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ANALYSIS AND FORECAST OF THE PERFORMANCE AND COST OF CONVENTIONAL AND ELECTRIC-HYBRID VEHICLES

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Prepared By:
Energy and Environmental Analysis, Inc.
1655 North Fort Myer Drive, Suite 600
Arlington, VA 22209
Contract No. 500-00-002 (WA 8)

Prepared For:
Sherry Stoner
Contract Manager

Leigh Stamets
Project Manager

Susan Brown
Manager
Transportation Technology Office

Nancy Deller
Deputy Director
Transportation Energy Division

Steve Larson,
Executive Director

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Final Report

Prepared for:
CALIFORNIA ENERGY COMMISSION
Sacramento, California

Prepared by:
ENERGY AND ENVIRONMENTAL ANALYSIS, INC.
1655 North Fort Myer Drive
Suite 600
Arlington, VA 22209

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1. INTRODUCTION

The CEC is investigating policies and measures to reduce fuel consumption and greenhouse gas emissions from light-duty vehicles. This report provides a preliminary analysis of the costs and benefits of advanced fuel-efficient technologies including the electric hybrid drivetrain. Electric-hybrid vehicles have been recently introduced into the marketplace by two Japanese manufacturers, Toyota and Honda, but it is widely known that most manufacturers plan to introduce electric-hybrid vehicles into the marketplace by 2006. However, considerable potential also exists to improve the fuel economy of vehicles by improving conventional engine technology.

The term “hybrid” is not specific to any particular design and embraces all designs that feature both an internal combustion engine and an electric motor for motive power. If conventional vehicles and pure electric vehicles are two ends of the spectrum, hybrid vehicles can employ any combination of engine size and motor size between these two ends, with each combination representing different tradeoffs in cost, efficiency and performance. Three different design types have emerged in the marketplace and each offers a different level of cost and fuel efficiency. These designs and their cost-benefit are examined in this report.

Since hybrid vehicles are a new technology, current costs may not be indicative of future costs. In the future, costs will decline due to efficiencies of scale (production volume) and due to learning (improved design). The efficiencies of scale are modeled relatively easily, but efficiencies of learning are far more difficult to estimate. We have estimated possible design improvements mostly from expert opinion, and such forecasts extend to about 2010. The pace and extent of learning improvements beyond 2010 can only be estimated by historical comparisons with other technology developments.

In considering future hybrid vehicles, it appears most likely that the hybrid drivetrain will be incorporated into a conventional vehicle body modified for adapting to the drivetrain and fuel system's space requirements. Predicting future hybrid vehicle characteristics also requires an understanding of how future vehicle body characteristics will change for conventional vehicles. In addition, efficiency comparisons against future vehicles will require an estimate of how conventional vehicle drivetrains will be improved. EEA has published several analyses[1] of conventional vehicle improvements, and these analyses are briefly summarized with the results for a mid-size car and SUV shown in this report.

There is a very large selection of technical papers focusing on hybrid vehicles, and most of these are associated with the PNGV program.[2] Many of the analyses are in support of the 80 MPG goal set by PNGV and not directly relevant to the forecast of more practical products for the market. In addition, papers dating before 1998 did not have the advantage of examining the performance and operation of the Toyota Prius introduced in Japan in early 1999. A significant number of papers on the simulation of, and optimal control for hybrid vehicles have been generated by NREL[3], while socio-economic analyses of hybrids have been published by Argonne National Laboratory.[4] However, detailed vehicle performance data have only been released by Toyota and Honda that have production hybrid cars, and Nissan and Mitsubishi, that have displayed prototype vehicles. Even less information on costs are available; most of the cost data published by PNGV are 'targets' not based on real data. Indeed, the only independent publicly available data on hybrid vehicles' cost and retail price over time are from earlierEEA reports, where information was compiled from confidential data submitted by manufacturers and parts suppliers. Some of these data were discussed at a hybrid and electric vehicles workshop held at U-C Davis in December 1999. These manufacturer-supplied data continue to be the basis for our review of hybrid vehicle costs. It should be noted that EEA lists the 'retail price equivalent' or RPE impact of technology, which represents the average cost to the consumer in a competitive market.

More recently, the '42-volt' system for low electric power hybrids (or mild hybrids) has received considerable press attention. However, little information on vehicle performance and cost is available in technical papers. Rather, we have relied on press releases by manufacturers and suppliers, as well as direct meetings with their technical staff, to arrive at estimates of mild hybrid vehicle characteristics. These characteristics and system costs have been investigated in more detail in this work effort for the CEC.

Section 2 summarizes our analytical technique for estimating fuel economy benefits, while Section 3 provides an overview of conventional vehicle developments. Section 4 provides our analysis of future hybrid vehicles. Section 5 examines the barriers to commercialization from the context of the three different stakeholders: the consumer, the auto industry and the government. Section 6 provides a brief overview of our vehicle attribute forecasting methodology for the CEC, and summarizes the forecasts developed under six scenarios specified by CEC. Forecast details were provided in electronic format to the CEC separately.

2. VEHICLE ATTRIBUTE FORECASTING METHODOLOGY

In forecasting future vehicle fuel economy and cost, we have attempted to keep a number of attributes constant. The attributes include:

- interior passenger room;
- cargo room, to the maximum extent possible;
- acceleration performance;
- noise, vibration and harshness (NVH).

This does not imply that future vehicles will have constant attributes. Rather, comparisons between technologies are made at constant attributes to examine the influence of technology alone.

An important issue is that manufacturers have the flexibility to vary the size, comfort, safety and performance features of any vehicle within fairly wide ranges. We have selected two baseline (2000) vehicles for the analyses, a midsize car and a compact SUV (as examples to illustrate the effects of technology development). Even with this size specification, however, manufacturers have the option of varying body rigidity, interior volume (within limits), safety and luxury options, and acceleration performance. In the last decade, all of these have increased significantly for almost every market class of car and light truck. However, the forecasts have been derived for a constant interior room and constant acceleration performance scenario.

Electrically powered (fuel cell) and gasoline-electric hybrid vehicles do not have the same performance characteristics as conventional vehicles. For this report, we have set performance requirements for EVs and hybrids as follows: Continuous power demand (i.e., power output that must be sustained indefinitely) is set to a level that allows a vehicle to climb a six percent grade at 60 mph with a modest payload, which equates to 30 kW per ton. Of course, it is recognized that such a long grade is encountered rarely, but this requirement is to cover a number of other situations where the vehicle is fully loaded with five passengers and luggage, such as 80 km/hr climb up a three or four percent grade. Peak power demand is based on a 0 to 100 km/hr acceleration time under 12 seconds, with a nominal load which equates to 50 kw/ton. This is typical of many family sedans that have a 120 kW (160 hp) engine for a weight of 1.75 tons. We have required that peak power be sustained for over 1 minute, to cover situations where two highway "merge" cycles are required back-to-back, or the need to climb a steep highway entrance ramp (for an elevated highway) and then have enough power to merge into 70 mph traffic. Hence, the 50 kw/ton and 30 kw/ton power requirements are to cover a wide variety of traffic conditions under full load, not just the example cases cited above, and most i.c. engine powered vehicles meet or easily exceed these performance levels.

The choice of these median vehicle attributes has some underlying logic in that it is an "accepted" market equilibrium today. However, it is debatable if these characteristics should be reproduced by non-conventional vehicle types, such as hybrid or fuel cell powered vehicles. In fact, this assumption poses significant difficulties for some non-conventional vehicle design, and reduction of vehicle attributes, especially acceleration performance, may make more sense economically.

Given the set of characteristics, EEA has utilized a fuel economy modeling approach known as the "lumped-parameter" approach, as developed by Sovran and Bohn.[5] The method, while theoretically inferior to a detailed simulation model, does not require the numerous input assumptions of the simulation model, and is easier to use in practice. The model provides closed-form evaluations of the integrated second-by-second values for the FTP test cycle.[*] The model's forecasts have been benchmarked against several advanced high fuel economy vehicles (both production and prototype) and the model output shows good agreement with measured fuel economy values.

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[*] FTP is the Federal Test Procedure which is the basis for all fuel economy values cited in this report.

3. CONVENTIONAL VEHICLES

The forecast for conventional vehicles starts from the known characteristics of a conventional midsize car and midsize SUV model for 2000. Curb weight, aerodynamic drag co-efficient, engine specifications, drivetrain and fuel economy on the FTP cycles are based on actual data for a selected representative model in the U.S. The following technological changes can be expected by 2010 and 2020, in the absence of any new regulations beyond what is already proposed. The technologies have been fully documented in several recent reports (1, 7).

Weight Reduction through material substitution will occur, but our forecast is only for modest reduction from the current 1430 kg to 1350 kg, about five percent to 2010 and another five percent to 2020. The likely sources of weight reduction are:

- increased use of RIM (plastic) or SMC in body closures such as the fenders/hood;
- increased use of aluminum forgings in suspension and load carrying members;
- use of lightweight seats;
- use of all aluminum engines (already used in many vehicles), and aluminum castings for casings.

Some part of the weight reduction will be lost to weight increases associated with new safety and emission standards. We estimate that new safety and emission standards will add 62 kg to the weight of a midsize vehicle, and 65 kg to the weight of a midsize SUV. Many current midsize SUVs use body-on-frame construction, and additional weight reduction is possible with a unibody design.

Drag Reduction is a very cost-effective technology, with very low variable cost. Currently, the average drag co-efficient for cars is 0.31, and we can expect it to decline to 0.28 by 2010. By 2020, we expect the average drag co-efficient to decline to 0.25 for passenger cars. For SUVs, drag co-efficients will decline from current levels of 0.44 to 0.40 in 2010 and 0.36 in 2020.

Reduced Rolling Resistance is likely through the use of silica compounds in tires. Rolling resistance co-efficient will decline by at least ten percent to 2010 and by another ten percent to 2020. The new hybrid Prius and Honda Insight already use tires with 20 percent lower rolling resistance relative to tires used in conventional cars, and several tire manufacturers have confirmed that a 20 percent reduction in rolling resistance is possible with no loss in handling or traction.

Most conventional engines have already converted to four-valve overhead cam designs. Complete valve control is the obvious next step: most luxury cars (Mercedes, BMW, Lexus) already feature variable valve timing (VVT). Variable valve lift and timing (VVLT) has been introduced by Honda which features a two-position control; other designs with fully variable control of valve lift are also nearing production. By 2010, most vehicles are likely to feature either VVT or VVLT.

The incorporation of variable valve lift and timing (VVLT) also makes possible cylinder deactivation by disabling the valves completely. A more simple system for cylinder deactivation that does not require VVLT has also been designed, and will likely be used with OHV engine designs. At present, manufacturers believe that only V-8 engines have adequate balance to selectively disable two- or four-cylinders at light load. However, such deactivation systems have also been utilized in V-6 and even four-cylinder engines (with modest NVH impact) in Japan.

For the drivetrain, the five-speed automatic transmission and the continuously variable transmission (CVT) are being introduced in the U.S. market. The low cost CVT designs are torque limited and likely to be used with engines under 2.5L displacement, but promise significant fuel economy benefits for small engines. In addition, refinements to the torque converter are resulting in lower hydraulic and spin loss. Some torque converters in production already feature partial lock-up at low speed for modest improvements in fuel economy.

The gasoline direct-injection (GDI) engine is also a strong contender for future drivetrains. It is a lean burn engine at light loads, but can revert to normal stoichiometric operation at high loads.

Such engines are already available in Europe and Japan, but have not been introduced in the U.S. due to fuel and emissions constraints. GDI engines need special types of exhaust aftertreatment to meet emission standards, and the exhaust aftertreatment is sensitive to fuel sulfur. Recent moves by the U.S. to cap fuel sulfur content at 50 ppm by 2004 have paved the way for GDI introduction as well. However, there is a legitimate concern that the trade-offs required to meet the LEV2 standards may reduce the fuel economy benefit to a level only marginally better than an advanced stoichiometric burn engine.[6]

The direct injection (DI) turbocharged diesel has gained popularity only in Europe where more than a third of all new cars sold are powered by such engines. In North America, very few diesels are sold in light-duty vehicles. Concern about their ability to meet future emission standards has receded in Europe, with the new generation of highly turbocharged diesels featuring high-pressure “common rail” fuel injection systems showing excellent performance and low emissions. While the state-of-the-art of diesel emission control technology suggests that Euro V emission standards can be met, it is much less certain that the California LEV2 standards can be met. In addition, it appears that emission control can add significantly to the cost of diesels and can increase future RPE differentials between diesel and gasoline engines by $500 to $800. However, a completely new type of combustion called ‘Homogenous Charge Compression Ignition’ is under development for diesel engines, and it shows the promise of a dramatic reduction in emissions. It could be commercialized in the 2010-2015 time frame in California.

The CEC Fuel Economy Forecasting Model was updated with some additional information on conventional technologies that was obtained from the recent study by EEA[7] under contract to the National Academy of Sciences’ Committee on the Effectiveness and Impact of CAFE. As part of the NAS effort, EEA met with the technical staff of many major auto-manufacturers. While these meetings confirmed EEA’s earlier projections for many technologies, it also allowed us to update information on cost and performance of several technologies. In particular, there have been significant cost reductions from some technologies, notably variable valve timing, cylinder deactivation and electric power steering. A brief summary of the key findings of our effort for the NAS is provided in Table 1. These findings have been incorporated into the CEC model for our baseline and scenario forecasts.

EEA analyzed the effect of including all technologies in a hypothetical 2010 midsize car (about the size of a 2000 Honda Accord/Ford Taurus) and a midsize SUV about the size of a Ford Explorer, that keeps the size and performance of the 2000 baseline vehicle constant. The current base price of a V-6 engine powered car is about $22,000 in the U.S., and it has a base fuel economy of 26.5 MPG on the EPA 55/45 cycle. For the SUV, the current base price is about $28,000 and its fuel economy is 20.2 MPG.

The 2020 midsize car will be about five percent lighter under a "business as usual" (BAU) case, with lower drag and rolling resistance <u>after</u> accounting for a 135 lb weight gain due to new safety standards. It can use a 2.5L V-6 with VVLT (which provides higher specific power) and a more advanced five-speed automatic transmission. Alternatively, a high output four-cylinder engine can be substituted for the 2.5L V-6 with some loss of smoothness, and a CVT can be substituted for the automatic transmission. Other alternatives included a four-cylinder GDI engine with an even higher specific output, or an advanced V-6 diesel engine with specific output similar to the base (2000) gasoline engine. These alternatives are more likely to be in widespread use by 2020. The SUV has the same set of options but its weight can also be reduced by adopting a unibody design rather than the current body-on-frame design. Note that the BAU analysis presented here <u>pertains to a specific vehicle and performance level</u>. The mix of cars, light trucks, and engines sold is a separate (non-technological) issue but the mix shifts to 2020 can easily negate the 4.5 MPG technological gain to 2010, and the 7.6 MPG gain to 2020.

Tables 2 and 3 show the evolution of a hypothetical midsize car and SUV over time to 2020 under a scenario of modest fuel prices ($1.50/gallon 2000 real) that are flat over time in inflation adjusted terms. By 2010, we anticipate that a same-size vehicle will have fuel economy about 20 percent better than the equivalent 2000 model (a little higher for SUV, a little lower for the midsize car). By 2020, we anticipate that fuel economy can increase by 30 percent, at constant attributes. However, some of this gain will be lost to changing attributes or class mix for the

TABLE 1
SUMMARY OF KEY FINDINGS FROM NAS STUDY

Technology	Findings	
Composite Body Closures	-	About 5 percent weight savings possible at a cost less than $0.50/lb. saved.
Aluminum Body	-	Secondary weight reduction leads to cost savings.
Ultra-High Strength Steel Body	-	Early results suggest that weight savings of aluminum can be approached at lower cost.
Electric Power Steering	-	Costs had been overestimated in earlier studies.
Variable Valve Timing	-	Ability to eliminate external EGR results in significant cost reduction.
Cylinder Deactivation	-	Low cost increment over a VVTL system.
Advanced Torque Converter	-	Modest improvements in efficiency possible through redesign/early lockup.
Continuously Variable Transmission	-	Current costs are high due to limited belt supplier sourcing.
Electrically Shifted Manual Transmission	-	Potential to provide CVT benefits at no cost, but opinions on consumer acceptability vary.
42-Volt Hybrid	-	RPE of around $1000 possible for mild hybrid by 2015. Value of hedonic benefits are high.
On-Demand Electric 4WD	-	F/E benefit of 20 percent over conventional 4WD may be available

TABLE 2
HYPOTHETICAL MID-SIZE CAR
CONSTANT ATTRIBUTE CASE

	2000 Base	**2010 BAU**	**2020 BAU**	**2020 BAU+ GDI**	**2020 BAU+ DI-Diesel**
Weight	3320	3295	3150	3100	3205
Body	Steel	High Strength Low Alloy Steel Intensive	Composites, Al Forgings	Composites, Al Forgings	Composites, Al Forgings
C_D	0.31	0.28	0.25	0.25	0.25
C_R	0.0095	0.0085	0.0075	0.0075	0.0075
Engine	3.0l V-6	2.7l V-6	2.5l V-6	2.4L I-4 GDI	2.7L V-6
Valves	4	4 w/VVLT	4 w/VVLT	4 w/VVT	4
HP	200	200	190	170	190
Transmission	4-Auto	5-Auto	CVT	CVT	CVT
Power Steering	Hydraulic	Hydraulic	Hydraulic	Electric	Electric
F/E (MPG)	26.5	31.1	34.1	36.05	42.1
Hedonic Attributes	Base	No Change	No Change	Some Loss of NVH	Some Loss of NVH
Inc. RPE	Base	535	680	780	2280

Includes fuel economy penalty for safety equipment and Tier 2 emission (estimated at about four percent). Improvements common to all 2020 cases are engine friction reduction by 15 percent, low friction lubricants and accessory improvements (x/EPS)

TABLE 3
HYPOTHETICAL COMPACT 4WD SUV CONSTANT ATTRIBUTE CASE

	2000 BASE	**2010 BAU**	**2020 BAU**	**2020 BAU +GDI**	**2020 BAU +DI Diesel**
Weight	4150	3940	3740	3760	3820
Body	Steel Body-on –Frame	HSLA Intensive (Unibody)	Composites Al. Casting +Forgings	Composites Al. Casting +Forgings	Composites Al. Casting +Forgings
C_D	0.45	0.41	0.38	0.38	0.38
C_R	0.0105	0.0095	0.0085	0.0085	0.0085
Engine	4.0L V-6	3.5L V-6	3.0L V-6	3.0L V-6 GDI	3.3L V-6 DI
Valves	2	4 W/VVT	4 W/ VVLT	4 W/ VVT	4
HP	205	220	220	220	200
Transmission	4 – Auto	5-Auto	5-Auto	5-Auto	5-Auto
Motor	None	None	None	None	None
Power Steering	Hydraulic	Hydraulic	Hydraulic	Hydraulic	Hydraulic
F/E (MPG)	20.3	24.6	27.2	28.3	35.9
Hedonic Attributes	Base	No Change	Some Loss of Towing Capacity	Some Loss of Towing Capacity	Some Gain in Towing Capacity
Inc. RPE	Base	665	1015	1315	2665

Includes fuel economy penalty for safety equipment and Tier 2 emission (estimated at about three percent). Improvements common to all 2020 cases are engine friction reduction by 15 percent, low friction lubricants and accessory improvements (x/EPS).

fleet as a whole. The GDI and DI diesel engines could emerge as competitors by 2020, but only the DI diesel makes a sizeable impact on fuel economy for 2020. It is in terms of this baseline that the hybrid should be evaluated.

4. HYBRID VEHICLE TECHNOLOGY

4.1 OVERVIEW

Over the last two years, the market has evolved to represent a wide variety of hybrid vehicle types. In general, we apply the term 'hybrid' to imply that the vehicle obtains motive power from both an electric motor and an internal combustion engine. Current conventional vehicles can be visualized at one end of the spectrum of possibilities, with the pure electric vehicle at the other end. Obviously, a continuum of hybrid designs are possible, representing different combinations of i.c. engine and motor sizes, as well as different electrical energy storage capability.

A few years ago, the major division between hybrid design was visualized as "parallel" versus "series". In the parallel design, both engine and electric motor drive the wheels directly with either one or both used at different driving conditions. In the series hybrid design, only the electric motors drive the wheels with the engine driving an electrical generator. Analytically and in actual practice, the series hybrid has been shown to be too expensive and less efficient than a well designed parallel hybrid, so that the series design has been largely abandoned.

Among parallel designs, three broad types have emerged, and they can be classified according to the ratio of engine to motor power. As noted in Section 2 of this report, a vehicle with average performance requires an engine or motor capable of supplying 30 kW per ton of vehicle weight on a continuous basis and 50~55 kW per ton on a short term (less than one minute) basis. Designs where the engine is capable of supplying only the continuous power and the electrical motor supplying the difference between engine power and peak power are usually the most fuel-efficient designs. This is the type of design used by the Toyota Prius and Nissan Tino. However, a typical 1500 kg vehicle will require an electrical motor of at least 30 kW output, and attendant battery size requirements are large, so that total costs are high. Other recent designs have traded off reductions in efficiency for reductions in cost. The most popular variant of this is called the ‘42 volt’ system. The third type is embodied by the Honda Insight, which uses a 144 volt system. In contrast, the Toyota Prius and Nissan Tino hybrids use batteries of about 300 volts. Manufacturers have announced plans to introduce all three types of hybrids. As noted in Table 4, a wide variety of hybrid vehicles of all three design types will be introduced in the next three model years.

The relationship between motor power and battery voltage is due to maximum current limitations, which are typically in the range of 250 to 300 amps. Higher currents lead to high resistance loss, and also require specialized connectors and expensive power electronics. Hence, 42V systems are typically limited to about 12 kW power, and 150V systems to less than 40 kW power. (The power requirements are not only for the motor but all other systems as well.) Of course, voltage increases also increase costs, but the biggest step occurs at about 50 volts. Above this voltage, humans can be electrocuted by accidental contact with battery positive voltage, and so expensive battery isolation systems and current leak detection systems are required. (The battery cannot use the frame as ground and must be kept “floating”.) These systems add to cost and complexity.

4.2 COMPONENT COSTS

The major new components in hybrid vehicles are the electric power to shift power, and to store energy. The components can be grouped into:

- battery/battery control module;
- electric motors/generators;
- power control units and inverters;
- wiring harness for high power circuits.

The costs of each of these components groups have to be considered separately as they have different cost reduction potential with learning and production volume.

Batteries for energy storage are a major cost component for hybrids. These batteries are generally designed for maximum power, as opposed to maximum energy storage, per unit of

TABLE 4
RECENTLY ANNOUNCED HYBRID VEHICLE COMMERCIALIZATION PLANS

MANUFACTURER	MODEL YEAR	MODEL FOR HYBRID
Toyota	2001	Prius (300V)
	2003	Matrix MAV (300V)
Honda	2001	Insight (150V)
	2003	Civic sedan (150V)
Ford	2004	Escape (300V)
	2005+	Explorer (42V)
GM	2004	Saturn SUV (42V)
	2004	Chevy pickup (42V)
	2005	Chevy Suburban (42V)
Daimler Chrysler	2004	Dodge Durango SUV (300V)
	2005	Dodge Ram pickup (300V)
	2006	Mercedes S-class (42V)

weight. Recent research by EEA confirms the opinions of the ARB battery panel that only the Nickel Metal Hydride (Ni-MH) and advanced lead acid battery are "production ready" and available for use in the near term (to 2005, and possibly to 2010). In the post-2005 time frame Lithium-Ion batteries may become commercially ready, although its current operating life is only two or three years, while its cost is higher than the cost of equivalent Ni-MH batteries. Lithium Polymer batteries are still in an early stage of development, and unlikely to be commercially available before 2010.

Details on the cost of Ni-MH batteries and future cost reductions were provided by Panasonic EV Energy[8], which is the supplier of batteries for both hybrid vehicles currently in production (Toyota Prius and Honda Insight). In general, hybrid vehicle batteries have about 65 percent of the specific energy but almost four times the specific power of electric vehicle batteries. Panasonic stated that cost per unit weight of battery are similar for HEV and EV batteries. Current HEV batteries (second generation) are rated at 46 Wh/kg and 1000 W/kg at the module level, while EV batteries are rated 66 Wh/kg and 250 W/kg. These values must be discounted by 20 to 25 percent at the battery pack level to account for the weight of the box, connectors and wiring. In addition, a battery control unit and battery cooling system adds to total battery pack costs.

Since the Ni-MH battery is a new technology, there is the potential for significant cost reduction from learning. Panasonic has recently (2001) introduced the second-generation hybrid battery that features prismatic rather than cylindrical cells. Battery specific power has been improved by 25 percent relative to the first generation model, and costs have been reduced by 30 percent. Panasonic expects smaller additional cost reductions from learning in the future, and believe that each new design cycle (once every five years) will bring about a cost reduction about ten percent.

Lead-acid batteries are also a possibility for hybrid vehicles, especially where power requirements are not excessive, as in 42-volt systems. A new type of valve regulated lead-acid battery called the "glass fiber mat" type has shown significant improvement over conventional lead acid batteries in terms of life and specific power. At the module level, specific power capabilities of 400 W/kg and specific energy levels of 25 Wh/kg have been demonstrated. However, battery life is still only four to five years (optimistically) as opposed to a life of 10 to 12 years for a Ni-MH battery in hybrid application.

Lead-acid battery production technology is relatively mature although there can be significant design improvements, and large cost savings from learning and scale are not likely. Based on conversations with battery manufacturers, cost reduction of ten percent can occur in the 2003 – 2008 time frame with an additional 10 percent in the 2008 – 2012 time frame. Cost reductions from scale volumes follow the standard estimate of 25 to 30 percent per order of magnitude increase in production. Table 5 summarizes battery cost information for the short term (2004-2008) and long term (2012+), assuming that hybrid vehicle technology finds at least a modest market.

Motor costs are relatively well understood, as motor technology is more mature than advanced battery technology. There are two major types of motors: induction and permanent magnet motors. In general, induction motors are cheaper than permanent magnet (PM) motors, although the controller requirements make the controller somewhat more expensive. In total, however, the induction motor and the controller are cheaper by about 15 percent. The permanent magnet motor is more efficient, especially at lower speeds and lighter loads. To date, both the Honda and Toyota hybrids use PM motors, possibly because of their focus on maximizing efficiency on the low speed Japanese test cycle.

Costs for induction motors have been estimated by EEA based on an average of data obtained from suppliers such as Siemens and Delphi.[9] At high production volume, a cost for (motor and controller) at $(300 + 30 * kW) provides a reasonable fit to the data obtained. A 6 kW motor/controller (used on a 42V system) would cost about $480, while a 30 kW motor would cost about $1200. As noted, PM motors of 6 kW and 30 kW could cost $550 and $1400 approximately. Current production costs at low sales volume (of about 20,000/year) are about 25

TABLE 5
BATTERY COSTS FOR HYBRIDS

Battery cost ($/kWh)	**Low Volume**	**High Volume**
Ni-MH (Short term)	$700	$550
Ni-MH (Long term)	$500	$400
Lead Acid (Short term)	$200	$150
Lead Acid (Long term)	$160	$120

Production Assumptions

- Low Volume - 50,000/year
- High Volume - 500,000/year

to 30 percent higher. In addition to the economies of scale, costs could decline another 20 percent principally due to cost reductions in the controller's power electronics.

Costs of other auxiliary components such as the wiring harness and battery and motor cooling systems are relatively low, but are also not subject to economies of scale or learning, as they are already relatively mature technologically. Low voltage, low power motors and 42V batteries will probably not need any significant external cooling system other than induced air-cooling.

4.3 300V SYSTEMS

There has been considerable analysis of, and test data from, the Toyota Prius design[10] which closely adheres to the design principles described in Section 4.1. The Prius weighs 1300 kg empty, so that 1500 kg as a loaded design weight is appropriate. The engine is rated at 44 kW while the electric motor is rated at 30 kW, closely matching to the postulated 45 kW continuous and (45+30) kW peak requirement for a 1.5 ton vehicle. The U.S. version of the Prius has 53 percent better fuel economy relative to a similar performance high technology vehicle, and 70 percent better than the class average. However, the Prius includes a number of non-drivetrain related improvements such as low rolling resistance tires, aerodynamic body, etc., so a 45 percent improvement from the drivetrain alone is a reasonable estimate for the efficiency benefit of a 300V system.

Toyota's Prius uses a very clever design that enables replacement of the entire transmission with a set of planetary gears that are connected to the engine, motor and generator and acts as a CVT. The new transmission requires some unusual types of operation such as operating the generator to power the motor, but significant cost savings are possible by eliminating the automatic transmission. Data provided by Toyota[11] suggested that the current variable cost of the Prius is $4150, which corresponds to an RPE of about $7200 at low volume production. As shown in Table 6, battery and motor cost reductions in the future are expected to reduce the cost penalty to $3000 at 20,000 units per year and, possibly, to $2300 at a sales volume of 100,000/year. This corresponds to an RPE of $4800 and $3650 respectively. In addition, improvements to

TABLE 6
COST OF INTEGRATED 300V SYSTEMS

	Current	**Future (2004+)**
Motor	700	550
Generator	450	350
Battery	1500	800
System Controls	200	100
Inverter	1300	700
Elec. Power Steering	100	50
Power Harness	50	50
Safety Isolation	100	70
Total	**4400**	**2670**
Saving on Engine	-100	-100
Saving on Transmission	-200	-200
Net Variable Cost	**~4100**	**~2370**

components such as the motor, generator and battery are expected to increase the fuel efficiency benefit to about 50 percent over an equivalent conventional vehicle.

4.4 150V SYSTEMS

Such systems are embodied by the Honda Insight that has what Honda refers to as an ‘IMA’ or integrated motor assist drivetrain. As implied by the intermediate voltage level, the motor and battery size is intermediate to that of 42V system and a 300V system. The major GHG advantages over the 42V systems are:

- the motor size for a typical 3000 lb. car can be in the 15-18 kW range, adequate to provide significant assist to the engine in a number of operating regimes;
- the larger motor allows for engine downsizing by 15 to 20 percent;
- the larger battery size allows greater recovery of braking energy, and the potential for very low speed all electric operation.

On the Insight, the Honda IMA system[13] is paired with an advanced lightweight aluminum body, and an advanced three-cylinder low friction, lean burn engine so that the fuel economy attained is double that of a similar Civic on the Japanese cycle. Data presented by Honda shows that the body, engine and IMA system each contribute to about one-third of the total improvement in fuel economy. Over the U.S. FTP cycle, the IMA type systems alone could potentially provide a 25 to 28 percent benefit in fuel economy (city/highway). However, costs are more than double that of the 42V system since:

- the 150V system requires extensive electrical isolation for safety;
- low cost, low voltage components like MOSFET motor controllers cannot be used;
- packaging of the 15 kW motor will require changes to the engine and transmission.

Some cost savings are expected from the smaller engine and simpler transmission. Our estimate of current moderate volume production costs for this system is in the range of US$2200, which works out to an RPE of about US$3500. By 2010, we expect high volume production, and RPE could decline to about $2500, as costs of the battery and controllers decline. The 150V systems are similar to 300V systems but better suited to small cars.

4.4 42V SYSTEMS

The recent emergence of 42V systems has been widely reported in the trade press and even in the mainstream press (USA Today, March 29, 2000). It is well known that electrical power demands in cars have risen rapidly over the last 15 years, and that current limitations of existing 12V systems (actually 14V) are a major difficulty for auto-manufacturers, especially in luxury cars.

What makes the 42V system interesting is that it is being driven by other (non-GHG related) forces, but it makes some types of hybrid vehicles more likely and at low cost. The non-GHG related systems of interest to manufacturers include:

- four wheel steering, especially for large SUVs;
- electric brakes (brake-by-wire);
- instant electric heat for passengers;
- heat pump based air conditioning.

Of more interest to this study are the fuel economy technologies. The single most important development is the integrated "starter-alternator" which is a motor/generator that is sandwiched between the engine and transmission. This allows the following F/E related benefits:

- idle engine stop with instantaneous start;
- launch assistance to the engine;
- reduction in size or elimination of the torque converter for automatic transmissions;
- regenerative braking energy recovery.

As noted, the 42V system current limitations will limit the integrated starter-alternator to relatively low power of 10 kW to 12 kW (so that a typical boost level will be 5 kW to 6 kW per ton of car weight). The 42V system will also make electric power steering more easily achievable. The larger 42V battery will be able to recover some braking energy but this is likely to be small.

Hard data on the fuel economy effect of 42V systems is not yet available since there are no pre-production or production models available. However, engineering analysis and input from system suppliers[12] suggest that following estimates of benefits are reasonable:

- idle shut off: five to six percent;
- launch assist and regenerative braking: 1.5 to 2 percent;
- torque converter loss: 0.5 to 1 percent;
- improved alternator efficiency: 0.5 to 1 percent.

A total fuel economy benefit of eight to ten percent appears possible if the 42V integrated starter alternator is designed to complement the engine and transmission. The 42V system will also make the use of electric power steering (EPS) cheaper and better suited to larger vehicles. EPS provides an additional 2 to 2.5 percent benefit in fuel economy relative to the hydraulic system used currently.

Initial estimates of system cost suggest that an induction motor based system (which may not be quite as efficient as a permanent magnet motor based system) is likely to have a retail price of under US$1000 by 2010, assuming high volume production.[10] Current RPE estimates are about $1600 for moderate volume production and $1900 at low volume. In addition, the costs of the 42V system can also be spread across other consumer features such as instant winter heating, four wheel steering on large vehicles, active ride control, etc. We do not anticipate low volume production for this system. Table 7 shows our estimated costs for the post-2005 time frame.

On the negative side, such systems do not have adequate power to provide any mode of operation as a zero-emission vehicle, which may be important for obtaining PZEV credits or ATPZEV credits in California, and the battery size is usually too small to provide significant power assist to the engine except at launch. Nevertheless, system costs adjusted for hedonic benefits are low enough that the 42V system may be an attractive option.

Several supplier companies such as Delphi and Continental have publicly stated that 42V systems will be introduced in 2004/2005 but have not yet identified the manufacturers or models likely to use the system. Both GM and Ford have announced 42V products, and it is rumored that many luxury vehicles will move to 42V systems over the 2004-2006 time frame.

TABLE 7
COSTS OF 42V SYSTEMS IN HIGH VOLUME PRODUCTION

	Current 42V System @20,000/Year	**Future (2010+) System @200,000/Year**
Motor (8 kW)	200	130
Inverter/Controller	700	270
1 kWh Battery (Lead-Acid)*	300	150
Harness/Cooling	150	150
Total Cost	1350	700
Total RPE	**1900**	**~1050**

* Cost with Ni-MH battery will be 2.5 to 3 times as high. Battery costs include cost of box, connectors and monitoring system.

Four Wheel Drive Systems

A new type of hybrid system that offers the potential for "on-demand" four-wheel drive (4WD) capability instead of continuous 4WD capability may offer the most significant potential for fuel economy. In these designs, one set of wheels is powered like other parallel hybrid vehicles, while the second set is driven by an electric motor only. (The voltage of the system determines the power of the motor) The electric motor driven axle is necessarily power limited to the maximum electrical output available, which is about 12 kW in a 42V system, and hence, is not a true "full function" 4WD system. Given the most SUVs are rarely (if even) driven under serious off-road conditions, the on-demand 4WD system may provide the level of traction desired by most customers. The system has the advantage of eliminating several costly mechanical parts like the axle shafts and center differential, and customers may be willing to pay the 4WD mechanical premium price. GM has recently announced a 4WD 42V system and has <u>claimed</u> a 20 percent fuel economy benefit over a conventional 4WD drivetrain. Note that the 4WD mechanical drivetrain typically imposes a ten percent fuel economy penalty over a 2WD drivetrain.

Recent details released by GM show that one 12 kW motor powers one axle, while the second is coupled to the engine and one axle like a "conventional" 42V system. Battery size and control logic are not yet public, but it appears reasonable to assume that under 4WD operation, the 12 kW motor coupled to the engine serves as a generator to provide power to the second motor, with the battery only providing instantaneous peak power. Our cost estimates suggest that only the additional motor and controller would be incremental to a 2WD system, with potentially some additional cost for a larger battery and more complex wiring harness. Nevertheless, the savings from the elimination of axle shafts and center differential will also be larger, so that the net cost of the system could potentially be only 50 to 60 percent higher than that of a 2WD system, i.e., \$1600 to \$1700 in high volume production and the RPE about \$2600 to \$2700. Since the typical RPE of a conventional 4WD system is about \$2500, the "on-demand" 4WD system can be essentially a cost competitive option to conventional 4WD.

Hybrid Summary

Although there are a continuum of design possibilities for hybrid vehicles, the markets appear to be moving towards three types of systems: the 42V systems, the 150V system and the 300V system. Each system represents a step increase in electrical power availability, and different tradeoffs in efficiency, cost and performance. Estimates of efficiency benefits and costs for the three system types on a typical midsize car and SUV based on EEA analysis are shown in Tables 8 and 9.

The above benefits and costs include the electric power steering system as part of the package. Nevertheless, it is obvious that costs increase non-linearly with benefit, so that the 42V system has the best cost-benefit from a GHG point of view. The fact that some of the 42V system costs could be further allocated to other features makes it even more attractive. As a result, competitive pressure alone could be adequate for manufacturers to introduce the 42V system with integrated starter-alternators as a potential GHG enhancing technology. High initial costs are a barrier to widespread use of 42V hybrids.

In general, costs for hybrid vehicles of a given type scale in proportion to vehicle weight. However, the 150V and 300V hybrid cannot maintain peak power for any period much over a minute, and hence, offer inferior towing capability relative to the base conventional vehicle. This is a hedonic “cost” that may be important to some classes of consumers, especially those who purchase SUVs or pickup trucks. The “on-demand” 4WD system looks particularly interesting since it can compete with existing 4WD systems, and offer a significant benefit at a potentially low incremental cost. System performance would not be identical to a mechanical 4WD system due to power limitations but could be attractive to many consumers who use 4WD for bad weather, as opposed to rough terrain, conditions.

TABLE 8
HYPOTHETICAL HYBRID MID-SIZE CAR
CONSTANT ATTRIBUTE CASE

	2000 BASE	**2020 BAU**	**2020 BAU + 42V**	**2020 BAU+ 150V**	**2020 BAU+ 300V**
Weight	3320	3150	3200	3250	3500
Body	Steel	Composites, Al Forgings	Composites, Al Forgings	Composites, Al Forgings	Composites, Al Forgings
C_D	0.31	0.25	0.25	0.25	0.25
C_R	0.0095	0.0075	0.0075	0.0075	0.0075
Engine	3.0L V-6	2.5L V-6	2.4L I-4	2.0L I-4	1.7L I-4
Valves	4	4 w/VVLT	4 w/VVLT	4 w/VVT	4 w/VVT
HP	200	180	170	140	110
Transmission	4 – Auto	CVT	CVT	CVT	ECVT
Motor	None	None	9 kW	18 kW	36 kW
Power Steering	Hydraulic	Hydraulic	Electric	Electric	Electric
F/E (MPG)	26.5	34.1	37.1	40.3	44.8
Hedonic Attributes	Base	No Change	No Change	Some Loss Of Towing	Loss Of Towing
Inc. RPE	Base	680	1760	2780	3980

Includes fuel economy penalty for safety equipment and Tier 2 emission (estimated at about four percent). Improvements common to all 2020 cases are engine friction reduction by 15 percent, low friction lubricants and accessory improvements (x/ESP)

TABLE 9
HYPOTHETICAL 2020 COMPACT 4WD SUV
CONSTANT ATTRIBUTE CASE

	2000 Base	**2010 BAU**	**2020 BAU w/o Hybrid**	**2020 Full Hybrid**	**2020 On-Demand 4WD**
Weight	4150	3940	3740	3860	3780
Body	STEEL Body-On –Frame	HSLA Intensive (Unibody)	Composites, Al. Castings, +Forgings	Composites, Al. Castings, +Forgings	Composites, Al. Castings, +Forgings
C_D	0.45	0.41	0.38	0.38	0.38
C_R	0.0105	0.0095	0.0085	0.0085	0.0085
Engine	4.0L V-6	3.5L V-6	3.0L V-6	2.2L I-4	2.8L V-6
Valves	2	4 w/VVT	4 w/VVLT	4 w/VVT	4 w/VVLT
HP	205	220	220	135	195
Transmission	4 – Auto	5-Auto	5-Auto	ECVT	CVT
Motor	None	None	None	40 kW (300V)	2 *x* 10 kW(42V)
Power Steering	Hydraulic	Hydraulic	Hydraulic	Electric	Electric
F/E (MPG)	20.3	24.5	27.2	38.6	32.6
Hedonic Attributes	Base	No Change	Some Loss Of Towing Capacity	Serious Loss Of Towing & Off-Road Capability	Some Loss Of Towing & Off-Road Capability
IRPE $	Base	665	1015	5430	2095

Includes fuel economy penalty for safety equipment and Tier 2 emission (estimated at about 3%). Improvements common to all 2015 cases are engine friction reduction by 15 percent, low friction lubricants and accessory improvements (x/EPS).

5. BARRIERS TO MARKET PENETRATION

5.1 TYPES OF BARRIERS

Although there are a variety of technologies available to improve fuel economy, introduction and market penetration are by no means assured. Broadly speaking, barriers exist at all the three stakeholders: government, the consumer, and at industry. At the consumer and industry level, all barriers can be fundamentally traced to economics, although the causes can be widely different.

The EEA model of technology penetration assumes an "efficient" market in that consumers prefer technologies that pay for themselves in fuel savings over three or four years, and that manufacturers generally supply these technologies in response to the free market forces. Some caveats apply to this general model. First, although consumers may be willing to pay for these technologies, they can also substitute improvements in other vehicle attributes (such as space, performance and luxury features) for fuel economy. Second, initial costs for a new technology could prevent transition to high market volumes if the cost-sales volume relationship is steep. Third, manufacturers may be less willing to accept new technology introduction risk if the technology is a relatively radical departure from existing technologies. These and other barriers are explored below.

5.2 CONSUMER RELATED BARRIERS

Consumer related barriers are associated with:

- limited time horizon for technology payback;
- limited information about new technology;
- understandable reluctance to invest in new technology where the support infrastructure is not fully developed.

As noted, consumers expect payback in fuel savings for investing in new technology over a relatively short time period of three to four years. This is related to the typical period of ownership for a new car of three to four years; most new car buyers are unsure that the resale market will value fuel saving technology. Yet, the vehicle itself will be in use for a period of 12 to 14 years. The phenomena can also be viewed as consumers discounting future savings steeply due to uncertainty about actual fuel savings, future fuel prices and the fact that the car is a depreciating asset.

Consumers also have limited information on new technology, but this barrier pertains mostly to revolutionary technology such as a hybrid vehicle. Few consumers know the difference between pure electric and electric hybrid technology, or even what the benefits of these technologies are. Even with the prevalence of information on fuel economy, few consumers know that exact fuel economy rating of the car they purchase, and often use size or power as a surrogate for fuel economy.

Finally, new technologies that require different fuels or alternative maintenance sources also face high consumer resistance. The vehicle is the second largest investment made by most consumers (after their home) and reliability and maintainability are very highly valued. Hence, with most new technologies, there is a period where it must be sold at low sales volumes to "early adopters", to establish a field reputation for reliability. Familiarity also has the positive contribution of making more consumers aware of the specifics of technology.

5.3 MANUFACTURER RELATED BARRIERS

Manufacturers also face a number of barriers within the company related to:

- initial high costs at low volumes due to lack of scale economies;
- competing against lower cost entry level manufacturers;
- uncertainties in future oil price projections.

New technology that represents revolutionary (as opposed to evolutionary) changes in the vehicle need a period where the technology is produced in low volumes; over this period, both the manufacturer and consumer become more familiar with technology. At low volume production, economies of scale are not available. Work by EEA for the DOE on alternative fuel vehicles showed that manufacturers are unlikely to offer any technology that sells less than 2000 to 3000/year per vehicle model, and even at these production levels, special low volume facilities with high labor content are required. Sales volume levels of at least 20,000 to 30,000 per year per model are required for integration into assembly lines for mass production. For adequate consumer choice, at least six to eight models are needed (one for each of the largest manufacturers), which sets a lower technology penetration limit of one percent of the new vehicle fleet. Even at these production levels, technology costs are estimated at 30 to 35 percent higher than at true mass production levels.

The high initial cost of new technologies with modest initial sales provides a significant barrier to the introduction of revolutionary technology, unless manufacturers believer that initial consumer resistance will quickly fade and/or ultimate market potential is very high.

The second issue of product differentiation against low cost manufacturers is driven both by demand and manufacturer strategy. As new "entry" level manufacturers like Hyundai, Kia and Suzuki introduce larger and better quality models, existing manufacturers must differentiate their higher cost products with higher levels of comfort, luxury and performance. Of course, consumers have responded favorably to this strategy historically. However, it is widely known that consumers rarely, if ever, fully use the levels of performance offered in modern cars, and some economists believe that performance demand is based on relative differences between cars rather than absolute levels of performance. Hence, performance levels can be set by competitive rather than demand driven forces.

Third, auto-manufacturers are reluctant to <u>commit</u> to a fuel economy path in the future, even when analysis shows that the path is likely to be attained in a business-as-usual case. Most fuel economy forecasts are based on a projection of macroeconomic fundamentals such as oil price and income growth, and current projections call for modest price increases for crude oil and modest income growth for the decade. However, it is possible that oil prices can collapse in the future as they did in 1998, and the economy can boom. These factors cause significant consumer shifts in vehicle preferences. Hence, the scenario risk is significant for manufacturers.

5.4 GOVERNMENT BARRIERS

In general, government at the state and Federal levels seek to improve fuel efficiency, and most barriers arise from the imposition of emissions standards and related recall previsions. These barriers are particularly true in California, which has the most stringent emissions standards in the world. The absolute level of the new "LEV II" standards are so low that it currently appears unlikely that diesel and gasoline direct injection (GDI) lean-burn engines can meet the NO_x emissions standards. The diesel engine, in particular, has very significant fuel economy potential and manufacturers believe that it has good potential in light trucks in the 49 states. At present, there is no explicit incorporation of energy savings goals in setting emission standards. While the diesel/GDI is the most obvious example of a barrier, several other barriers also exist.

Current durability standards require the demonstration of emissions control capability over the useful life of the vehicle. Many lower cost hybrid designs could plan to utilize lead-acid batteries that must be replaced once or twice over the life of the vehicle. Manufacturers are concerned that at periods near the end of the useful life of the battery (right before replacement) emissions performance could suffer slightly but potentially trigger an expensive recall. Manufacturers are also concerned about emissions warranty issues with regard to battery replacement.

Other newer issues may emerge from the revised ZEV mandate. The ARB has defined a new class of vehicles called "advanced technology partial zero emission vehicles" or ATPZEV. At this point, ARB has suggested that 42V hybrids may not be classified as ATPZEV's, and only 300V hybrids could qualify. Given the high cost of the 300V hybrid, our market penetration model suggest that these vehicles will likely fall far short of the ATPZEV sales goals set by ARB, unless they are subsidized. On the other hand, the 42V could potentially meet ATPZEV sales goals but manufacturers may have no incentive to do so. The tradeoffs in terms of social versus private benefits needs to more closely examined in such cases.

Other more modest barriers may exist in the safety area with new fuels like hydrogen, where refueling issues may arise. These issues could be addressed in the context of industry-government partnerships like the fuel cell partnership.

5.5 INITIATIVES TO OVERCOME BARRIERS

A large number of initiatives can be sponsored by the State of California that can rely on fiscal and non-fiscal subsidies, command-and-control measures, consumer information, and manufacturers-and-government partnerships. Substantial public interest has been focused on these initiatives and a wide variety of suggestions have been made to the State of California from groups promoting conservation. This section is not intended to be a comprehensive listing or evaluation of all of the suggested initiatives, but a select list of initiatives that EEA regards has having potential for success. Based on our experience in evaluating a large number of initiatives, we have selected six as promising, although success is by no means guaranteed.

5.5.1 Command-and-Control

The most direct form of intervention for fuel efficiency would be California specific CAFE standards or more generally fuel economy standards. No detailed analysis of its effects has been completed to date, but our experience suggests it will be difficult to implement and almost certainly impact the domestic and European manufactures more than the Japanese or Korean manufactures. However, the ARB has already imposed a set of command-and-control measures for zero emission vehicles and ATPZEVs, where manufacturers are required to meet specific sales goals.

In this context, two initiatives may be valuable. First, ARB may decide to exclude “mild hybrids” from the ATPZEV definition. Yet, our analysis suggests that only mild hybrids have the lower cost required to possibly meet ATPZEV sales targets without continuous subsidies. If the ATPZEV definition includes only 300V “full hybrids”, required subsidies to meet sales targets could be large. (Note that a 42V system need not necessarily be in a mild hybrid vehicle and 42V systems may emerge without fuel efficiency benefits.) Hence, CEC could play a key role in setting definitions for ATPZEVs.

A second initiative in this area is to shield the recall risk for 42V hybrids using lead-acid batteries. As noted, there could be a period of time near the end of the battery life when emission standards could be exceeded. Providing a short term waiver against this risk for the first generation of 42V hybrids could be a very helpful factor in manufacturers deciding to introduce more mild hybrid models.

In addition, the ARB has set ambitious goals for ZEVs, but neither battery electric or fuel cell electric vehicles appear to be low cost solutions in the period examined.

5.5.2 Fiscal Initiatives

A variety of initiatives involving vehicles subsidies, fees-and-rebates (feebates) and tax subsidies have been proposed. Detailed analysis of feebates has been completed by DOE in 1995, and those results suggested that supply side effects are dominant, and that feebates structured on fuel economy (independent of vehicle size) have effects similar to the imposition of CAFE standards. Hence, more structured or alternative forms of feebates needs to be considered.

Subsidies for high fuel economy vehicles such as hybrids have been extensively debated last year at the Federal level. The major problems have been in defining which vehicles should receive the subsidy, in terms of technology definition and minimum fuel economy level. Nevertheless, any subsidy cannot be permanent, and the ultimate logic of a subsidy must be to support a specific set of technologies to overcome initial market barriers when economies of scale are not available and consumers are unsure of the new technology. A good case can be made for the 42V mild hybrid, where relatively small initial subsidies in the range of \$500 - \$700 may be adequate to overcome low sales volume inefficiencies and subsides can be phased out over a period of five to six years. A similar case can be made for full hybrids but subsidies meet to be larger, in the \$1500 to \$2000 range, and ultimate market size expectations also smaller. The details of how such subsidies out to be set-up is deserving of study.

5.5.3 Research Partnerships

Government's role in supporting pre-competitive research and demonstration programs for new technologies has been widely acknowledged, and the Federal program to develop hybrids has been credited for the introduction or planned introduction of a number of hybrid vehicle models. Nevertheless, the pre-competitive phase of hybrid vehicle research is clearly over, and additional research roles in this area are outside the realm of normal government intervention.

Fuel cell and battery electric vehicles do have significant energy advantages over most other vehicle types and still appear to require additional research to meet cost and performance goals. California already has ongoing research partnerships in those technologies, such as the Fuel Cell Vehicle Partnership, and their continuation may be a useful initiative even in the energy efficiency context.

5.5.4 Consumer Information

The correct political and world situation may make the consumer more receptive to useful information on fuel efficiency. Information that could direct consumer choice could be focused:

- vehicle choice within classes;
- information on choice of options;
- information on new technology.

Analysis by EEA has shown that across different car models closely matched by size and performance, fuel economy can vary by 20 percent between the "best" and "worst" model. The current DOE Fuel Economy guide does not segment the fleet into market classes, but by size class that leads to confusing comparisons with Mercedes sports coupes compared to Hyundai subcompacts due to similar interior volume. A better segmentation by size and price might provide more useful choices to the consumer. For example, few consumers are aware of the magnitude of fuel economy differences within market class.

Consumers also often purchase little used options that can significantly degrade fuel economy. Typically, a V-6 engine option over a four-cylinder engine can reduce fuel economy by 15 to 20 percent. Four-wheel drive can reduce fuel economy by 10 to 12 percent. Many buyers simply purchase the entire options ‘package’ without reflecting on the effect of option purchases on fuel economy, but little information is available on their fuel economy effect.

The state can also accelerate or increase information on new technologies by working with auto-manufacturers on specific technologies such as hybrids or fuel cell vehicles. Unbiased reports on the favorable and unfavorable aspects of these technologies from a trustworthy source may inspire greater consumer confidence in innovative technology. Coordination of information programs with the ARB to supply efficiency information is a useful first step.

5.5.5 Summary

A number of initiatives of different types are suggested for CEC consideration. While such initiatives have been discussed publicly, our research shows that little work has been done to date on the exact specifications of these initiatives or the resulting winners and losers, and the results of the effects of these initiatives are asserted with little analytical backup. Most of the initiatives recognized in this section require careful design and specification to attain reasonable success.

6. FORECAST OF VEHICLE ATTRIBUTES

6.1 OVERVIEW

The California Energy Commission (CEC) has developed a demand model for personal use vehicles in California. This model requires, as inputs, the attributes of vehicles available to California purchasers. Rather than requiring the attributes of vehicles for each make and model, vehicles are grouped into broadly homogenous classes classified by size and market intent, and cover both cars and light trucks. In addition, the vehicle choice model is also capable of selecting alternative fuel vehicles that could be entering the market in the future. The model developed by EEA is capable of supplying the detailed attributes of conventional and hybrid vehicles as required by the CEC choice model. The EEA model is itself responsive to broad macroeconomic variables of fuel price and personal income. This report documents the model developed for CEC, and detailed model results for different scenarios were provided on computer disc. It should be noted that the model was adapted from an existing EEA model called the Fuel Economy Model (FEM) for this project, and not rebuilt as a special purpose CEC model.

The vehicle attribute forecasting model for the California Energy Commission (CEC) over the next twenty years utilizes a methodology developed initially for the Department of Energy (DOE) in the early 1980s, and refined continually from that time. The model incorporating this methodology is automated and requires only three input streams over the forecast period:

- gasoline prices;
- personal disposable income;
- CAFE standards.

The first variable is utilized to forecast technology adoption rates and the mix of size classes sold (not required for the CEC analysis). The second variable is utilized to estimate performance demand. The model operates at the market class level, and forecasts fuel economy, weight and horsepower, as well as detail of the market penetration of each technology by market class and year. CAFE standards are utilized as a 'market forcing' input, and the model responds by increasing technology adoption rates to the point where it becomes cheaper to pay the fine for not meeting CAFE standards rather than increase fuel economy. The following sections document the model methodology, operation, and the scenarios provided for CEC.

6.2 DESCRIPTION OF MODEL METHODOLOGY

The fuel economy of the fleet of new vehicles can change as a result of three factors: i.e.,

- a change in technological characteristics of each vehicle;
- a change in the level of acceleration performance of vehicles;
- a change in the mix of vehicle classes sold.

The Fuel Economy Model (FEM) developed for DOE considers each of the three factors when projecting fuel economy in the future. First, the entire fleet of new cars and light duty trucks are disaggregated into 14 market classes that are relatively homogenous in terms of consumer perceived attributes such as size, price and utility.

Second, technological improvements to each of these market classes are forecast based on the availability of new technologies to improve fuel economy, as well as their cost effectiveness. The central assumptions involved in this technological forecast are as follows:

- all manufacturers can obtain the same benefits from a given technology, provided they have adequate lead time (i.e., no technology is proprietary to a given manufacturer in the long term);
- manufacturers will generally adopt technological improvements that are perceived as cost-effective to the consumer, even without any regulatory pressure. However, the term cost-effectiveness needs to be interpreted in the manufacturer's context.

These forecasts also account for manufacturer lead time and tooling constraints that limit the rate of increase of market penetration of new technology. Based on the technological improvements adopted, a fuel economy forecast assuming constant performance is developed for each of the market classes.

Third, the demand for increased acceleration performance for each size class is estimated based on an econometric equation relating fuel prices and personal disposable income to demand for performance or horsepower, by market class. This relationship is used to forecast the change in horsepower, and the change in horsepower is used to forecast the change in fuel economy through an engineering relationship that links performance and fuel economy.

Fourth, the change in the mix of market classes sold is determined by an econometric demand model that has been developed for DOE. The model forecasts the mix of sales as a function of:

- fuel prices
- personal disposable income
- vehicle prices
- vehicle fuel economy
- future demographic shifts
- rate of change of fuel prices

The sales mix by class is used to calculate fleet fuel economy, but this output of the model is not directly utilized for CEC. The model forecasts sales mix for the six car classes and the seven light truck classes, while import market shares by market classes are held at fixed values based on subjective estimates. The fleet mix is required to estimate compliance with CAFE regulations.

The model allows specification of Corporate Average Fuel Economy (CAFE) standards by year, and allows the specification of differential standards for domestic and import vehicles, as well as the penalty (in dollars) per car per mile per gallon below the standard. The method by which standards are accounted for in the forecast is by incorporating the penalty in the technology cost-effectiveness calculation. Hence, if the penalty is not large, the model assumes that manufacturers will only adopt technology to the point where it becomes cheaper to pay the penalty for noncompliance. If standards are set at high levels, the model will show a shortfall in actual CAFE relative to the CAFE standard.

Finally, the model also accounts for all known safety and emission standard changes during the forecast period, but these are generally limited to the 2010 time frame. Emission standards and safety standards increase vehicle weight, and in some cases decrease engine efficiency. The model accounts for the California "Low Emission Vehicle" standards. Safety standards include penalties for air bags, side intrusion and roof crush (rollover) strength requirements that are mandatory over the next ten years. Separately, anti-skid brakes are assumed to be incorporated in all vehicles, although they are not required by law.

The forecasts are calculated at most disaggregate level of manufacturer type (domestic/ import), vehicle type (car/light truck) and market class. Cars and light trucks are classified into seven market classes each, where each market class represents an aggregation of vehicle models that are similar in size and price, and are perceived by consumers to offer similar attributes. The seven classes for cars and for light duty trucks are described in Table 10. This leads to a total of 28 possible classes (7 classes x 2 vehicle types x 2 manufacturer types) but some have no vehicles, e.g., there are no domestic minicompact cars. For the CEC, the import and domestic classes are combined using fixed shares within market class. For the CEC, the luxury car market is disaggreaged into the six size classes, so that each class has two subgroups divided by price: high and low.

The heart of the model is the technology forecasting algorithm. The algorithm identifies available technology for each market class, calculates their cost-effectiveness, determines the market share and adjusts the benefits of interactions with other new technologies. The components of the technology adoption process are as follows:

Baseline - the purpose of the baseline is to set a reference from which all cost increments, fuel efficiency changes, and performance changes are measured. The FEM uses actual 1995 data on vehicle attributes, prices and technology use, aggregated to the market class level. As a result, the forecast builds from known and exactly specified vehicle technology characteristics. For this analysis, the period 1995-2000 is a forecast, not the actual values.

TABLE 10
MARKET CLASSES FOR THE FUEL ECONOMY MODEL

Class	Definition[*]	Example Models (1995 baseline)
Minicompact	Interior passenger volume < 80 ft^3	Chevy Metro, Toyota Paseo (no domestic cars)
Subcompact	Passenger volume between 80 ft^3 and 89 ft^3	Nissan Sentra, Honda Civic, GM Saturn, Ford Escort
Sports	Two door high performance cars costing less than $25,000 (1990$)	Honda Prelude, Chevy Camaro, Ford Mustang
Compact	Passenger volume between 89 and 95 ft^3	Honda Accord, Toyota Camry, Ford Tempo, Pontiac Grand Am
Intermediate	Passenger volume between 96 and 105 ft^3	Nissan Maxima, Ford Taurus, Chevy Lumina
Large	Passenger volume >105 ft^3	Ford Crown Victoria, Buick LeSabre
Luxury	Cars over $25,000 (in 1990$)	Lincoln Continental, Cadillac, all Mercedes, Lexus LS400
Compact Pickup	Trucks with inertia weight between 3000 and 4250 lbs.	All import vans, Ford Ranger, GM S-10/15
Compact Van	Vans with inertia weight between 3250 and 4250 lbs.	All import vans, Dodge MiniRam, Ford Aerostar
Compact Utility	SUVs with inertia weight between 3500 and 4500 lbs.	Nissan Pathfinder, Toyota SR-5, Ford Explorer, Jeep Cherokee
Standard Pickup	Trucks with inertia weight over 4250 lbs.	GM C-10, Ford F-150
Standard Van	Vans with inertia weight over 4250 lbs.	GM C15 van, Ford E-150 (no imports)
Standard Utility	SUVs with inertia weight over 4500 lbs.	Toyota Land Cruiser, GM Suburban, Ford Blazer
Mini-truck	SUVs below 3500 lbs. inertia weight	Honda CRV

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[*] Weight based classes are specified for 2WD models; 4WD models have cut-off levels 250 lbs. higher.

Technology Data - the list of available technology improvements and their attributes are organized into a technology matrix, one for cars and one for light trucks. The matrix contains information on technology incremental cost, fuel economy benefit, impact on vehicle weight, potential impact on performance, and the first available year. The information is non-dimensionalized where applicable, so that all market classes within a vehicle type can use the same information set. The technology information is summarized in Tables 11 and 12 for cars and light trucks, respectively. The cost-benefit ratio is $ per percent improvement provides insight into technology cost-effectiveness.

The technological data for each of the 55 technologies incorporated into the FEM is described in detail in two reports to the Department of Energy.[*] The technologies available in the short-term are documented in “Documentation of Attributes of Technologies Incorporated in the TCSM” draft report to Martin Marietta, February 1992 and technologies available beyond 2010 and documented in the report "Potential Fuel Economy in the 2010+ Time Frame" report to Martin Marietta, December 1990. These attribute data have been more recently updated in 1999, but do not include all of the latest updates from the 2001 National Academy of Sciences study.

Technology Adoption Algorithm - this element of the model selects technology based on the following steps. First, a technology is identified as available for adoption if its "first available date" is earlier than the forecast year. Second, the cost-effectiveness of the technology is calculated as described in the following paragraph. Third, a maximum market penetration level is set based on the introduction date to model short term tooling constraints. Fourth, the cost-effectiveness criterion is combined with the maximum market penetration to estimate the actual market penetration. In this step, highly cost-effective technologies (low cost/benefit ratio) have nearly 100 percent market penetration. Fifth, if the calculated market penetration exceeds the previous period's market penetration, then the penetration is increased to the new level. However, if the calculated new penetration level is lower, market penetration remains

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[*] Reports were developed through Oak Ridge National laboratories, Martin Marietta Corp.

TABLE 11
TECHNOLOGY COSTS AND BENEFITS (CARS)

TECHNOLOGY	FE BENEFIT PERCENT	COST (2000 $)	COST-BENEFIT
WEIGHT REDUCTION		per lb. saved	3000 lb base
-HSLA INTENSIVE	3.3	0.40	18.2
-SMC/RIM CLOSURES	1.7	0.80	36.4
-LIGHT INTERIORS	1.7	0.70	31.8
-AL FORGINGS/CASTINGS	3.3	1.25	56.8
-AL. INTENSIVE STRUCTURE	5.0	1.80	81.8
DRAG REDUCTION			
- 10% REDUCTION	2.2	25	11.4
- 20% REDUCTION	4.3	75	17.4
- 30% REDUCTION	6.3	150	23.8
ROLLING RESISTANCE			
- 10% REDUCTION	2.0	20	10.0
- 20% REDUCTION	3.9	50	12.8
- 30% REDUCTION	5.7	90	15.8
SPARK IGNITION ENGINES		(for V-6)	
- 4-VALVES/CYLINDER	5.0	180	36.0
- VVTL	7.2	250	34.7
- CYLINDER CUTOUT	7.0	150	21.4
- INTAKE THROTTLING	4.0	400	100.0
- VARIABLE COMPRESSION	8.0	600	75.0
- SUPERCHARGING	6.0	500	83.3
- DIRECT INJECTION (LEAN)	12.5	600	48.0

TABLE 11
TECHNOLOGY COSTS AND BENEFITS (CARS)
(Continued)

TECHNOLOGY	FE BENEFIT PERCENT	COST (2000 $)	COST-BENEFIT
TRANSMISSIONS			
- 5-SPEED AUTOMATIC	3.5	180	51.4
- CVT	6.0	120	20.0
- 6-SPEED AUTOMATIC	5.0	300	60.0
- LOW LOSS CONVERTER	2.0	30	15.0
- AGGRESSIVE SHIFT	5.0	(hedonic)	?
ACCESSORIES			
- EFFICIENT ALTERNATOR	0.7	16	22.9
- GEAR DRIVE OIL PUMP	0.5	5	10.0
- ELECTRIC POWER STRNG.	2.0	50	25.0
- ELECTRIC WATER PUMP	0.5	40	80.0
ELECTRONIC CONTROL			
- ELECTRONIC THROTTLE	1.0	15	15.0
- EARLY CONVERTER LOCK	1.5	hedonic	?
- ELEC. ACTUATED VALVES	2.0 over VVTL	see intake port throttling	100.0
DRIVELINE			
- REDUCED BRAKE DRAG	1.0	10	10.0
- EFFICIENT 4WD TRANSFER	1.5	40	26.7

Note: Technology benefits are not additive and depend on what technologies are previously adopted. All benefits measured from vehicle with 2-valve/cylinder OHC engine with 4-speed automatic transmission.

TABLE 12
TECHNOLOGY COSTS AND BENEFITS (TRUCKS)

TECHNOLOGY	FE BENEFIT PERCENT	COST (2000 $)	COST-BENEFIT
WEIGHT REDUCTION		per lb. saved	4500 lb base
- HSLA INTENSIVE	3.3	0.40	27.3
- SMC/RIM CLOSURES	1.7	0.80	54,6
- LIGHT INTERIORS	1.7	0.70	47.7
- AL FORGINGS/CASTINGS	3.3	1.25	85.2
- AL. INTENSIVE STUCTURE	5.0	1.80	122.7
DRAG REDUCTION			
- 10% REDUCTION	2.2	30	13.6
- 20%REDUCTION	4.3	80	18.6
- 30%REDUCTION	6.3	200	31.7
		except pickups	
ROLLING RESISTANCE			
- 10%REDUCTION	2.0	30	15.0
- 20%REDUCTION	3.9	70	17.8
- - 30%REDUCTION	5.7	120	21.0
SPARK IGNITION ENGINES		(for V-6)	
- 4VALVES/CYLINDER	4.0	180	45.0
- VVTL	7.7	250	32.5
- CYLINDER CUTOUT	7.5	150	20.0
- INTAKE THROTTLING	4.0	400	100.0
- VARIABLE COMPRESSION	8.0	600	75.0
- SUPERCHARGING	6.0	500	83.3
- DIRECT INJECTION (LEAN)	12.5	600	48.0

TABLE 12
TECHNOLOGY COSTS AND BENEFITS (TRUCKS)
(Continued)

TECHNOLOGY	FE BENEFIT PERCENT	COST (2000 $)	COST-BENEFIT
TRANSMISSIONS			
- 5-SPEED AUTOMATIC	3.5	180	51.4
- CVT (mini trucks only)	6.0	120	20.0
- 6-SPEED AUTOMATIC	5.0	300	60.0
- LOW LOSS CONVERTER	2.0	30	15.0
- AGGRESSIVE SHIFT	5.0	(hedonic)	?
ACCESSORIES			
- EFFICIENT ALTERNATOR	0.7	20	29.9
- GEAR DRIVE OIL PUMP	0.5	5	10.0
- ELECTRIC POWER STRNG.	2.0	70	35.0
- ELECTRIC WATER PUMP	0.5	40	80.0
ELECTRONIC CONTROL			
- ELECTRONIC THROTTLE	1.0	15	15.0
- EARLY CONVERTER LOCK	1.5	hedonic	?
- ELEC. ACTUATED VALVES	2.0 over VVTL	see intake port throttling	100.0
DRIVELINE			
- REDUCED BRAKE DRAG	1.0	10	10.0
- EFFICIENT 4WD TRANSFER	2.0	40	20.0

Note: Technology benefits are not additive and depend on what technologies are previously adopted. All benefits measured from vehicle with 2-valve/cylinder OHC engine with 4-speed automatic transmission.

unchanged. Finally, vehicle characteristics of price, weight and fuel economy are derived by summing benefits over all adopted technologies, after adjusting for synergetic effects.

The cost effectiveness algorithm is based on four specific elements:

- Value of Fuel Saved (F) which is the discounted value of fuel saved over a specific period (e.g., 4 years) due to technology adoption. The period and discount rate are specified in the inputs to the model.
- Value of Performance (P) which is applicable to technologies where the benefits can be utilized to increase horsepower, and is expressed in dollars per horsepower. The value varies with disposable income, as well as the cost of driving per mile.
- CAFE Value (R) which is applicable only if the particular manufacturer group fails to meet applicable CAFE standards. This value is set in an iterative loop, and is initially zero.
- Cost of Technology (C) which is read directly from the technology matrix.

The cost-effectiveness ratio is simply (F+P+R)/C-1, with ratio greater than 0 implying a positive value to the consumer (cost-effective).

Market penetration is determined by the maximum market penetration as determined by tooling constraints multiplied by an exponential function of cost-effectiveness (known as a sigmoid function).

The model utilizes an exponential distribution to capture the fact that even non-cost-effective technologies can have limited market penetration due to the distribution of consumer willingness to pay for technology. The fraction is:

$$\text{Market Share} = M_{max} * P_{max} * \frac{1}{1 + 2e^{-4CE}}$$

where M_{max} is the maximum physical maximum market share possible

P_{max} is the production constraint

CE is the cost-effectiveness.

A cost-effectiveness of 0 implies that in the absence of production or physical constraints, technology market penetration will reach 50 percent in the long term, corresponding to the market penetration peak. A very low cost effectiveness technology will reach a very low maximum market penetration of about 12 percent over the long term, while a very cost-effective technology will reach 95+ percent.

Technology synergy constraints are addressed by a series of special subroutines or notes that check for the presence of two non-additive or synergetic technologies that are adopted simultaneously. Broadly, the technology notes are labeled as follows:

- "Requires" - if a technology can only be adopted if some other technology is already present. For example, valve timing control requires the adoption of overhead cam, 4-valve engines.
- "Synergistic" - if a technology produces different benefits in combination with another technology.
- "Supersedes" - if a technology replaces a technology that already exists in the vehicles.
- "Mandatory" - if a technology must be adopted to meet emission or safety regulations.
- These subroutines either force introduction or removal of technologies, and adjust the total fuel economy benefits.

Summing across technologies produces forecasts by class of price, fuel economy, weight and horsepower. This set of forecasts is based on a constant performance assumption.

The fuel economy and horsepower forecast is then adjusted for performance changes using the following equation:

$$\frac{HP_{new}}{HP_{old}} = K\ (\text{Income})^{1/2} * \left(\frac{\text{Fuel Economy}^{1/2}}{\text{Fuel Cost}}\right)$$

where K is a constant. The horsepower change affects fuel economy, which is readjusted based on the equation

$$\Delta FE = -0.22\ \Delta HP - 0.58(\Delta HP)^2$$

Finally, the adjusted fuel economy values are summed across market class by using the preset market shares (temporarily fixed) to calculate the CAFE by manufacturer type. If the forecast CAFE is less than the standard, the fuel economy is recalculated after resulting the regulatory cost in dollars per MPG per car for the MPG shortfall relative to the standard. If the recalculated CAFE is still below the standard, no second iteration occurs, as the manufacturer is then assumed to pay the fine.

6.3 FEM MODIFICATIONS FOR THE CEC

The CEC requires a forecast of the same 13 classes using gasoline engines as modeled by the FEM, and also requires forecasts for the same 13 classes of vehicles that utilize mild hybrid and full hybrid technology (13 + 13 classes). In addition, the CEC requires a forecast of several variables not forecast by the FEM, but these variables can be derived from existing attribute forecasts in the FEM.

6.3.1 New Variables

As noted, the CEC model requires new variables to forecast:

- top speed;
- 0 to 30 mph acceleration time;
- range.

For top speed, data was collected from car enthusiast magazines on actual tested top speed, and this top speed value was related to the HP to weight ratio. The current FEM calculates both HP and weight, and the ratio can be used to derive top speed from forecast variables. The regression shows that top speed varies with $(HP/WT)^{0.5}$. The equation used to derive top speed for cars is:

$$\text{Top speed} = 518\ (HP/WT)^{0.5}$$

Based the ratio of Frontal Area X C_D to weight for trucks versus cars, light truck top speed is given by:

$$\text{Top speed} = 450\ (HP/WT)^{0.5}$$

The CEC requirement for 0 to 30 mph time was derived from the more standard 0 to 60 mph time relationships for cars and light trucks. For cars, the 0 to 60 mph time is given by

$$T\ (0\text{-}60) = 0.822\ (HP/WT)^{-0.795}$$

Available data from car enthusiast magazines showed that 0 to 30 mph time for about 50 late model cars was, on average, 38 percent of 0 to 60 mph time, so that the 0 to 60 mph time like below equation is modified to as follows to obtain 0 to 30 mph time:

$$T\ (0\text{-}30) = 0.312\ (HP/WT)^{-0.795}$$

For light trucks, we have:

$$T\ (0\text{-}30) = 0.272\ (HP/WT)^{-0.795}$$

Note that the co-efficient for light truck 0-30 mph time is smaller than that for cars, due to the emphasis on low-end torque for trucks. A light truck with the same HP/WT ratio as a car will have a faster 0-30 mph time due to higher torque available at low engine speed.

For hybrid vehicles, the acceleration time is set to a factor such that it is as though the electric motor had 30 percent higher horsepower at low speed than an i.c. engine, to account for the low end torque characteristics of an electric motor. More accurately, it was estimated that if the low speed acceleration time is similar to that for gasoline cars, top speed would be lower since the engine and motor horsepower would be lower than that of an equivalent gasoline car.

Range for all gasoline cars was determined from the tank size and fuel economy. Range is calculated based on EPA "Combined" fuel economy (undiscounted) since highway fuel economy is not forecast by FEM, but the discounted highway fuel economy is very similar to undiscounted combined fuel economy. Identical tank sizes are used for mild hybrids, but range is separately determined for full hybrids.

Three other variables of interest are also incorporated into the CEC. First, the FEM provides the unadjusted combined fuel economy of vehicles, and this is reduced by 16 percent to determine "on-road" combined fuel economy. This on-road adjustment is applied to all vehicles. Second, the CEC forecast requires the number of models for each class, and this has largely been a subjectively determined output based on an examination of product plans (and is therefore, unresponsive to the economic scenario modeled). Third, the CEC model requires shoulder room and variance of shoulder room by class; shoulder room is set to the baseline (1995) value, while the variance is scaled by the number of models.

6.3.2 Mild Hybrid Vehicles

All mild hybrid vehicles were assumed to be derivatives of conventional vehicles, where the integrated started-generator has been incorporated. We also assume that for cost minimization, a lead-acid battery that requires replacement two or three times over the vehicle's useful life is utilized. Designs are assumed to maximize fuel economy as opposed to performance. Specific variables are derived as follows:

- Vehicle Price – since the hybrid component costs scale with vehicle weight, we have used a surrogate of the base gasoline vehicle weight to determine price increments. The forecast is based on our estimate of a long-term price increment (at volume production) of $1000 for a 3000 lb. compact car. Short-term prices are adjusted for sales volume and learning, and are 37 percent higher in 2004/2005 relative to 2015.
- Vehicle Performance – fuel economy, weight, horsepower and acceleration performance are determined as per the discussion in Section 3, for a constant performance case. In this case 0-30 mph time does not change, while horsepower is increased for the engine +ISG at the same rate as the weight increase (computed at four percent for the lead-acid battery case). Range scales directly as fuel economy since the same tank size is assumed. Vehicle size is also assumed to be the same as the conventional vehicles in the same size class.
- Battery Life and Cost – current estimates of advanced glass-fiber mat lead-acid batteries life is from three to four years, but manufacturers expect a four-year life to be attained by 2004/2005. Informed estimates suggest battery life could improve to five years by 2014/2015 due to technology advancement. Replacement costs are based on battery size calculated for the specific vehicle weight and marked-up to a retail price equivalent. Battery size is determined as 0.5 kWh per ton of vehicle weight, with an ultimate (2015+) price of $100/kWh.

6.3.3 Full Hybrid Vehicles

Full hybrid vehicles are based largely on designs similar to the Toyota Prius in terms of motor and battery size, and in terms of fuel economy. As with mild hybrids, electrical components increase in size with increasing vehicle weight, with the costs rising in proportion. Due to the relatively high cost increment for "full hybrid" vehicles, it appears that the market may favor full hybrid drivetrains for smaller vehicles. In addition, these designs are not well suited for towing or high-speed hill climb, so that larger vehicles are less likely to utilize such designs from a functionality viewpoint. Specific assumptions regarding vehicle price and other attributes are detailed below:

- Vehicle Price – Vehicle incremental price is normalized to weight using the detailed Prius data shown in Section 4. Near term RPEs are on a "full cost" basis and, hence, may be higher than those charged by Honda and Toyota, who are subsiding the products in terms of not recovering fixed costs. Costs are expected to decline by 25 percent over the 2001 to 2015 period due to learning and scale efficiencies, but added content to improve performance increases cost pressure upwards. The cost functions assume only modest success for full hybrids in terms of sales volume, and so the larger cost decline included for mild hybrids are not applicable here.
- Vehicle Attributes – Fuel economy improvements over conventional cars for engine and drivetrain improvements are estimated at 50 percent over a conventional car. Many engine improvements for conventional vehicles do not apply to hybrid engines, but other types of improvements to hybrids (mostly in electrical systems) are incorporated so that the fuel economy differential of 50 percent is maintained over time. Estimated acceleration time is somewhat slower, and top speed is 15 percent less than the equivalent value for a conventional vehicle.
- Battery Life and Cost – The full hybrid is modeled with a Nickel Metal Hydride battery that currently has an expected useful life of ten years, with future improvements increasing life to 12 years by 2015. Costs are based on initial battery costs of $750/kWh declining to $500/kWh by 2010, with full retail markup added to these values. Battery size is estimated at 1 kWh per ton (2000 lbs.) of vehicle weight.

6.4 FORECASTS

Vehicle attribute forecasts were provided for five different cases, and for three vehicle types: conventional, mild hybrids and full hybrids. Forecasts for six car and seven light truck classes further subdivided by import and domestic, normal and luxury, were provided to 2020.

The six different cases were:

- Baseline – EEA expectations;
- Baseline – CEC expectations;
- Socially cost-effective case;
- CAFE case set at 38 MPG in 2015 for cars;
- CAFE case with different ramp-up in schedule;
- Feebate case.

All cases utilized the same set of input values for the model for fuel prices and personal income growth. The input values provided by CEC are shown in Table 13. Following a fuel price spike in 2001, prices decline modestly by 2005 and are flat (in constant dollars) thereafter. Personal income in California is forecast to decline slightly in 2001, but rebound to "normal" growth rates by 2005/2006. Growth rates between 2010 and 2020 are less than the two-percent historical long-term growth rate.

Inputs for the base case calculations assume technology payback over four years with fuel savings discounted at eight percent (real). EEA projects that the large weight increases within classes will moderate, as will demand for horsepower, from the 1990-2000 period. In addition, EEA projects that gasoline direct injection (GDI) engines will meet future "LEV II" emission standards.

In the alternative "CEC base case", in-class weight and horsepower trends continue to grow at the rates observed in the last decade, and the GDI engine is assumed to be incapable of meeting LEV II standards. This can be a plausible scenario if, for example, the growth in asset values (like stocks and real estate) mirrors the growth rate of the 1990s.

The "socially cost effective" scenario is an example of the case where society values fuel savings over the life of the car. Here, the fuel savings are computed over 14 years, with the savings discounted at 12 percent to calculate net present value. The model starts this calculation in 1995 so that 2000 fuel economy is higher than the actual value in this case.

TABLE 13
FORECAST FUEL PRICES AND GROWTH RATES

Year	Fuel Price (2001$)	Personal Income Growth (%)
2001	1.71	-0.48
2002	1.66	+0.34
2003	1.69	+1.79
2004	1.67	+1.48
2005	1.64	+2.10
2006	1.64	+2.76
2007	1.64	+2.12
2008	1.64	+2.80
2009	1.64	+1.64
2010	1.64	+1.84
2020	1.64	+1.28 (average)

Source: CEC.

The CAFE scenarios utilize the four-year, eight percent discount rate based fuel savings calculations but set CAFE standards to increase to 38 MPG for light cars and 28.5 MPG for light trucks in 2015. The first CAFE case assumes CAFE increases start in 2003, and has the built-in assumption that manufacturers are aware by 1999 that this will occur. The second assumes CAFE increase starting in 2005 to reach the same levels in 2015, and standards continue to increase to 2020 at the same rate in this scenario. CAFE penalties are $100 per MPG per car in both cases to maximize response.

The feebate case models a situation where a vehicle gets a fee or rebate of $183,000 per GPM (inverse of MPG). This translates into a study scale of feebates per MPG with increasing MPG. For example, increasing MPG from 20 to 21 results in a GPM reduction of 0.002381 for a fee decrease of $435.71. Increasing MPG from 30 to 31 decreases GPM but 0.001072 for a fee decrease of $196. Hence, larger fees and rebates apply to lower fuel economy vehicles. As expected, car MPG values are close to the high CAFE case, but truck MPG values are higher. In addition, smaller vehicles have somewhat smaller increases in MPG relative to the high CAFE case, but the results are not dramatically different, since in both cases technology introduction rate constraints prevents a more rapid response.

Figures 1 to 4 show that results for all cases except the last CAFE and feebate case, for midsize domestic (low price) cars and compact domestic SUVs (low price). In all cases, there is a relatively large increase in fuel economy in 2003/2004. This is due to the lagged response of manufacturers to the fuel price increase that occurred in late 2000. (Note that the fuel price forecast shows that prices continue to stay high in the future.) It is interesting to note that the vehicle prices in the high CAFE case are about $1000 to $1200 higher than in the base case. Also, the vehicles in the CEC cases are heavier and more powerful than in the EEA base case, accounting for the higher price, in spite of the lower fuel economy.

The two base cases reflect the significant uncertainty in consumer trends in the future, with fuel economy differing by 13 percent in 2010 for both cars and SUVs of which nine percent is due to assumptions on weight/horsepower trends, and four percent due to the GDI engine. The CAFE

FIG 1 Fuel Economy Forecast for Domestic Mid-sized Cars

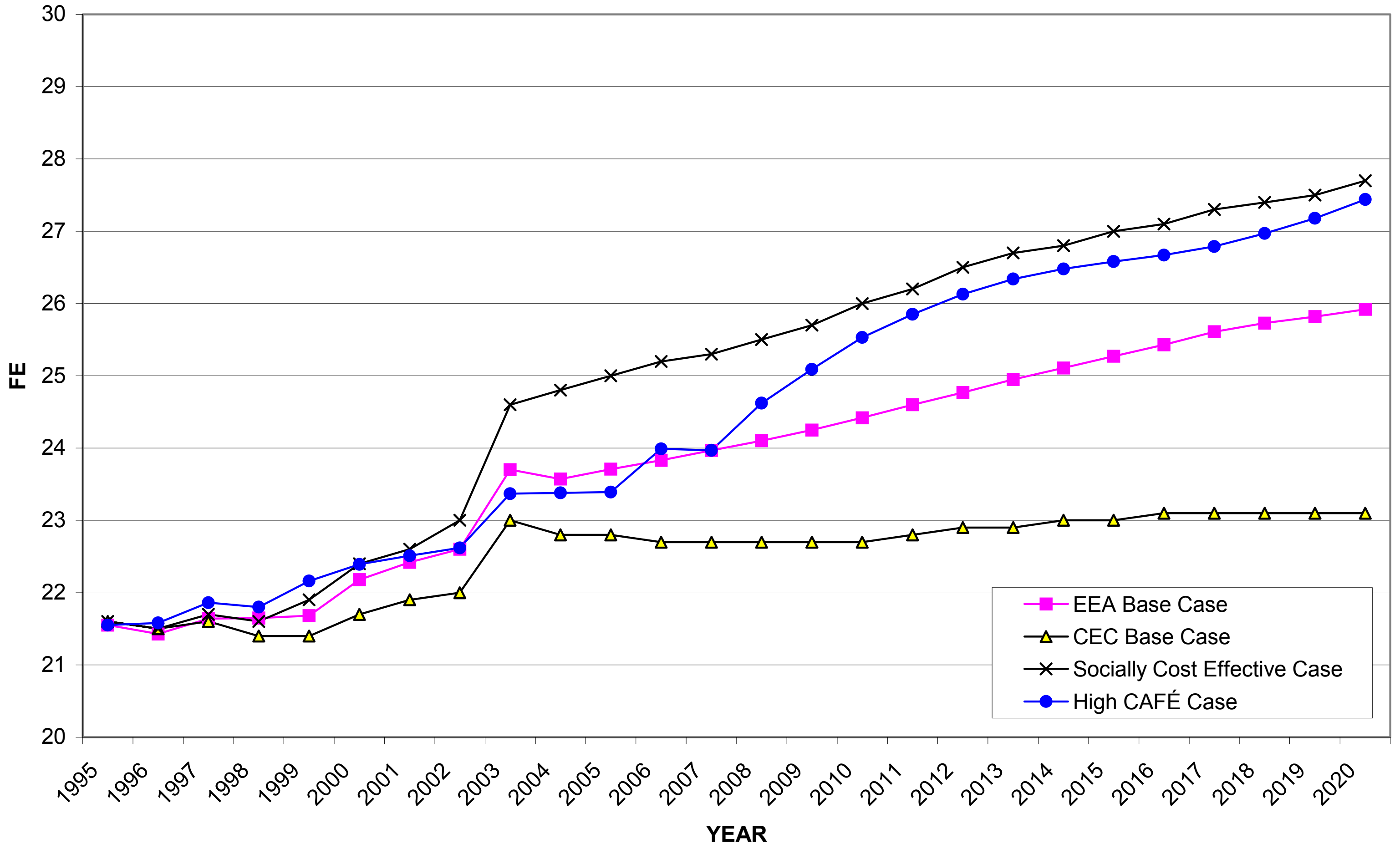


FIG 2 Retail Price Effects for Domestic Mid-sized Cars

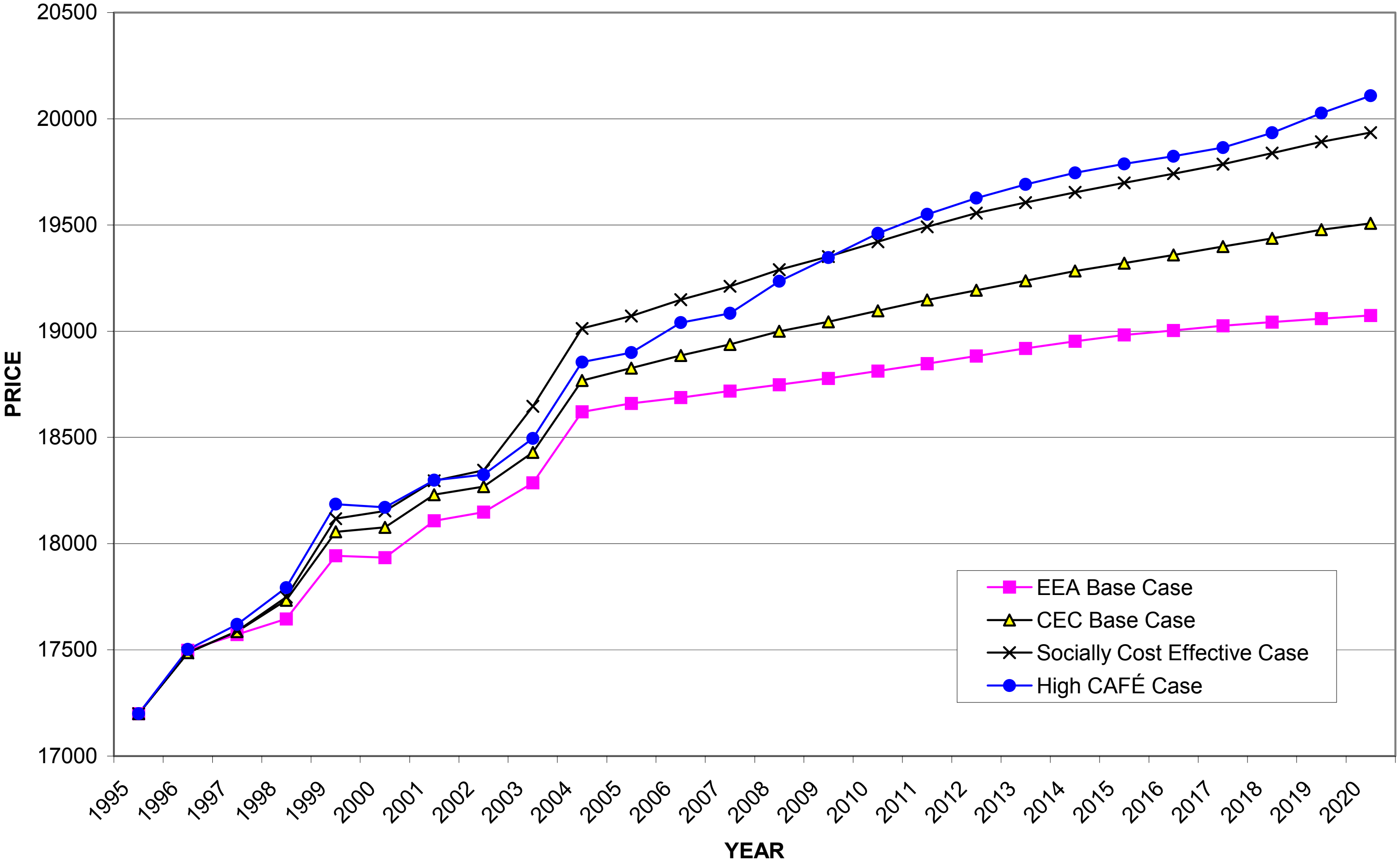


FIG 3 Fuel Economy Forecast for Domestic Compact SUVs

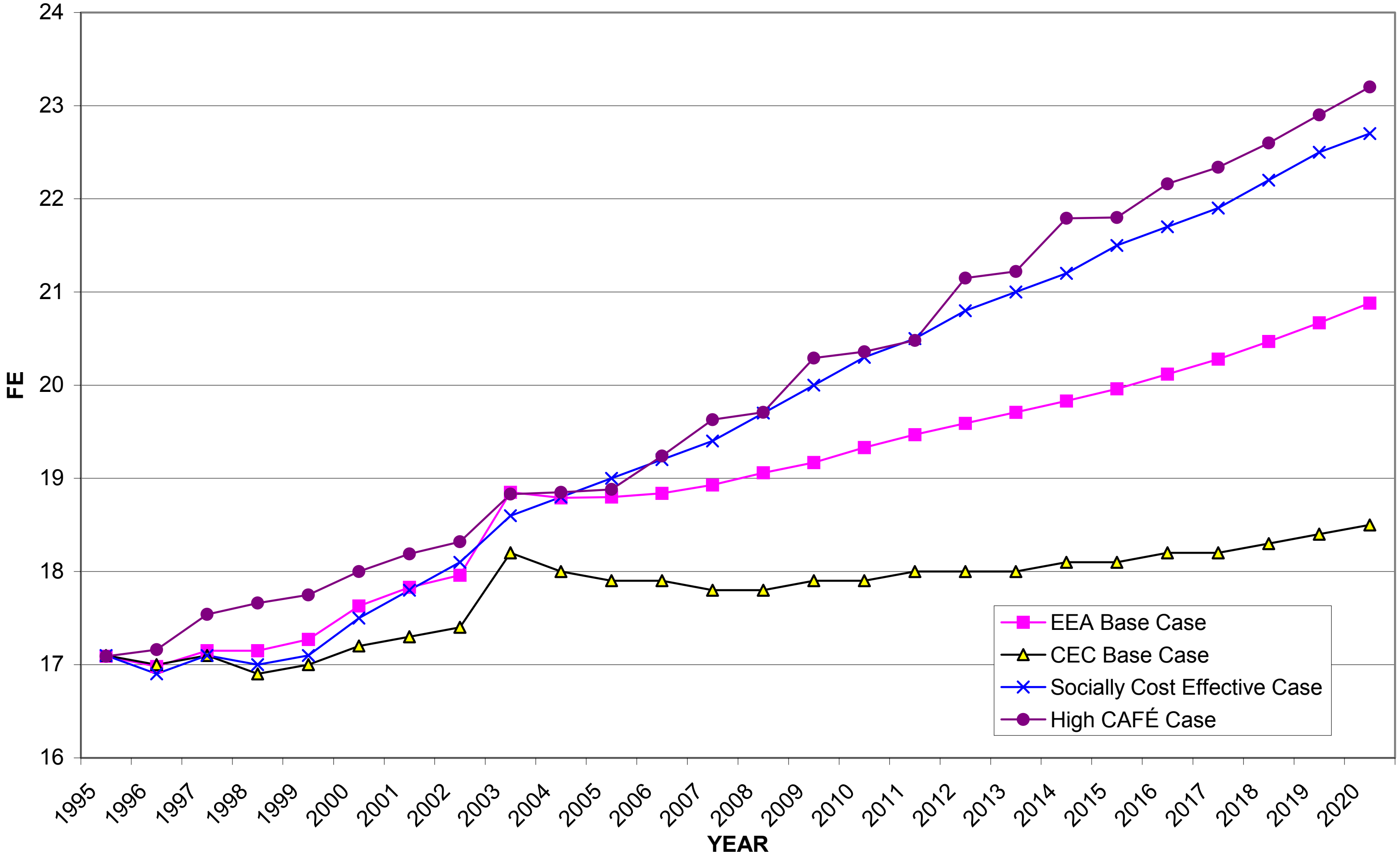
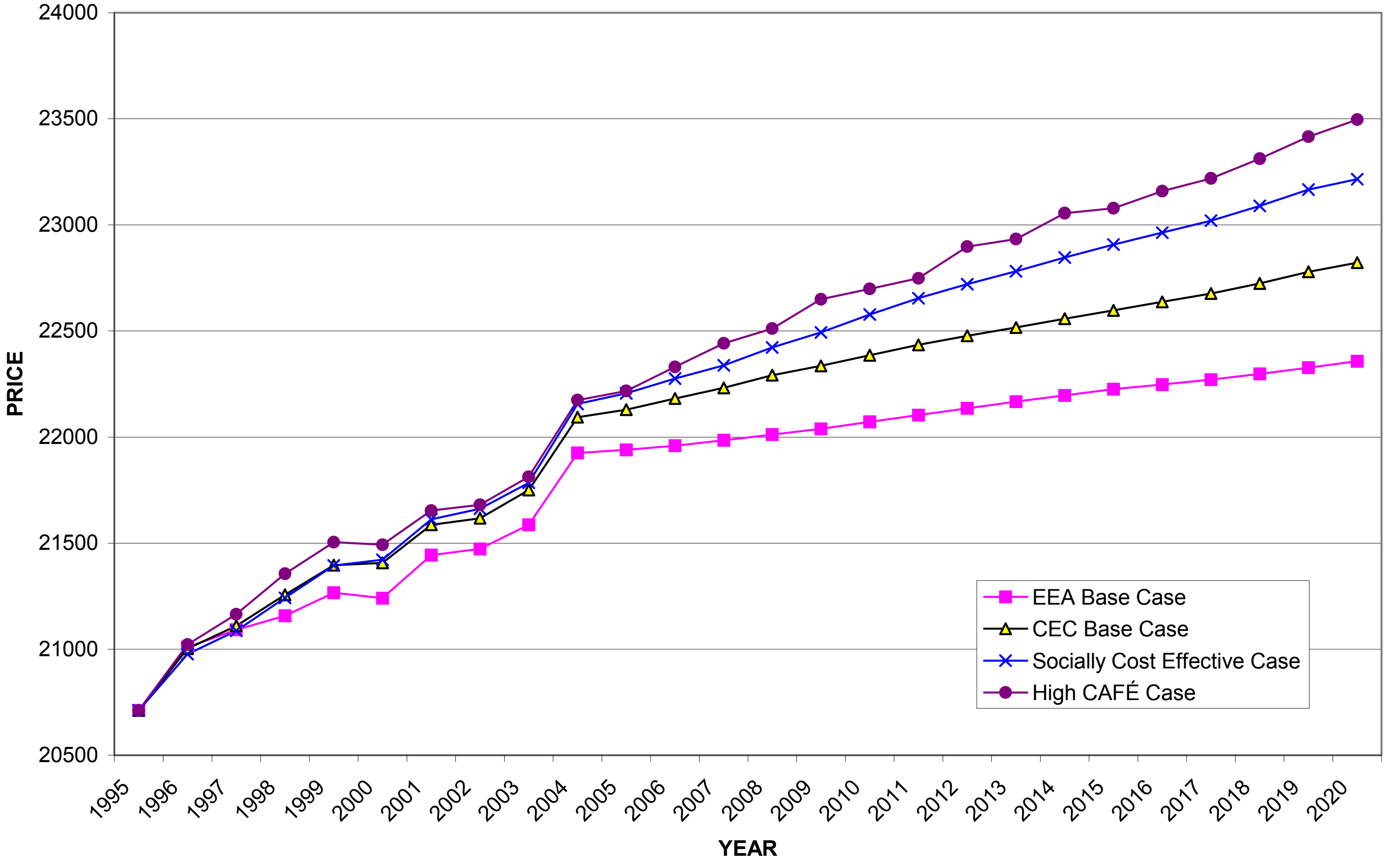


FIG 4 Retail Price Effects for Domestic Compact SUVs



case and 14-year case are very close to each other and this is consistent with the NAS report finding that a 35 to 40 percent increase in fuel economy can be cost effective over the life of the vehicle for cars and trucks. The 14-year payback period case has a very large response to the fuel price increase in 2000, due to the built-in assumptions in the FEM on the reaction to a fuel price "shock". This may not be realistic if manufacturers and consumers perceive the price increase to be a temporary rather than permanent increase.

In the CAFE driven cases, the additional regulatory penalties drive increased technology usage to increase fuel economy ten percent over the EEA case, and 20 percent over the CEC base case. These numbers do not include fuel economy benefits from hybrid vehicle, whose market penetration is determined by the CEC model. The fuel economy benefits are not as large as expected due to the fact the model automatically "trades away" some of the fuel economy benefits for increased performance/luxury if fuel prices are low and CAFE standards are high. Tables 14 and 15 provide some insight into the technology adoption for cars and light trucks, respectively, under the CAFE case. Market penetration in 2020 has been organized into four bins, and a visual examination of the tables shows the reader broad summary of technology utilization in the forecast. Even under a high CAFE scenario, some technologies have very low penetration due to their high cost, e.g., aluminum intensive structures, variable compression ratio engines, electric water pumps.

A key shortcoming of the forecast is its inability to equilibrate supply with demand. The number of models within class is not endogenously determined, and no equilibration of supply and demand occur. EEA understands that our "forecast" of the number of models is a significant determinant of market share in the CEC model; hence, the supply forecast drives the demand forecast to a large degree. Ideally, an interactive or stepwise solution with demand and supply equilibrating over time would provide for a more accurate modeling of the process. These issues could be addressed in future versions of the model.

TABLE 14
CAFE CASE TECHNOLOGY MARKET PENETRATION (CARS)

TECHNOLOGY	VERY LOW	LOW	MEDIUM	HIGH
WEIGHT REDUCTION				
- HSLA INTENSIVE				*
- SMC/RIM CLOSURES			*	
- LIGHTWT. INTERIORS				*
- AL FORGINGS/CASTINGS			*	
- AL. INTENSIVE STRUCTURE	*			
DRAG REDUCTION				
- 10% REDUCTION				*
- 20% REDUCTION				*
- 30% REDUCTION		*		
ROLLING RESISTANCE				
- 10% REDUCTION				*
- 20% REDUCTION				*
- 30% REDUCTION		*		
SPARK IGNITION ENGINES				
- 4VALVES/CYLINDER				*
- VVTL				*
- CYLINDER CUTOUT		(V-8/6)		
- INTAKE THROTTLING		*		
- VARIABLE COMPRESSION	*			
- SUPERCHARGING	*			
- DIRECT INJECTION (LEAN)		*		

TABLE 14
CAFE CASE TECHNOLOGY MARKET PENETRATION (CARS)
(Continued)

TECHNOLOGY	VERY LOW	LOW	MEDIUM	HIGH
TRANSMISSIONS				
- 5-SPEED AUTOMATIC		*		
- CVT			*	
- 6-SPEED AUTOMATIC				
- LOW LOSS CONVERTER				*
- AGGRESSIVE SHIFT			*	
ACCESSORIES				
- EFFICIENT ALTERNATOR				*
- GEAR DRIVE OIL PUMP				*
- ELECTRIC POWER STRNG.			*	
- ELECTRIC WATER PUMP	*			
ELECTRONIC CONTROL				
- ELECTRONIC THROTTLE				*
- EARLY CONVERTER LOCK				*
- ELEC. ACTUATED VALVES	*			
DRIVELINE				
- REDUCED BRAKE DRAG				*
- EFFICIENT 4WD TRANSFER	*			

Note Very low = Less than 10% market share
Low = Less than 35% but over 10% market share
Medium = Less than 70% but over 35% market share
High = Over 70% market share

TABLE 15
CAFE CASE TECHNOLOGY MARKET PENETRATION (TRUCKS)

TECHNOLOGY	VERY LOW	LOW	MEDIUM	HIGH
WEIGHT REDUCTION				
- HSLA INTENSIVE				*
- SMC/RIM CLOSURES				*
- LIGHT INTERIORS				*
- AL FORGINGS/CASTINGS		*		
- AL. INTENSIVE STRUCTURE	*			
DRAG REDUCTION				
- 10% REDUCTION				*
- 20% REDUCTION			*	
- 30% REDUCTION	*			
ROLLING RESISTANCE				
- 10% REDUCTION				*
- 20% REDUCTION				*
- 30% REDUCTION	*			
SPARK IGNITION ENGINES				
- 4VALVES/CYLINDER				*
- VVTL			*	
- CYLINDER CUTOUT			*	
- INTAKE THROTTLING	*			
- VARIABLE COMPRESSION	*			
- SUPERCHARGING	*			
- DIRECT INJECTION (LEAN)		*		
TRANSMISSIONS				
- 5-SPEED AUTOMATIC				*
- CVT		*		
- 6-SPEED AUTOMATIC	*			
- LOW LOSS CONVERTER				*
- AGGRESSIVE SHIFT		*		

TABLE 15
CAFE CASE TECHNOLOGY MARKET PENETRATION (TRUCKS)
(Continued)

TECHNOLOGY	VERY LOW	LOW	MEDIUM	HIGH
ACCESSORIES				
- EFFICIENT ALTERNATOR				*
- GEAR DRIVE OIL PUMP				*
- ELECTRIC POWER STRNG.			*	
- ELECTRIC WATER PUMP	*			
ELECTRONIC CONTROL				
- ELECTRONIC THROTTLE				*
- EARLY CONVERTER LOCK				*
- ELEC. ACTUATED VALVES	*			
DRIVELINE				
- REDUCED BRAKE DRAG				*
- EFFICIENT 4WD TRANSFER			*	

Note Very low = Less than 10% market share
Low = Less than 35% but over 10% market share
Medium = Less than 70% but over 35% market share
High = Over 70% market share

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