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The Future of Hybrid-Electric ICE Vehicles and Fuels Implications

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Executive Summary

The Future of Hybrid-Electric ICE Vehicles and Fuels Implications

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Objectives

The objectives of the study were to identify developments in hybrid-electric driveline technologies and hybrid vehicles using internal combustion engines (ICE) and to assess the effects of these developments on vehicle fuel economy and fuel quality over the next twenty years. The emphasis in the study is on light-duty vehicles including passenger cars, light trucks, vans, and SUVs

Scope of the Work

The study focused on the following general areas: (1) formulation of a taxonomy/framework for characterizing hybrid-electric driveline and vehicle designs, (2) in-depth analysis of the characteristics of specific hybrid vehicle designs in terms of acceleration, fuel economy, emissions, fuel quality requirements, and incremental cost utilizing vehicle simulation programs and detailed cost breakdowns based on the cost of the electric drive components, (3) summary of the marketing pathways for hybrid vehicles and projected effects of those markets on the fuels business in the next twenty years, (4) identification of additional work on vehicle modeling, new engine developments and fuel requirements, energy and environmental policies, and component cost projections required to reduce uncertainties in the fuels business projections.

Approach

For each of the vehicle classes considered in the study (compact and mid-size cars and mid-size SUVs), the characteristics of a conventional ICE powered vehicle were determined and hybrid–electric vehicles having the same size, road load parameters, performance, and utility were conceptualized. Only parallel hybrid drivelines, which permit the engine to drive directly to the wheels when required by the control strategy, were considered in this study. The operation of each of the conventional and hybrid vehicles were then simulated for various driving cycles using the **Advisor 2002** computer program. Two types of hybrid –electric vehicles were conceptualized. One, termed a **mild** hybrid had a relatively small electric drive system in that the electric motor supplied only about 15% of the total power of the driveline. In a second set of hybrid vehicles, termed **full** hybrids, the engine and electric motor supplied close to the same power. It was expected that the **mild** hybrid would save less fuel than the **full** hybrid, but the incremental cost of the **mild** hybrid compared to the ICE conventional vehicle would be significantly less than that of the **full** hybrid. Computer simulations were run for the US driving cycles (FUDS and Highway), the Japanese 10/15 cycle, and the European ECE-EUDC cycle. Each vehicle class and hybrid driveline were simulated for three engines- a baseline port fuel injected (PFI) gasoline engine, an advanced PFI lean-burn gasoline engine based on the Honda Insight engine, and a turbo-charged direct injected diesel engine based on the Audi 2.5L engine. The fuel economy for each of the vehicles and drivelines was determined from the vehicle simulations using **Advisor** and the differences between the fuel economies of the hybrid and conventional ICE vehicles calculated for each of the driving cycles. All the vehicles utilized a continuously variable transmission (CVT) as such transmissions appear to be well suited for hybrid vehicles designed to maintain engine operation near the maximum engine efficiency.

A spreadsheet economic model was developed that could be used to assess the relative economic attractiveness of the vehicles using the hybrid-electric drivelines and advanced engines for various values of fuel price, discount rate, and vehicle use characteristics (miles per years and years of use). The key inputs to the spreadsheet in addition to the vehicle design parameters are the calculated fuel economy and the unit component cost for the engines and electric driveline components, including the battery. The spreadsheet model was run and the fuel saved, breakeven gasoline price and net cost savings (or additional cost) of ownership of each of the hybrid vehicles determined. These results can be used to assess the marketability of the various advanced driveline systems for each of the vehicles classes and designs.

Results

The key results of the study are the fuel economy improvements predicted for hybridizing the various vehicles and the economic attractiveness of hybridization expressed as fraction of the fuel saved and the breakeven fuel price. All of these parameters vary with vehicle class, engine type, and driving cycle. Fuel economy results are shown in Tables S-1 and S-2 for the mid-size car. Table S-1 presents the fuel economy values and Table S-2 gives the fuel economy improvement factors. Note that hybridization has the potential to improve fuel economy by at least 50% for urban driving cycles and 15-25% for highway driving. As expected the improvements are larger for **full** hybrid than for the **mild** hybrid drivelines. The improvements are largest (percentage-wise) for the PFI gasoline engine with those for the advanced PFI lean-burn gasoline and turbo-charged diesel engine being about the same. It is expected the strictest emission standards (SULEV in California) will be able to be meet using all the gasoline engines, but reaching those standards (especially for NOx and particulates) with the diesel engines will be difficult and well beyond the present state-of-the-art. The fuel economy results indicate that the fuel economy potential of vehicles using the advanced lean-burn gasoline engine are close to those of vehicles using diesel engines. This conclusion should be viewed with caution because the engine map data for both the lean-burn and high speed diesel engines are very limited and may not reflect the characteristics of the best present diesel engines or the future development of the lean-burn gasoline engines. It should also be noted that the results presented in this report were not the result of optimizing either the vehicle design or control strategy. The generic control strategies available in **Advisor 2002** were used and they were undoubtedly more optimum for some vehicle designs than for others. This is likely partly the reason for the differences in the relative improvements for the various vehicles and driving cycles.

The economic attractiveness parameters are summarized in Table S-3, S-4, and S-5. Table S-3 presents fuel saving and breakeven fuel price results for the composite FUDS/HW and European ECE-EUDV driving cycles for **full** and **mild** hybrids for various vehicle classes and engines. Results in Table S-3 are shown for the reference conventional ICE vehicle having the baseline PFI gasoline engine (CV/PFI) and for the reference vehicle having the advanced engine (CV/Adv.). The fuel savings for the CV/Adv cases are the result of hybridizing the driveline in each vehicle as the engine technology remained the same. The **full** hybrid designs yield the largest fuel saving fraction in all cases, but the **mild** hybrid vehicle designs have a lower breakeven fuel price. For the mid-size car and mid-SUV, the fuel savings potential of hybridization is 30-40% for vehicles using PFI engines like those currently being marketed. Higher fuel savings in the **mild** hybrids can be expected using ultracapacitors for energy storage than using nickel metal hydride batteries.

Tables S-4 and S-5 summarize the cost results, including the differential cost to the consumer of the hybrid vehicles, for the three engines types and vehicle classes studied. The results presented permit the calculation of the effective value ($/gal) of the fuel saved based on the differential cost of the hybrid driveline compared to that of the conventional vehicles. The effective fuel price calculations were done for a total vehicle mileage of 100,000 miles. Note that the trends of the fuel price results follow closely those of the breakeven fuel price for a vehicle use period of 8 years, 12000 miles/yr. The economic results in Table S-4 have as the baseline vehicle for all engines a conventional ICE vehicle using the gasoline PFI engine. Those in Table S-5 have as the baseline vehicle a conventional ICE vehicle using the same engine type as in the hybrid vehicle. Comparing Tables S-4 and S-5 indicates the cost effectiveness of hybridizing for each of the engine types. From the tables, it is clear that it is most cost effective to hybridize vehicles using the PFI engine and least cost effective to hybridize vehicles using the lean-burn engine. This occurs because the lean burn engine is more efficient, shows a relatively small region of low efficiency on its torque-speed map, and cost only slightly more than the PFI engine. Hybridizing vehicles using the diesel engines is less cost effective than vehicles using the gasoline PFI engines, but more cost effective than using the lean burn engine. This is the case because the diesel engine is the highest cost engine and has a relatively small region of high efficiency compared to the lean burn engine.

The breakeven gasoline prices shown in Tables S-4 (using the PFI engine vehicles as the baseline) indicate that the fuel price is comparable to present gasoline prices ($1.25-1.50/gal) for the **mild** hybrid vehicles and much higher than current gasoline prices for the **full** hybrid designs. The projected breakeven gasoline prices are highly dependent on the component costs assumed. For example, increasing the assumed costs of the electric motor/electronics in the mild hybrids by 25% results in an increase of the breakeven gasoline price of about 15-20% for all the vehicle types. The breakeven gasoline prices of $1.25-$1.50/gal are far below the gasoline prices in Europe and Japan. The breakeven fuel price results shown in Tables S-3 and S-5 show clearly that the selection of the baseline ICE vehicle has a large effect on the breakeven price for all vehicle classes and engine types.

Fuels implications

Various aspects of how hybrid vehicle operation might lead to the need for special fuels and lubrications in future vehicles were identified in this study. It was concluded that none of the fuel/lube issues seemed to be critical in the near term with the hybrid vehicles using engines much like those in conventional ICE vehicles. To justify this conclusion it is noted that both Honda and Toyota have begun to market hybrid vehicles in the United States and that those vehicles are using the same fuel (gasoline) as the conventional ICE vehicles. As far as is known, the available gasoline seems to work well in the vehicles resulting in good fuel economy improvements and smooth operation. It is expected that the marketed hybrids will have the same low and infrequent maintenance as conventional vehicles. The long warranties (80-100K miles) offered by the manufacturers on the hybrid driveline do not seem to reflect any uncertainty on their part concerning the durability of the engine and transmission. In the case of the Honda Insight, it is recommended that a super-low viscosity oil be used to take full advantage of the low friction characteristics of the engine. That oil is presently commercially available. This experience with fuels and lubes in hybrid vehicles currently in use seems to indicate that no drastic changes in fuel/lube are necessary to permit hybrids to be sold and used by consumers.

While there do not seem to be significant short-term fuel issues, there could be important longer-term issues with further work on the development of hybrid vehicles and special engines for those vehicles. The optimization of combustion systems and hybridization could have an impact on future fuel requirements because the engines in hybrid vehicles operate in an on-off mode and at high torque and in a relatively narrow RPM range. Further testing and more extensive field experience with hybrid vehicles are needed before it will be possible to determine for sure if hybrid vehicles do have special fuel and lube requirements. Also further work/testing is needed to determine whether greater fuel economy improvements would result from the use of special fuels/lubricants in hybrids. This is especially true with respect to the advanced lean-burn and GDI engines for which there is very little field experience even in conventional ICE vehicles. Hybridization could also impact the relative demand for gasoline and diesel fuel.

Marketing Hybrid Vehicles (Present and Future)

It is difficult to assess clearly the plans of the auto companies in Europe, Japan, and the United States for the development and marketing of light-duty hybrid-electric vehicles, including vans and SUVs. There have been rather frequent news releases by the United States automakers regarding their plans to develop and eventually market hybrid vehicles, but in most cases during the period of development it was announced or rumored that the automaker had concluded that the fuel savings where too small to justify the additional cost of the hybrid vehicle and thus plans to market the vehicle would be delayed or dropped. At the present time, the only hybrid that has been announced by a U.S. automaker and remains on track for marketing is the Escape SUV from Ford. It is expected that Toyota and Honda will continue to market their hybrids indefinitely and that both companies will expand their hybrid vehicle line to include mid-size cars and small/mid SUVs and mini-vans. Toyota currently markets the Estima, a mini-van, in Japan. With the success of Toyota and Honda in marketing hybrids in the smaller vehicle classes, it is somewhat surprising that other companies have not announced firm plans to market hybrid vehicles in various vehicle classes. Most of the "talk" of hybrids involves development of larger vehicles, particularly SUVs which have relatively low fuel economy and sell at a premium price. It seems likely the first hybrid vehicles from the U.S. automakers will be SUVs and pick-up trucks.

A number of companies worldwide are developing vehicles that utilize a 42V electrical system. This is being done primarily to permit a significant increase in power to drive vehicle accessories. Development of the 42V systems will enhance the ability of companies to develop higher voltage, more powerful hybrid drivelines, but even though the 42V systems can result in small fuel economy improvements (about 10% at most), they are not considered hybrid drivelines in the context of this study. Marketing of vehicles using the 42V electrical system has started in Japan and Europe, but the mass marketing of those vehicles by most automakers seems to be at least 5 years in the future.

Uncertainties/future work

The areas of largest uncertainty in the present work are related to the engine characteristics and component costs, especially the electric driveline components. The fuel economy improvement potential of hybridization depends critically on the details of the engine maps (bsfc vs. engine torque and RPM) because the presence of the electric motor and energy storage in the hybrid driveline permits the control of the system (engine and electric motor) to achieve near maximum efficiency of the engine. Detailed knowledge of the engine map is thus needed to optimize the system control strategy to maximize fuel economy for various driving cycles. It was necessary in this study to use the engine maps currently available in **Advisor** even though they were not explicitly for recent or advanced engines that can be exploited in the future hybrid vehicles considered in this study. Future work could make direct use of the engine data currently be obtained at Argonne National Laboratory as it is unlikely detailed engine data will become available from the auto manufacturers.

At the present time there is considerable uncertainty concerning the costs of the electric driveline components – the electric motor, power electronics, and batteries/ ultracapacitors. The costs of the components are highly dependent on the assumed level of maturity of the technology and the volume of production. In addition, in determining the impact of the hybrid driveline components on the sticker price of the vehicle, it is necessary to assume a markup factor to apply to the cost of the components to the OEM. In this study, it was assumed that all the technologies were mature and in high volume production and that the markup factor was 1.75-2 for the driveline components. Realizing the uncertainty of the cost inputs the spreadsheet economic model was configured such that the user could easily change the inputs from the keyboard prior to making a run if desired. It is certainly true that the uncertainties in the costs of the driveline components will change the values of the incremental costs of the hybrid vehicles and the breakeven gasoline price, but it is unlikely that they will alter the basic trends in the results. That is that **mild** hybrids are more economically attractive than **full** hybrids and that hybrid vehicles can be marketed successful at current fuel prices in the United States, Europe, and Japan.

Table S-1: Fuel Economy Simulation Results from Advisor for Mid-size Cars - Full and Mild hybrids and Conventional ICE – using Various Engines

				Mpg		
Type of driveline	Engine type	FUDS	Highway	US06	Japan 10/15	ECE-EUDC
Full hybrid	Gasoline PFI	35.8	44.2	30.0	33.2	35.0
	Lean burn	44.3	55.8	37.5	40.1	44.4
	TC Diesel	40.1(45.1)	53.7(60.4)	38.3(43)	36(41)	40(45)
Mild hybrid	Gasoline PFI Bat.	33.8	37.3	25.1	31.8	30.7
	Ultracap	37.2	42.9	29.4	34.2	34.7
	Lean burn Bat.	42.1	48.7	35.1	39.3	41.7
	Ultracap	45.4	54.8	38.7	43.0	45.0
	TC Diesel Bat.	37.3(42)	45(50.6)	33.2(37)	34(38)	36(41)
	Ultracap	41.2(46.3)	51.9(58.4)	36.8(41)	36(41)	40(45)
Convent. ICE –CVT	Gasoline PFI	20.4	32.3	23.3	16.5	20.2
	Lean burn	29.7	44.4	29.4	25.0	29.5
	TC Diesel	24.5(27.7)	35.1(39.5)	24.2(27)	20(23)	24(26)

All vehicles use CVTs and nickel metal hydride batteries
and have 0-60 mph acceleration times of about 9 sec
For diesel engine powered vehicles, the first mpg given is the gasoline equivalent mpg and the second number in ( )
No correction factors have been applied to the calculated values of mpg

Table S-2: The Fuel Economy Improvement Factor for Mid-size Cars Full and Mild hybrids- with Various Engines

			Fuel Economy *	Factor		
Type of driveline	Engine type	FUDS	Highway	US06	Japan 10/15	ECE-EUDC
Full hybrid	Gasoline PFI	1.75	1.37	1.29	2.0	1.73
	Lean burn	1.49	1.26	1.28	1.60	1.51
	TC Diesel	1.63	1.53	1.59	1.78	1.73
Mild hybrid	Gasoline PFI					
	Bat.	1.66	1.16	1.08	1.92	1.52
	Ultracap	1.82	1.33	1.26	2.08	1.72
	Lean burn					
	Bat.	1.42	1.1	1.19	1.57	1.41
	Ultracap	1.53	1.23	1.32	1.72	1.53
	TC Diesel					
	Bat.	1.52	1.28	1.37	1.65	1.58
	Ultracap	1.61	1.48	1.52	1.78	1.73
Convent. ICE –CVT	Gasoline PFI	1.0	1.0	1.0	1.0	1.0
	Lean burn	1.0	1.0	1.0	1.0	1.0
	TC Diesel	1.0	1.0	1.0	1.0	1.0

Table S-3: Summary of Fraction Fuel Saved and Breakeven Fuel Price Results for Various Driving Cycles and Baseline Vehicles for Full and Mild Hybrids

				Fraction fuel saved		Breakeven Fuel price ($/gal)	
Vehicle class	**Engine type**	**Driving cycle**	**Baseline Vehicle**	**Full**	**Mild**	**Full**	**Mild**
Compact	PFI	FUDS/HW	CV/PFI	.31	.23	2.65	1.58
Mid-size	“	“	“	.37	.30	2.36	1.25
Mid-SUV	“	“	“	.36	.28	2.39	1.55
Compact	TCD	“	“	.47	.41	2.53	2.16
Mid-size	“	“	“	.52	.46	2.27	2.04
Mid-SUV	“	“	“	.51	.45	2.28	2.13
Mid-size	PFI	“	CV/Adv.	.37	.30	2.36	1.25
“	Lean-burn	“	“	.27	.21	4.17	2.37
“	TCD	“	“	.37	.29	1.93	1.35
Mid-SUV	PFI	“	“	.36	.28	2.39	1.55
“	Lean burn	“	“	.23	.18	4.85	3.36
“	TCD	“	“	.32	.25	2.41	2.08
Compact	PFI	ECE-EUDC*	CV/PFI	.36	.28	.63	.36
Mid-size	“	“	“	.42	.34	.57	.30
Mid-SUV	“	“	“	.44	.38	.54	.32
Compact	TCD	“	“	.51	.46	.65	.52
Mid-size	“	“	“	.55	.51	.59	.51
Mid-SUV	“	“	“	.57	.58	.57	.46

*** fuel price given in terms of $/L for vehicles in Europe**

Table S-4: Summary of Cost Results for Various Engines and Vehicle Classes for Full and Mild Hybrids with the PFI Gasoline Conventional Vehicle as the Baseline

		Full	HEV					Mild	HEV		
Engine/ Vehicle	Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even		Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even
PFI											
Compact	2461	.31	1104	2.23	2.65		1063	.23	800	1.33	1.58
Mid-car	3371	.37	1699	1.98	2.36		1441	.30	1370	1.05	1.25
Mid-SUV	4273	.36	2125	2.01	2.39		2139	.28	1638	1.31	1.55
Lean-burn											
Compact	2701	.45	1574	1.72	2.04		1403	.40	1395	1.00	1.20
Mid-car	3631	.49	2248	1.62	1.92		1921	.45	2060	.93	1.11
Mid-SUV	4613	.47	2770	1.67	1.98		2739	.43	2536	.78	1.28
TC-diesel											
Compact	3541	.47	1660	2.13	2.53		2593	.41	1430	1.81	2.16
Mid-car	4541	.52	2373	1.91	2.27		3601	.46	2099	1.71	2.04
Mid-SUV	5803	.51	3021	1.92	2.28		4839	.45	2696	1.79	2.13

Notes: (1) **All fuel use is based on the FUDS/Highway composite driving cycle and 100,000 miles.**

(2) **The baseline vehicle in all cases is the conventional vehicle using a gasoline PFI engine**

(3) **The breakeven gasoline price is calculated for a use period of 8 years and mileage of 12,000 miles/yr and a discount rate of 4%.**

Table S-5: Summary of Cost Results for Various Engines and Vehicle Classes for Full and Mild Hybrids with Advanced Engine ICE Vehicles as the Baseline

		Full	HEV					Mild	HEV		
Engine/ Vehicle	Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even		Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even
PFI											
Compact	2461	.31	1104	2.23	2.65		1063	.23	800	1.33	1.58
Mid-car	3371	.37	1699	1.98	2.36		1441	.30	1370	1.05	1.25
Mid-SUV	4273	.36	2125	2.01	2.39		2139	.28	1638	1.31	1.55
Lean-burn											
Compact	2321	.22	538	4.31	5.13		1023	.14	359	2.84	3.39
Mid-car	3091	.27	881	3.51	4.17		1381	.21	692	2.00	2.37
Mid-SUV	3953	.23	969	4.08	4.85		2079	.18	735	2.82	3.36
TC-diesel											
Compact	1831	.29	767	2.38	2.84		883	.20	536	1.64	1.96
Mid-car	2111	.37	1302	1.62	1.93		1171	.29	1029	1.14	1.35
Mid-SUV	2833	.32	1395	2.03	2.41		1869	.25	1070	1.75	2.08

Notes: (1) All fuel use is based on the FUDS/Highway composite driving cycle and 100,000 miles.

(2) The baseline vehicle in all cases is the conventional vehicle using the conventional ICE vehicle using the same engine

(3) The breakeven gasoline price is calculated for a use period of 8 years and mileage of 12,000 miles/yr and a discount rate of 4%.

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1. Introduction

1.1 Objectives

The objectives of the study were to identify developments in hybrid-electric driveline technologies and hybrid vehicles using internal combustion engines (ICE) and to assess the effects of these developments on vehicle fuel economy and fuel quality over the next twenty years. The emphasis in the study is on light-duty vehicles including passenger cars, light trucks, vans, and SUVs.

1.2 Scope of the work

The study focused on the following general areas: (1) formulation of a taxonomy/framework for characterizing hybrid-electric driveline and vehicle designs, (2) in-depth analysis of the characteristics of specific hybrid vehicle designs in terms of acceleration, fuel economy, emissions, fuel quality requirements, and incremental cost utilizing vehicle simulation programs and detailed cost breakdowns based on the cost of the electric drive components, (3) summary of the marketing pathways for hybrid vehicles and projected effects of those markets on the fuels business in the next twenty years, (4) summary of additional work on vehicle modeling, new engine developments and fuel requirements, energy and environmental policies, and component cost projections required to reduce uncertainties in the fuels business projections.

2. Vehicle and Driveline Considerations

2.1 Vehicle characteristics by class

At the outset of the study, it was necessary to define a baseline design for each of the classes of light-duty vehicles currently being offered for sale by the car manufacturers. Three passenger car classes (compact, mid-size, and full-size) and three sport utility vehicles (SUV) classes (small, mid-size, and large) are considered. The average characteristics of US 2002 model year vehicles in each of the classes are given in Table 1. All the vehicles use port-fuel-injected, gasoline engines (PFI). The fuel economy values shown are those actual measured (uncorrected) by EPA on the dynamometer and were used to determine the CAFÉ numbers for each of the car manufacturers. The information given in Table 1 was derived from various recent issues of the car magazines and the 2002 EPA Fuel Economy Guide. In the hybrid-electric vehicle studies, the vehicle size and road load characteristics were specified such that the performance and utility of each of the hybrid vehicles were the same as the 2002 models of the respective classes. No weight reductions using light-weight materials or streamlining of the vehicles to reduce the road loads were included in the present study. Note in Table 1 the mini-car class, which has a significant fraction of the market in Europe and Japan, is not included. As an initial approximation, it is reasonable to assume that the influence of hybridization on that class will be close to that of the compact car class on the European and Japanese driving cycles.

2.2 Engine characteristics

2.2.1 Types of engines and engine maps

Most light-duty vehicles sold in the United States presently utilize stoichiometric, port-fuel-injected engines having two or four valves per cylinder. This type of engine has been significantly improved in recent years by the manufacturers in terms of both efficiency and emissions, but the engine maps (brake specific values – gm/kwh vs. torque and RPM) of the improved engines are not available in the open literature. Hence in this study, the baseline PFI engine for the vehicles was the 1.9L Saturn engine identified as **SI63** in the **Advisor** program (Reference 1). This engine was selected because it had the most favorable bsfc map of the PFI gasoline engines available in **Advisor**. The 1.9L Saturn engine has a peak power of 63 kW (33 kW/L) and a maximum efficiency of 34%. All the PFI engines used in the hybrid vehicle simulations were scaled using the characteristics of the Saturn engine.

The second engine included in this study was the Honda Insight engine designated as **INSIGHT** in **Advisor**. This is a lean burn, gasoline engine that operates at A/F ratios as lean as 22:1 at light loads. The 1.0L Insight engine has a maximum power of 50 kW (54 kW/L) and a maximum efficiency of 40%, which is very high for a gasoline engine. The bsfc engine maps used in **Advisor** are based on test data taken at the Argonne National Laboratory. This engine is very efficient with a high specific power and is considered to be a proto-typical, advanced lean burn PFI engine for future hybrids. It consistently yielded the best fuel economy of any of the gasoline engines available in **Advisor**. All the lean burn engines were scaled using the characteristics of the **INSIGHT** engine. It should be noted that the 20% improvement in efficiency of the Insight engine compared to the Saturn engine is greater than the 5-10% expected from lean operation alone. Additional efficiency benefits are apparently due to advanced engine control technology that Honda has incorporated into the Insight engine that were not part of the Saturn engine technology. Further study is clearly needed to determine the magnitude of the potential improvements in fuel economy that will result in the future through the use of advanced lean-burn gasoline engines in hybrid vehicles.

The third engine type included in the study was the turbocharged diesel. The engine of this type used in the vehicle simulations was that designated as **CI88** in **Advisor**. Its characteristics are based on the Audi 2.5L engine having a maximum power of 90 kW (36 kW/L) and a peak efficiency of 42%, which is comparable to that of state-of-the art diesel engines for light-duty vehicles. This engine was considered the proto-typical turbocharged diesel engine. All engines of this type used in the vehicle simulations were scaled using its characteristics.

A few vehicle simulations were performed using the **Prius** engine developed by Toyota. It is designated as **PRIUS_JPN** in the **Advisor** program. This engine utilizes the Atkinson cycle and was developed for use in the Toyota **Prius** that was first marketed in Japan. The **Prius** maps used in **Advisor** are based on test data taken at Argonne National Lab (ANL). The Japanese version of the engine tested had a maximum power of 43 kW (29 kW/L) and a peak efficiency of 39%. The version of the engine in the **Prius** sold in the United States has a maximum power of 52 kW (35 kW/L). This engine has not yet been tested at ANL. The **Prius** engines were developed for use with the Toyota planetary gear arrangement for configuring the hybrid driveline. It was found in the simulation not to be optimum for use in the single-shaft, hybrids considered in this study.

Another advanced engine of interest was the direct-injection gasoline (GDI) engine. It was not possible to obtain detailed engine maps for this type of engine to use in the vehicle simulations because data from the engine developers and auto manufacturers are proprietary and testing of a GDI engine at ANL has not been completed yet. The limited data for a GDI engine given in Reference 2 seems to indicate that the GDI engine is not likely to have equal or better fuel efficiency than the Honda **Insight** lean burn engine.

2.22 Key issues in selecting engines for use in hybrid vehicles

There are a number of important considerations/issues in selecting engines for hybrid-electric vehicles. In general, these are very similar to those used in selecting engines for an ICE vehicle when fuel economy is of prime concern. However, since fuel economy improvement is the primary motivation for the development of hybrid-electric vehicles, these issues are especially key for hybrid vehicles. The first issue is high engine efficiency or low bsfc especially at relatively low RPM and low torque fractions. The reason that hybridization offers the possibility of a large fuel economy improvement is that all engines have efficiencies much less than the maximum at low load (power) operating conditions. This is shown on Figure 1 in which it is seen that the minimum bsfc attainable for a particular engine increases markedly at low power fractions. The objective of a control strategy in a hybrid vehicle is to maintain engine operation in the high efficiency (low bsfc) portions of the engine map and to prevent the engine from operating at high bsfc. In order to minimize the battery and electric motor/electronics costs, an optimum engine for a hybrid vehicle would show the minimum bsfc being approached at relatively low power fractions. Note in Figure 1 that the lean burn engine has this optimum characteristic. When the minimum power fraction for efficient operation occurs at a higher power fraction, it requires a larger electric drive system to prevent inefficient engine operation.

A second characteristic important for use of engines in a hybrid vehicle is specific power (kW/L) because high values of kW/L result in a smaller engine and make packaging the motor, electronics, and battery less difficult. In this regard, the significant improvement in the specific power of modern engines is advantageous for the development of hybrid vehicles. In addition, for use in hybrids the engines must be suitable for on/off operation with the capability of fast start, warm-up, and response times.

For use in hybrid vehicles, the engine must also have low engine out emissions and have available fuels and emission after-treatment technology that can be used to reduce the vehicle exhaust emissions to meet stringent worldwide emission standards. The most stringent standards are currently the California SULEV levels. Hybrid vehicles must be very clean as well as very efficient in order to compete with conventional ICE vehicles with advanced emission aftertreatment and fuel cell powered vehicles. That hybrid vehicles can be very clean has been shown by Toyota with the **Prius** and Honda with the **Insight** and hybrid **Civic**. The Prius and Insight with the continuously variable transmission (CVT) meet the SULEV standard and the 5-spd **Insight** and the Honda hybrid **Civics** meet the ULEV standard. It has been demonstrated that both diesel engines and lean burn gasoline engines can operate very efficiently, but in both cases operation of the engine with excess air results in making it difficult to meet stringent NOx standards. Development of the NOx aftertreatment systems with very high conversion efficiency is a key issue in the rapid commercialization of lean-burn and diesel engines. It is unclear at the present time whether hybridization will make this less difficult than with the same engines in conventional ICE vehicles.

2.2.3 Limitations in available engine data

A goal of the study was to compare hybridization impacts for various advanced engine technologies. Meeting this goal was found to be difficult due to the limited availability of data for advanced engines.

As discussed in the previous section, the availability of engine maps for the various engines is critical to being able to design and simulate the operation of hybrid-electric vehicles on the computer. In general, there is not much such data available in the literature especially for the improved PFI, turbocharged high-speed diesels, and advanced engines such as lean burn and direct injection gasoline engines. The data that are available are often fragmented in that only partial maps are given and even the scales are left off the plots. Nearly all the data are for steady-state, hot engine operation and only at a few selected speeds and torques. Often the selected operating points are at high loads where the engines are most efficient and not at the light loads that are of prime importance in evaluating the engines for hybrid-electric vehicle applications. Another consideration of key importance is the lack of data for the same engine technology, but different displacement and peak power. As noted in the previous section, the engine maps for the engines used in the different vehicle classes were scaled from the map of a single engine of a particular type. The implications of this method for scaling the engine characteristics are difficult to assess at this time.

There are only a few engines for which both fuel flow and emissions data are available. Fuel flow data and bsfc maps are available for a number engines in Advisor, but emission data are available for only a few engines. This is because engine emissions (gm/sec) are much more difficult to measure than fuel flow as they depend on both the concentrations of the pollutants and the exhaust mass flow rate. The calculation of the exhaust emissions of the vehicle depend both on the engine out emissions and the conversion efficiencies of the after-treatment technology used in the hybrid vehicle. Meeting the strict ULEV and SULEV standards requires very high conversion efficiencies (>99%) and that tends to uncouple the engine out and vehicle exhaust emissions especially for steady engine operation. Steady engine emissions data are not presently available for any of the engines used in this study. It is expected that emissions data including some transient engine data will be available from Argonne Laboratory (ANL) within the next year. Some data, including transient data for the Insight and Prius engines have been taken but not yet published in a form to be used in the **Advisor** program. In addition, it is expected that fuel flow and emission data will be available from ANL for the turbocharged high speed diesel and direct injection gasoline engines in the relatively near term. In the meantime, it has been necessary to make do with the limited engine data available.

2.3 Hybrid-electric powertrain characteristics

2.3.1 Driveline configurations

The primary distinctions in hybrid drivelines are between series and parallel arrangements. In the case of the series arrangement, the engine is not connected to the driveshaft of the vehicle, but rather to a generator to produce electricity on-board the vehicle from the fuel. In the case of the parallel configuration, both the electric motor and engine are connected to the driveshaft and either can provide torque to the wheels. Except for transit buses, all the hybrid-electric vehicles presently being developed and marketed are of the parallel type or can be operated in the parallel mode for highway driving. It is possible to design a powertrain system such that it can be operated in either the series and parallel mode when it is advantageous to do so. An example of this is the Toyota **Prius** that utilizes a planetary gear arrangement to attain this dual mode operation. As discussed in Reference 3, the PAICE Corp. is developing a single shaft hybrid driveline that has dual mode capability. The simple parallel hybrid driveline combines an electric motor and engine to power the vehicle with the electric motor operating as a generator when power from the engine is available to recharge the batteries on-board the vehicle as it is driven. The dual mode hybrid powertrain utilizes a generator in addition to the electric motor and engine. The power from the engine can be split with part being used to power the generator to produce on-board electricity and the remainder is used to provide power directly to the wheels. In the dual mode arrangement, the engine operation can maintained very near the minimum bsfc line at all times to maximize the fuel economy gain of the hybrid vehicle. The control of the dual mode systems is more complex than for the simple parallel systems and in addition the dual mode systems are considerably more expensive as they require both a generator and an electric motor and in most cases a relatively large electric motor and battery.

In this study only single shaft, parallel hybrid drivelines are considered, because minimizing the incremental cost of the hybrid vehicle is a key consideration. The cost of the electric drive components in a series hybrid or multiple-shaft, planetary hybrid will be at least as high as the **full** single shaft, parallel hybrid configurations considered along with the mild hybrid in this study.

2.3.2 Degree of hybridization

One of the key considerations in designing a parallel hybrid powertrain is the power (kW) of the electric motor/electronics/battery system relative to that of the engine. This trade-off becomes especially important when economic considerations are included in the design analysis. Hybrid power trains have been designed and built in which the power of the electric motor is much larger than that of the engine and others in which the engine power is much larger than that of the electric motor. In this study, the degree of hybridization is defined as the fraction of the total powertrain power (engine plus electric motor) to the wheels that can be provided by the electric motor. A **full** hybrid is defined as a hybrid vehicle in which the electric motor can provide about 50% or greater of the total power. The **plug-in** hybrid is a special case of the **full** hybrid in which the electric motor and battery are sized to permit the vehicle to operate as an electric vehicle for a specified all-electric range with the battery being plugged into the grid at night (Reference 4). A **medium** hybrid is defined as a hybrid vehicle in which the electric motor can provide 20-30% of the total power to the wheels. A **mild** hybrid is defined as a hybrid vehicle in which the electric motor can provide only 10-15% or less of the total power. Compared to **full** hybrids, the **mild** hybrids offer lower battery and motor/electronics costs, but sacrifice some fuel economy benefit. The initial simulation results for **the mild, medium, and full** hybrid vehicles indicated that it was necessary to consider only the mild and full hybrid cases as the medium hybrid cases did not offer any special advantage. Hence in this study only the **mild** and **full** hybrids were simulated and compared in terms of fuel savings and incremental cost relative to the conventional ICE vehicles.

2.3.3 Electric drive component selection

There are many types of electric driveline components available for use in a hybrid vehicle. Both AC induction and brushless DC permanent magnet motors have been used in electric and hybrid vehicles. In this study, AC induction motors are used in all the hybrid drivelines as that type of motor/electronics is lower in cost and are felt to be better suited for on/off engine operation. Brushless DC permanent magnet motors have slightly higher peak efficiency than the AC induction motors and are favored by the Japanese auto companies (Honda and Toyota). The electric motor used in all the hybrid vehicle simulations was scaled from the MC AC75 motor in **Advisor**. This is an AC induction motor developed by Westinghouse Corp for electric cars. It has a continuous rating of 75kW and the peak efficiency of the motor/electronics is 92%.

Nickel metal hydride batteries were used in the vehicle simulations. The batteries were scaled from the 6V, 28Ah module developed by the Ovonic Battery Co. The module weighed 3.6 kg, stored 175Wh, and had a peak power rating of 1.6 kW. This performance corresponds to an energy density of 48.6 Wh/kg and a peak power density of 444 W/kg. Experience to date has indicated that nickel metal hydride batteries are well suited for hybrid vehicle applications and can be expected to have good cycle and calendar life. Both the Toyota and Honda hybrid vehicles currently being marketed use nickel metal hydride batteries. The battery packs were configured such that the voltage for the **mild** hybrids was 150-160V and for the **full** hybrid the pack voltage was 335V.

Drivelines using ultracapacitors as the energy storage unit have also been studied. The ultracapacitors used in **Advisor** are modeled after the Maxwell 2700F devices, but with higher energy density and lower resistance than the 2700F devices. In **Advisor**, it is assumed that the ultracapacitors have an energy density of 6 Wh/kg for operation between 3V and 1V and a peak power of 2 kW/kg. As discussed in Reference 5, there are now commercially available capacitors approaching that performance.

2.3.4 Control Strategies

As noted previously, the hybrid vehicles studied utilized a simple parallel hybrid driveline in which the electric motor and the engine are positioned on a single shaft. For nearly all the simulation runs, the motor/engine shaft was connected to a continuously variable transmission (CVT) that provided torque/power to the wheels through a clutch. For a few runs, the CVT was replaced by a 5-speed manual transmission to determine the effect of the CVT on the acceleration times and fuel economy of the hybrids. The control strategy used in the Advisor for the CVT runs was that designated PTC-PAR-CVT. This strategy maintained the battery state-of-charge near 50% by turning the engine on/off at vehicle stops and used the electric motor as a generator for both on-board battery charging and for recovery of energy during braking. The 5-speed manual transmission runs used the control strategy designated PTC_PAR_BAL. These control strategies turn the engine on/off a number of times during the FUDS and Federal Highway cycles. The strategy does maintain the average engine efficiency at a high value – less than 5% below the maximum efficiency value for the engine. It was found that both control strategies worked well for both the mild and full hybrid drivelines and in driveline systems using either batteries or ultracapacitors.

In **Advisor** the transmission control (gear shifting for the 5-speed manual and control of the CVT speed ratio as a function of power and vehicle speed) are included in the control strategy algorithm. No attempt was made to change the transmission control strategy in the present study. Comparative runs were made periodically with the CVT and 5-speed manual transmissions as a "sanity check" on the CVT results. It was found consistently that the acceleration times and highway fuel economy were slightly better using the 5-speed manual than with the CVT. This was to be expected and served a check on the validity of the CVT results.

3.Vehicle Modeling and Simulations

3.1 Component modeling

All the components in the hybrid drivelines were modeled using the standard models in the simulation programs (References 6,7). No work was done in this study to improve the models for either the engine/transmission or electric drive components. In general, the engine/transmission and electric motor/controller components were modeled in terms of input tables of efficiency as a function of torque and device RPM. The scaling is done internal to the simulation programs by setting for the run the appropriate maximum torque to attain the specified peak power. The efficiency maps are then scaled to account for the change in maximum torque. The simulation programs display or write out the average efficiencies of the components so the user can validate that the scaling is functioning properly. It is necessary to check the average efficiencies as the system voltage is altered, because that can cause significant reductions in the efficiencies of the electric motor/electronics. It was found that the MC AC75 motor could be used over voltage ranges of both the **mild** and **full** hybrids.

The batteries were sized by specifying the number of modules in the series string and setting the Ah capacity to attain the battery weight and energy storage (kWh) desired for the hybrid driveline. The adequacy of the battery pack to provide the power needed was verified by calculating the peak power required to meet the peak power demand of the motor. For the nickel metal hydride batteries used in this study, a peak power density of 350-400 W/kg was used. The efficiency of the battery was tracked for each simulation run to be sure that it was in an acceptable range (greater than 75%). In the case of the ultracapacitors, the unit was sized by voltage and weight. An intermediate cell voltage (about 2V per cell) was used to determine the number of cells required in series to meet the specified system voltage. The size (Ah or capacitance) of the cells was scaled to yield the desired weight for the energy storage unit. The adequacy of the ultracapacitor unit was assessed by checking the ability of the control strategy to maintain the state-of-charge of the capacitors greater than 50% and the average efficiency over the driving cycle of the simulation greater than 95%. All the battery and ultracapacitor units used in the simulations met the requirements discussed above.

3.2 Simulation Programs

Most of the simulation runs discussed in this report were done using the **Advisor** program (Reference 1, 6,7). **Advisor** was developed at the National Renewable Energy Laboratory with DOE funding. It has become the most widely used simulation program for evaluating hybrid vehicles outside the automobile industry. It has undergone continuous development since about 1996 with a number of versions of the program becoming available. In this study, runs were made using both the Version 3.2 and Version 2002, which became available near the end of the study. A series of runs were made to check the consistency of results obtained using the two versions of **Advisor**. It was found that the two versions yield essentially the same results for fuel economy and acceleration times. The differences were at most a few tens of a second in acceleration times and a few tens of a mile per gallon for the fuel economy on a specified driving cycle. The results were not consistently higher or lower for one of the program versions. The run times of the two versions were very comparable with the Version 2002 being slightly faster – about 10 seconds out of 70 seconds for the FUDs cycle run. The run time for both programs was 10-20 seconds shorter for the Federal Highway cycle than for the FUDS cycle.

3.3 Limitations of the simulation capabilities

As stated previously, the primary simulation tool used in this study was **Advisor**, which utilizes a backward facing approach starting with the power demand at the wheels required to meet the specified driving cycle and working back through the driveline components. The assumption is made that the components can be modeled using the quasi-steady approach with the component characteristics based on steady state test data. No attempt is made to account for transient operation of the components. Engine operation is thought to be the most affected by transients especially in the calculation of the hydrocarbon and carbon monoxide emissions. The effect of transients on the electric drive components is not thought to be significant as those components have very short response times and are controlled using electronics that depend on chopping frequencies of many kHz.

Even though at the present time, there are efficiency maps for a number of engines available in **Advisor,** there are no maps for the improved PFI engines being used in 2002 model cars or for lean burn engines other than the Insight 50 kW engine. There is also minimal information on high-speed turbocharged diesel engines suitable for light duty passenger cars, vans, and trucks. There are no data available as yet for direct injection gasoline (GDI) engines. As noted previously there are essentially no data available on the emissions (steady or transient) for the engines of interest for hybrid vehicles. It is expected that this situation will change over the next couple of years when data from Argonne Lab become available. The Argonne data should include data taken under transient conditions on the FUDS driving cycle. This would permit work to proceed on including the effects of transients on emissions in the modeling of hybrid vehicles.

3.4 Validation of the Advisor program

In order to validate to the **Advisor** program for hybrid vehicles as well as for conventional ICE vehicles, **Advisor** was run for a number of vehicles for which there was published fuel economy data. The simulation results for gasoline-engine vehicles are shown in Table 2. The comparisons are made using the EPA Fuel Economy values modified (increased) by the correction factors that had been used to degrade the actual measured fuel economy for use in the published fuel economy guide. In general, the comparisons are reasonable, but not precise in most instances. This might have been expected as it was not possible to use the efficiency maps for the actual engines in the vehicles as such information is not available from the manufacturers. Simulation results are given in Table 3 for vehicles powered by turbocharged diesel engines. The test data for the U.S. driving cycles (FUDS and Highway) were taken from the EPA Fuel Economy Guide and those for the European cycle (ECE-EUDC) from the "Car Diesel" magazine published in the United Kingdom. As in the case of the gasoline-fueled cars, the comparisons for the diesel-fueled cars are reasonable, but in some cases the differences are significant. The differences are greatest for the European cycle for which the only source of data is the car magazine.

Fuel economy comparisons for the Honda Insight and Civic are also shown in Table 2. The detailed control strategies for the hybrid drivelines in the hybrid vehicles, including the transmission, are not known as such information is proprietary to the manufacturer. Hence within the degree of uncertainty in the inputs, the comparisons between the simulation and measured fuel economies for the hybrids are deemed to be satisfactory.

Only very limited work has been done to validate the **Advisor** program for drivelines using a CVT. Considerable work has been done at UC Davis on modeling CVT operation in hybrid vehicles (Reference 8), but that work has not been coordinated with the modeling and control of the CVT in **Advisor**. The results obtained in this study for vehicles using a CVT appear to be reasonable, but there is a need to validate them in detail using dynamometer test data.

4.0 Fuel economy projections for hybrid-electric vehicles

There have been several recent studies (References 4,9) of hybrid vehicles in which the overall technology was assessed and extensive fuel economy calculations presented. Those studies are excellent background for the present study. One of the primary differences between the studies is that the present study considers engines other than the standard PFI gasoline engines and energy storage units other than batteries. A key objective of the fuel economy calculations in the present study is to determine the effect of the degree of hybridization on fuel economy reductions for several classes of hybrid vehicles.

4.1 Cases considered

Six vehicle classes are identified in Table 1 from small compact passenger cars to large SUVs. This study of hybrids was limited to three classes: compact and mid-size passenger cars and a mid-size SUV. This was done to limit the scope of the study to the time available and to focus on the vehicle classes most important in the market place. The powertrain characteristics of the hybrid-electric vehicles studied are given in Table 4. For each vehicle type, **full** and **mild** hybrids were studied. The road load parameters (C_D, A_f, and f_r) for the hybrids are the same as the corresponding conventional ICE vehicles. The weights of the hybrid vehicles are somewhat higher than that of the conventional vehicles to account for the added weight of the electric drive components. The weights of the **full** and **mild** hybrids were taken to be the same. In reality, the weight of the **mild** hybrid will be slightly less than that of the **full** hybrid. All the vehicles were designed to have the same acceleration and gradeability characteristics (0-60 mph in 9-10 seconds and a gradeability of 55mph on a 6% grade). Small differences (several tenths of a second) in the acceleration times were present in the results, but those differences were considered to be within the uncertainty of the calculations.

The engines considered in the study were the port fuel-injected (PFI) gasoline engine, the advanced PFI lean burn gasoline engine represented by the Honda **Insight** engine, and the turbocharged diesel engine. These engines, which are discussed in Section 2.2, are thought to be the prime candidates for use in future ICE vehicles as well as hybrid-electric vehicles. They represent a full range of efficiency possibilities and thus yield results showing the complete range of expected fuel economy improvements using hybrid vehicle technology. The engines cited also represent a range of emission challenges to meet the worldwide emissions standards. The technology to meet the most stringent standards (SULEV in California) with the PFI engines currently exists and both ICE and hybrid vehicles meeting that standard are being marketed by Japanese auto manufacturers. No vehicles that meet the SULEV standard using the lean burn gasoline engines are currently being marketed, but vehicles meeting the ULEV standard with lean-burn engines are available from Honda. R&D on gasoline direct injection(GDI) engines is being done by several companies (Reference 10 and 11) as a possible alternative to diesel engines, but work to date has not indicated that the GDI engines are cleaner and more efficient than the gasoline lean-burn engines, which are already on the market in passenger cars..

The emissions situation regarding diesel engines is more difficult to project than for gasoline engines. Recent work (Reference 12,13) on reducing NOx and particulate emissions from diesel engines indicates that progress is being made, but the emissions targets being set even in clean diesel programs are quite high. For example, as shown in Figure 2 taken from Reference 14, the EURO-4 standard for 2008 is .4 gm/mi NOx and .04 gm/mi particulates compared to the US Tier 2, bin 5 standard of .07 gm/mi NOx and .018 gm/mi particulates. Figure 2 indicates that the emissions of diesel powered cars currently on the market in Europe have NOx emissions nearly than order of magnitude higher than the ULVEV standard in California. Since the emission requirements in the United States, particularly California, are much more strict than in Europe, the use of diesel engines will be much greater in Europe and as a result, it seems likely that hybrid-electric vehicles using diesel engines will appear first in Europe.

All the vehicles considered (hybrids and conventional ICE) utilize CVT transmissions as it is felt that to reach high volume sales of hybrids, an automatic type transmission is required. The use of the CVT is also consistent with the desire/need to have the hybrid driveline under computer control independent of the driver. CVT technology is relatively new in production vehicles so it can be expected the technology will significantly improve in terms of efficiency, durability, and ease of control in the years to come. Honda has marketed in the United States an ICE vehicle (Civic HX) for about five years and recently began to market the Insight and Civic hybrids using the CVT in the driveline. All of these vehicles are reliable and have excellent fuel economy for their class. In order to use the CVT in larger vehicles like large cars and SUVs, it will be necessary to complete the development of the CVT using a steel chain (References 15) in replace of the link-type steel belt currently used in the smaller passenger cars. This development will also improve the efficiency of the CVT at high and low speed ratios compared to 1:1.

Some simulations were done using a 5-speed manual transmission for comparison with the results using the CVT. In most cases the fuel economy values using the two transmissions were quite close with the fuel economy on the FUDS being a few percent higher using the CVT and that on the Highway cycle being a few percent higher using the 5-speed manual. It is felt that these differences are highly dependent on the shifting/ratio control strategies utilized to control the hybrid driveline. These results indicate that the more optimum control of the engine using the CVT compensates for the higher efficiency of the 5-speed transmission.

All the **full** hybrid vehicle calculations were done using nickel metal hydride batteries for energy storage. The calculations for the **mild** hybrid vehicles were done using both batteries and ultracapacitors for the energy storage. The batteries are a more mature technology, but the capacitors offer the opportunity for higher efficiency for shuttling energy in and out of storage and thus larger fuel economy improvement.

4.2 Simulations of the hybrid vehicles

Simulations were performed using **Advisor** for each of the vehicles listed in Table 3. A wide range of driving cycles were considered including the Federal Urban Driving Cycle (FUDS), the Federal Highway Driving Cycle (FHWS), the US06 driving cycle, the Japanese 10-15 Driving cycle, and the European ECE+EUDC driving cycle. As indicated in Table 5, the characteristics of these driving cycles differ significantly in terms of average speed, maximum speeds, stops per mile, and maximum acceleration. The results of the simulations are given in Tables 6-8. All the cases were run using a CVT transmission and utilized the control strategy in Advisor designated as PTC- PAR-CVT. This strategy as it exists in the **Advisor** (Versions 3.2 and 2002) seemed to be suitable for all the cases run from small to large vehicles, **full** to **mild** hybrid configurations, batteries and ultracaps, and all the driving cycles. It is undoubtedly true that the control strategy, as implemented in **Advisor**, is not optimized and larger fuel economy improvements than those calculated in this study should be attainable if the control strategy were tailored to a specific set of driveline components and vehicle characteristics. Hence the results given in Tables 6-8 should be considered as nominal fuel economy gains and not the best that are possible.

4.3 Implications of the fuel economy results

If hybrid electric vehicles are to have a large impact on the light duty vehicle market, hybrid technology must be applicable to all classes of vehicles and eventually satisfy all customer requirements in terms of utility, convenience, and cost. To justify their introductions, hybrid vehicles must offer good performance and significant fuel savings at a modest increase in initial cost. In this section, performance and fuel savings are considered. Cost will be considered in Section 6. The increase in fuel economy for each of the vehicles simulated is given in Tables 9-11 in terms of a fuel economy improvement factor which is defined as the ratio of the fuel economy of the hybrid vehicle divided by the fuel economy of an ICE vehicle using the same engine. The results in Tables 9-11 show that the improvement factor varies from near 1 (no improvement) to over 2 (double the fuel economy) for the different vehicles, engines, and driving cycles. Most of the increases range from 20-60% with the largest increases occurring for the urban driving cycles. The largest increases are projected for **full** hybrids using PFI gasoline engines, but the increases for the mild **hybrids** in most cases are not much smaller than for the **full** hybrids. Vehicles using the more efficient engines offer higher fuel economy (mpg) in absolute terms, but in some cases a smaller incremental improvement compared to a ICE vehicle using the same type of engine.

As noted previously, the fuel economy improvements using the same hybrid driveline can vary significantly between driving cycles. In general, the improvement is the smallest for the Federal Highway cycle and the largest for the Federal Urban driving cycle and the Japanese 10-15 cycle. Both urban cycles have much stop-and-go driving with many opportunities for energy recovery using regenerative braking. In addition, the average power requirement for those cycles is relatively low, which forces the engine in a conventional ICE vehicle to operate inefficiently much of the time. On the highway, the opportunities for energy recovery in braking are minimal and the average power required to drive the vehicle is higher than in city driving. This permits the engine in a conventional vehicle to operate much of the time in a more efficient mode than for city driving. This means that the potential for fuel economy improvement using a hybrid-electric driveline is significantly less for highway cycles than for city driving cycles. Hence the fuel savings for a particular user would depend on the fraction of the time the user drives in the city and on the highway. It is assumed by EPA that the fractions for the United States are .55 for the city and .45 for the highway. The differences (percentage-wise) in the fuel savings between the **full** and **mild** hybrids are greater for highway driving than for city driving. The size (power rating) of the electric motor could be increased to improve both the acceleration performance and highway fuel economy of the **mild** hybrid, but this would adversely affect the economic attractiveness of the hybrid compared to the conventional ICE vehicle. Note also from Tables 9-11 that the use of ultracapacitors for the **mild** hybrid in place of the batteries shows an increase in the fuel economy improvement factor and a significant narrowing of the differences between the **full** and **mild** hybrid fuel economy on the highway driving cycle. It is also undoubtedly true that the control strategy for the hybrid can be tailored to get a greater improvement in highway driving. It is likely that the strategies in **Advisor** have been optimized for urban driving where the potential fuel economy gains are greatest.

The simulation results (Tables 7-11) indicate that the differences in how the vehicle classes respond to hybridization are not large. However, in general the improvement factors increase slightly as the size of the vehicle increases. This is due to the use of the larger engines in the conventional ICE baseline vehicles and the resultant inefficient operation over much of the driving cycles. The use of the electric drive in the hybrids permits the improvement in fuel economy to be achieved with no sacrifice in performance (acceleration times or top speed). This can be done using a relatively small degree of hybridization. In general, the improvement factors for the different vehicle sizes, hybrid designs, and driving cycles follow consistent and predictable patterns, but there are anomalies that do not. One explanation for the anomalies is that the same control strategies are used for all the cases and the strategies are far from optimal for a few cases while satisfactory for most cases. This is another indication that the control strategy for a hybrid should be tailored to the vehicle design and type of driving expected with the vehicle.

A close inspection of the **Advisor** simulation results shows that while it is clearly most advantageous to use an efficient engine especially one with high efficiency at relatively small power fractions, the efficiency of the electric motor/electronics and the energy storage unit are important in attaining large fuel economy improvements for all size vehicles. As indicated in the Tables 6-8, for the **mild** hybrids the drivelines using ultracapacitors showed consistently higher fuel economy than those using nickel metal hydride batteries. The batteries even though having a high peak power density (400-500 W/kg) exhibited an average efficiency of 70-75% on the FUDS cycle while the ultracapacitors had an average efficiency of 97-98% on the same cycle. For the **full** hybrid cases, the batteries had an average efficiency of 90-94% due to larger size. For this reason and the need for much larger energy storage in the **full** hybrids, only battery energy storage was considered for those cases.

All the hybrid vehicles utilized a parallel arrangement with the engine and electric motor on a single shaft connected to a CVT. This is the configuration used by Honda in the Insight and Hybrid Civic. It appears to be applicable to vehicles of all classes. The use of the single-shaft arrangement and CVT yields a vehicle with an efficient automatic transmission, the possibilities for an arbitrary selection of engine and motor size (maximum power), and relatively simple control algorithms. The simulation results for fuel economy show that the hybrid driveline need not be complex and have large electric drive components to achieve relatively large improvements in fuel economy.

5. Fuel and Lubrication Issues

5.1 Special considerations for hybrid vehicles

Engine operation in a hybrid vehicle can be quite different than that in a conventional ICE vehicle. In the hybrid vehicle, power from the engine is turned off and on relatively often while the vehicle is traveling at cruising speeds and the engine is turned off (shut down to zero RPM) nearly every time the vehicle comes to rest. In addition, the engines spend a much greater fraction of their operating life at high torque and possibly in modes in which several cylinders are deactivated to save fuel. The advent of lean burn engines and ultraclean (SULEV) exhaust emission after-treatment systems may require cleaner fuels than currently available. These issues are discussed in the following sections based on the simulation results of Section 4.

5.1.1 Engine stop/start control strategies

Probably the most significant difference between the operation of engines in the hybrid and ICE vehicles is that nearly all control strategies for hybrid vehicles involve engine start and stop much more frequently than for conventional vehicles, in which the engine is turned off by the driver only when they desire to park the vehicle. In discussing engine on/off, it is necessary to distinguish between actually decoupling the engine from the driveline via opening a clutch and restarting the engine when power is needed from it and the rather simple operation of ceasing to fuel the engine when no power is desired from it or to allow it to be in an idle mode when no power is needed. The **Advisor** program has a clutch in the driveline and decouples the engine from the driveline when the engine is turned off. However in the calculations, the engine is turned back on when the vehicle is in motion in a perfectly smooth manner. In practice the auto manufacturers marketing hybrid vehicles seem to start the engine at low speeds and reduce power to the engine when desired by ceasing the fueling and ignition to the engine during periods of zero power demand. This approach leads to smooth vehicle operation in the real world and less stress on the engine even though it leads to a lower gain in fuel economy. It also minimizes the impact of engine on/off operation on emissions. The hybrid vehicles designed and built at UC Davis (References 16, 17) actually decouple the engine from the driveline via opening and closing a clutch when the engine power is set equal to zero by the control strategy. Test data for the UC Davis hybrids indicate this approach does result in impressive fuel economy gains in both a passenger car and large SUV.

5.12 Cold start

Engine cold start in hybrid vehicles is not much different than in ICE vehicles as in most cases the control strategy for the engine does not shut the engine off before it is warmed up. In addition, the power of the starter motor for the engine is much larger for the hybrid vehicle making very fast engine starts possible even when the engine is cold. For example, engine starting with the vehicle at rest in the Honda hybrids is said to be in less than .1 sec. Engines in hybrid vehicles likely will warm-up faster than those in ICE vehicles because the engines are smaller and operate more frequently at high torques. This is advantageous for reducing both fuel consumption and emissions. For the hybrids considered in this study, it is not expected that the engines would be off for long periods in which the engine would cool down to the extent that restarting the engine would be considered a "cold start" event from an emission or driveability point of view. If cold start or catalyst warm-up were considered to be a problem, the hybrid vehicles have energy storage units as part of the driveline that could be used to electrically heat the necessary components. Hence it would appear that cold starts should not be an emissions or driveability problem for hybrid-electric vehicles.

5.13 Selection/control of engine operating points

A primary objective of the control strategy for the hybrid vehicles is to keep the engine operating at high efficiency conditions and away from those operating conditions (torque and RPM) that result in efficiencies much less than the maximum for the engine. Parallel hybrids necessarily operate over a range of torque and RPM, but the range is much less than in an ICE vehicle. For most engines, efficient operation occurs at high torque fractions of .7 or higher at all RPM with the fraction for highest efficiency increasing at the higher RPM. This means that the engines in hybrids will spend most of their life at high torque and thus high operating temperature. On the other hand, the engines will experience periods of being turned off (power output zero) with cycling between very light loads and high loads occurring on a regular basis. This will occur even when the vehicle average speed is low as in an urban area. This mode of operation is not too different from an engine in an industrial application. It may be advisable to rate and test engines for hybrids differently than those used in ICE vehicles.

5.14 Engine design and control

Engines designed for hybrid vehicles will in most cases incorporate lean burn (that is operation at A/F ratios much greater than 15), low friction, and valve deactivation. These features will make it possible to achieve large fuel economy gains in **mild** hybrids by permitting the engine to utilize an optimum control strategy with frequent periods of zero power command and efficient operation at relatively low engine loads (torque fractions of .5-.6). Both the fuels and the engine lubricants should be optimized for use with engines operating as in hybrid.

5.15 Use of diesel engines

As shown in Tables 6-8, diesel engines benefit from hybridization to about the same degree (improvement factor) as the other engines and result in higher fuel economy (mpg diesel) in most cases. The advantage of the diesel engine in hybrids over the baseline PFI gasoline engine is significant (25-35%) and is similar to that of the diesel engine in the base ICE vehicle case. The advantage of the diesel in both the hybrid and the conventional ICE cases is much smaller (8-12%) over the advanced lean burn gasoline engine cases. When the fuel economy of the diesel engine is expressed in terms of mpg gasoline equivalent, the advantage of the diesel engine is significantly reduced being 15-25% for the PFI gasoline engine and nearly zero for the advanced lean burn gasoline engine. No hybrid vehicles are currently marketed in the United States that use diesel engines. In addition, there has only been limited R&D activity in the world using diesel engines. One such program is the work being done by Ricardo (Reference 24) in the development of a hybrid vehicle designated as i-MoGen (intelligent Motor Generator). The hybrid system being developed is a 42 V system with a 6 kW electric motor and a 75 kW diesel engine. Ricardo estimates that the system will result in about a 15% improvement in fuel economy compared to a baseline ICE vehicle using the same engine. This improvement is significantly less than the 40-50% improvement projected in the present study using a more aggressive mild hybrid approach. The emissions targets in the Ricardo program are .04 gm/mi HC, .2 gm/mi NOx, and .02 gm/mi particulates. These targets are well a above the California ULEV and SULEV standards.

If a family of lean burn engines of various sizes (power ratings) having the bsfc map characteristics of the Honda **Insight** engine can be developed, it appears that such an engine technology would be a strong competitor for the diesel engine even in terms of fuel economy for hybrid vehicles, particularly for **mild** hybrids. Emissions after-treatment technology does not presently exist that would permit hybrid vehicles using either the diesel or advanced lean burn, PFI gasoline engine to meet SULEV standards. Honda has achieved ULEV standards with their lean burn engine in the Insight and Civic, but the ULEV standard has not as yet been attained using a diesel engine in either a hybrid or ICE vehicle in Europe or the United States. It appears that the choice of the engine for hybrids will be dependent primarily on the emissions standards set and the ability of the particular engines to met them and economic factors such as engine cost and the price of the fuel for each engine type.

5.2 Modeling/simulation results pertinent to fuel/lube issues

Various aspects of hybrid vehicle operation associated with fuel/lube issues have been discussed qualitatively in previous sections. In this section, quantitative information/data will be presented on these issues based primarily on the simulation results.

5.21 Frequency of stop/start events

It is of interest to estimate the frequency and duration of the engine stop events in hybrid-electric vehicles. For a specified driving cycle, these characteristics depend both on the configuration of the hybrid driveline and the control strategy. As noted previously in some cases turning the engine on/off can be simply setting the command power to zero by cutting off the fuel flow or setting it to the idle flow rate. In other cases stopping and starting the engine could involve decoupling the engine from the driveline by opening and closing a clutch. The second approach is more difficult to engineer maintaining good driveability for the vehicles, but in principle it should result in a higher fuel economy. In the hybrid drivelines envisioned in this study with the engine and motor on the same shaft with no clutch between them, the engine would be turned off/on by setting the fuel flow rate to zero. In order to investigate the engine on/off events a series of runs were made using the SIMPLEV program (Reference 18) in which the energy storage unit (batteries or ultracapacitors) were cycled between a minimum and maximum state-of-charge using the same generator power rating as used in the **Advisor** simulations. The state-of-charge range over which the storage units were cycled was selected so that the energy used in the SIMPLEV and **Advisor** simulations was the same. These results for the engine on/off event timing should be that for a near ideal control strategy. Runs were made for the compact car with the PFI engine on the FUDS and Federal Highway cycles for the **mild** hybrid configuration. The on/off times vary somewhat over the cycle, but so only the average times will be noted here. The results were as follows:

Batteries

FUDS cycle	on 105 sec, off 190 sec
Highway cycle	on 412 sec, off 70 sec

Ultracapacitors

FUDS cycle	on 100 sec, off 180 sec
Highway cycle	on 413 sec, off 87 sec or on 200 sec, off 60 sec

These results indicate that control strategies can be developed for which the engine on/off times are reasonable and should not stress the engine greatly. In modern engines for which the fuel is set to zero during decelerations, the frequency of engine on/off events is comparable to that for a hybrid vehicle.

5.2.2 Operating regions on the engine maps

The operating regions on the engine maps for the conventional ICE and hybrid (**full** and **mild**) vehicles can be viewed and printed out from **Advisor**. As shown in Figures 3-5, it is clear that the engine operation for the hybrids is confined to a much smaller region of the map than is the case for the conventional ICE vehicles. This is the primary reason that the hybridization results in improved fuel economy. The results shown in Figures 3-5 are for the PFI gasoline engine, but the control strategy for the CVT and power split between the engine and motor results in operation close to the optimum efficiency line on the torque-speed map for all the engine types.

In general, hybridization requires the engines to operate at relatively low RPM and high torque to achieve near maximum efficiency. The differences in the operating modes of engines in hybrids and conventional ICE vehicles could have an impact on the fuel requirements. For the PFI, stoichiometric engines, the issue is primarily that of the octane needed to control knock at the low RPM, high load conditions. It may be possible to tailor fuel properties like octane for use in hybrid vehicles using standard PFI gasoline engines to provide optimal engine efficiency. The situation is more complex for the lean-burn and GDI gasoline engines because those engines operate in two rather different modes - light load lean and high load stoichiometric. The use of these engines in hybrid vehicles could have an important impact on a range of fuel characteristics – sulfur, octane, and composition-needed for hybrids.

Diesel engines are also beginning to utilize multiple combustion modes to reduce emissions and to enable aftertreatment regeneration. Such engines could require special fuels.

5.2.3 Coolant, exhaust gas, and catalyst temperatures

These temperatures are available from the **Advisor** simulations for each of the vehicles of interest in this study. Plots of these temperatures over the repeated driving cycles for the **mild** hybrid are displayed in Figures 6-8. The exhaust gas temperature varies over a wide range depending on engine torque being reasonably high when the engine is operating at high torque and very low when the engine is off. The coolant and catalyst temperatures take a period of time to rise during warm-up and then change little during the hybrid operation as both the coolant and catalyst have high thermal mass. This indicates that thermal effects during engine on/off operation should not have a significant impact on vehicle emissions. The greatest concerns with respect to on/off operation are in the areas of mechanical loads on the system when the engine is restarted or the torque is suddenly increased after it has been set to zero for a period of time-sometimes for relatively long periods (many minutes) and at other times for a relatively short time (several seconds).

5.24 **Engine out emissions and catalyst efficiencies required to satisfy ULEV/SULEV emission standards**

Simulations were run with **Advisor** to determine the vehicle emissions without aftertreatment. This can be done using the after-treatment option ICNULL, which sets the catalyst conversion efficiencies to zero. Unfortunately it was not possible to make the emissions simulations using the same engines as used for the fuel economy simulations. Emissions data are not available in **Advisor** for the SI 63, INSIGHT and CI68 engines. The engines used in the emissions simulations were the SI 41 1.0 L, Geo gasoline engine (41kW) and the CI 60 1.7L Mercedes diesel engine (60 kW). The emissions calculated assumed quasi-steady engine operation and do not include transient effects which will undoubtedly increase the emissions, especially the HC and CO emissions. Simulations were made for conventional ICE, and **full** and **mild** hybrid vehicles on the FUDS driving cycle as that is the cycle for which the emission standards are given. The emission standards of interest are the California ULEV and SULEV standards: **ULEV** HC .04 gm/mi, CO 1.0 gm/mi, NOx .05 gm/mi, PM .01 gm/mi; **SULEV** . HC .01 gm/mi, CO 1.0 gm/mi, NOx .02 gm/mi, PM .01 gm/mi.

The results of the emissions simulations are summarized in Table 12 for the compact class vehicle. As would be expected, the engine-out emissions for the conventional ICE vehicle are high for the engines used in the simulations as neither engine is a state-of-art design. Nevertheless, the untreated engine out emissions can be used to estimate the approximate catalyst conversion efficiencies needed to meet the stringent California emission standards. More modern engines would require somewhat lower catalyst conversion efficiencies, but only marginally lower. Note in Table 12 that the diesel engines have relatively low HC and HC emissions but high NOx and PM emissions. The engine-out emissions of the gasoline engine are high for all the pollutants except PM which is taken as zero. In the case of the gasoline engine, the required catalyst conversion efficiencies are high, well beyond 90% in most instances and over 99% for the SULEV standard for HC and NOx. Fortunately these high conversion efficiencies are attainable for gasoline engines operated near stoichiometric conditions. Gasoline engine powered vehicles are already on the market that meet the SULEV standard. In order to meet the SULEV standard after-treatment systems having the same high conversion efficiencies must be developed for the advanced lean burn gasoline engine if they are to be used in the hybrid vehicles of the future.

In the case of the diesel engine, the required conversion efficiencies are very high (over 99%) only for the NOx. For HC and PM, the conversion efficiencies required are more modest being in the range of 85-98. For the diesel engine, all these conversion efficiencies are well beyond the present state-of-the-art and much development is needed. It is still uncertain whether it will be possible to meet the Tier 2 or LEV standards with the diesel engine. The results shown in Table 12 indicate that hybridization has only a marginal effect on the quasi-steady emissions of vehicles. It is likely that hybridization will increase slightly the NOx emissions because of the high torque fraction operation of the engine. This increase will make it marginally more difficulty for hybrid vehicles using advanced lean-burn and diesel engines to the NOx standards than conventional ICE vehicles using the same engines. Information on expected conversion efficiencies for an emissions control aftertreatment system being developed by Ricardo for their 42V hybrid-electric diesel hybrid (Reference 24). The emissions control system consists of an oxi-catalyst with an 80% efficiency, a passive de-NOx unit with an efficiency of 10-20%, DPF particulate filter with an efficiency of about 90%. It is projected this system will met the ULEV standards for HC, CO, and particulates, but the NOx emissions would be relatively high at .2 gm/mi NOx.

5.3 Discussion of the implications of HEV operation on fuel/lube issues

Various aspects of how hybrid vehicles operate have been discussed both qualitatively and quantitatively in previous sections. In this section, the implications of HEV operation on fuel/lube issues will be summarized. First it should be noted that both Honda and Toyota have begun to market hybrid vehicles in the United States and that those vehicles are using the same fuel (gasoline) as the conventional ICE vehicles. As far as is known, the available gasoline seems to work well in the vehicles resulting in good fuel economy improvements and smooth operation. It is expected that the marketed hybrids will have the same low and infrequent maintenance as conventional vehicles. The long warranties (80-100K miles) offered by the manufacturers on the hybrid driveline do not seem to reflect any uncertainty on their part concerning the durability of the engine and transmission. In the case of the Honda Insight, it is recommended that a super-low viscosity oil be used to take full advantage of the low friction characteristics of the engine. That oil is presently commercially available. This experience with fuels and lubes in hybrid vehicles currently in use seems to indicate that no drastic changes in fuel/lube are necessary to permit hybrids to be sold and used by consumers. This does not mean that the available fuels and lubes are optimum for hybrid vehicles and that in future use of the vehicles, problems will not become evident that are the result of on-off and high torque operation of the engines in hybrids.

Further testing and more extensive field experience with hybrid vehicles is needed before it will be possible to determine if hybrid vehicles do have special fuel and lube requirements. Further work/testing is needed to determine whether greater fuel economy improvements would result from the use of special fuels/lubricants in hybrids that utilize on-off operation and advanced engines. This is especially true with respect to the advanced lean-burn and GDI engines for which there is very little field experience even in conventional ICE vehicles.

6.0 Cost model and issues

6.1 Method of analysis (spreadsheet model)

6.1.1 General approach

The goal of this cost study was to develop a cost model that could be used to estimate the economics of various hybrid vehicle designs and to compare the differential costs of the hybrid driveline with the value to the consumer of fuel savings resulting from hybridization. An detailed cost model like that developed for electric vehicles at ITS-Davis (Reference 19,20) was beyond the scope of this study.

The cost model developed permits the quick analysis of the economics of various hybrid vehicle designs for compact and mid-size cars and a mid-size SUVs operated in

North America, Europe, and Japan. The economics were analyzed as a function of fuel price, use-pattern (driving cycle and miles/year), and discount rate. The key components in the hybrid driveline are the engine/transmission, electric motor/electronics, and the energy storage unit. In this study, gasoline port fuel injected (PFI), advanced lean burn PFI gasoline, and turbocharged diesel engines were considered. The transmission was a continuously variable (CVT). The electric motor/electronics were of the AC induction type. The energy storage technologies considered were nickel metal hydride batteries and carbon/carbon ultracapacitors. Two classes of drivelines were analyzed – a full hybrid that utilized an engine and electric motor of about the same power rating and a mild hybrid in which the engine power was much greater than the power of the electric motor. The component characteristics of the drivelines analyzed are given in Table 4. A key consideration in the analysis was to compare the economic attractiveness of the **full** and **mild** hybrid designs in terms of the initial cost of the vehicles and the breakeven fuel price. The spreadsheet model was written such that the user could easily change both the problem to be analyzed and the inputs on which the results are based. The details of the spreadsheet model are discussed in Appendix 1.

6.1.2 Input/output parameters

The key input data to the cost analysis are the fuel economy projections for each of the vehicle/driveline combinations and the unit costs of the driveline components. The fuel economy values were obtained from the vehicle simulations using **Advisor 2002** (see Section 4). The real-world fuel economies used in the economic analyses are calculated from the simulated fuel economy values using real world factors that are input by the user. For example, for the FUDS cycle the real world factor is .9 and for the Federal Highway cycle the factor is .78. The costs of the engine/transmission and electric motor/electronics are calculated as the product of the maximum power rating of the components and the unit cost of the components ($/kW). In the case of the batteries and ultracapacitors, the unit costs are given as $/kg and the cost is simply the product of the unit cost and the weight of the component. For pulse power energy storage components, it seems advantageous to base the cost on weight rather than power (kW) or energy stored (Wh), because the energy and power of the devices actually used by the vehicle may be quite different than their rated values depending on the driveline control strategy. The input values for the fuel economy and unit component costs are given in Tables 13 and 14. The values shown are the default cost values used in spreadsheet. These input cost values are far below current costs for limited production of components for hybrid vehicles. It is expected that the component costs will be much lower for mass production of hybrids. Additional input values involve the price of the fuel, the annual mileage use of the vehicles, the years over which the analysis is to be done, and the discount rate. Values of all the input parameters can be changed by the user from the keyboard as the case to be run is setup.

The spreadsheet is run as an EXCEL macro with the output displayed in a large table. Each row of the table is for a specific engine type, hybrid design (full or mild), and energy storage technology (batteries or ultracapacitors). The output sheet itself is specific for a vehicle type and driving cycle and input economic values (fuel price, discount, etc.). Table 15 shows a typical output sheet of the economic model. Key output parameters are the average composite fuel economy for the vehicle use, differential driveline cost, fuel saved, fraction of fuel saved, actual and discounted fuel saved (gallons) and cost of the fuel saved, actual and discounted differential ownership cost of the vehicle, and actual and discounted breakeven fuel price ($/gal). For the different engines, the differential costs of the various hybrid vehicle designs are referenced to either the baseline ICE PFI engine vehicle or in the case of the advanced engines, the ICE vehicle using the same engine. By choosing this second option one is able to separate out the effects of hybridization and the use of engines more efficient than the baseline PFI engine. The more advanced engines are more efficient, but higher in cost.

The spreadsheet model is set up to consider lithium-ion batteries, permanent magnet DC motors, and a 5-speed transmission, but those options have not yet been implemented.

6.1.3 Uncertainty of the cost inputs

At the present time there is considerable uncertainty concerning the costs of the electric driveline components – the electric motor, power electronics, and batteries/ ultracapacitors. There is a smaller uncertainty about the costs of engines – particularly the advanced lean burn gasoline and turbocharged diesel engines, and the continuously variable transmissions (CVT). There is an increasing volume of literature on the costs of the electric driveline components for the vehicles, but the costs presented in the literature span a wide range – often differing by a factor of 2-3. In this study, information developed at UC Davis was used primarily because its source, basis, and limitations were better understood than similar information developed elsewhere.

The costs of the components are highly dependent on the assumed level of maturity of the technology and the volume of production. In order to determine the impact of the hybrid driveline components on the sticker price of the vehicle, it is necessary to assume a markup factor to apply to the cost of the components to the OEM. In this study, it was assumed that all the technologies were mature and in high volume production and that the markup factor was 1.75-2 for the driveline components. Realizing the uncertainty of the cost inputs the spreadsheet model was configured such that the user could easily change the inputs from the keyboard prior to making a run if desired.

The primary sources of cost information used in this study were References 19 and 20. Reference 19 is a detailed cost study of electric vehicles and comparisons with conventional ICE vehicles of the same size. Reference 20 is a study of the cost of zero-emission vehicles (EVs and fuel cell powered vehicles) over the period of time in which the vehicles were being introduced and the markets were becoming mature. Hence this reference contains projections of electric driveline costs for various levels of market maturity. For the motor and power electronics, the cost function assumed was expressed as

$$\text{EMCost}(\$) = A + B*P(\text{kW})$$

where A and B are constants and P is the peak power of the electric driveline. The cost information given in References 19-20 are for motors in the 50-100 kW range which is applicable for the **full** hybrid cases, but not for the **mild** hybrid cases that utilize 10-25 kW motors. Information on the costs of the smaller vehicle motors/electronics is not readily available, so in this study the data for the larger motors was curve fit with a linear function and the result used for all motor sizes. The resulting relationship for the AC induction motor/electronic used in the spreadsheet model is

$$\text{Cost} (\$) = 467 + 27.6*P(kW)$$

Information on permanent magnetic DC motor systems is much less available, but it is expected that those motor systems will be somewhat higher in cost than the AC induction motors.

The cost of batteries are usually given in \$/kWh. In a hybrid vehicle, however, the battery is sized primarily by power (kW) rather than energy stored (kWh) and the batteries are designed to have a high power density usually resulting in an energy density significantly less than that for an electric vehicle battery. For these reasons, it does not seem appropriate to express the unit cost of the battery in terms of \$/kWh. Instead, in this study the unit cost of the battery is given in terms of \$/kg. Hence the battery-cost relationships are

$$\text{BatCost}(\$) = \text{Bat. Wgt.(kg)}*\$/\text{kg}$$

$$\$/\text{kg} = \$/\text{kWh}*\text{Wh/kg}/1000$$

$$\text{Bat.Wgt.} = \text{Pmax(kW)}/\ \text{(W/kg)max}$$

The default characteristics of the batteries used in this study are summarized in Table 16. The resulting unit costs for the batteries are \$25/kg for the nickel metal hydride batteries and \$42/kg for the lithium-ion batteries. It is assumed in the cost analysis that the life of all the energy storage units is at least that of the period of the economic analysis (that is eight (8) years in most cases).

The ultracapacitors units in the **mild** hybrids are sized by the energy storage requirement (Wh). Hence the key performance characteristic of the ultracapacitors is Wh/kg. The cost of the ultracapacitor unit is expressed as

$$\text{CapCost} (\$) = \text{Cap.Wgt.}*\ (\$/\text{kg})\text{cap}$$

$$\$/\text{kg} = \$/\text{Wh} * \text{Wh/kg}$$

The default values used were 5 Wh/kg and \$7/Wh resulting in a cost of \$35/kg for the ultracapacitor unit. This cost is much less than current pricing, but it is within the range of projected prices in the relatively near future for ultracapacitors manufactured in high volume.

It was difficult to obtain cost information on evolving and advanced engines and transmissions even though those components are used in conventional ICE vehicles currently being marketed worldwide. What was done was to estimate the price to the OEM of the gasoline PFI engine and to add an incremental cost for the lean burn gasoline and the turbocharged diesel engines. The increment for the lean burn engine was thought to be quite small based on information in Reference 21. In the case of the diesel engine, the increment was based on the difference in the cost of the gasoline and diesel versions of the Volkswagen Jetta. Further it was assumed that in mass production, the cost of the continuously variable transmission would be the same as the 4-speed automatic with lockup. In the cost study, the cost of the engine and transmission were combined into a single unit cost for the mechanical components. The default values used were \$32/kW for the PFI engine, \$36/kW for the lean burn engine, and \$50/kW for the turbocharged diesel engine. These values can be easily changed by the user of the spreadsheet model at the keyboard if desired.

There are no default values for the economic parameters – namely, the fuel prices, years of use and annual miles traveled, and discount rate. The user must set values for these parameters before making the run. For the United States, the fuel price is set in \$/gal and for Europe and Japan the price is set in \$/liter. The spreadsheet model permits the user to select a wide range of values for all the economic parameters.

A typical output sheet for the spreadsheet model is shown in Figure 15. Nearly all the input parameters for the calculation are listed at the top of the sheet for easy reference in evaluating the run and for comparison with other runs using different sets of input parameters.

6.1.4 Cases considered

A wide range of cases can be considered. A set of results is given in Appendix 2 for compact and mid-size cars and mid-SUVs. Results are given for United States, European, and Japanese driving cycles. Each run gives results for **full** and **mild** hybrids for three engine types and nickel metal hydride batteries and ultracapacitors for energy storage. The results for a conventional ICE vehicle are also given. The user can choose to select as the reference or baseline cost case either a conventional vehicle using the gasoline PFI engine or an ICE vehicles using the advanced engines (lean-burn or diesel). This latter selection permits the user to directly assess the effect on the fuel savings and cost of hybridization for each engine type.

6.2 Discussion/interpretation of the results

As noted above, a complete set of spreadsheet results are given in Appendix 2. A subset of those results is given in Tables 17 and 18. The parameters of primary interest are the differential cost to the consumer of hybridization, resultant fraction of fuel saved and the breakeven gasoline price. The cost results shown in the tables are for a discount rate of 4% and a use-period of eight (8) years. Several conclusions are clear from the tables. First in all cases, the **full hybrid** designs save more fuel for all the driving cycles than the **mild hybrid** designs, but in all cases the breakeven fuel price is lower for the **mild hybrids** than for the **full hybrids.** This means that the **mild** hybrid designs are more cost effective than the **full** hybrid designs. Using ICE vehicle with the PFI engine as the reference vehicle (see Table 17), the breakeven fuel price for the **mild hybrids** is close to the present gasoline price in the United States and much below the fuel price in Japan and Europe. The breakeven fuel prices for the **full hybrids** are well above the gasoline price in the United States, but below the fuel price in Europe and Japan. Using the PFI engine in the reference vehicle, the fuel saving fraction is greater than 30% for the **mild hybrid** cases and greater than 40% for **full hybrid** cases, but the saving fraction varies significantly with engine type, driving cycle, and vehicle class.

Both the fuel saving fraction and breakeven fuel price for the advanced engine cases depend on the reference ICE vehicle used. This is shown clearly by comparing Table 17 and 18. As would be expected, hybridization with the advanced engines looks more attractive using as the reference vehicle an ICE vehicle using the PFI engine than when the reference ICE vehicle uses the same advanced engine as in the hybrid. The cost effectiveness of hybridizing using the turbocharged diesel (TCD) engine is not as great (higher breakeven fuel cost) as that with the gasoline engines primarily because of the relatively high cost of the diesel engine. It was very difficult to obtain information on the differential cost of diesel engines. The value ($/kW) used for the diesel engines was estimated based on the difference in showroom cost of the same passenger car with a gasoline and a diesel engine. The advanced lean burn gasoline engine in the **mild hybrids** appears to be the most cost effective solution compared to present ICE cars as its fuel savings potential is comparable to the diesel engine and its breakeven gasoline price is even lower than for hybrid vehicles using the PFI engine. In the case of the hybrids using the lean-burn engine about one-half the fuel savings is due to replacing the PFI engine and the remainder is due to hybridization. It was assumed that the cost of the PFI lean burn engine was on slightly higher than that of the standard PFI engine. The diesel (TCD) engine has the highest fuel saving potential in both the **full** and **mild** hybrid designs, but its breakeven fuel price is also the highest for all the cases considered.

The economic results indicate that when considering both fuel savings potential and economic attractiveness (low breakeven fuel price), the mid-size car class offers the best prospects for hybridization. The fuel savings potential for the mid-SUV class is high, but the breakeven fuel price is significantly higher than for the mid-size car class. The compact car class has a lower fractional fuel savings potential than the other vehicle classes, but its breakeven fuel price is favorable for the **mild hybrid** cases. These trends are seen particularly clearly in Table 17. Note also in Table 17 that economic value of the fuel saved ($/gal saved) calculated directly from the differential cost of the hybrid driveline and the gallons of fuel saved by hybridization over 100,000 miles of travel closely tracks the trend of the breakeven fuel price. It appears that over the lifetime of the hybrid vehicles the differential cost of the hybrid driveline can be recovered from fuel savings even at the present low fuel prices.

The fuel economy results in Tables 9-11 using different energy storage technologies in **mild hybrids** indicate that the fuel economy using ultracapacitors is the highest for all the cases considered. Hence the fuel savings potential using the ultracapacitors is also the greatest. The breakeven gasoline prices for cases using nickel metal hydride batteries and ultracapacitors are essentially the same for a battery cost of $25/kg and a capacitor cost of $35/kg (see Table 15 and the cost results in Appendix 2).

It must be emphasized that all the results cited are highly dependent on the cost inputs used in the economic analysis and in addition it has been assumed that the life of all the energy storage units is at least eight (8) years – the period of the economic analysis. Changes in the economic inputs can have a large influence on the quantitative conclusions indicated in this section, but the same trends would be apparent using any set of reasonable cost inputs. Additional spreadsheet runs were made for cost inputs significantly lower and higher (cost factors between .75 and 1.5) than the default cost values shown in Table 14, which correspond to mature technologies and mass production

of components, to determine the effect on the differential vehicle costs and the breakeven gasoline price. The results of those runs are summarized in Table 19
. As would be expected, the differential powertrain costs and as a result the breakeven gasoline price vary significantly as the cost of the electric motor/electronics are changed. For the **mild** hybrid designs, the breakeven gasoline price remains below or slightly above the current price of gasoline in the United States even when the electric component costs are increased by a factor of 1.5 above the default values shown in Table 14. The breakeven gasoline price for the **full** hybrid designs become much higher than the present cost of gasoline when the component costs are increased.

7.0 Marketing Experience and Strategies

7.1 Sales of hybrid vehicles in Japan and the United States (up to August 2002)

Toyota and Honda are the only auto manufacturers in the world at the present time selling/leasing hybrid-electric cars to the general public. Both manufacturers are selling hybrids in the United States, especially in California, but both first introduced their hybrids to the market in Japan. Toyota started sales of the **Prius** in Japan in the fall of 1997 and in the United States in the fall of 2000. Honda started sales of the **Insight** in the United States in the fall of 1999 and the Hybrid **Civic** in April 2002. All the hybrids are full function cars with all the comfort features expected by car buyers in the United States. The **Prius** satisfies the SULEV exhaust emission standards. The 5-speed Honda **Insight** satisfies the ULEV standard and the CVT Insight satisfies the SULEV standard. The Hybrid **Civic** satisfies the ULEV standard. Sales of all the hybrids have been good with both Toyota and Honda being able to sell all the vehicles they have chosen to manufacture. According to car sales data in "Automotive News", Toyota's sales of the Prius in the United States were 1174 cars/month in 2001 and 1736 cars/month in 2002. Honda sold about 6000 Insights in 2001. Honda has a sales target of 2000 cars/month in 2002-3 for the Hybrid Civic and to date they are meeting that sales target.

The car magazines have given good reports for the Prius, but were luke warm for the Insight due to its small size and only two seats. However, the car magazines are very complimentary to the new Honda hybrid Civic and feel it is the wave of the future. Sales by Toyota and Honda in both Japan and the United States seem to indicate that hybrid-electric vehicles will be well received in the market place. The only down side of the hybrids is that their selling price is $2-3K higher than the top of the line car of the

manufacturer in the same vehicle class. Whether this price differential reflects the actual cost difference in the manufacture of the hybrids at the present time is difficult to assess. The sales experience of Toyota and Honda to date indicates that comfortable, clean, well performing, efficient hybrids will be well received and purchased by the public even at a significant, but not large, price differential compared with the standard ICE vehicles of the same size and performance.

7.2 Current Plans of the auto companies for developing/marketing hybrids

It is difficult to assess clearly the plans of the auto companies in Europe, Japan, and the United States for the development and marketing of light-duty hybrid-electric vehicles, including vans and SUVs. There have rather frequent news releases by the United States automakers regarding their plans to develop and eventually market hybrid vehicles, but in most cases during the period of developed it was announced or rumored that the automaker had concluded that the fuel savings where too small to justify the additional cost of the hybrid vehicle and thus plans to market the vehicle would be delayed or dropped. An example of this sequence of events is the Durango that was to be marketed by Diamler-Chrysler. At the present time, the only hybrid that has been announced by a U.S. automaker and remains on track for marketing is the Escape SUV from Ford. It is expected that Toyota and Honda will continue to market their hybrids indefinitely and that both companies will expand their hybrid vehicle line to include mid-size cars and small/mid SUVs and mini-vans. Toyota currently markets the Estima, a mini-van, in Japan. It is dual mode design with a hybrid driveline on the front wheels and electric drive on the rear wheels (Reference 22). With the success of Toyota and Honda in marketing hybrids in the smaller vehicle classes, it is somewhat surprising that other companies have not announced firm plans to market hybrid vehicles in various vehicle classes. Most of the "talk" of hybrids involves development of larger vehicles, particularly SUVs which have relatively low fuel economy and sell at a premium price. Hence it seems likely the first hybrid vehicles from the U.S. automakers will be SUVs and pick-up trucks.

A number of companies worldwide are developing vehicles that utilize a 42V electrical system. This is being done primarily to permit a significant increase in power to drive vehicle accessories (Reference 23). Development of the 42V systems will enhance the ability of companies to develop higher voltage, more powerful hybrid drivelines, but even though the 42V systems can result in small fuel economy improvements (about 10% at most), they are not considered hybrid drivelines in the context of this study. Marketing of vehicles using the 42V electrical system has started in Japan and Europe, but the mass marketing of those vehicles by most automakers is at least 5 years in the future.

7.3 The Impact of the California ZEV Mandate on hybrid vehicle markets

The California ZEV (Zero Emission Vehicle) Mandate as currently written states that 2% of the light-duty vehicle sales of the large auto manufacturers must be ZEVs (battery or H2 fuel cell powered), 2% can be Advanced Technology (AT) PZEVs (partial credit ZEVs), and 6% can be PZEVs. All PZEVs must satisfy the California SULEV emissions standards. The ATPZEVs in addition to being PZEVs also incorporate to a significant extent advanced electric driveline components like those in ZEVs. The ATPZEVs are likely to be hybrid vehicles similar to those considered in this report. Hence the inclusion in the ZEV Mandate of the ATPVEVvehicles seem to offer a potential market in California for hybrid vehicles. If these vehicles have significantly better fuel economy than the SULEV PZEVs, they should be more attractive to new vehicle purchasers than the conventional ICE SULEV PZEV vehicles. Thus the sales of the ATPZEV and thus hybrid vehicles could be much greater than that needed to meet the 2% of ATPZEVs mandated by the regulations. The key issue will be the incremental cost of the ATPZEVs relative to the PZEV vehicles. The economic studies presented in

Section 6 indicate that **mild** hybrid vehicles can be designed that make economic sense to new car purchasers even at the present fuel prices. Hence it is likely that some automakers will market ATPZEVs that will be attractive to the broad vehicle market and meet a significant fraction of the 8% non-ZEV portion of the ZEV Mandate sales with hybrid vehicles. This would be attractive to the automaker as an ATPZEV gets a .45 ZEV credit compared to a .2 ZEV credit for a conventional ICE PZEV. For example, Honda and Toyota could meet 80% of their ZEV Mandate requirements by having 13% of their sales be vehicles like the hybrid Civic or the Prius.

7.4 Projections of sales of hybrid vehicles for 2003-2015

It is difficult to project sales of hybrid vehicles in the next 10-15 years. Such projections depend on how the California ZEV Mandate is implemented in that time period and whether states such as New York and Massachusetts continue to follow the California emissions regulations. In addition, the price and availability of gasoline during that period, regulatory actions on CAFÉ and other fuel economy standards, and tax credits and other incentives are critical to the growth of the hybrid vehicle market. The results of this study indicate that all the auto companies could develop and market hybrid vehicles in the near future that would be attractive to new vehicle buyers. The key questions are whether market conditions and government regulations force the hand of most of the auto manufacturers to produce cost-effective hybrid vehicles. In light of the success of the Honda and Toyota hybrid vehicles and the high probability that the California ZEV Mandate will be implemented in some form that will include the ATPZEV class of vehicles, it seems likely hybrid vehicle sales will be a significant fraction of total light-duty sales by 2010 and be a dominant fraction by 2020. If gasoline prices increase significantly in the period 2003-2008, sales of hybrid vehicles could be a dominant fraction by 2015 or earlier.

References

1. **Advisor** (Advanced Vehicle Simulator), Version 2002, developed by the National Renewable Energy Laboratory (NREL), available by downloading from the NREL website.
2. Jost, K., Spark-ignition Engine Trends, Automotive Engineering International, January 2002, Pg 26-39
3. Polletta, D., Louckes, T., and Severinsky, A., Fuel Economy and Performance Impact of Hybrid Drive Systems in Light Trucks, Vans and SUVs, SAE paper 2001-01-2826rgina, June 3-5, 2002
4. Graham, R., Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, EPRI, July 2001
5. See the component descriptions in the M-files in the **Advisor** program
6. Friedman, D.J., Burke, A.F., and Miller, M., Hybrid Vehicle Component Modeling: Flywheels, Ultracapacitors, and Fuel Cells, ITS Report, work performed on NREL contract XCB-5-153-33-01, March 1998
7. Burke, A.F., Ultracapacitors:why, how, and where is the technology, Journal of the Power Sources, 91 (2000), pg 37-50

8. Frank, A., A., Bradley, T.H., and Huff, B.R., Test and Evaluation of the UC Davis Servo-Hydraulic CVT Control System and GCI CVT Chain in a Hybrid Electric Vehicle, UC Davis Report to Nissan Motor Company, 2000
9. Plotkin, S., etals, Hybrid Electric Technology Assessment: Methodology, Analytical Issues, and the Interim Results, Argonne National Laboratory Report ANL/ESD/02-2, October 2001
10. Fry, M., King, J., and White, C., A Comparison of Gasoline Direct Injection Systems and Discussion of Developments Technique, SAE paper No. 199-01-0171, Detroit, Mich, March 1999
11. Direct Injection SI Engine Technology, SAE Publication No. SP-1584, 2001
12. Johnson, J.H. (editor), Diesel Nitrogen Oxide Emissions-Landmark Research 1995-2001, SAE Publication PT-89, 2002
13. Johnson, J.H., Diesel Particulate Emissions Landmark Research, 1994-2001, SAE Publication PT-86, 2002
14. Tomazic, D., Integration of Emission Control Systems for CIDI Engines to Achieve PZEV, FEV Engine Technology, Inc., presentation at the SAE PZEV Emissions Technology TOPTEC , January 24-25, 2002, San Diego, California
15. Van Rooji, J.H.M., and Cadee, T.P., GCI's High Torque Chain CVT, Japanese Society of Mechanical Engineers 96-36493
16. Alexander, M., Johnson, B., etals, A Mid-size Sedan Designed for High Fuel Economy and Low Emissions: the 1999 UC Davis Future Car, ITS-Davis report UCD-ITS-RR-99-11, 2000
17. Meyr, N., Huff, B., etals, Design and Development of the UC Davis Future Truck, ITS-Davis report UCD-ITS-RR-01-05, 2001
18. Burke, A.F., Development of Test Procedures for Hybrid/Electric Vehicles (and SIMPLEV for Series Hybrid Vehicles), Idaho National Engineering Lab report DOE/ID-10385, July 1992
19. DeLucchi. M.A., etals, Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model, ITS-Davis report UCD-ITS-RR-99-4, April 2000
20. Lipman, T.E., Zero-Emission Vehicle Scenario Cost Analysis using a Fuzzy Set-based Framework, , ITS-Davis report UCD-ITS-RR-99-18, December 1999
21. Spectrum- Technology – Highlights and R&D Activities at FEV, Innovative Valve Train Systems, etc., published by the FEV Engine Technology, Inc., Issue 19, February 2002
22. Oba, H., Yamanaka, A., etals, Development of a Hybrid Powertrain System using a CVT in a Minivan, paper prepared for Toyota for presentation at the SAE Congress, Detroit, 2002
23. Simopoulos, G., McBain, J.A., Schneider, E.D., and Wingeier, E.W., Fuel Economy Improvements in an SUV equipped with an Integrated Starter Generator, SAE paper No. 2001-01-2825, 2001
24. Gordon, R., General Presentation on the i-MoGen 42V Hybrid Vehicle, Ricardo, March 2002

Table 1:Characteristics of ICE Vehicles of Various Types

Type	Curb Weight kg	C_D	A_f Ft^2	Rolling resist. coeff.	P_{max} kW	0-60mph sec	EPAmpg City/hw*
Compact car	1160	.3	21.4	.007	95	10	25/31
Mid-size car	1500	.3	23.1	.007	135	8.5	20/28
Full-size car	1727	.32	23.7	.007	180	8.0	17/25
Small SUV	1590	.38	26.4	.008	135	10	19/25
Mid-size SUV	1910	.42	28.0	.008	165	9.5	15/19
Large SUV	2500	.45	34	.008	200	9.5	14/16

All vehicles have A4 transmissions
*** The Mpg shown are those in the EPA Fuel Economy Guide. Measured fuel economy has been corrected by .9 for the FUDS and by .78 for the highway cycle.**

Table 2: Comparisons of Advisor Simulation Results and EPA fuel Economy Test data

	Advisor	simulations		EPA	Tests*
Vehicle	FUDS	Highway		FUDS	Highway
Honda Insight 5-spd	64.8	85.8		67.7	87.2
Honda Civic-AT4-VTEC	38.5	54.2		33(30)	49(38)
Honda Civic HEV-CVT	54.6	70.3		53.3(48)	60.2(47)
Compact car – gasoline PFI-5 spd	26.3	39.9		27.8(25)	39.7(31)
Mid-size car Gasoline PFI	20.4	31.6		22.2(20)	35.9(28)
Mid-size SUV Gasoline PFI	15.5	23.5		16.6(15)	24.3(19)

- **first mpg is the measured value and the second in ( ) is the mpg after the correction using the .9 (city) and .78 (highway) factors, respectively.**

Table 3: Comparisons of Advisor Calculated Fuel Economy for Vehicles using Diesel Engines with Test Data

Vehicle	Engine Type Rating	0-60 mph (sec)	Driving cycle	MPG Advisor	MPG Test
Golf 1436 kg	2L gasol. 86 kW	10	FUDS	26.7	26.1
			Highway	40.0	38.5
	1.9L TDI Diesel 67.5 kW	12	FUDS	39.7	38-46
			Highway	56.9	57-63
			European	40.0	-----
Reference Compact 1350 kg	TDI Diesel 105 kW	8.5	FUDS	32.7	----
			Highway	46.2	----
			European	31.1	----
Audi A4 1421 kg	1.9L TDI Diesel 67.5 kW	13	European	40.2	43.5
Audi A6 1551 kg	1.9L TDI Diesel 86 kW	11	European	35.3	42
Audi A6 1751 kg	2.5L TDI Diesel 125 kW	9	European	26.4	29.8
			Highway	39.4	----

All the vehicles simulated on Advisor used CVT transmissions

All test data for vehicles using diesel engines on the European cycle were obtained from the "Diesel Car" magazine quoted as "govt. data"; other test data are from the EPA Fuel Economy Guide corrected back to the measured values.

MPG for diesel engines is in miles per gallon diesel fuel

Table 4: Hybrid Vehicle Designs - Powertrain Characteristics for Full and Mild Hybrids

		Full Hybrid			Mild Hybrid		
Vehicle Class	Test Weight kg	Engine KW	Motor KW	Batteries V/Ah	Engine kW	Motor kW	Batteries V/Ah
Compact car	1350	60	40	335/12	85	10	150/8
Mid-size car	1660	75	65	335/20	120	15	150/13
Mid-size SUV	2170	90	75	335/24	150	20	150/18

All vehicles have CVT transmissions and Nickel Metal Hydride batteries

Table 5: Characteristics of Various Driving Cycles

Parameter	FUDS	Highway	US06	ECE-EUDC	Japan 10/15
Distance (Miles)	7.45	10.2	8.0	6.83	2.58
Time (Sec)	1372	765	600	1180	636
Aver. Spd. (mph)	19.5	48.2	47.9	20.9	14.6
Max. spd. (mph)	56.6	59.9	80	74.5	43.5
Max. Accel. (mph/sec)	3.35	3.35	8.5	2.33	1.78
Aver. Accel. (mph/sec)	1.12	----	----	1.06	1.34
% time idle (sec)	18	0	5.5	22.1	28.8
Stops/mi.	2.4	1 stop	.625	1.9	2.7

Table 6: Simulation Results from Advisor for Compact Cars- Full and Mild hybrids and Conventional ICE – with Various Engines

				Mpg		
Type of driveline	**Engine type**	**FUDS**	**Highway**	**US06**	**Japan 10/15**	**ECE-EUDC**
Full hybrid	**Gasoline PFI**	**43.1**	**52.3**	**34.4**	**39.9**	**41.4**
	Lean burn	**53.3**	**65.2**	**42.8**	**48.3**	**52.2**
	TC Diesel	**48.6(54.1)**	**63.2(71.1)**	**43.5(49)**	**44(49)**	**48(54)**
Mild hybrid	**Gasoline PFI**					
	Bat.	**40.2**	**43.8**	**30.1**	**38.8**	**36.6**
	Ultracap	**43.9**	**50.0**	**32.9**	**40.7**	**39.8**
	Lean burn					
	Bat.	**50.4**	**57.4**	**41.9**	**48.2**	**49.9**
	Ultracap	**54.2**	**64.0**	**43.6**	**49.8**	**52.2**
	TC Diesel					
	Bat.	**44.7(50.3)**	**53.1(59.7)**	**39.3(44)**	**41(46)**	**43(49)**
	Ultracap	**48.3(54.3)**	**60.5(68.0)**	**41.5(48)**	**43(49)**	**47(52)**
Convent. ICE –CVT	**Gasoline PFI**	**27.0**	**41.0**	**29.0**	**21.9**	**26.4**
	Lean burn	**39.1**	**56.1**	**36.3**	**33.4**	**38.4**
	TC Diesel	**32.9(37.1)**	**46.9(52.8)**	**31.4(35)**	**27(30)**	**32(36)**

All vehicles use CVTs and nickel metal hydride batteries and have 0-60 mph acceleration times of about 9 sec

For diesel engine powered vehicles, the first mpg given is the gasoline equivalent mpg and the second number in ( ) is the mpg on diesel fuel.

Table 7: Simulation Results from Advisor for Mid-size Cars-
Full and Mild hybrids and Conventional ICE –
with Various Engines

				Mpg		
Type of driveline	**Engine type**	**FUDS**	**Highway**	**US06**	**Japan 10/15**	**ECE-EUDC**
Full hybrid	**Gasoline PFI**	**35.8**	**44.2**	**30.0**	**33.2**	**35.0**
	Lean burn	**44.3**	**55.8**	**37.5**	**40.1**	**44.4**
	TC Diesel	**40.1(45.1)**	**53.7(60.4)**	**38.3(43)**	**36(41)**	**40(45)**
Mild hybrid	**Gasoline PFI**					
	Bat.	**33.8**	**37.3**	**25.1**	**31.8**	**30.7**
	Ultracap	**37.2**	**42.9**	**29.4**	**34.2**	**34.7**
	Lean burn					
	Bat.	**42.1**	**48.7**	**35.1**	**39.3**	**41.7**
	Ultracap	**45.4**	**54.8**	**38.7**	**43.0**	**45.0**
	TC Diesel					
	Bat.	**37.3(42)**	**45(50.6)**	**33.2(37)**	**34(38)**	**36(41)**
	Ultracap	**41.2(46.3)**	**51.9(58.4)**	**36.8(41)**	**36(41)**	**40(45)**
Convent. ICE –CVT	**Gasoline PFI**	**20.4**	**32.3**	**23.3**	**16.5**	**20.2**
	Lean burn	**29.7**	**44.4**	**29.4**	**25.0**	**29.5**
	TC Diesel	**24.5(27.7)**	**35.1(39.5)**	**24.2(27)**	**20(23)**	**24(26)**

All vehicles use CVTs and nickel metal hydride batteries and have 0-60 mph acceleration times of about 9 sec

For diesel engine powered vehicles, the first mpg given is the gasoline equivalent mpg and the second number in ( )

Table 8: Simulation results from Advisor for Mid-size SUVs – Full and Mild Hybrids and conventional ICE– with Various Engines

				Mpg		
Type of driveline	**Engine type**	**FUDS**	**Highway**	**US06**	**Japan 10/15**	**ECE-EUDC**
Full hybrid	**Gasoline PFI**	**28.3**	**31.6**	**20.4**	**28.3**	**28.2**
	Lean burn	**33.9**	**38.2**	**25.1**	**34.1**	**34.1**
	TC Diesel	**32(36)**	**37.8(42.6)**	**26(29.2)**	**30(34)**	**33(37)**
Mild hybrid	**Gasoline PFI**					
	Bat.	**26.3**	**26.6**	**18.5**	**27.3**	**25.4**
	Ultracap	**28.9**	**30.3**	**20.0**	**29.7**	**28.3**
	Lean burn					
	Bat.	**32.6**	**34.3**	**24.7**	**33.6**	**33.0**
	Ultracap	**35.3**	**38.1**	**26.5**	**35.5**	**35.4**
	TC Diesel					
	Bat.	**29.6(33.3)**	**33(37.1)**	**24.1(27)**	**30(33)**	**34(38)**
	Ultracap	**31.9(35.9)**	**36.7(41.3)**	**26.4(30)**	**32(35)**	**36(40)**
Convent. ICE –CVT	**Gasoline PFI**	**15.9**	**24.5**	**17.6**	**13.1**	**15.8**
	Lean burn	**23.5**	**33.5**	**22.2**	**20.0**	**22.9**
	TC Diesel	**19.8(22.3)**	**29(32.7)**	**19.6(22)**	**16(18)**	**19(21)**

All vehicles use CVTs and nickel metal hydride batteries and have 0-60 mph acceleration times of about 9 sec.

For diesel engine powered vehicles, the first mpg given is the gasoline equivalent mpg ad the second number ( ) is the mpg in diesel fuel

Table 9: The Fuel Economy Improvement Factor for Compact Cars- Full and Mild hybrids- with various Engines

			Fuel Economy	Factor		
Type of driveline	**Engine type**	**FUDS**	**Highway**	**US06**	**Japan 10/15**	**ECE-EUDC**
Full hybrid	**Gasoline PFI**	**1.60**	**1.28**	**1.19**	**1.82**	**1.57**
	Lean burn	**1.36**	**1.16**	**1.18**	**1.45**	**1.36**
	TC Diesel	**1.46**	**1.35**	**1.40**	**1.63**	**1.50**
Mild hybrid	**Gasoline PFI**					
	Bat.	**1.49**	**1.07**	**1.04**	**1.77**	**1.39**
	Ultracap	**1.63**	**1.22**	**1.13**	**1.86**	**1.51**
	Lean burn					
	Bat.	**1.29**	**1.02**	**1.15**	**1.44**	**1.30**
	Ultracap	**1.39**	**1.14**	**1.20**	**1.49**	**1.36**
	TC Diesel					
	Bat.	**1.36**	**1.13**	**1.26**	**1.53**	**1.36**
	Ultracap	**1.47**	**1.29**	**1.37**	**1.63**	**1.44**
Convent. ICE –CVT	**Gasoline PFI**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
	Lean burn	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
	TC Diesel	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Table 10: The Fuel Economy Improvement Factor for Mid-size Cars - Full and Mild hybrids- with various Engines

			Fuel Economy	Factor		
Type of driveline	Engine type	FUDS	Highway	US06	Japan 10/15	ECE-EUDC
Full hybrid	Gasoline PFI	1.75	1.37	1.29	2.0	1.73
	Lean burn	1.49	1.26	1.28	1.60	1.51
	TC Diesel	1.63	1.53	1.59	1.78	1.73
Mild hybrid	Gasoline PFI					
	Bat.	1.66	1.16	1.08	1.92	1.52
	Ultracap	1.82	1.33	1.26	2.08	1.72
	Lean burn					
	Bat.	1.42	1.1	1.19	1.57	1.41
	Ultracap	1.53	1.23	1.32	1.72	1.53
	TC Diesel					
	Bat.	1.52	1.28	1.37	1.65	1.58
	Ultracap	1.61	1.48	1.52	1.78	1.73
Convent. ICE –CVT	Gasoline PFI	1.0	1.0	1.0	1.0	1.0
	Lean burn	1.0	1.0	1.0	1.0	1.0
	TC Diesel	1.0	1.0	1.0	1.0	1.0

Table 11: The Fuel Economy Improvement Factor for Mid-size SUVs-Full and Mild hybrids- with various Engines

			Fuel Economy	Factor		
Type of driveline	**Engine type**	**FUDS**	**Highway**	**US06**	**Japan 10/15**	**ECE-EUDC**
Full hybrid	Gasoline PFI	1.78	1.29	1.17	2.16	1.79
	Lean burn	1.44	1.14	1.13	1.71	1.49
	TC Diesel	1.61	1.28	1.33	1.89	1.76
Mild hybrid	Gasoline PFI					
	Bat.	1.65	1.08	1.05	2.08	1.61
	Ultracap	1.82	1.22	1.14	2.27	1.79
	Lean burn					
	Bat.	1.39	1.02	1.11	1.68	1.44
	Ultracap	1.50	1.13	1.19	1.78	1.55
	TC Diesel					
	Bat.	1.49	1.13	1.23	1.83	1.81
	Ultracap	1.60	1.26	1.36	1.94	1.90
Convent. ICE –CVT	Gasoline PFI	1.0	1.0	1.0	1.0	1.0
	Lean burn	1.0	1.0	1.0	1.0	1.0
	TC Diesel	1.0	1.0	1.0	1.0	1.0

Table 12: Catalyst Efficiencies required to Meet the ULEV and SULEV Emission Standards for Hybrid Vehicles using Gasoline and Diesel engines

Hybrid type	Engine		Engine out emissions Gm/mi	Efficiency required to meet ULEV (%)	Efficiency require to meet SULEV (%)
Full	PFI	HC	1.121	96.3	99.1
		CO	7.932	78.6	87.4
		NOx	3.049	98.4	99.3
		PM	0	0	0
	Diesel	HC	.093	57	89.2
		CO	.538	----	---
		NOx	1.588	96.8	98.7
		PM	.056	82	82
Mild	PFI	HC	1.289	96.9	99.2
		CO	7.809	78.2	87.2
		NOx	3.223	98.5	99.4
		PM	0	0	0
	Diesel	HC	.115	65.2	91
		CO	.67	-----	----
		NOx	1.678	97	98.8
		PM	.065	85	85
Conventional ICE Vehicle	PFI	HC	2.83	98.6	99.6
		CO	15.5	89	93.5
		NOx	2.829	98.2	99.3
		PM	0	0	0
	Diesel	HC	.651	93.8	98.5
		CO	2.043	17	51
		NOx	1.346	96.3	98.5
		PM	.058	83	83

Table 13: Mpg inputs for various hybrid drivelines and vehicle classes

MPG derived from Advisor Simulations									
Types of Vehicle Components					Drive Cycle				
Type of Vehicle	Type of Drivetrain	Engine Type	Transmission Type	Energy Storage	FUDS	Highway	US06	Japan 10/15	ECE-EUDC
Compact Car	Full HEV	PFI	CVT/auto	NiMH (gen 2)	43.1	52.3	34.4	39.9	41.4
	Full HEV	Lean Burn	CVT/auto	NiMH (gen 2)	53.3	65.2	42.8	48.3	52.2
	Full HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**54.1**	**71.1**	**49.0**	**49.0**	**54.0**
Mid-Size Car	Full HEV	PFI	CVT/auto	NiMH (gen 2)	35.8	44.2	30.0	33.2	35.0
	Full HEV	Lean Burn	CVT/auto	NiMH (gen 2)	42.6	57.4	37.3	44.5	44.0
	Full HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**45.1**	**60.4**	**43.0**	**41.0**	**45.0**
Mid-Size SUV	Full HEV	PFI	CVT/auto	NiMH (gen 2)	28.3	31.6	20.4	28.3	28.2
	Full HEV	Lean Burn	CVT/auto	NiMH (gen 2)	33.9	38.2	25.1	34.1	34.1
	Full HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**36.0**	**42.6**	**29.2**	**34.0**	**37.0**
Compact Car	Mild HEV	PFI	CVT/auto	NiMH (gen 2)	40.2	43.8	30.1	38.8	36.6
	Mild HEV	Lean Burn	CVT/auto	NiMH (gen 2)	50.4	57.4	41.9	48.2	49.9
	Mild HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**50.3**	**59.7**	**44.0**	**46.0**	**49.0**
Mid-Size Car	Mild HEV	PFI	CVT/auto	NiMH (gen 2)	33.8	37.3	25.1	31.8	30.7
	Mild HEV	Lean Burn	CVT/auto	NiMH (gen 2)	42.1	48.7	35.1	39.3	41.7
	Mild HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**42.0**	**50.6**	**37.0**	**38.0**	**41.0**
Mid-Size SUV	Mild HEV	PFI	CVT/auto	NiMH (gen 2)	26.3	26.6	18.5	27.3	25.4
	Mild HEV	Lean Burn	CVT/auto	NiMH (gen 2)	32.6	34.3	24.7	33.6	33.0
	Mild HEV	TC Diesel	CVT/auto	NiMH (gen 2)	**33.3**	**37.1**	**27.0**	**33.0**	**38.0**
Compact Car	Mild HEV	PFI	CVT/auto	ultracapacitor	43.9	50.0	32.9	40.7	39.8
	Mild HEV	Lean Burn	CVT/auto	ultracapacitor	54.2	64.0	43.6	49.8	52.2
	Mild HEV	TC Diesel	CVT/auto	ultracapacitor	**54.3**	**68.0**	**48.0**	**49.0**	**52.0**
Mid-Size Car	Mild HEV	PFI	CVT/auto	ultracapacitor	37.2	42.9	29.4	34.2	34.7
	Mild HEV	Lean Burn	CVT/auto	ultracapacitor	45.4	54.8	38.7	43.0	45
	Mild HEV	TC Diesel	CVT/auto	ultracapacitor	**46.3**	**58.4**	**41.0**	**41.0**	**45.0**
Mid-Size SUV	Mild HEV	PFI	CVT/auto	ultracapacitor	28.9	30.3	20.0	29.7	28.3
	Mild HEV	Lean Burn	CVT/auto	ultracapacitor	35.3	38.1	26.5	35.5	35.4
	Mild HEV	TC Diesel	CVT/auto	ultracapacitor	**35.9**	**41.3**	**30.0**	**35.0**	**40.0**
Compact Car	Conv. ICE	PFI	CVT/auto	-	27.0	41.0	29.0	21.9	26.4
	Conv. ICE	Lean Burn	CVT/auto	-	39.1	56.1	36.3	33.4	38.4
	Conv. ICE	TC Diesel	CVT/auto	-	**37.1**	**52.8**	**35.0**	**30.0**	**36.0**
Mid-Size Car	Conv. ICE	PFI	CVT/auto	-	20.4	32.3	23.3	16.5	20.2
	Conv. ICE	Lean Burn	CVT/auto	-	29.7	44.4	29.4	25.0	29.5
	Conv. ICE	TC Diesel	CVT/auto	-	**27.7**	**39.5**	**27.0**	**23.0**	**26.0**
Mid-Size SUV	Conv. ICE	PFI	CVT/auto	-	15.9	24.5	17.6	13.1	15.8
	Conv. ICE	Lean Burn	CVT/auto	-	23.5	33.5	22.2	20.0	22.9
	Conv. ICE	TC Diesel	CVT/auto	-	**22.3**	**32.7**	**22.0**	**18.0**	**21.0**

Table 14: Component cost inputs and driveline costs for various hybrid drivelines and vehicle classes

Vehicle Component Costs

Engine/Transmission **(CVT/auto)** Costs [PFI]

				Fixed Cost	'ariable Cost
Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$1,920	$2,080	$2,720	$0	$32.0
Mild Hybrid	$2,720	$3,840	$4,800	$0	$32.0
Conventional	$3,040	$4,320	$5,280	$0	$32.0

Engine/Transmission **(CVT/auto)** Costs [Lean Burn]

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$2,160	$2,340	$3,060	$0	$36.0
Mild Hybrid	$3,060	$4,320	$5,400	$0	$36.0
Conventional	$3,420	$4,860	$5,940	$0	$36.0

Engine/Transmission **(CVT/auto)** Costs [TC Diesel]

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$3,000	$3,250	$4,250	$0	$50.0
Mild Hybrid	$4,250	$6,000	$7,500	$0	$50.0
Conventional	$4,750	$6,750	$8,250	$0	$50.0

Engine/Transmission **(Manual)** Costs [PFI]

				Fixed Cost	'ariable Cost
Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$1,800	$1,950	$2,550	$0	$30.0
Mild Hybrid	$2,550	$3,600	$4,500	$0	$30.0
Conventional	$2,850	$4,050	$4,950	$0	$30.0

Engine/Transmission **(Manual)** Costs [Lean Burn]

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$1,980	$2,145	$2,805	$0	$33.0
Mild Hybrid	$2,805	$3,960	$4,950	$0	$33.0
Conventional	$3,135	$4,455	$5,445	$0	$33.0

Engine/Transmission **(Manual)** Costs [TC Diesel]

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid	$2,850	$3,088	$4,038	$0	$47.5
Mild Hybrid	$4,038	$5,700	$7,125	$0	$47.5
Conventional	$4,513	$6,413	$7,838	$0	$47.5

Motor Costs

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kW
Full Hybrid AC motor	$1,571	$2,261	$2,813	$467	$27.6
Full Hybrid DC BPM	$2,000	$2,900	$3,620	$560	$36.0
Mild Hybrid AC motor	$743	$881	$1,019	$467	$27.6
Mild Hybrid DC BPM	$920	$1,100	$1,280	$560	$36.0

Battery Costs (NiMH, gen. 2)

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kg
Full Hybrid	$2,010	$3,350	$4,020	$0	$25.0
Mild Hybrid	$640	$1,040	$1,600	$0	$25.0

Battery Costs (Li-Ion)

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kg
Full Hybrid	$1,126	$1,876	$2,626	$0	$42.0
Mild Hybrid	$357	$584	$895	$0	$42.0

Ultracapacitator Costs

Vehicle	Compact Car	Mid-Size Car	Mid-Size SUV	$	$/kg
Mild Hybrid	$910	$1,365	$2,100	$0	$35.0

Motor Power (kW)

	Full Hybrid	Mild Hybrid
Compact Car	40	10
Mid-Sized Car	65	15
Mid-Sized SUV	85	20

Engine Power (kW)

	Full Hybrid	Mild Hybrid	CV
Compact Car	60	85	95
Mid-Sized Car	65	120	135
Mid-Sized SUV	85	150	165

Battery Voltage (V)

	Full Hybrid	Mild Hybrid
Compact Car	335	160
Mid-Sized Car	335	160
Mid-Sized SUV	335	160

Battery Amp-Hour (Ah)

	Full Hybrid	Mild Hybrid
Compact Car	12	8
Mid-Sized Car	20	13
Mid-Sized SUV	24	20

Battery Energy (Wh) [V*Ah]

	Full Hybrid	Mild Hybrid
Compact Car	4020	1280
Mid-Sized Car	6700	2080
Mid-Sized SUV	8040	3200
NiMH (gen.2) ~ 50 Wh/kg		50
Li-Ion ~ 75 Wh/kg		75

Battery Weight (kg) [Wh / (Wh/kg)]

NiMH	Full Hybrid	Mild Hybrid
Compact Car	80.4	25.6
Mid-Sized Car	134.0	41.6
Mid-Sized SUV	160.8	64.0

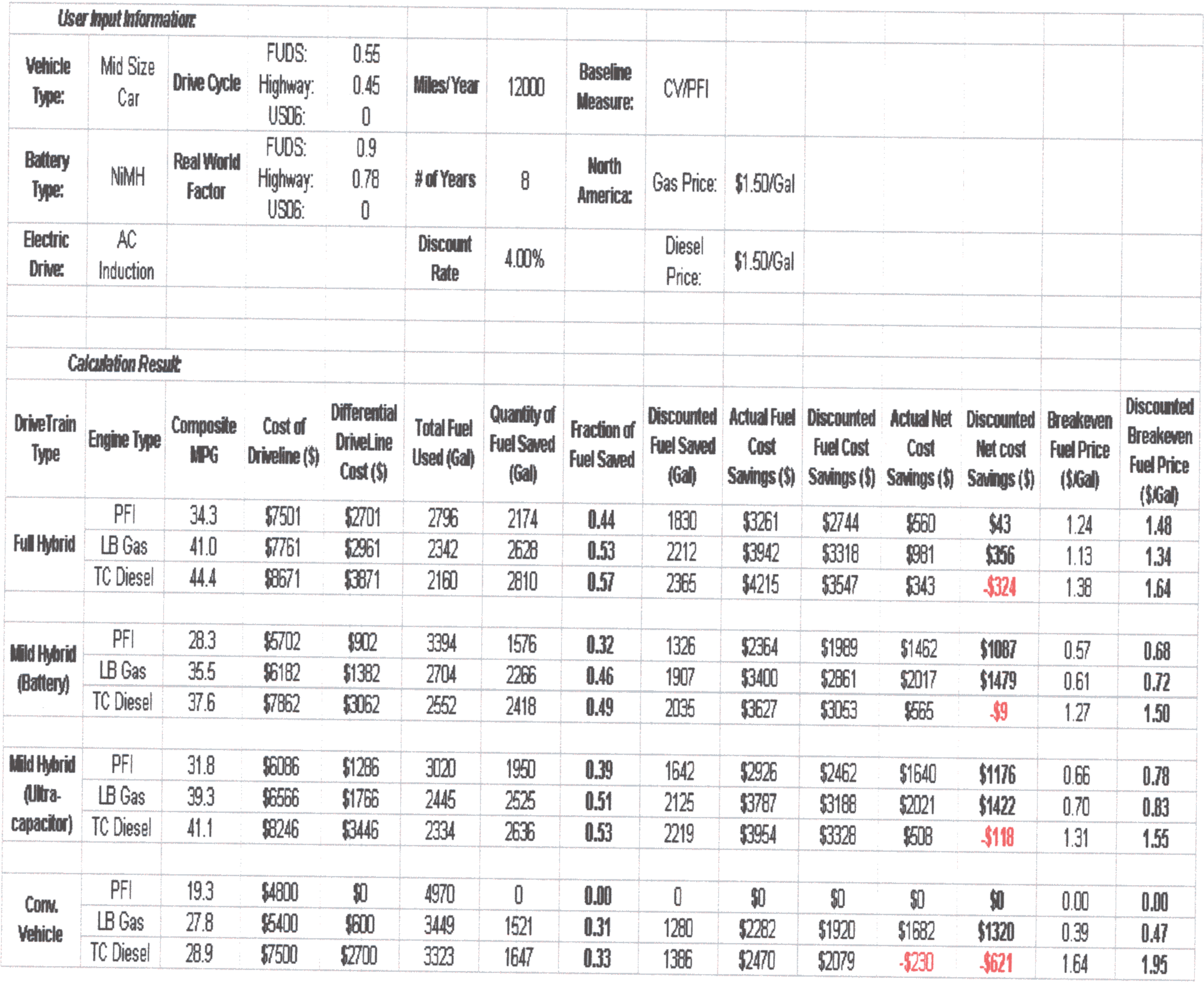
Battery Weight (kg) [Wh / (Wh/kg)]

Li-Ion	Full Hybrid	Mild Hybrid
Compact Car	26.80	8.5
Mid-Sized Car	44.67	13.9
Mid-Sized SUV	62.53	21.3

Weight (kg) [Wh / (Wh/kg)]

Ultracapacitor	Mild Hybrid
Compact Car	26.00
Mid-Sized Car	39.00
Mid-Sized SUV	60.00

Table 15: A Typical output sheet from the spreadsheet economic model



User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (Gal)**	**Quantity of Fuel Saved (Gal)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (Gal)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/Gal)**	**Discounted Breakeven Fuel Price ($/Gal)**
Full Hybrid	PFI	34.3	$7501	$2701	2796	2174	**0.44**	1830	$3261	$2744	$560	**$43**	1.24	**1.48**
	LB Gas	41.0	$7761	$2961	2342	2628	**0.53**	2212	$3942	$3318	$981	**$356**	1.13	**1.34**
	TC Diesel	44.4	$8671	$3871	2160	2810	**0.57**	2365	$4215	$3547	$343	**-$324**	1.38	**1.64**
Mild Hybrid (Battery)	PFI	28.3	$5702	$902	3394	1576	**0.32**	1326	$2364	$1989	$1462	**$1087**	0.57	**0.68**
	LB Gas	35.5	$6182	$1382	2704	2266	**0.46**	1907	$3400	$2861	$2017	**$1479**	0.61	**0.72**
	TC Diesel	37.6	$7862	$3062	2552	2418	**0.49**	2035	$3627	$3053	$565	**-$9**	1.27	**1.50**
Mild Hybrid (Ultra-capacitor)	PFI	31.8	$6086	$1286	3020	1950	**0.39**	1642	$2926	$2462	$1640	**$1176**	0.66	**0.78**
	LB Gas	39.3	$6566	$1766	2445	2525	**0.51**	2125	$3787	$3188	$2021	**$1422**	0.70	**0.83**
	TC Diesel	41.1	$8246	$3446	2334	2636	**0.53**	2219	$3954	$3328	$508	**-$118**	1.31	**1.55**
Conv. Vehicle	PFI	19.3	$4800	$0	4970	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	27.8	$5400	$600	3449	1521	**0.31**	1280	$2282	$1920	$1682	**$1320**	0.39	**0.47**
	TC Diesel	28.9	$7500	$2700	3323	1647	**0.33**	1386	$2470	$2079	-$230	**-$621**	1.64	**1.95**

Table 16: Summary of the performance and cost characteristics of various energy storage devices

Parameter	NiMtHydride	Lithium-ion	C/C ultracaps
Energy density			
Wh/kg	48	74	5
Wh/L	115	155	6.5
Density gm/cm3	2.4	2.1	1.3
Power density			
W/kg-peak	600	900	4000
W/kg-90% eff.	200	380	1600
Cost			
$/Wh	.50	.50	7
$/kg	24	37	35

Table 17: Summary of Cost Results for Various Engines and Vehicle Classes for Full and Mild Hybrids-baseline ICE vehicle with the PFI Gasoline Engine

		Full	HEV					Mild	HEV		
Engine/ Vehicle	Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even		Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even
PFI											
Compact	2461	.31	1104	2.23	2.65		1063	.23	800	1.33	1.58
Mid-car	3371	.37	1699	1.98	2.36		1441	.30	1370	1.05	1.25
Mid-SUV	4273	.36	2125	2.01	2.39		2139	.28	1638	1.31	1.55
Lean-burn											
Compact	2701	.45	1574	1.72	2.04		1403	.40	1395	1.00	1.20
Mid-car	3631	.49	2248	1.62	1.92		1921	.45	2060	.93	1.11
Mid-SUV	4613	.47	2770	1.67	1.98		2739	.43	2536	.78	1.28
TC-diesel											
Compact	3541	.47	1660	2.13	2.53		2593	.41	1430	1.81	2.16
Mid-car	4541	.52	2373	1.91	2.27		3601	.46	2099	1.71	2.04
Mid-SUV	5803	.51	3021	1.92	2.28		4839	.45	2696	1.79	2.13

Notes: **(1) All fuel use is based on the FUDS/Highway composite driving cycle and 100,000 miles.**

(2) The baseline vehicle in all cases is the conventional vehicle using a gasoline PFI engine

(3) The breakeven gasoline price is calculated for a use period of 8 years and mileage of 12,000 miles/yr and a discount rate of 4%.

Table 18: Summary of Cost Results for Various Engines and Vehicle Classes for Full and Mild Hybrids-baseline ICE Vehicle with the Advanced Engine

		Full	HEV					Mild	HEV		
Engine/ Vehicle	Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even		Diff. Cost $	Frac. Fuel saved	Fuel Saved gal	$/gal fuel saved	$/gal break even
PFI											
Compact	2461	.31	1104	2.23	2.65		1063	.23	800	1.33	1.58
Mid-car	3371	.37	1699	1.98	2.36		1441	.30	1370	1.05	1.25
Mid-SUV	4273	.36	2125	2.01	2.39		2139	.28	1638	1.31	1.55
Lean-burn											
Compact	2321	.22	538	4.31	5.13		1023	.14	359	2.84	3.39
Mid-car	3091	.27	881	3.51	4.17		1381	.21	692	2.00	2.37
Mid-SUV	3953	.23	969	4.08	4.85		2079	.18	735	2.82	3.36
TC-diesel											
Compact	1831	.29	767	2.38	2.84		883	.20	536	164	1.96
Mid-car	2111	.37	1302	162	1.93		1171	.29	1029	1.14	1.35
Mid-SUV	2833	.32	1395	2.03	2.41		1869	.25	1070	1.75	2.08

Notes: (1) All fuel use is based on the FUDS/Highway composite driving cycle and 100,000 miles.

(2) The baseline vehicle in all cases is the conventional vehicle using the conventional ICE vehicle using the same engine

(3) The breakeven gasoline price is calculated for a use period of 8 years and mileage of 12,000 miles/yr and a discount rate of 4%.

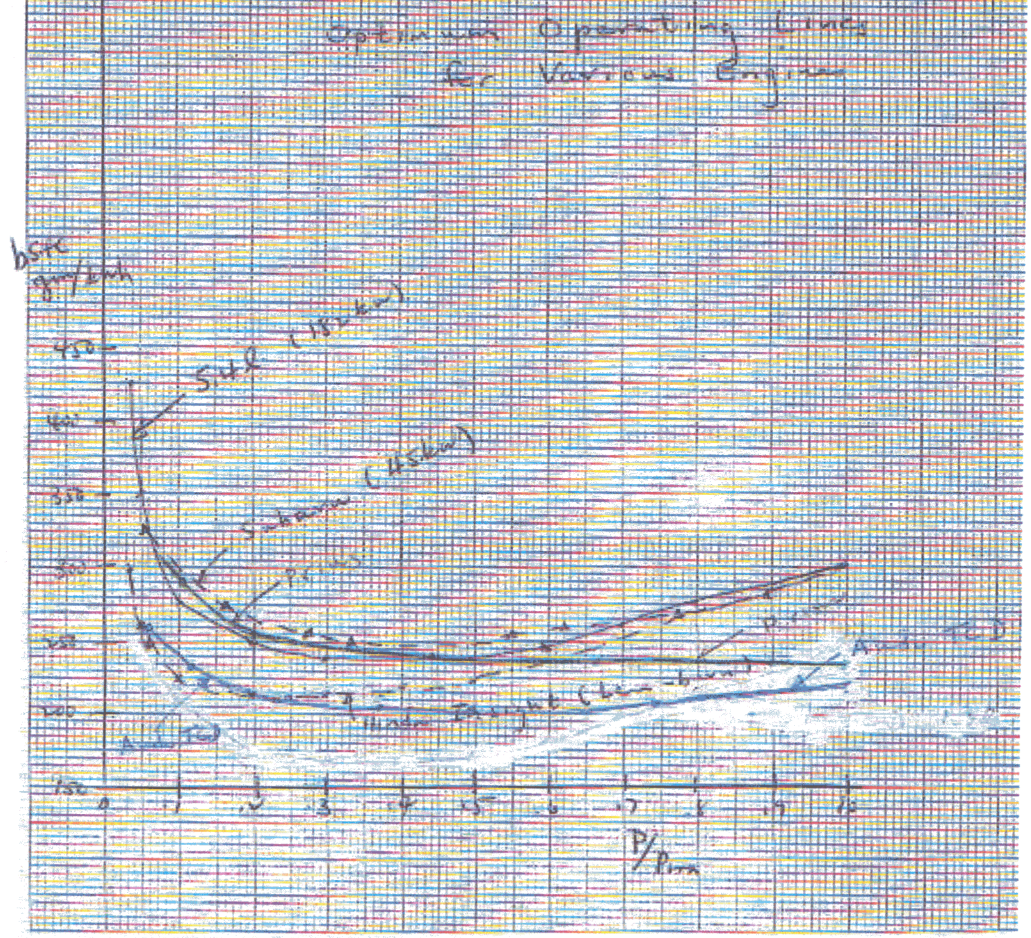
Table 19: The Effect of Electric Drive Component Unit Cost on the Differential Powertrain Cost and Breakeven Gasoline Price for Full and Mid Hybrid Vehicles

		Full	Hybrid		Mild	Hybrid
Vehicle*/ Cost factor	$/kW electric	Differ. Powertr. Cost ($)	Breakeven Gasoline Price ($/gal.)	$/kW electric	Differ. Powertr. Cost ($)	Breakeven Gasoline Price ($/gal.)
Compact Car						
.75	30	2068	2.23	55	877	1.30
1.0**	39	2461	2.65	74	1063	1.58
1.25	49	2854	3.07	93	1249	1.86
1.5	59	3247	3.50	111	1434	2.13
Mid-size Car						
.75	26	2806	1.96	44	1221	1.06
1.0	35	3371	2.36	59	1370	1.25
1.25	44	3937	2.75	73	1662	1.44
1.5	52	4502	3.15	88	1881	1.63
Mid-size SUV						
.75	25	3570	2.00	38	1884	1.37
1.0	33	4273	2.39	51	2139	1.55
1.25	41	4977	2.78	64	2394	1.74
1.5	50	5880	3.18	76	2648	1.92

*** All vehicles utilize the baseline PFI gasoline engine and nickel metal hydride batteries. The fuel economy improvements used are for the composite FUDS/Highway cycle and a use-pattern of 8 years and 12,000 miles/yr.**

**** The factor "1" refers to the baseline electric motor/electronics cost function of $\$/kW = 467 + 27.6 * P(kW)$; other factors result in the baseline cost being multiplied by that factor**

Figure 1:


Optimum Operating Lines
for Various Engines
bsfc
gm/kwh
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400
350
300
250
200
150
Stihl (182 kw)
Subaru (45 kw)
Prius
Prius
Audi TCD
Honda Insight (non-hybrid)
Audi TCD
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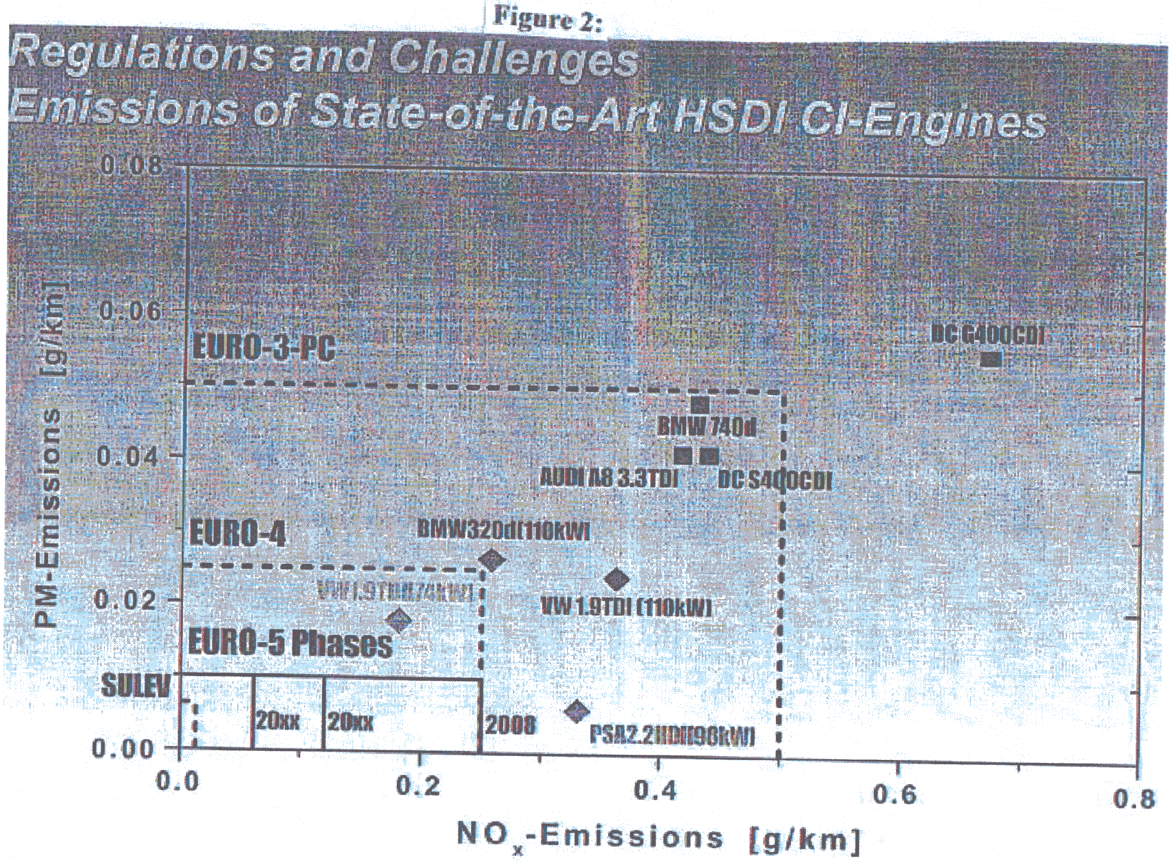
P/Pmax

Figure 2:


Regulations and Challenges
Emissions of State-of-the-Art HSDI CI-Engines
PM-Emissions [g/km]
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0.06
0.04
0.02
0.00
EURO-3-PC
DC G400CDI
BMW 740d
AUDI A8 3.3TDI
DC S400CDI
EURO-4
BMW320d(110kW)
VW1.9TDI(74kW)
VW 1.9TDI (110kW)
EURO-5 Phases
SULEV
20xx
20xx
2008
PSA2.2HDI(98kW)
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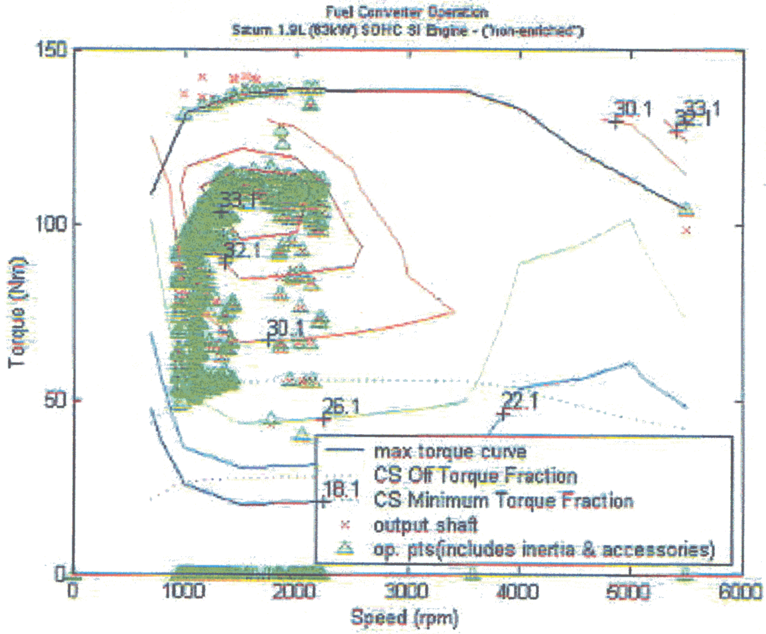
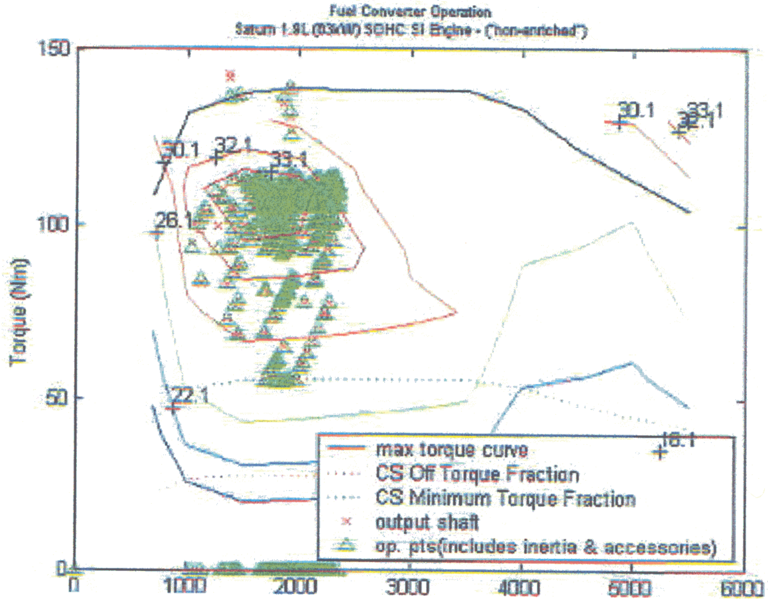
0.2
0.4
0.6
0.8
NO$_x$-Emissions [g/km]

Figure 3: Compact Car – Full Hybrid

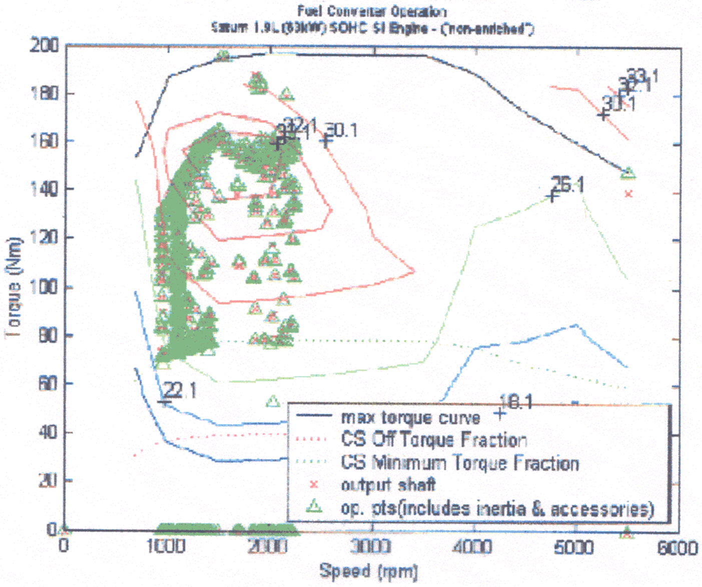


FUDS

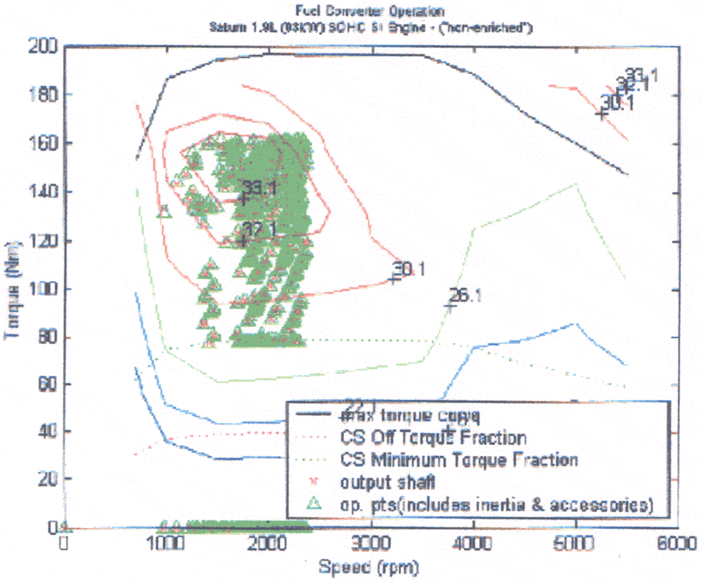


Highway

Figure 4: Compact Car- Mild Hybrid

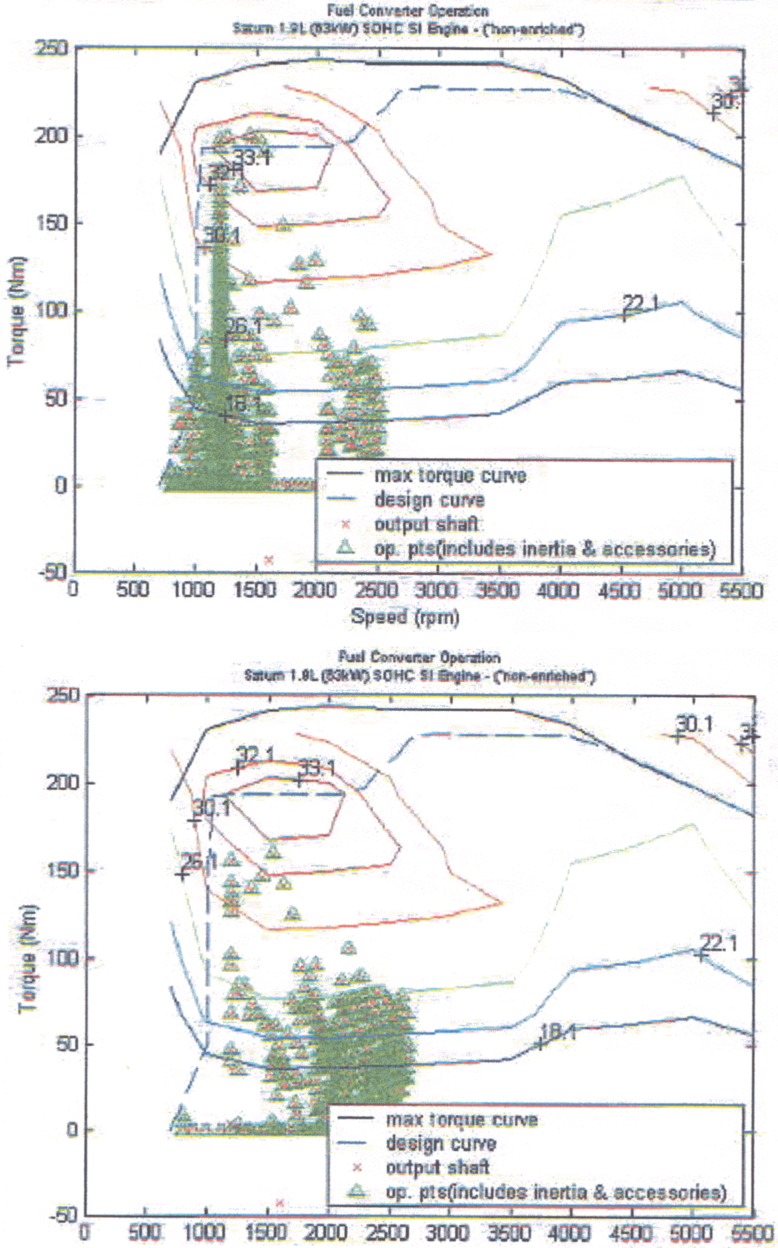


FUDS



Highway

Figure 5: Compact Car – Conventional ICE



FUDS

Highway

Figure 6: Coolant Temperature vs. time

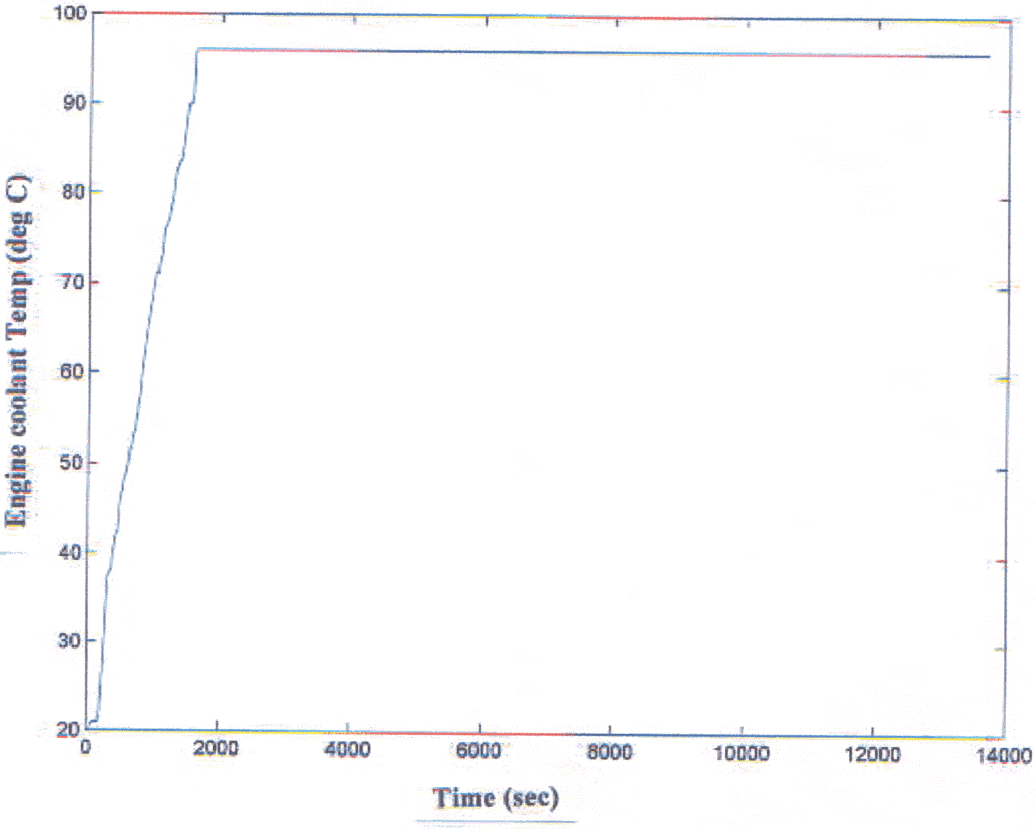


Figure 7: Engine exhaust gas temperature vs. time

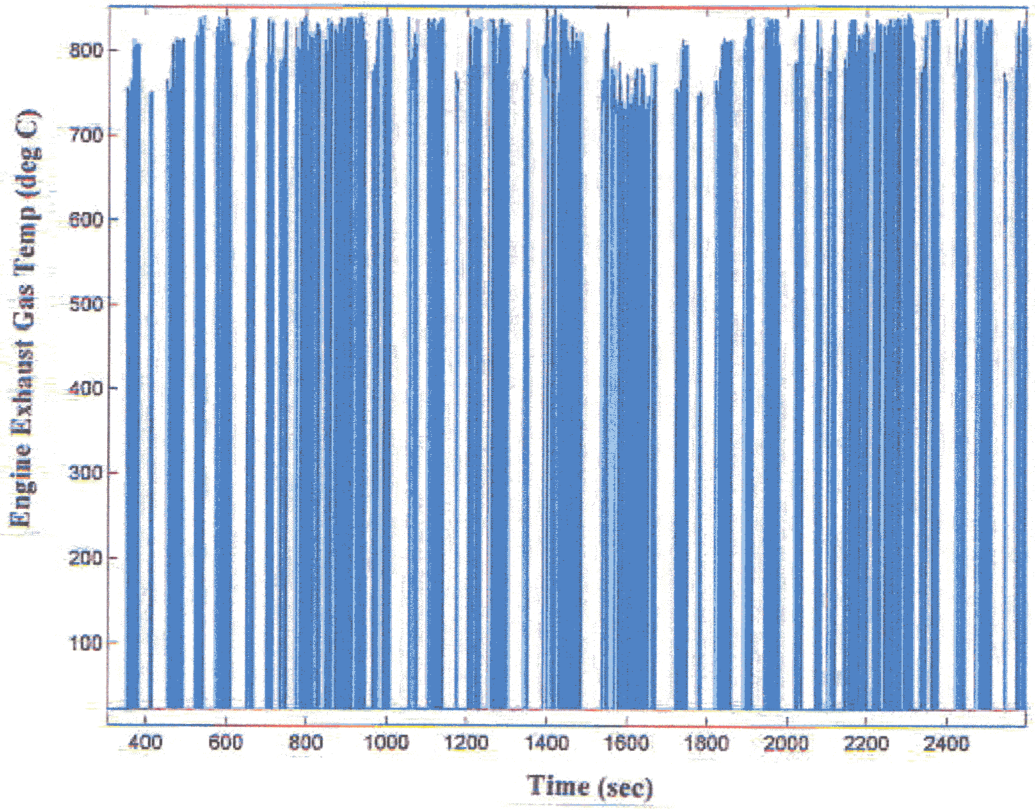
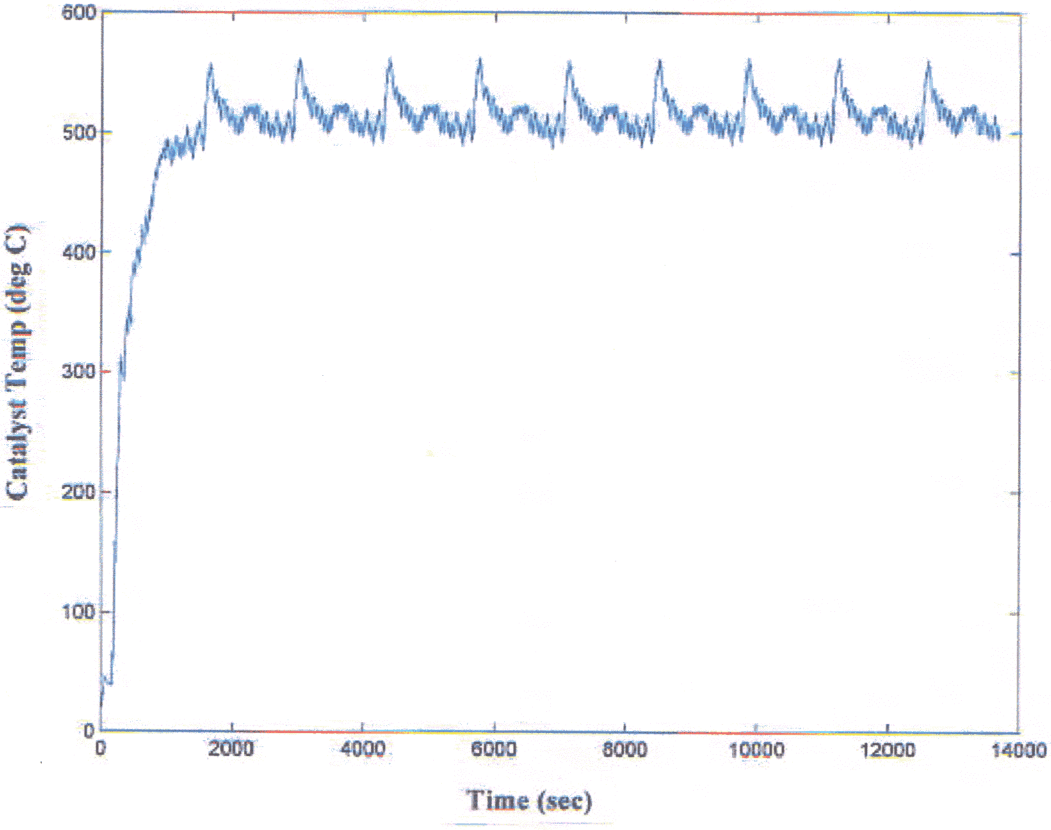


Figure 8: Catalyst temperature vs. time



Appendix 1

Description of the Hybridization Cost Model

Assumptions, Cost Functions and Standard Inputs

- *Introduction*: There is a tremendous degree of uncertainty surrounding the future costs of the Hybrid Electric Vehicle (HEV) driveline made up of the engine, transmission, electric motor, energy storage, and associated components. A healthy debate has even emerged with regard to present costs and the cost functions as they vary with production volume evidenced by discrepancies in the literature generated by competing methodologies. Reconciling between the range of cost functions arrived at through equally valid approaches is one of the more difficult aspects of this analysis. This cost function mediation if you will requires transparency of assumptions, good judgment, and knowledge of what cost functions best fit our criteria. The mild and full HEVs under consideration are parallel configurations as opposed to series, and are representative of a number of HEV models scheduled to hit the market over the next few years. The main motivation for this spreadsheet model is to maximize fuel economy gain while minimizing the initial driveline cost differential.

- *Overview of User Choices (Configurations)*:
    1. Vehicle Type: a) Compact Car (Honda Civic) b) Mid-Size Car (Ford Taurus) c) Mid-Size SUV (Ford Explorer)
    2. Battery Type: a) NiMH (generation 2) b) Li-Ion *Additionally, for mild HEVs, the ultracapacitor configuration will automatically be included in the analysis.
    3. Electric Drive Type: a) AC Induction Motor b) DC Brushless Permanent Magnet (BPM)
    4. Driving Cycle a) USA (3 parts) b) Europe c) Japan
    5. Average number of miles driven per year, number of years, and discount rate
    6. Baseline Measure: a) PFI Engine b) Advanced Engine
    7. Fuel Price for gasoline and diesel

- *Joint engine/transmission cost function* calculated as a variable expression of power output in kW. This function differentiates between the large cost fluctuation that arises between the three types of engine under consideration: 1) Port Fuel Injected (PFI) Gasoline [$32/kW][1] 2) Lean Burn Gasoline [$36/kW] and 3) Turbo-Charged (TC) Diesel [$50/kW]. The above cost estimates include a Continuous Variable Transmission (CVT) for the HEVs and a standard 4-speed automatic for the conventional vehicles (CVs), which are cosely related in cost. These cost functions will be somewhat lower for manual transmissions. The various maximum engine power outputs for the 9 basic configurations are

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[1] These cost functions are estimated on a linear basis without a fixed cost component added to the cost function. These cost estimates are based on CVT/auto transmissions and were estimated by Dr. Andrew Burke.

detailed in Table 1. The preliminary cost estimates for the different types of engines may be modified to include a fixed cost component and a more tailored variable cost constituent to more accurately determine the costs of a relatively small engine and relatively large engine where economies of scale may emerge to make the last 90 kW of engine power less expensive to produce than the first 90 kW, for example.

Table 1	**Engine Power (kW)**		
Vehicle	Full Hybrid	Mild Hybrid	Conventional Vehicle
Compact Car	60	85	105
Mid-Sized Car	65	120	150
Mid-Sized SUV	85	150	180

- *Electric Motor w/ accessory components cost function* for either an AC Induction motor or a DC Brushless Permanent Magnet (BPM) as specified by the user. These cost functions were derived by reviewing the most current and relevant literature on the subject including two California Air Resources Board (CARB) reports prepared by Mark DeLucchi and Timothy Lipman respectively, an Electric Power Research Institute (EPRI) report on Hybrid Electric Vehicles (HEVs), and an Argonne National Labatory (ANL) report on Hybrid Electric Vehicle Technology written by S. Plotkin and others. The electric motor cost function consists of the costs of the motor, controller, transaxle, and miscellaneous components. For AC Induction motors, ANL estimated this cost at \$625 + \$32.7/kW* $\text{MotorPower}_{\text{peak}}$ at high production volumes (Plotkin et al 2001), and an interpretation of ITS Davis results yields the following approximate function for the high volume production of 100,000 units per year:[2] Motor + Controller + Transaxle + Misc. Components → (\$10.80/kW *

Table 2	**Motor Power (kW)**	
Vehicle	Full Hybrid	Mild Hybrid
Compact Car	40	10
Mid-Sized Car	65	15
Mid-Sized SUV	85	20

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[2] The ITS Davis reports estimated production at 20,000/yr. and 200,000/yr., but the production level of interest is 100,000/yr. hence an extrapolated estimation is required. Cost at 100,000/yr. was estimated to be much closer to 200,000/yr. than 20,000/yr.

$\text{MotorPower}_{peak}) + (\$500 + \$7.5/kW * \text{MotorPower}_{peak}) + (\$11.00/kW * \text{MotorPower}_{peak}) + (\$2.20 * \text{MotorPower}_{peak}) = \$500 + \$31.5/kW * \text{MotorPower}_{peak}$ (DeLucchi 1999, Lipman 1999^{b}).

- *Energy Storage w/ related components cost function* for second generation Ni-MH batteries, Li-Ion batteries, and in the case of the Mild Hybrid configurations, ultracapacitors are also analyzed. Determining these cost functions is achieved in the same fashion as the electric motor cost functions above by employing literature investigation of all of the above sources in addition to an Argonne report developed by Vyas & others concerning batteries for electric drive vehicles. Information on ultracapacitors has been furnished by Dr. Burke, who as an authority on the subject is an excellent source considering the scanty literature that exists regarding the costs of this new technology as applied to vehicles. The costs are determined on a per kilogram (\$/kg) basis, which is considered the most accurate and unwavering method to measure cost over a variety of battery sizes.[3] The weight of the battery is determined from an estimate of energy density (e.g. ~53 Wh/kg for gen. 2 NiMH) combined with the energy required from each battery to match the performance requirements of the given confuration. This energy density is lower than that of batteries for pure EVs and the power density in (W/kg) will be higher, which leads to a more expensive battery than that of a pure EV. The estimated specific energy of 53 Wh/kg is in the intermediate battery type range according to ANL and this corresponds to a specific power in the neighborhood of 350 W/kg (Plotkin et al 2001 p.62). The ANL estimated cost of this battery type at between 550-600b\$/kWh corresponds very closely with our estimate of \$30/kg. DuLeep estimates high power NiMH batteries at \$800/kWh for high volume production (>20,000 units per year), while ANL estimates \$639/kWh possibly due to a corresponding higher volume production (DuLeep 1999, Plotkin et al 2001). Hence our choice of \$30/kg may be construed as optimistic, but is closely aligned with the ANL paper, which is considered the most up-to-date report on HEVs available. A 1997 ANL report prepared by Vyas and others reports NiMH batteries for HEVs remaining between \$35-40/kg over the next twenty years (Vyas et al 1997). Despite its importance, battery replacement costs, while indeed large, are outside the scope of the model.

- *All cost functions* are estimated as Retail Price Equivalent (RPE)[4] and include dealer markup, fixed costs (incl. corporate and production overhead), manufacturing costs (incl. labor and materials), and other implicit costs that are passed on to the consumer (Plotkin, et al 2001, DeLucchi 1999). Two methods were identified as possibilities for arriving at the RPE: The Base method and the ANL method, which are both adaptations of the Lindgren RPE method (Graham 2001, p. 2-10). The increased R&D and engineering costs (development costs) associated with the new technology driving the Hybrid Electric Vehicles (HEVs)

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[3] Battery costs are often shown as \$/kWh, but this more readily leads to cost distortions than the per kilogram method.

[4] Estimations/projections of Manufacturer's Suggested Retail Price (MSRP) do not result in meaningful or accurate numbers for vehicle cost comparisons (Graham 2001, p. 2-9).

are not factored into this analysis, but neither is the projected decrease in maintenance costs expected for HEVs, hence the two cancel one another out to some degree. For this reason, their exclusion should not pose a big threat to the validity of the results. HEVs and CVs share much of the component costs that comprise the overall vehicle cost in common including the body group, vehicle assembly, and virtually the entire chassis group. The two component areas where the vehicles greatly diverge are the engine and transmission groups (Plotkin, et al 2001), or what we refer to as the driveline group. In effect the differential initial driveline cost is merely the RPEs of the various hybrid and conventional configurations. Due to the large percentage of components HEVs and CVs share, this incremental approach is a sufficient one.

- *Levels of Production* are taken to be 100,000 units per annum by year 2010, which translates to high production. Hence this model is somewhat forward-looking and not necessarily applicable to the current situation of HEV production. With the success of the Toyota and Honda HEVs coupled with many auto manufacturers plans to introduce at least one HEV model in the near future, treating the production as high volume appears to be a logical decision.

- *Fuel Economy* is estimated for a number of cycles from the results of Advisor simulations. The user has a choice between a specified US driving cycle that is set as a default at 55% city driving (FUDS) and 45% highway driving, but can include any combination of these two cycles along with a third cycle, aggressive US driving (US06), or any of these cycles individually. The more internationally minded user is given the option of choosing between the standard European driving cycle (ECE-EUDC) and the typical Japanese driving cycle (Japan 10/15). The two non-US driving cycles are of special significance due to the much greater fuel costs overall, and the large disparity between gasoline and diesel prices that will tend to advantage the TC Diesel engine significantly.

- *Fuel cost* is then calculated by using the fuel economy figures discussed above over a user specified period of time to determine the fuel savings for the various configurations as compared to the conventional baseline design. This approach was chosen over one that merely asked the user to input the total vmt figure to increase flexibility and simplify the discounting process. The user also has the option of specifying the fuel cost, the average number of miles driven per year, and the discount rate, or simply running the model with the default values for these variables that were established from mean averages detailed in the literature. The model does not yet account for the steadily declining vmt figure that occurs throughout the life of a vehicle on average. Such a variably declining vmt stream has been adequately estimated by the Oak Ridge National Laboratory (ORNL) and should be incorporated into a future version of the model to increase the accuracy of the discounted fuel savings.

- *The discount rate* will be set at the default rate of 4% that was arrived at by subtracting the rate of inflation (estimated at 3 %) from the opportunity cost of money for consumers, which is the most simplistic expression for discount rate. The opportunity cost is essentially the rate of return on earnings made from investments that have minimal risk associated with them. With a rate estimated at 7 %, the real discount rate becomes 4 %, which is the default number in the model. A higher opportunity cost than 7 % may be stipulated by the model user who fancies himself a savvy investor, or conversely a lower opportunity cost could be given for a particularly investment phobic user. Hence the model provides flexibility in either direction.

- *The fuel price* (gasoline and diesel independently) will be specified by the user to account for the wide discrepancy that exists between the various regions under consideration. A user interested in running the model for California would specify the gas price at roughly $1.65-$1.75 per gallon while a user running the model for the southeastern US would opt for a price much closer to a dollar. Obviously, the disparity across the Atlantic and Pacific Oceans is much greater than that found within the US. Europe and Japan have comparable fuel prices, which will be input in dollars per liter. A table will be provided to show approximate gasoline and diesel prices for Japan, France, Germany and the UK if the user is in the Europe/Japan mode, and for the US and Canada if the user is in North America mode. These approximations are based upon data from the International Energy Agency (IEC) and ORNL's Transportation Energy Data Book, and are summarized in Table 3.

Table 3 **Country**	**$/gal gas**	**$/L gas**	**$/gal diesel**	**$/L diesel**
japan	$3.50	$0.92	$2.50	$0.66
france	$4.00	$1.05	$2.65	$0.70
uk	$5.00	$1.32	$4.50	$1.18
germany	$3.75	$0.99	$2.75	$0.72
usa	$1.50	$0.39	$1.35	$0.36
canada	$2.00	$0.53	$1.50	$0.39

- *Model Outputs* will be displayed in standard spreadsheet table format for quick printing, saving, or desired chart/graph generation. Perhaps a future version of the model will generate a more elaborate presentation of results, but the bare bones display is certainly sufficient. The following list summarizes the outputs of the model:

  1) Average mpg for the chosen driving cycle determined as the average of the percentages from the three US cycles with the default set at 55% city driving (FUDS) and 45% highway. Hence if a user chooses the default and the fuel economies are 30 mpg and 40 mpg respectively, the average mpg will be (0.55)(30) + (0.45)(40) = 34.5 mpg. For the European and Japanese cycles, there is only one cycle eliminating the need to calculate an average.

2) *Cost of Driveline ($Cost_{DL}$)* is the summation of the results derived from the engine/transmission, motor and accessory, and energy storage cost functions for the hybrid configurations, and merely the engine/transmission cost function outcome for the conventional vehicle.

3) *Differential Driveline Cost ($DifCost_{DL}$)* is the difference in cost between the hybrid configuration driveline cost and that of the conventional baseline measure. If the PFI conventional is chosen as the baseline then the cost differential between the conventional advanced vehicle configurations and the standard PFI setup will also be shown.

4) *Total Fuel Used* estimates the quantity of fuel consumed from the following simple formula: $Q_{\text{Fuel Total}} = (mpy_{\text{average}} * t) / mpg_{\text{average}}$ where mpy_{average} is the average miles driven per year and t is the number of years as input by the user.

5) *Quantity of Fuel Saved* is simply $Q_{\text{Fuel Total}}$ for each configuration subtracted from $Q_{\text{Fuel Total}}$ for the baseline measure. $Q_{\text{Fuel Saved}} = Q_{\text{Fuel Total Baseline}} - Q_{\text{Fuel Total}}$

6) *Fraction of Fuel Saved* is one of the key outputs that helps convey the fuel economy distinctions between the numerous configurations in a simple manner. The expression is $\text{Fraction}_{\text{Fuel Saved}} = Q_{\text{Fuel Saved}} / Q_{\text{Fuel Total Baseline}}$.

7) *Discounted Fuel Saved* is $Q_{\text{Fuel Saved}}$ discounted through the number of years and at the discount rate specified by the user. The proper expression is as follows: $Q_{\text{Fuel Saved Discounted}} = Q_{\text{Fuel Saved}} * [((1+r)^n - 1) / ((nr(1+r)^n)]$, where r is the discount rate and n is the number of years.

8) *Actual Fuel Cost Savings (FCS)* is FCS = $Q_{\text{Fuel Saved}} * P_{\text{fuel}}$, where P_{fuel} is either the price of gasoline or diesel in either $/gallon or $/liter.

9) *Discounted Fuel Cost Savings (DFCS)* is calculated by the same method as above with DFCS = $Q_{\text{Fuel Saved Discounted}} * P_{\text{fuel}}$.

10) *Actual Net Cost Savings (NCS)* shows to what extent the alternative configuration offset the inflated initial cost with its heightened fuel economy and resultant fuel savings. A positive value indicates that the alternative configuration more than made up the greater initial cost when compared with the baseline, while a negative number alerts the user to the opposite conclusion. NCS = FCS - $DifCost_{DL}$.

11) *Discounted Net Cost Savings (DNCS)* is a more rigorous test for the alternative configurations to pass since the future benefits in the form of fuel cost savings are reduced through the discounting process. DNCS = DFCS - $DifCost_{DL}$.

12) *Breakeven Fuel Price (BFP)* is the price fuel would have to be for the initial differential driveline cost to exactly equal the cost savings achieved through increased fuel economy. (BFP = $DifCost_{DL} / Q_{\text{Fuel Saved}}$) If the fuel price is lower than the BFP, the configuration in question is less desirable than the conventional alternative, but if the BFP is lower than the fuel price, the hybrid is a more attractive option from a simple Benefit-Cost Analysis.

13) *Discounted Breakeven Fuel Price (DBFP)* is the same as 12) with the discounted quantity of fuel saved substituted for $Q_{\text{Fuel Saved}}$, so the equation is simply DBFP = $DifCost_{DL} / Q_{\text{Fuel Saved Discounted}}$. Figure 1 illustratively demonstrates the concept of the breakeven price.

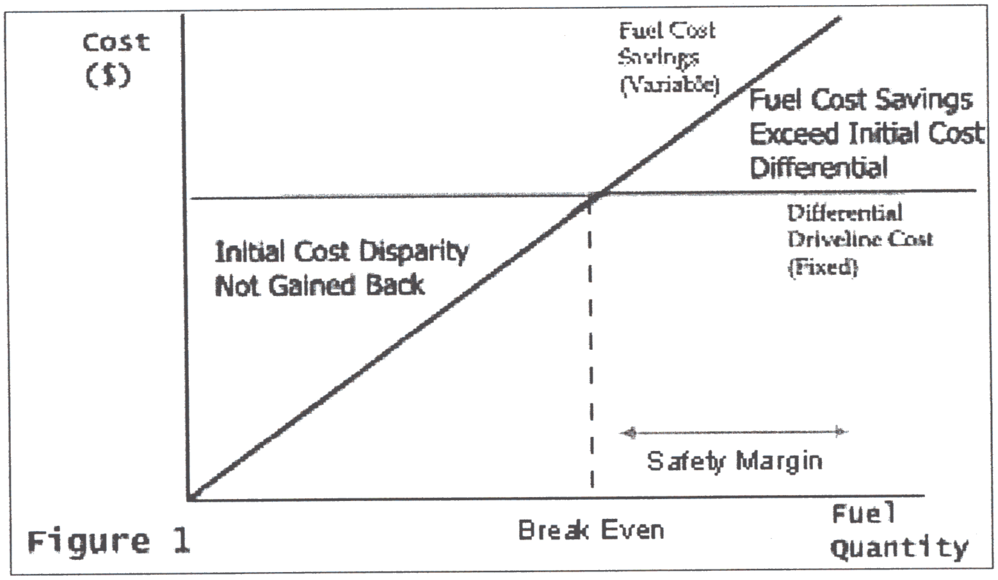

Figure 1

- *Experience Curves and Future Cost Reductions* would be a nice feature to include in the model. The user could select a time in the future or specify aproduction level, and the appropriate cost path for the driveline components could be estimated via a simulation to arrive at a future cost. For instance, a report by Lipman and Sperling shows the cost of 40-kW BPM drive systems falling dramatically from a production level of 1000 units requiring a hand-built assembly process of $12,000 to ~$3,500 at 100,000 units and ~$1,500 at 10,000,000 units (Lipman and Sperling 1997). The economies of scales that emerge as these new technologies enter mass production can have large implications on the cost differential between HEVs and CVs. Scenarios for future fuel costs couls also be developed to show potential rises in oil costs and the resultant impact on HEV practicality and affordability.

- *Limitations of the Model:* In addition to the limitations mentioned earlier, a number of important factors are excluded from the model, at least for the time being. These include the following:

    - i. *Favorable policies and incentives* that promote HEVs are difficult to incorporate into the model primarily due to the large inconsistencies that exist across states, regions and countries. Federal tax credits, rebates, bonuses and deductions possess enough universal applicability to be included in a future version of the model.
    - ii. *Battery replacement and its costs* are not included in the study, but are also not as pertinent as they would be in a pure EV analysis.
    - iii. *Assumption that HEVs and CVs have the same VMT count over lifetime of vehicle.* Whether increased fuel economy will induce more driving is a possibility that is not addressed by this model.
    - iv. *Environmental benefits received by the consumer* for driving a less polluting, more efficient vehicle are expressed only in the choice of discount rate. A user could choose a lower discount rate to adjust for perceived yet difficult to quantify future benefits of lower emissions, GHG, and fuel consumption. In a similar sense, emissions and GHG produced per gallon/liter of fuel could be assessed in the model and a monetary value assessed to be added to the overall cost-benefit analysis. Volatile Organic Compound (VOC) and NO_x emissions resulting in smog and the particulate matter constituents of the emission milieu have a much greater impact in urban areas than rural areas where the small number of vehicles do not allow a large confluence of deleterious emissions. GHG emissions, primarily CO_2 gas, are essentially independent of region and are of global as opposed to local concern. The fact that local emissions and the larger fuel economy gains both occur in urban settings makes these more peopled areas more sensible places for HEV penetration. The fuel economy improvement factor (FEIF) is the measure of the size of fuel economy gains of HEVs over their CV counterparts. The FEIF is on average much greater for the FUDS cycle than for the highway cycle based on advisor simulations. This suggests the greatest level of fuel savings for HEVs will occur in the stop-and-go, gridlocked urban driving conditions, where these improvements are most needed. Increased sophistication in this area of the model would be helpful, but even as the model now stands, the user has the option of choosing exclusively a FUDS cycle to simulate a purely urban driving cycle.

Bibliography

DeLucchi, Mark, et al (1999) *Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model.* Report for the California Resources Board, Institute of Transportation Studies, UC Davis: Davis, CA.

Dhameja, Sandeep (2001) *Electric Vehicle Battery Systems.* Butterworth-Heinemann: Boston.

DuLeep, K.G. (1999) "Cost and Pricing of Hybrid Vehicles," in *Ultra-Clean Vehicles: Technology Advances, Relative Marketability and Policy Implications.* Institute of Transportation Studies, UC Davis: Davis, CA.

Graham, R., et al (2001) *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.* Electric Power Research Institute: Palo Alto, CA.

Lipman, Timothy (1999[a]) *A Review of Electric Vehicle Cost Studies: Assumptions, Methodologies, and Results.* Report for the California Resouces Board, Institute of Transportation Studies, UC Davis: Davis, CA.

Lipman, Timothy (1999[b]) *The Cost of Manufacturing Electric Vehicle Drivetrains.* Report for the California Resouces Board, Institute of Transportation Studies, UC Davis: Davis, CA.

Lipman, Timothy (1999[c]) *The Cost of Manufacturing Electric Vehicle Batteries.* Report for the California Resouces Board, Institute of Transportation Studies, UC Davis: Davis, CA.

Lipman, Timothy E., and D. Sperling. "Forecasting Cost Path of Electric Vehicle Drive System: Monte Carlo Experience Curve Simulation," Transportation Research Record, No. 1587. September, 1997, 19-26.

Plotkin, S., et al (2001) *Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results.* Argonne National Laboratory: Argonne, IL.

Vyas, Anant, Santini, Dan, and Cuenca, Roy (2000) "Comparison of Indirect Cost Multipliers for Vehicle Manufacturing." Argonne National Laboratory: Argonne, IL.

Weiss, Malcolm et al (2000) *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies.* Energy Laboratory, MIT: Cambridge, MA.

Appendix 2: Cost Model Output Sheets for Various Cases

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price: $1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price: $1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	39.7	$5501	$2461	2420	1104	0.31	929	$1655	$1393	-$806	-$1068	2.23	2.65
	LB Gas	49.2	$5741	$2701	1950	1574	0.45	1324	$2360	$1986	-$341	-$715	1.72	2.04
	TC Diesel	51.5	$6581	$3541	1863	1660	0.47	1397	$2490	$2096	-$1051	-$1445	2.13	2.53
Mild Hybrid (Battery)	PFI	35.2	$4103	$1063	2724	800	0.23	673	$1200	$1010	$137	-$53	1.33	1.58
	LB Gas	45.1	$4443	$1403	2129	1395	0.40	1174	$2092	$1761	$689	$358	1.01	1.20
	TC Diesel	45.8	$5633	$2593	2094	1430	0.41	1203	$2144	$1805	-$449	-$788	1.81	2.16
Mild Hybrid (Ultra-capacitor)	PFI	39.3	$4373	$1333	2444	1080	0.31	909	$1619	$1363	$286	$30	1.23	1.47
	LB Gas	49.3	$4713	$1673	1948	1576	0.45	1326	$2364	$1989	$691	$316	1.06	1.26
	TC Diesel	50.7	$5903	$2863	1895	1629	0.46	1371	$2443	$2056	-$420	-$807	1.76	2.09
Conv. Vehicle	PFI	27.2	$3040	$0	3524	0	0.00	0	$0	$0	$0	$0	0.00	0.00
	LB Gas	38.6	$3420	$380	2488	1036	0.29	872	$1554	$1308	$1174	$928	0.37	0.44
	TC Diesel	36.5	$4750	$1710	2630	893	0.25	752	$1340	$1128	-$370	-$582	1.91	2.27

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	33.2	$7691	$3371	2892	1699	**0.37**	1430	$2548	$2144	-$823	**-$1227**	1.98	**2.36**
	LB Gas	41.0	$7951	$3631	2342	2248	**0.49**	1892	$3373	$2838	-$258	**-$793**	1.61	**1.92**
	TC Diesel	43.3	$8861	$4541	2218	2373	**0.52**	1997	$3559	$2995	-$982	**-$1546**	1.91	**2.27**
Mild Hybrid (Battery)	PFI	29.8	$5761	$1441	3221	1370	**0.30**	1153	$2055	$1729	$614	**$288**	1.05	**1.25**
	LB Gas	37.9	$6241	$1921	2531	2060	**0.45**	1733	$3090	$2600	$1169	**$679**	0.93	**1.11**
	TC Diesel	38.5	$7921	$3601	2491	2099	**0.46**	1767	$3149	$2650	-$452	**-$951**	1.72	**2.04**
Mild Hybrid (Ultra-capacitor)	PFI	33.5	$6086	$1766	2868	1722	**0.38**	1450	$2584	$2174	$818	**$408**	1.03	**1.22**
	LB Gas	41.7	$6566	$2246	2303	2288	**0.50**	1925	$3431	$2888	$1185	**$642**	0.98	**1.17**
	TC Diesel	43.3	$8246	$3926	2215	2375	**0.52**	1999	$3563	$2998	-$363	**-$928**	1.65	**1.96**
Conv. Vehicle	PFI	20.9	$4320	$0	4591	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	29.8	$4860	$540	3223	1368	**0.30**	1151	$2052	$1727	$1512	**$1187**	0.39	**0.47**
	TC Diesel	27.3	$6750	$2430	3520	1070	**0.23**	901	$1606	$1351	-$824	**-$1079**	2.27	**2.70**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	25.1	$9553	$4273	3826	2125	**0.36**	1788	$3187	$2682	-$1086	**-$1591**	2.01	**2.39**
	LB Gas	30.2	$9893	$4613	3180	2770	**0.47**	2331	$4155	$3497	-$458	**-$1116**	1.67	**1.98**
	TC Diesel	32.8	$11083	$5803	2930	3021	**0.51**	2542	$4531	$3813	-$1272	**-$1990**	1.92	**2.28**
Mild Hybrid (Battery)	PFI	22.3	$7419	$2139	4313	1638	**0.28**	1378	$2456	$2067	$317	**-$72**	1.31	**1.55**
	LB Gas	28.1	$8019	$2739	3414	2536	**0.43**	2134	$3804	$3201	$1065	**$462**	1.08	**1.28**
	TC Diesel	29.5	$10119	$4839	3255	2696	**0.45**	2269	$4044	$3403	-$795	**-$1436**	1.80	**2.13**
Mild Hybrid (Ultra-capacitor)	PFI	24.9	$7919	$2639	3858	2092	**0.35**	1761	$3139	$2642	$500	**$3**	1.26	**1.50**
	LB Gas	30.8	$8519	$3239	3116	2835	**0.48**	2386	$4252	$3579	$1013	**$340**	1.14	**1.36**
	TC Diesel	32.3	$10619	$5339	2975	2975	**0.50**	2504	$4463	$3756	-$876	**-$1583**	1.79	**2.13**
Conv. Vehicle	PFI	16.1	$5280	$0	5950	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	23.1	$5940	$660	4150	1801	**0.30**	1515	$2701	$2273	$2041	**$1613**	0.37	**0.44**
	TC Diesel	22.2	$8250	$2970	4325	1626	**0.27**	1368	$2439	$2052	-$531	**-$918**	1.83	**2.17**

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	Advanced Engine	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (Gal)**	**Quantity of Fuel Saved (Gal)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (Gal)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/Gal)**	**Discounted Breakeven Fuel Price ($/Gal)**
Full Hybrid	PFI	39.7	$5501	$2461	2420	1104	**0.31**	929	$1655	$1393	-$806	**-$1068**	2.23	**2.65**
	LB Gas	49.2	$5741	$2321	1950	538	**0.22**	452	$806	$679	-$1515	**-$1642**	4.32	**5.13**
	TC Diesel	51.5	$6581	$1831	1863	767	**0.29**	645	$1150	$968	-$681	**-$863**	2.39	**2.84**
Mild Hybrid (Battery)	PFI	35.2	$4103	$1063	2724	800	**0.23**	673	$1200	$1010	$137	**-$53**	1.33	**1.58**
	LB Gas	45.1	$4443	$1023	2129	359	**0.14**	302	$538	$453	-$485	**-$570**	2.85	**3.39**
	TC Diesel	45.8	$5633	$883	2094	536	**0.20**	451	$804	$677	-$79	**-$206**	1.65	**1.96**
Mild Hybrid (Ultra-capacitor)	PFI	39.3	$4373	$1333	2444	1080	**0.31**	909	$1619	$1363	$286	**$30**	1.23	**1.47**
	LB Gas	49.3	$4713	$1293	1948	540	**0.22**	454	$810	$682	-$483	**-$611**	2.39	**2.85**
	TC Diesel	50.7	$5903	$1153	1895	735	**0.28**	619	$1103	$928	-$50	**-$225**	1.57	**1.86**
Conv. Vehicle	PFI	27.2	$3040	$0	3524	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	38.6	$3420	$0	2488	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	TC Diesel	36.5	$4750	$0	2630	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	Advanced Engine		
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal	
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal	

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	33.2	$7691	$3371	2892	1699	**0.37**	1430	$2548	$2144	-$823	**-$1227**	1.98	**2.36**
	LB Gas	41.0	$7951	$3091	2342	881	**0.27**	741	$1321	$1112	-$1770	**-$1979**	3.51	**4.17**
	TC Diesel	43.3	$8861	$2111	2218	1302	**0.37**	1096	$1953	$1644	-$158	**-$467**	1.62	**1.93**
Mild Hybrid (Battery)	PFI	29.8	$5761	$1441	3221	1370	**0.30**	1153	$2055	$1729	$614	**$288**	1.05	**1.25**
	LB Gas	37.9	$6241	$1381	2531	692	**0.21**	582	$1038	$873	-$343	**-$508**	2.00	**2.37**
	TC Diesel	38.5	$7921	$1171	2491	1029	**0.29**	866	$1543	$1299	$372	**$128**	1.14	**1.35**
Mild Hybrid (Ultra-capacitor)	PFI	33.5	$6086	$1766	2868	1722	**0.38**	1450	$2584	$2174	$818	**$408**	1.03	**1.22**
	LB Gas	41.7	$6566	$1706	2303	920	**0.29**	774	$1380	$1161	-$326	**-$545**	1.85	**2.20**
	TC Diesel	43.3	$8246	$1496	2215	1305	**0.37**	1098	$1957	$1647	$461	**$151**	1.15	**1.36**
Conv. Vehicle	PFI	20.9	$4320	$0	4591	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	29.8	$4860	$0	3223	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	TC Diesel	27.3	$6750	$0	3520	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	Advanced Engine	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction				**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	25.1	$9553	$4273	3826	2125	**0.36**	1788	$3187	$2682	-$1086	**-$1591**	2.01	**2.39**
	LB Gas	30.2	$9893	$3953	3180	969	**0.23**	816	$1454	$1224	-$2499	**-$2729**	4.08	**4.85**
	TC Diesel	32.8	$11083	$2833	2930	1395	**0.32**	1174	$2092	$1761	-$741	**-$1072**	2.03	**2.41**
Mild Hybrid (Battery)	PFI	22.3	$7419	$2139	4313	1638	**0.28**	1378	$2456	$2067	$317	**-$72**	1.31	**1.55**
	LB Gas	28.1	$8019	$2079	3414	735	**0.18**	619	$1103	$928	-$976	**-$1151**	2.83	**3.36**
	TC Diesel	29.5	$10119	$1869	3255	1070	**0.25**	900	$1605	$1351	-$264	**-$518**	1.75	**2.08**
Mild Hybrid (Ultra-capacitor)	PFI	24.9	$7919	$2639	3858	2092	**0.35**	1761	$3139	$2642	$500	**$3**	1.26	**1.50**
	LB Gas	30.8	$8519	$2579	3116	1034	**0.25**	870	$1551	$1305	-$1028	**-$1274**	2.49	**2.96**
	TC Diesel	32.3	$10619	$2369	2975	1349	**0.31**	1136	$2024	$1703	-$345	**-$666**	1.76	**2.09**
Conv. Vehicle	PFI	16.1	$5280	$0	5950	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	23.1	$5940	$0	4150	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	TC Diesel	22.2	$8250	$0	4325	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	ECE-EUDC	**Miles/ Year**	10000	**Baseline Measure: Europe/ Japan:**	CV/PFI
Battery Type:	NiMH	**Real World Factor**	.9	**# of Years**	8	Gas Price:	$1.00/L
Electric Drive:	AC Induction			**Discount Rate**	4.00%	Diesel Price:	$1.00/L

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (L)**	**Quantity of Fuel Saved (L)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (L)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/L)**	**Discounted Breakeven Fuel Price ($/L)**
Full Hybrid	PFI	25.4	$9553	$4273	11931	9363	**0.44**	7880	$9363	$7880	$5090	**$3607**	0.46	**0.54**
	LB Gas	30.7	$9893	$4613	9866	11428	**0.54**	9617	$11428	$9617	$6815	**$5004**	0.40	**0.48**
	TC Diesel	33.3	$11083	$5803	9093	12201	**0.57**	10268	$12201	$10268	$6398	**$4465**	0.48	**0.57**
Mild Hybrid (Battery)	PFI	22.9	$7419	$2139	13246	8048	**0.38**	6773	$8048	$6773	$5909	**$4634**	0.27	**0.32**
	LB Gas	29.7	$8019	$2739	10195	11099	**0.52**	9341	$11099	$9341	$8360	**$6602**	0.25	**0.29**
	TC Diesel	34.2	$10119	$4839	8854	12440	**0.58**	10470	$12440	$10470	$7601	**$5631**	0.39	**0.46**
Mild Hybrid (Ultra-capacitor)	PFI	25.5	$7919	$2639	11888	9405	**0.44**	7916	$9405	$7916	$6766	**$5277**	0.28	**0.33**
	LB Gas	31.9	$8519	$3239	9504	11790	**0.55**	9922	$11790	$9922	$8551	**$6683**	0.27	**0.33**
	TC Diesel	36.0	$10619	$5339	8411	12883	**0.60**	10842	$12883	$10842	$7544	**$5503**	0.41	**0.49**
Conv. Vehicle	PFI	14.2	$5280	$0	21294	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	20.6	$5940	$660	14692	6602	**0.31**	5556	$6602	$5556	$5942	**$4896**	0.10	**0.12**
	TC Diesel	18.9	$8250	$2970	16021	5273	**0.25**	4438	$5273	$4438	$2303	**$1468**	0.56	**0.67**

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	ECE-EUDC	**Miles/ Year**	10000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	.9	**# of Years**	8	**Europe/ Japan:**	Gas Price:	$1.00/L
Electric Drive:	AC Induction			**Discount Rate**	4.00%		Diesel Price:	$1.00/L

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (L)	Quantity of Fuel Saved (L)	Fraction of Fuel Saved	Discounted Fuel Saved (L)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/L)	Discounted Breakeven Fuel Price ($/L)
Full Hybrid	PFI	37.3	$5501	$2461	8127	4617	**0.36**	3886	$4617	$3886	$2156	**$1425**	0.53	**0.63**
	LB Gas	47.0	$5741	$2701	6445	6299	**0.49**	5301	$6299	$5301	$3598	**$2600**	0.43	**0.51**
	TC Diesel	48.6	$6581	$3541	6230	6514	**0.51**	5482	$6514	$5482	$2973	**$1941**	0.54	**0.65**
Mild Hybrid (Battery)	PFI	32.9	$4103	$1063	9192	3552	**0.28**	2989	$3552	$2989	$2489	**$1926**	0.30	**0.36**
	LB Gas	44.9	$4443	$1403	6742	6002	**0.47**	5051	$6002	$5051	$4599	**$3648**	0.23	**0.28**
	TC Diesel	44.1	$5633	$2593	6866	5878	**0.46**	4947	$5878	$4947	$3285	**$2354**	0.44	**0.52**
Mild Hybrid (Ultra-capacitor)	PFI	35.8	$4373	$1333	8453	4291	**0.34**	3611	$4291	$3611	$2958	**$2278**	0.31	**0.37**
	LB Gas	47.0	$4713	$1673	6445	6299	**0.49**	5301	$6299	$5301	$4626	**$3628**	0.27	**0.32**
	TC Diesel	46.8	$5903	$2863	6470	6274	**0.49**	5280	$6274	$5280	$3411	**$2417**	0.46	**0.54**
Conv. Vehicle	PFI	23.8	$3040	$0	12744	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	34.6	$3420	$380	8762	3983	**0.31**	3352	$3983	$3352	$3603	**$2972**	0.10	**0.11**
	TC Diesel	32.4	$4750	$1710	9346	3398	**0.27**	2860	$3398	$2860	$1688	**$1150**	0.50	**0.60**

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	ECE-EUDC	**Miles/ Year**	10000	**Baseline Measure: Europe/ Japan:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	.9	**# of Years**	8		Gas Price:	$0.95/L
Electric Drive:	AC Induction			**Discount Rate**	4.00%		Diesel Price:	$1.00/L

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (L)	Quantity of Fuel Saved (L)	Fraction of Fuel Saved	Discounted Fuel Saved (L)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/L)	Discounted Breakeven Fuel Price ($/L)
Full Hybrid	PFI	31.5	$7691	$3371	9613	7043	**0.42**	5927	$6691	$5631	$3320	**$2260**	0.48	**0.57**
	LB Gas	39.6	$7951	$3631	7646	9009	**0.54**	7582	$8559	$7203	$4928	**$3572**	0.40	**0.48**
	TC Diesel	40.5	$8861	$4541	7477	9179	**0.55**	7725	$9179	$7725	$4638	**$3184**	0.49	**0.59**
Mild Hybrid (Battery)	PFI	27.6	$5761	$1441	10959	5697	**0.34**	4794	$5412	$4554	$3971	**$3113**	0.25	**0.30**
	LB Gas	37.5	$6241	$1921	8068	8587	**0.52**	7227	$8158	$6866	$6237	**$4945**	0.22	**0.27**
	TC Diesel	36.9	$7921	$3601	8206	8450	**0.51**	7111	$8450	$7111	$4849	**$3510**	0.43	**0.51**
Mild Hybrid (Ultra-capacitor)	PFI	31.2	$6086	$1766	9696	6960	**0.42**	5857	$6612	$5565	$4846	**$3799**	0.25	**0.30**
	LB Gas	40.5	$6566	$2246	7477	9179	**0.55**	7725	$8720	$7339	$6474	**$5093**	0.24	**0.29**
	TC Diesel	40.5	$8246	$3926	7477	9179	**0.55**	7725	$9179	$7725	$5253	**$3799**	0.43	**0.51**
Conv. Vehicle	PFI	18.2	$4320	$0	16656	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	26.6	$4860	$540	11405	5251	**0.32**	4419	$4988	$4198	$4448	**$3658**	0.10	**0.12**
	TC Diesel	23.4	$6750	$2430	12940	3715	**0.22**	3127	$3715	$3127	$1285	**$697**	0.65	**0.78**

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 759.)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	33.2	$7126	$2806	2892	1699	0.37	1430	$2548	$2144	-$257	-$661	1.65	1.96
	LB Gas	41.0	$7386	$3066	2342	2248	0.49	1892	$3373	$2838	$307	-$227	1.36	1.62
	TC Diesel	43.3	$8296	$3976	2218	2373	0.52	1997	$3559	$2995	-$416	-$980	1.68	1.99
Mild Hybrid (Battery)	PFI	29.8	$5541	$1221	3221	1370	0.30	1153	$2055	$1729	$834	$509	0.89	1.06
	LB Gas	37.9	$6021	$1701	2531	2060	0.45	1733	$3090	$2600	$1389	$900	0.83	0.98
	TC Diesel	38.5	$7701	$3381	2491	2099	0.46	1767	$3149	$2650	-$232	-$731	1.61	1.91
Mild Hybrid (Ultra-capacitor)	PFI	33.5	$5866	$1546	2868	1722	0.38	1450	$2584	$2174	$1038	$629	0.90	1.07
	LB Gas	41.7	$6346	$2026	2303	2288	0.50	1925	$3431	$2888	$1406	$862	0.89	1.05
	TC Diesel	43.3	$8026	$3706	2215	2375	0.52	1999	$3563	$2998	-$143	-$707	1.56	1.85
Conv. Vehicle	PFI	20.9	$4320	$0	4591	0	0.00	0	$0	$0	$0	$0	0.00	0.00
	LB Gas	29.8	$4860	$540	3223	1368	0.30	1151	$2052	$1727	$1512	$1187	0.39	0.47
	TC Diesel	27.3	$6750	$2430	3520	1070	0.23	901	$1606	$1351	-$824	-$1079	2.27	2.70

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(cost 75%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	39.7	$5108	$2068	2420	1104	**0.31**	929	$1655	$1393	-$413	**-$675**	1.87	**2.23**
	LB Gas	49.2	$5348	$2308	1950	1574	**0.45**	1324	$2360	$1986	$52	**-$322**	1.47	**1.74**
	TC Diesel	51.5	$6188	$3148	1863	1660	**0.47**	1397	$2490	$2096	-$658	**-$1052**	1.90	**2.25**
Mild Hybrid (Battery)	PFI	35.2	$3917	$877	2724	800	**0.23**	673	$1200	$1010	$323	**$133**	1.10	**1.30**
	LB Gas	45.1	$4257	$1217	2129	1395	**0.40**	1174	$2092	$1761	$875	**$544**	0.87	**1.04**
	TC Diesel	45.8	$5447	$2407	2094	1430	**0.41**	1203	$2144	$1805	-$263	**-$602**	1.68	**2.00**
Mild Hybrid (Ultra-capacitor)	PFI	39.3	$4187	$1147	2444	1080	**0.31**	909	$1619	$1363	$472	**$216**	1.06	**1.26**
	LB Gas	49.3	$4527	$1487	1948	1576	**0.45**	1326	$2364	$1989	$877	**$502**	0.94	**1.12**
	TC Diesel	50.7	$5717	$2677	1895	1629	**0.46**	1371	$2443	$2056	-$234	**-$621**	1.64	**1.95**
Conv. Vehicle	PFI	27.2	$3040	$0	3524	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	38.6	$3420	$380	2488	1036	**0.29**	872	$1554	$1308	$1174	**$928**	0.37	**0.44**
	TC Diesel	36.5	$4750	$1710	2630	893	**0.25**	752	$1340	$1128	-$370	**-$582**	1.91	**2.27**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 75%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (Gal)**	**Quantity of Fuel Saved (Gal)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (Gal)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/Gal)**	**Discounted Breakeven Fuel Price ($/Gal)**
Full Hybrid	PFI	25.1	$8850	$3570	3826	2125	**0.36**	1788	$3187	$2682	-$383	**-$887**	1.68	**2.00**
	LB Gas	30.2	$9190	$3910	3180	2770	**0.47**	2331	$4155	$3497	$245	**-$413**	1.41	**1.68**
	TC Diesel	32.8	$10380	$5100	2930	3021	**0.51**	2542	$4531	$3813	-$569	**-$1286**	1.69	**2.01**
Mild Hybrid (Battery)	PFI	22.3	$7164	$1884	4313	1638	**0.28**	1378	$2456	$2067	$572	**$183**	1.15	**1.37**
	LB Gas	28.1	$7764	$2484	3414	2536	**0.43**	2134	$3804	$3201	$1320	**$717**	0.98	**1.16**
	TC Diesel	29.5	$9864	$4584	3255	2696	**0.45**	2269	$4044	$3403	-$540	**-$1181**	1.70	**2.02**
Mild Hybrid (Ultra-capacitor)	PFI	24.9	$7664	$2384	3858	2092	**0.35**	1761	$3139	$2642	$755	**$258**	1.14	**1.35**
	LB Gas	30.8	$8264	$2984	3116	2835	**0.48**	2386	$4252	$3579	$1268	**$595**	1.05	**1.25**
	TC Diesel	32.3	$10364	$5084	2975	2975	**0.50**	2504	$4463	$3756	-$621	**-$1328**	1.71	**2.03**
Conv. Vehicle	PFI	16.1	$5280	$0	5950	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	23.1	$5940	$660	4150	1801	**0.30**	1515	$2701	$2273	$2041	**$1613**	0.37	**0.44**
	TC Diesel	22.2	$8250	$2970	4325	1626	**0.27**	1368	$2439	$2052	-$531	**-$918**	1.83	**2.17**

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI		
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal	
Electric Drive:	AC Induction	(Cost 125%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal	

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (Gal)**	**Quantity of Fuel Saved (Gal)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (Gal)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/Gal)**	**Discounted Breakeven Fuel Price ($/Gal)**
Full Hybrid	PFI	39.7	$5894	$2854	2420	1104	**0.31**	929	$1655	$1393	-$1199	**-$1461**	2.59	**3.07**
	LB Gas	49.2	$6134	$3094	1950	1574	**0.45**	1324	$2360	$1986	-$734	**-$1108**	1.97	**2.34**
	TC Diesel	51.5	$6974	$3934	1863	1660	**0.47**	1397	$2490	$2096	-$1444	**-$1838**	2.37	**2.82**
Mild Hybrid (Battery)	PFI	35.2	$4289	$1249	2724	800	**0.23**	673	$1200	$1010	-$49	**-$239**	1.56	**1.86**
	LB Gas	45.1	$4629	$1589	2129	1395	**0.40**	1174	$2092	$1761	$503	**$172**	1.14	**1.35**
	TC Diesel	45.8	$5819	$2779	2094	1430	**0.41**	1203	$2144	$1805	-$635	**-$974**	1.94	**2.31**
Mild Hybrid (Ultra-capacitor)	PFI	39.3	$4559	$1519	2444	1080	**0.31**	909	$1619	$1363	$100	**-$156**	1.41	**1.67**
	LB Gas	49.3	$4899	$1859	1948	1576	**0.45**	1326	$2364	$1989	$505	**$130**	1.18	**1.40**
	TC Diesel	50.7	$6089	$3049	1895	1629	**0.46**	1371	$2443	$2056	-$606	**-$993**	1.87	**2.22**
Conv. Vehicle	PFI	27.2	$3040	$0	3524	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	38.6	$3420	$380	2488	1036	**0.29**	872	$1554	$1308	$1174	**$928**	0.37	**0.44**
	TC Diesel	36.5	$4750	$1710	2630	893	**0.25**	752	$1340	$1128	-$370	**-$582**	1.91	**2.27**

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 125%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	33.2	$8257	$3937	2892	1699	**0.37**	1430	$2548	$2144	-$1388	**-$1792**	2.32	**2.75**
	LB Gas	41.0	$8517	$4197	2342	2248	**0.49**	1892	$3373	$2838	-$824	**-$1358**	1.87	**2.22**
	TC Diesel	43.3	$9427	$5107	2218	2373	**0.52**	1997	$3559	$2995	-$1547	**-$2111**	2.15	**2.56**
Mild Hybrid (Battery)	PFI	29.8	$5982	$1662	3221	1370	**0.30**	1153	$2055	$1729	$393	**$68**	1.21	**1.44**
	LB Gas	37.9	$6462	$2142	2531	2060	**0.45**	1733	$3090	$2600	$948	**$459**	1.04	**1.24**
	TC Diesel	38.5	$8142	$3822	2491	2099	**0.46**	1767	$3149	$2650	-$673	**-$1172**	1.82	**2.16**
Mild Hybrid (Ultra-capacitor)	PFI	33.5	$6307	$1987	2868	1722	**0.38**	1450	$2584	$2174	$597	**$188**	1.15	**1.37**
	LB Gas	41.7	$6787	$2467	2303	2288	**0.50**	1925	$3431	$2888	$965	**$421**	1.08	**1.28**
	TC Diesel	43.3	$8467	$4147	2215	2375	**0.52**	1999	$3563	$2998	-$584	**-$1148**	1.75	**2.07**
Conv. Vehicle	PFI	20.9	$4320	$0	4591	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	29.8	$4860	$540	3223	1368	**0.30**	1151	$2052	$1727	$1512	**$1187**	0.39	**0.47**
	TC Diesel	27.3	$6750	$2430	3520	1070	**0.23**	901	$1606	$1351	-$824	**-$1079**	2.27	**2.70**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 125%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

Drive Train Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	25.1	$10257	$4977	3826	2125	**0.36**	1788	$3187	$2682	-$1790	**-$2294**	2.34	**2.78**
	LB Gas	30.2	$10597	$5317	3180	2770	**0.47**	2331	$4155	$3497	-$1162	**-$1820**	1.92	**2.28**
	TC Diesel	32.8	$11787	$6507	2930	3021	**0.51**	2542	$4531	$3813	-$1976	**-$2693**	2.15	**2.56**
Mild Hybrid (Battery)	PFI	22.3	$7674	$2394	4313	1638	**0.28**	1378	$2456	$2067	$62	**-$327**	1.46	**1.74**
	LB Gas	28.1	$8274	$2994	3414	2536	**0.43**	2134	$3804	$3201	$810	**$207**	1.18	**1.40**
	TC Diesel	29.5	$10374	$5094	3255	2696	**0.45**	2269	$4044	$3403	-$1050	**-$1691**	1.89	**2.25**
Mild Hybrid (Ultra-capacitor)	PFI	24.9	$8174	$2894	3858	2092	**0.35**	1761	$3139	$2642	$245	**-$252**	1.38	**1.64**
	LB Gas	30.8	$8774	$3494	3116	2835	**0.48**	2386	$4252	$3579	$758	**$85**	1.23	**1.46**
	TC Diesel	32.3	$10874	$5594	2975	2975	**0.50**	2504	$4463	$3756	-$1131	**-$1838**	1.88	**2.23**
Conv. Vehicle	PFI	16.1	$5280	$0	5950	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	23.1	$5940	$660	4150	1801	**0.30**	1515	$2701	$2273	$2041	**$1613**	0.37	**0.44**
	TC Diesel	22.2	$8250	$2970	4325	1626	**0.27**	1368	$2439	$2052	-$531	**-$918**	1.83	**2.17**

User Input Information:

Vehicle Type:	Compact Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 150 %)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	39.7	$6287	$3247	2420	1104	**0.31**	929	$1655	$1393	-$1591	**-$1853**	2.94	**3.50**
	LB Gas	49.2	$6527	$3487	1950	1574	**0.45**	1324	$2360	$1986	-$1126	**-$1500**	2.22	**2.63**
	TC Diesel	51.5	$7367	$4327	1863	1660	**0.47**	1397	$2490	$2096	-$1836	**-$2231**	2.61	**3.10**
Mild Hybrid (Battery)	PFI	35.2	$4474	$1434	2724	800	**0.23**	673	$1200	$1010	-$235	**-$425**	1.79	**2.13**
	LB Gas	45.1	$4814	$1774	2129	1395	**0.40**	1174	$2092	$1761	$318	**-$14**	1.27	**1.51**
	TC Diesel	45.8	$6004	$2964	2094	1430	**0.41**	1203	$2144	$1805	-$820	**-$1160**	2.07	**2.46**
Mild Hybrid (Ultra-capacitor)	PFI	39.3	$4744	$1704	2444	1080	**0.31**	909	$1619	$1363	-$85	**-$341**	1.58	**1.88**
	LB Gas	49.3	$5084	$2044	1948	1576	**0.45**	1326	$2364	$1989	$319	**-$55**	1.30	**1.54**
	TC Diesel	50.7	$6274	$3234	1895	1629	**0.46**	1371	$2443	$2056	-$791	**-$1178**	1.99	**2.36**
Conv. Vehicle	PFI	27.2	$3040	$0	3524	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	38.6	$3420	$380	2488	1036	**0.29**	872	$1554	$1308	$1174	**$928**	0.37	**0.44**
	TC Diesel	36.5	$4750	$1710	2630	893	**0.25**	752	$1340	$1128	-$370	**-$582**	1.91	**2.27**

User Input Information:

Vehicle Type:	Mid Size Car	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cost 150%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	**Engine Type**	**Composite MPG**	**Cost of Driveline ($)**	**Differential DriveLine Cost ($)**	**Total Fuel Used (Gal)**	**Quantity of Fuel Saved (Gal)**	**Fraction of Fuel Saved**	**Discounted Fuel Saved (Gal)**	**Actual Fuel Cost Savings ($)**	**Discounted Fuel Cost Savings ($)**	**Actual Net Cost Savings ($)**	**Discounted Net cost Savings ($)**	**Breakeven Fuel Price ($/Gal)**	**Discounted Breakeven Fuel Price ($/Gal)**
Full Hybrid	PFI	33.2	$8822	$4502	2892	1699	**0.37**	1430	$2548	$2144	-$1953	**-$2357**	2.65	**3.15**
	LB Gas	41.0	$9082	$4762	2342	2248	**0.49**	1892	$3373	$2838	-$1389	**-$1923**	2.12	**2.52**
	TC Diesel	43.3	$9992	$5672	2218	2373	**0.52**	1997	$3559	$2995	-$2112	**-$2676**	2.39	**2.84**
Mild Hybrid (Battery)	PFI	29.8	$6201	$1881	3221	1370	**0.30**	1153	$2055	$1729	$174	**-$152**	1.37	**1.63**
	LB Gas	37.9	$6681	$2361	2531	2060	**0.45**	1733	$3090	$2600	$728	**$239**	1.15	**1.36**
	TC Diesel	38.5	$8361	$4041	2491	2099	**0.46**	1767	$3149	$2650	-$893	**-$1391**	1.93	**2.29**
Mild Hybrid (Ultra-capacitor)	PFI	33.5	$6526	$2206	2868	1722	**0.38**	1450	$2584	$2174	$377	**-$32**	1.28	**1.52**
	LB Gas	41.7	$7006	$2686	2303	2288	**0.50**	1925	$3431	$2888	$745	**$201**	1.17	**1.40**
	TC Diesel	43.3	$8686	$4366	2215	2375	**0.52**	1999	$3563	$2998	-$804	**-$1368**	1.84	**2.18**
Conv. Vehicle	PFI	20.9	$4320	$0	4591	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	29.8	$4860	$540	3223	1368	**0.30**	1151	$2052	$1727	$1512	**$1187**	0.39	**0.47**
	TC Diesel	27.3	$6750	$2430	3520	1070	**0.23**	901	$1606	$1351	-$824	**-$1079**	2.27	**2.70**

User Input Information:

Vehicle Type:	Mid Size SUV	**Drive Cycle**	FUDS: Highway: US06:	0.55 0.45 0	**Miles/ Year**	12000	**Baseline Measure:**	CV/PFI	
Battery Type:	NiMH	**Real World Factor**	FUDS: Highway: US06:	0.9 0.78 0	**# of Years**	8	**North America:**	Gas Price:	$1.50/Gal
Electric Drive:	AC Induction	(Cut 150%)			**Discount Rate**	4.00%		Diesel Price:	$1.50/Gal

Calculation Result:

DriveTrain Type	Engine Type	Composite MPG	Cost of Driveline ($)	Differential DriveLine Cost ($)	Total Fuel Used (Gal)	Quantity of Fuel Saved (Gal)	Fraction of Fuel Saved	Discounted Fuel Saved (Gal)	Actual Fuel Cost Savings ($)	Discounted Fuel Cost Savings ($)	Actual Net Cost Savings ($)	Discounted Net cost Savings ($)	Breakeven Fuel Price ($/Gal)	Discounted Breakeven Fuel Price ($/Gal)
Full Hybrid	PFI	25.1	$10960	$5680	3826	2125	**0.36**	1788	$3187	$2682	-$2493	**-$2997**	2.67	**3.18**
	LB Gas	30.2	$11300	$6020	3180	2770	**0.47**	2331	$4155	$3497	-$1865	**-$2523**	2.17	**2.58**
	TC Diesel	32.8	$12490	$7210	2930	3021	**0.51**	2542	$4531	$3813	-$2679	**-$3396**	2.39	**2.84**
Mild Hybrid (Battery)	PFI	22.3	$7928	$2648	4313	1638	**0.28**	1378	$2456	$2067	-$192	**-$581**	1.62	**1.92**
	LB Gas	28.1	$8528	$3248	3414	2536	**0.43**	2134	$3804	$3201	$556	**-$47**	1.28	**1.52**
	TC Diesel	29.5	$10628	$5348	3255	2696	**0.45**	2269	$4044	$3403	-$1305	**-$1945**	1.98	**2.36**
Mild Hybrid (Ultra-capacitor)	PFI	24.9	$8428	$3148	3858	2092	**0.35**	1761	$3139	$2642	-$10	**-$507**	1.50	**1.79**
	LB Gas	30.8	$9028	$3748	3116	2835	**0.48**	2386	$4252	$3579	$504	**-$170**	1.32	**1.57**
	TC Diesel	32.3	$11128	$5848	2975	2975	**0.50**	2504	$4463	$3756	-$1386	**-$2093**	1.97	**2.34**
Conv. Vehicle	PFI	16.1	$5280	$0	5950	0	**0.00**	0	$0	$0	$0	**$0**	0.00	**0.00**
	LB Gas	23.1	$5940	$660	4150	1801	**0.30**	1515	$2701	$2273	$2041	**$1613**	0.37	**0.44**
	TC Diesel	22.2	$8250	$2970	4325	1626	**0.27**	1368	$2439	$2052	-$531	**-$918**	1.83	**2.17**