power Unit for Series Hybrid Vehicles, Stirling

Thermal Motors, Poster at the 1997 Customer Co-ordination Meeting, Detroit, Michigan, October 1997
19. Schaefer, F. and Van Basshuysen, R., Reduced Emissions and Fuel Consumption in Automotive Engines, Springer-Verlag and SAE International, 1995
20. Klaiber, T., Fuel Cells for Transport: Can the Promise be fulfilled? Technical Requirements and Demands from Customers, Journal of Power Sources, Volume 61, pp 61-69, 1996
21. Research and Development of Proton-Exchange-Membrane (PEM) Fuel Cell Systems for Transportation Applications, U.S. Department of Energy Report DOE/CH/10435-03, Allison Gas Turbine Division, General Motors Corp., November 1996
22. Prater,K. B., Solid Polymer Fuel Cells for Transport and Stationary Applications, Journal of Power Sources, Vol. 61, Pg 105-109, 1996
23. Howard, P.F., Ballard Zero-Emission Fuel Cell Engine, paper presented at the Intertech conference on Commercializing Fuel Cell Vehicles, Chicago, Ill. September 1996
24. Wimmer, R., Fuel Cell Bus Testing and Development at Georgetown University, Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Paper 97156, August 1997
25. Ahmed, S., etals, Partial Oxidation Reformer Development for Fuel Cell Vehicles, Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Paper 97081, August 1997
26. Peppley, B.A., etals, Hydrogen Generation for Fuel Cell Power Systems by High-Pressure Catalytic Methanol Steam Reforming, Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Paper 97093, August 1997
27. Froment, G.F. and Bischoff, K.B., Chemical Reactor Analysis and Design, pg 482-489, Wiley Series in Chemical Engineering, John Wiley & Sons,1990
28. Landgrebe, A.R., Sen, K.R., and Wheeler, D.J., Proceedings of the Workshop on Direct Methanol-Air Fuel Cells, Electrochemical Society Publication Volume 92-14, 1992
29. Halpert, G., etals, Progress with the Direct Methanol Liquid-Feed Fuel Cell System, Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Paper 97447, August 1997
30. Lipman, T.E. and DeLucchi, M.A., Hydrogen-Fueled Vehicles, International Journal of Vehicle Design, Vol. 17, Nos 5 and 6 (Special Issue), pg 562-586, 1996
31. Ogden, J., etals, Hydrogen Energy System Studies, Final Report to the National Renewable Energy Laboratory under Contract Xr-11265-2 (Princeton University), January 1995
32. Swan, D., Dickson, B., and Arikara, L., Proton Exchange Membrane Fuel Cell Characterization for Electric Vehicle Applications, SAE Paper No. 940296, 1994
33. Post, R.F., Bender, D.A., and Merritt, B.T., Electromechanical Battery Program at the Lawrence Livermore National Laboratory, UCRL-JC-117506, paper presented at the 29th Intersociety Energy Conversion Engineering Conference, Monterey, California, August 1994
34. Smith, R., Model and Characteristics of the Lawrence Livermore Electromechanical Battery System, private communication, August 1997
35. Miller, J.R. and Burke, A.F., Electric Vehicle Capacitor Test Procedures Manual , Idaho National Engineering Laboratory Report DOE/ID-10491, October 1994

36. Plotkin, S. and Duleep, K.G., Advanced Automotive Technology (Visions of a Super-efficient Family Car), Office of Technology Assessment, 1996
37. Moore, T.C. and Lovins, A.B., Vehicle Design Strategies to Meet and Exceed PNGV Goals, SAE Paper No. 951906, August 1995
38. Burke, A.F., Electric/Hybrid Super Car Designs using Ultracapacitors, Proceedings of the 30th Intersociety Energy Conversion Engineering Conference, Orlando, Florida, August 1995
39. Burke, A.F., Dynamometer and Road Testing of Advanced Electric Vehicles and Projections of Future Range Capability, Proceedings of the 12th International Electric Vehicle Symposium, Anaheim, California, December 1994
40. Burke, A.F. and MacDowall, R.d., The Performance of Advanced Vans - Test and Simulation, Proceedings of the 11th International Electric Vehicle Symposium, Florence, Italy, 1992
41.Kramer, W.E., Burke, A.F., and MacDowall, R.D., Performance Testing of the AC Propulsion ELX Electric Vehicle, Idaho National Engineering Laboratory, EG&G Report No. EP-11320, 1994
42. Friedman, D., Currier, B., and Burke, A.F., Development and Validation of the Advanced Vehicle Technology Evaluator (AVTE) Vehicle Simulation Program at UC Davis (A User's Manual), an ITS-Davis Report, January 1997
43. Friedman, D., etals, Testing and Simulation of the UC Davis Hybrid Electric Vehicle - AfterShock, ITS-Davis Report, work performed for NREL under Contract XCB-5-15295-01, November 1997
44. Effa, R.C. and Larsen, L.C., Development of Real-World Driving Cycles for Estimating Facility-Specific Emissions of Light Duty Vehicles, California Air Resources Board, paper presented at the Air and Waste Management Association, Specialty Conference on the Emissions Inventory, Pasadena, California, October 1993
45. Gammariello, R.T. and Long, J.R., An Emissions Comparison between the Unified Cycle and the Federal Test Procedure, California Air Resources Board, paper presented at the Air and Waste Management Association, Specialty Conference on Emissions Inventory, Pasadena, California, October 1993
46. Velocity Schedule for Various Arterial and Freeway Driving Cycles (computer files), private communication from L.C. Larsen, California Air Resources Board, 1996
47. Honda Multi Matic, Technical Description of the System and its Operation, Honda, 1997
48. Fuel Economy Guide - Model Year 1997, United States Department of Energy Publication, October 1996
49. Ochoa, D. and Jones, L., 1991 Statewide Travel Survey - Final Report, State of California, Department of Transportation, December 1993
50. Magbuhat, S. and Long, J., Improving California's Motor Vehicle Emissions Inventory Activity Estimates Through the Use of Datalogger-equipped Vehicles, California Air Resources Board, paper presented at the 6th CRC On-Road Vehicle Emissions Workshop, San Diego, March 1996

51. Davis, S.C., Transportation Energy Databook - Edition 17, United States Department of Energy Report ORNL-6919, August 1997

52. 1990 Nationwide Personal Transportation Survey, Federal Highway Administration, March 1992

53. Schwartz, H.J., The Computer Simulation of Automobile Use Patterns for Defining Battery Requirements for Electric Vehicles, NASA TMX-71900, September 1976

54. Burke, A.F. and Smith, G.E., Impact of Use-Pattern on the Sesign of Electric and Hybrid Vehicles, SAE Paper No. 810265, February 1981

55. Goodwin, R.W. and Ross, M., Off-Cycle Emissions from Modern Passenger Cars with Properly-functioning Emissions Controls, SAE Paper No. 960064, February 1996

56. Barth, M., An, T., Norbeck, J., and Ross, M., Modal Emissions Modeling,: A Physical Approach, 75th Annual Meeting of the Transportation Research Board, Paper No. 960905 (Record 1520), Washington, D.C., 1996

57. An, F., Scora, G., Barth, M., and Norbeck, J., Characterization and Modeling of Vehicle Lean-Burn Hydrocarbon Emissions, 7th CRC On-Road Vehicle Emissions Workshop, San Diego, April 1997

58. An, F. and Ross, M., A Model of Fuel Economy and Driving Patterns, SAE Paper No. 930328, March 1993

59. An, F., Barth, M., and Scora, G., Impacts of Diverse Driving Cycles on Electric and hybrid Electric Vehicle Performance, SAE Paper No. 972646, August 1997

60. Darrow, K.G., Light Duty Vehicle Full Fuel Cycle Emissions Analysis, prepared for the Gas Research Institute, Report No. GRI-93/0472, April 1994

61. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis (Volume 1 - Main Report, Volume 2-Appendices), Acurex Environmental Final Report FR-96-114, September 1996

62. Mark, J., Ohi, J.M., and Hudson, D.V., Fuel Savings and Emissions Reductions from Light Duty Fuel Cell Vehicles, National Renewable Energy Laboratory Report No. NREL/TP-463-6157, April 1994

63. Powerplant Emissions for California, Summary of data from the California Energy Commission staff on powerplant emissions related to electric vehicle battery recharging.

64. Suga, T., Knight, B., and Aral, S., Near-Zero Emissions Natural Gas Vehicle, Honda Civic GX, SAE Paper 972643, August 1997

65. Cackette, T., Opportunities for Mobile Source Emission Reductions, California Air Resources Board, presentation at the Symposium on Exploring New Technologies for Clean Air, Irvine, California, September 29, 1997

66. DeCicco, J.M., Geller, H.S., and Morrill, J., Feebates for Fuel Economy: Market Incentives for Encouraging Production and Sales of Efficient Vehicles, report prepared by the American Council for an Energy-Efficient Economy, Washington, D.C., May 1993

67. DeCicco, J. and deLaski, A., The Green Machine Challenge: A Concept for Promoting Ultra-Efficient Vehicles, American Council for an Energy-Efficient Economy, March 1997

68. DeCicco, J., Developing a Market Creation Program to Promote Efficient Cars and Light Trucks, American Council for an Energy-Efficient Economy, Washington, D.C., August 1997
69. Greene, D.L., Why Cafe Worked, paper presented at the Conference for Fostering Sustainable Transportation Technologies, Monterey, California, August 1997
70. Kirby, etals, An Evaluation of the Effectiveness of the U.S. CAFE Policy, Energy Policy, Volume 1, No.2, pp 107-109, 1995
71. "Honda Develops World's Cleanest Petrol Engine", Press release from Honda on the ZLEV engine, October 20, 1997

Table 1: Carbon dioxide emission (gm/mi) for various fuels for vehicles having an equivalent gasoline fuel economy of 27.5 mpg

Fuel	$\frac{gmCO_2}{mi}$
Gasoline	308
Diesel	321
Natural gas	268
Methanol	265
Hydrogen	
from Natural Gas	419
from Biomass	193
from Solar	71

Table 2: Carbon Dioxide Emissions $\left(\frac{gm}{mi}\right)$ for Vehicle Electricity Usage for Various Powerplant Fuel/Technologies

Fuel/Technology	Powerplant Efficiency (%)	FF	$\left(\frac{KJ}{gm}\right)$ Fuel	$\left(\frac{gmCO_2}{kwh}\right)_{pp}$	$\left(\frac{gmCO_2}{mi}\right)$
Coal Steam	33	3.06	33.2	100 5	314
Oil Steam	33	3.12	42.5	801	250
Gas Steam	33	2.75	45	666	208
Advanced Gas Tech.	47	2.75	45	468	146
National Average (1992)				696	217

Electricity Distribution: efficiency = .95

Vehicle parameters: .200 $\frac{kwh}{mi}$ at battery

Battery efficiency = .75, charger efficiency = .9

Table 3a: Relative Rankings of Engines for Hybrid Vehicles

	Packaging			Emissions					
Engine Type	**Weight**	**Volume**	**Efficiency**	**HC/CO**	**NOX**	**Particulate**	**Cost**	**Operat. Mode**	**Develop. Status**
Spark Ignition									
Valve Injection	3	3	3	3	3	1	1	O/F	CR
Direct Injection	3	3	2	2	3	1	2	O/F	MT
Rotary	2	2	4	4	2	1	3	O/F	CR
Two-Stroke	1	1	3	4	2	4	3	O/F	CR
Diesel									
Prechamber/turbo	4	4	2	1	1	5	4	O/F	MT
Direct Injection/turbo	4	4	1	2	3	4	4	O/F	MT
Gas Turbine									
Metal									
W/O recup	2	2	4	1	2	1	3	Std.	CR
With recup.	3	3	3	1	2	1	4	Std.	MT
Ceramic									
With recup.	2	2	2	1	2	1	4	Std.	FT
Stirling									
H_e working fluid	4	4	2	1	1	1	4	Std.	MT
H_2 working fluid	4	4	1	1	1	1	5	Std.	MT

Rating: 1 - high . . . . . 5 - low
Development Status: CR - Currently Ready, mT - Medium Term, FT - Far Term
Operating Mode: O/F - on/off, Std - Steady (continuous)

Table 3b: Engine Characteristics for Hybrid Vehicles

				Emissions (gm/kWh) (Nominal)			
Engine Type	kg/kW	l/kW	Maximum Efficiency (%)	HC	CO	NOX	Manufacturer/Developer
Spark Ignition							
Valve Injection	2.0	4.0	32	3.0	20	8.0	Auto Companies
Direct Injection	2.5	4.1	38	5.0	4.0	3.5	Auto Companies
Rotary	.8	1.0	30	3.0	4.0	5.0	Moller International
Two-Stroke	1.0	1.75	30	3.0	3.0	6.0	Orbital
Diesel							
Prechamber/Turbo	2.6	4.2	35	.1	1.0	3.0	Auto Companies
Direct Injection/Turbo	3.0	4.4	42	1.0	1.0	15.0	Auto Companies
Gas Turbine							
Metal							
With Recup.	2.5	5.3	30	.08	.30	.03	Capstone
Incl. generator				(catalytic combustion)			
Ceramic							
with Recup.	2.0	4.0	40	.08	.30	.03	Allison
				(catalytic combustion)			
Stirling							
H_2 Working Fluid/ Wobble Plate Drive	2.7-3	2-2.5	35-40	.01	.15	.22	Stirling Thermal Motors

Table 4: Progress in PEM Fuel Cell Stuck Weight and Volume Reduction (1990-1996)

Fuel Cell Stack Characteristic	Year of Technology*		
	1990-1	**1992-3**	**1995-6**
Output (kW)	5	13	30
Weight (kg)	40	40	32
Power Density			
kW/kg	.125	.325	.94
kW/l	.156	-	1.0
Efficiency(%)	47	-	55%

*Based on reported characteristics of Ballard fuel cell stacks.

Table 5: Greenhouse Gas Emissions From Hydrogen Production and Storage

Fuel Cycle*	**gm CO_2/gm H_2**
Natural gas/Compressed H_2	13.2
Biomass/Compressed H_2	6.1
Solar PV/Compressed H_2	2.3

*Based on Reference (30, 31)

Table 6: PEM Fuel Cell Characteristics Used in the Vehicle Simulations

Power Fraction	Stack[1] Efficiency (%)	(bsfc) Gasoline (gm/kWh)	(bsfc) H_2 (gm/kWh)	$\eta^{(2)}$System
0	64.5	127	39	0
.05	64.5	127	39	.258
.10	64.5	127	39	.387
.15	64.5	127	39	.516
.20	63.2	130	40	.569
.25	61.9	132	41	.588
.33	60.3	136	42	.558
.50	57.3	143	44	.547
.67	53.9	152	47	.516
.833	50.6	162	50	.485
1.0	44.6	184	57	.430

η_{stack} = 81.97/(bsfc)gasoline = 25.35/$(bsfc)_{H2}$

(1) Stack efficiency includes isentropic air compression with pressure and stochiometric ratio varied with power

(2) System efficiency includes air compression losses and cooling

Table 7: Pulse Power Device Characteristics

	Pulse Batteries			
Characteristic	Lead-Acid (Thin-Film)	Ni Mt Hydride (Thin-Plate)	Electrochemical Capacitors (organic-3V/cell	Composite Fly-Wheel
Energy Density				
Wh/kg	20	50	5-10	15
Wh/l	50	135	6-12	25
Fraction Energy Used	.1-.2	.1-.2	.75	.75
Power Density				
W/kg	1000	500	1000	1500
Round-trip Efficiency (%)	90	55	90	90
Life	-	-	>10 yrs.	>10 yrs.
Status of Development	Prototype Devices	Prototype Devices	Prototype Devices	Lab Testing

Table 8: Discharge Characteristics of Pulse Power Batteries

Sealed Lead-Acid (Thin-Film)

1 Cell Per Module
.083 Module Wt. (kg)
1.25 Ah Capacity
1.23 Puekert Constant
-0.025 Puekert Exponent
3 "C" Rating Time, h

0 DOD	2.08 Voc	-0.00175 Resistance (Λ)
0.1	2.075	-0.00175
0.2	2.07	-0.00175
0.3	2.057	-0.00175
0.4	2.044	-0.00175
0.5	2.022	-0.00175
0.6	2.004	-0.00175
0.7	1.981	-0.00180
0.8	1.949	-0.00190
0.9	1.913	-0.00195
1	1.884	-0.00210

1.3V Nimthyd
1 Cell Per Module
0.38 Module Wt. (kg)
15 Ah Capacity
17.1 Puekert Constant
-.08 Puekert Exponent
3 "C" Rating Time, h

0 DOD	1.400 Voc	-.0018 Resistance (Λ)
.1	1.379	-.0018
.2	1.358	-.0018
.3	1.338	-.0018
.4	1.317	-.0018
.5	1.296	-.0018
.6	1.285	-.0019
.7	1.265	-.0020
.8	1.241	-.0022
.9	1.222	-.0026
1.0	1.120	-.0030

Table 9: Discharge Characteristics of the Carbon/Organic Electrolyte Ultracapacitor

Cell Weight: .408 kg
Ah Capacity: 2.77 (3300 F)
Puekert Constant: 2.778
Puekert Constant: -.0022

DOD	VOC	R(Δ)
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	.9	.000206
.8	.6	.000206
.9	.3	.000206
1.0	.0	.000206

Table 10: Discharge Characteristics of the Lawrence Livermore Flywheel

Module Weight: 30 kg
Equivalent Ah Capacity: 10Ah (1kWh at 200V)
Puekert Constant: 10
Puekert Exponent: -.00001

DOD	(VOC) Equivalent	R(Λ)
0	200	.02125
.1	180	.02125
.2	160	.02125
.3	140	.02125
.4	120	.02125
.5	100	.02125
.6	80	.02125
.7	60	.02125

Table 11: Specific Volume and Weight Characteristics of the Motor and Electronics in an Electric Driveline

	System Rating/ Voltage	Motor		Inverter		System		
Type/Developer	kW/v	kg/kW	L/kW	kg/kW	L/kW	kg/kW	L/kW	Efficiency (%)
AC Induction/AC Propulsion	100/336	.46	.28	.32	.59	.78	.87	90/93
AC Induction/General Electric	75/336	.79	.2	.30	.51	1.09	.71	89-94
Brushless D.C. PM/Unique Mobility	60/200	.83	.30	.30	.75	1.13	1.05	85-90

Table 12: Electric Vehicle Battery Module Characteristics

Type	(Wh/kg)c/3	(Wh/l)c/3	(W/kg)80% DOD
Sealed Lead-Acid	40	85	350
Nickel Metal Hybrid	75	220	230
Lithium-ion	110	180	350

Table 13: Hybrid Vehicle and Driveline Characteristics used in the Vehicle Simulations

Vehicle Type	Test Weight (kg)	C_D	$A_f (m^2)$	Rolling Resistance	Accessory Load (W)	AC Induction Electric Drive (kW)	Regen. Breaking Ratio	Engine/ Generator (kW)
Mid-Size, 1995 Materials	1400-1580	.27	2.0	.006	250	84	.65	40
Compact-Size, Light-Weight Materials	750-850	.24	1.85	.006	200	32	.65	25

Table 14: Driving Cycle Characteristics for City and Highway Driving

Driving Cycle	Time (Sec.)	Distance (km)	V av (km/h)	V max (km/h)	α max m/sec^2
FUDS	1372	12.0	31.4	91.2	1.5
Highway	765	16.5	77.6	96.4	1.5
UC-92	1435	15.8	39.7	109.4	4.0
US-06	600	12.9	77.2	129.2	3.8
ART 14	907	5.8	23.0	70.9	1.6
ART 34	944	14.5	55.1	87.0	2.3
FW 30	909	12.7	50.4	98.2	-
FW70	1008	31.6	112.4	122.4	-

able 15: Running Emission Results for Mid-size Hybrid Vehicles using a Port Injected Gasoline Engine on Various Driving Cycles

mmary of Vehicle Results

mptions:						
l miles Driven per Year	10860					
ber of Work Days	224					1
ıd trip work dist	15					
random Driving Dist	7500		SULEV Standard			
on	LA basin		CO	1	g/ml	
orative Emissions	0	0=none, 1=present average values	NOx	0.02	g/ml	
ol Strategy	0	0 = sustaining, 1 = depleting	ROG	0.008	g/ml	
ction Criteria	n?????ch					

Running Emissions (gm/ml)

	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap)	CO2	Gal/year	kWh/year
)24CH	NIMH	Honda	ART14	24.000	0.000	24.100	0.213	0.186	0.032	0.032	0.000	342.491	450.622	0.000
)38CH	NIMH	Honda	ART14	38.000	0.000	27.300	0.188	0.117	0.030	0.030	0.000	302.346	397.802	0.000
22CH	NIMH	Honda	FW70	22.000	0.000	33.200	0.154	0.169	0.023	0.023	0.000	248.616	327.108	0.000
39CH	NIMH	Honda	FW70	39.000	0.000	33.500	0.151	0.165	0.022	0.022	0.000	246.389	324.179	0.000
)56CH	NIMH	Honda	FUD/HWY	56.000	0.000	41.500	0.124	0.109	0.018	0.018	0.000	198.893	261.687	0.000
34CH	NIMH	Honda	FUDS	34.000	0.000	36.100	0.143	0.127	0.021	0.021	0.000	228.644	300.831	0.000
55CH	NIMH	Honda	FUDS	55.000	0.000	39.500	0.129	0.071	0.021	0.021	0.000	208.963	274.937	0.000
36CH	NIMH	Honda	HWY	36.000	0.000	42.300	0.122	0.108	0.018	0.018	0.000	195.131	256.738	0.000
58CH	NIMH	Honda	HWY	58.000	0.000	45.400	0.113	0.071	0.018	0.018	0.000	181.807	239.207	0.000
)25CH	NIMH	Honda	UC-92	25.000	0.000	27.000	0.190	0.167	0.028	0.028	0.000	305.705	402.222	0.000
42CH	NIMH	Honda	UC-92	42.000	0.000	30.700	0.168	0.105	0.026	0.026	0.000	268.861	353.746	0.000
18CH	NIMH	Honda	US06	18.000	0.000	25.500	0.208	0.166	0.031	0.031	0.000	323.688	425.882	0.000
32CH	NiMH	Honda	US06	32.000	0.000	25.600	0.211	0.142	0.031	0.031	0.000	322.424	424.219	0.000

Table 16: Fuel Economy for Conventional ICE Cars (1996-97)

				Fuel Economy (mpg)	
Model	Test Weight (kg)	Engine (cyl/L/kW)	Transm.	FUDS (1)	Highway (2)
Honda Civic	1182	4/1.6/80	M5	36	49
		4/1.6/80	A4	32	45
Geo Metro	958	4/1.3/41	M5	43	55
		4/1.3/41	A3	33	44
Dodge Neon	1201	4/2.0/99	M5	32	50
		4/2.0/99	A3	28	44
Ford Aspire	1047	4/1.3/47	M5	38	54
		4/1.3/47	A3	31	40
Ford Escort	1198	4/2.0/95	M5	31	47
		4/2.0/95	A4	29	44
Honda Accord	1434	4/2.2/98	M5	28	41
		4/2.2/98	A4	26	37
Ford Taurus	1662	6/3.0/	A4	22	36
Toyota Camry	1469	4/2.2/94	M%	26	40
		4/2.2/94	A4	26	38
		6/3.0/140	A4	21	33
Chrysler Cirrus	1567	4/2.4/112	A4	22	38

(1) EPA Fuel Economy/.9

(2) EPA Fuel Economy/.78

Table 17: Comparisons of the Fuel Economy of Conventional ICE and Series Hybrid Vehicles

Vehicle[1]	Test Weight (kg)	Transm.	City[2]	Highway[2]
Mid-size				
Conventional ICE (Ford Taurus)	1668	A4	22	36
Series Hybrid (gasoline engine, charge sustaining)	1655	-	33.9	38.6
Sub-compact				
Conventional ICE (Geo. Metro)	958	A3 M5	33 43	44 55
Series Hybrid (gasoline engine, charge sustaining)	956	-	56.3	57.0

(1) Conventional and Series Hybrid Vehicles had same weight, C_DA, and fr

(2) Fuel economy of ICE Vehicles were taken from the 1997 EPA Fuel Economy Guide corrected by 10% for FUDS and 22% for highway

18: Total Full Fuel Cycle Emissions in the LA Basin of Mid-size Electric Vehicles using Various Types of Batteries on Different Driving Cycles

ry of Vehicle Results

s:						
riven per Year		10860				
ork Days		224				
ork dist		15				
n Driving Dist		7500		SULEV Standard		
		LA basin		CO	1	g/ml
Emissions		0	0=none, 1=present average values	NOx	0.02	g/ml
tegy		1	0 = sustaining, 1 = depleting	ROG	0.008	g/ml
riteria		??????cev				

Total Emissions (gm/ml)

	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
/	Li-Ion	EV	ART14	71.000	1.000	0.000	0.018	0.018	0.003	0.000	0.000	157.004	0.000	3383.053
/	Li-Ion	EV	FW70	70.000	1.000	0.000	0.016	0.015	0.003	0.000	0.000	133.343	0.000	2873.234
/	Li-Ion	EV	FUD/HWY	101.000	1.000	0.000	0.013	0.012	0.002	0.000	0.000	108.491	0.000	2337.721
/	Li-Ion	EV	FUDS	58.000	1.000	0.000	0.013	0.013	0.002	0.000	0.000	112.674	0.000	2427.857
/	Li-Ion	EV	FUDS	99.000	1.000	0.000	0.014	0.013	0.003	0.000	0.000	115.991	0.000	2499.328
/	Li-Ion	EV	FUDS	152.000	1.000	0.000	0.014	0.014	0.003	0.000	0.000	121.274	0.000	2613.169
/	Li-Ion	EV	US06	57.000	1.000	0.000	0.018	0.017	0.003	0.000	0.000	149.675	0.000	3225.135
/	NIMH	EV	ART14	64.000	1.000	0.000	0.032	0.032	0.006	0.000	0.000	275.156	0.000	5928.954
/	NIMH	EV	ART34	83.000	1.000	0.000	0.025	0.025	0.005	0.000	0.000	217.481	0.000	4686.200
/	NIMH	EV	FW31	90.000	1.000	0.000	0.025	0.024	0.005	0.000	0.000	209.675	0.000	4517.989
/	NIMH	EV	FW70	66.000	1.000	0.000	0.027	0.028	0.005	0.000	0.000	230.240	0.000	4961.127
V	NIMH	EV	FUD/HWY	94.000	1.000	0.000	0.025	0.024	0.005	0.000	0.000	209.996	0.000	4524.906
V	NIMH	EV	FUDS.	36.000	1.000	0.000	0.018	0.018	0.003	0.000	0.000	154.995	0.000	3339.780
V	NIMH	EV	FUDS	57.000	1.000	0.000	0.022	0.021	0.004	0.000	0.000	185.346	0.000	3993.755
V	NIMH	EV	FUDS	89.000	1.000	0.000	0.026	0.026	0.005	0.000	0.000	221.767	0.000	4778.555
:V	NIMH	EV	UC-92	71.000	1.000	0.000	0.027	0.027	0.005	0.000	0.000	233.521	0.000	5031.811
:V	NIMH	EV	US06	57.000	1.000	0.000	0.029	0.028	0.005	0.000	0.000	247.436	0.000	5331.663
V	Pb-acid	EV	ART14	42.000	1.000	0.000	0.024	0.023	0.004	0.000	0.000	203.174	0.000	4377.907
V	Pb-acid	EV	FW70	42.000	1.000	0.000	0.020	0.019	0.004	0.000	0.000	167.777	0.000	3615.205
V	Pb-acid	EV	FUD/HWY	60.000	1.000	0.000	0.017	0.017	0.003	0.000	0.000	148.293	0.000	3195.364
V	Pb-acid	EV	FUDS	40.000	1.000	0.000	0.017	0.016	0.003	0.000	0.000	141.867	0.000	3056.897
V	Pb-acid	EV	FUDS	59.000	1.000	0.000	0.019	0.018	0.003	0.000	0.000	159.838	0.000	3444.127
V	Pb-acid	EV	FUDS	104.000	1.000	0.000	0.024	0.024	0.005	0.000	0.000	208.091	0.000	4483.867
V	Pb-acid	EV	HWY	60.000	1.000	0.000	0.017	0.016	0.003	0.000	0.000	142.178	0.000	3063.597
V	Pb-acid	EV	US06	38.000	1.000	0.000	0.022	0.021	0.004	0.000	0.000	186.773	0.000	4024.504

able 19: Running Emissions Results for Compact, Light-weight Hybrid Vehicles using a Port Injected Gasoline Engine on Various Driving Cycles

mmary of Vehicle Results

mptions:					
l miles Driven per Year	10860		1		
nber of Work Days	224				
nd trip work dist	15				
l random Driving Dist	7500		SULEV Standard		
ion	LA basin		CO	1	g/ml
porative Emissions	0	0=none, 1=present average values	NOx	0.02	g/ml
trol Strategy	0	0 = sustaining, 1 = depleting	ROG	0.008	g/ml
ction Criteria	n?????ah				

Running Emissions (gm/mi)

	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
022AH	NIMH	Honda	ART14	22.000	0.000	48.500	0.151	0.055	0.025	0.025	0.000	170.186	223.918	0.000
049AH	NIMH	Honda	ART14	48.500	0.000	58.400	0.127	0.061	0.020	0.020	0.000	141.336	185.959	0.000
025AH	NIMH	Honda	FW31	25.300	0.000	65.700	0.110	0.042	0.019	0.019	0.000	125.632	165.297	0.000
061AH	NIMH	Honda	FW31	60.500	0.000	69.600	0.106	0.040	0.017	0.017	0.000	118.593	156.034	0.000
028AH	NIMH	Honda	FUD/HWY	27.500	0.000	69.500	0.106	0.040	0.018	0.018	0.000	118.763	156.259	0.000
062AH	NIMH	Honda	FUD/HWY	62.000	0.000	72.200	0.102	0.038	0.017	0.017	0.000	114.322	150.416	0.000
030AH	NIMH	Honda	FUDS	29.800	0.000	69.600	0.105	0.039	0.017	0.017	0.000	118.593	156.034	0.000
065AH	NIMH	Honda	FUDS	64.500	0.000	74.900	0.099	0.047	0.015	0.015	0.000	110.201	144.993	0.000
027AH	NIMH	Honda	HWY	27.000	0.000	71.400	0.103	0.039	0.017	0.017	0.000	115.603	152.101	0.000
060AH	NIMH	Honda	HWY	60.200	0.000	74.100	0.100	0.048	0.016	0.016	0.000	111.391	146.559	0.000
021AH	NIMH	Honda	UC-92	20.500	0.000	50.100	0.146	0.055	0.024	0.024	0.000	164.751	216.766	0.000
049AH	NIMH	Honda	UC-92	49.200	0.000	56.200	0.132	0.063	0.021	0.021	0.000	146.869	193.238	0.000

e 20: Total Full Fuel Cycle Emissions in the LA Basin of Compact, Light-weight Electric Vehicles using Various Types of Batteries on Different Driving Cycles

nary of Vehicle Results

ions:					
s Driven per Year	10860				1
of Work Days	224				
p work dist	15				
dom Driving Dist	7500		SULEV Standard		
	LA basin		CO	1	g/mi
ive Emissions	0	0=none, 1=present average values	NOx	0.02	g/mi
trategy	1	0 = sustaining, 1 = depleting	ROG	0.008	g/mi
n Criteria	??????aev				

Total Emissions (gm/mi)

	Battery	Engine	Drive Cycl	Elec Rang	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
EV	Li-Ion	EV	ART14	47.000	1.000	0.000	0.010	0.010	0.002	0.000	0.000	83.404	0.000	1797.167
EV	Li-Ion	EV	ART14	84.000	1.000	0.000	0.010	0.010	0.002	0.000	0.000	87.135	0.000	1877.555
EV	Li-Ion	EV	ART14	123.000	1.000	0.000	0.011	0.011	0.002	0.000	0.000	92.359	0.000	1990.115
EV	Li-Ion	EV	FW31	56.000	1.000	0.000	0.008	0.008	0.001	0.000	0.000	65.312	0.000	1407.316
EV	Li-Ion	EV	FW31	102.000	1.000	0.000	0.008	0.008	0.001	0.000	0.000	67.519	0.000	1454.872
EV	Li-Ion	EV	FW31	156.000	1.000	0.000	0.008	0.008	0.002	0.000	0.000	70.459	0.000	1518.215
AEV	Li-Ion	EV	FUD/HWY	56.000	1.000	0.000	0.008	0.008	0.001	0.000	0.000	67.624	0.000	1457.132
AEV	Li-Ion	EV	FUD/HWY	100.000	1.000	0.000	0.008	0.008	0.002	0.000	0.000	69.249	0.000	1492.149
AEV	Li-Ion	EV	FUD/HWY	154.000	1.000	0.000	0.008	0.008	0.002	0.000	0.000	71.612	0.000	1543.059
AEV	Li-Ion	EV	FUDS	62.000	1.000	0.000	0.008	0.008	0.001	0.000	0.000	65.842	0.000	1418.728
AEV	Li-Ion	EV	FUDS	108.000	1.000	0.000	0.008	0.008	0.001	0.000	0.000	68.101	0.000	1467.405
AEV	Li-Ion	EV	FUDS	165.000	1.000	0.000	0.008	0.008	0.002	0.000	0.000	71.623	0.000	1543.301
AEV	NiMH	EV	ART14	52.000	1.000	0.000	0.016	0.016	0.003	0.000	0.000	136.636	0.000	2944.174
AEV	NiMH	EV	ART14	77.000	1.000	0.000	0.019	0.019	0.004	0.000	0.000	163.930	0.000	3532.305
AEV	NiMH	EV	ART14	100.000	1.000	0.000	0.022	0.021	0.004	0.000	0.000	186.066	0.000	4009.290
AEV	NiMH	EV	FW31	64.000	1.000	0.000	0.013	0.013	0.002	0.000	0.000	113.526	0.000	2446.212
AEV	NiMH	EV	FW31	99.000	1.000	0.000	0.016	0.015	0.003	0.000	0.000	134.276	0.000	2893.319
AEV	NiMH	EV	FW31	129.000	1.000	0.000	0.017	0.017	0.003	0.000	0.000	148.875	0.000	3207.902
AEV	NiMH	EV	FUD/HWY	64.000	1.000	0.000	0.014	0.013	0.003	0.000	0.000	116.412	0.000	2508.403
AEV	NiMH	EV	FUD/HWY	98.000	1.000	0.000	0.016	0.016	0.003	0.000	0.000	136.099	0.000	2932.620
AEV	NiMH	EV	FUD/HWY	130.000	1.000	0.000	0.018	0.017	0.003	0.000	0.000	150.292	0.000	3238.443
AEV	NiMH	EV	FUDS	68.000	1.000	0.000	0.014	0.013	0.003	0.000	0.000	116.689	0.000	2514.366
AEV	NiMH	EV	FUDS	102.000	1.000	0.000	0.016	0.016	0.003	0.000	0.000	135.309	0.000	2915.587
AEV	NiMH	EV	FUDS	134.000	1.000	0.000	0.018	0.018	0.003	0.000	0.000	153.627	0.000	3310.303
AEV	Pb-acid	EV	ART14	33.000	1.000	0.000	0.012	0.012	0.002	0.000	0.000	103.992	0.000	2240.773
AEV	Pb-acid	EV	ART14	46.000	1.000	0.000	0.013	0.013	0.002	0.000	0.000	114.435	0.000	2465.793
AEV	Pb-acid	EV	ART14	66.000	1.000	0.000	0.016	0.015	0.003	0.000	0.000	133.271	0.000	2871.670
AEV	Pb-acid	EV	FW31	40.000	1.000	0.000	0.010	0.010	0.002	0.000	0.000	82.873	0.000	1785.712
AEV	Pb-acid	EV	FW31	57.000	1.000	0.000	0.011	0.011	0.002	0.000	0.000	92.063	0.000	1983.731
AEV	Pb-acid	EV	FW31	82.000	1.000	0.000	0.013	0.012	0.002	0.000	0.000	106.798	0.000	2301.244

ble 20 (cont.)

0AEV	Pb-acid	EV	FUD/HWY	40.000	1.000	0.000	0.010	0.010	0.002	0.000	0.000	84.980	0.000	1831.111	
7AEV	Pb-acid	EV	FUD/HWY	57.000	1.000	0.000	0.011	0.011	0.002	0.000	0.000	93.572	0.000	2016.252	
2AEV	Pb-acid	EV	FUD/HWY	82.000	1.000	0.000	0.013	0.012	0.002	0.000	0.000	107.632	0.000	2319.222	
3AEV	Pb-acid	EV	FUDS	43.000	1.000	0.000	0.010	0.010	0.002	0.000	0.000	84.585	0.000	1822.616	
1AEV	Pb-acid	EV	FUDS	61.000	1.000	0.000	0.011	0.011	0.002	0.000	0.000	95.190	0.000	2051.123	
7AEV	Pb-acid	EV	FUDS	87.000	1.000	0.000	0.013	0.013	0.002	0.000	0.000	111.262	0.000	2397.428	

Table 21: Comparisons of Fuel Economy for Series and Parallel Hybrid Vehicles - AVTE Results

	Fuel Economy (mpg) Gasoline Engine		Fuel Economy (mpg) Swirl Chamber Diesel[1]	
Vehicle	**FUDS**	**Highway**	**FUDS**	**Highway**
Small, light-weight				
Series Hybrid Charge sustaining	62.4	71.1	75.7	85.2
Parallel Hybrid Charge Sustaining	68.2	79.5	75.9	88.8
Charge Depleting gasoline alone	90.1	86.1	95.6	94.0
including pp	71.1	80.5	75.8	88.1
Mid-size (1995 materials)				
Series Hybrid Charge sustaining	39.2	48.2	47.9	58.5
Parallel Hybrid Charge Sustaining	42.8	54.1	48.0	60.6
Charge Depleting gasoline alone	55.3	56.6	59.0	62.3
including pp	45.4	54.7	49.1	60.6

(1) Fuel economy shown for diesel engines is gasoline equivalent

Table 22: Comparison of the Fuel Economy of Series Hybrid Vehicles using Nickel Metal Hybrid Batteries and Ultracapacitors - SIMPLEV Results

	Fuel Economy (mpg) Gasoline Engine		Fuel Economy (mpg) Swirl Chamber Diesel[1]	
Vehicle	**FUDS**	**Highway**	**FUDS**	**Highway**
Small, lightweight				
15 Ah, Ni. Mt. Hy. Bat.	69.6	71.4	86.2	84.1
330 Wh Ultracapacitor	81.4	75.1	96.3	91.2
Mid-size (1995 Materials)				
32 Ah, Ni. Mt. Hy. Bat.	36.1	42.3	43.5	49.8
660 Wh Ultracapacitor	44.3	47.3	54.6	57.6

(1) Fuel economy shown for the diesel engine is gasoline equivalent

Table 23: Use-Pattern Statistics for Various Annual Random Travel Mileages and Round-trip Work Travel Distances

Miles/year			6540	Calculated
Average miles/day			17.91781	Calculated
Number of Work Days			224	Input
Round trip work distance			10	Input
Total random distance			4300	Input
				Work
Electric Range		Hybrid	Electric	Miles
0		6540	0	
2		6092	448	2240
4		5644	896	2240
6		5196	1344	2240
8		4748	1792	2240
10		4300	2240	2240
12		3662.521	2877.479	2240
14		3071.409	3468.591	2240
16		2591.315	3948.685	2240
18		2170.931	4369.069	2240
20		1795.963	4744.037	2240
22		1457.803	5082.197	2240
24		1150.586	5389.414	2240
26		869.9901	5670.01	2240
28		612.6568	5927.343	2240
30		375.8705	6164.13	2240
32		157.3698	6382.63	2240
34		0	6540	2240
36		0	6540	2240
38		0	6540	2240
40		0	6540	2240

Miles/year			10860	Calculated
Average miles/day			29.75342	Calculated
Number of Work Days			224	Input
Round trip work distance			15	Input
Total random distance			7500	Input
				Work
Electric Range		Hybrid	Electric	Miles
0		10860	0	
2		10412	448	3360
4		9964	896	3360
6		9516	1344	3360
8		9068	1792	3360
10		8620	2240	3360
12		8172	2688	3360
14		7724	3136	3360
16		7159.4	3700.6	3360
18		6541.932	4318.068	3360
20		5911.294	4948.706	3360
22		5341.472	5518.528	3360
24		4822.021	6037.979	3360
26		4344.88	6515.12	3360
28		3904.693	6955.307	3360
30		3497.526	7362.474	3360
32		3120.291	7739.709	3360
34		2770.453	8089.547	3360
36		2445.854	8414.146	3360
38		2144.609	8715.391	3360
40		1865.042	8994.958	3360
42		1605.637	9254.363	3360
44		1365.004	9494.996	3360
46		1141.862	9718.138	3360
48		935.0158	9924.984	3360
50		743.3445	10116.66	3360
52		565.7932	10294.21	3360
54		401.3639	10458.64	3360
56		249.1092	10610.89	3360
58		108.1275	10751.87	3360
60		0	10860	3360
62		0	10860	3360
64		0	10860	3360
66		0	10860	3360
68		0	10860	3360
70		0	10860	3360

Miles/year			16000	Calculated
Average miles/day			43.83562	Calculated
Number of Work Days			224	Input
Round trip work distance			25	Input
Total random distance			10400	Input
				Work
Electric Range		Hybrid	Electric	Miles
0		16000	0	
2		15552	448	5600
4		15104	896	5600
6		14656	1344	5600
8		14208	1792	5600
10		13760	2240	5600
12		13312	2688	5600
14		12864	3136	5600
16		12416	3584	5600
18		11968	4032	5600
20		11520	4480	5600
22		11072	4928	5600
24		10624	5376	5600
26		10043.29	5956.712	5600
28		9370.327	6629.673	5600
30		8699.354	7300.646	5600
32		8054.421	7945.579	5600
34		7439.206	8560.794	5600
36		6853.655	9146.345	5600
38		6297.213	9702.787	5600
40		5769.073	10230.93	5600
42		5268.296	10731.7	5600
44		4793.87	11206.13	5600
46		4344.746	11655.25	5600
48		3919.856	12080.14	5600
50		3518.128	12481.87	5600
52		3138.495	12861.5	5600
54		2779.903	13220.1	5600
56		2441.314	13558.69	5600
58		2121.709	13878.29	5600
60		1820.091	14179.91	5600
62		1535.489	14464.51	5600
64		1266.959	14733.04	5600
66		1013.58	14986.42	5600
68		774.4638	15225.54	5600
70		548.7492	15451.25	5600
72		335.6052	15664.39	5600
74		134.2309	15865.77	5600
76		0	16000	5600
78		0	16000	5600
80		0	16000	5600

Table 24: Vehicle Powertrain Component and Driving Cycle Designation Nomenclature

Type Description	
First Position - Power source	
C	Capacitor
G	Gasoline Conventional Vehicle
L	Lithium Ion
N	Nickel Metal Hydride
P	Pb acid
Second and Third Position - Drive cycle	
FU	FUDS
HY	Highway
FH	FUDS/HWY
LA	LA92
UC	UC-92
US	US06
A1	ART14
A3	ART34
F3	FW31
F7	FW70
Fourth through Sixth Position - All electric range	
Number	Range in all electric mode (to 75% DOD)
Seventh Position - Vehicle body type	
A	Advanced
C	Conventional
Eighth and (Ninth) Position - Special details	
D	Diesel
DD	DI Diesel
DR	DI RFG
EV	EV
FC	Fuel Cell
H	Honda
S	Stirling
UL	ULEV

ble 25: Running Emission Results for Mid-size Hybrid Vehicles using Direct Injection Gasoline and Diesel Engines on Various Driving Cycles in the Charge Sustaining Mode

mmary of Vehicle Results

mptions:					
l miles Driven per Year	10860				
ber of Work Days	224				1
nd trip work dist	15				
l random Driving Dist	7500		SULEV Standard		
on	LA basin		CO	1	g/mi
orative Emissions	0	0=none, 1=present average values	NOx	0.02	g/mi
rol Strategy	0	0 = sustaining, 1 = depleting	ROG	0.008	g/mi
ction Criteria	n?????cd?				

Running Emissions (gm/mi)

	Battery	Engine	Drive Cycle	Elec Rang	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
023CD	NiMH	Diesel	ART14	23.000	0.000	31.300	0.049	0.587	0.003	0.003	0.000	322.142	346.965	0.000
041CD	NiMH	Diesel	ART14	41.000	0.000	34.600	0.044	0.532	0.003	0.003	0.000	291.417	313.873	0.000
041CDD	NiMH	DI Diesel	ART14	41.000	0.000	42.700	0.041	2.650	0.046	0.046	0.000	236.137	254.333	0.000
032CD	NiMH	Diesel	FW31	32.000	0.000	48.600	0.031	0.367	0.002	0.002	0.000	207.470	223.457	0.000
054CD	NiMH	Diesel	FW31	54.000	0.000	50.200	0.030	0.361	0.002	0.002	0.000	200.857	216.335	0.000
054CDD	NiMH	DI Diesel	FW31	54.000	0.000	62.100	0.028	1.830	0.030	0.030	0.000	162.368	174.879	0.000
021CD	NiMH	Diesel	FW70	21.000	0.000	43.900	0.030	0.311	0.001	0.001	0.000	229.682	247.380	0.000
036CD	NiMH	Diesel	FW70	36.000	0.000	46.100	0.029	0.312	0.001	0.001	0.000	218.721	235.575	0.000
033CDD	NiMH	DI Diesel	FUD/HWY	33.000	0.000	70.200	0.025	1.620	0.026	0.026	0.000	143.633	154.701	0.000
034CD	NiMH	Diesel	FUD/HWY	34.000	0.000	51.200	0.030	0.358	0.002	0.002	0.000	196.934	212.109	0.000
059CD	NiMH	Diesel	FUD/HWY	59.000	0.000	55.000	0.028	0.332	0.002	0.002	0.000	183.328	197.455	0.000
059CDD	NiMH	DI Diesel	FUD/HWY	59.000	0.000	66.300	0.026	1.710	0.029	0.029	0.000	152.082	163.801	0.000
061CDR	NiMH	DI RFG	FUD/HWY	61.000	0.000	51.600	0.014	0.033	0.023	0.023	0.000	159.962	210.465	0.000
030CDD	NiMH	DI Diesel	FUDS	30.000	0.000	60.500	0.029	1.880	0.031	0.031	0.000	166.662	179.504	0.000
033CD	NiMH	Diesel	FUDS	33.000	0.000	49.700	0.031	0.363	0.002	0.002	0.000	202.878	218.511	0.000
057CD	NiMH	Diesel	FUDS	57.000	0.000	51.700	0.030	0.353	0.002	0.002	0.000	195.030	210.058	0.000
057CDD	NiMH	DI Diesel	FUDS	57.000	0.000	60.900	0.029	1.860	0.032	0.032	0.000	165.567	178.325	0.000
059CDR	NiMH	DI RFG	FUDS	59.000	0.000	47.300	0.016	0.036	0.025	0.025	0.000	174.504	229.598	0.000
036CD	NiMH	Diesel	HWY	36.000	0.000	56.800	0.027	0.319	0.002	0.002	0.000	177.518	191.197	0.000
062CD	NiMH	Diesel	HWY	62.000	0.000	58.900	0.026	0.307	0.002	0.002	0.000	171.189	184.380	0.000
062CDD	NiMH	DI Diesel	HWY	62.000	0.000	71.100	0.024	1.600	0.025	0.025	0.000	141.815	152.743	0.000
064CDR	NiMH	DI RFG	HWY	64.000	0.000	56.000	0.012	0.031	0.021	0.021	0.000	147.394	193.929	0.000
024CD	NiMH	Diesel	UC-92	24.000	0.000	37.000	0.041	0.499	0.003	0.003	0.000	272.515	293.514	0.000
042CD	NiMH	Diesel	UC-92	42.000	0.000	40.200	0.038	0.459	0.002	0.002	0.000	250.822	270.149	0.000
018CD	NiMH	Diesel	US06	18.000	0.000	34.300	0.040	0.504	0.002	0.002	0.000	293.966	316.618	0.000
031CD	NiMH	Diesel	US06	31.000	0.000	35.000	0.040	0.501	0.002	0.002	0.000	288.087	310.286	0.000

able 20: Running Emission Results for Mid-size Hybrid Vehicles using Direct Injected Gasoline and Diesel Engines with Different All-electric Ranges in the Charge Depleting Mode

mmary of Vehicle Results

mptions:					
l miles Driven per Year	10860				
ber of Work Days	224				1
nd trip work dist	15				
l random Driving Dist	7500		SULEV Standard		
on	LA basin		CO	1	g/ml
orative Emissions	0	0=none, 1=present average values	NOx	0.02	g/ml
rol Strategy	1	0 = sustaining, 1 = depleting	ROG	0.008	g/ml
ction Criteria	n?????cd?				

Running Emissions (gm/mi)

	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
023CD	NiMH	Diesel	ART14	23.000	0.508	31.300	0.024	0.289	0.001	0.001	0.000	158.445	170.654	2301.352
041CD	NiMH	Diesel	ART14	41.000	0.828	34.600	0.008	0.091	0.001	0.001	0.000	50.047	53.903	4353.279
041CDD	NiMH	DI Diesel	ART14	41.000	0.828	42.700	0.007	0.455	0.008	0.008	0.000	40.553	43.678	4353.279
32CD	NiMH	Diesel	FW31	32.000	0.713	48.600	0.009	0.105	0.001	0.001	0.000	59.610	64.204	2259.545
54CD	NiMH	Diesel	FW31	54.000	0.963	50.200	0.001	0.013	0.000	0.000	0.000	7.423	7.995	3985.811
54CDD	NiMH	DI Diesel	FW31	54.000	0.963	62.100	0.001	0.068	0.001	0.001	0.000	6.001	6.463	3985.811
21CD	NiMH	Diesel	FW70	21.000	0.456	43.900	0.016	0.169	0.001	0.001	0.000	125.020	134.654	1709.942
36CD	NiMH	Diesel	FW70	36.000	0.775	46.100	0.007	0.070	0.000	0.000	0.000	49.260	53.055	3277.634
033CDD	NiMH	DI Diesel	FUD/HWY	33.000	0.713	70.200	0.007	0.465	0.007	0.007	0.000	41.269	44.449	2161.734
034CD	NiMH	Diesel	FUD/HWY	34.000	0.745	51.200	0.008	0.091	0.001	0.001	0.000	50.239	54.110	2405.582
59CD	NiMH	Diesel	FUD/HWY	59.000	0.990	55.000	0.000	0.003	0.000	0.000	0.000	1.825	1.966	4058.823
59CDD	NiMH	DI Diesel	FUD/HWY	59.000	0.990	66.300	0.000	0.017	0.000	0.000	0.000	1.514	1.631	4058.823
61CDR	NiMH	DI RFG	FUD/HWY	61.000	1.000	51.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4001.259
30CDD	NiMH	DI Diesel	FUDS	30.000	0.678	60.500	0.009	0.605	0.010	0.010	0.000	53.674	57.810	2242.000
33CD	NiMH	Diesel	FUDS	33.000	0.713	49.700	0.009	0.104	0.001	0.001	0.000	58.291	62.783	2446.798
57CD	NiMH	Diesel	FUDS	57.000	0.977	51.700	0.001	0.008	0.000	0.000	0.000	4.474	4.818	4272.849
57CDD	NiMH	DI Diesel	FUDS	57.000	0.977	60.900	0.001	0.043	0.001	0.001	0.000	3.798	4.090	4272.849
59CDR	NiMH	DI RFG	FUDS	59.000	0.990	47.300	0.000	0.000	0.000	0.000	0.000	1.737	2.286	4238.771
36CD	NiMH	Diesel	HWY	36.000	0.775	56.800	0.006	0.072	0.000	0.000	0.000	39.980	43.061	2441.638
62CD	NiMH	Diesel	HWY	62.000	1.000	58.900	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3919.629
62CDD	NiMH	DI Diesel	HWY	62.000	1.000	71.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3919.629
64CDR	NiMH	DI RFG	HWY	64.000	1.000	56.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3876.624
24CD	NiMH	Diesel	UC-92	24.000	0.556	37.000	0.018	0.222	0.001	0.001	0.000	121.001	130.325	2158.265
42CD	NiMH	Diesel	UC-92	42.000	0.852	40.200	0.006	0.068	0.000	0.000	0.000	37.084	39.941	3916.285
18CD	NiMH	Diesel	US06	18.000	0.398	34.300	0.024	0.304	0.001	0.001	0.000	177.082	190.727	1691.403
31CD	NiMH	Diesel	US06	31.000	0.678	35.000	0.013	0.161	0.001	0.001	0.000	92.780	99.929	3105.712

Table 27: Running Emission Results for Mid-size Hybrid Vehicles using a Port Injected Gasoline Engine with Different All-electric Ranges in the Charge Depleting Mode

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860							1				
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard						
Region			LA basin					CO	1	g/ml				
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
Control Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
Selection Criteria			n?????ch											
		Running Emissions (gm/ml)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap)	CO2	Gal/year	kWh/year
NA1024CH	NIMH	Honda	ART14	24.000	0.556	24.100	0.095	0.083	0.014	0.014	0.000	152.072	200.084	2473.011
NA 038CH	NIMH	Honda	ART14	38.000	0.803	27.300	0.037	0.023	0.006	0.006	0.000	59.707	78.557	3972.843
NF 022CH	NIMH	Honda	FW70	22.000	0.508	33.200	0.076	0.083	0.011	0.011	0.000	122.281	160.888	1906.835
NF 039CH	NIMH	Honda	FW70	39.000	0.803	33.500	0.030	0.033	0.004	0.004	0.000	48.656	64.018	3287.498
NFH056CH	NIMH	Honda	FUD/HWY	56.000	0.977	41.500	0.003	0.003	0.000	0.000	0.000	4.562	6.003	3743.692
NFU034CH	NIMH	Honda	FUDS	34.000	0.745	36.100	0.036	0.032	0.005	0.005	0.000	58.328	76.744	2543.402
NFU055CH	NIMH	Honda	FUDS	55.000	0.963	39.500	0.005	0.003	0.001	0.001	0.000	7.723	10.161	3972.147
NHY036CH	NIMH	Honda	HWY	36.000	0.775	42.300	0.027	0.024	0.004	0.004	0.000	43.947	57.822	2415.099
NHY058CH	NIMH	Honda	HWY	58.000	0.990	45.400	0.001	0.001	0.000	0.000	0.000	1.810	2.382	3678.352
NUC025CH	NIMH	Honda	UC-92	25.000	0.556	27.000	0.084	0.074	0.012	0.012	0.000	135.738	178.593	2131.286
NUC042CH	NIMH	Honda	UC-92	42.000	0.852	30.700	0.025	0.016	0.004	0.004	0.000	39.751	52.301	3731.989
NU 018CH	NIMH	Honda	US06	18.000	0.398	25.500	0.125	0.100	0.019	0.019	0.000	194.986	256.546	1678.540
NU 032CH	NIMH	Honda	US06	32.000	0.713	25.600	0.061	0.041	0.009	0.009	0.000	92.639	121.886	3130.411

Table 28: Running Emission Results for Hybrid Vehicles using Stirling Engines with Different All-electric Ranges in the Charge Depleting Mode

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860							1				
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard						
Region			LA basin					CO	1	g/ml				
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
Control Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
Selection Criteria			n??????s											
		Running Emissions (gm/mi)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1018CS	NIMH	Stirling	ART14	18.000	0.398	31.800	0.008	0.096	0.018	0.018	0.000	156.356	205.721	1755.715
NA1049AS	NiMH	Stirling	ART14	48.500	0.914	69.400	0.001	0.006	0.000	0.000	0.000	10.240	13.473	2783.988
NF3024CS	NIMH	Stirling	FW31	24.000	0.556	49.200	0.005	0.044	0.001	0.001	0.000	74.491	98.009	1780.568
NF3061AS	NIMH	Stirling	FW31	60.500	1.000	88.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2504.331
NFH034CS	NIMH	Stirling	FUD/HWY	34.000	0.745	53.300	0.003	0.025	0.001	0.001	0.000	39.506	51.978	2230.175
NFH061CS	NIMH	Stirling	FUD/HWY	61.000	1.000	53.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4001.259
NFH062AS	NIMH	Stirling	FUD/HWY	62.000	1.000	91.400	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2524.159
NFU031CS	NIMH	Stirling	FUDS	31.000	0.678	50.000	0.003	0.032	0.001	0.001	0.000	53.165	69.951	2218.366
NFU059CS	NIMH	Stirling	FUDS	59.000	0.990	48.500	0.000	0.001	0.000	0.000	0.000	1.694	2.229	4238.771
NFU065AS	NIMH	Stirling	FUDS	64.500	1.000	89.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2576.945
NHY060AS	NIMH	Stirling	HWY	60.200	1.000	92.700	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2581.619
NHY064CS	NIMH	Stirling	HWY	64.000	1.000	57.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3876.624

Table 29: Running Emission Results for Hybrid Vehicles using Stirling Engines in Charge Sustaining Mode

St mmary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860							1				
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard						
Region			LA basin					CO	1	g/ml				
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
Sel ction Criteria			n??????s											
		Running Emissions (gm/ml)												
Typ	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1018CS	NIMH	Stirling	ART14	18.000	0.000	31.800	0.013	0.159	0.030	0.030	0.000	259.561	341.509	0.000
NA1049AS	NIMH	Stirling	ART14	48.500	0.000	69.400	0.007	0.074	0.000	0.000	0.000	118.934	156.484	0.000
NF3024CS	NIMH	Stirling	FW31	24.000	0.000	49.200	0.012	0.099	0.002	0.002	0.000	167.765	220.732	0.000
NF3061AS	NIMH	Stirling	FW31	60.500	0.000	88.500	0.006	0.056	0.001	0.001	0.000	93.266	122.712	0.000
NFH034CS	NIMH	Stirling	FUD/HWY	34.000	0.000	53.300	0.010	0.098	0.002	0.002	0.000	154.860	203.752	0.000
NFH061CS	NIMH	Stirling	FUD/HWY	61.000	0.000	53.200	0.008	0.095	0.001	0.001	0.000	155.151	204.135	0.000
NFH062AS	NIMH	Stirling	FUD/HWY	62.000	0.000	91.400	0.006	0.055	0.000	0.000	0.000	90.307	118.818	0.000
NFU031CS	NIMH	Stirling	FUDS	31.000	0.000	50.000	0.010	0.098	0.002	0.002	0.000	165.081	217.200	0.000
NFU059CS	NIMH	Stirling	FUDS	59.000	0.000	48.500	0.009	0.104	0.001	0.001	0.000	170.186	223.918	0.000
NFU065AS	NIMH	Stirling	FUDS	64.500	0.000	89.500	0.006	0.056	0.000	0.000	0.000	92.224	121.341	0.000
NHY060AS	NIMH	Stirling	HWY	60.200	0.000	92.700	0.006	0.053	0.001	0.001	0.000	89.040	117.152	0.000
NHY064CS	NIMH	Stirling	HWY	64.000	0.000	57.200	0.010	0.085	0.002	0.002	0.000	144.301	189.860	0.000

Table 30: Summary of Upstream Emission Factors for Different Fuels

Evaporative Emissions					Refueling Emissions RFG			
	ROG				ROG	0.21	gm/gal	
RFG								
Running	0.04	gm/mi						
Hot Soak	0.36	gm/trip						
Diurnal	1.7	gm/day						
CNG								
Diesel								
Upstream Emissions Fuel Table								
CNG LA Basin	0.05444	0.08132	0.53875	0	0	297.5068		
CNG LA State	0.13509	0.36311	0.71097	0	0	416.6462		
CNG LA Total	0.40298	1.09367	1.51487	0	0	733.06		
Diesel LA Bas	0.1264	0.20944	0.50752	0	0	593.538		
Diesel LA Stat	0.1459	0.32351	0.5348	0	0	641.036		
Diesel LA Tota	0.1956	0.5992	0.62645	0	0	756.228		
H2 LA Basin	4	21	2.9	0	0	11695		
H2 LA State	4	21	2.9	0	0	11695		
H2 LA Total	4	21	2.9	0	0	11695		
RFG LA Basin	0.1384	0.30135	1.3427	0	0	857.1819		
RFG LA State	0.1702	0.4958	1.3869	0	0	937.4333		
RFG LA Total	0.25	0.95576	1.53	0	0	1128.906		
CO2 Table								
CNG	5612.992							
Diesel	10083.04							
H2	0							
RFG	8254.045							

Table 31: Summary of Powerplant Emission Factors (gm/kWh) for Generation of Electrical Power used in Various Areas of California

Powerplant						
			Emissions (gm/kWh)			
	CO	Nox	ROG	PM	SOx	CO2
CA State	0.09	0.288	0.023	0.034	0.203	473
CA Total	0.092	0.326	0.023	0.035	0.243	489
LA Basin	0.059	0.058	0.011	0.019	0.004	321
LA State	0.082	0.093	0.018	0.019	0.004	357
LA Total	0.089	0.414	0.021	0.033	0.311	504
US Total						
Note: All numbers from CEC calculations using ELFIN						

32: Total Full Fuel Cycle Emissions for Electric Vehicles using Various Types of Batteries Charged using Electricity Generated within California (LA state)

ary of Vehicle Results

ns:						
Driven per Year	10860					1
Work Days	224					
work dist	15					
om Driving Dist	7500		SULEV Standard			
	LA state		CO	1	g/ml	
e Emissions	0	0=none, 1=present average values	NOx	0.02	g/ml	
ategy	1	0 = sustaining, 1 = depleting	ROG	0.008	g/ml	
Criteria	??????cev					

Total Emissions (gm/mi)

	Battery	Engine	Drive Cycl	Elec Rang	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
EV	Li-Ion	EV	ART14	71.000	1.000	0.000	0.026	0.029	0.006	0.000	0.000	157.004	0.000	3383.053
EV	Li-Ion	EV	FW70	70.000	1.000	0.000	0.022	0.025	0.005	0.000	0.000	133.343	0.000	2873.234
EV	Li-Ion	EV	FUD/HWY	101.000	1.000	0.000	0.018	0.020	0.004	0.000	0.000	108.491	0.000	2337.721
EV	Li-Ion	EV	FUDS	58.000	1.000	0.000	0.018	0.021	0.004	0.000	0.000	112.674	0.000	2427.857
EV	Li-Ion	EV	FUDS	99.000	1.000	0.000	0.019	0.021	0.004	0.000	0.000	115.991	0.000	2499.328
EV	Li-Ion	EV	FUDS	152.000	1.000	0.000	0.020	0.022	0.004	0.000	0.000	121.274	0.000	2613.169
EV	Li-Ion	EV	US06	57.000	1.000	0.000	0.024	0.028	0.005	0.000	0.000	149.675	0.000	3225.135
EV	NiMH	EV	ART14	64.000	1.000	0.000	0.045	0.051	0.010	0.000	0.000	275.156	0.000	5928.954
EV	NiMH	EV	ART34	83.000	1.000	0.000	0.035	0.040	0.008	0.000	0.000	217.481	0.000	4686.200
EV	NiMH	EV	FW31	90.000	1.000	0.000	0.034	0.039	0.007	0.000	0.000	209.675	0.000	4517.989
EV	NiMH	EV	FW70	66.000	1.000	0.000	0.037	0.042	0.008	0.000	0.000	230.240	0.000	4961.127
EV	NiMH	EV	FUD/HWY	94.000	1.000	0.000	0.034	0.039	0.007	0.000	0.000	209.996	0.000	4524.906
EV	NiMH	EV	FUDS	38.000	1.000	0.000	0.025	0.029	0.006	0.000	0.000	154.995	0.000	3339.780
EV	NiMH	EV	FUDS	57.000	1.000	0.000	0.030	0.034	0.007	0.000	0.000	185.346	0.000	3993.755
EV	NiMH	EV	FUDS	89.000	1.000	0.000	0.036	0.041	0.008	0.000	0.000	221.767	0.000	4778.555
EV	NiMH	EV	UC-92	71.000	1.000	0.000	0.038	0.043	0.008	0.000	0.000	233.521	0.000	5031.811
EV	NiMH	EV	US06	57.000	1.000	0.000	0.040	0.046	0.009	0.000	0.000	247.436	0.000	5331.663
EV	Pb-acid	EV	ART14	42.000	1.000	0.000	0.033	0.037	0.007	0.000	0.000	203.174	0.000	4377.907
EV	Pb-acid	EV	FW70	42.000	1.000	0.000	0.027	0.031	0.006	0.000	0.000	167.777	0.000	3615.205
EV	Pb-acid	EV	FUD/HWY	60.000	1.000	0.000	0.024	0.027	0.005	0.000	0.000	148.293	0.000	3195.364
EV	Pb-acid	EV	FUDS	40.000	1.000	0.000	0.023	0.026	0.005	0.000	0.000	141.867	0.000	3056.897
EV	Pb-acid	EV	FUDS	59.000	1.000	0.000	0.026	0.029	0.006	0.000	0.000	159.838	0.000	3444.127
EV	Pb-acid	EV	FUDS	104.000	1.000	0.000	0.034	0.038	0.007	0.000	0.000	208.091	0.000	4483.867
EV	Pb-acid	EV	HWY	60.000	1.000	0.000	0.023	0.026	0.005	0.000	0.000	142.178	0.000	3063.597
EV	Pb-acid	EV	US06	38.000	1.000	0.000	0.030	0.034	0.007	0.000	0.000	186.773	0.000	4024.504

33: Total Full Fuel Cycle Emissions for Electric Vehicles using Various Types of Batteries Charged using Electricity Generated Anywhere (LA total)

ary of Vehicle Results											
ns:											
Driven per Year		10860							1		
Work Days		224									
work dist		15									
m Driving Dist		7500					SULEV Standard				
		LA total					CO	1	g/mi		
e Emissions		0	0=none, 1=present average values				NOx	0.02	g/mi		
ategy		1	0 = sustaining, 1 = depleting				ROG	0.008	g/mi		
Criteria		??????cev									

Total Emissions (gm/mi)

	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
V	Li-Ion	EV	ART14	71.000	1.000	0.000	0.028	0.129	0.007	0.000	0.000	157.004	0.000	3383.053
V	Li-Ion	EV	FW70	70.000	1.000	0.000	0.024	0.110	0.006	0.000	0.000	133.343	0.000	2873.234
V	Li-Ion	EV	FUD/HWY	101.000	1.000	0.000	0.019	0.089	0.005	0.000	0.000	108.491	0.000	2337.721
V	Li-Ion	EV	FUDS	58.000	1.000	0.000	0.020	0.093	0.005	0.000	0.000	112.674	0.000	2427.857
V	Li-Ion	EV	FUDS	99.000	1.000	0.000	0.020	0.095	0.005	0.000	0.000	115.991	0.000	2499.328
V	Li-Ion	EV	FUDS	152.000	1.000	0.000	0.021	0.100	0.005	0.000	0.000	121.274	0.000	2613.169
V	Li-Ion	EV	US06	57.000	1.000	0.000	0.026	0.123	0.006	0.000	0.000	149.675	0.000	3225.135
V	NiMH	EV	ART14	64.000	1.000	0.000	0.049	0.226	0.011	0.000	0.000	275.156	0.000	5928.954
V	NiMH	EV	ART34	83.000	1.000	0.000	0.038	0.179	0.009	0.000	0.000	217.481	0.000	4686.200
V	NiMH	EV	FW31	90.000	1.000	0.000	0.037	0.172	0.009	0.000	0.000	209.675	0.000	4517.989
V	NiMH	EV	FW70	66.000	1.000	0.000	0.041	0.189	0.010	0.000	0.000	230.240	0.000	4961.127
EV	NiMH	EV	FUD/HWY	94.000	1.000	0.000	0.037	0.172	0.009	0.000	0.000	209.996	0.000	4524.906
EV	NiMH	EV	FUDS	36.000	1.000	0.000	0.027	0.127	0.006	0.000	0.000	154.995	0.000	3339.780
EV	NiMH	EV	FUDS	57.000	1.000	0.000	0.033	0.152	0.008	0.000	0.000	185.346	0.000	3993.755
EV	NiMH	EV	FUDS	89.000	1.000	0.000	0.039	0.182	0.009	0.000	0.000	221.767	0.000	4778.555
EV	NiMH	EV	UC-92	71.000	1.000	0.000	0.041	0.192	0.010	0.000	0.000	233.521	0.000	5031.811
EV	NiMH	EV	US06	57.000	1.000	0.000	0.044	0.203	0.010	0.000	0.000	247.436	0.000	5331.663
V	Pb-acid	EV	ART14	42.000	1.000	0.000	0.036	0.167	0.008	0.000	0.000	203.174	0.000	4377.907
V	Pb-acid	EV	FW70	42.000	1.000	0.000	0.030	0.138	0.007	0.000	0.000	167.777	0.000	3615.205
V	Pb-acid	EV	FUD/HWY	60.000	1.000	0.000	0.026	0.122	0.006	0.000	0.000	148.293	0.000	3195.364
V	Pb-acid	EV	FUDS	40.000	1.000	0.000	0.025	0.117	0.006	0.000	0.000	141.867	0.000	3056.897
V	Pb-acid	EV	FUDS	59.000	1.000	0.000	0.028	0.131	0.007	0.000	0.000	159.838	0.000	3444.127
V	Pb-acid	EV	FUDS	104.000	1.000	0.000	0.037	0.171	0.009	0.000	0.000	208.091	0.000	4483.867
V	Pb-acid	EV	HWY	60.000	1.000	0.000	0.025	0.117	0.006	0.000	0.000	142.178	0.000	3063.597
V	Pb-acid	EV	US06	38.000	1.000	0.000	0.033	0.153	0.008	0.000	0.000	186.773	0.000	4024.504

able 34(a) : Total Full Fuel Cycle Emissions for ULEV and SULEV ICE Vehicles with Zero Evaporative and Refueling Emissions

ummary of Vehicle Results

ssumptions:							
otal miles Driven per Year	10860						
umber of Work Days	224						
ound trip work dist	15						
otal random Driving Dist	7500		SULEV Standard			REFUEL/EVAP EMIS.	
egion	LA Basin		CO	1	g/mi	refuel (gm/gal)	0.21
vaporative Emissions	0	0=none, 1=present average values	NOx	0.02	g/mi	Hot soak (gm/trip)	0.36
ontrol Strategy	0	0 = sustaining, 1 = depleting	ROG	0.008	g/mi	Diurnl (gm/day)	1.7
election Criteria	g????????						

Total Emissions (gm/mi)

ype	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
FH000ASU	none	SULEV	FUD/HWY	0.000	0.000	51.000	1.003	0.026	0.030	0.008	0.000	183.979	212.941	0.000
FH000CSU	none	SULEV	FUD/HWY	0.000	0.000	35.000	1.004	0.029	0.040	0.008	0.000	268.084	310.286	0.000
FH000CUL	None	ULEV	FUD/HWY	0.000	0.000	27.500	1.705	0.211	0.089	0.040	0.000	341.198	394.909	0.000
FH000ASU	none	SULEV	FUD/HWY	0.000	0.000	40.000	1.003	0.028	0.036	0.008	0.000	234.574	271.500	0.000
FH000CSU	none	SULEV	FUD/HWY	0.000	0.000	70.000	1.002	0.024	0.024	0.008	0.000	134.042	155.143	0.000
FH000CUL	None	ULEV	FUD/HWY	0.000	0.000	50.000	1.703	0.206	0.067	0.040	0.000	187.659	217.200	0.000
FH000ASU	none	SULEV	FUD/HWY	0.000	0.000	70.000	1.002	0.024	0.024	0.008	0.000	134.042	155.143	0.000
FH000CSU	none	SULEV	FUD/HWY	0.000	0.000	50.000	1.003	0.026	0.031	0.008	0.000	187.659	217.200	0.000
FH000CUL	None	ULEV	FUD/HWY	0.000	0.000	42.000	1.703	0.207	0.072	0.040	0.000	223.404	258.571	0.000

le 34(b) : Total Full Fuel Cycle Emissions for ULEV and SULEV ICE Vehicle with Evaporative and Refueling Emissions of Present Cars

nmary of Vehicle Results														
ptions:														
niles Driven per Year			10860											
er of Work Days			224											
l trip work dist			15											
andom Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.		
n			LA Basin					CO	1	g/mi		refuel (gm/gal)		0.21
rative Emissions			1	0=none, 1=present average values				NOx	0.02	g/mi		Hot soak (gm/trip)		0.36
l Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/mi		Diurnl (gm/day)		1.7
tion Criteria			g????????											
		Total Emissions (gm/mi)												
	Battery	Engine	Drive Cycl	Elec Rang	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
00ASU	none	SULEV	FUD/HWY	0.000	0.000	51.000	1.003	0.026	0.152	0.008	0.121	183.979	212.941	0.000
00CSU	none	SULEV	FUD/HWY	0.000	0.000	35.000	1.004	0.029	0.162	0.008	0.121	268.084	310.286	0.000
00CUL	None	ULEV	FUD/HWY	0.000	0.000	27.500	1.705	0.211	0.210	0.040	0.121	341.198	394.909	0.000
00ASU	none	SULEV	FUD/HWY	0.000	0.000	40.000	1.003	0.028	0.158	0.008	0.121	234.574	271.500	0.000
00CSU	none	SULEV	FUD/HWY	0.000	0.000	70.000	1.002	0.024	0.146	0.008	0.121	134.042	155.143	0.000
00CUL	None	ULEV	FUD/HWY	0.000	0.000	50.000	1.703	0.206	0.188	0.040	0.121	187.659	217.200	0.000
00ASU	none	SULEV	FUD/HWY	0.000	0.000	70.000	1.002	0.024	0.146	0.008	0.121	134.042	155.143	0.000
00CSU	none	SULEV	FUD/HWY	0.000	0.000	50.000	1.003	0.026	0.152	0.008	0.121	187.659	217.200	0.000
00CUL	None	ULEV	FUD/HWY	0.000	0.000	42.000	1.703	0.207	0.193	0.040	0.121	223.404	258.571	0.000

Table 35: Comparisons of ICE and Electric Vehicle on the FUDSWAY Cycle

Vehicle	gm CO_2/mi
Mid-size ICE	
27 mpg	341
35 mpg	268
42 mpg	223
50 mpg	187
Mid-size EV (100 mile range)	
Pb-Acid	208
Ni. Mt. Hy.	222
Li-ion	116
Light-weight ICE	
40 mpg	234
50 mpg	184
70 mpg	134
Light-weight EV (100 mile range)	
Pb - Acid	107
Ni. Mt. Hy.	135
Li-ion	68

Table 36: Total Full Fuel Cycle Emissions for a Mid-size Hybrid Vehicle for a Use-pattern of 4300 miles per year random Travel and 10 miles Round-trip to Work in the Charge Depleting Mode

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			6540							1				
Number of Work Days			224											
Round trip work dist			10											
Total random Driving Dist			4300					SULEV Standard						
Region			LA basin					CO	1	g/ml				
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
Control Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
Selection Criteria			n?????ch											
		Total Emissions (gm/ml)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1024CH	NiMH	Honda	ART14	24.000	0.824	24.100	0.060	0.056	0.019	0.006	0.000	254.737	47.742	2416.701
NA1038CH	NiMH	Honda	ART14	38.000	1.000	27.300	0.032	0.031	0.006	0.000	0.000	272.004	0.000	3529.580
NF7022CH	NiMH	Honda	FW70	22.000	0.777	33.200	0.052	0.056	0.017	0.005	0.000	206.977	43.910	1868.313
NF7039CH	NiMH	Honda	FW70	39.000	1.000	33.500	0.026	0.026	0.005	0.000	0.000	225.007	0.000	2919.734
NFH056CH	NiMH	Honda	FUD/HWY	56.000	1.000	41.500	0.024	0.024	0.005	0.000	0.000	207.243	0.000	2689.221
NFU034CH	NiMH	Honda	FUDS	34.000	1.000	36.100	0.022	0.022	0.004	0.000	0.000	187.536	0.000	2433.506
NFU055CH	NiMH	Honda	FUDS	55.000	1.000	39.500	0.026	0.026	0.005	0.000	0.000	223.336	0.000	2898.051
NHY036CH	NiMH	Honda	HWY	36.000	1.000	42.300	0.020	0.020	0.004	0.000	0.000	171.307	0.000	2222.911
NHY058CH	NiMH	Honda	HWY	58.000	1.000	45.400	0.023	0.023	0.004	0.000	0.000	200.513	0.000	2601.895
NUC025CH	NiMH	Honda	UC-92	25.000	0.824	27.000	0.053	0.050	0.017	0.005	0.000	223.854	42.614	2111.427
NUC042CH	NiMH	Honda	UC-92	42.000	1.000	30.700	0.028	0.028	0.005	0.000	0.000	240.152	0.000	3116.258
NUS018CH	NiMH	Honda	US06	18.000	0.668	25.500	0.086	0.074	0.031	0.010	0.000	253.189	85.135	1700.487
NUS032CH	NiMH	Honda	US06	32.000	0.976	25.600	0.033	0.031	0.007	0.001	0.000	243.872	6.147	3050.086

Table 41: Total Full Fuel Cycle Emissions for a Mid-size Hybrid Vehicle in the Charge Sustaining Mode with Evaporative and Refueling Emissions equal to those of Present Cars

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860							1				
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard						
Region			LA basin					CO	1	g/ml				
Evaporative Emissions			1	0=none, 1=present average values				NOx	0.02	g/ml				
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
Selection Criteria			n?????ch											
		Total Emissions (gm/ml)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1024CH	NIMH	Honda	ART14	24.000	0.000	24.100	0.219	0.199	0.209	0.032	0.121	389.334	450.622	0.000
NA1038CH	NIMH	Honda	ART14	38.000	0.000	27.300	0.193	0.128	0.201	0.030	0.121	343.698	397.802	0.000
NF7022CH	NIMH	Honda	FW70	22.000	0.000	33.200	0.158	0.178	0.185	0.023	0.121	282.619	327.108	0.000
NF7039CH	NiMH	Honda	FW70	39.000	0.000	33.500	0.155	0.174	0.183	0.022	0.121	280.088	324.179	0.000
NFH056CH	NiMH	Honda	FUD/HWY	56.000	0.000	41.500	0.127	0.116	0.172	0.018	0.121	226.095	261.687	0.000
NFU034CH	NiMH	Honda	FUDS	34.000	0.000	36.100	0.147	0.135	0.180	0.021	0.121	259.916	300.831	0.000
NFU055CH	NIMH	Honda	FUDS	55.000	0.000	39.500	0.133	0.079	0.176	0.021	0.121	237.543	274.937	0.000
NHY036CH	NiMH	Honda	HWY	36.000	0.000	42.300	0.125	0.115	0.171	0.018	0.121	221.819	256.738	0.000
NHY058CH	NiMH	Honda	HWY	58.000	0.000	45.400	0.116	0.078	0.169	0.018	0.121	206.673	239.207	0.000
NUC025CH	NIMH	Honda	UC-92	25.000	0.000	27.000	0.195	0.178	0.199	0.028	0.121	347.517	402.222	0.000
NUC042CH	NiMH	Honda	UC-92	42.000	0.000	30.700	0.173	0.115	0.191	0.026	0.121	305.634	353.746	0.000
NUS018CH	NiMH	Honda	US06	18.000	0.000	25.500	0.213	0.178	0.205	0.031	0.121	367.959	425.882	0.000
NUS032CH	NiMH	Honda	US06	32.000	0.000	25.600	0.216	0.154	0.205	0.031	0.121	366.522	424.219	0.000

Table 42: Total Full Fuel Cycle Emission Results for a Mid-size Hybrid Vehicle using Direct Injected Gasoline and Diesel Engines operating in the Charge Depleting Mode

Summary of Vehicle Results

Assumptions:		
Total miles Driven per Year	10860	
Number of Work Days	224	
Round trip work dist	15	
Total random Driving Dist	7500	
Region	LA Basin	
Evaporative Emissions	0	0=none, 1=present average values
Control Strategy	1	0 = sustaining, 1 = depleting
Selection Criteria	n?????cd?	

SULEV Standard		
CO	1	g/mi
NOx	0.02	g/mi
ROG	0.008	g/mi

REFUEL/EVAP EMIS.	
refuel (gm/gal)	0.21
Hot soak (gm/trip)	0.36
Diurnl (gm/day)	1.7

Total Emissions (gm/mi)

Type	Battery	Engine	Drive Cycle	Elec Rang	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1023CD	NiMH	Diesel	ART14	23.000	0.508	31.300	0.039	0.304	0.012	0.001	0.000	277.131	170.654	2301.352
NA1041CD	NiMH	Diesel	ART14	41.000	0.828	34.600	0.032	0.116	0.007	0.001	0.000	255.831	53.903	4353.279
NA1041CDD	NiMH	DI Diesel	ART14	41.000	0.828	42.700	0.031	0.479	0.014	0.008	0.000	245.625	43.678	4353.279
NF3032CD	NiMH	Diesel	FW31	32.000	0.713	48.600	0.022	0.119	0.006	0.001	0.000	168.944	64.204	2259.545
NF3054CD	NiMH	Diesel	FW31	54.000	0.963	50.200	0.023	0.035	0.004	0.000	0.000	192.957	7.995	3985.811
NF3054CDD	NiMH	DI Diesel	FW31	54.000	0.963	62.100	0.023	0.089	0.005	0.001	0.000	191.428	6.463	3985.811
NF7021CD	NiMH	Diesel	FW70	21.000	0.456	43.900	0.027	0.181	0.009	0.001	0.000	213.753	134.654	1709.942
NF7036CD	NiMH	Diesel	FW70	36.000	0.775	46.100	0.025	0.089	0.006	0.000	0.000	205.065	53.055	3277.634
NFH033CDD	NiMH	DI Diesel	FUD/HWY	33.000	0.713	70.200	0.019	0.478	0.012	0.007	0.000	144.687	44.449	2161.734
NFH034CD	NiMH	Diesel	FUD/HWY	34.000	0.745	51.200	0.021	0.105	0.005	0.001	0.000	165.647	54.110	2405.582
NFH059CD	NiMH	Diesel	FUD/HWY	59.000	0.990	55.000	0.022	0.025	0.004	0.000	0.000	190.327	1.966	4058.823
NFH059CDD	NiMH	DI Diesel	FUD/HWY	59.000	0.990	66.300	0.022	0.039	0.004	0.000	0.000	189.993	1.631	4058.823
NFH061CDR	NiMH	DI RFG	FUD/HWY	61.000	1.000	51.600	0.022	0.021	0.004	0.000	0.000	185.694	0.000	4001.259
NFU030CDD	NiMH	DI Diesel	FUDS	30.000	0.678	60.500	0.022	0.619	0.015	0.010	0.000	161.749	57.810	2242.000
NFU033CD	NiMH	Diesel	FUDS	33.000	0.713	49.700	0.023	0.119	0.006	0.001	0.000	176.216	62.783	2446.798
NFU057CD	NiMH	Diesel	FUDS	57.000	0.977	51.700	0.024	0.031	0.005	0.000	0.000	203.107	4.818	4272.849
NFU057CDD	NiMH	DI Diesel	FUDS	57.000	0.977	60.900	0.024	0.066	0.005	0.001	0.000	202.381	4.090	4272.849
NFU059CDR	NiMH	DI RFG	FUDS	59.000	0.990	47.300	0.023	0.023	0.005	0.000	0.000	198.692	2.286	4238.771
NHY036CD	NiMH	Diesel	HWY	36.000	0.775	56.800	0.020	0.086	0.005	0.000	0.000	156.292	43.061	2441.638
NHY062CD	NiMH	Diesel	HWY	62.000	1.000	58.900	0.021	0.021	0.004	0.000	0.000	181.905	0.000	3919.629
NHY062CDD	NiMH	DI Diesel	HWY	62.000	1.000	71.100	0.021	0.021	0.004	0.000	0.000	181.905	0.000	3919.629
NHY064CDR	NiMH	DI RFG	HWY	64.000	1.000	56.000	0.021	0.021	0.004	0.000	0.000	179.910	0.000	3876.624
NUC024CD	NiMH	Diesel	UC-92	24.000	0.556	37.000	0.031	0.236	0.010	0.001	0.000	230.239	130.325	2158.265
NUC042CD	NiMH	Diesel	UC-92	42.000	0.852	40.200	0.027	0.090	0.006	0.000	0.000	221.615	39.941	3916.285
NUS018CD	NiMH	Diesel	US06	18.000	0.398	34.300	0.036	0.316	0.012	0.001	0.000	268.859	190.727	1691.403
NUS031CD	NiMH	Diesel	US06	31.000	0.678	35.000	0.031	0.180	0.008	0.001	0.000	243.871	99.929	3105.712

Table 43: Total Full Fuel Cycle Emission Results for a Mid-size Hybrid Vehicle using Direct Injection Gasoline and Diesel Engines operating the the Charge Sustaining Mode

Summary of Vehicle Results								
Assumptions:								
Total miles Driven per Year		10860						1
Number of Work Days		224						
Round trip work dist		15						
Total random Driving Dist		7500				SULEV Standard		
Region		LA basin				CO	1	g/mi
Evaporative Emissions		0	0=none, 1=present average values			NOx	0.02	g/mi
Control Strategy		0	0 = sustaining, 1 = depleting			ROG	0.008	g/mi
Selection Criteria		n?????cd?						

Total Emissions (gm/mi)

Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA 023CD	NiMH	Diesel	ART14	23.000	0.000	31.300	0.053	0.594	0.019	0.003	0.000	346.302	346.965	0.000
NA 041CD	NiMH	Diesel	ART14	41.000	0.000	34.600	0.048	0.538	0.018	0.003	0.000	313.274	313.873	0.000
NA 041CDD	NiMH	DI Diesel	ART14	41.000	0.000	42.700	0.044	2.655	0.058	0.046	0.000	253.847	254.333	0.000
NF3032CD	NiMH	Diesel	FW31	32.000	0.000	48.600	0.034	0.371	0.012	0.002	0.000	223.030	223.457	0.000
NF3054CD	NiMH	Diesel	FW31	54.000	0.000	50.200	0.033	0.365	0.012	0.002	0.000	215.922	216.335	0.000
NF3054CDD	NiMH	DI Diesel	FW31	54.000	0.000	62.100	0.030	1.833	0.038	0.030	0.000	174.545	174.879	0.000
NF7021CD	NiMH	Diesel	FW70	21.000	0.000	43.900	0.033	0.316	0.013	0.001	0.000	246.908	247.380	0.000
NF7036CD	NiMH	Diesel	FW70	36.000	0.000	46.100	0.032	0.317	0.012	0.001	0.000	235.125	235.575	0.000
NFH033CDD	NiMH	DI Diesel	FUD/HWY	33.000	0.000	70.200	0.027	1.623	0.033	0.026	0.000	154.406	154.701	0.000
NFH034CD	NiMH	Diesel	FUD/HWY	34.000	0.000	51.200	0.032	0.362	0.012	0.002	0.000	211.704	212.109	0.000
NFH059CD	NiMH	Diesel	FUD/HWY	59.000	0.000	55.000	0.030	0.336	0.011	0.002	0.000	197.078	197.455	0.000
NF 059CDD	NiMH	DI Diesel	FUD/HWY	59.000	0.000	66.300	0.028	1.713	0.037	0.029	0.000	163.488	163.801	0.000
NF 061CDR	NiMH	DI RFG	FUD/HWY	61.000	0.000	51.600	0.017	0.039	0.049	0.023	0.000	181.840	210.465	0.000
NFU030CDD	NiMH	DI Diesel	FUDS	30.000	0.000	60.500	0.031	1.883	0.039	0.031	0.000	179.161	179.504	0.000
NFU033CD	NiMH	Diesel	FUDS	33.000	0.000	49.700	0.034	0.367	0.012	0.002	0.000	218.094	218.511	0.000
NFU057CD	NiMH	Diesel	FUDS	57.000	0.000	51.700	0.032	0.357	0.012	0.002	0.000	209.657	210.058	0.000
NFU057CDD	NiMH	DI Diesel	FUDS	57.000	0.000	60.900	0.031	1.863	0.040	0.032	0.000	177.985	178.325	0.000
NFU059CDR	NiMH	DI RFG	FUDS	59.000	0.000	47.300	0.019	0.042	0.053	0.025	0.000	198.371	229.598	0.000
NHY036CD	NiMH	Diesel	HWY	36.000	0.000	56.800	0.029	0.323	0.011	0.002	0.000	190.832	191.197	0.000
NHY062CD	NiMH	Diesel	HWY	62.000	0.000	58.900	0.028	0.311	0.011	0.002	0.000	184.028	184.380	0.000
NHY062CDD	NiMH	DI Diesel	HWY	62.000	0.000	71.100	0.026	1.603	0.032	0.025	0.000	152.451	152.743	0.000
NHY064CDR	NiMH	DI RFG	HWY	64.000	0.000	56.000	0.014	0.036	0.045	0.021	0.000	167.553	193.929	0.000
NUC024CD	NiMH	Diesel	UC-92	24.000	0.000	37.000	0.044	0.505	0.017	0.003	0.000	292.953	293.514	0.000
NUC042CD	NiMH	Diesel	UC-92	42.000	0.000	40.200	0.041	0.464	0.015	0.002	0.000	269.634	270.149	0.000
NUS018CD	NiMH	Diesel	US06	18.000	0.000	34.300	0.044	0.510	0.017	0.002	0.000	316.014	316.618	0.000
NUS031CD	NiMH	Diesel	US06	31.000	0.000	35.000	0.044	0.507	0.017	0.002	0.000	309.693	310.286	0.000

Table 44: Total Full Fuel Cycle Emission Results for Hybrid Vehicles using Stirling engines in the charge Sustaining Mode

ummary of Vehicle Results														
ssumptions:														
otal miles Driven per Year			10860											
umber of Work Days			224											
ound trip work dist			15											
otal random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.		
egion			LA Basin					CO	1	g/mi		refuel (gm/gal)		0.21
vaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/mi		Hot soak (gm/trip)		0.36
ontrol Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/mi		Diurnl (gm/day)		1.7
election Criteria			n??????s											
		Total Emissions (gm/mi)												
ype	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
A1018CS	NiMH	Stirling	ART14	18.000	0.000	31.800	0.017	0.168	0.072	0.030	0.000	295.061	341.509	0.000
A1049AS	NiMH	Stirling	ART14	48.500	0.000	69.400	0.009	0.078	0.019	0.000	0.000	135.201	156.484	0.000
F3024CS	NiMH	Stirling	FW31	24.000	0.000	49.200	0.015	0.105	0.029	0.002	0.000	190.710	220.732	0.000
F3061AS	NiMH	Stirling	FW31	60.500	0.000	88.500	0.008	0.059	0.016	0.001	0.000	106.022	122.712	0.000
FH034CS	NiMH	Stirling	FUD/HWY	34.000	0.000	53.300	0.013	0.104	0.027	0.002	0.000	176.040	203.752	0.000
FH061CS	NiMH	Stirling	FUD/HWY	61.000	0.000	53.200	0.011	0.101	0.026	0.001	0.000	176.371	204.135	0.000
FH062AS	NiMH	Stirling	FUD/HWY	62.000	0.000	91.400	0.008	0.058	0.015	0.000	0.000	102.658	118.818	0.000
FU031CS	NiMH	Stirling	FUDS	31.000	0.000	50.000	0.013	0.104	0.029	0.002	0.000	187.659	217.200	0.000
FU059CS	NiMH	Stirling	FUDS	59.000	0.000	48.500	0.012	0.110	0.029	0.001	0.000	193.463	223.918	0.000
FU065AS	NiMH	Stirling	FUDS	64.500	0.000	89.500	0.008	0.059	0.015	0.000	0.000	104.837	121.341	0.000
HY060AS	NiMH	Stirling	HWY	60.200	0.000	92.700	0.007	0.056	0.015	0.001	0.000	101.218	117.152	0.000
HY064CS	NiMH	Stirling	HWY	64.000	0.000	57.200	0.012	0.090	0.025	0.002	0.000	164.038	189.860	0.000

able 45: Total Full Fuel Cycle Emission Results for Hybrid Vehicles using Fuel Cells fueled with Compressed Hydrogen from Reformed Natural Gas

ummary of Vehicle Results														
sumptions:														
tal miles Driven per Year			15328							1				
mber of Work Days			224											
ur d trip work dist			22											
tal random Driving Dist			10400					SULEV Standard						
gion			LA Basin					CO	1	g/mi				
aporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/mi				
ntrol Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/mi				
lection Criteria			???????FC											
		Total Emissions (gm/mi)												
pe	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
A1000AFC	NIMH	Fuel Cell	ART14	0.000	0.000	118.000	0.034	0.178	0.025	0.000	0.000	99.110	129.898	0.000
F3???AFC	NIMH	Fuel Cell	FW31	0.000	0.000	163.000	0.025	0.129	0.018	0.000	0.000	71.748	94.037	0.000
FH???AFC	NIMH	Fuel Cell	FUD/HWY	0.000	0.000	173.000	0.023	0.121	0.017	0.000	0.000	67.601	88.601	0.000
FH031CFC	NIMH	Fuel Cell	FUD/HWY	31.000	0.000	95.500	0.042	0.220	0.030	0.000	0.000	122.461	160.503	0.000
FH060CFC	NIMH	Fuel Cell	FUD/HWY	60.000	0.000	98.500	0.041	0.213	0.029	0.000	0.000	118.731	155.614	0.000
FU???AFC	NIMH	Fuel Cell	FUDS	0.000	0.000	172.000	0.023	0.122	0.017	0.000	0.000	67.994	89.116	0.000
FU030CFC	NIMH	Fuel Cell	FUDS	30.000	0.000	89.200	0.045	0.235	0.033	0.000	0.000	131.110	171.839	0.000
FU058CFC	NIMH	Fuel Cell	FUDS	58.000	0.000	90.200	0.044	0.233	0.032	0.000	0.000	129.656	169.933	0.000
HY???AFC	NIMH	Fuel Cell	HWY	0.000	0.000	179.000	0.022	0.117	0.016	0.000	0.000	65.335	85.631	0.000
HY063CFC	NIMH	Fuel Cell	HWY	63.000	0.000	105.000	0.038	0.200	0.028	0.000	0.000	111.381	145.981	0.000
UC???AFC	NIMH	Fuel Cell	UC-92	0.000	0.000	124.000	0.032	0.169	0.023	0.000	0.000	94.315	123.613	0.000

Table 46: Total Full Fuel Cycle Emission Results for a Compact, light-weight Hybrid Vehicle using a Port Injected Gasoline Engine in the Charge Depleting Mode

ummary of Vehicle Results														
umptions:														
l miles Driven per Year			10860							1				
nber of Work Days			224											
nd trip work dist			15											
l random Driving Dist			7500					SULEV Standard						
ion			LA basin					CO	1	g/ml				
porative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
trol Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
lection Criteria			n?????ah											
		Total Emissions (gm/ml)												
e	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap)	CO2	Gal/year	kWh/year
1022AH	NIMH	Honda	ART14	22.000	0.508	48.500	0.082	0.037	0.027	0.012	0.000	153.133	110.133	1249.305
1049AH	NIMH	Honda	ART14	48.500	0.914	58.400	0.026	0.021	0.007	0.002	0.000	143.035	16.011	2783.988
025AH	NIMH	Honda	FW31	25.300	0.556	65.700	0.056	0.026	0.019	0.008	0.000	112.659	73.395	1061.147
061AH	NIMH	Honda	FW31	60.500	1.000	69.600	0.014	0.013	0.003	0.000	0.000	116.223	0.000	2504.331
028AH	NIMH	Honda	FUD/HWY	27.500	0.600	69.500	0.049	0.024	0.016	0.007	0.000	107.602	62.516	1154.705
062AH	NIMH	Honda	FUD/HWY	62.000	1.000	72.200	0.014	0.013	0.003	0.000	0.000	117.143	0.000	2524.159
U030AH	NIMH	Honda	FUDS	29.800	0.640	69.600	0.045	0.022	0.014	0.006	0.000	105.224	56.102	1222.883
U065AH	NIMH	Honda	FUDS	64.500	1.000	74.900	0.014	0.014	0.003	0.000	0.000	119.593	0.000	2576.945
Y027AH	NIMH	Honda	HWY	27.000	0.600	71.400	0.048	0.024	0.016	0.007	0.000	106.615	60.853	1164.409
Y060AH	NIMH	Honda	HWY	60.200	1.000	74.100	0.014	0.014	0.003	0.000	0.000	119.810	0.000	2581.619
C021AH	NIMH	Honda	UC-92	20.500	0.456	50.100	0.087	0.039	0.029	0.013	0.000	150.514	117.990	1046.603
C049AH	NIMH	Honda	UC-92	49.200	0.914	56.200	0.026	0.020	0.006	0.002	0.000	134.526	16.637	2588.973

Table 47: Total Full Fuel Cycle Emission Results for a Compact, light-weight Hybrid Vehicle using a Port Injected Gasoline Engine in the Charge Sustaining Mode

ummary of Vehicle Results														
ss mptions:														
ot l miles Driven per Year			10860							1				
ur ber of Work Days			224											
ou d trip work dist			15											
otal random Driving Dist			7500					SULEV Standard						
egion			LA basin					CO	1	g/ml				
vaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
or rol Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
el ction Criteria			n?????ah											
		Total Emissions (gm/ml)												
yp	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap)	CO2	Gal/year	kWh/year
A 022AH	NIMH	Honda	ART14	22.000	0.000	48.500	0.154	0.061	0.053	0.025	0.000	193.463	223.918	0.000
A1049AH	NIMH	Honda	ART14	48.500	0.000	58.400	0.129	0.068	0.043	0.020	0.000	160.667	185.959	0.000
F3025AH	NIMH	Honda	FW31	25.300	0.000	65.700	0.112	0.047	0.039	0.019	0.000	142.815	165.297	0.000
F3061AH	NIMH	Honda	FW31	60.500	0.000	69.600	0.108	0.044	0.036	0.017	0.000	134.813	156.034	0.000
FH028AH	NIMH	Honda	FUD/HWY	27.500	0.000	69.500	0.108	0.044	0.037	0.018	0.000	135.006	156.259	0.000
FH062AH	NIMH	Honda	FUD/HWY	62.000	0.000	72.200	0.104	0.042	0.036	0.017	0.000	129.958	150.416	0.000
FU030AH	NIMH	Honda	FUDS	29.800	0.000	69.600	0.107	0.043	0.036	0.017	0.000	134.813	156.034	0.000
FU065AH	NIMH	Honda	FUDS	64.500	0.000	74.900	0.101	0.051	0.033	0.015	0.000	125.273	144.993	0.000
H 027AH	NIMH	Honda	HWY	27.000	0.000	71.400	0.105	0.043	0.038	0.017	0.000	131.414	152.101	0.000
H 060AH	NIMH	Honda	HWY	60.200	0.000	74.100	0.102	0.052	0.034	0.016	0.000	126.626	146.559	0.000
U 021AH	NIMH	Honda	UC-92	20.500	0.000	50.100	0.149	0.061	0.051	0.024	0.000	187.284	216.766	0.000
U 049AH	NIMH	Honda	UC-92	49.200	0.000	56.200	0.134	0.068	0.045	0.021	0.000	166.958	193.238	0.000

Table 48: Total Full Fuel Cycle Emission Results for a Compact, light-weight Hybrid Vehicle using Direct Injected Gasoline and Diesel Engines in the Charge Depleting Mode

ummary of Vehicle Results														
sumptions:														
tal miles Driven per Year			10860							1				
nber of Work Days			224											
und trip work dist			15											
al random Driving Dist			7500					SULEV Standard						
gion			LA basin					CO	1	g/ml				
porative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml				
trol Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml				
ection Criteria			n?????ad?											
		Total Emissions (gm/ml)												
e	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
A1048AD	NIMH	Diesel	ART14	41.000	0.828	42.700	0.031	0.479	0.014	0.008	0.000	245.625	43.678	4353.279
1048ADD	NiMH	DI Diesel	ART14	41.000	0.828	42.700	0.031	0.479	0.014	0.008	0.000	245.625	43.678	4353.279
1048ADR	NIMH	DI RFG	ART14	41.000	0.828	42.700	0.031	0.479	0.014	0.008	0.000	245.625	43.678	4353.279
1049ADR	NIMH	DI RFG	ART14	48.500	0.914	64.800	0.016	0.018	0.006	0.002	0.000	141.668	14.429	2783.988
3060ADD	NIMH	DI Diesel	FW31	54.000	0.963	62.100	0.023	0.089	0.005	0.001	0.000	191.428	6.463	3985.811
3025ADR	NIMH	DI RFG	FW31	25.300	0.556	78.600	0.011	0.017	0.015	0.007	0.000	102.252	61.349	1061.147
3061ADR	NIMH	DI RFG	FW31	60.500	1.000	82.800	0.014	0.013	0.003	0.000	0.000	116.223	0.000	2504.331
H061ADD	NIMH	DI Diesel	FUD/HWY	60.800	1.000	96.200	0.014	0.014	0.003	0.000	0.000	121.141	0.000	2610.300
H030ADR	NIMH	DI RFG	FUD/HWY	27.500	0.600	82.500	0.011	0.016	0.014	0.006	0.000	99.091	52.665	1154.705
H061AD	NIMH	Diesel	FUD/HWY	60.800	1.000	96.200	0.014	0.014	0.003	0.000	0.000	121.141	0.000	2610.300
H062ADR	NiMH	DI RFG	FUD/HWY	62.000	1.000	85.600	0.014	0.013	0.003	0.000	0.000	117.143	0.000	2524.159
U030ADR	NIMH	DI RFG	FUDS	29.800	0.640	82.900	0.010	0.015	0.012	0.005	0.000	97.448	47.101	1222.883
U063AD	NiMH	Diesel	FUDS	63.000	1.000	98.300	0.014	0.014	0.003	0.000	0.000	121.574	0.000	2619.623
U063ADD	NIMH	DI Diesel	FUDS	63.000	1.000	107.300	0.014	0.014	0.003	0.000	0.000	121.574	0.000	2619.623
U065ADR	NiMH	DI RFG	FUDS	64.500	1.000	83.400	0.014	0.014	0.003	0.000	0.000	119.593	0.000	2576.945
Y027ADR	NIMH	DI RFG	HWY	27.000	0.600	84.500	0.011	0.016	0.013	0.006	0.000	98.464	51.419	1164.409
Y059AD	NIMH	Diesel	HWY	59.000	0.990	95.900	0.014	0.016	0.003	0.000	0.000	120.825	1.128	2579.252
Y059ADD	NIMH	DI Diesel	HWY	59.000	0.990	110.400	0.014	0.024	0.003	0.000	0.000	120.678	0.979	2579.252
Y060ADR	NIMH	DI RFG	HWY	60.200	1.000	86.500	0.014	0.014	0.003	0.000	0.000	119.810	0.000	2581.619

Table 49: Total Full Fuel Cycle Emission Results for a Compact, light-weight Hybrid Vehicle using Direct Injected Gasoline and Diesel Engines in the Charge Sustaining Mode

Summary of Vehicle Results

Assumptions:														
Total miles Driven per Year			10860											
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.		
Region			LA Basin					CO	1	g/mi		refuel (gm/gal)		0.21
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/mi		Hot soak (gm/trip)		0.36
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/mi		Diurnl (gm/day)		1.7
Selection Criteria			n?????ad?											

Total Emissions (gm/mi)

Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NA1???AD	NiMH	Diesel	ART14	48.000	0.000	73.500	0.024	0.270	0.008	0.001	0.000	147.473	147.755	0.000
NA1???ADD	NiMH	DI Diesel	ART14	48.000	0.000	78.600	0.024	1.443	0.030	0.024	0.000	137.904	138.168	0.000
NA1???ADR	NiMH	DI RFG	ART14	48.000	0.000	64.800	0.013	0.032	0.040	0.019	0.000	144.799	167.593	0.000
NA1049ADR	NiMH	DI RFG	ART14	48.500	0.000	64.800	0.013	0.032	0.040	0.019	0.000	144.799	167.593	0.000
NF3???ADD	NiMH	DI Diesel	FW31	60.000	0.000	104.500	0.018	1.092	0.023	0.018	0.000	103.725	103.923	0.000
NF3025ADR	NiMH	DI RFG	FW31	25.300	0.000	78.600	0.012	0.026	0.032	0.015	0.000	119.376	138.168	0.000
NF3061ADR	NiMH	DI RFG	FW31	60.500	0.000	82.800	0.011	0.025	0.031	0.015	0.000	113.321	131.159	0.000
NFH???ADD	NiMH	DI Diesel	FUD/HWY	61.000	0.000	108.500	0.017	1.052	0.022	0.017	0.000	99.901	100.092	0.000
NFH030ADR	NiMH	DI RFG	FUD/HWY	27.500	0.000	82.500	0.011	0.025	0.031	0.015	0.000	113.733	131.636	0.000
NFH061AD	NiMH	Diesel	FUD/HWY	60.800	0.000	96.200	0.019	0.221	0.006	0.001	0.000	112.674	112.890	0.000
NFH062ADR	NiMH	DI RFG	FUD/HWY	62.000	0.000	85.600	0.011	0.024	0.030	0.014	0.000	109.614	126.869	0.000
NFU030ADR	NiMH	DI RFG	FUDS	29.800	0.000	82.900	0.011	0.025	0.031	0.015	0.000	113.184	131.001	0.000
NFU063AD	NiMH	Diesel	FUDS	63.000	0.000	98.300	0.018	0.202	0.006	0.001	0.000	110.267	110.478	0.000
NFU063ADD	NiMH	DI Diesel	FUDS	63.000	0.000	107.300	0.017	1.062	0.022	0.017	0.000	101.018	101.212	0.000
NFU065ADR	NiMH	DI RFG	FUDS	64.500	0.000	83.400	0.011	0.025	0.030	0.014	0.000	112.505	130.216	0.000
NHY027ADR	NiMH	DI RFG	HWY	27.000	0.000	84.500	0.011	0.024	0.030	0.014	0.000	111.041	128.521	0.000
NHY059AD	NiMH	Diesel	HWY	59.000	0.000	95.900	0.018	0.206	0.006	0.001	0.000	113.027	113.243	0.000
NHY059ADD	NiMH	DI Diesel	HWY	59.000	0.000	110.400	0.017	1.032	0.021	0.016	0.000	98.182	98.370	0.000
NHY060ADR	NiMH	DI RFG	HWY	60.200	0.000	86.500	0.011	0.023	0.030	0.014	0.000	108.473	125.549	0.000

Table 50: Summary of SIMPLEV Simulation Results for Hybrid Vehicles having Weights and Road load Characteristics close to 1996 Models

Vehicle Summary

							Energy Consumption							
				Elec Rang	Ave DOD	Charge	Battery	Wall Plug		Hybrid Emissions				
ype	Battery	Cycle	Fuel	75% DOD	at Charge	Eff	Wh/mi	Wh/mi	ml/unit	ROG	Co	NOx	mpg equiv	
FH118AEV	Li-Ion	FUD/HWY	none	118	0.267	0.970	157	179.8	0	0	0	0	0.0	y
FH129CEV	Li-Ion	FUD/HWY	none	129	0.244	0.970	194	222.1	0	0	0	0	0.0	y
FH047AD	NiMH	FUD/HWY	Diesel	47	0.670	0.722	155	238.5	68	0.002	0.025	0.049	58.8	y
FH047ADD	NiMH	FUD/HWY	Diesel	47	0.670	0.722	155	238.5	84.5	0.021	0.02	0.226	73.0	y
FH047ADR	NiMH	FUD/HWY	RFG	47	0.670	0.722	155	238.5	66.5	0.018	0.011	0.052	66.5	y
FH047AFC	NiMH	FUD/HWY	H2	0	NA	NA	NA	NA	138	0	0	0	138.0	y
FH047AH	NiMH	FUD/HWY	RFG	47	0.670	0.722	155	238.5	56.2	0.015	0.092	0.053	56.2	y
FH047AS	NiMH	FUD/HWY	RFG	47	0.670	0.722	155	238.5	71.5	0	0	0.007	71.5	y
FH051CD	NiMH	FUD/HWY	Diesel	51	0.618	0.704	193	304.7	55.5	0.002	0.031	0.062	48.0	y
FH051CDD	NiMH	FUD/HWY	Diesel	51	0.618	0.704	193	304.7	62.4	0.029	0.028	0.306	53.9	y
FH051CDR	NiMH	FUD/HWY	RFG	51	0.618	0.704	193	304.7	49.1	0.024	0.015	0.035	49.1	y
FH051CFC	NiMH	FUD/HWY	H2	0	NA	NA	NA	NA	116.9	0	0	0	116.9	y
NFH051CH	NiMH	FUD/HWY	RFG	51	0.618	0.704	193	304.7	41.5	0.02	0.124	0.071	41.5	y
NFH051CS	NiMH	FUD/HWY	RFG	51	0.618	0.704	193	304.7	52.7	0	0	0.005	52.7	y
NFH083AEV	NiMH	FUD/HWY	none	83	0.379	0.598	160	297.2	0	0	0	0	0.0	y
NFH091CEV	NiMH	FUD/HWY	none	91	0.346	0.581	197	376.9	0	0	0	0	0.0	y

Table 51a: Comparison of Total and Exhaust Emissions for Various Designs of Mid-size Cars

	Charge Depleting			Charge Sustaining		
Mid-size Cars	gm/mi: (total)			gm/mi: (total)		
Hybrid Design (gasoline engine)	NMOG	No_x	CO_2	NMOG	No_x	CO_2
Evap. Emissions		(LA State)			(LA State)	
Present	.017	.032	158	.175	.083	226
1/3 Present	.013	.032	158	.121	.083	226
1/10 Present	.012	.032	158	.102	.083	226
Exhaust Emissions	.001	.032	-	.020	.071	-
Conventional Design						
Exhaust Emissions						
ULEV	-	-	-	.04	.2	-
SULEV	-	-	-	.008	.02	-
Total Emissions (present evap)						
ULEV	-	-	-	.218	.235	402
SULEV	-	-	-	.167	.047	-
Electric Vehicle Designs						
Nickel Mt. Hydride						
LA Basin	.004	.022	190	-	-	-
LA Total	.007	.137	190	-	-	-
Lithium-ion						
LA Basin	.002	.013	112	-	-	-
LA Total	.005	.089	112	-	-	-

Table 51b: Comparison of Total and Exhaust Emissions for Various Designs of Compact-size Cars

	Charge Depleting			Charge Sustaining		
Compact Cars		gm/mi: (total)			gm/mi: (total)	
Hybrid Design (gasoline engine)	NMOG	No_x	CO_2	NMOG	No_x	CO_2
Evap. Emissions		(LA State)			(LA State)	
Present	.021	.026	125	.161	.062	167
1/3 Present	.015	.026	125	.107	.062	167
1/10 Present	.013	.026	125	.088	.062	167
Exhaust Emissions	.002	-	-	.015	.053	-
Conventional Design						
Exhaust Emissions						
ULEV	-	-	-	.04	.20	-
SULEV	-	-	-	.008	.02	-
Electric Vehicle Designs						
Nickel Mt. Hydride						
LA Basin	.003	.017	150	-	-	-
LA Total	.006	.123	150	-	-	-
Lithium-ion						
LA Basin	.002	.010	112	-	-	-
LA Total	.005	.089	112	-	-	-

Table 52: Emissions Breakdowns for Various Low-emission ICE Vehicles

		HYBRID EMISSIONS					
Detailed Vehicle Results							
Control Strategy		0	0 for charge sustaining, 1 for charge depleting				
Evaporative Emissio		1	0 for none, 1 for present value				
Running or Total		0	0 for total, 1 for running				
						Random M	7500
Veh Type:	**Mid-size, SULEV**		Drive Cycl	FUD/HWY		Work Miles	15
Region:	Iastate		Mi. (elec)	0		kWh/year	0
Fuel:	RFG		Mi. (Hybrid	10860		Gal/year	310.29
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrea	0.000	0.000	0.000	0.000	0.000	0.000	
Hybrid							
Upstrea	0.007	0.027	0.038	0.000	0.000	32.254	
Running	1.000	0.020	0.008	0.000	0.000	235.8	
Evap	0.000	0.000	0.121	0.000	0.000	0.0	
Total	1.007	0.047	0.167	0.000	0.000	268.1	
Tot (gm/yr)	10937.6	513.8	1814.2	0.0	0.0	2911395.5	
Tot (gm/mi	1.007	0.047	0.167	0.000	0.000	268.084	
Veh Type:	**Compact, SULEV**		Drive Cycl	FUD/HWY		Random M	7500
Region:	Iastate		Mi. (elec)	0		Work Miles	15
Fuel:	RFG		Mi. (Hybrid	10860		kWh/year	0
						Gal/year	212.94
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrea	0.000	0.000	0.000	0.000	0.000	0.000	
Hybrid							
Upstrea	0.005	0.019	0.026	0.000	0.000	22.135	
Running	1.000	0.020	0.008	0.000	0.000	161.8	
Evap	0.000	0.000	0.121	0.000	0.000	0.0	
Total	1.005	0.039	0.155	0.000	0.000	184.0	
Tot (gm/yr)	10913.2	420.7	1685.7	0.0	0.0	1998016.5	
Tot (gm/mi	1.005	0.039	0.155	0.000	0.000	184	
Veh Type:	**Mid-size, ULEV**		Drive Cycl	FUD/HWY		Random M	7500
Region:	Iastate		Mi. (elec)	0		Work Miles	15
Fuel:	RFG		Mi. (Hybrid	10860		kWh/year	0
						Gal/year	402.22
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrea	0.000	0.000	0.000	0.000	0.000	0.000	
Hybrid							
Upstrea	0.009	0.035	0.057	0.000	0.000	41.811	
Running	1.700	0.200	0.040	0.000	0.000	305.7	
Evap	0.000	0.000	0.121	0.000	0.000	0.0	
Total	1.709	0.235	0.218	0.000	0.000	347.5	
Tot (gm/yr)	18562.6	2556.4	2367.5	0.0	0.0	3774031.2	
Tot (gm/mi	1.709	0.235	0.218	0.000	0.000	348	

Table 53: Total Emissions for Fuel Cell powered fueled with Compressed Hydrogen from Reformed Natural Gas

Summary of Vehicle Results															
Assumptions:															
Total miles Driven per Year			10860												
Number of Work Days			224												
Round trip work dist			15												
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.			
Region			LA Basin					CO	1	g/ml		refuel (gm/gal)		0.21	
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml		Hot soak (gm/trip)		0.36	
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml		Diurnl (gm/day)		1.7	
Selection Criteria			?fh????fc												
		Total Emissions (gm/ml)													
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year	
NFH047AFC	NiMH	Fuel Cell	FUD/HWY	0.000	0.000	138.000	0.029	0.152	0.021	0.000	0.000	84.746	78.696	0.000	
NFH051CFC	NiMH	Fuel Cell	FUD/HWY	0.000	0.000	116.900	0.034	0.180	0.025	0.000	0.000	100.043	92.900	0.000	

Table 54: Total Emissions for Compact-size Hybrid Vehicles in the Charge Sustaining Mode

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860											
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.		
Region			LA state					CO	1	g/ml		refuel (gm/gal)		0.21
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml		Hot soak (gm/trip)		0.36
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml		Diurnl (gm/day)		1.7
Selection Criteria			nfh047a??											
		Total Emissions (gm/mi)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap)	CO2	Gal/year	kWh/year
NFH047AD	NiMH	Diesel	FUD/HWY	47.000	0.000	68.000	0.027	0.054	0.010	0.002	0.000	159.401	159.706	0.000
NFH047ADD	NiMH	DI Diesel	FUD/HWY	47.000	0.000	84.500	0.022	0.230	0.027	0.021	0.000	128.275	128.521	0.000
NFH047ADR	NiMH	DI RFG	FUD/HWY	47.000	0.000	66.500	0.014	0.059	0.039	0.018	0.000	141.097	163.308	0.000
NFH047AFC	NiMH	Fuel Cell	FUD/HWY	0.000	0.000	138.000	0.029	0.152	0.021	0.000	0.000	84.746	78.696	0.000
NFH047AH	NiMH	Honda	FUD/HWY	47.000	0.000	56.200	0.095	0.062	0.040	0.015	0.000	166.956	193.238	0.000
NFH047AS	NiMH	Stirling	FUD/HWY	47.000	0.000	71.500	0.002	0.014	0.019	0.000	0.000	131.230	151.888	0.000

Table 55: Total Emissions for Compact-size Hybrid Vehicles in the Charge Depleting Mode

Summary of Vehicle Results														
Assumptions:														
Total miles Driven per Year			10860											
Number of Work Days			224											
Round trip work dist			15											
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.		
Region			LA state					CO	1	g/ml		refuel (gm/gal)		0.21
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml		Hot soak (gm/trip)		0.36
Control Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml		Diurnl (gm/day)		1.7
Selection Criteria			nfh047a??											
		Total Emissions (gm/ml)												
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year
NFH047AD	NIMH	Diesel	FUD/HWY	47.000	0.895	68.000	0.020	0.026	0.005	0.000	0.000	124.337	16.792	2318.035
NFH047ADD	NIMH	DI Diesel	FUD/HWY	47.000	0.895	84.500	0.020	0.044	0.007	0.002	0.000	121.065	13.513	2318.035
NFH047ADR	NiMH	DI RFG	FUD/HWY	47.000	0.895	66.500	0.019	0.026	0.008	0.002	0.000	122.413	17.171	2318.035
NFH047AFC	NIMH	Fuel Cell	FUD/HWY	0.000	0.000	138.000	0.029	0.152	0.021	0.000	0.000	84.746	78.696	0.000
NFH047AH	NiMH	Honda	FUD/HWY	47.000	0.895	56.200	0.027	0.026	0.008	0.002	0.000	125.132	20.318	2318.035
NFH047AS	NIMH	Stirling	FUD/HWY	47.000	0.895	71.500	0.018	0.021	0.006	0.000	0.000	121.375	15.970	2318.035

Table 56: Total Emissions for Mid-size Hybrid Vehicles in the Charge Depleting Mode

Summary of Vehicle Results															
Assumptions:															
Total miles Driven per Year			10860												
Number of Work Days			224												
Round trip work dist			15												
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.			
Region			LA state					CO	1	g/ml		refuel (gm/gal)		0.0699	
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml		Hot soak (gm/trip)		0.12	
Control Strategy			1	0 = sustaining, 1 = depleting				ROG	0.008	g/ml		Diurnl (gm/day)		0.566	
Selection Criteria			nfh051c??												
		Total Emissions (gm/ml)													
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybrid	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year	
NFH051CD	NiMH	Diesel	FUD/HWY	51.000	0.932	55.500	0.026	0.031	0.006	0.000	0.000	156.444	13.394	3082.951	
NFH051CDD	NiMH	DI Diesel	FUD/HWY	51.000	0.932	62.400	0.025	0.048	0.008	0.002	0.000	154.966	11.913	3082.951	
NFH051CDR	NiMH	DI RFG	FUD/HWY	51.000	0.932	49.100	0.025	0.029	0.009	0.002	0.000	156.156	15.139	3082.951	
NFH051CFC	NiMH	Fuel Cell	FUD/HWY	0.000	0.000	116.900	0.034	0.180	0.025	0.000	0.000	100.043	92.900	0.000	
NFH051CH	NiMH	Honda	FUD/HWY	51.000	0.932	41.600	0.032	0.032	0.009	0.001	0.000	158.552	17.912	3082.951	
NFH051CS	NiMH	Stirling	FUD/HWY	51.000	0.932	52.700	0.023	0.027	0.007	0.000	0.000	155.263	14.105	3082.951	

Table 57: Total Emissions for Mid-size Hybrid Vehicles in the Charge Sustaining Mode

Summary of Vehicle Results															
Assumptions:															
Total miles Driven per Year			10860												
Number of Work Days			224												
Round trip work dist			15												
Total random Driving Dist			7500					SULEV Standard				REFUEL/EVAP EMIS.			
Region			LA state					CO	1	g/ml		refuel (gm/gal)		0.21	
Evaporative Emissions			0	0=none, 1=present average values				NOx	0.02	g/ml		Hot soak (gm/trip)		0.36	
Control Strategy			0	0 = sustaining, 1 = depleting				ROG	0.008	g/ml		Diurnl (gm/day)		1.7	
Selection Criteria			nfh051c??												
		Total Emissions (gm/ml)													
Type	Battery	Engine	Drive Cycle	Elec Range	Frac Elec	Mpg (hybri	CO	NOx	ROG(tot)	ROG(exh)	ROG(evap	CO2	Gal/year	kWh/year	
NFH051CD	NiMH	Diesel	FUD/HWY	51.000	0.000	55.500	0.034	0.068	0.012	0.002	0.000	195.302	195.676	0.000	
NFH051CDD	NiMH	DI Diesel	FUD/HWY	51.000	0.000	62.400	0.030	0.311	0.038	0.029	0.000	173.706	174.038	0.000	
NFH051CDR	NiMH	DI RFG	FUD/HWY	51.000	0.000	49.100	0.018	0.045	0.052	0.024	0.000	191.099	221.181	0.000	
NFH051CFC	NiMH	Fuel Cell	FUD/HWY	0.000	0.000	116.900	0.034	0.180	0.025	0.000	0.000	100.043	92.900	0.000	
NFH051CH	NiMH	Honda	FUD/HWY	51.000	0.000	41.500	0.128	0.083	0.053	0.020	0.000	226.095	261.687	0.000	
NFH051CS	NiMH	Stirling	FUD/HWY	51.000	0.000	52.700	0.003	0.014	0.026	0.000	0.000	178.045	206.072	0.000	

Table 58: Total Emissions for Electric and Hybrid Vehicles with 1996 Evaporative and Refueling Emissions

		HYBRID EMISSIONS					
Detailed Vehicle Results							
Control Strategy		0	0 for charge sustaining, 1 for charge depleting				
Evaporative Emissior		1	0 for none, 1 for present value				
Running or Total		0	0 for total, 1 for running				
	Compact EV,					Random M	7500
Veh Type:	NFH NimtHyd bat.		Drive Cycl	FUD/HWY		Work Miles	15
Region:	lastate		Mi. (elec)	10860		kWh/year	3227.8
Fuel:	none		Mi. (Hybrid	0		Gal/year	0
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrean	0.026	0.123	0.006	0.010	0.092	149.798	
Hybrid							
Upstrean	0.000	0.000	0.000	0.000	0.000	0.000	
Running	0.000	0.000	0.000	0.000	0.000	0.0	
Evap	0.000	0.000	0.000	0.000	0.000	0.0	
Total	0.000	0.000	0.000	0.000	0.000	0.0	
Tot (gm/yr)	287.3	1336.3	67.8	106.5	1003.8	1626801.9	
Tot (gm/mi	0.026	0.123	0.006	0.010	0.092	149.798	
	Mid-size HEV						
Veh Type:	n, DI Gas.		Drive Cycl	FUD/HWY		Random M	7500
Region:	lastate		Mi. (elec)	0		Work Miles	15
Fuel:	RFG		Mi. (Hybrid	10860		kWh/year	0
						Gal/year	221.18
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrean	0.000	0.000	0.000	0.000	0.000	0.000	
Hybrid							
Upstrean	0.005	0.019	0.031	0.000	0.000	22.992	
Running	0.015	0.035	0.024	0.000	0.000	168.1	
Evap	0.000	0.000	0.121	0.000	0.000	0.0	
Total	0.020	0.054	0.176	0.000	0.000	191.1	
Tot (gm/yr)	218.2	591.5	1916.7	0.0	0.0	2075332.9	
Tot (gm/mi	0.020	0.054	0.176	0.000	0.000	191	
	Compact-size HEV,						
Veh Type:	nth04/ar		Drive Cycl	FUD/HWY		Random M	7500
Region:	lastate'	Port I Gas.	Mi. (elec)	0		Work Miles	15
Fuel:	RFG		Mi. (Hybrid	10860		kWh/year	0
						Gal/year	193.24
			Emissions (gm/mi)				
	CO	NOx	ROG	PM	SOx	CO2	
Electric							
Upstrean	0.000	0.000	0.000	0.000	0.000	0.000	
Hybrid							
Upstrean	0.004	0.017	0.027	0.000	0.000	20.087	
Running	0.092	0.053	0.015	0.000	0.000	146.9	
Evap	0.000	0.000	0.121	0.000	0.000	0.0	
Total	0.096	0.070	0.164	0.000	0.000	167.0	
Tot (gm/yr)	1047.4	760.3	1776.3	0.0	0.0	1813146.7	
Tot (gm/mi	0.096	0.070	0.164	0.000	0.000	167	

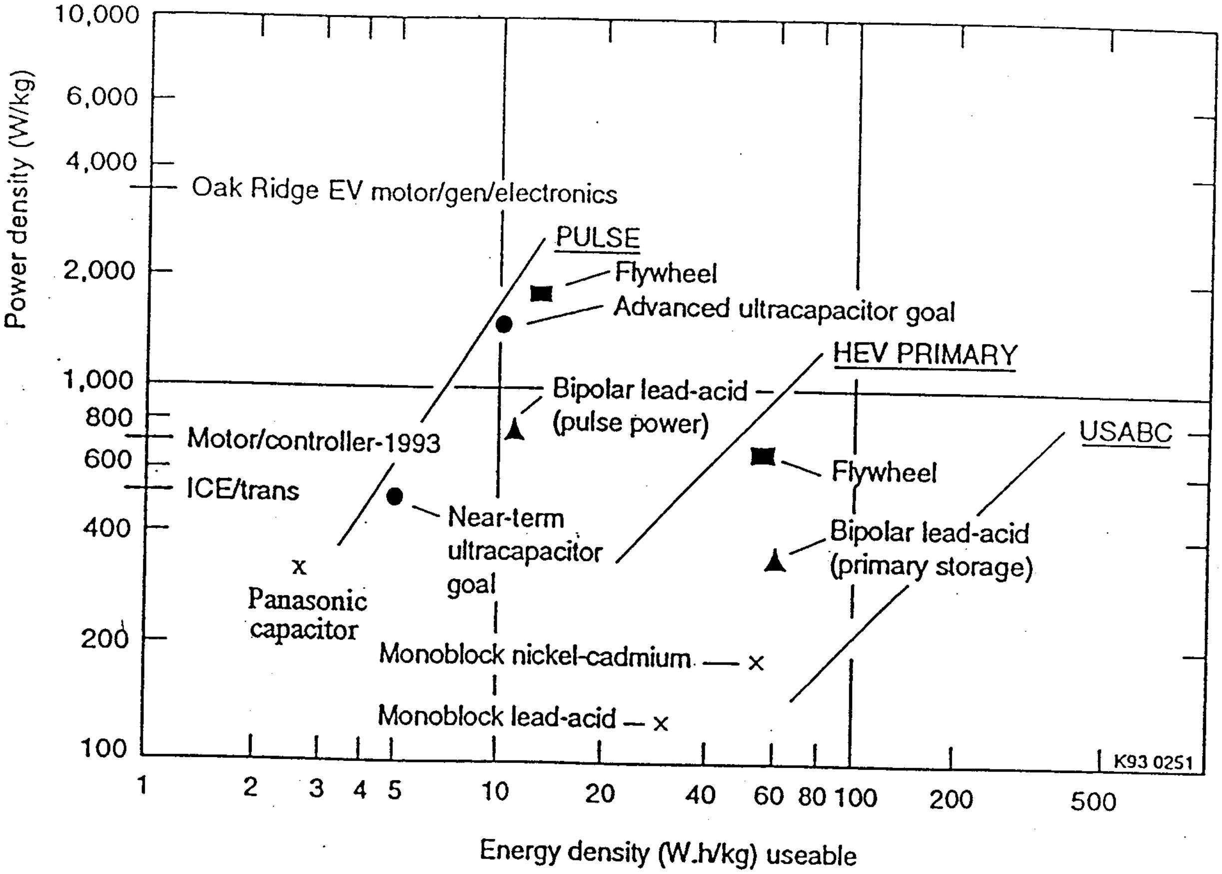
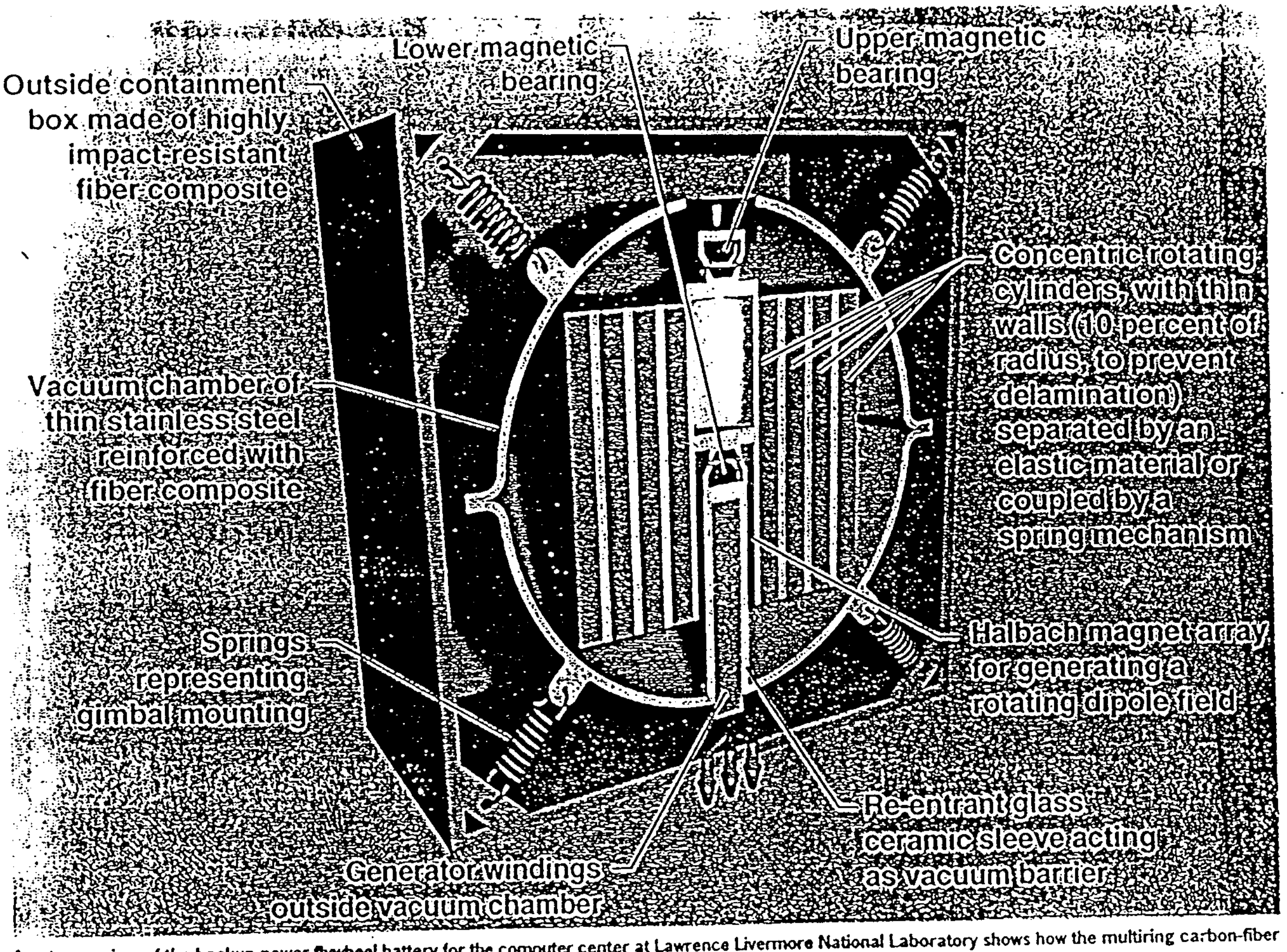
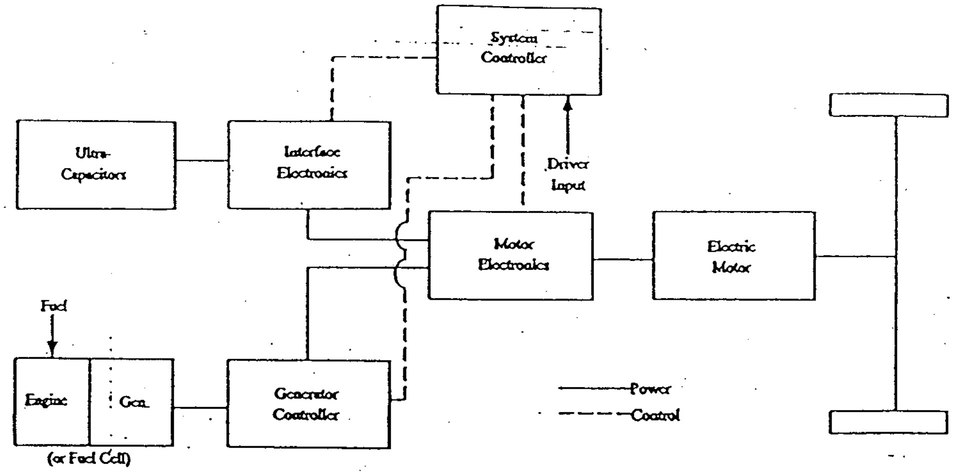


Figure 1 : Ragone Plot for Primary Energy Storage and Pulse Power Units



A cutaway view of the backup-power flywheel battery for the computer center at Lawrence Livermore National Laboratory shows how the multiring carbon-fiber composite rotor spins almost friction-free on a magnetic bearing while suspended in an evacuated chamber.

Figure 2 ; Flywheel System


SERIES HYBRID DRIVELINE SCHEMATIC

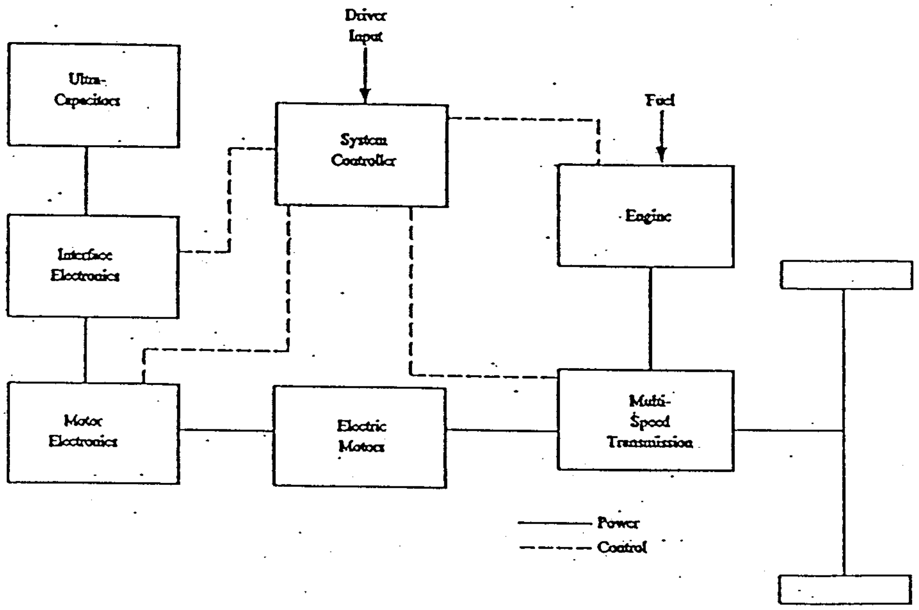
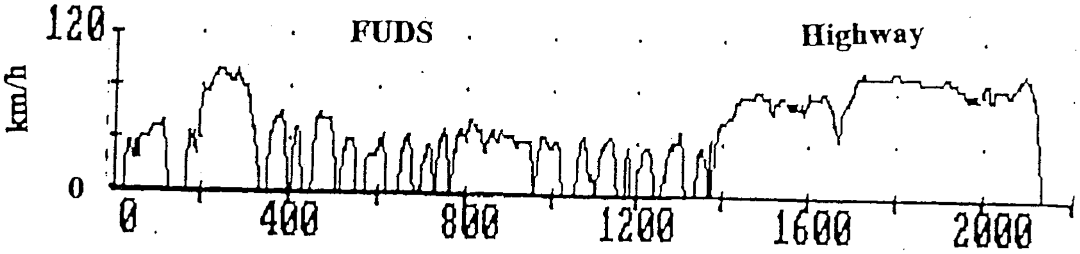
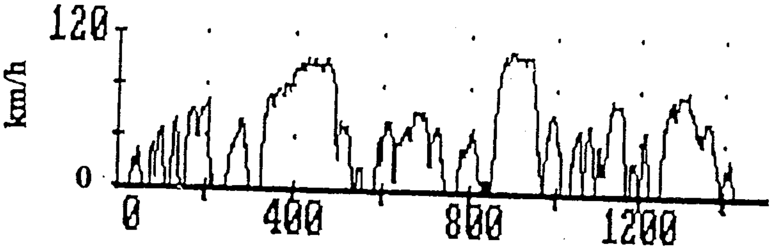

PARALLEL HYBRID DRIVELINE SCHEMATIC

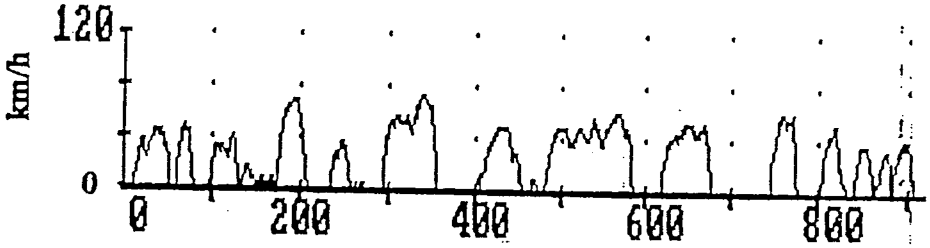
Figure 3 : Hybrid Powertrain Schematics for Series and Parallel Configurations



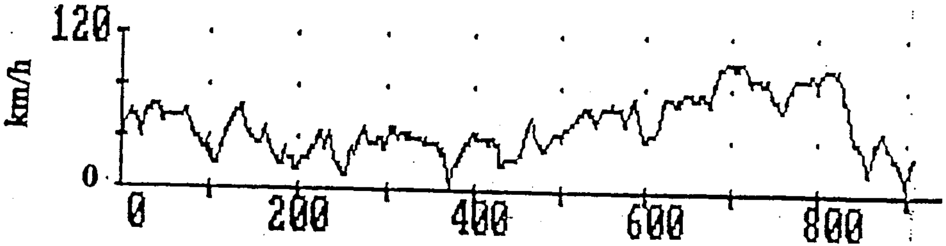
FUDSWAY



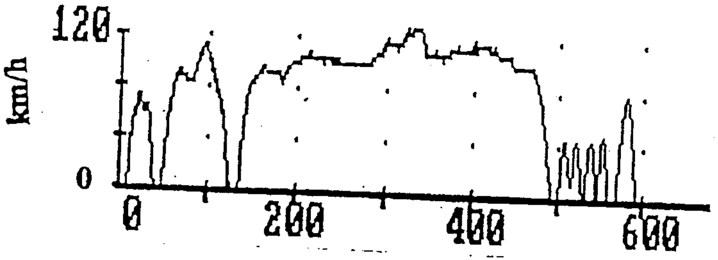
UC-92



ART 14



FW31



US-06

Figure 4: Driving Cycle Speed vs. time Schedules

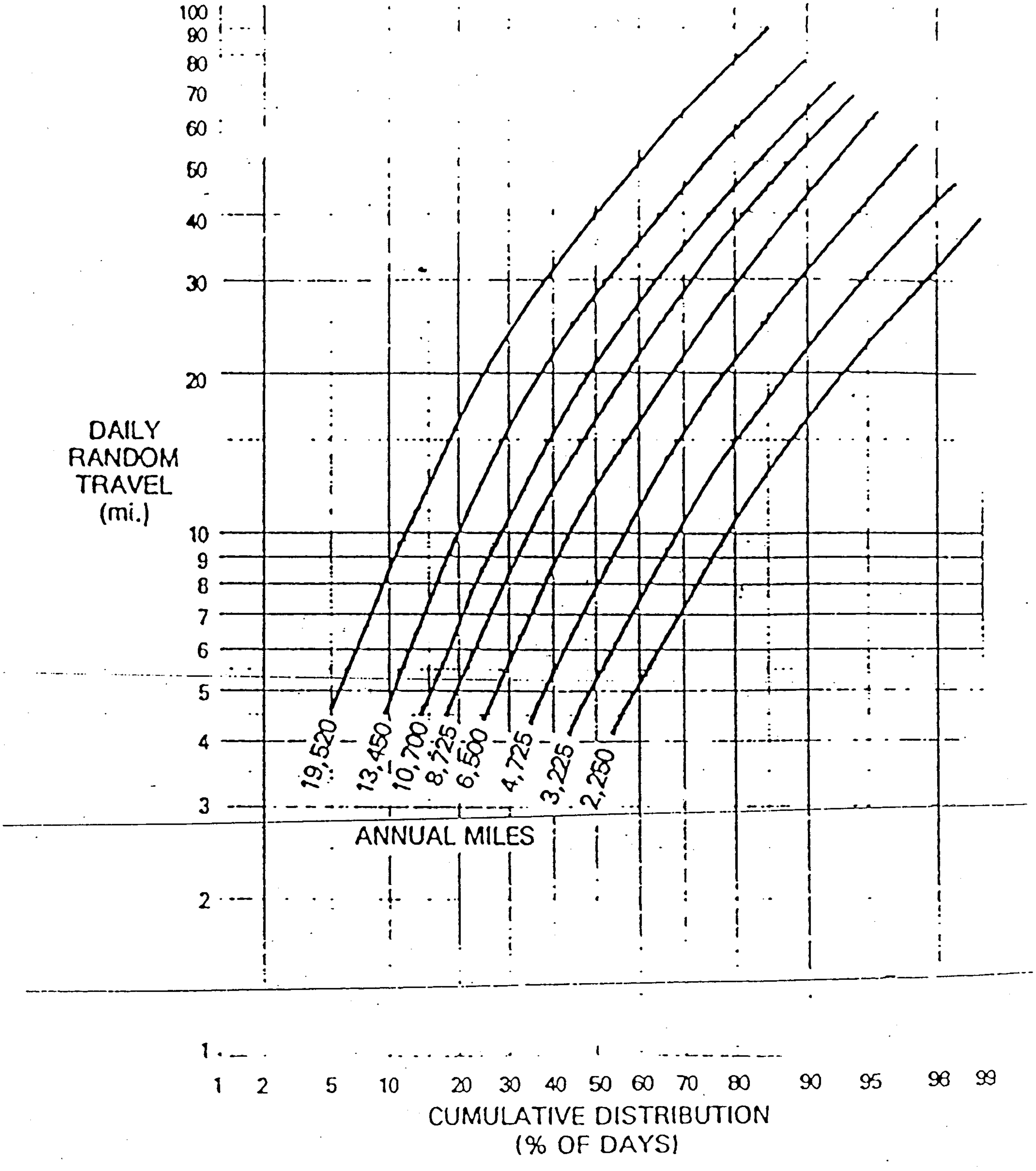


Figure 5 : Daily Random All-purpose Travel - as a function of Annual Miles

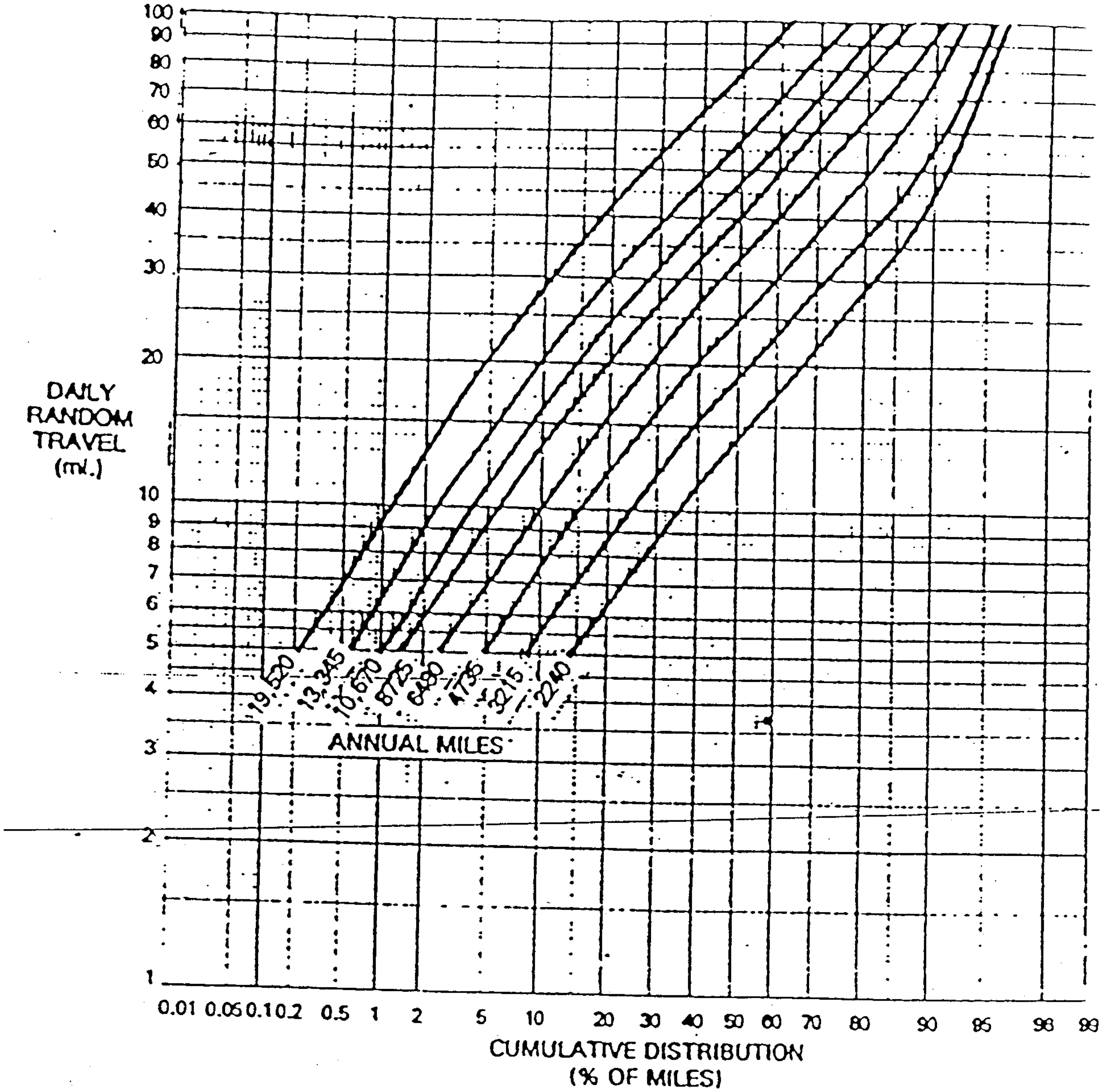


Figure 6 : Daily Random All-purpose Travel - percent of Vehicle Miles - as a function of Annual Miles