Title

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Abstract

This paper is concerned with the present status and future projections for emerging technologies that can be utilized in light-duty vehicles in the next five to ten years to significantly reduce their CO2 emissions. The emerging technologies considered are modern clean diesel engines and hybrid-electric powertrains using batteries and/or ultracapacitors for energy storage. Throughout the study, six classes of vehicles – compact passenger cars to large SUVs - were considered. For each vehicle class, computer simulations (Advisor 2002) and cost analyses were performed for conventional ICE and mild and full parallel hybrids using port-fuel injected and lean burn gasoline engines and direct-injection turbo-charged diesel engines to determine the fuel economy and differential costs for the various vehicle designs using the conventional gasoline PFI engine vehicle as the baseline. CO2 emissions (gmCO2/mi) for each driveline and vehicle case were calculated from the fuel economy values. On a percentage or ratio basis, the analyses indicated that the fuel economy gains, CO2 emissions reductions, and cost/price increases due to the use of the advanced engines and hybrid-electric drivelines were essentially independent of vehicle class. This means that a regulation specifying the same fractional reductions in CO2 emissions for all the vehicle classes would not favor one class over the others.

The results of the study were then used to calculate the increase in the CAFÉ standard (miles per gallon gasoline for the new car fleet) that was feasible using each of the emerging technologies and the associated vehicle price increase that would be incurred. It was determined that the CAFÉ standard could be increased to 38 mpg and 48 mpg using the PFI and lean-burn gasoline engines, respectively, in mild hybrids with an associated percentage price increase of 7-9%. The CAFÉ standard could be increased to 42 mpg and 52 mpg using the PFI and lean-burn gasoline engines, respectively, in full hybrids with an associated cost increase of 16-18%. The CAFÉ increases using the diesel engines in mild hybrids were close to those of gasoline engines in full hybrids. The vehicle price increases using diesel engines in hybrids were 17-23% compared to the baseline ICE vehicles using the PFI engine. The fleet CO2 emissions corresponding to the cited CAFÉ standards were 185-234 gmCO2/mi for the mild hybrids using gasoline engines and 170-208 gmCO2/mi for full hybrids. The corresponding values using diesel engines are189-216 gmCO2/mi. The CO2 emissions of the new car fleet for a CAFÉ standard of 27.5 mpg are 322 gmCO2/mi indicating that implementing the hybrid powertrain technologies in the new car fleet could reduce CO2 emissions of the fleet by 25-50%.

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1. Introduction

In recent years there has been considerable discussion in the United States (US) concerning increasing the present Corporate Average Fuel Economy (CAFÉ) standard for light –duty vehicles from the present value of 27.5 miles per gallon (mpg). The US auto companies have vigorously resisted any legislation to increase CAFÉ claiming it would limit consumer choice and/or lead to downsizing of vehicles and significantly higher prices. With the emergence of hybrid-electric vehicles from Japanese manufacturers and modern diesel engine vehicles from European manufacturers, the validity of the claims of the US manufacturers regarding the effects of increasing CAFÉ standards are less likely to be true than in the past. This paper utilizes the results from References 1 and 2 to assess these claims. The cited references resulted from studies done at the University of California-Davis for the California Air Resources (CARB) in support of their activities to satisfy California Law AB1493, which directed the CARB to set economically feasible CO2 emissions standards to reduce greenhouse gases emissions from present values. In this paper, improvements in fuel economy and thus CO2 emissions resulting from the utilization of the emerging technologies are assessed for various size classes of vehicles. The exhaust and CO2 emission implications of higher CAFÉ standards based on the improved fuel economy possibilities are also assessed along with their economic feasibility.

2. Emerging Technologies

2.1 Hybrid-electric vehicles

Hybrid-electric powertrain technology is an emerging technology that will lead to increased fuel economy and lower CO2 emissions in the years ahead. This technology is already being utilized in hybrid vehicles being marketed by Toyota and Honda in the United States. These hybrids are the Toyota Prius and the Honda Insight and Civic. Both auto companies first marketed their hybrid vehicles in Japan before doing so in the United States. These vehicles are fully certified by EPA with their fuel economies being listed in the EPA Fuel Economy Guide. In addition, the vehicles have been tested by and discussed in several of the car magazines (References 3-5) where they have received favorable reviews. Hence early generations of the hybrid-electric powertrain technology are now in the dealer's showrooms. Vehicle characteristic, price, and sales data on the Toyota and Honda hybrids are included in the UC Davis light-duty Vehicle Data base (Reference 1). A recent in-depth review of hybrid-electric vehicle technology is given in Reference (6).

The approaches taken by Toyota and Honda are quite different so the two hybrid drivelines will be discussed separately. First consider the hybrid driveline in the Prius (Reference 7 and 8). It utilizes a three-shaft design with a planetary gear set arrangement. The electric motor is attached to the ring gear that is connected to the wheels of the vehicle. The engine is attached to the carrier gear of the planetary set. This arrangement permits the engine output to be split between the ring gear and the sun gear to which a generator is attached. The generator can be used as a motor to start the engine at any vehicle speed. The Prius driveline can function as a parallel hybrid with both the engine and motor torque being applied to the wheels or as a series hybrid with most of the engine output being applied to the generator to recharge the nickel metal hydride batteries (Reference 9) which store 1.8 kWh of energy. The batteries are also recharged via regenerative braking. As far as the vehicle's driver is concerned, the planetary gear set functions as an automatic transmission under total computer control in all driving modes. The engine in the Prius utilizes the Atkinson cycle and was a special design for the hybrid application (Reference x). Three generations of the Prius have been marketed by Toyota starting in 1998 in Japan. The third generation of the Prius (Reference 10) became available in the United States in September 2003. As indicated in Table 1, each successive generation of the Prius has had better acceleration performance and higher fuel economy than the previous generation.

The Honda hybrids (Insight and Civic) utilize a single-shaft arrangement (Reference 11 and 12) with the electric motor and engine on the same shaft. The shaft is connected to the wheels through either a 5-speed manual transmission or a continuously variable transmission (CVT) and a clutch. The Insight uses a 1 liter, 3-cylinder engine and the Civic a 4-cylinder, 1.3 liter engine. The engine is operated in the on/off mode with it being turned off and restarted every time the vehicle comes to a stop. The engine is started in less than .1 seconds. The electric motor is used as a starter motor and to assist the engine during accelerations or periods of high power demand like going up a grade. The electric motor is also used as a generator to recharge the battery and to recover energy during regenerative braking. Both the Honda hybrids use a nickel metal hydride battery that stores about 900 Wh. The engines can be operated in either the stoichiometric or lean burn modes (Reference 13) depending on whether the target emission level for the vehicle is SULEV or ULEV. When the CVT is used, the vehicle is totally computer controlled. The fuel economy of the Insight and Civic are given in Table 1.

As of 2003, the Prius and Civic satisfy all the requirements for an ATPZEV under the ZEV Mandate-that is both vehicles satisfy the SULEV emission standards, including the 10 year/150,000 mile warranty on the battery, and are classified as high voltage HEVs with an electric motor of at least 10kW. The Honda hybrids have relatively low power electric drivelines (10kW) and would be termed a mild hybrid. The Prius has a much higher power electric driveline (30 –50 kW) and is close to a full hybrid. Neither hybrid vehicle is designed to operate on the FUDS driving cycle as an EV and hence neither has a non-zero all-electric range by ARB definition. As would be expected, the fuel economy gain from hybridization is larger for the Prius than the Honda hybrids due primarily to the higher power of the electric driveline in the Prius. As discussed in References 14, there is a trade-off between cost and fuel economy gain in hybrid that favor the simpler Honda approach if economic attractiveness is a key design consideration. There are also a trade-offs between initial cost, fuel economy, and acceleration performance such that high performance can be achieved without sacrificing fuel economy, but at a higher initial cost. .

Table1: Fuel economy and emissions of the Toyota and Honda Hybrid Cars (2003)

Vehicle	Trans./ Year	Electric Motor (kW)	0-60 mph accel. (sec.)	Emissions	Unadjusted mpg (City)	Unadjusted mpg (Hwy)
Honda Insight	M5	10	11.2	ULEV	67	87
	CVT	10	-	SULEV	63	72
Honda Civic	M5	10	-	ULEV	51	65
	CVT	10	12.0	SULEV	54	61
Toyota Prius	2000	33	12.6	SULEV	57	58
	2004	50	10.1	SULEV	67	64

Source: compiled from Reference 15

2.2 High-speed diesel

The modern diesel engines (Reference 16 and 17) used in light-duty vehicles today are turbo-charged, direct injected engines that operate at high RPM and have a high specific power approaching 50 kW/liter. These engines have 4-valves per cylinder and utilize common rail, high pressure (1350-1600 bar) injectors having 5-7 holes per injector and injection pulse shaping. In addition, the engines employ a swirl supported combustion process and utilize electronic engine management. Much of the electronic engine control technology developed for spark-ignition engines is now utilized in the modern diesel engines used in light-duty vehicles. The primary advantages of the diesel engine compared to the spark-ignition (SI), gasoline engine are high torque at low and intermediate engine RPM and their higher efficiency, especially at part-load conditions resulting in higher vehicle fuel economy. The maximum torque of the diesel engine occurs at much lower RPM than for a gasoline engine and the torque per liter of displacement of the diesel engines is 100-110 ft-lb/L compared to 60-70 ft-lb/L for the gasoline engines. Further the ratio of torque to horsepower for the diesel engines is 1.6-1.8 compared to .9-1.1 for the gasoline engines. The result of the higher torque of the diesel engine is that diesel engine-powered vehicles require a lower power- to-weight ratio than vehicles using gasoline engines. For a 0-60 mph acceleration time of 9 seconds, the power-to-weight ratio for the diesel engine-powered vehicles is .044 hp/lb and for a gasoline vehicle, it is .052 hp/lb.

It is well accepted that diesel engine-powered vehicles have significantly higher fuel economy and consequently lower CO_2 emissions than gasoline fueled vehicles. These differences can be quantified using available test data for gasoline and diesel fueled vehicles. Correlations of fuel economy and acceleration performance data taken from References 15 and 18 have been made for several weight classes of passenger cars. None of the vehicles used in the correlation meet the California ULEV or SULEV emission standards. In the case of the diesel engines, technology is not yet available to reduce their emissions to ultra-clean levels. Further it is not known at the present time how much the fuel economy of diesel powered cars will be reduced by the technology needed to meet the ultra-clean ULEV and SULEV standards. The fuel economy values used for the diesel engine vehicles are for the European combined driving cycle (ECE-EUDC); for the gasoline engine vehicles, the fuel economy was calculated by averaging the fuel economies for the US Federal Urban (FUDS) and the Highway cycles. The fuel economy values from the Fuel Economy Guide were corrected by the factor (1/.84) to get back to the EPA test data for the gasoline engine vehicles. The fuel economy advantage of the diesel engine is shown in Table 2 for all vehicle weight classes and acceleration performance. Quantitatively, the advantage is 1.4-1.55 with the variation being largest between vehicle classes. Correcting the advantage factors for the higher energy content of a gallon of diesel fuel compared to a gallon of gasoline, the advantage of the diesel engine vehicles in terms of equivalent gasoline mpg is reduced to 1.24-1.38. If one corrects for the differences in the carbon/hydrogen content of diesel and gasoline fuels, it is found that the advantage of the diesel engines in terms of gmCO2/mi is reduced further to 1.18-1.32. Hence in general in terms of reducing CO2 emissions, the advantage of diesel engine powered vehicle over gasoline engine powered vehicles is 20-30 %. This advantage is certainly significant but not as large as would be inferred directly from the fuel economy values in diesel mpg

Table 2: Summary of the fuel economy of gasoline and diesel engine-powered passenger cars as a function of 0-60 mph acceleration time

	small	<1200	kg	mid-1200-	1600	kg	large	>1600	Kg
Acceleration 0-60 mph seconds	**Diesel**	**Gas.**	**Ratio**	**Diesel**	**Gas.**	**Ratio**	**Diesel**	**Gas.**	**Ratio**
7	**46.5**	**31.6**	**1.47**	**42.0**	**27.3**	**1.54**	**35.5**	**25.5**	**1.39**
8	**48.5**	**33**	**1.47**	**43.8**	**28.5**	**1.54**	**37.3**	**26.7**	**1.40**
9	**50.5**	**34.5**	**1.46**	**45.5**	**30.0**	**1.52**	**39.3**	**28.2**	**1.39**
10	**52.5**	**35.8**	**1.47**	**47.7**	**31.2**	**1.53**	**41.5**	**29.5**	**1.41**
11	**54.5**	**37.3**	**1.46**	**49.8**	**32.5**	**1.53**	**43.4**	**30.7**	**1.41**
12	**56.5**	**38.7**	**1.46**	**52.0**	**33.6**	**1.55**	**45.2**	**32.0**	**1.41**

Diesel fuel economy on the European ECE-EUDC driving cycle –Reference 4
Gasoline (Gas.) fuel economy average of the FUDS and Fed. HW cycles- Reference 7
Acceleration times based on tests given in References 4-6

3. Improvements in Fuel Economy for Various Classes of Vehicles

3.1 Vehicle descriptions

In order to quantitatively assess the tradeoffs between fuel economy and cost differential, it is necessary to consider specific vehicle designs, powertrain configurations and control strategies, and component performance characteristics and cost. This was done in the studies reported in References 14 and 19. For each of the vehicle classes considered in the study (cars and SUVs), the characteristics of a conventional ICE powered vehicle (Table 3) were determined and hybrid–electric vehicles having the same size, road load parameters, performance, and utility were conceptualized (Table 4). Only parallel hybrid drivelines, which permit the engine to drive directly to the wheels when required by the control strategy, were considered. 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. 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 (Reference 13), and a turbo-charged direct injected diesel engine based on the Audi 2.5L engine. All the vehicle drivelines 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. All the components in the hybrid drivelines were modeled using the standard models in the Advisor simulation computer program.

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 various hybrid drivelines. 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 these requirements.

Table 3: 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

Table 4: Characteristics of the hybrid vehicles

		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**
Full-size car	**1865**	**100**	**85**	**335/27**	**160**	**20**	**150/18**
Small-SUV	**1726**	**75**	**65**	**335/20**	**120**	**15**	**150/13**
Mid-SUV	**2170**	**90**	**75**	**335/24**	**150**	**20**	**150/18**
Large-SUV	**2636**	**110**	**95**	**335/30**	**180**	**25**	**150/22**

All vehicles have CVT transmissions and nickel metal hydride batteries

3.2 Fuel economy improvement factors

The fuel economy results for the six vehicle classes are given in ratio form in Tables 5. A ratio of 1.0 refers to the conventional ICE vehicle in each class using the PFI gasoline engine. Fuel economy improvement ratios are shown for conventional ICE and hybrid vehicles using the PFI and lean-burn gasoline engines and turbo-charged diesel engines. Note in Table 5 that hybrid vehicles using the PFI gasoline engine result in fuel economy improvements close to those of non-hybridized vehicles using advanced lean-burn gasoline and diesel engines. Hybridization of the powertrains using the advanced engines results in further improvements in fuel economy up to nearly a doubling of the fuel economy in the case of full hybrid designs. Use of the lean-burn gasoline engine results in fuel economy values close to those of the turbo-charged diesel engine. At the present time, the selection of engine type is primarily driven by the emission standards to be met. PFI gasoline engines using a three –way catalyst that requires stoichiometric engine operation results in vehicle emissions that meet the most stringent California standards (SULEV). This is the case for both conventional ICE or hybrid vehicle designs. The diesel and lean-burn gasoline engines would require a lean-burn catalyst having conversion efficiencies for NOx close to that of the three-way catalyst if vehicles using those engines were to meet the SULEV standards. In the case of the lean-burn gasoline engines, it appears that Honda is currently able to meet the ULEV standards at least for relatively small passenger cars. When a lean-burn catalyst with very high conversion efficiency is developed, the large improvements in fuel economy indicated in Table 5 for the lean-burn gasoline and diesel engines will be possible without a sacrifice in ultra-clean vehicle emissions.

Table 5: Fuel economy (mpg) improvement ratios relative to PFI Engine-powered vehicles

	ICE		PFI		Lean-burn		Diesel	
Vehicle Class	Diesel	Lean-burn	Mild	Full	Mild	Full	Mild	Full
Compact Car	1.46	1.42	1.28	1.44	1.64	1.77	1.66	1.96
Mid-size car	1.53	1.42	1.42	1.60	1.81	1.98	1.81	2.04
Full-size Car	1.40	1.42	1.42	1.60	1.81	1.98	1.81	2.04
Small-SUV	1.50	1.42	1.35	1.52	1.72	1.87	1.74	2.0
Mid-SUV	1.40	1.42	1.42	1.60	1.73	1.85	1.8	2.0
Large-SUV	1.40	1.42	1.42	1.60	1.81	1.98	1.81	2.04

3.3 Cost considerations

Cost/price projections for vehicles using advanced engines and hybrid powertrains are given in Table 6. The cost projection results for the differences in costs of the various vehicle powertrains are given in absolute 2003$ using the conventional PFI engine powertrain as the baseline. The cost and fuel economy results are given in ratio form in Table 7 and in graphical form in Figure 1. Note that both the fuel economy improvement and cost ratios increase between the mild and full hybrid cases. In terms of the breakeven gasoline price, the mild hybrid designs are more economically attractive than the full hybrid designs (Reference 19). There is no doubt that the full hybrid design will result in a greater improvement in fuel economy, but at a significantly higher differential cost of the powertrain. Note that on a percentage basis, hybridizing the vehicles using diesel engines are the most costly because of the higher unit cost of diesel engines compared to the gasoline engines. All the results indicate that development of the lean-burn gasoline engine is the most cost effective approach to improving fuel economy of light-duty vehicles. The lean-burn engines seem to yield fuel economy improvements close to that of the direct injection turbo-charged diesel engines at a much lower differential cost. It is also likely that meeting the SULEV emissions standards with the lean-burn gasoline engine will be less difficult than with the diesel engines. In the near-term, significant improvements (30-40%) can be achieved by hybridizing vehicles using the PFI gasoline engines that can meet the SULEV emissions standards. As indicated in Table 6, the projected differential cost of mild hybrids using the PFI engines is only $1000-2500 for components in mass production. Fuel economy improvements of 50-60% appear to be possible in full hybrids using the PFI engines, but the differential costs of the powertrains are $2500-5000. As indicated in the historical review of light-duty vehicle price changes from 1975-2003 (Reference 1), price increases of these magnitudes in 2003$ were experienced by consumers during that period and sales of new vehicles continued at a high level in good economic times. Consumers seem to be more concerned about the performance and utility of the vehicles they purchase than the price and the auto companies and banks offer consumers creative means of affording the vehicles because they strongly desire to do business with them.

Table 6: Cost/Price differentials (2003$) for ICE and hybrid vehicles using various engines relative to the ICE PFI vehicle

	ICE			Hybrid PFI		Hybrid Lean-burn		Hybrid Diesel	
Vehicle Class	PFI	Lean-burn	Diesel	Mild	Full	Mild	Full	Mild	Full
Compact car	0	380	1710	1054	2415	1340	2683	2588	3529
Mid-size car	0	540	2430	1428	3333	1949	3682	3593	5047
Full-size car	0	720	3240	1820	4772	2471	5181	4712	6578
Small-SUV	0	540	2430	1363	3633	1857	3982	3540	5047
Mid-SUV	0	660	2970	2121	4270	2640	4692	4839	5767
Large-SUV	0	800	3600	2245	5234	3000	5686	5505	7222

Table 7: Fuel economy (F.E.) and cost (Ct.) ratios for hybrid vehicles using various engines relative to ICE PFI vehicles

	PFI Mild		Full		Lean-burn Mild		Full		Diesel Mild		Full	
Vehicle Class	F.E.	Ct.	F.E.	Ct.	F.E.	Ct.	F.E.	Ct.	F.E.	Ct.	F.E.	Ct.
Compact car	1.28	1.07	1.44	1.15	1.64	1.09	1.77	1.17	1.66	1.16	1.96	1.22
Mid-size car	1.42	1.07	1.60	1.17	1.81	1.10	1.98	1.18	1.81	1.18	2.04	1.25
Full-size car	1.42	1.07	1.60	1.18	1.72	1.09	1.87	1.19	1.74	1.18	2.0	1.25
Small-SUV	1.35	1.06	1.52	1.17	1.73	1.09	1.85	1.18	1.8	1.16	2.0	1.23
Mid-SUV	1.42	1.07	1.60	1.15	1.81	1.09	1.98	1.17	1.81	1.17	2.04	1.20
Large-SUV	1.42	1.06	1.60	1.15	1.81	1.09	1.98	1.16	1.81	1.16	2.04	1.21

F.E. and Ct. are referenced to the conventional ICE vehicle of that class

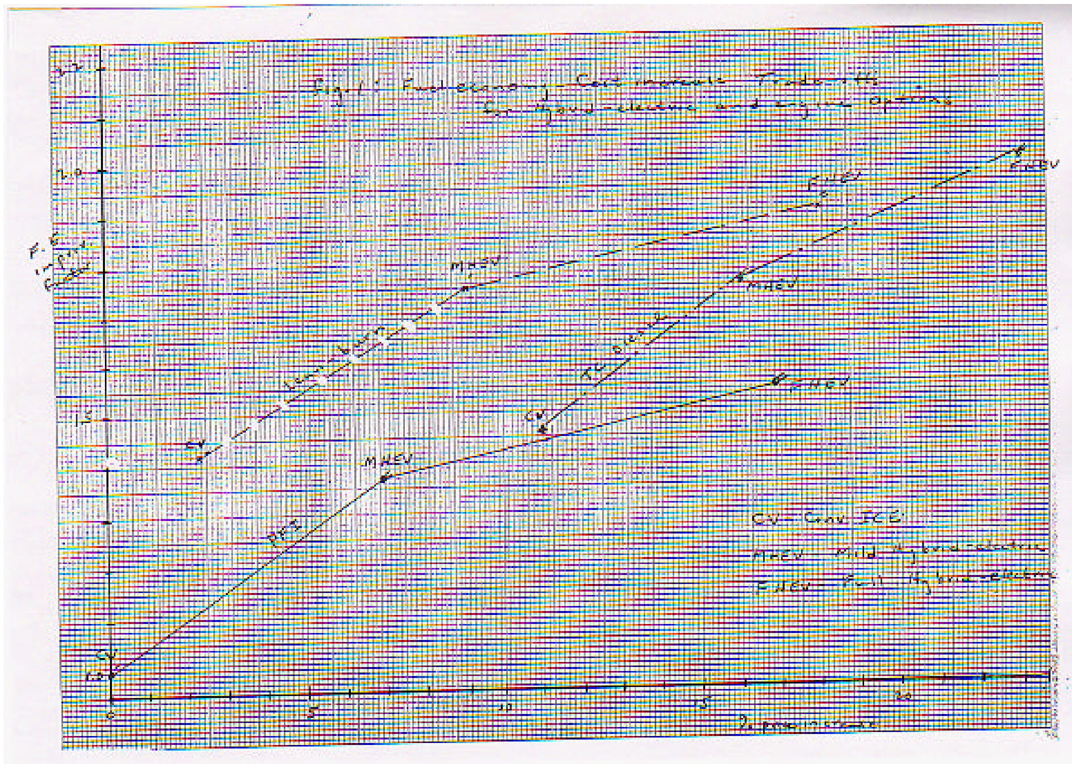


Figure 1: Fuel Economy-Cost Increase Trade-offs for Hybrid-electric and Engine Options

3.4 Vehicle Attributes

The results given in Tables 5-7 have been used to calculate the CO_2 emissions (gmCO_2/mi) for the various classes of light-duty vehicles. The CO_2 results are given in Tables 8-10 along with other vehicle attributes (0-60 mph acceleration time, fuel economy-mpg, and price-2003$). In determining the real world fuel economy and CO_2 emission values, the fuel economy values (EPA test data and simulation results) were reduced by .84 which is the average of the degradation factors for the FUDS cycle (.9) and the Federal Highway cycle (.78). All the values in the tables were calculated starting with baseline values for near top-rated models in each of the vehicle classes. The baseline values are given in Table 11. The fuel economy values for each case were calculated using the fuel economy improvements factors in Table 5 and the vehicle prices were calculated using the cost /price differentials given in Table 6. The CO_2 emissions values (gmCO_2/mi) were calculated from the fuel economy values utilizing the following relationships: for gasoline fuel, gmCO_2/mi = 8820/ mpg and for diesel fuel, gm CO_2 = 10400/mpg. These relationships account for the differences in the density and carbon/hydrogen ratio between gasoline and diesel fuel. These differences reduce by a factor of 1.18 the advantage of vehicles using diesel engines compared to those using gasoline engines. This further enhances the attractiveness of the lean-burn, gasoline engine as the engine for future use in light-duty vehicles.

Tables 8-10 and Figure 1 indicate that significant reductions (30-40%) in CO_2 emissions can be achieved with modest increases in vehicle prices. Note that all the vehicles considered in this study have the same weight and size as present vehicles in each of the vehicle classes. Improvements in aerodynamics and rolling resistance to reduce the road load of the vehicles were not utilized to achieve the fuel economy and CO2 emission improvements shown in the tables. In addition, all the vehicles have good acceleration performance – 0-60 mph in 9 seconds. As would be expected, the CO2 emissions are strongly dependent on vehicle size increasing markedly from the compact car class to the large SUV class. It appears from the vehicle simulations and cost analyses (Table 5-10) that the fractional (%) changes in fuel economy, and thus CO2 emissions, and costs are essentially independent of vehicle class, and thus vehicle weight and size. This means that a regulation specifying the same fractional reductions in CO2 emissions for all classes would not favor one class over the others.

Table 8: Attributes of vehicles using conventional ICE powertrains

	PFI vehicles			Lean-burn vehicles			Turbo-diesel vehicles		
Vehicle Class	Mpg Gasol.	gmCO2 /mi	Price 2003$	Mpg Gasol.	GmCO2 /mi	Price 2003$	Mpg diesel	gmCO2 /mi	Price 2003$
Compact car	28.6	308	16260	40.6	217	16640	41.8	249	17970
Mid-size car	24.4	362	20250	34.7	254	20790	37.3	279	22680
Full-size car	21.4	412	26700	30.2	292	27420	30.0	347	29940
Small-SUV	22.3	396	21925	31.7	278	22465	33.5	310	24355
Mid-SUV	17.2	513	28510	24.4	362	29710	24.1	432	31480
Large-SUV	15.1	584	35150	21.4	412	35950	21.1	493	38750

All vehicles - 0-60 mph 9 seconds

Fuel economy - numerical average of the FUDS and Fed. HW fuel economies derated by .84 for real world driving

Table 9: Attributes of vehicles using mild hybrid powertrains

	PFI vehicles			Lean-burn vehicles			Turbo-diesel vehicles		
Vehicle Class	Mpg Gasol.	gmCO2 /mi	Price 2003$	Mpg Gasol.	GmCO2 /mi	Price 2003$	Mpg diesel	gmCO2 /mi	Price 2003$
Compact car	36.6	241	17314	46.9	188	17660	47.5	219	18848
Mid-size car	34.7	254	21678	44.2	200	22199	44.2	235	23843
Full-size car	30.4	290	28520	38.7	228	29171	39.4	264	31412
Small-SUV	30.1	293	23288	38.4	230	23782	38.8	268	25465
Mid-SUV	24.4	362	30631	29.8	296	31150	31.0	335	33349
Large-SUV	21.4	412	37395	27.3	323	38151	27.3	381	40655

All vehicles - 0-60 mph 9 seconds

Fuel economy - numerical average of the FUDS and Fed. HW fuel economies derated by .84 for real world driving

Table 10: Attributes of Vehicles using full hybrid powertrains

	PFI vehicles			Lean-burn vehicles			Turbo-diesel vehicles		
Vehicle Class	Mpg Gasol.	gmCO2 /mi	Price 2003$	Mpg Gasol.	GmCO2 /mi	Price 2003$	Mpg diesel	gmCO2 /mi	Price 2003$
Compact car	41.2	214	18675	50.6	174	18943	56.1	185	19789
Mid-size car	39.0	226	23583	48.3	183	23932	49.8	209	25297
Full-size car	34.2	258	31472	42.4	208	31881	43.7	238	33278
Small-SUV	33.9	260	25558	41.7	212	25907	44.6	233	26972
Mid-SUV	27.5	321	32780	31.8	277	33202	34.4	302	34277
Large-SUV	24.2	365	40384	29.9	295	40836	30.8	338	42372

All vehicles - 0-60 mph 9 seconds
Fuel economy - numerical average of the FUDS and Fed. HW fuel economies derated by .84 for real world driving

Table 11: Baseline vehicle characteristics using the PFI gasoline engine

Class	City mpg	Highway mpg	Average mpg	gmCO2/ mi	Price 2003$
Compact car	28	40	34	259	16260
Mid-size car	22	36	29	304	20250
Full-size car	19	32	25.5	346	26700
Small SUV	21	32	26.5	333	21925
Mid-size SUV	17	24	20.5	430	28510
Large-size SUV	15	21	18	490	35155

Fuel economy values based on EPA test data

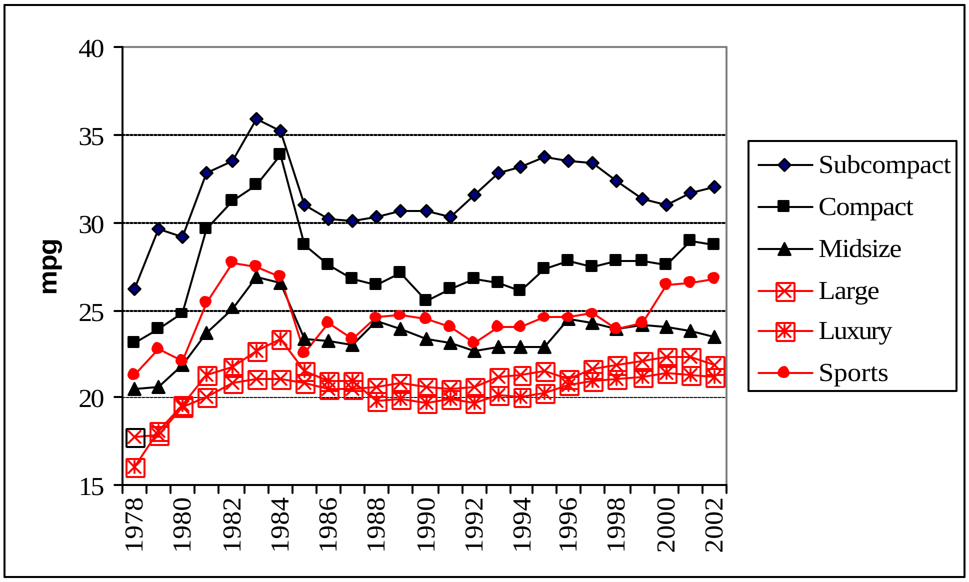
4. CAFÉ Standard Implications

4.1 Current status of the CAFÉ standards in the United States

In 1975, the Congress passed the Energy Policy and Conservation Act that established Corporate Average Fuel Economy Standards (CAFE) for passenger cars. The standards became effective in 1978 starting at 18 mpg increasing to 27.5 mpg in 1985. The rate of increase in mpg was highest in the period 1980-1984. Light truck CAFE standards were also established starting at 17.5 mpg in 1982 increasing to 20.7 mpg in 1996. These standards are currently applicable to light trucks, minivans, and sport utility vehicles. The light truck standard will increase by 1.5 mpg to 22.2 mpg in 2007.

4.2 Present fuel economy of various classes of vehicles

The change in the fuel economy of various classes of vehicles is shown in Figure 2 for the time period since the CAFÉ standards became effective in 1978. In the case of passenger cars, the fuel economy increased rapidly between 1978-1984 and has been essentially level since 1985. The trends in fuel economy have been much different for minivans and SUVs with the fuel economy of those classes of vehicles showing a small, but significant increase in recent years. This increase has been market driven as the CAFÉ standard for those vehicles has remained at 20.7 mpg since 1996.



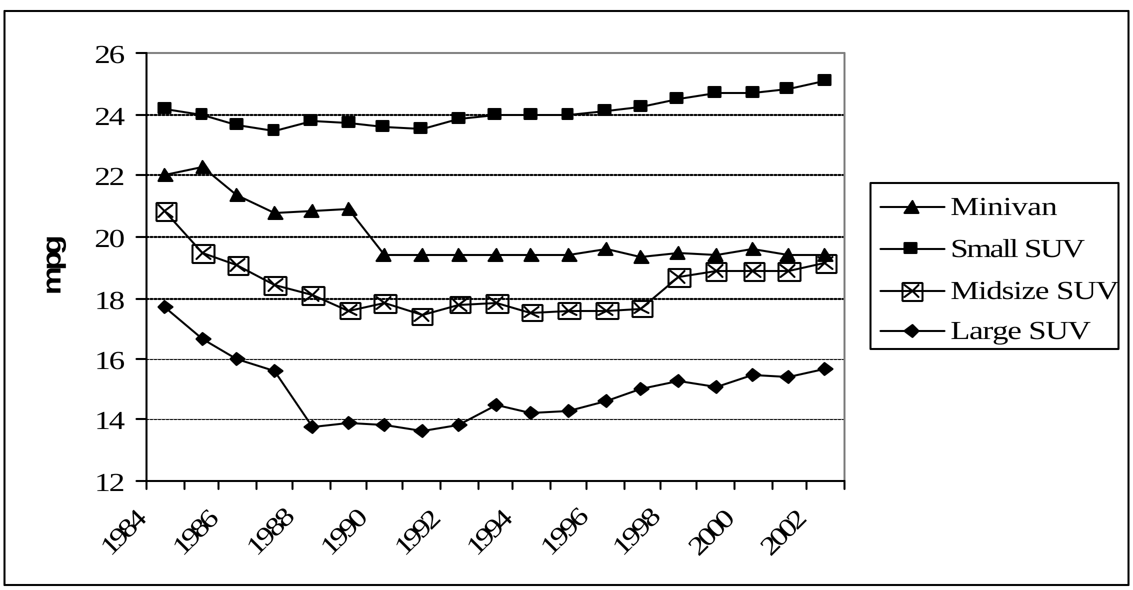


Figure 2: Changes in vehicle fuel economy from 1978-2002 for various classes of vehicles

4.3 Increased CAFÉ standards using the emerging technologies

As shown in Tables 6-10, relatively large improvements in fuel economy and reductions in CO2 emissions from light-duty vehicles can be achieved by using hybrid-electric powertrains and lean-burn and diesel engines. It is of interest to calculate how large an increase in the CAFÉ standards could be justified using the emerging technologies. Calculations have been performed for each of the technologies shown in the tables assuming that the sales mix of the various vehicle classes is the same as in the year 2000 in the United States (see Table 12 for the sales mix assumed). The results of the calculations,

Table 12: Sales mix by class in the United States (2000)

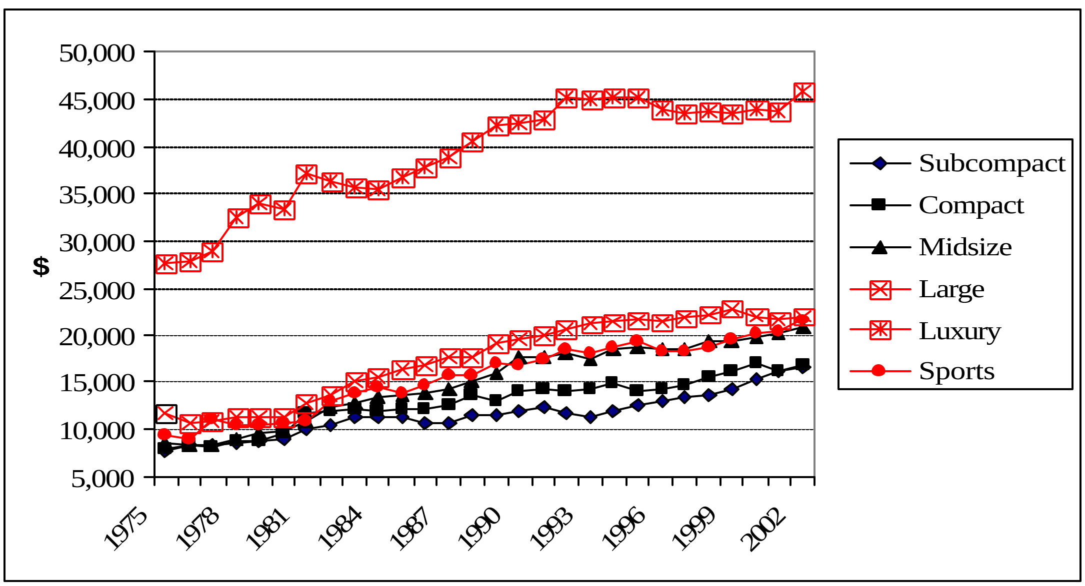
Class	Percent sales
Passenger Cars	
Compact and smaller	30.6
Mid-size	24.4
Large	9.4
Vans and SUVs	
minivans	9.4
Small SUV	5.5
Midsize SUV	15.6
Large SUV	5.1

Table 13: CAFÉ, CO2 Emission, and Price values for Various Technologies

Technology	Mild	Hybrid		Full	Hybrid	
Engine	CAFÉ Mpg *	CO2 gm/mi	Price factor	CAFÉ Mpg	CO2 gm/mi	Price factor
PFI	37.7	234	1.07	42.4	208	1.16
Lean-burn	47.8	185	1.09	52.0	170	1.18
TC diesel	48.1	216	1.17	55.0	189	1.23
Baseline PFI ICE Vehicles	27.4	322	1.0			

*** The fuel economy values are based on the unadjusted EPA test data and simulation results for the various vehicle classes**

which are given in Table 13, indicate that large increases in the CAFÉ standard are feasible using the emerging technologies. The most cost-effective approach is to use mild hybrid hybrid powertrains with gasoline engines – either PFI (port fuel injected) or lean-burn . The incremental cost of these high fuel economy vehicles is only 7-9% greater than conventional ICE vehicles. In addition, these vehicles are the same size and weight as conventional vehicles of the same class. Hence from the consumers point-of-view the only difference is a relatively small increase in price. As shown in Figure 3, these price increases are small compared to price increases experienced by consumers in the years since the original CAFÉ standards were put in place. Hence it appears that the CAFÉ standards for light-duty vehicles can be increased to 40-45 mpg using existing technology with minimal sacrifice by automobile consumers in terms of vehicle size, performance, and price. Larger increases in the CAFÉ standards (up to 50%) are achievable with larger price increases. These increases in CAFÉ would undoubtedly be implemented over a extended period (probably 10-15 years) so the auto industry would have time to introduce the new technologies in all the vehicle classes.



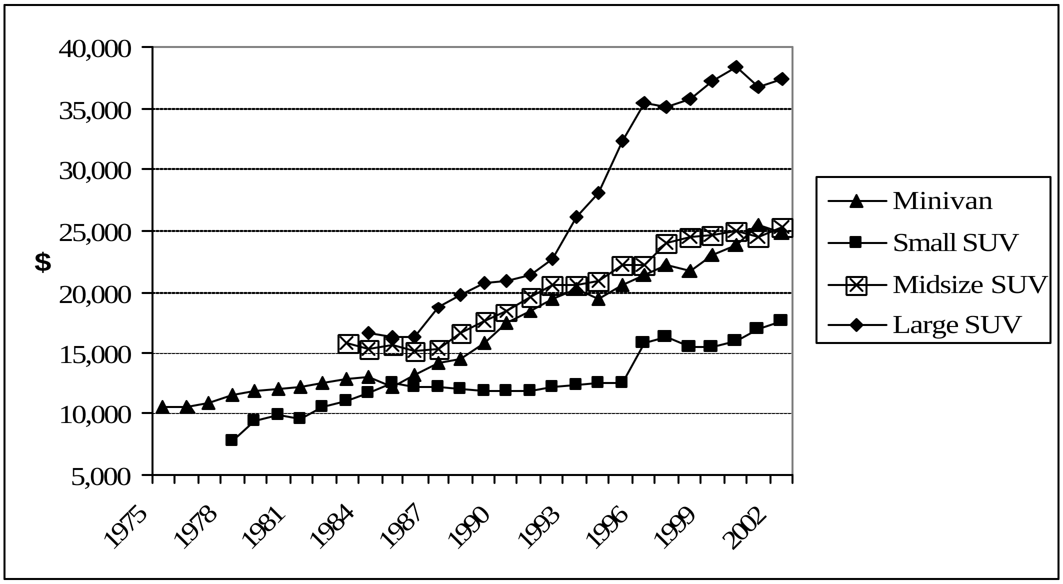


Figure 3: Changes in the Retail Price of Vehicles of Various Classes for 1975-2002l

The Energy Information Administration (EIA) of the United States Department of Energy has recently made projections for 2004-2020 of the average fuel economy of the new vehicle light-duty fleet including SUVs and light trucks (Reference 21). These projections included assumptions relative to the increase in the fuel economy of conventional ICE vehicles and the penetration in the market of hybrid-electric vehicles. The assumptions used in the EIA projections were relatively conservative regarding the sales penetration of hybrids and the improvements in the fuel economy of the vehicles. Additional projections of fleet fuel economy were made as part of the present study using the fuel economy improvement factors given in Table 7. Those projections are compared with the EIA projections in Figures 4 and 5. The assumed HEV market penetrations for the various scenarios are given in Figure 6. In Figures 4 and 5, the designations high and low refer to the assumed rated of market penetration (first label) and the rate of fuel economy improvement (second label). Note that by 2020, the fleet fuel economy with high hybrid market penetration begins to reflect the fuel economy improvements made possible by mild hybrid technology. These large improvements in fuel economy could be achieved sooner by increasing the CAFÉ standards as indicated in Table 13.

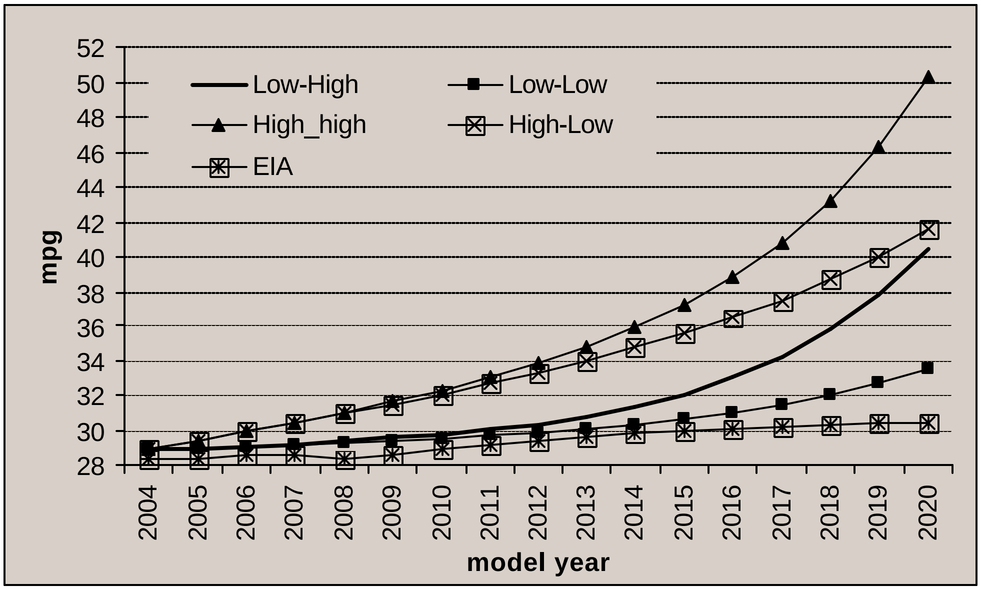


Figure 4: New Vehicle Fleet Fuel Economy for Passenger Cars (2004-2020)

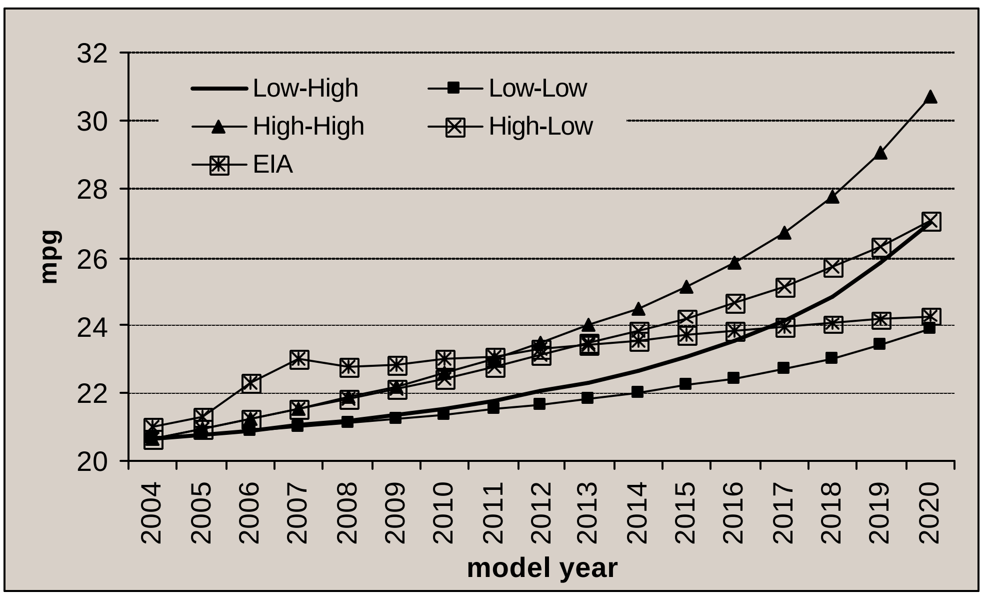


Figure 5: New Vehicle Fleet Fuel Economy for Light Trucks (2004-2020)

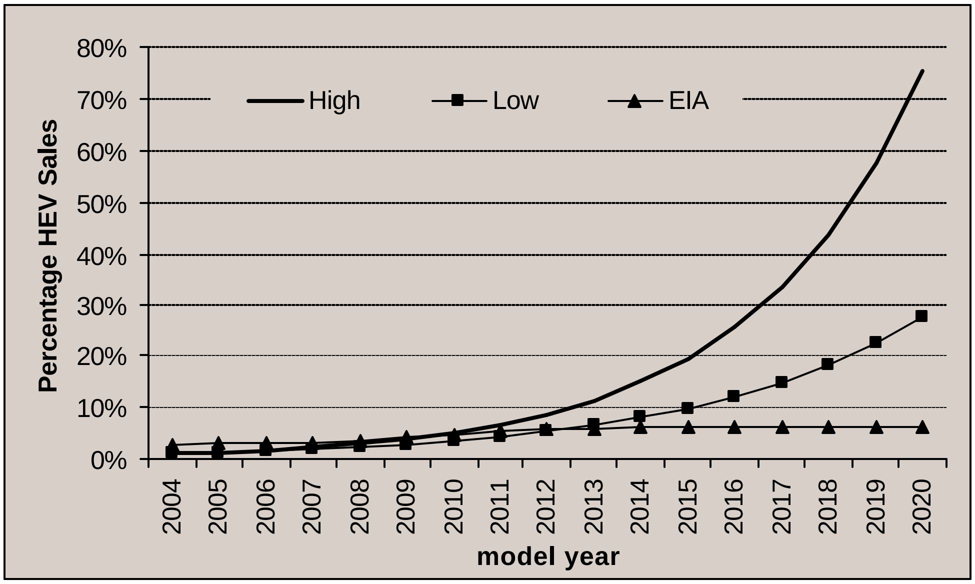


Figure 6a: HEV Penetration curves for passenger cars (2004-2020)

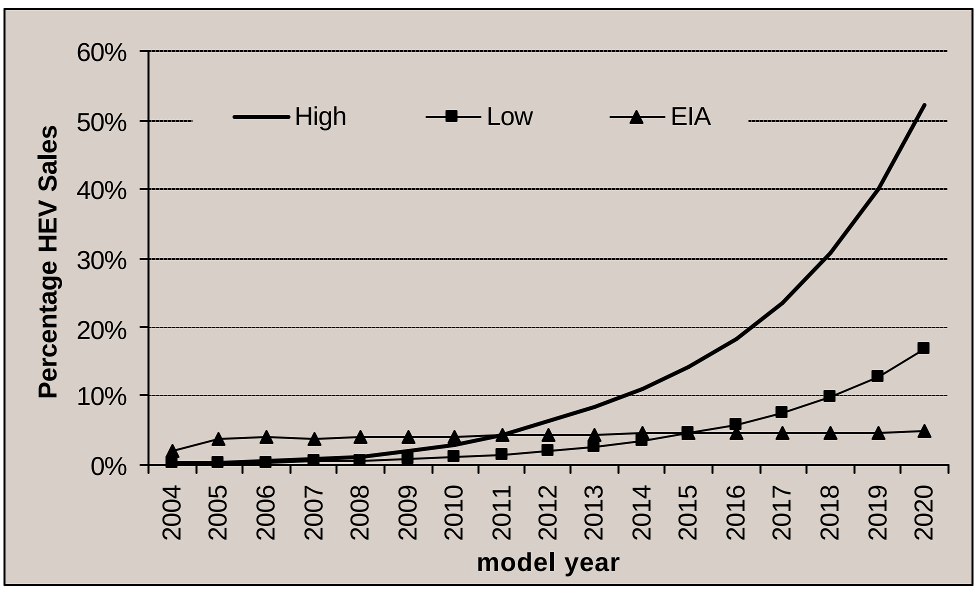


Figure 6b: HEV Penetration curves for Light Trucks (2004-2020)

4.5 Exhaust and CO2 implications of higher CAFÉ standards

The CO2 emissions (gm/mi) corresponding to each of the increased CAFÉ standards are shown in Table 13. The results indicate that large reductions in CO2 emissions are possible using the emerging hybrid-electric and engine technologies. The reductions range from 28% using a PFI engine in mild hybrids to 48% using a lean-burn gasoline engine in full hybrids. As shown in Table 7, the fuel economy improvement and thus the CO2 reductions do not vary significantly over the various vehicle classes so the CO2 reductions will not vary with changes in the sales mix. Table 7 also indicates that the incremental cost on a percentage basis does not vary with vehicle class. This means that one would not expect large changes in the sales mix due to the utilization of the emerging technologies to reduce CO2 emissions.

Exhaust emission standards have been becoming more stringent in all countries around the world. Emissions standards currently in effect and planned in the United States and Europe are shown in Table 14. It would be expected that most future light-duty vehicles in the US would have to meet the California ULEV and SULEV standards and those in Europe would have to meet the Euro 5 or lower standard. It is expected that hybrid-electric vehicles using gasoline engines would be able to meet the stringent standards (see Table 1 for existing hybrids marketed by Toyota and Honda), but much work on emissions aftertreatment technology is needed before the diesel engines can meet the stringent emission standards. In the near-term (5 years), the relatively high emissions of the diesel engines would seem to limit their use in the United States, especially California.

Table14: Federal, California, and European Emissions Standards

Standard	Year	CO	HC	NOx	PM	HC + NOx
Fed. Tier 1 Gasoline	-	4.2	0.32	0.6	0.1	0.92
Fed. Tier 1 Diesel	-	4.2	0.32	1.25	0.1	1.6
Euro 3	2001	1.0	0.09	0.81	0.08	0.9
NLEV	-	4.2	0.09	0.3	0.08	0.39
Euro 4	2005	0.81	0.08	0.4	0.04	0.48
Fed. Tier 2 (Bin 5)	2007	4.2	0.09	0.07	0.01	0.16
Euro 5 (proposed)	2008	1.6	0.08	0.13	0.004	0.21
California ULEV	2004	1.0	0.04	0.05	0.01	0.09
California SULEV	-	1.0	0.01	0.02	0.01	0.03

Source: compiled from References 19 and 20

References

1. Burke, A.F., Abeles, E., and Chen, Belinda, The Response of the Auto Industry and Consumers to Changes in the Exhaust Emission and Fuel Economy Standards (1975-2003): A Historical Review of the Changes in Technology, Prices, and Sales of Various Classes of Vehicles, ITS-Davis report UCD-ITS-RR-04-4, March 2004

2. Burke, A.F., Present Status and Future Projections of the Emerging hybrid-Electric and Diesel Technologies to Reduce CO2 Emissions of New Light-Duty Vehicles in California, ITS-Davis report UCD-ITS-RR-04-2, January 2004
3. Motor Trend, Hyper-mileage Hybrids, ppg 70-74, August 2002
4. Consumers Report, Car Road Tests issue, Spring 2003
5. Consumers Report, New Car Preview, November 2003
6. German, J.M., Hybrid Powered Vehicles, SAE Publication T-119, 2003
7. Hermance, D., Toyota Hybrid System, 1999SAE TOPTEC conference, Albany, N.Y., may 1999
8. Okmura, M., Development of Hybrid Electric Drive using a Boost Converter, EVS-20, Long Beach, California, November 2003
9. Ito, K., Development of Prismatic Type Nickel Metal Hydride Battery for HEV, EVS-20, Long Beach, California, November 2003
10. Hirose, T., Takaoka, T., Ueda, T., and Kobayashi, Y., the New High Expansion Ratio Gasoline Engine for the Toyota Hybrid System, JSAE Paper 9739552, October 1997
11. Hasegawa, K., A Technical Description for a Motor Assisted Hybrid, presentation of Honda R&D Co. at the SAE Hybrid Vehicle Symposium in San Diego, California, Jan 28-29, 2004
12. Ogawa, H., Masato, M., and Takahiro, E., Development of a Power Train for the Hybrid Automobile-The Hybrid Civic, SAE paper 2003-01-0083, March 2003
13. Duoba, M., In-situ test data for the Honda Insight Engine, Argonne National Laboratory, 2001
14. Burke, A.F., Saving Petroleum with Cost-effective Hybrids, SAE paper 2003-01-3279, November 2003
15. EPA Fuel Economy Guide, published by the United States Department of Energy, 2003
16. Ashley, S., Diesel Cars Come Clean, Mechanical Engineering, Volume 119, No. 8, August 1997
17. Tomazic, D., Integration of Emission Control Systems in CIDI Engines to Achieve PZEV Emissions: Technology, Regulations, and Challenges, SAE TOPTEC, January 24-25, 2002, San Diego, California
18. Diesel Car Magazine, published in the UK, June 2001
19. Burke, A.F., Abeles, E., Zhou, L., Sperling, D., and Brodrick, C.J., The Future of Hybrid-Electric Vehicles and Fuels Implications, ITS-Davis report UCD-ITS-RR-02-09, October 2002
20. Jackson, N., European Regulations-Technology Options and Challenges, presentation at the SAE Powertrain and Fluids Conference, October 2003, Pittsburgh, Pa.
21. Energy Information Administration, Department of Energy, Supplemental Tables to the Annual Energy Outlook 2004, Table 45. Light-Duty Vehicle Sales by Technology Type (United States), 2004, http://www.eia.doe.gov/oiaf/aeo/supplement/supref.html