Title

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UCD-ITS-RR-04-2

June 2004

by

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Table of Contents

Table of Figures and Tables

Abstract

This report is concerned with the present status of 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. The status of each of these technologies is assessed based on available information and data from the literature. In addition, the present marketing situation for each technology is summarized and prospects for marketing the technologies in California assessed.

In the case of the modern diesel engines, it was found that such engines have much higher toque characteristics than gasoline engines of the same displacement and vehicles powered by diesel engines have higher fuel economy (mpg) by 40-50% than similar (same size and performance) vehicles powered with gasoline engines. This is the reason that diesel-powered vehicles have presently reached almost a 50% market share in Europe. The major problem with the diesel engine for use in California is that “so-called clean” diesel powered vehicles have NOx emissions that are still 10X higher than Tier 1 vehicles with gasoline engines and to meet the SULEV NOx standard, a reduction of at least an additional factor of three is required. Whether this will be possible with diesel engines is uncertain.

Hybrid-electric passenger cars are currently being marketed in Japan and the United States by Toyota and Honda. These hybrids show large improvements (at least 30-50%) in fuel economy compared to conventional ICE vehicles of the same size and performance. All the hybrids meet SULEV emission standards and have been designated AT-PZEVs by CARB. The hybrids have been well received in the market with annual global sales approaching 100,000 in 2004. There seems to be no reason that hybrid sales will not continue to increase between 2005-2010 especially as the ZEV Mandate requirements become more demanding in 2008 and beyond.

1. Introduction

This report is concerned with the present status of technologies that can be utilized in light duty vehicles in the next five to ten year to significantly reduce their CO2 emissions. These technologies are advanced, clean diesel engines and hybrid-electric powertrains using batteries. In the case of the "clean" diesels, they are presently marketed in large quantities in Europe in light-duty vehicles where emission standards are much less stringent than in California. Large improvements in emissions of the diesel engine powered vehicles will be necessary before they can be sold in California. Marketing of hybrid-electric vehicles in the United States is in its infancy with current sales less than 1% of sales. The exhaust emissions of the hybrids meet the California SULEV standards and show significant improvements in fuel economy compared to conventional ICE vehicles of the same size class. Hence there are no regulatory barriers to marketing the current hybrid-electric technology in California even when the most stringent emission standards of the ARB are in force.

The subject of future markets for diesel powered and hybrid-electric vehicles in California and the United States has been the subject of a number of conferences, reports, and papers in recent months. In many respects there has been a high level of consensus in the studies available relative to both technologies. In the case of diesel-powered vehicles, it is recognized that developing the engine and emission aftertreatment technologies to reduce the NOx and particulate emissions to SULEV levels is the key issue. Further there are cost and fuel quality issues regarding diesel engines that are important, but less difficult to cope with. In the case of hybrid-electric vehicles, it is agreed by most people familiar with the technology that significant improvements (at least 50%) in city driving can be achieved in hybrids with relatively large electric driveline components and somewhat less improvements in hybrids using smaller electric drive components. For hybrids, the key issues are the initial vehicle price increase, which becomes larger as the power of the electric drive components is increased and consumer response to these price differentials. It is also generally agreed that hybrid drivelines are adaptable to all classes of light duty vehicles.

2. Current Status (2003)-Advanced Diesel Engine-Powered Vehicles

2.1 Review of the technology

In the United States, nearly all heavy and medium-duty trucks utilize diesel engines. However, less than 1% of light-duty vehicles (passenger cars, vans, and SUVs) use diesel engines. In Europe, in recent years the use of diesel engines in light-duty vehicles has increased rapidly (Reference 1) so that in 2002, diesel engine powered vehicles have a market share of about 40% with some projections indicating close to 50% by 2006. The European auto companies have agreed voluntarily to increase the average fuel economy of their light-duty vehicles by 25% by 2008. This would result in average CO2 emission of 225 gm/mi (140 gm/km). Increasing the sales fraction of diesel-powered vehicles is a key component of their strategy to meet the 25% target.

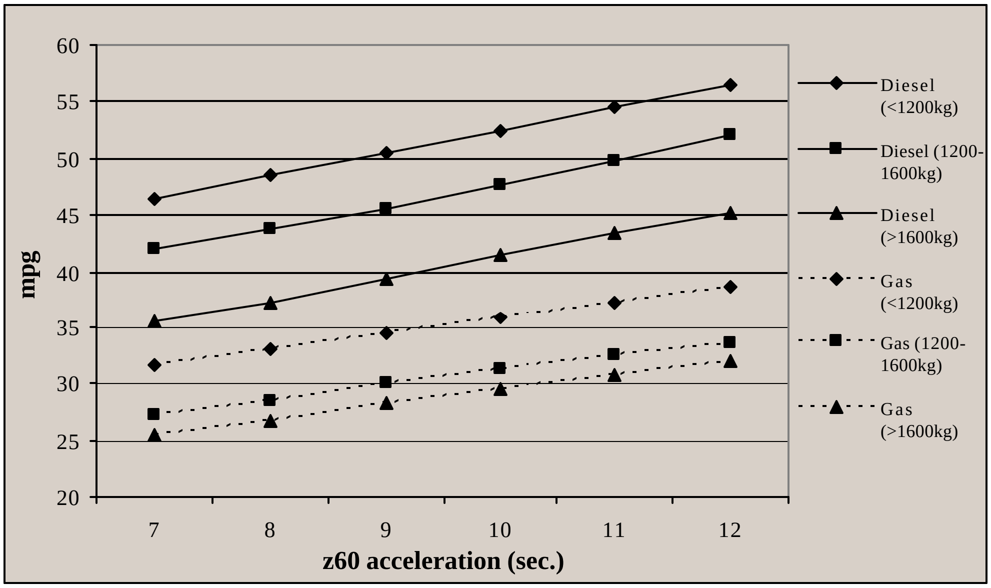
The modern diesel engines (Reference 2, 3) used in light-duty vehicles today are turbo-charged, direct injected engines that operate at high RPM and have a high specific power approaching 50 kW/liter. These engines have 4-valves per cylinder and utilize common rail, high pressure (1350-1600 bar) injectors 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 torque advantage of the diesel engines relative to gasoline engines is shown in Tables 1 and 2. Note from Table 2 that the maximum torque of the diesel engine occurs at much lower RPM than for a gasoline engine and that 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. As shown in Table 1, 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. Hence the claim made that diesel engine-powered vehicle feel to have better performance than gasoline engine-powered vehicles is substantiated by the engine characteristics cited in Tables 1 and 2.

Table 1Power-to-weight (Hp/lb veh) required for specified 0-60 mph acceleration times with gasoline and diesel engines

Acceleration 0-60 mph seconds	Gasoline engine-powered.	Diesel Engine-powered	Ratio of diesel/gasoline Hp/lb veh
7	.059	.069	.855
8	.050	.059	.847
9	.044	.052	.846
10	.041	.046	.891
11	.037	.042	.88
12	.035	.038	.92

Table Notes: Vehicle and engine data sources: References 4-6, 15, 35

Figure 1 Fuel Economy - Acceleration Correlations for Gasoline and Diesel Engine Vehicles



It is well accepted that diesel engine-powered vehicles have significantly higher fuel economy and consequently lower CO2 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 (4-6) are shown in Figure 1 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. As indicated in Figure 1, the trends in the fuel economy data are clear even though there is considerable scatter in the data. The correlation lines from Figure 1 were used to develop the data summaries shown in Table 3. Note that as expected the fuel economies within a weight class decrease as the 0-60 mph acceleration time decreases.

The fuel economy advantage of the diesel engine is shown in Table 3 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. The fuel properties and correction factors used to relate the gasoline and diesel fuel economy values are summarized in Table 4. 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 Characteristics of modern gasoline and diesel engines

Gasoline Engines

Vehicle Model	Engine type	Engine Displac. liters	Hp/ RPM	Ft-lb /RPM	Ft-lb /liter	RPMtorq/ RPMhp	Torq/ hp
Honda Accord	L4	2.4	160/5500	161/4500	67	.82	1.0
	V6	3.0	240/6250	212/5000	71	.80	.88
Honda Insight	L3	1.0	73/5700	91/2000	91	.35	1.25
Honda Odyssey	V6	3.5	240/5500	242/4500	69	.82	1.0
Toyota Camry	L4	2.4	157/5600	162/4000	68	.71	1.03
	V6	3.0	192/5300	209/4400	70	.83	1.09
Toyota Corrolla	L4	1.8	130/6000	125/4200	69	.70	.96
Toyota Highlander	V6	3.0	220/5800	222/4400	74	.76	1.0
Ford Taurus	V6	3.0	200/5800	200/4400	67	.78	1.0
Ford Explorer	V6	4.0	210/5100	254/3700	64	.73	1.2
Ford Focus	L4	2.0	130/5300	135/4500	68	.85	1.04
Diesel Engines TDC							
Audi A3	L4	1.9	90/3750	144/2200	76	.59	1.6
Audi A4	V6	2.5	180/4000	273/1500	109	.375	1.52
	L4	1.9	115/4000	210/1900	110	.475	1.83
Mercedes C220	L4	2.15	136/4000	206/1750	108	.9	1.62
Mercedes E320	V6	3.2	195/4400	350/1600	109	.36	1.8
Mercedes A170	L4	1.7	89/4200	133/1600	78	.38	1.49
VW Golf	L4	1.9	130/4000	228/1900	120	.475	1.75

Sources of the engine data: References 4, 35

Table 3 Summary of the fuel economy of gasoline and diesel engine-powered passenger cars as a function of 0-60 mph acceleration time

Acceleration 0-60 mph seconds	***Small (<1200 kg)***			***Midsize (1200-1600 kg)***			***Large (>1600kg)***		
	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

Table Notes: 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

Table 4 Physical and Chemical Properties of Gasoline and Diesel Fuel

Property	***Gasoline***	***Diesel fuel***
Density gm/cm^3	.75	.86
Lower HV (MJ/kg)	44	43.2
Lower HV (MJ/liter)	33	37.15
Composition for calculating CO2	C_8H_{18}	$C_{13}H_{24}$
MW	114	180
GmCO2/mi	8820/mpg	10400/mpg

Next consider the exhaust emissions from diesel and gasoline fueled vehicles presently being marketed. The VW Jetta is the only passenger car marketed in the United States with both a gasoline and diesel engine. US EPA test data (Reference 7) for the VW Jetta with both engines are shown in Table 5. Note that NOx emissions of the diesel engine vehicles are 10-20 times higher than those of the gasoline engine vehicles and that the particulate emissions are also significant.

The higher emissions of diesel engine-powered vehicles become a more serious problem when one considers the implementation in the relatively near future (2007) of the stringent ULEV and SULEV standards in California and the Tier 2 Federal standards. The emission standards in Europe, the United States, and California are compared in Table 6. The driving cycle for the United States and California emissions tests is the FUDS (Federal Urban Driving Schedule) and the driving cycle for the tests in Europe is the ECE-EUDC schedule. This new European cycle is comparable to the FUDS cycle in that fuel economy values obtained for the same vehicle on the two cycles differ by a small percentage (less than 10%).

Table 5 Emissions and Fuel Economy for the VW Jetta (Diesel & Gasoline) - EPA 2002 Test Data

Criteria	Diesel – 90 HP		Gasoline – 115 HP	
	L4	M5	L4	M5
Emissions (FUDS Cycle)				
HC (gm/mi)	0.026	0.035	0.017	0.022
CO (gm/mi)	0.07	0.23	0.31	0.58
NOx (gm/mi)	0.60	0.53	0.03	0.06
Particulates (gm/mi)	0.049	0.057	-	-
Fuel Economy				
FUDS (mpg)	38.1	46.8	25.1	26.1
Highway (mpg)	57.2	63.2	37.5	37.4

Note that the Euro 3 emissions standards are more stringent for all pollutants than the Tier 1 standards for diesel light-duty vehicles in the United States. Comparisons of the standards in the United States and Europe become quite different when one considers California and future years for the Federal Tier 2 standards. The large differences in the standards occur for NOx and to a lesser extent particulates. The NOx standards are .07 and .02 gm/mi for Tier 2 and SULEV, respectively while the Euro 4 standard for NOx is .4 gm/mi and is only .13 gm/mi for the proposed Euro 5 standard. These differences in the NOx standards will result in a large challenge for companies developing diesel-powered light-duty vehicles desiring to enter the US/California market.

Table 6 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

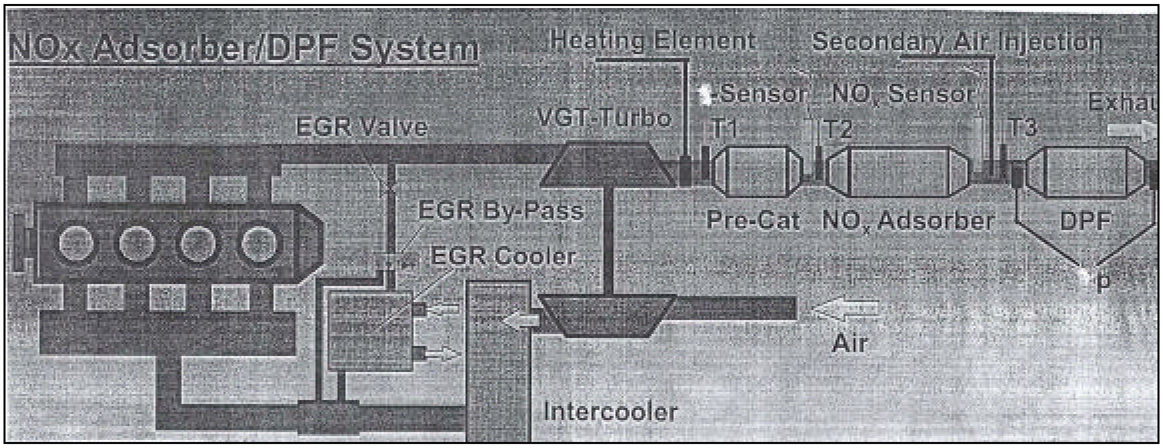
Source: compiled from References (8-9)

In both the United States and Europe, the future standards are being set independent of engine type and light-duty vehicle class. This compounds the difficulty of marketing diesel engines in the larger light-duty vehicle classes. The particulate standards in the United States will be more stringent than in Europe unless the Euro 5 standards (.004 gm/mi compared to .01 gm/mi) are adopted. Meeting the particulate standards with diesel engines appears to be less difficult than meeting the most stringent NOx standards in the United States.

The development of technology for ultra-clean light-duty diesel vehicles is in the early stages. Much of this development and the demonstration of the new technologies is being performed in Europe as they investigate the feasibility of meeting the Euro 4 and Euro 5 emission standards in diesel-powered vehicles. The new technologies being developed (References 3, 10-12) include further improvements in the common rail fuel injection systems, NOx emission aftertreatment using a NOx adsorption catalyst, and particulate filters. A schematic of a typical system is shown in Figure 2. The system is quite complex and requires precise control of engine operation to regenerate the NOx adsorption catalyst and the particulate filter. There is a fuel economy penalty of about 5% using this approach because the engine must operate slightly rich during the periods of regeneration. Both to achieve high conversion efficiency and long life in the aftertreatment devices, low sulfur diesel fuel of 10-15ppm is needed. Hence Europe and the United States will require low sulfur diesel fuel by 2007. Whether these systems or modification of them can be developed to meet the ultra-clean emission standards (Euro 5, ULEV, or SULEV) for light-duty vehicles remains to be seen. The development of a practical particulate filter system for light-duty vehicles seems to have high priority in Europe (Reference 9, 12) with strong consideration being given to retrofitting diesel powered cars already in use. Hence it is likely that diesel engine vehicles meeting the .01 gm/mi particulate standard will be available before those meeting a low NOx standard (< .05 gm/mi).

Another fuel issue for diesel-powered vehicles is the Cetane number of the diesel fuel available for sale. The modern high speed, clean diesel engines are designed for a diesel fuel having a Cetane number of 50-55. Diesel fuel quality in Europe has been set based on the requirements of the modern, clean diesel engine and its continuing development. In the United States, the average Cetane number is about 45. California has been setting diesel fuel quality standards since 1999 that are considerable more demanding than those in most areas of the United States (Reference 13). The California diesel fuel standards are shown in Table 7. Note that at the present time the Cetane number of diesel fuel in California is 50 and starting in 2006, it will be 53 well within the range required by the modern diesel engines for light duty vehicles. Hence in 2006, diesel fuel in California (and other states that follow California emission regulations) will be both low (< 15ppm) in Sulfur and high in Cetane number. Even though the oil companies will supply high quality diesel fuel to California, they are reluctant to make the investments in the refinery processes and equipment needed to produce diesel fuel with a Cetane number of 50-55 for the entire United States without the near certainty of a large market for light duty diesel vehicles.

Figure 2 Schematic of the Emission After-treatment System for a SULEV Turbo-Diesel Engine



Source: Tomazik, Reference 3

Table 7 California regulations for diesel fuel

Specification	**Pre-1993**	**1999**	**2006**[*]
Aromatics, Vol. %	**35**	**19**	**<10**
Sulfur, ppmW	**440**	**140**[**]	**<15**
Cetane NO.	**43**	**50**	**53**

Table Notes: ***** regulations approved July 2003 ****** there is currently significant (about 20%) low sulfur (15 ppm) diesel fuel available in California

2.2 Marketing Prospects for Diesel-powered vehicles

The prospects for marketing large numbers of diesel-powered light-duty vehicles in the United States and California are dependent primarily on the ability of the vehicles to meet applicable emission standards, especially the NOx standards, and the availability of low sulfur diesel fuel. Light-duty vehicles of all size classes are currently being marketed in Europe (Reference 1,4, 9) by many auto companies. It can be expected that the vehicle offerings will continue to increase in numbers, diversity, and quality as the European market for diesel-powered vehicles grows. There seems little doubt that public policy in the European Union will continue to encourage the sale of diesel engine vehicles. It is also significant that the European countries are continuing to make their emission standards more stringent especially if the proposed Euro 5 standard is adopted. It is also likely that low sulfur diesel fuel will be available in Europe before it is widely available in the United States. All of this activity in Europe would seem to increase the likelihood that diesel-powered light-duty vehicles would be mass marketed in the United States sometime in the future.

The rapid improvements in recent years in diesel engine technology for light-duty vehicles have resulted in vehicles that have attributes very similar to those of gasoline-fueled vehicles using spark-ignition (SI) engines. These attributes include performance, quietness, and driveability. The power ratings of diesel engines available for light-duty vehicles are now comparable to SI engines (see Table 1). As shown in the previous section, turbo-charged, direct injection diesel engines (TDI) now have higher specific power and better low-end torque than gasoline SI engines. These advances in diesel engine technology and the utilization of complex emissions aftertreatment systems will result in a greater cost differential than previously between gasoline SI and TDI diesel engines. This engine cost difference will make the price of diesel-powered vehicles significantly higher than comparable gasoline-fueled vehicles. In 2003 (Reference 14), the sticker price difference between the SI gasoline powered VW Jetta and Golf passenger cars and the same vehicles with turbo-charged diesel engines was $1700. This price difference will likely affect the marketing of the diesel engine vehicles where fuel prices are much lower than in Europe.

Auto companies in the United States are now expressing considerable interest in marketing diesel-powered vehicles especially in the SUV and light truck vehicle classes. It can be expected they will proceed with the development of those vehicles as soon as it becomes clear that the vehicles can meet the applicable emission standards and low sulfur diesel fuel will be available.

3. Current Status (2003) - Hybrid-electric vehicles

3.1 Review of the technology

Hybrid-electric powertrain technology is the second 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 5, 6, 15) 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 16). A recent in-depth review of hybrid-electric vehicle technology is given in Reference (17).

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 18-20). 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 21) 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 19). Three generations of the Prius have been marketed by Toyota starting in 1998 in Japan. The third generation of the Prius (Reference 20) became available in the United States in September 2003. As indicated in Table 8, 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 22) 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 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 8.

Table 8 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

Sources: compiled from References (7 and 24).

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 23, 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 (Reference 23, 24).

3.2 Marketing Prospects for Hybrid-Electric Vehicles

In assessing the market prospects for hybrid-electric vehicles, the requirements of the revised ZEV Mandate (Reference 25) are of critical importance. Those new requirements, which allow the use of ZEV credits generated using AT PZEVs in the gold and silver categories, seem to assure the marketing of large numbers of hybrid-electric vehicles in California starting in 2005 if not before. As shown in Table 9, which was developed by ARB staff (Reference 25, page 25), the annual sales of AT PZEVs in California are projected to increase to over 100,000 by 2010 and over 300,000 by 2015. These are potential mass markets and should result in the pricing of hybrid-electric models close to that of comparable PZEV models. Based on the fuel economy gains achieved by Toyota and Honda in the Prius and Civic, it can be expected that the fuel economy of the ATPZEV vehicles will be 30-50% higher than that of conventional ICE vehicles of the same time period. The mass marketing of hybrids in California should result in mass marketing of hybrids throughout the United States and the world.

Table 9 ARB Projections of AT PZEV Sales for 2005-2020

Model Year	2001 Regulation		2003 January Staff Proposal		2003 Revised Staff Proposal	
	ZEV	AT PZEV	ZEV	AT PZEV	ZEV	AT PZEV
2005	0	13350	0	17244	250 total over this period	22418
2006	0	19848	0	25636		33327
2007	0	27905	0	43253		56229
2008	4333	47110	0	64069		83290
2009	8988	64768	2303	88084	0	117445
2010	11108	70648	4804	96082	0	128109
2011	12032	76529	5204	104079	0	138772
2012	18269	98061	17782	96991	0	193983
2013	18269	98061	17782	96991	0	193983
2014	18269	98061	17782	96991	0	193983
2015	24359	130748	23709	129322	0	316120
2016	24359	130748	23709	118545	0	316120
2017	24359	130748	23709	118545	0	316120
2018	30448	163435	29636	148181	0	395150
2019	30448	163435	29636	148181	0	395150
2020	30448	163435	29636	148181	0	395150

Source: Reference 25

In order to meet the ZEV Mandate requirements in 2005-2008, all the large auto companies will likely start marketing hybrids that meet the ATPZEV criteria in the next several years. There have been many announcements and rumors regarding additional hybrid vehicles to be marketed by a number of auto companies, but to date (2003) only Toyota and Honda have hybrid models available for sale. It can be expected that the next hybrid vehicles for sale will be SUVs and light trucks and that is likely to happen within 2-3 years. The technologies used in those vehicles are likely to be similar to that used by Honda and Toyota in the Civic and Prius, but with higher power components in the larger vehicles.

The sale of hybrids in the United States started in 2000 with the introduction of the Honda Insight and the Toyota Prius. The introduction of the Honda hybrid Civic occurred in 2001. Sales of hybrids in North America and world-wide through 2002 are summarized in Table 10. Most of these sales have been in Japan and the United States. Sales have increased each year with a total of 59, 300 hybrids being sold world-wide in 2002. Both Toyota and Honda have limited the production of their hybrids as they probed the market to determine how the higher price of the hybrids would be accepted. The price differences between a standard ICE gasoline and the hybrid models are the following: comparing the 2003 Prius with a comparably equipped Echo or Corolla, one finds a price differential of $4815-$5250 and in the case of the 2003 hybrid Civic a price differential of $3765 compared to a similarly equipped standard Civic. It would be expected that these price differences would decrease as the production volume of the hybrids increases. As indicated in Table 10, this will occur starting in 2005-6 with the implementation of the ZEV Mandates for ATPZEVs in California and other states with the same emission regulations as California. It is of interest to note that the price of the 2004 Prius is the same as that of the 2003 Prius even though the car was restyled and its performance significantly improved by increasing the driveline component powers. The 2004 Prius is comparable to a Camry in interior space. The sticker price of a 4-door, V6 Camry was $22260 in 2003 indicating that the price differential for the 2004 Prius has largely disappeared.

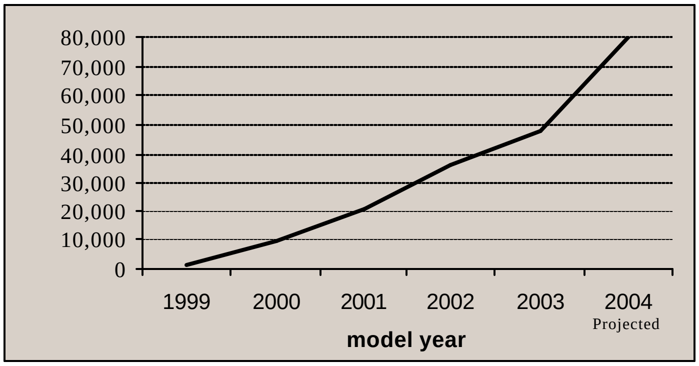
Table 10 Hybrid Vehicle Sales to Date - North America & Worldwide

Year	North America	Global	Cumulative Total
1997	0	300	300
1998	0	17,700	18,000
1999	0	15,500	33,500
2000	9,600	24,200	57,700
2001	20,700	42,100	99,800
2002	35,900	59,300	159,100
2003 (Through August)	27,118 (U.S. only)	Not available	-

Source: Data from Honda American Motor Co. and Toyota Motor Co.

Table 10 and Figure 3 show that hybrid vehicle sales have been steadily increasing. Toyota had over 10,000 orders for the 2004 Toyota Prius in the United States before the first vehicle was delivered. Toyota predicts a sales volume of 36,000 for the first year of the new Prius in the U.S. vehicle market. Already over 11,000 of the 2004 Prius hybrids have been sold in Japan, which is four times the target mark set by Toyota (Reference 26). Toyota has been actively marketing and advertising the Prius and seems to be meeting their sales volume targets.

Figure 3 Sales of Hybrid Electric Vehicles in the U.S. to date



Source: *Automotive News*, Auto Data Center.

Table 11JD Power Projections of Hybrid Vehicle1 Characteristics (1999-2009)

		Passenger Cars			Light Trucks		
		Compact	**Midsize**	**Luxury**	**Pickup**	**SUV**	**Minivan**
	Average Year of Introduction[2]	2001.7	2005.5	2006.7	2003.9	2005.3	2006.0
Fuel Economy	Hybrid City	50.3	33.0	29.0	18.7	30.9	28.5
	Hybrid Highway	50.7	31.8	25.5	22.9	25.8	29.0
	Hybrid Combined	50.3	32.4	27.3	20.1	28.0	28.3
	Conventional City	34.5	23.0	18.5	15.1	18.6	18.0
	Conventional Highway	41.7	31.0	25.0	19.8	23.2	24.5
	Conventional Combined	37.4	26.0	21.0	16.9	20.4	20.4
Price	Hybrid Price	$20,084	$22,953	$54,363	$30,729	$29,494	$33,735
	Conventional Price	$15,911	$19,969	$50,863	$29,174	$26,938	$29,735
	Retail Price of Hybridization	**$3,500**	**$2,778**	**$3,500**	**$1,556**	**$2,778**	**$4,000**
	Fuel Economy Improvement	**25.1%**	**17.5%**	**22.9%**	**15.5%**	**25.9%**	**27.4%**
	Projected Number of Models	4	9	3	5	13	4
	Improvement Factor[3]	**13.9**	**15.9**	**15.3**	**10.0**	**10.7**	**14.6**

Source: J.D. Power & Associates; Notes – (1) Hybrids under consideration include those using ISGs (Integrated Starter-Generators) particularly with pickup trucks; (2) The mean of those introductory years for those particular models; (3) The improvement factor is intended to be an illustrative number – it equals the retail price of hybridization divided by 1000xpercentage fuel economy improvement (Hence the lower then number, the more cost effective the hybridization).

Table 12 is a summary of the previous and expected launch dates for hybrid vehicles by various auto manufacturers. Based on the new launches expected in the next few years, it is expected that hybrid vehicle sales will continue to increase rapidly as more models become available. A summary of the characteristics of the new hybrid vehicles is summarized in Table 11.

Table 12 Previous and Expected Launch Dates of Hybrid Vehicles

Make and model	Release date
Honda Insight hatchback	December 1999
Toyota Prius sedan	June 2000
Honda Civic hybrid sedan	April 2002
Ford Escape SUV	December 2003
GMC Sierra pickup	2004
Chevy Silverado pickup	2004
Lexus RX 330 SUV	2005
Saturn VUE SUV	2005
Chevrolet Equinox SUV	2006
Chevrolet Malibu sedan	2007
Honda Accord sedan	2004
Toyota Camry sedan	2004
Honda Pilot SUV	2004

Source: J.D. Power & Associates

4. Summary and Conclusions

This report is concerned with the present status of emerging technologies that can be utilized in light-duty vehicles in the next five to ten years to significantly reduce the CO2 emissions. The emerging technologies considered are modern clean diesel engines and hybrid-electric powertrains using batteries. The status of each of these technologies is assessed based on available information and data from the literature. In addition, the present marketing situation for each technology is summarized and prospects for marketing the technologies in California are assessed.

In the case of the modern diesel engines, it was found that such engines have much higher toque characteristics than gasoline engines of the same displacement and vehicles powered by diesel engines have higher fuel economy (mpg) by 40-50% than similar (same size and performance) vehicles powered with gasoline engines. This is the reason that diesel-powered vehicles have presently reached almost a 50% market share in Europe. The major problem with the diesel engine for use in California is that “clean” diesel powered vehicles have NOx emissions that are 10X higher than Tier 1 vehicles with gasoline engines and to meet the SULEV NOx standard, a reduction of at least an additional factor of three is required. Whether this will be possible with diesel engines is uncertain.

Hybrid-electric passenger cars are currently being marketed in Japan and the United States by Toyota and Honda. These hybrids show large improvements (at least 30-50%) in fuel economy compared to conventional ICE vehicles of the same size and performance. All the hybrids meet SULEV standards and have been designated AT-PZEVs by CARB. The hybrids have been well received in the market with annual global sales approaching 100,000 in 2004. There seems to be no reason that hybrid sales will not continue to increase between 2005-2010 especially as the ZEV Mandate requirements become more demanding in 2008 and beyond.

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