United States
Environmental Protection
Agency

Office of Transportation and Air Quality
www.epa.gov/otaq/technology

EPA420-R-05-012
October 2005

Interim Report: New Powertrain Technologies and Their Projected Costs

EPA420-R-05-012
October 2005

Interim Report: New Powertrain Technologies and Their Projected Costs

Jeff Alson
Benjamin Ellies
David Ganss

Transportation and Climate Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE
This interim report presents technical analysis of issues using data that are currently available to EPA. It does not represent final EPA decisions or positions. EPA welcomes comments from interested parties, and will make appropriate changes to this analysis as relevant information becomes available.

Table of Contents

Abstract

This interim report projects the cost effectiveness, from a consumer perspective, of four technology strategies capable of improving new personal vehicle fuel economy over the next decade: packages of individual gasoline vehicle technologies, advanced diesel engines, gasoline electric hybrids, and diesel electric hybrids. These economic projections are based on a future high-volume scenario where economies-of-scale for these technologies are similar to those for conventional vehicles today. They do not account for the higher manufacturer and consumer costs during a transition period.

Based on EPA's review of the technical literature, all of these technology packages are projected to increase personal vehicle retail cost, ranging from around $1000 for a gasoline vehicle package in a midsize car to about $6000 for a diesel electric hybrid in a large SUV. But, by increasing vehicle fuel economy by 20% to 70%, these technologies will also reduce vehicle operating costs (primarily fuel expenditures). This report projects the consumer payback period, i.e., how many years it takes for a consumer to recoup in discounted operating savings an amount equal to the higher initial cost of the vehicle.

Based on a set of common economic assumptions, these technologies are projected to pay back to consumers in 2 to 11 years. Since all of these technologies pay back in less than the projected 14-year life of a vehicle, they would all provide net savings over a typical vehicle lifetime. These discounted lifetime savings range from $300 for one of the midsize car scenarios to over $4000 for some of the large SUV scenarios. In all cases, the payback period is shorter and the lifetime savings are greater when the advanced technologies are used in a large SUV rather than in a midsize car.

The assumed 14-year lifetime accounts for all the consumers who own the vehicle over that timeframe. Individual consumers who buy an advanced technology vehicle and sell the vehicle prior to the 14th year may or may not achieve payback depending on whether vehicle resale value reflects future operating cost savings.

This report makes two important conclusions:

- Multiple powertrain technologies have the potential to offer personal vehicle fuel economy improvements of 20% to 50% compared to today's gasoline vehicles; diesel electric hybrids have the potential to increase fuel economy by 70%.
- All of these technology packages pay back to consumers collectively over a 14-year timeframe, and many will pay back to individual consumers who own vehicles for less than 14 years.

These results should not be taken to imply that these technologies will necessarily move into the mainstream market in the near future. Decisions by manufacturers to invest in, and consumers to buy, new technologies involve many factors well beyond the scope of this paper. The point of this paper is not to predict future manufacturer or consumer behavior, but rather to project the cost effectiveness if they do adopt new personal vehicle technologies.

Executive Summary

This interim study examines the cost-effectiveness of automotive powertrain technologies with the potential for significantly improving new personal vehicle fuel economy in the next 5 to 10 years. It relies on independent projections of fuel economy improvement potential and incremental cost for individual technologies, and evaluates the technologies on a common economic basis. This study uses two consumer metrics for economic comparisons: the number of years that it would take for a consumer to pay back his or her up front investment in the fuel economy technology with discounted operating cost savings over time, and the net discounted consumer savings over a typical 14-year vehicle lifetime.

The economic projections in this report are based on a future high-volume scenario where the economies of scale and relative profit for the advanced technology vehicles approach those for high-volume conventional vehicles today. Costs for new technologies will undoubtedly be higher during a transition period when economies of scale will be much lower and there will be a series of initial investments, but estimates of these transition costs are beyond the scope of this paper. On the other hand, costs may ultimately be lower than those projected here for any technology that achieves long-term market maturity, as sustained market share would justify continued cost reduction that cannot be predicted at this time.

The four technologies evaluated in this study are:

- various packages of "incremental" improvements to gasoline vehicles
- advanced diesel engines
- gasoline/battery hybrid vehicles
- diesel/battery hybrid vehicles

The first three technologies are, at least in part, already commercialized in multiple personal vehicle models in one or more of the major world automotive markets.

This study evaluates the new powertrain technologies in two specific vehicle applications: large sport utility vehicles (SUVs) with four-wheel drive, and midsize cars with front-wheel drive. In general, this report assumes no change in vehicle size or 0-to-60 mile per hour acceleration performance; however, some of the referenced literature anticipates an increase in acceleration or torque performance for the diesel and hybrid vehicles (which is consistent with current market trends). Assuming equal fuel tank size, advanced technology vehicles will always provide increased vehicle range relative to conventional vehicles.

This analysis requires both technology-specific inputs as well as a generic set of common economic assumptions.

The primary technology-specific inputs are projections of fuel economy improvement potential and incremental retail cost. EPA reviewed the technical literature and selected technology projections by independent experts for each of the technologies. The two sets of technology projections for gasoline vehicle technology packages were derived from studies by the National Academy of Sciences (NAS) and the Northeast States Center for a Clean Air Future (NESCCAF). One set of diesel vehicle projections was based on work done by FEV Engine Technology, Inc. and EPA, while the second was based on a study by Oak Ridge National Laboratory (ORNL). The two sets of technology projections for gasoline/battery hybrid vehicles were drawn from reports by the Electric Power Research Institute (EPRI) and ORNL. Finally, EPA derived the technology projections for diesel/battery hybrids based on information from several sources. In order to put all of the cost projections on a comparable basis, EPA adjusted cost projections of the independent studies to reflect the retail markup used by EPA in regulatory decisions.

Important technology-specific inputs are shown in the first three columns of Tables ES-1 through ES-4 (for Gasoline Vehicles, Advanced Diesel Vehicles, Gasoline/Battery Hybrids, and Diesel/Battery Hybrids, respectively).

The technology packages are projected to improve fuel economy from 20% (NAS gasoline technology package for the midsize car) to 72% (EPA diesel/battery hybrid for the large SUV). The incremental prices of the various technology packages are predicted to range from $712 (NAS gasoline technology package for the midsize car) to $5912 (EPA diesel/battery hybrid for the large SUV).

Table ES-1: Key Results for Gasoline Vehicles

		Fuel Economy Improvement (%)	CO2 Reduction (%)	Vehicle Price Increase* ($)	Consumer Payback (years)	Lifetime Savings ($)
Large SUV	NAS	42%	30%	$1,467	1.8	$4,386
	NESCCAF	31%	24%	$1,619	2.5	$3,288
Midsize Car	NAS	20%	17%	$712	3.8	$897
	NESCCAF	41%	29%	$1,318	3.9	$1,552

* Cost values adjusted to reflect use of EPA's 1.26 retail markup factor as discussed in Section 1.4.2.

Table ES-2: Key Results for Advanced Diesel Vehicles

		Fuel Economy Improvement (%)	CO2 Reduction		Vehicle Price Increase*	Consumer Payback (years)	Lifetime Savings ($)
			Vehicle (%)	Lifecycle[1] (%)			
Large SUV	FEV/EPA	41%	18%	21%	$1,760	2.1	$4,284
	ORNL	33%	14%	16%	$2,560	4.1	$2,597
Midsize Car	FEV/EPA	40%	18%	21%	$1,252	3.8	$1,563
	ORNL	33%	14%	16%	$1,810	7.7	$634

* Cost values adjusted to reflect use of EPA's 1.26 retail markup factor as discussed in Section 1.4.2.

---

[1] This column adds the difference in diesel fuel production refining impacts to the vehicle CO2 reduction figures. On a lifecycle basis, the total benefit of diesel engines is somewhat higher because there are higher per-gallon energy losses for gasoline production than for diesel production.

Table ES-3: Key Results for Gasoline/Battery Hybrid Vehicles

		Fuel Economy Improvement (%)	CO2 Reduction (%)	Vehicle Price Increase* ($)	Consumer Payback (years)	Lifetime Savings ($)
Large SUV	EPRI	52%	34%	$4,464	5.0	$3,179
	ORNL	35%	26%	$3,039	4.1	$2,882
Midsize Car	EPRI	45%	31%	$2,500	7.4	$934
	ORNL	40%	29%	$2,683	9.5	$509

* Cost values adjusted to reflect use of EPA's 1.26 retail markup factor as discussed in Section 1.4.2.

Table ES-4: Key Results for Diesel/Battery Hybrid Vehicles

		Fuel Economy Improvement (%)	CO2 Reduction		Vehicle Price Increase* ($)	Consumer Payback (years)	Lifetime Savings ($)
			Vehicle (%)	Lifecycle (%)			
Large SUV	EPA-derived	72%	33%	35%	$5,912	5.8	$3,321
Midsize Car	EPA-derived	71%	33%	35%	$4,123	11.4	$344

* Cost values adjusted to reflect use of EPA's 1.26 retail markup factor as discussed in Section 1.4.2.

To ensure methodological consistency in the economic comparisons (from a consumer perspective of the various technologies), this study evaluates each technology on a common economic basis with the following assumptions:

- economies-of-scale based on a high-volume, mature production scenario
- retail markup factor of 1.26
- downward laboratory-to-road fuel economy adjustment of 0.85
- 14-year vehicle miles traveled profile based on EPA's MOBILE6 emissions model
- nominal gasoline and diesel fuel price of $2.25 per gallon
- discount rate of 7 percent per year
- equivalent operating costs except for fuel expenditures and, for hybrid vehicles, brake maintenance expenditures
- no federal tax credit for hybrids or diesels
- no market externalities

The final two columns of Tables ES-1 through ES-4 show projections for the two most important economic outputs of this analysis: consumer payback and net lifetime consumer savings. Projections of the consumer paybacks for the various technologies range from about 2 years (for both gasoline packages and the FEV/EPA diesel package for the large SUV) to over 11 years (EPA diesel/battery hybrid package for the midsize car). In every case, the analysis projects that the new technologies will have shorter payback periods for an owner of a large SUV than for an owner of a midsize car. Industry statements suggest that cost paybacks of 3-4 years or less are generally necessary to stimulate market-driven introduction of new technologies. Several of the technologies appear to meet this threshold.

Since all of the technology packages have projected consumer payback periods of less than 14 years, they also have projected net lifetime consumer savings as well. The projected net lifetime savings range from $2600 to $4400 for large SUVs and from $300 to $1600 for midsize cars. These lifetime savings will accrue collectively to all individual consumers who own the vehicle during the assumed 14-year lifetime. Individual consumers who buy a new advanced technology vehicle and sell the vehicle prior to the 14th year will realize smaller savings (and even net costs if they sell before the payback period) unless vehicle resale value reflects the future savings associated with the technology.

The actual fuel economy improvement and cost of emerging powertrain technologies will not be known unless and until they are commercialized and sustain reasonable economies-of-scale. Such comparisons are certain to change as these technologies continue to be developed and refined. It is also likely that the best powertrain choices for individual vehicle models will vary by manufacturer, vehicle class, and/or consumer preferences with respect to vehicle attributes other than the economic metrics used in this paper.

This report makes two important conclusions:

- Multiple powertrain technologies have the potential to offer personal vehicle fuel economy improvements of 20% to 50%, and diesel electric hybrids have the potential to increase fuel economy by 70%.
- All of these technology packages pay back to consumers collectively over a 14-year timeframe, and many will pay back to individual consumers who own vehicles for less than 14 years.

While no one can predict at this time which future technologies will be most popular, the technologies studied in this paper are projected to be cost-effective, provide significant fuel savings, and provide equivalent or better vehicle performance and utility.

These results should not be taken to imply that these technologies will necessarily move into the mainstream market in the near future. Decisions by manufacturers to invest in, and consumers to buy, new technologies involve many factors well beyond the scope of this paper. The point of this paper is not to predict future manufacturer or consumer behavior, but rather to project the cost effectiveness, on a collective consumer basis, if they do adopt new personal vehicle technologies.

In August 2005, EPA asked 15 individuals to provide a technical review of a draft of this report. As of October 12, 2005, EPA had received comments from 8 of these reviewers. The most important comments, and EPA’s responses to these comments, are summarized in Appendix E. EPA welcomes additional comments on this interim report.

1. Introduction

Both the automobile industry and the federal government have large research and development programs to develop and evaluate new technologies for improving vehicle fuel economy. However, there is much disagreement within the large body of literature describing advanced vehicle technologies, not only with respect to substantive issues of fuel economy improvement potential and cost, but also on methodological issues involving economic assumptions used in the various analyses.

The purpose of this paper is to:

- summarize recent independent estimates of the likely fuel economy and cost impacts of new automotive technologies that have the potential to be commercialized in the next 5 to 10 years, and to
- place these estimates on a common economic basis to allow an economic comparison (from a consumer perspective) of the various technologies based on the best current technology projections.

1.1 Technologies Evaluated in This Report

This study examines four automotive powertrain technologies with the potential for significantly improving new personal vehicle fuel economy in the near term.

The first three technologies in this study are, at least in part, already commercialized in multiple personal vehicle models in one or more of the major world automotive markets: various packages of "incremental" improvements to gasoline vehicles, advanced diesel engines, and gasoline/battery hybrid vehicles. Many of the individual technologies in the gasoline vehicle package have been incorporated into certain production vehicles, particularly in the European and Japanese markets. One-half of new personal vehicle sales in Europe now are diesel vehicles. Nine gasoline/battery hybrid models are on sale in the U.S. market, and manufacturers have announced plans for several other models to be introduced in the next 2 to 3 years.

The fourth technology--diesel/battery hybrids--is not currently commercialized in the personal vehicle market anywhere in the world, but is under development and will likely be considered for commercialization in the next decade.

Two technologies that are not part of this study are hydraulic hybrid vehicles and fuel cell vehicles. EPA is optimistic about the potential of hydraulic hybrid and fuel cell vehicles in the long term, but these technologies are still under development and no personal vehicle manufacturer has yet made production commitments. Several private companies, such as Eaton Corporation and Parker-Hannifin Corporation, are actively developing hydraulic hybrid applications for heavy-duty applications. EPA is a leader in the development of hydraulic hybrid technology, and recently provided detailed projections on cost and fuel economy improvement for personal vehicle applications for hydraulic hybrids. [Reference 1-1] Fuel cell vehicles are the subject of intense research and development within both the industry and the federal government's FreedomCar project, but it will likely be some time before anyone can project future fuel cell vehicle cost with confidence.

1.2 Vehicle Classes

This report focuses on two vehicle classes which, because of their high sales volumes, have the potential to yield large aggregate fuel and carbon savings: large sport utility vehicles (SUVs) with 4-wheel drive (e.g., Dodge Durango, Ford Expedition) and midsize cars with front wheel drive (e.g., Chevrolet Malibu, Honda Accord). These two classes alone represent over 25% of the overall personal vehicle market and a higher proportion of overall fuel use and carbon emissions. [Reference 1-2] The impact of various technologies on fuel economy and cost for these high-volume classes will translate to other vehicle classes in varying degrees.

Based on representative vehicles in the 2002 model year federal fuel economy database, the baseline large SUV vehicle is assumed to have a curb weight of about 5300 pounds, a composite city/highway, laboratory fuel economy of 17.2 mpg, and an adjusted "label" composite fuel economy of 14.6 mpg. The baseline midsize car is assumed to have a curb weight of about 3200 pounds, a composite city/highway, laboratory fuel economy of 29.0 mpg, and an adjusted "label" composite fuel economy of 24.7 mpg.

This study assumes no change in vehicle size. In general, the report assumes no change in vehicle performance as well, but sometimes diesels and hybrids are assumed to have increased torque and/or acceleration performance consistent with recent market trends. Gasoline/battery hybrid vehicles that involve engine downsizing would not retain the same performance for certain low-frequency vehicle operating modes such as sustained towing and sustained high-grade acceleration, but those hybrid designs that did retain the base engine would retain these capabilities. Some of the technologies analyzed in this paper will involve changes in vehicle weight (which affect fuel economy), due to direct hardware changes inherent in the technologies. No use of lightweight materials is assumed for any of the technology packages. Advanced technology vehicles will generally provide increased vehicle range relative to conventional vehicles.

1.3 Technology-Specific Inputs

The primary technology-specific inputs are projections of fuel economy improvement potential and incremental cost. A comprehensive review of the literature was carried out and recent technology projections by independent experts were selected. Accordingly, it is important to note that the technology-specific inputs of fuel economy improvement and incremental cost for the individual technologies are from multiple sources.

Fuel economy improvement projections are for composite EPA city/highway driving (based on the EPA city and highway driving cycles used for fuel economy testing), and applies a weighting of 55% city driving and 45% highway driving. All analyses in this report use consumer fuel economy estimates, i.e., laboratory or CAFE fuel economy values reduced by 15% to account for laboratory-to-road shortfall.

Cost projections are much more complex. The central cost input taken from independent sources for each new technology is the incremental cost to the manufacturer, all other things being equal, of the new technology relative to the baseline conventional gasoline vehicle. This cost projection involves a myriad of design and manufacturing cost issues, sometimes involving individual components that have not been commercialized in personal vehicle applications. One important methodological issue is that studies often make different assumptions about retail markup factors. As discussed in the next section, this study uses a single consistent retail markup for all of the technologies, which means that the incremental retail cost projections from individual studies in the literature are sometimes adjusted in order to apply this consistent markup, thereby allowing this paper to isolate meaningful cost differences of various technologies.

1.4 Common Assumptions Used in the Economic Comparisons

To ensure consistency in the comparison of the efficiency and cost projections for the various technologies, this study evaluates each technology on a common economic basis with the same set of economic assumptions. All economic assessments are made from the perspective of the consumer(s) who would own and drive the vehicles, rather than from the perspective of society at large. An economic analysis from a societal perspective would require some changes in the economic assumptions, for example, excluding economic impacts related to taxes, including societal costs and benefits associated with externalities, and including possible impacts related to a potential rebound effect (i.e., where lower driving costs may lead to greater travel).

1.4.1 Economies of Scale

Cost in the automotive industry is driven to large degree by economies-of-scale. Every attempt was made in this study to rely exclusively on technology cost projections that were based upon a mature, high-volume production environment where economies-of-scale for new technologies are comparable to those for conventional technologies. The central assumption is that the cost projections are for a longer-term scenario where the economies-of-scale and relative profit for the advanced technology vehicles approach those for high-volume conventional vehicles today. The rationale for this assumption is threefold: 1) it allows an “apples and apples” comparison with conventional technology, 2) a valid long-term business case is a critical parameter for justifying investment in a new technology, and 3) it is consistent with the cost assumptions in most technology studies. It is important to note that these cost projections are not relevant to a transition period where the advanced technology is initially commercialized and production volumes are low. There can be significant transition costs associated with research and development, engineering, retooling manufacturing facilities, and lower economies-of-scale. In fact, in some cases, transition costs can be high enough to delay or prevent a technology’s introduction—especially if future expected price decreases due to competition or other factors limit the lifetime profit potential of the technology. The complexities of the transition period are beyond the scope of this paper.

On the other hand, in high-volume automotive manufacturing, once a technology achieves market maturity there is a strong economic incentive to continually reduce cost.

So, it is also quite possible that the actual costs may drop below this report's projected cost estimates if and when any of these advanced technologies actually achieve market maturity. The bottom line is that the cost projections in this study are most relevant to a period 5-10 years beyond initial commercialization when economies-of-scale are reached.

1.4.2 Retail Price Equivalent

Cost in the automotive industry can be expressed in many different ways, some of which are cost to manufacture, cost to an automaker buying a component from a supplier, or retail price to a consumer. In calculations of consumer payback and lifetime consumer savings, this report uses retail price to a consumer, and every effort is made to ensure that all retail price projections are expressed in an equivalent manner. The starting point for calculating a retail price projection in this report is the cost to a vehicle manufacturer of buying a component from an automotive supplier (for which the price paid by the vehicle manufacturer to the supplier already includes a "supplier markup" to account for overhead and profit at the supplier level). For this projected cost, this study relies on independent projections from the literature. A retail price equivalent (RPE) factor is used to convert the cost of the component to the vehicle manufacturer to an incremental retail price to take into account markup at the vehicle manufacturer and dealer levels. In cost-benefit analyses of public policies, EPA uses a retail price equivalent factor of 1.26 for light-duty vehicles, based on a study that was done for EPA that examined appropriate values for manufacturer overhead, manufacturer profit, dealer interest expense, dealer profit, and sales commissions. [Reference 1-3] Other recent studies have used RPEs of 1.4 or 1.6. Appendix D contains a sensitivity analysis of consumer payback time using RPEs of 1.4 and 1.6. This study adjusts the incremental retail cost projections from other studies in order to apply a consistent 1.26 retail markup.

1.4.3 Laboratory-to-Road Fuel Economy Adjustment

This report assumes that real world fuel economy is 85% of the composite city/highway value obtained in laboratory testing using the EPA city and highway driving cycles. This 15% reduction reflects the adjustments that EPA uses for the fuel economy values it provides to consumers via new vehicle labels, the Fuel Economy Guide, and the Green Vehicle Guide website: a 10% reduction in city fuel economy and a 22% reduction in highway fuel economy.

Accordingly, for purposes of the economic calculations, the baseline SUV vehicle in this analysis is assumed to have a composite city/highway, real world fuel economy of 17.2 mpg (laboratory) times 0.85, or 14.6 mpg. The baseline midsize car is assumed to have a composite city/highway, real world fuel economy of 29.0 mpg (laboratory) times 0.85, or 24.7 mpg.

EPA is currently evaluating the methods used to generate consumer label fuel economy values. EPA has begun a collaborative process with stakeholders to update the current methodology and plans to propose appropriate changes in the near future.

1.4.4 Vehicle Miles Traveled Profile

This report adopts the vehicle miles traveled (VMT) profiles from EPA's MOBILE6 emissions model. Accordingly, this report assumes that large SUVs travel about 20,000 miles in the first year of operation, decreasing to 15,300 miles in the fifth year, 11,000 miles in the tenth year, and 8400 miles in the 14th year, which is the last year in the profile, for a total of 188,000 miles. Midsize cars are assumed to travel 14,900 miles in the first year of operation, decreasing to 12,200 miles in the fifth year, 9500 miles in the tenth year, and 7700 miles in the 14th year, for a total of 153,000 miles.

These values do not include the effect of vehicle scrappage (which is appropriate when analyzing from a societal perspective) because the goal here is to analyze the economic impacts from a consumer perspective. By using a 14-year timeframe, the above cumulative mileage values for both SUVs and midsize cars are slightly less than the cumulative mileage values from MOBILE6 using a 30-year timeframe and scrappage rates. Because this analysis is from a consumer, rather than from a societal, perspective, no rebound effect is assumed.

1.4.5 Fuel Price

This report uses a nominal price of $2.25 per gallon for both gasoline and diesel fuel, based on the national average in April 2005. [Reference 1-4] Fuel taxes are included in the fuel price because the analysis is from a consumer perspective (as opposed to a societal perspective, where transfer payments such as fuel taxes would be excluded).

Since fuel prices are volatile and an important assumption in the consumer payback methodology, Appendix C contains a sensitivity analysis which shows the consumer payback results for fuel prices ranging from $1.50 per gallon to $3.00 per gallon. Nominal fuel prices less than $2.25 per gallon in the future would make fuel-saving technologies less cost effective and nominal fuel prices greater than $2.25 per gallon in the future would make these technologies more cost effective. As is the case for vehicle costs, no future inflation is assumed.

1.4.6 Discount Rate

A discount rate recognizes that a dollar is worth more to a consumer today that it will be to a consumer tomorrow. Since a consumer will pay the extra cost associated with new fuel economy technology at the time of vehicle purchase, but will only monetarily benefit from operating savings over time, use of a discount rate in economic calculations is appropriate. This report uses a 7% discount rate as recommended by the Office of Management and Budget for cost-benefit analysis. [Reference 1-5] Accordingly, the savings in the second year are discounted by 1-0.93 or 7%, the savings in the third year are discounted by 1-(0.93) to the second power or 13.5%. Savings in the 14th year are discounted by 1-(0.93) to the 13th power, or 61%.

It should be noted that the Office of Management and Budget also recommends that a 3% discount rate be used in cost-benefit analyses, particularly in those cases where public policy primarily affects private consumer consumption as opposed to corporate cost of capital. [Reference 1-6] Assuming a 3% discount rate would shorten the projected consumer payback periods and increase the lifetime consumer savings projections relative to the projections in this paper that are based on a 7% discount rate.

1.4.7 Operating Costs and Consumer Payback

New powertrain technologies have the potential to affect a wide range of operating costs. This study assumes that all operating costs remain constant, with two exceptions: fuel expenditures for all advanced technologies due to higher vehicle fuel economy, and brake maintenance expenditures for gasoline/battery hybrids due to regenerative braking which will reduce the use and maintenance of friction brakes. Two other potential sources of operating costs and consumer payback are not addressed in this report. They are the potential for other maintenance cost increases or decreases associated with the new technologies, and the monetized value to consumers of time saved from less refueling of a vehicle with greater range.

1.4.7.1 Fuel Savings

The calculation of fuel savings is relatively straightforward. The addition of any new fuel economy technology yields a higher real world fuel economy than the real world fuel economies of the baseline vehicles given in Section 1.4.3. This higher real world fuel economy reduces the number of gallons of fuel necessary to travel the number of miles driven each year, taken from the MOBILE6 emissions model discussed in Section 1.4.4. The fewer gallons of gasoline needed is multiplied by the $2.25 price per gallon discussed in Section 1.4.5, which yields the total dollars saved by the consumer in that year. All fuel savings beyond the first year are then discounted at 7% per year as discussed in Section 1.4.6.

1.4.7.2 Warranty and Maintenance Issues

Warranty and maintenance costs can be placed in three categories: warranty, scheduled maintenance, and non-scheduled maintenance. Warranty costs are borne by the manufacturer and are included in the manufacturing cost increases in the original source material. Scheduled maintenance costs are discussed in sections 1.4.7.3 and 1.4.7.4. Non-scheduled maintenance items are repairs that are not covered under warranty, nor are they part of normal, scheduled maintenance. A transmission that fails and requires a rebuild is an example of non-scheduled maintenance. While non-scheduled maintenance expenses can be large and can significantly impact consumer payback, they are by nature unpredictable and so are not addressed in this paper.

1.4.7.3 Brake Maintenance Savings

The calculation of brake maintenance savings, relevant only for hybrid vehicles, is somewhat more complex than fuel savings. Based on a review of the literature, the baseline large SUV is assumed to have front brake maintenance performed four times (replacing only pads twice and replacing both pads and rotors twice) and rear brake maintenance two times (replacing only pads once and replacing both pads and rotors once) over the 188,000 mile expected vehicle lifetime. Because of regenerative braking, where some of the energy otherwise lost as heat in friction brakes will be captured instead by the electric motor/generator and stored in the battery, hybrids will experience less friction brake wear. Electric hybrid large SUVs are assumed to have 50% less brake wear on the front brakes and no change in the brake wear on the rear brakes. For the electric hybrid SUVs, this assumption yields two front brake maintenance events (replacing only pads once and replacing both pads and rotors once) and two rear brake maintenance events (replacing only pads once and replacing both pads and rotors once). The baseline midsize car is assumed to have front brake maintenance performed three times (replacing only pads twice and replacing both pads and rotors once) and rear brake maintenance once (replacing only pads). Electric hybrid midsize cars are also assumed to have 50% less front brake wear, leading to one front brake maintenance event (replacing only pads) and one rear brake maintenance event (replacing only pads). Typical costs were assigned to these brake maintenance events based on surveys of prices by brake shops in the literature. Brake maintenance savings were also discounted by the 7% discount rate discussed in Section 1.4.6.

1.4.7.4 Non-Brake Maintenance Issues

Adopting new technologies for vehicles or making them more complex may potentially increase maintenance and repair costs due simply to the fact that there are more failure modes for more complex systems. In the case of the technologies discussed in this report, there are not enough data yet to determine if there are any increased maintenance costs associated with these technologies. Any possible maintenance cost impacts would be expected to be small. In the case of electric hybrids, there is some anecdotal evidence from a taxi fleet in Vancouver, BC (www.hybridcars.com/blogs/taxi) that the electric drive systems and batteries are quite robust.

In some cases, advanced technologies may reduce routine maintenance costs. For instance, a hybrid vehicle with a downsized engine may require less engine oil and smaller filters, thus reducing maintenance costs. Also, a hybrid drive system can help reduce load on the engine in situations where engine wear is accelerated, such as during cold accelerations. This could result in lower maintenance and longer oil life.

Finally, many complex technologies introduced to motor vehicles have not increased maintenance costs to any significant extent. Technologies such as anti-lock brakes, electronic fuel injection, and electronically-controlled automatic transmissions have all entered widespread use without increasing consumer maintenance expense once the technology has matured. In the case of electronic fuel injection, consumer maintenance expense has been significantly reduced.

Because of the uncertainty of any effects (positive and negative) these new technologies would have on maintenance expenditures, no value is assumed in the economic analysis. EPA will monitor new information as it becomes available and will add non-brake maintenance into this analysis if appropriate.

1.4.7.5 Potential Refueling Time Savings

If, in adopting new technologies to improve personal vehicle fuel economy, manufacturers decide to maintain fuel tank volume, dramatic increases in vehicle range between fill-ups are possible. The time saved in fewer refueling stops has some value to consumers. In an August 2005 Preliminary Regulatory Impact Analysis (PRIA) on a proposed new light truck CAFE rule, NHTSA cited a “value of travel time per vehicle hour” of $21.90. NHTSA also assumed each refueling event lasts 5 minutes, so the value to a consumer of saving one refueling event is $1.83. While this paper will not assume any potential refueling time savings, EPA will consider this in future analyses.

1.4.8 Federal Tax Treatment

The Energy Policy Act of 2005 replaces the current $2000 federal income tax deduction for the purchase of a hybrid electric vehicle [Reference 1-7] with a new federal income tax credit for the purchase of a qualifying hybrid or diesel vehicle. This federal tax credit will be phased out for each manufacturer after 60,000 units are sold and will be completely unavailable after 2009 or 2010.

This paper is based on a high-volume scenario and therefore does not include the temporary federal income tax credit. Of course, it is always possible that Congress will revisit the issue in the future.

Some individual states also offer incentives to consumers who purchase advanced technology vehicles, but this analysis assumes no favorable state tax treatment.

1.4.9 Market Externalities

Because all economic assessments in this paper are from the perspective of individual consumers who own and drive vehicles (rather than from a societal perspective), this study does not include any of the market externalities that could be considered in a societal perspective. For example, benefits due to reductions in oil imports, greenhouse gas emissions, or trade deficit, and potential impacts due to changes in vehicle congestion, accidents, or noise are not evaluated.

1.5 Metrics for Economic Comparisons

This report uses two metrics for economic comparisons: consumer payback period and net lifetime consumer savings. Consumer payback period is the number of years it takes for discounted, future operating savings to offset the initial incremental cost of the technology to the consumer. Lifetime consumer savings are the net savings that will accrue to consumers over a 14-year vehicle lifetime, i.e., the difference between the discounted lifetime operating savings and the incremental technology cost. The operating savings associated with fuel economy technologies are primarily fuel savings, plus brake maintenance savings associated with hybrid vehicles that use regenerative braking instead of friction braking part of the time.

The calculation of both consumer payback and lifetime consumer savings are straightforward, using a relatively simple set of spreadsheet calculations based on the technology and economic inputs discussed above. Lifetime consumer savings is calculated by summing all of the discounted fuel savings (and, if applicable, discounted brake savings) and then subtracting the incremental retail price of the new technology, resulting in a “net” consumer savings over the assumed 14-year life of the vehicle. Consumer payback is expressed in years, and requires a year-by-year comparison of the discounted operating savings and the incremental retail price increase. The consumer payback period is the year (or fraction of a year) where the cumulative, discounted operating savings equals the incremental retail price increase. A more detailed description and set of sample calculations are included in Appendix A.

References

1-1 *Progress Report on Clean and Efficient Automotive Technologies Under Development at EPA.* EPA Interim Technical Report, EPA420-R-04-002, January 2004, available at www.epa.gov/otaq/technology under Documents.

1-2 *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2003*, Karl H. Hellman and Robert M. Heavenrich, U.S. EPA, April 2004, page 37. http://www.epa.gov/otaq/fetrends.htm.

1-3 *Update of EPA's Motor Vehicle Emissions Control Equipment Retail Price Equivalent (RPE) Calculation Formula*. Jack Faucett Associates, contractor report for EPA Office of Mobile Sources, 1985.

1-4 *Gasoline and Diesel Fuel Update*, U. S. Department of Energy/Energy Information Administration, April 2005, www.eia.doe.gov.

1-5 Office of Management and Budget Circular A-94.

1-6 Office of Management and Budget Circular A-4, September 17, 2003.

1-7 IRS News Release No. IR-2002-64, May 21, 2002.

2. Gasoline Vehicle Technology Package

2.1 Technology Description

Gasoline vehicles account for over 98% of U.S. personal vehicle sales. There are many incremental improvements that could be made to today's gasoline vehicles that would increase fuel economy without changing the vehicle's basic type of propulsion system, general size, or performance. These improvements include changes in aerodynamic characteristics, reduction in tire rolling resistance, operating efficiency gains in the engine and transmission, and possibly materials substitution. Individually, these improvements may only provide marginal increases in fuel economy. However, combining several improvements in a package could provide a significant fuel economy increase.

For this report, two sources were referenced to generate an updated assessment of potential gasoline vehicle technology improvements. These sources are the 2002 National Academy of Sciences (NAS) report, *"Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards"* [Reference 2-1], and *"Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles,"* a 2004 report published by Northeast States Center for a Clean Air Future (NESCCAF) [Reference 2-2]. Only technologies that could be expected to meet future EPA emission standards and which did not have a major negative impact on vehicle performance were included. The set of individual technologies evaluated in the NAS report is listed in Table 2-1 (cars only).[2] Note that the figures for individual technologies are merely illustrative and their effects on combined packages of technologies may vary.

NAS projected the fuel economy benefit and NESCCAF projected the greenhouse gas (GHG) reductions that would result from combinations of these individual technologies, each using their own analysis criteria and assumptions. EPA staff converted the NESCCAF GHG reductions to fuel economy benefit in order to compare the results of the two studies.[3] This report uses the results from these technology packages.

---

[2] This table was taken directly from the NAS reports (NAS Table 3-1).

[3] Refer to Section 2.2.2 for further information on how fuel economy improvement was derived from NESCCAF's projected GHG reductions.

Table 2-1: NAS Technologies - Passenger Cars

		Retail Price Equivalent (RPE) ($)	
Baseline: overhead cam, 4-valve, fixed timing, roller finger follower.	Fuel Consumption Improvement %	Low	High
Production-intent engine technology			
Engine friction reduction	1-5	35	140
Low-friction lubricants	1	8	11
Variable valve timing	2-3	35	140
Variable valve lift and timing	1-2	70	210
Cylinder deactivation	3-6	112	252
Engine accessory improvement	1-2	84	112
Engine supercharging and downsizing	5-7	350	560
Production-intent transmission technology			
Five-speed automatic transmission	2-3	70	154
Continuously variable transmission	4-8	140	350
Automatic transmission w/aggressive shift logic	1-3	0	70
Six-speed automatic transmission	1-2	140	280
Production-intent vehicle technology			
Aero drag reduction	1-2	0	140
Improved rolling resistance	1-1.5	14	56
Safety technology			
Safety weight increase	-3 to -4	0	0
Emerging engine technology			
Intake valve throttling	3-6	210	420
Camless valve actuation	5-10	280	560
Variable compression ratio	2-6	210	490
Emerging transmission technology			
Automatic shift/manual transmission (AST/AMT)	3-5	70	280
Advanced CVTs --allows high torque	0-2	350	840
Emerging vehicle technology			
42-V electrical system	1-2	70	280
Integrated starter/generator (idle off-restart)	4-7	210	350
Electric power steering	1.5-2.5	105	150
Vehicle weight reduction (5%)	3-4	210	350

2.1.1 Technologies Already in the Marketplace

Table 2-2 provides examples of some of the advanced technologies listed in Table 2-1 that are already on some vehicles in the marketplace. These examples show that many of these technologies are already in use.

Table 2-2: Examples of Advanced Gasoline Engine and Vehicle Technologies Already in the Marketplace
(late-model vehicles)

Technology[4]	Sample Manufacturers (Models)
Variable Valve Lift & Timing	Honda, Toyota, BMW
Gas Direct Injection (S)	Audi (A3, A4, A6), Isuzu (Rodeo), Mazda (Speed 6)
Boosting	Audi, Dodge (Neon SRT), VW (Jetta), Saab, Subaru (Outback), Volvo (S40), Buick (Regal), Nissan (Xterra)
Cylinder Deactivation	Chevrolet (Trailblazer, Impala SS), DaimlerChrysler*, Honda (Odyssey, Pilot, Hybrid Accord)
Electric Power Steering	Saturn (Vue), Chevrolet (Equinox, Malibu, Cobalt), Honda (Civic)
Automatic 6-Speed Trans.	Ford (Fusion), Audi, BMW, Jaguar, VW
CVT	Honda (Civic), Ford (Five Hundred, Freestyle) Nissan (Murano)
Automated Manual Trans.	Audi (A3, TT), VW (Beetle, Jetta)

* all vehicles equipped with "Hemi" V8 engines – includes Dodge Ram, Durango, Chrysler 300C

2.1.2 NAS Technology Packages

For each vehicle class, NAS studied two "cost-efficient" packages reflecting different consumer payback periods and discount rates. The NAS "Case 1" 14-year payback scenario was selected for use in this report since it better represents the full lifetime of a vehicle and the perspective of those consumers that might own their vehicle for its full lifetime. EPA staff attempted to determine the cost-efficient package content by replicating the cost-efficiency methodology outlined in the NAS report. The technologies presumed to meet the criteria[5] of the cost-efficient package for the 14-year payback are listed in Tables 2-3 (Large SUV) and 2-4 (Midsize Car).

Many technologies listed in Tables 2-3 and 2-4 represent further advancements beyond what is typical of today's vehicles. Current vehicles benefit from some degree of improvement in aerodynamic drag, lower rolling resistance, and lower frictional losses compared to vehicles of the past. The listed items represent a significant further improvement potential for most of the fleet.[6]

---

[4] Notes on table nomenclature: Gas Direct Injection (S) – stoichiometric; CVT – continuously variable transmission.

[5] NAS assumed that all technologies identified in its "Path 3" were candidates for a cost-efficient package. Cost efficient technologies were determined using an "incremental marginal" approach, where only those individual technologies that can pay for themselves (via discounted savings in fuel consumption) over the 14-year lifetime are included. For further details, refer to Chapter 4 of the NAS report.

[6] Although some of these technologies do exist in the marketplace (as indicated in Table 2-2), they are not yet mainstream technology (with the exception of multi-valve overhead camshafts).

Table 2-3: NAS "14-Year, Cost-Efficient" Technology Package For Large SUV with Gasoline Engine[7]

Efficiency Loss Mechanism	Production-Intent or Emerging Technology
Friction Losses	Low friction lubricants Engine friction reduction
Pumping Losses	Multi-valve, overhead camshaft Variable valve timing Camless valve actuation
Transmission Losses	5-speed automatic transmission with Automated manual transmission
Accessory Losses	Engine accessory improvement Electric power steering 42 volt electrical system
Vehicle Losses	Improved rolling resistance Aerodynamic drag reduction Integrated starter / generator (idle off)[8]

Table 2-4: NAS "14-Year, Cost-Efficient" Technology Package For Midsize Car with Gasoline Engine

Efficiency Loss Mechanism	Production-Intent or Emerging Technology
Friction Losses	Low friction lubricants Engine friction reduction
Pumping Losses	Variable valve timing Multi-valve, overhead camshaft
Transmission Losses	Continuously variable transmission
Accessory Losses	(none)
Vehicle Losses	Improved rolling resistance Aerodynamic drag reduction

---

[7] Technologies have been sorted by "efficiency loss mechanism" on a thermodynamic basis.

[8] Idling the engine is defined in this context as a vehicle loss, because none of the engine output is being used to propel the vehicle. Integrated starter/generators provide this idle-off capability.

2.1.3 NESCCAF Technology Packages

NESCCAF's technology packages are based primarily on analysis by AVL Powertrain Engineering, Inc., a leading international automobile industry consultant specializing in technology development. AVL used its CRUISE vehicle simulation model to evaluate 10-15 different vehicle technology packages for each car or truck class. EPA selected three of the NESCCAF packages within each vehicle class with the following criteria in mind:

a) include a mix of lower cost / lower fuel economy benefit and higher cost / higher fuel economy benefit options, that is representative of the average cost effectiveness of all of the technology packages,
b) include a variety of different technologies, and
c) consider a feasibility timeframe of 5 to 10 years.

The three NESCCAF technology packages selected for each vehicle class are summarized in Tables 2-5 and 2-6, below.

Table 2-5: Three NESCCAF Technology Packages Selected By EPA For Large SUV with Gasoline Engine[9,10]

Loss Area	Option 1	Option 2	Option 3
Indicated Efficiency	Gas Direct Injection (S)		Gas Direct Injection (S)
Friction Losses	Low friction lubricants Engine friction reduction	Low friction lubricants Engine friction reduction	Low friction lubricants Engine friction reduction
Pumping Losses	Variable valve timing (C) Cylinder deactivation	Variable valve timing (C) Variable valve lift (D) Cylinder deactivation	Camless valve actuation (EH)
Transmission Losses	6-speed + automated manual transmission Aggressive shift logic	6-speed auto transmission Aggressive shift logic Early TC lockup	6-speed + automated manual transmission Aggressive shift logic
Accessory Losses	Improved alternator EH power steering	Electric accessories EH power steering	Improved alternator EH power steering
Vehicle Losses	Improved rolling resistance Aerodynamic drag reduction	Improved rolling resistance Aerodynamic drag reduction Integrated starter/generator	Improved rolling resistance Aerodynamic drag reduction

---

[9] NESCCAF did not specify a Large SUV category in its report. NESCCAF's definition of Large Truck, for purposes of projected fuel consumption improvements, is assumed to be comparable to a Large SUV.

[10] Notes on nomenclature for Tables 2-5 and 2-6: Gas Direct Injection – S (stoichiometric); Variable valve timing – C (coordinated), I (intake valve only), D (dual, independent control); Variable valve lift – D (discrete); Camless valve actuation – EH (electrohydraulic); Power steering – EH (electrohydraulic), TC – torque converter

Note that all of the NESCCAF gasoline vehicle technology packages in Tables 2-5 and 2-6 (though not all of the packages in the original NESCCAF study) include the following technologies:

- Friction reduction (low friction lubricants, engine friction reduction)
- Valve timing capability, often including deactivation or lift flexibility
- 6 speed transmission gearing
- Power steering improvements
- Vehicle loss reduction (tires and aero drag reduction)
- Efficient air conditioning

EPA believes that, within the next decade, gas direct injection will be feasible, with the possibility that HCCI (homogeneous charge compression ignition) or turbocharging may be suitable to select packages. Automated manual transmissions and camless valve actuation also offer significant opportunities. These assumptions are reflected in the subset of NESCCAF packages chosen for this analysis.

Table 2-6: Three NESCCAF Technology Packages Selected By EPA For Midsize Car with Gasoline Engine[11]

Loss Area	Option 1	Option 2	Option 3
Indicated Efficiency	Gas Direct Injection (S)	Gas Direct Injection (S)	Gas HCCI
Friction Losses	Low friction lubricants Engine friction reduction	Low friction lubricants Engine friction reduction	Low friction lubricants Engine friction reduction
Pumping Losses	Variable valve timing (D) Turbocharging/downsizing	Camless valve actuation (EH)	Variable valve timing (I) Variable valve lift (D)
Transmission Losses	6-speed auto transmission Aggressive shift logic Early TC lockup	6-speed + automated manual transmission Aggressive shift logic	6-speed + automated manual transmission Aggressive shift logic
Accessory Losses	Electric power steering Electric accessories Efficient air conditioning	Improved alternator Electric power steering Efficient air conditioning	Improved alternator Electric power steering Efficient air conditioning
Vehicle Losses	Improved rolling resistance Aerodynamic drag reduction Integrated starter / generator	Improved rolling resistance Aerodynamic drag reduction	Improved rolling resistance Aerodynamic drag reduction

---

[11] The NESCCAF report did not include a midsize car category. However, the Large Car analysis is assumed to be applicable and is the source for the midsize car category in this report. NESCCAF cited a typical “Large Car” as a Ford Taurus.

2.2 Technology-Specific Inputs

2.2.1 NAS Package Fuel Economy Improvement

The NAS study reports fuel consumption savings for each of the technologies included in their cost-efficient packages. The NAS committee estimated the fuel consumption savings after considering information from manufacturers, consultants, other studies, and presentations at public meetings.

NAS determined the overall fuel consumption savings for each of the 14-year cost-efficient packages and applied it to their base fuel economy for each of the vehicle classes under consideration. Table 2-7 provides the fuel economy values for the 14-year cost-efficient packages. This table is directly excerpted from Table 4.2 in the NAS report. Three fuel economies for the cost-efficient packages are given representing the effect of a low estimate of fuel savings, average fuel savings, and a high estimate of fuel savings. This report uses the average fuel economy values from NAS.

It is important to emphasize that NAS did not perform any manufacturer-specific technology analysis. All of the NAS projections represent industry-average estimates. Accordingly, it is not possible to use the NAS projections to forecast the average fuel economy improvement potential for an individual manufacturer or model, as each manufacturer and model has a unique technology baseline.

Table 2-7: NAS Fuel Economy and Costs for 14-Year, Cost-Efficient Package[a]

			Low Cost/High mpg			Average			High Cost /Low mpg		
Vehicle Class	Base mpg[b]	Base Adjusted[c]	FE mpg, (%)	Cost ($)	Savings ($)	FE mpg, (%)	Cost ($)	Savings ($)	FE mpg, (%)	Cost ($)	Savings ($)
Cars											
Subcompact	31.3	30.2	38.0 (21)	588	1,018	35.1 (12)	502	694	31.7 (1)	215	234
Compact	30.1	29.1	37.1 (23)	640	1,121	34.3 (14)	561	788	31.0 (3)	290	322
Midsize	27.1	26.2	35.4 (31)	854	1,499	32.6 (20)	791	1,140	29.5 (9)	554	651
Large	24.8	23.9	34.0 (37)	1,023	1,859	31.4 (27)	985	1,494	28.6 (15)	813	1,023
Light trucks											
Small SUVs	24.1	23.3	32.5 (35)	993	1,833	30.0 (25)	959	1,460	27.4 (14)	781	974
Mid SUVs	21.0	20.3	30.2 (44)	1,248	2,441	28.0 (34)	1,254	2,057	25.8 (23)	1,163	1,589
Large SUVs	17.2	16.6	25.7 (49)	1,578	3,198	24.5 (42)	1,629	2,910	23.2 (35)	1,643	2,589
Minivans	23.0	22.2	32.0 (39)	1,108	2,069	29.7 (29)	1,079	1,703	27.3 (19)	949	1,259
Small pickups	23.2	22.4	32.3 (39)	1,091	2,063	29.9 (29)	1,067	1,688	27.4 (18)	933	1,224
Large pickups	18.5	17.9	27.4 (48)	1,427	2,928	25.5 (38)	1,450	2,531	23.7 (28)	1,409	2,078

[a] Other assumptions see Reference 8

[b] Base is before downward adjustment of -3.5 percent for future safety and emissions standards

[c] Base after adjustment for future safety and emissions standards (-3.5 percent)

The fuel economy improvements derived from NAS for use in the payback calculations of this report are given in Table 2-8. Values in Table 2-8 are the average fuel economy values from Table 4-2 of the NAS report excerpted above, with the addition of calculated CO2 reduction.

Table 2-8: Percent Fuel Economy Improvement for the NAS Gasoline Technology Packages

Vehicle Class	NAS Base Fuel Economy (mpg) [12]	NAS 14-year Cost-Efficient Package FE (mpg)	Fuel Economy Improvement (%)	Tailpipe CO2 Reduction (%)
Large SUV	17.2	24.5	42%	30%
Midsize Car	27.1	32.6	20%	17%

2.2.2 NESCCAF Package Derived Fuel Economy Improvement

NESCCAF projected CO2-equivalent exhaust emissions reductions for each of its technology packages. For the three technology packages that EPA selected for each class, EPA converted these CO2 emissions reductions into fuel economy improvement, and both tailpipe CO2 and fuel economy projections are shown in Tables 2-9 and 2-10 for the large SUV and midsize car scenarios, respectively. Note that the cost and fuel savings estimates for the consumer payback analysis are calculated by averaging the three large SUV and midsize car technology package options discussed above.

Table 2-9: EPA's Projected Fuel Economy Improvement Calculated for the NESCCAF Gasoline Technology Packages - Large SUV[13]

Package	Package CO2 Emissions[14] (g/mi)	Tailpipe CO2 Reduction (%)	Fuel Economy Improvement (%)
Option 1	418	19%	23%
Option 2	380	26%	36%
Option 3	383	26%	35%
Average	**394**	**24%**	**31%**

Included in the package analysis is a reduction in CO2 emissions due to a more efficient air conditioning system (e.g., incorporating a variable displacement compressor). Because the NESCCAF analysis includes CO2-equivalent emissions from reductions that do not impact fuel economy (such as air conditioner refrigerant leakage), some adjustments had to be made to the NESCCAF baseline and package CO2 emissions projections to properly reflect only tailpipe CO2.

---

[12] These are laboratory/unadjusted mileage figures. For EPA's economic analysis, the standard -15% correction factor was applied to the baseline to determine real-world savings.

[13] Adjusted baseline CO2 emissions for large SUV (NESCCAF Large Truck) = 516 g/mi.

[14] From Table 3-8 in the NESCCAF report.

The following adjustments were made to isolate tailpipe CO2 emissions from the baseline and package projections:

- 8.5 g/mi and 0.4 g/mi of A/C direct refrigerant CO2-equivalent emissions were subtracted from the baselines and advanced technology packages, respectively
- A/C efficiency gains were originally modeled based on use of R-152a, which included a higher efficiency due to the refrigerant. Because no change to the working fluid is assumed by EPA, an associated 5% CO2 efficiency improvement was removed from the "Alternative A/C System" estimates in Table 3-1 of the NESCCAF report. The resulting adjustments to Large Car and Large Truck advanced technology packages are +0.4 g/mi and +0.6 g/mi, respectively.
- These two adjustments to the advanced technology packages approximately balance out, therefore, no adjustment was made to the advanced technology packages.
- Baseline CO2 emissions rates were adjusted as follows: the Large Truck was adjusted from 525 g/mi down to 516 g/mi, and the Large Car was adjusted from 357 g/mi down to 348 g/mi.

Table 2-10: EPA's Projected Fuel Economy Improvement Calculated for the NESCCAF Gasoline Technology Packages - Midsize Car[15]

Package	Package CO2 Emissions[16] (g/mi)	Tailpipe CO2 Reduction (%)	Fuel Economy Improvement (%)
Option 1	225	35%	55%
Option 2	243	30%	43%
Option 3	274	21%	27%
Average	**247**	**29%**	**41%**

2.2.3 Incremental Retail Price

The NAS Committee estimated a range of costs for the various technologies. The NAS estimated the technology costs after considering information from manufacturers, their suppliers and published references.

NAS determined the combined cost of all the technologies in the 14-year, cost-efficient package. These costs are given in Table 2-7 and are taken directly from the NAS report.

NESCCAF's cost estimates were originally supplied by Martec International, a market research consulting firm. They are listed in Table 2-11, below. Costs for the Large SUV and Midsize Car were based on Tables 3-8 and 3-4, respectively, in the NESCCAF report. A $31 adjustment was deducted from each advanced technology package cost estimate to eliminate costs associated with the alternative A/C refrigerant R-152a

---

[15] Baseline CO2 emissions for midsize car (NESCCAF Large Car) = 348 g/mi

[16] From Table 3-4 in the NESCCAF report.

(originally modeled in the packages). Similarly to the fuel economy calculations, cost estimates for the EPA-selected NESCCAF packages were averaged for each vehicle category.

Table 2-11: NESCCAF Technology Costs For the Gasoline Technology Packages

Large SUV		Midsize Car	
Package	**Incremental Cost ($)**	**Package**	**Incremental Cost ($)**
Option 1	$859	Option 1	$1827
Option 2	$2399	Option 2	$1447
Option 3	$2140	Option 3	$1118
Average	**$1799**	**Average**	**$1464**

Both NAS and NESCCAF's average retail costs included a consistent retail price markup factor of 1.4. As discussed in Section 1.4.2, retail costs were changed to reflect the 1.26 retail price mark-up used for all analyses in this report. The resulting retail prices for the packages are listed in Table 2-12.

Table 2-12: EPA-Adjusted Incremental Retail Prices for the Gasoline Technology Packages

Vehicle Class	Scenario	Referenced Retail Price	EPA-Adjusted Retail Price
Large SUV	NAS	$1629	$1467
	NESCCAF	$1799	$1619
Midsize Car	NAS	$791	$712
	NESCCAF	$1464	$1318

2.3 Economic Results

Based on the technology-specific efficiency projections in Section 2.2, the incremental retail price projections discussed in Section 2.2.3 and the economic assumptions described in Section 1.4, Table 2-13 gives the consumer payback period and lifetime consumer savings for large SUV and midsize car for both the NAS and NESCCAF technology scenarios.

Table 2-13: Cost Effectiveness for Gasoline Technology Packages (From a consumer perspective)

Vehicle Class	Scenario	Consumer Payback (yrs)	Discounted Fuel Savings	Incremental Vehicle Price	Lifetime Consumer Savings
Large SUV	NAS	1.8	$5,853	$1,467	$4,386
	NESCCAF	2.5	$4,908	$1,619	$3,288
Midsize Car	NAS	3.8	$1,609	$712	$897
	NESCCAF	3.9	$2,869	$1,318	$1,552

EPA's projections of consumer payback for the NAS and NESCCAF technology packages appear comparable in terms of magnitude. The payback period for large SUVs is projected to be about 2 years, and the payback period for midsize cars is projected at about 4 years.

References

2-1. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*. National Research Council/National Academy of Sciences, 2002.

2-2. *Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles.* Northeast States Center for a Clean Air Future, September, 2004.

3. Diesel Engine

3.1 Technology Description

Diesel engines have been in commercial use since the early days of the automobile industry. Diesel engines utilize a combustion cycle quite distinct from that of gasoline-fueled, Otto-cycle engines that dominate the U.S. personal vehicle market today. Conventional diesel engines have the following characteristics: direct cylinder fuel injection (i.e., diesel fuel is not premixed with air prior to combustion), compression ignition (combustion is initiated by the injection of diesel fuel into the hot, compressed charge-air), little or no intake air throttling, high air-to-fuel ratios, and high compression ratios. Compared to gasoline engines of similar size, diesel engines typically are more costly, more durable, and more efficient. This section will only consider the efficiency benefits associated with diesel engines alone, although it is important to recognize that some of the technologies considered in Section 2 (such as more efficient transmissions, accessories, tires, and aerodynamics) could also be included in a broader "diesel vehicle package."

With all other things being equal, today's diesel engines are projected to achieve up to 40% higher fuel economy than today's gasoline engines, which is equivalent to about a 29% savings in fuel consumption. Since diesel fuel contains about 15% more energy and carbon than an equal volume of gasoline, a vehicle mile traveled with a diesel engine that has 40% higher fuel economy should reduce vehicle energy consumption and carbon emissions by about 18%. On a life-cycle basis, the total benefit of diesel engines is somewhat higher because there are higher per gallon energy losses for gasoline production than for diesel fuel production.

While diesel engines dominate the heavy-duty truck market and have made significant inroads into the medium-duty market as well, the only personal vehicles available with a diesel engine option in the U.S. market in the last few years were the Volkswagen New Beetle, Golf and Jetta, with typical annual sales of about 20,000 units representing a market share of less than 0.2%. But, several new diesel models have been introduced into the US market in 2004 and 2005: Volkswagen Passat, Mercedes E320, and Jeep Liberty. European automobile manufacturers have been at the forefront of recent advances in diesel engines for use in personal vehicles due to the fact that diesel engines now account for about 50% of all new car sales in Europe.

However, diesel combustion has in the past resulted in higher levels of oxides of nitrogen (NOx) and particulate matter (PM) emissions. Higher levels of NOx and PM emissions are due in part to the fact that aftertreatment solutions have been much more difficult for diesel engines than for gasoline engines. Increasing evidence suggests that automakers will be able to design diesel vehicles that can comply with the Tier 2 emission standards later this decade. U.S. and Japanese-based automobile companies are investing in diesel engine research and development, driven in part by the demand for diesels in Europe, but also by the possibility that diesel engines may return to the U.S. personal vehicle market.

At this time, the primary path towards compliance with EPA's Tier 2 standards in the future involves reducing engine-out emissions and advances in diesel emissions control aftertreatment. All diesel emissions control aftertreatment packages include some type of PM trap. Diesel NOx emissions control systems are more complex and multiple compliance approaches are under development, including NOx adsorption catalysts and urea/Selective Catalytic Reduction (SCR) technology.

In April 2002, EPA tested a prototype Toyota Avensis, a compact diesel car that Toyota was developing for the European market. [Reference 3-1] This vehicle used a DPNR (diesel particulate-NOx reduction) emission aftertreatment system that included both a particulate trap and a NOx adsorber. This low-mileage prototype met the Tier 2 bin 5 emission levels of 0.07 grams per mile NOx and 0.01 grams per mile PM. EPA has tested other low-mileage prototype diesel vehicles that have also met Tier 2 emission levels. While challenges remain with respect to both maintaining catalyst efficiency at high mileage and meeting EPA Supplementary Federal Test Procedure emission standards, there appear to be no fundamental barriers to the development and introduction of advanced diesel emission controls. Volkswagen recently announced plans to market a Tier 2 bin 5 compliant Jetta in the U.S. market by the 2007 model year. [Reference 3-2]

Some manufacturers are also developing SCR technology that injects urea into the exhaust to promote the catalytic reduction of NOx emissions. EPA is in discussions with manufacturers about potential compliance strategies that would ensure that the on-board urea supply is maintained so that SCR-equipped vehicles will always meet NOx emission standards in use.

EPA is also evaluating unique diesel engine concepts under its Clean Automotive Technology program with a goal of identifying a clean diesel engine combustion concept that could simultaneously be extremely efficient, clean, and cost effective. Results suggest the potential for a diesel engine design, using innovative air, fuel, and combustion management and conventional PM trap aftertreatment, which might be able to achieve Tier 2 bin 5 NOx levels without the need for NOx aftertreatment. [References 3-3 and 3-4] EPA is working with several manufacturers to continue to develop and refine this clean diesel combustion technology. EPA has publicly announced clean diesel combustion partnerships with International Truck and Engine Corporation [Reference 3-5] and Ford Motor Company. [Reference 3-6]

3.2 Technology-Specific Inputs

This report utilizes two sets of technology-specific inputs for diesel vehicles. The first set relies on the results of a study by FEV Engine Technology, Inc., a major engine design and consulting company, for all of the technology-specific assumptions for diesel engines. [Reference 3-7] Diesel emission aftertreatment system costs were developed separately by EPA and combined with the engine cost assumptions by FEV.

The second set of diesel vehicle projections is from a recent report published by Oak Ridge National Laboratory (ORNL), based on technology forecasts by K.G. Duleep, a vehicle technology expert with Energy and Environmental Analysis, Inc. who surveyed technology experts from automakers, suppliers, and government. [Reference 3-8]

It is important to note that the diesel vehicles analyzed in this report include all of the direct changes that would be necessary to support a diesel engine, including emissions aftertreatment, but do not include any of the non-engine technologies that are part of the gasoline vehicle packages in Section 2 and which could also be applied to diesel vehicles (such as more efficient transmissions, accessories, tires, and aerodynamics). Broader diesel packages, with these additional technologies, would increase both the projected fuel economy improvement and the projected retail cost.

3.2.1 Fuel Economy Improvement

FEV used a detailed vehicle simulation model to identify designs involving gasoline and diesel engines in both large SUV and midsize car applications that yielded comparable vehicle performance (defined by several different acceleration metrics) and range. The FEV simulation model projected that, for equivalent performance, a diesel engine in a large SUV would have 6% higher peak power, 22% higher maximum torque, and 3% higher vehicle weight (about 180 pounds), would yield a 41% improvement in vehicle fuel economy and an 18% reduction in tailpipe CO2[17], all relative to a baseline gasoline-fueled large SUV. Similarly, the FEV model projected that, for equivalent performance, a diesel engine in a midsize car would have 15% lower peak power, 54% higher maximum torque, and 3% higher vehicle weight (about 90 pounds), and would yield a 39.5% improvement in vehicle fuel economy (with a corresponding 18% decrease in tailpipe CO2), all relative to a baseline gasoline-fueled midsize car. Because the production of diesel fuel has a lower energy requirement than that for gasoline, the lifecycle CO2 savings are about 2% higher than the tailpipe CO2 savings.

The ORNL report projects that, in the long term, diesel vehicles will provide a 33% improvement in vehicle fuel economy, and a 13.5% decrease in tailpipe CO2, along with a 25% increase in torque, relative to comparable gasoline vehicles. These results are summarized in Table 3-1.

Table 3-1: FEV/EPA and ORNL Projection of Performance, Fuel Economy, and CO2 Emissions for Diesel Engines Relative to Gasoline Engines

Vehicle Class	Scenario	Power	Torque	Fuel Economy	Tailpipe CO2	Lifecycle CO2
Large SUV	FEV/EPA	+6%	+22%	+41%	-18%	-21%
	ORNL		+25%	+33%	-14%	-16%
Midsize Car	FEV/EPA	-15%	+54%	+39.5%	-18%	-20%
	ORNL		+25%	+33%	-14%	-16%

Other sources for projected fuel economy improvement potential for diesel vehicles include current vehicle offerings and manufacturer statements. Model-specific

---

[17] Tailpipe CO2 reduction per gallon for diesels is somewhat lower than the corresponding reduction in fuel consumption due to the fact that diesel fuel has about 15% greater total carbon content per gallon than gasoline. This figure does not include any diesel refining differences between gasoline and diesel.

comparisons of gasoline and diesel vehicles yield a wide range of fuel economy improvements. These comparisons are not particularly helpful, however, both because there are often significant performance differences between diesel and gasoline versions of the same model. Public statements by vehicle manufacturers typically support the 33-40% range from the FEV/EPA and ORNL scenarios. [References 3-9, 3-10, and 3-11]

3.2.2 Incremental Retail Price

The incremental retail price for a personal vehicle with a diesel engine is determined by three factors:

- incremental manufacturing cost of the diesel engine and associated vehicle systems
- incremental cost of diesel emission control aftertreatment
- retail price equivalent factor discussed in Section 1.4.2

For the FEV/EPA scenario, the FEV report provides a detailed listing of approximately 30 individual modifications for a diesel engine powertrain and related vehicle systems relative to a baseline gasoline vehicle.

FEV provided two estimates for these incremental manufacturing costs, one based on "current production costs" and one based on "mature production costs." This report uses the FEV mature cost projections, consistent with the objective of this report to consider costs in a long term, high-volume environment where economies of scale for new technologies are similar to those for today's conventional technologies. FEV's underlying assumption for its mature cost projections are that the costs of high-pressure common rail fuel injection and variable geometry turbocharging may be able to be reduced by 30% from current values. Table 3-2, below, shows the major components that would have to be added, deleted, or modified for a vehicle to accommodate a diesel engine powertrain, along with FEV's projections of the associated savings or costs, for both the large SUV and midsize car scenarios. FEV projected that the incremental manufacturing cost of a diesel engine in a mature market is $1042 for a large SUV and $739 for a midsize car.

It is generally accepted that, based on current state-of-the-art engine technology, emission control systems for diesel vehicles complying with EPA's Tier 2 emission standards will be more expensive than those for comparable gasoline vehicles. The FEV report did not address this issue. There is a major industry effort underway to develop viable and cost-effective diesel engine emission control systems and multiple compliance pathways are under development. While it is impossible at this time to predict the precise design and future cost of such systems with any certainty, Appendix B provides EPA's best estimate of the incremental manufacturing cost of diesel emission aftertreatment systems based on the best information currently available: $355 for a large SUV and $255 for a midsize car. EPA assumes there would be no overall fuel economy penalty for diesel vehicles with aftertreatment emission control systems. While EPA believes it is likely that there will be some increase in fuel consumption due to the operation of diesel aftertreatment emission controls, EPA believes that overall diesel vehicle fuel economy will be unchanged, due to engine optimization and other changes. EPA is monitoring progress in this area and will modify these projections as more information becomes available.

Table 3-2: Incremental Diesel Engine Cost Projections for Mature Scenario (FEV/EPA Scenario)

Component(s)	Large SUV	Midsize Car
Add high-pressure, common rail diesel fuel injection system	$980	$630
Delete gasoline fuel injection system	-$245	-$165
Add variable geometry turbocharger	$175	$126
Delete gasoline ignition system	-$120	-$75
Delete fuel pump and other changes to fuel system	-$94	-$75
Enhance powertrain mounting system	$87	$107
Other engine changes	$80	$70
Add air intercooler, ducts, and sensor	$80	$55
Larger battery and starter, add glow plugs	$72	$50
Delete exhaust gas oxygen sensor	-$60	-$30
Add supplemental heater	$50	$15
Modify transmission	$25	$25
Enhance sound insulation package	$25	$10
Smaller radiator	- $13	-$4
Total	**$1,042**	**$739**

This study applies the EPA retail price equivalent factor of 1.26 to both the incremental manufacturing cost of the diesel engine and the incremental manufacturing cost of diesel emissions aftertreatment to get an aggregate incremental retail price, shown in Table 3-3 for a large SUV and in Table 3-4 for a midsize car.

Table 3-3: Incremental Retail Price for Large SUV with Diesel Engine (FEV/EPA Scenario)

Component	Source	Incremental Manufacturing Price	Incremental Retail Price
Engine	FEV	$1,042	$1,313
Aftertreatment	EPA	$355	$447
Total			**$1,760**

Table 3-4: Incremental Retail Price for Midsize Car with Diesel Engine (FEV/EPA Scenario)

Component	Source	Incremental Manufacturing Price	Incremental Retail Price
Engine	FEV	$739	$931
Aftertreatment	EPA	$255	$321
Total			**$1,252**

For the ORNL scenario, Table 3-5 gives the total (engine and aftertreatment) incremental costs for a diesel vehicle relative to a gasoline vehicle. The ORNL values are based on a retail price equivalent markup of 1.6 [18]. As discussed in Section 1.4.2, the ORNL cost values were adjusted to reflect the 1.26 markup factor that was used elsewhere in this report. The adjusted values are also shown in Table 3-5.

Table 3-5: Incremental Retail Price for Diesel Engine Package (ORNL Scenario)

Vehicle Class	ORNL Retail Price	EPA-Adjusted Retail Price
Large SUV	$3,250	$2,560
Midsize Car	$2,300	$1,810

3.2.3 Federal Income Tax Deduction

As discussed in Section 1.4.8, the Energy Policy Act of 2005 allows for tax credits for qualifying diesel vehicles. However, these credits begin to phase out for each manufacturer after 60,000 units are sold, and will not be available after December 31, 2010. Since the scope of this report concerns high-volume scenarios in a 5-10 year timeframe, this tax credit is assumed to be unavailable.

---

[18] ORNL RPE factor per phone conservation with K.G. Duleep Feb 15, 2005.

3.3 Economic Results

Based on the technology-specific efficiency and cost projections discussed in Section 3.2 and the economic assumptions described in Section 1.4, Table 3-6 gives the payback period and vehicle lifetime savings for both a large SUV and a midsize car for both the FEV/EPA and ORNL scenarios.

Table 3-6: Cost Effectiveness for Vehicles with Diesel Engine (from a consumer perspective)

Vehicle Class	Scenario	Consumer Payback (yrs)	Discounted Fuel Savings	Incremental Vehicle Price	Lifetime Consumer Savings
Large SUV	FEV/EPA	2.1	$6,044	$1,760	$4,284
	ORNL	4.1	$5,157	$2,560	$2,597
Midsize Car	FEV/EPA	3.8	$2,815	$1,252	$1,563
	ORNL	7.7	$2,444	$1,810	$634

References

3-1 *Testing of the Toyota Avensis DPNR at U.S. EPA-NVFEL*. Joseph McDonald and Byron Bunker, U.S. EPA, Society of Automotive Engineers Paper 2002-01-2877.

3-2 "Volkswagen: 2007 U.S. EPA Bin 5 Diesel Car Coming" Diesel Fuel News, October 10, 2005.

3-3 *Assessing New Diesel Technologies.* Charles L. Gray, Jr., U.S. EPA, presentation before the Massachusetts Institute of Technology Light Duty Diesel Workshop, November 20, 2002.

3-4 *A Path to More Sustainable Transportation.* David Haugen, U.S. EPA, presentation at the 10th Annual Diesel Engine Emissions Reduction Conference, August 29, 2004, available at www.epa.gov/otaq/technology under Engine Research.

3-5 *EPA and International Truck to Develop Clean Diesel Combustion Technology.* EPA-420-F-04-036, May 2004, available at www.epa.gov/otaq/technology under Partnerships.

3-6 *EPA and Ford to Develop Clean Diesel Combustion Technology*. EPA-420-F-05-007, January 2005, available at www.epa.gov/otaq/technology under Partnerships.

3-7 *Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks*. FEV Engine Technology, Inc., contractor report prepared for U.S. EPA, January 28, 2003.

3-8 *Future Potential of Hybrid and Diesel Powertrains in the U.S. Light-Duty Vehicle Market*. David Greene, Oak Ridge National Laboratory, K.G. Duleep, Energy and Environmental Analysis, and Walter McManus, JD Power and Associates, August 2004.

3-9 *Clean Diesels Dispel Outdated 'Dirty" Image.* General Motors website at www.gm.com, July 30, 2002.

3-10 *Diesel Finds Liberty in North America. Automotive Engineering Magazine,* January 2003.

3-11 *Future Technology Diesel: Reducing Particulate Matter (Black Carbon) Emissions.* Matti Maricq, presentation before the California Air Resources Board's International Vehicle Technology Symposium, March 11, 2003.

4. Gasoline/Battery Hybrid

4.1 Technology Description

Gasoline/battery hybrid vehicles, often referred to as hybrid electric (HEV) or electric hybrid vehicles, are now not only a commercial reality, but are also achieving key market milestones on the way to mainstream acceptance: multiple offerings by multiple manufacturers, waiting lists for many models, and projected sales of 100,000 for the Toyota Prius in 2005. The Prius has been on sale since 1997 (in Japan), is now in its second generation in the U.S. and is offered in more than 20 countries around the world. In 2005, Toyota introduced into the U.S. market hybrid versions of the Lexus RX330 and Toyota Highlander. Honda offers the Insight and hybrid electric versions of its popular Civic and Accord sedans. Ford introduced the first HEV sport utility in the Escape in 2004, and GM, Chrysler, and Nissan are preparing to launch HEV vehicles in 2007-2008. Gasoline/battery hybrid sales in the U.S. in 2004 totaled over 85,000, and J.D. Power has forecast 2005 HEV sales of 222,000. Electric hybrid sales will likely continue to increase as the remaining large manufacturers introduce hybrids in the U.S. in the next few years.

Electric hybridization of a vehicle creates the opportunity to improve fuel economy in three different areas:

- The gasoline engine can be optimized (through downsizing, or other control techniques) to operate at or near its most efficient point more of the time.
- Some of the energy normally lost as heat while braking can be captured and stored in the battery for later use.
- The engine is turned off when it is not needed, such as when the vehicle is coasting or when stopped.

On the other hand, adding one or more electric motors, associated control circuitry, and a battery pack increases vehicle weight and cost. These costs tend to be incurred at the time of vehicle purchase, while the savings garnered by using less fuel and the reduced need for brake maintenance accrue over time.

In general, there are two types of gasoline/battery hybrids—series HEV and parallel HEV. In the series hybrid design, the wheels are driven *only* by the electric motor that derives its power from onboard batteries and the electric generator which, in turn, is driven by a small engine. Series HEVs were a popular concept with automakers in the early to mid 1990s, but inherent problems with cost and efficiency under heavy load conditions have caused them to fall out of favor. There is still some interest, however, and as technology improves, they may yet see some production applications.

In a parallel hybrid design, both the electric motor and the gasoline engine are connected to the wheels and operate individually in parallel, depending on vehicle load and control strategy. Typically, in a parallel design, the gasoline engine provides power for cruising and the electric motor supplies the additional power required for acceleration and short hill climbing. The electric motor also enables regenerative braking. All current production HEVs are parallel designs (although the current Toyota and Ford systems have characteristics of both series and parallel designs, and have been called series-parallel).

Within the class of parallel hybrids, there are two major approaches used today. These approaches have been dubbed "full" and "mild" (although these terms do not fully describe their attributes). The so-called "full" hybrids are typified by the Toyota Prius and Ford Escape. Full hybrids are capable of being propelled by the electric motor only while the engine is stopped. Under most conditions, the electric motors of full hybrid designs can propel the vehicle at speeds up to 15-25 mph. The so-called "mild" hybrids, on the other hand, require the engine to be turning whenever the vehicle is moving (although combustion does not necessarily need to occur). Honda's Integrated Motor Assist (IMA) system used on their HEVs is an example of this type of system. The term "mild" hybrid can be misleading. Honda's Insight meets the definition of a mild hybrid, but is the most fuel-efficient car sold in the U.S. due to a combination of hybridization, light weight, and other modifications.

An HEV's design and control strategy defines the amount of efficiency benefit from each of the three main HEV efficiency-related benefits discussed earlier. Some HEV designs, like the Honda Accord and Lexus RX400h, do not use engine downsizing, and some very mild hybrids may not even take advantage of regenerative braking. Other HEVs, like the Ford Escape, exploit all three features to make impressive fuel efficiency gains. Table 4-1 shows the expected range of benefits from each HEV feature.

Table 4-1: Expected FE Benefits of HEV Features

Feature	Usage	FE benefit
Idle Off	All HEVs	5-8%
Regenerative Braking	Most HEVs	5-20%
Engine Optimization/Downsizing	Some HEVs	5-15%

[Reference 4-1]

There are many ways to incorporate HEV technology into a gasoline-fueled vehicle. The HEVs in production today use one of three different approaches. These approaches will be discussed below. In addition, there is an approach being developed by GM and DaimlerChrysler and is planned for introduction in 2007-2008.

4.1.1 Belt Starter-Generator (BSG)

Belt Starter-Generator (BSG) systems, while incapable of significant launch assist, are still being produced and additional applications are under development (Toyota's Japanese market Crown sedan is one example). BSG systems have smaller electric motors and less battery capacity. BSG systems replace the conventional belt-driven alternator with a belt-driven, higher power starter-alternator. This adds idle-stop capability and possibly some limited regeneration capability. Originally meant to augment 42 volt electrical systems, BSG systems are somewhat less attractive now that manufacturers are less interested in adopting 42V systems. However, some manufacturers are still planning BSG systems on some small cars and SUVs. GM will be introducing a BSG system on the Saturn Vue SUV. [Reference 4-2].

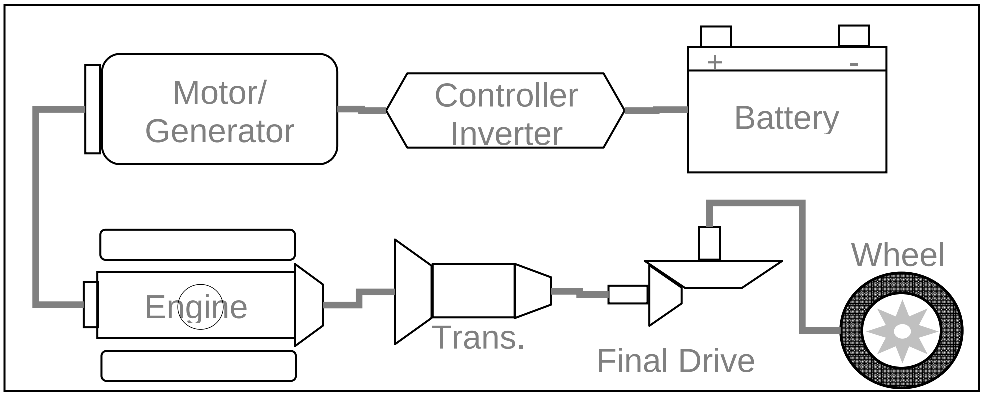


Figure 4-1: Schematic of BSG System [Reference 4-3]

4.1.2 Honda Integrated Motor Assist (IMA)

Honda's Integrated Motor Assist (IMA) utilizes a thin axial electric motor bolted to the engine's crankshaft and connected to the transmission through a torque converter or clutch. This electric motor acts as both a motor for helping to launch the vehicle and a generator for recovering energy while slowing down. It also acts as the starter for the engine and the electrical system's main generator. Since it is rigidly fixed to the engine, if the motor turns, the engine must turn also, but combustion does not necessarily need to occur. The Civic Hybrid also uses cylinder deactivation on three of its four cylinders during decelerations. (The 2006 Civic Hybrid features an improved system that uses cylinder deactivation on all four cylinders for decelerations and some cruise conditions.) The Accord also has cylinder deactivation, but it is on one bank of the V-6 engine and activates during cruise conditions as well as decelerations.

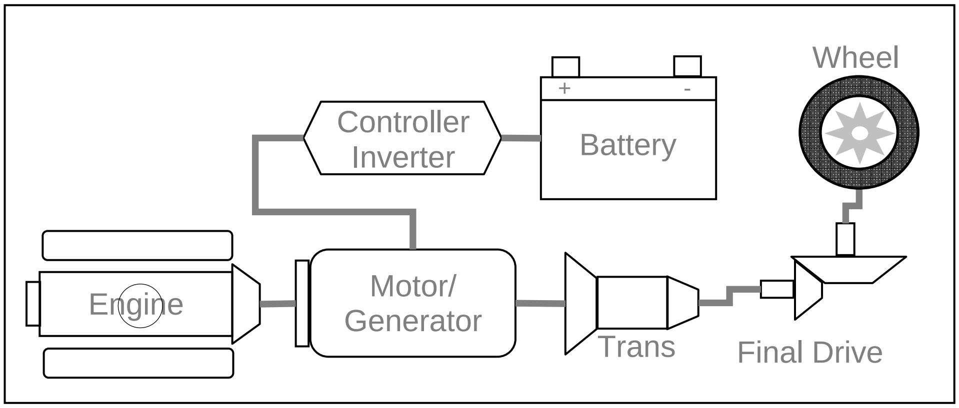


Figure 4-2: Schematic of Honda IMA System [Reference 4-3]

The IMA system is relatively low cost and easy to adapt to conventional vehicles, provided there is enough room to package the necessary battery pack, cabling, and power electronics. Packaging space is also a concern for the physically longer engine-motor-transmission assembly. Also, the limitation of not having the capability to propel the vehicle without the engine running may result in somewhat lower efficiency gains than could be possible with a true full hybrid design. However, in practice, the Honda system is highly efficient and compares very well to the Toyota Prius which is more expensive to manufacture. On the other hand, it is an impractical approach for so-called Plug-in HEVs that have a greater capability to operate on all electric power.

Continental's Integrated Starter-Alternator-Damper (ISAD) is a system quite similar to Honda's IMA. ISAD is in limited production in the Chevrolet Silverado, GMC Sierra, and Dodge Ram. These pickups are very mild hybrid designs, operating at 42 volts, and mainly add idle-stop capability. The main selling point of these designs is integrated AC power generation for contractors, campers and others.

4.1.3 Toyota Hybrid Synergy Drive

Toyota's Hybrid Synergy Drive system as used in the Prius is a completely different approach than Honda's IMA system. The heart of this system is called the Power Split system, developed by Aisin and Toyota. Versions of it are also used in the Lexus RX400h, Toyota Highlander and Ford Escape. The Power Split system replaces the vehicle's transmission with a single planetary gear and a motor/generator. A second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels. The planetary gear splits the engine's torque between the first motor/generator and the drive motor. The first motor/generator uses its engine torque to either charge the battery or supply additional power to the drive motor. The speed of the first motor-generator determines the relative speed of the engine to the wheels. In this way, the planetary gear allows the engine to operate completely independently of vehicle speed, much like a CVT.

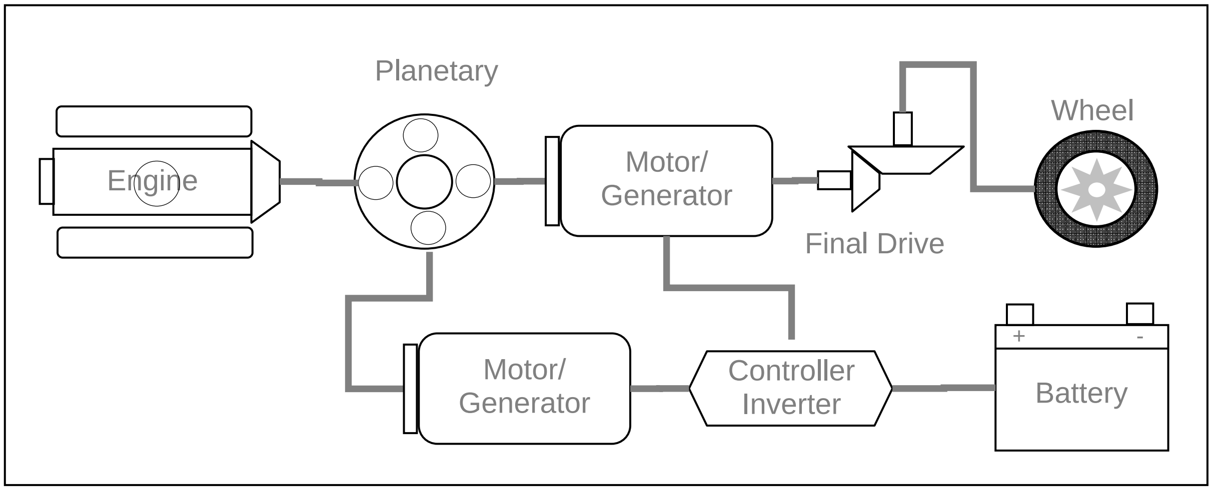


Figure 4-3: Schematic of Aisin/Toyota Power Split System [Reference 4-3]

The Power Split system allows for outstanding fuel economy in city driving. The vehicle also avoids the cost of a conventional transmission, replacing it with a much simpler single planetary and motor/generator. However, it is less efficient at highway speeds due to the requirement that the first motor/generator must be constantly spinning at a relatively high speed to maintain the correct ratio. Also, load capacity is limited to the first motor/generator's capacity to resist the reaction torque of the drive train.

A version of Toyota's Power Split system is also used in the Lexus RX400h and Toyota Highlander sport utility vehicles. This version has more powerful motor/generators to handle higher loads and also adds a third motor/generator on the rear axle of four-wheel-drive models. This provides the vehicle with four wheel drive capability and four wheel regenerative braking capability. Ford's eCVT system used in the hybrid Escape is another version of the Power Split system but four-wheel-drive models use a conventional transfer case and drive shaft to power the rear wheels.

4.1.4 GM Dual-Mode Hybrid System

GM and DaimlerChrylser have formed a joint venture (recently joined by BMW) to develop a new HEV system based on HEV transmission technology originally developed by GM's Allison Transmission Division for heavy-duty vehicles like city buses. This technology uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors, which makes the transmission act like a CVT. Like Toyota's Power Split design, these motors control the ratio of engine speed to vehicle speed. Clutches allow the motors to be bypassed, which improves both the transmission's torque capacity for heavy-duty applications and fuel economy at highway speeds. This transmission will be incorporated in new full-size HEV SUVs from GM and DaimlerChrysler in 2007 or 2008.

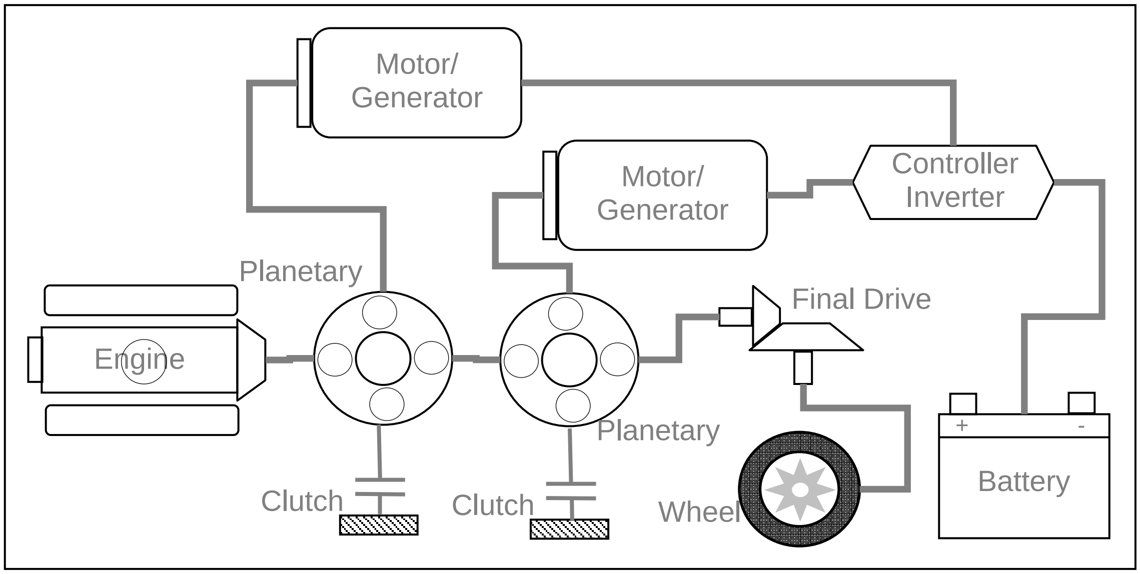


Figure 4-4: Schematic of GM-DCX HEV System [Reference 4-4]

4.1.5 Plug-in Hybrids

An offshoot of full hybrid technology presently garnering much attention is the so-called Plug-in Hybrid, or PHEV. PHEVs are, to date, mainly modifications of the Toyota Prius. Because the Prius is capable of electric-operation (albeit at low speeds and for only short distances), some individuals and organizations are modifying them by adding larger battery packs and add-on control units. The modifications allow significant all-electric range at near-highway speeds in the all-electric mode. There is currently a demonstration project in Austin, TX under the direction of the Austin city council. (http://www.austinenergy.com)

A PHEV could be capable of running a large amount of its miles in all-electric mode which could have significant positive air quality effects in urban areas in addition to providing significant fuel savings to its owner. As the batteries become depleted, they can either be recharged by plugging into a standard electrical outlet, or by the engine, which switches on automatically to provide both motive power and battery charging. If the PHEV's design and duty cycle are well-matched, it would only need to use its engine during long trips or during heavy acceleration.

While PHEVs are capable of higher fuel economy than "conventional" HEVs, there are some challenges that must be overcome. Battery size (and cost) increases with increased all-electric range. The electric motor must also increase in size and power to cover more of the operating map. These changes require more packaging space in the vehicle and will increase weight. Also, consumer acceptance of PHEVs must be better understood. Since consumers would be required to plug the vehicles in to take full advantage of the all-electric range, the willingness of the vehicle owner to do this must be evaluated. There are other issues too: evaporative emissions must be controlled in a vehicle that could potentially not experience engine running for extended periods of time to purge vapors, the control system becomes more complex as the system must make more decisions about how much battery power to save, and standardized test procedures would be more complex because of uncertainty in the amount of expected driving between recharging events. [Reference 4-5]

This chapter only analyzes non-PHEV vehicles, both because they are commercially available and because they are currently the most cost-effective of the electric hybrid designs.

4.2 Technology-Specific Inputs

This section discusses the fuel efficiency benefits of electric hybridization as well as the cost of HEV systems. It relies primarily on a series of studies sponsored by the Electric Power Research Institute (EPRI), [References 4-6, 4-7, 4-8] and an August 2004 study by Oak Ridge National Laboratory (ORNL) [Reference 4-9] for estimates of the fuel economy benefits and cost impacts of electric hybridization.

Since 1999, under the auspices of EPRI, the Hybrid Electric Vehicle Working Group, a consortium including General Motors, Ford, the California Air Resource Board, the University of California at Davis, the Department of Energy and others have published a series of reports analyzing electric hybrid issues. These studies include vehicle modeling, cost modeling, consumer acceptance modeling, and an examination of commercialization issues.

The EPRI working group has compared various gasoline/battery hybrid designs with equivalent conventional vehicles. The guiding principle in establishing the key performance parameters was that all electric hybrid vehicles had to be based on a conventional vehicle body, had to have similar roadload characteristics (aerodynamic drag, tire rolling resistance, and curb weight excluding any weight changes directly due to the electric hybrid powertrain), and had to closely approximate the main performance characteristics of a conventional vehicle (0-to-60 mph acceleration, top speed, and range).

The EPRI reports estimate the benefits and costs of gasoline/battery hybrid technology applied to a compact car, a midsize car, a midsize SUV, and a large SUV. This study only uses the EPRI results for the midsize car and large SUV, to be consistent with the remainder of the paper.

The ORNL study is a study of market potential of hybrid powertrains in the US market and so weighs customer acceptance of HEVs heavily in its analysis. This study uses estimates that future HEVs will feature an increase in performance of between 10 and 20 percent in addition to more modest fuel economy gains (relative to the EPRI projections) of 35% to 40%. This seems to be consistent with current HEV marketing trends which are emphasizing performance with an attendant fuel economy gain. Newer HEVs entering the market (e.g. Honda Accord, Lexus RX400h, and Toyota Highlander) feature hybrid systems with no engine downsizing. Future products from Toyota like the Lexus GS450 sport sedan will also offer full-size engines in addition to full HEV powertrains.

4.2.1 Fuel Economy Improvement

The EPRI reports model gasoline/battery hybrid component and vehicle characteristics with the ADVISOR computer model developed by the National Renewable Energy Laboratory (NREL) [Reference 4-10] with support from the Department of Energy.

Based on the ADVISOR mpg results shown in Table 4-2, EPRI projects that gasoline/battery hybrids will achieve 52% better fuel economy in large SUVs and 45% greater fuel economy in midsize cars relative to comparable non-hybrid vehicles. The corresponding decrease in tailpipe CO2 emissions is 34% for large SUVs and 31% for midsize cars.

Table 4-2: EPRI Projections of Fuel Economy Improvement for Gasoline/Battery Hybrids

	Large SUV	Midsize Car
Baseline gasoline vehicle	18.2 mpg	28.9 mpg
Gasoline-battery hybrid	27.6 mpg	41.9 mpg
Fuel economy increase	52%	45%
Tailpipe CO2 decrease	34%	31%

[Reference 4-11]

ORNL's study is an analysis of market potential of hybrid and diesel vehicles using a consumer choice model. Inputs to the model are a best-guess scenario of HEV introductions from 2008 through 2012 and a 2004 study by K. G. Duleep [Reference 4-3] that indicates manufacturers will use hybridization to improve performance as well as fuel economy. This study does not isolate the fuel economy effect of hybridization, but it does reflect current marketing trends in HEVs that emphasize improved performance along with improved fuel economy. The ORNL report indicates that mild hybridization using a system like Honda's IMA can result in an increase in torque of 15%, an increase in fuel economy of 20%, and a CO2 reduction of 17% . Similarly, full hybridization of a car or light truck like a smaller SUV will result in a torque increase of 20% and fuel economy gain of 40% with a CO2 reduction of 29%. Full hybridization of a larger light truck will lead to a 15% torque increase and 35% fuel economy increase with a corresponding CO2 decrease of 26%.

Table 4-3: ORNL Projection of Fuel Economy and Torque Improvement for HEVs

Hybrid System	Torque Increase	FE Increase	Tailpipe CO2 Decrease
Idle Stop	0%	7.5%	7%
ISAD	10%	12.5%	11%
IMA	15%	20%	17%
Full (car and small light truck)	20%	40%	29%
Full (large light truck)	15%	35%	26%

[Reference 4-12]

The reasonableness of the EPRI and ORNL estimates can be evaluated by analyzing the fuel economy benefit of HEVs on the market today that also have a non-HEV version on sale. Currently these products are: Honda Civic CVT, Honda Civic with manual transmission, Honda Accord, Ford Escape, Mercury Mariner, Lexus RX400h, and Toyota Highlander. These comparisons are shown in Table 4-4.

Comparing the Civic Hybrid to its non-hybrid counterpart, one can see that the HEV version gains 28% or 23% fuel economy, depending on whether it is equipped with a CVT or manual transmission. This vehicle shows somewhat less benefit than the EPRI estimates for a midsize car. This is because the conventional Civic used for comparison is already highly fuel efficient and offers such features as a lean burn engine. In fact, comparing the Civic Hybrid to a “more conventional” version of the Civic results in a fuel economy benefit of 46% and 40% for CVT and manual transmission, respectively, which is in excellent agreement with the EPRI estimates. The ORNL estimate of 20% FE gain with the addition of an IMA system is in relatively good agreement with the production Civic versions available, especially considering that Honda chose to improve torque minimally with hybridization on these models.

Table 4-4: A Comparison of EPA Fuel Economy Label Values of Vehicles Available with Both Conventional and Hybrid Drivetrains

	Adjusted (Label) Fuel Economy									
	Conv. Powertrain			HEV Powertrain			% Improvement			
	City	HWY	**Comp**	City	HWY	**Comp**	City	HWY	**Comp**	Notes
2005 Honda Civic CVT CV: 1.7L Lean, CVT HEV: 1.3L Lean, CVT	35	40	**37.1**	48	47	**47.5**	37%	18%	**28%**	All versions of Civic shown here have lean burn engines. Comparing Civic Hybrid to non-lean-burn, non-VTEC Civic yields a 46% and 40% difference for CVT and MTX HEVs respectively.
2005 Honda Civic MTX CV: 1.7L Lean, 5 man HEV: 1.3L Lean, 5 man	36	44	**39.2**	46	51	**48.1**	28%	16%	**23%**	
Honda Accord CV: 3.0L, 5 Auto HEV 3.0L, 5 Auto	21	30	**24.3**	29	37	**32.1**	38%	23%	**32%**	Accord Hybrid uses no engine downsizing, but has cylinder deactivation on the rear bank of cylinders.
Ford Escape/ Mercury Mariner 4X4 CV: 3.0L, 4 Auto HEV: 2.3L, CVT	18	22	**19.6**	33	29	**31.1**	83%	32%	**58%**	Escape HEV is optimized for fuel economy using engine downsizing, Atkinson cycle, etc. Towing capacity is reduced. 4X4 versions use mechanical rear drive.
Ford Escape/ Mercury Mariner 4X2 CV: 3.0L, 4 Auto HEV: 2.3L, CVT	20	25	**22.0**	36	31	**33.6**	80%	24%	**53%**	
Lexus RX 400h / Highlander 4X4 CV: 3.3L, 5 Auto HEV: 3.3L, Power Split	18	24	**20.3**	31	27	**29.1**	72%	13%	**43%**	The RX400h and Highlander use no engine downsizing, and have the same towing capacity as the conventional version. 4X4 versions use electric rear drive.
Toyota Highlander 4X2 CV: 3.3L, 5 Auto HEV: 3.3L, Power Split	19	25	**21.3**	33	28	**30.5**	74%	12%	**43%**	

Data from the 2005 Fuel Economy Guide, Honda.com, and Toyota.com

The Honda Accord, Lexus RX400h, and Toyota Highlander are three examples of HEVs where hybridization was used as a performance enhancement. These models add HEV systems to vehicles without engine downsizing, although the Accord does utilize cylinder deactivation on three of its six cylinders. The Accord system offers an increase in torque of about 10% and a fuel economy benefit of 32% over the conventional version. [Reference 4-13] This FE benefit exceeds the ORNL estimate of 20% for IMA systems. However, this difference is reasonable when considering that the torque improvement in the Accord is less, and that the addition of cylinder deactivation will help fuel economy. The Highlander and RX400h fuel economy gain of 43% is in excellent agreement with ORNL's estimate of 40% for a full hybrid system in a smaller light truck.

Finally, Ford's Escape features a full hybrid system and engine downsizing. Ford compares this vehicle to the V6 version of the Escape, and in so doing, the Escape HEV gains 58% fuel economy for the 4X4 model and 53% for the 4X2 model. This result is in reasonable agreement with the EPRI estimate of a 52% FE gain for a large SUV. Comparing a conventional Escape 4X2 with the four cylinder engine option to the Escape 4X2 HEV shows a difference of 44% fuel economy. This more closely reflects the effect of hybridization, but still includes the Atkinson cycle engine and transmission differences, which add to the HEV’s overall efficiency. It should be noted that the Escape hybrid has significantly lower towing capacity than the conventional V6 Escape.

In summary, the literature and market experience seem to support both the EPRI and ORNL projections of the fuel economy improvement due to battery hybridization. The vehicles that use hybridization as a performance enhancement show fuel economy gains in good agreement with the ORNL results, while the more “performance neutral” hybrids show good agreement with the EPRI study for fuel economy gains. This section will analyze two scenarios for cost and consumer payback, using both the ORNL and EPRI fuel economy and cost estimates.

4.2.2 Incremental Retail Price

EPRI assumed that gasoline/battery hybrids use the same bodies as conventional vehicles. Glider[19] costs were estimated by deleting dealer and manufacturer markups from the typical conventional vehicle Manufacturer’s Suggested Retail Price (MSRP) and subtracting the costs of the conventional vehicle drivetrain. EPRI then added the drivetrain-specific component costs back in and used the vehicle retail price equivalent (RPE) as the basis for estimating the costs of both electric hybrids and their corresponding conventional vehicles.

Two different methods were used by EPRI to estimate RPEs. In the first method, all components were assumed to be built by the vehicle manufacturer. Component costs were estimated as the cost of labor and materials for each component with both manufacturer and dealer markups added. In the second method, some components were assumed to be built by the vehicle manufacturer and some were assumed to be purchased from a supplier. Both manufacturer and dealer markups were applied to components that were built by the manufacturer. A single, smaller markup covering manufacturer and dealer mark-ups and development costs was applied to the electric components (motor, controller, and battery) which were assumed to be purchased from a supplier. In both cases, generally, component costs took into account technological advancements that could be foreseen or considered likely to occur by 2010 and that applied at production volumes of 100,000 vehicles per year. Also, both methods assumed that batteries are one of the largest cost components and a reduced mark-up was applied. [Reference 4-14]

Table 4-5 shows the major gasoline/battery vehicle components identified by EPRI, as well as the component costs developed by EPRI for midsize cars. [Reference 4-15] Using data from the EPRI report [Reference 4-16] and the individual markup factors listed in EPRI’s first report, [Reference 4-17] it was possible to back calculate total component costs for the large SUVs, but not the individual component costs. These costs are also shown in Table 4-5.

---

[19] A Glider is defined as a vehicle without its engine and transmission. It includes all other body, chassis, and interior components.

Table 4-5: EPRI Incremental Manufacturing Costs of Major Components for the Gasoline/Battery Hybrid Vehicle

Component	Large SUV	Midsize Car
Engine Downsizing		-$863
Exhaust System		-$50
Smaller Transmission		-$420
APM		$130
Electric Motor		$797
Power Inverter		$478
Electronics Thermal		$114
Energy Batteries/ Thermal		$1,263
Pack Tray/Hardware		$620
Miscellaneous		-$85
Total	$3,543	$1,984

The same 1.26 RPE used in the analysis of the other drivetrains discussed in this report was then applied in order to put the analysis of gasoline/battery hybrid vehicles on the same economic footing with the remainder of this paper. The results are shown in Table 4-6.

Table 4-6: EPA-Adjusted Incremental Retail Price for Gasoline/Battery Hybrids (EPRI Scenario)

Vehicle Class	Incremental Manufacturing Price	Incremental Retail Price
Large SUV	$3,543	$4,464
Midsize Car	$1,984	$2,500

ORNL's report contains cost estimates that are somewhat different than EPRI's. Using a variety of manufacturer and supplier information [Reference 4-18], ORNL concluded full hybridization costs in 2012 would be $3,320 for small cars, $3,920 for midsize and large cars, and $4,100 for large trucks.

The midsize and large car class in the ORNL report presumably covers a very large segment of the market, with curb weights ranging from approximately 3,100 lbs up to well over 4,000 lbs. The car portion of this EPA study focuses on hybridization of midsize cars which are at the lighter end of the ORNL midsize and large car class (such as the Honda Accord). Therefore, for the purposes of this study, an average of the ORNL small car and ORNL midsize and large car costs, or $3,620, will be used.

The large SUV case in the ORNL scenario will use the $4,100 RPE as assumed for large trucks.

Table 4-7 below shows the ORNL costs removing ORNL's RPE factor of 1.7 [Reference 4-19] to generate an incremental manufacturing price. Then, they are re-adjusted back up using the EPA incremental RPE of 1.26. This normalizes the ORNL and EPRI prices to the same retail price equivalent assumption.

Table 4-7: Adjusted Incremental Retail Price for Gasoline/Battery Hybrids (ORNL Scenario)

Vehicle Class	Incremental Manufacturing Price	Incremental Retail Price
Large SUV	$2,411	$3,039
Midsize Car	$2,129	$2,683

[Reference 4-20]

4.2.3 Battery Life and Cost

This study assumes that battery packs will not have to be replaced during the fourteen year life of the vehicle. This is an important assumption, as battery replacement could add a major consumer expense. However, field experience has shown battery life to be better than expected even just a few years ago, and this battery life assumption seems appropriate.

EPRI's treatment of this issue has evolved in its series of reports. In its 2001 report, EPRI stated that "The consumer cost of [a non-PHEV] battery replacement is estimated between $1,500 to $2,000 if the batteries have a salvage value. … If vehicle lifetimes were extended to 15 years or 150,000 miles, it is likely that all HEV designs will require battery replacements within this extended vehicle lifetime." In its 2002 report, EPRI stated that "because of the battery, the vehicle life assumption was limited to 100,000 miles and not 10 years of life." By 2003, EPRI had come to believe that significant progress had been made in battery development. They cite as evidence that five year old Toyota RAV/4 EVs, in real world driving, have traveled over 100,000 miles on the original NiMH battery pack with no appreciable degradation in battery performance or vehicle range and are projected to last for 130,000 to 150,000 miles. [Reference 4-21]

Currently, Toyota offers an 8-year, 100,000-mile warranty on hybrid-related components, including the battery, battery control module, hybrid control module and inverter with converter. [Reference 4-22] Honda currently covers its hybrid systems with an eight-year, 80,000-mile warranty. Ford offers an eight-year, 100,000 mile warranty on its hybrid systems.

Panasonic has recently stated that current NiMH battery technology has a 98-99% chance of surviving ten years and a estimated 90% survivability rate at 14-15 years [Reference 4-23]. Therefore it seems likely that by 2010, batteries will easily last the expected fourteen years / 150,000 miles. Of course, if a battery pack does have to be replaced, it would have a deleterious effect on both consumer payback and lifetime vehicle savings if it is not covered by the manufacturer's warranty.

HEV battery costs are dropping rapidly. Panasonic claims that NiMH battery costs (per kW) have decreased 50% from the first generation Prius to the second generation Prius. This could put current battery costs at around $40/kW. Over the next five years, Panasonic forecasts an additional cost decrease of 30%-40%, which includes increased production volumes. [Reference 4-24] However, rising material costs due to greater demand, may reduce these savings.

Lithium-Ion batteries are still undergoing intense development, since they promise significantly more energy density than NiMH batteries and potential lower overall cost. The problem with Li-Ion in vehicle applications has been short life and safety. However, the French company Saft has recently shown Li-Ion battery technology with an expected life of fifteen years [Reference 4-25]. Also, many battery companies are developing materials with less potential for thermal runaway. Nevertheless, it is still somewhat early to determine if Li-Ion technology will be in volume production in 2010.

4.2.4 Electric Motor Development and Cost

Like batteries, electric motor costs are also declining due to improved technology and higher production volumes. For HEVs, permanent magnet (PM) motors are generally preferred due to higher efficiency and lower controller costs. However, PM motors are significantly more expensive than induction motors even including their lower controller costs. PM motor costs are declining more quickly than induction motor costs and so the price gap is decreasing. Toyota says that motor costs have come down about 40% over the last five years, and now approach commodity levels. [Reference 4-26]

Additionally, Hitachi is developing significantly more powerful and lighter weight electric motors. By 2010, the total motor-controller cost for a 60 kW motor could be about $800, or about one half the cost of current motors. [Reference 4-27]

4.2.5 Brake Maintenance

As discussed in Section 1.4.7.3, electric hybrid vehicles will have reduced brake maintenance expenditures. This analysis adopts the EPRI assumption that the overall brake wear on a gasoline/battery hybrid vehicle will be reduced by 50% on the front brakes and by 0% on the rear brakes, relative to a conventional vehicle. [Reference 4-28] This yields a discounted lifetime brake maintenance savings of $533 for the large SUV and $377 for the midsize car.

4.2.6 Federal Income Tax Deduction

As discussed in Section 1.4.8, the Energy Policy Act of 2005 allows for tax credits for hybrid electric vehicles. However, these credits begin to phase out for each manufacturer after 60,000 units are sold, and will not be available after December 31, 2009. Since the scope of this report concerns high-volume scenarios in a 5-10 year timeframe, this tax credit is assumed to be unavailable.

4.3 Economic Results

Based on the technology-specific efficiency and cost projections discussed in Section 4.2 and the economic assumptions described in Section 1.4, Tables 4-8 (EPRI) and 4-9 (ORNL) show the vehicle lifetime savings and the number of years that it is expected to take until the vehicle's initial cost increase is offset by discounted savings on fuel and brake maintenance.

Table 4-8: Cost Effectiveness for Gasoline/Battery Hybrid Vehicles (EPRI Scenario)

	Large SUV	Midsize Car
Incremental Vehicle Price	$4,464	$2,500
Fuel Economy Gain	52%	45%
Tailpipe CO2 decrease	34%	31%
Discounted Fuel Savings	$7,111	$3,057
Discounted Brake Savings	$533	$377
Lifetime Savings	$3,179	$934
Payback Period	**5.0 years**	**7.4 years**

Table 4-9: Cost Effectiveness for Gasoline/Battery Hybrid Vehicles (ORNL Scenario)

	Large SUV	Midsize Car
Incremental Vehicle Price	$3,039	$2,683
Fuel Economy Gain	35%	40%
Tailpipe CO2 decrease	26%	29%
Discounted Fuel Savings	$5,389	$2,815
Discounted Brake Savings	$533	$377
Lifetime Savings	$2,882	$509
Payback Period	**4.1 years**	**9.5 years**

The above results show that for a large SUV, the EPA-adjusted EPRI and ORNL estimates indicate the possibility of full payback of the incremental retail price of a full HEV in 5.0 years and 4.1 years, respectively. The payback period for midsize cars is somewhat longer, at 7.4 to 9.5 years. These payback periods assume there is no federal tax credit available to consumers as the high-volume scenario shown here would result in the phase-out of the credit.

References

4-1 *Hybrid Powered Vehicles.* John M. German, 2003, SAE International, Warrendale, PA; pp 22-25

4-2 “Analysis of Hybrid Technology.” K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 9

4-3 “A Comparative Study of the Production Applications of Hybrid Electric Powertrains.” Harry L. Husted, Delphi Corporation, SAE Technical Paper 2003-01-2307

4-4 “Electrically Variable Transmission with Selective Input Split; Neutral and Reverse Modes.” US Patent 20020142876, Hargitt, et. al.

4-5 “Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.” Electric Power Research Institute, Palo Alto, CA: 2002. 1006892

4-6 *Assessment of Current Knowledge of Hybrid Vehicle Characteristics and Impacts*. Electric Power Research Institute, Palo Alto, CA: 1999. TR-113201

4-7 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*. Electric Power Research Institute, Palo Alto, CA: 2001. 1000349

4-8 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*. Electric Power Research Institute, Palo Alto, CA: 2002. 1006892

4-9 “Future Potential of Hybrid and Diesel Powertrains in the U. S. Light-Duty Vehicle Market.” Oak Ridge National Laboratory, August 2004, ORNL/TM-2004/181

4-10 “ADVISOR Paves Road to Faster Vehicle Evaluation and Testing.” Office of Energy Efficiency and Renewable Energy/DOE, http://www.ott.doe.gov/pdfs/advisor.pdf, April, 1999.

4-11 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*. Electric Power Research Institute, Palo Alto, CA: 2001. 1000349; p. 3-28

4-11 *(cont.) Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*. Electric Power Research Institute, Palo Alto, CA: 2002. 1006892, p. A-5

4-12 “Future Potential of Hybrid and Diesel Powertrains in the U. S. Light-Duty Vehicle Market.” Oak Ridge National Laboratory, August 2004, ORNL/TM-2004/181, p.9

4-13 www.honda.com, 2005 Accord Hybrid Specifications

4-14 Battery module mark-ups are 50% of battery module costs not to exceed $800.

4-15 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Option.* Electric Power Research Institute, Palo Alto, CA: 2001. 1000349; Appendix C, Table C-2, Component Costs for the Base Case Vehicles.

4-16 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*. Electric Power Research Institute, Palo Alto, CA: 2002. 1006892; Appendix A, Table A-17, Full-Size SUV Component Retail Price Equivalent Average for Base and ANL Methods

4-17 *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*. Electric Power Research Institute, Palo Alto, CA: 2001. 1000349; Table C-8, Functions Used for Estimating HEV Component Costs.

4-18 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA;

4-19 ORNL RPE factor per phone conversation with K.G. Duleep Feb 15, 2005

4-20 "Future Potential of Hybrid and Diesel Powertrains in the U. S. Light-Duty Vehicle Market." Oak Ridge National Laboratory, August 2004, ORNL/TM-2004/181, p.10

4-21 *Advanced Batteries for Electric-Drive Vehicles: A Technology and Cost-Effectiveness Assessment for Battery Electric, Power Assist Hybrid Electric, and Plug-in Hybrid Electric Vehicles.* Electric Power Research Institute, Palo Alto, CA: 2003. 1001577, Preprint Report, Version 16, March 25, 2003.

4-22 "Prius Warranty." Toyota, http://www.toyota.com/html/shop/vehicles/warranty.html

4-23 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 6

4-24 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 6

4-25 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 8

4-26 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 4

4-27 "Analysis of Hybrid Technology." K. G. Duleep, November 2003; Energy and Environmental Analysis, Inc, Arlington, VA; p. 4

4-28 *Advanced Batteries for Electric-Drive Vehicles: A Technology and Cost-Effectiveness Assessment for Battery Electric, Power Assist Hybrid Electric, and Plug-in Hybrid Electric Vehicles*. Electric Power Research Institute, Palo Alto, CA: 2003. 1001577, Version 16, March 25, 2003.

5. Diesel/Battery Hybrid

5.1 Technology Description

Diesel hybrid electric vehicles seek to combine the engine efficiency gains of a diesel engine with the other powertrain efficiency gains of a hybrid electric vehicle (HEV) system. Diesel HEV and gasoline HEV system definitions will be quite similar except that a diesel engine's different torque characteristics as compared to a gasoline engine may affect the amount of engine downsizing that is practical.

There is currently only one diesel HEV personal vehicle sold today (in very limited numbers to fleet customers only)—the Dodge Ram Contractor's Special. This pickup is a version of the Ram 2500/3500 truck with the Cummins turbo-diesel engine. This vehicle adds an integrated starter-alternator-damper between the engine and transmission. The vehicle features idle-stop capability and regenerative braking. However, it does not offer launch assist. Although it is technically a mild hybrid, its main attraction is the ability to generate AC power at a jobsite, cabin, or during an emergency. DaimlerChrysler claims a 15% fuel economy benefit with this system. [Reference 5-1]

In addition to the Ram, there are also some heavy-duty diesel HEVs in operation. These include city buses and delivery vehicles. Heavy-duty applications are not reviewed in this report.

Although diesel hybrid-electric personal vehicles are not a real market reality yet, automakers appear to be very interested in the technology as evidenced by several recent concept vehicles featuring diesel HEV systems. In 2005, both Ford and GM showed concept vehicles in Detroit with diesel HEV powertrains, but with different approaches. The GM concept was a version of the Opel Astra small car with a 1.7L diesel engine and GM's Advanced Hybrid System 2. The Ford concept, called Meta One, is an SUV with a twin-turbo diesel V-6 and electric hybridization. It offers a total of 427 lb-ft of torque. But while biased for performance, Meta One is PZEV emissions-capable using selective catalytic reduction (SCR). [Reference 5-2] Mercedes-Benz, also has shown a prototype diesel HEV version of its S-Class large sedan and Vision Grand Sports Tourer wagon. This powertrain consists of a diesel V8 and hybrid system which is tuned mainly for improved performance, but also offers improved fuel economy and reduced emissions. [Reference 5-3]

More important, Volkswagen has recently announced plans to produce in Europe a diesel HEV version of its Golf compact car in 2006. This vehicle has a 1.4L, 3-cylinder supercharged diesel and a 15 kW electric motor mated to a twin clutch electronically-controlled manual transmission. VW claims a 25% increase in fuel economy over a conventional diesel Golf. [Reference 5-4]

In the near-to-mid term, hybridization may be an excellent enabler for automakers to introduce cleaner diesel technologies. Some cleaner-diesel technologies are sensitive to engine operating conditions and are less effective under moderately or highly transient conditions. An HEV powertrain can help smooth out transitions, effectively decoupling the engine from the rest of the drivetrain.

One specific technology where hybridization could be especially useful is with homogeneous charge compression ignition (HCCI) engines. HCCI is a promising technology which can, in some embodiments, combine the lower costs of port-fuel injection gasoline engine intake systems with the higher thermal efficiency of diesel engines. HCCI engines are currently challenged by transients and a hybrid drive system could mitigate the transient effects, allowing opportunities to lower the cost of the HCCI hardware while enabling diesel-like thermal efficiencies.

Currently, diesel engine costs are too high to make diesel HEVs cost effective. However, as diesels gain wider acceptance in the marketplace and economies of scale help reduce production costs, diesel HEVs will likely be introduced. Lower costs of batteries, motors, and other HEV components will also help offset the additional cost of conventional high-pressure injection diesel engines, and an HEV system’s capability of managing powertrain transitions will help the diesel engine reduce emissions.

Given the emerging interest by manufacturers, and the inherent synergies of diesel engines with electric hybrid technology, EPA is optimistic about the future commercialization of diesel HEVs.

5.2 Technology-Specific Inputs

This section discusses the fuel economy and costs of diesel HEV systems. While EPA is not aware of any independent studies of the fuel economy and costs of diesel HEV systems, some estimates can be made using studies of gasoline HEV systems and diesel engines, as well as statements made by automakers either studying diesel HEV technology, or readying it for production. Additionally, there is a recent MIT study that discusses the fuel economy potential of diesel electric hybrids in a fifteen year timeframe [Reference 5-5]. EPA will monitor developments with diesel hybrids and will modify these projections as more information becomes available.

This analysis is clearly not as rigorous as the others in this report. But we believe this method is conservative in that it does not account for any of the natural synergies of combining diesel and HEV technologies. Such synergies include possibly lower engine costs due to the HEV system’s ability to dampen transient effects, thereby reducing emission control issues, and possible engine downsizing opportunities.

5.2.1 Fuel Economy Improvement

Currently, the best source of information for the fuel economy benefit of diesel hybridization alone comes from the manufacturers that are developing the technology. VW and GM both claim a 25% fuel economy increase over a conventional diesel vehicle of the same type with engine downsizing. [References 5-4, 5-6] Mercedes-Benz claims a 15%-20% fuel economy increase over a conventional diesel vehicle with no engine downsizing [Reference 5-7]. The MIT study mentioned above implies that a 30% reduction in fuel consumption is possible in the hybridization of a diesel vehicle. This fuel consumption savings converts to a fuel economy increase of around 40% at the higher base fuel economy level the MIT report assumes, due largely to decreased vehicle weight. For the purposes of this analysis, a 25% fuel economy improvement in addition to the diesel fuel economy improvement will be used to calculate the overall diesel HEV benefit. It is assumed that some engine downsizing will be used in diesel HEVs and, consistent with other sections of this report, no vehicle weight reduction is assumed.

Tables 5-1 and 5-2 summarize the results from Chapters 3 and 4, and calculate the possible total diesel HEV benefit assuming an additional 25% fuel economy increase due to hybridization.

Since the industry sources state the diesel HEV benefit to be 25% above a comparable diesel vehicle, the diesel vehicle fuel economy must first be calculated by multiplying the baseline conventional vehicle fuel economy by the assumed benefit of the diesel engine. Then, this new diesel baseline is multiplied by the assumed 25% diesel HEV gain to yield the total fuel economy improvement. For each vehicle type, the two source studies are averaged because they will be used with the combined cost data from the diesel and gasoline HEV sections. This cost data is averaged because it comes from different sources in some cases.

Table 5-1: Projected Cumulative FE Benefit of Diesel HEV System for Large SUV
(Baseline Fuel Economy of 14.6 MPG)

	Diesel FE benefit	CO2 decrease		Diesel FE (mpg)	Assumed HEV benefit	Diesel HEV FE (mpg)	Total FE benefit	Total CO2 decrease	
		Tailpipe	Lifecycle					Tailpipe	Lifecycle
FEV/EPA	41%	18%	21%	20.6	25%	25.8	77%	35%	37%
ORNL	33%	14%	16%	19.4	25%	24.3	66%	31%	33%
Average	**37%**	**16%**	**19%**	**20.0**		**25.1**	**72%**	**33%**	**35%**

Table 5-2: Projected Cumulative FE Benefit of Diesel HEV System for Midsize Car
(Baseline Fuel Economy of 24.7 MPG).

	Diesel FE benefit	CO2 decrease		Diesel FE (mpg)	Assumed HEV benefit	Diesel HEV FE (mpg)	Total FE benefit	Total CO2 decrease	
		Tailpipe	Lifecycle					Tailpipe	Lifecycle
FEV/EPA	40%	18%	21%	34.6	25%	43.3	75%	34%	36%
ORNL	33%	14%	16%	32.8	25%	41.0	66%	31%	33%
Average	**37%**	**16%**	**19%**	**33.7**		**42.2**	**71%**	**33%**	**35%**

The above tables show that adding a 25% improvement to a diesel vehicle to approximate the effect of hybridization yields an average total diesel HEV fuel economy improvement of 72% for the full size SUV and 71% for the midsize car. The corresponding tailpipe CO2 decrease of 33% and lifecycle CO2 average decrease of 35% is the same for both the large SUV and midsize car. Because the production of diesel fuel has a lower energy requirement than that for gasoline, the CO2 savings over the complete lifecycle are about 2% higher than the tailpipe CO2 savings.

5.2.2 Incremental Retail Price

Diesel HEV costs are difficult to identify with any great certainty since this technology is still in its infancy. However, since the HEV system costs are similar to those of a gasoline HEV, and the diesel engine is at least nominally similar, this report will use a sum of the costs for a diesel engine and gasoline HEV system to estimate diesel HEV costs roughly. This approach is somewhat conservative in that it does not account for some diesel engine and control system cost savings that may be possible due to electric hybridization.

Since the studies cited in Chapters 3 and 4 of this report deal only with a single technology, diesel or gasoline HEV, the prices will be averaged for each technology before they are summed. A summary of the studies and their incremental retail prices appears below:

Table 5-3: Projected Incremental Retail Prices for Diesel HEV

	Large SUV			Midsize Car		
Source	**Diesel**	**Gas HEV**	**Diesel HEV**	**Diesel**	**Gas HEV**	**Diesel HEV**
FEV/EPA	$1,760	--	**$5,912**	$1,252	--	**$4,123**
ORNL	$2,560	$3,039		$1,810	$2,683	
EPRI	--	$4,464		--	$2,500	
average	$2,160	$3,752		$1,531	$2,592	

Summing the averages of the incremental retail prices of the diesel engine and gasoline HEV packages yields an estimated incremental retail price for diesel HEV of $5,912 for the large SUV and $4,123 for the midsize car. These prices will be used in the economic analysis for consumer payback.

Since a diesel HEV would likely share most of its HEV system components with gasoline HEVs, the costs of batteries, electric motors, and other HEV-specific components will be similar to those of gasoline HEVs. See Sections 4.2.3 and 4.2.4 for a discussion of these components. Additionally, diesel HEVs would benefit from the same reduced brake maintenance as gasoline HEVs.

5.2.3 Federal Income Tax Deduction

As discussed in Section 1.4.8, the Energy Policy Act of 2005 allows for tax credits for hybrid electric and diesel vehicles. However, these credits begin to phase out for each manufacturer after 60,000 units are sold, and will not be available after 2009 or 2010. Since the scope of this report concerns high-volume scenarios in a five to ten year timeframe, this tax credit is assumed to be unavailable.

5.3 Economic Results

Based on the above estimates of fuel efficiency and cost, and the economic assumptions described in Section 1.4, Table 5-4 shows the vehicle lifetime savings and number of years required to offset the estimated initial cost of a diesel HEV due to discounted savings on fuel and brake maintenance.

The analysis indicates that the incremental investment in a large SUV diesel hybrid can potentially pay back to the consumer in 5.8 years and offer a $3,321 total lifetime savings. A midsize car diesel HEV could pay back to the consumer in about 11 years. These results do not include the effect of any federal tax credit.

Table 5-4: Cost Effectiveness for Diesel/Battery Hybrid Vehicles

	Large SUV	**Midsize Car**
Incremental Vehicle Price	$5,912	$4,123
Fuel Economy Gain	72%	71%
Tailpipe CO2 decrease	33%	33%
Lifecycle CO2 decrease	35%	35%
Discounted Fuel Savings	$8,701	$4,091
Discounted Brake Savings	$533	$377
Lifetime Savings	$3,321	$344
Payback Period	**5.8 years**	**11.4 years**

References

5-1 http://media.daimlerchrysler.com

5-2 http://www.media.ford.com

5-3 http://www.daimlerchrysler.com

5-4 Hybrid and Electric Vehicle Progress, May 1, 2005

5-5 The Performance of Future ICE and Fuel Cell Powered Vehicles and Their Potential Fleet Impact; Heywood, Weiss, Schafer, Bassene, Natarajan; Laboratory for Energy and the Environment; Massachusetts Institute of Technology; 2004

5-6 http://www.media.gm.com

5-7 http://www.daimlerchrysler.com

Conclusions

This report integrates existing technical literature on the projected fuel efficiency improvement potential and cost of advanced powertrains and applies a common economic analysis to determine their cost effectiveness – from a collective consumer perspective over the typical vehicle lifetime. The technology packages are:

- packages of individual gasoline vehicle technologies
- advanced diesel engines
- gasoline electric hybrids
- diesel electric hybrids

The report makes the following projections:

1) These technologies would result in substantial improvements in new personal vehicle fuel economy

Compared to a baseline gasoline-engine powered vehicle typical of today's vehicles, potential fuel economy improvements ranged from 20% to 70%. The lower end of the range applied modifications to existing gasoline engine-powered vehicles. Maximum fuel economy improvement would be achieved via a diesel hybrid drivetrain. These fuel economy improvements can be achieved with no loss in vehicle performance or size.

2) All of these technology packages are projected to result in a net cost benefit to owner(s) over a 14-year vehicle lifetime as the cumulative operating cost savings more than offset the higher initial vehicle purchase price

All of these technologies will increase new vehicle purchase price. Projected increases in vehicle cost ranged from around $1000 for an advanced gasoline engine package in a midsize car to about $6000 for a diesel electric hybrid in a large SUV.

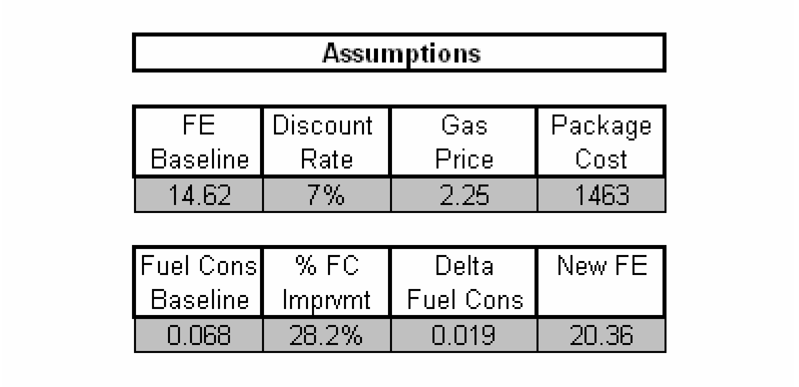
Consumers of large SUVs could recover the additional cost of new technologies within 2 to 6 years, and are projected to save between $2600 and $4400 over the lifetime of the vehicle. Consumers of midsize cars could recover costs within 4 to 11 years, and are projected save between $300 and $1600 over the vehicle’s lifetime.

In general, applying technology to vehicles with the lowest base fuel economy results in the greatest net benefits. The payback and lifetime savings potential is greater for large SUVs than for midsize cars, based on their higher base operating costs.

These results should not be taken to imply that these technologies will necessarily move into the mainstream market in the near future. Decisions by manufacturers to invest in, and consumers to buy, new technologies involve many factors well beyond the scope of this paper, including transition costs which will be higher than the long-term equilibrium costs evaluated in this paper. The point of this paper is not to predict future manufacturer or consumer behavior, but rather to project the cost effectiveness if they do adopt new personal vehicle technologies.

Appendix A: Sample Consumer Payback and Savings Calculations

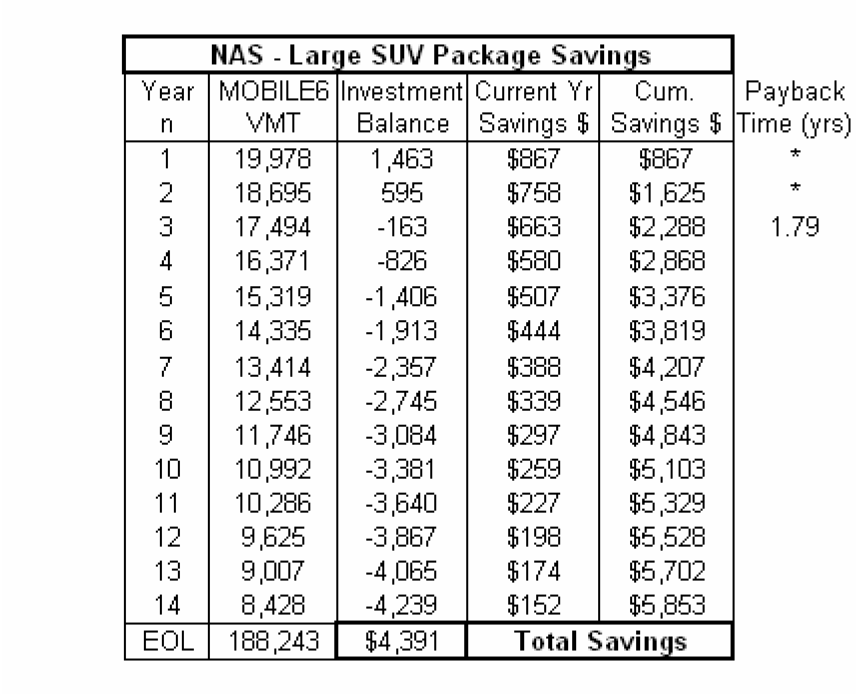
Included below are examples of the spreadsheets used to determine lifetime consumer savings for advanced gasoline technology SUVs.



Assumptions

FE Baseline	Discount Rate	Gas Price	Package Cost
14.62	7%	2.25	1463

Fuel Cons Baseline	% FC Imprvmt	Delta Fuel Cons	New FE
0.068	28.2%	0.019	20.36



NAS - Large SUV Package Savings

Year n	MOBILE6 VMT	Investment Balance	Current Yr Savings $	Cum. Savings $	Payback Time (yrs)
1	19,978	1,463	$867	$867	*
2	18,695	595	$758	$1,625	*
3	17,494	-163	$663	$2,288	1.79
4	16,371	-826	$580	$2,868	
5	15,319	-1,406	$507	$3,376	
6	14,335	-1,913	$444	$3,819	
7	13,414	-2,357	$388	$4,207	
8	12,553	-2,745	$339	$4,546	
9	11,746	-3,084	$297	$4,843	
10	10,992	-3,381	$259	$5,103	
11	10,286	-3,640	$227	$5,329	
12	9,625	-3,867	$198	$5,528	
13	9,007	-4,065	$174	$5,702	
14	8,428	-4,239	$152	$5,853	
EOL	188,243	$4,391	**Total Savings**		

Definitions and equations:

"**Total Savings**", S_{total}, is the projected discounted total savings to the consumer if the vehicle was driven at the given mileage schedule for the expected 14-year life of the vehicle. This is expressed as the sum of the discounted annual savings less the initial package cost of the vehicle, or:

$$S_{total} = \sum_{i=1}^{14} (S_i \ldots S_n) - C_p$$

Where:

- The package cost, **Cp**, refers to the incremental retail price (as determined for advanced gasoline packages, diesel engines, gas electric hybrids and diesel electric hybrids in Sections 2.2.3, 3.2.2, 4.2.2, and 5.2.2, respectively).

- S_i is the annual discounted fuel savings for year i (calculated as the product of gas price, reduction in fuel consumption, and miles traveled). Mathematically, annual fuel savings is expressed as:

$$S_i = \frac{VMT_i(mi) * P_{gas}(\$/gal) * \Delta FC(gal/mi)}{(1 + r_{disc})^{i-1}}$$

and

- **$\mathbf{VMT_i}$** is the MOBILE6 predicted vehicle miles traveled for year i;
- **r_{disc}** is the discount rate;
- **$\mathbf{P_{gas}}$** is the fuel price;
- **ΔFC** is delta fuel consumption – the reduction in the amount of fuel consumed, per mile, due to the efficiency gain of the new technology.

ΔFC is defined as:

$$\Delta FC\,(gal/mi) = \frac{1}{FE_{base}} * (\%\,FC\,improvement)$$

So, for year 4 in the spreadsheet above,

$$S_4 = \frac{16371(mi) * 2.25(\$/gal) * 0.019\,(gal/mi)}{(1 + 0.07)^{(4-1)}} = \$580$$

Spreadsheet nomenclature

"**Year i**" corresponds to the year of a vehicle's expected life (assuming no scrappage). Note that for Investment Balance and Payback Time, it references the start of a given year.

"**MOBILE6 VMT**" is the expected annual vehicle miles traveled for a given year of vehicle life. The mileage figures have been established by EPA's MOBILE6 model and are used extensively in regulatory work.

"**Investment Balance**" refers to the net amount of additional cost (positive) or savings (negative) that the consumer has realized at the start of a given year i. It is expressed as the difference between the package cost and the cumulative savings realized through year (i-1).

Current Year Savings is defined as the discounted savings due to reduced fuel consumption (and brake maintenance savings, in the case of hybrids) for that given year.

The **Payback Time** was determined by interpolating between the years in which the investment balance sign changed from positive to negative. Because year i is defined as the beginning of a year, the time elapsed is offset one row.

The last full column, "**Cumulative Savings**" is the sum of all savings realized by the vehicle through the end of year i, and includes both fuel savings and brake savings (hybrids).

Appendix B: Diesel Aftertreatment Costs

This appendix describes the methodology used to determine manufacturer aftertreatment cost projections for the FEV-EPA diesel packages described in Section 3. It explains the rationale for the projections first discussed in the report, "Progress Report on Clean and Efficient Automotive Technologies Under Development at EPA: Interim Technical Report" (EPA420-R-04-002, January 2004), in which EPA provides an estimate of the incremental cost of exhaust emission control for a light-duty diesel engine compared to a conventional gasoline engine of similar performance. The cost comparison was made for a system similar to the Toyota Diesel Particulate NOx Reduction (DPNR) system described in "Testing of the Toyota Avensis DPNR at the U.S. EPA-NVFEL," SAE Technical Paper No. 2002-01-2877[20] and a similar performing gasoline 3-way catalyst system. The costs were derived from data provided by emission control system manufacturers, vehicle manufacturers, and engine manufacturers as summarized in a series of EPA reports.[21,22,23,24]

The following table summarizes the various components of differential cost and the resultant incremental costs for diesel engines when compared to a gasoline engine.

Table B1: Incremental Manufacturing Cost of a Diesel Emission Control System (Relative to a Conventional Gasoline 3-Way Catalyst System)

	2.5L TDI Diesel vs. 3.0L Gasoline	**4.5L TDI Diesel vs. 5.4L gasoline**
Approximate Rated Power	150 bhp	260 bhp
Catalyst Volume (Diesel/SI)	3.8L / 3.0L	6.8L / 5.4L
Substrate Cost Difference (wall-flow vs. flow-through)	$130	$210
OBD and Regeneration System Cost Difference	$100	$100
Coatings (PGM and Adsorbant) Cost Difference	$25	$45
Estimated System Cost Difference	$255	$355

Notes: The diesel catalyst system was assumed to be sized at 1.5 times engine swept volume and SI catalyst 1.0 times engine swept volume.

---

[20] J. McDonald, B. Bunker, "Testing of the Toyota Avensis DPNR at the U.S. EPA-NVFEL", SAE Technical Paper No. 2002-01-2877

[21] "Estimating NOx Adsorber and Diesel Particulate Filter Costs", EPA Air Docket A-99-06, Document Number II-B-29, May 15, 2000.

[22] "Estimated Economic Impact of New Emission Standards for Heavy-Duty On-Highway Engines", March 1997, EPA 420-R-97-009.

[23] "Cost Estimates for Heavy-Duty Gasoline Vehicles", EPA Air Docket A-99-06, Document Number II-A-13, September 1998.

[24] "Economic Analysis of Diesel Aftertreatment System Changes Made Possible by Reduction of Diesel Fuel Sulfur Content", EPA Air Docket A-99-06, Document Number II-A-28, December 1999.

The difference in cost between wall-flow (DPNR-type) and flow through (gasoline 3-way) catalyst substrates accounts for half or more of the difference in the costs of the emission control systems expected for clean light-duty diesel technology in comparison to SI exhaust emission controls at Tier 2/LEV II emission levels.

The materials used for many wall-flow substrates are similar to the materials used for flow-through substrates (cordierite). The primary difference for the increased cost of wall-flow substrates is due to differences in manufacturing costs, particularly the processes for plugging alternating substrate cells. The price of producing wall-flow substrates should decrease towards the price of comparably-sized flow-through substrates as production processes are put into place to supply sufficient volumes of substrates for levels of production more in line with the levels necessary to supply significant numbers of light-duty diesel vehicles.

The price difference for the On-Board Diagnostics (OBD) and PM/NOx/SOx regeneration system includes the use of a wide-range oxygen sensor (versus the switching sensor used for SI applications) for control, the need for direct exhaust injection for regeneration, and the need for a differential pressure sensor in the exhaust for OBD and PM regeneration control. For this analysis, we projected that platinum group metal (PGM) loading would converge to a similar level in the long-term for NOx storage catalysts and gasoline 3-way catalysts at a ratio of 50 g/ft^3. Hence, the cost difference in the coatings for a DPNR-like system is caused by the larger catalyst volume and the resulting higher PGM content (NOx adsorbant material makes up ~$1 or less of the cost per device). PGM costs were based on the average prices of Platinum and Rhodium over the first 2 quarters of 2002 (Pt: $520/troy-oz., Rh: $931/troy-oz.).

Appendix C: Sensitivity of Consumer Payback to Fuel Price

The following tables show the sensitivity of payback time to fuel price, which was assumed to be $2.25 per gallon in the main body of the paper. As illustrated below, fuel prices under $2.00 per gallon would yield payback periods in excess of 14 years for the most expensive packages, whereas $3.00 fuel would reduce payback time of most packages to 5 years or less.

Table C1: Years to Payback Advanced Gasoline Packages at Various Fuel Prices

Package	**$1.50**	**$2.00**	**$2.25**	**$2.50**	**$3.00**
NAS-Large SUV	2.9	2.0	**1.8**	1.6	1.3
NAS-Midsize Car	6.5	4.4	**3.8**	3.3	2.7
NESCCAF-Large SUV	4.1	2.8	**2.5**	2.2	1.8
NESCCAF-Midsize Car	6.9	4.6	**3.9**	3.5	2.8

Table C2: Years to Payback Diesel Packages at Various Fuel Prices

Package	**$1.50**	**$2.00**	**$2.25**	**$2.50**	**$3.00**
FEV-EPA Large SUV	3.5	2.4	**2.1**	1.9	1.5
FEV-EPA Midsize Car	6.6	4.4	**3.8**	3.3	2.7
ORNL-Large SUV	7.5	4.8	**4.1**	3.6	2.8
ORNL-Midsize Car	>14	9.5	**7.7**	6.6	5.1

Table C3: Years to Payback Gasoline Hybrid Packages at Various Fuel Prices

Package	**$1.50**	**$2.00**	**$2.25**	**$2.50**	**$3.00**
EPRI-Large SUV	9.3	6.0	**5.0**	4.3	3.6
EPRI-Midsize Car	>14	9.0	**7.4**	6.3	5.3
ORNL-Large SUV	7.0	4.8	**4.1**	3.7	3.1
ORNL-Midsize Car	>14	11.6	**9.5**	8.1	6.1

Table C4: Years to Payback Diesel Hybrid Packages at Various Fuel Prices

Package	**$1.50**	**$2.00**	**$2.25**	**$2.50**	**$3.00**
EPA-derived Large SUV	11.5	6.8	**5.8**	5.0	3.9
EPA-derived Midsize Car	>14	>14	**11.4**	9.5	7.1

Appendix D: Sensitivity of Consumer Payback to Retail Price Equivalent Factor

Tables D1 through D4 show sensitivity of consumer payback to changes in assumed RPE. While EPA uses a 1.26 RPE in its regulatory analyses, other recent technology studies have typically used RPEs of 1.4 or 1.6. As illustrated below, a higher RPE increases the initial consumer investment cost and the time to payback with discounted operating savings. Packages with lower payback times are relatively less affected by higher RPEs.

Table D1: Years to Payback Advanced Gasoline Packages at Various RPE

Package	RPE = 1.26	RPE = 1.4	RPE = 1.6
NAS-Large SUV	1.8	2.0	2.4
NAS-Midsize Car	3.8	4.3	5.1
NESCCAF-Large SUV	2.5	2.8	3.3
NESCCAF-Midsize Car	3.9	4.5	5.4

Table D2: Years to Payback Diesel Packages at Various RPE

Package	RPE = 1.26	RPE = 1.4	RPE = 1.6
FEV-EPA Large SUV	2.1	2.4	2.8
FEV-EPA Midsize Car	3.8	4.3	5.2
ORNL-Large SUV	4.1	4.7	5.7
ORNL-Midsize Car	7.7	9.3	12.1

Table D3: Years to Payback Gasoline Hybrid Packages at Various RPE

Package	RPE = 1.26	RPE = 1.4	RPE = 1.6
EPRI-Large SUV	5.0	5.9	7.2
EPRI-Midsize Car	7.4	9.0	11.4
ORNL-Large SUV	4.1	4.8	6.0
ORNL-Midsize Car	9.5	11.7	>14

Table D4: Years to Payback Diesel Hybrid Packages at Various RPE

Package	RPE = 1.26	RPE = 1.4	RPE = 1.6
EPA-derived Large SUV	5.7	6.7	8.5
EPA-derived Midsize Car	11.2	>14	>14

Appendix E: External Reviewer Comments and Responses

A preliminary draft of this report was distributed to 15 external organizations for their technical review. The organizations included other federal agencies, state agencies, automobile manufacturers, automotive suppliers, industry experts, and non-profit organizations. Comments were received from 8 reviewers. Details of the technical reviews have been kept confidential to allow for an objective and honest critique of the material. This report has been improved by the collective time and effort invested by all of the draft report reviewers. EPA would like to thank each of them for their candor and insight. This is an interim report and additional comments are welcome.

This section summarizes the most substantial comments and EPA's response to each of them.

E.1 Economic Methodology and Assumptions

Market limitations of consumer payback
Several reviewers emphasized that good consumer payback does not necessarily mean that there will be a business case, i.e., that manufacturers will invest in, or that consumers will buy, a new technology. One reviewer stated that *"Over 14 years a motor vehicle may be owned by four or five owners, but only the first is concerned about the payback of an increased initial cost for improved fuel economy….when customers are attempting to consider a vehicle and its increased cost in terms of 'cost effectiveness,' they almost always use a time period of approximately four years and 50,000 miles."* Another reviewer cited one specific example, *"U.S. consumers haven't broadly accepted diesels to date, what's going to change that in the future?"*

EPA completely agrees that consumer payback is only one relevant factor, and likely a small factor in past decision making by manufacturers and consumers alike. This paper is not predicting future manufacturer or consumer behavior, but simply projecting the cost effectiveness, on a collective consumer basis, <u>if</u> manufacturers and consumers do decide to adopt new personal vehicle technologies. Additional language has been added in the Abstract, Executive Summary, and Conclusions to clarify this distinction.

Transition costs
Multiple reviewers pointed out that the focus on a long-term, high-volume scenario ignored the very real transition costs that can be an important barrier for automobile manufacturers. Further, one commenter pointed out that *"individual, smaller-line manufacturers at lower levels will not experience those same cost savings"* as larger manufacturers.

EPA agrees that transition costs are real and important. Since, as explained in Section 1.4.1, short-term transition costs are both temporary and complex, it was beyond the scope of this paper to address them. Text has been added in the Abstract, Executive Summary, Section 1.4.1, and Conclusions to clarify this important assumption.

Retail price equivalent (“retail markup”)

Several reviewers suggested that the 1.26 retail price equivalent (RPE) markup factor was too low.

One commenter questioned which aspects of cost (variable or total) were reflected in the manufacturer’s cited component cost. *“Our own analysis shows that the typical 1.6 to 1.7 factor is reasonable as the multiplier for variable cost to RPE, whereas the 1.26 looks closer to (but still lower than) our multiplier for variable + fixed cost to RPE… I recommend that EPA use the costs and benefits unchanged from the referenced reports to avoid charges of ‘cherry picking’ the results from the studies, or alternatively, provide additional discussion of this issue in the report.”*

Another reviewer said the 1.26 RPE “*seems far too low*” and suggested that a value of 1.7 “*is a much more representative RPE*.”

A third commenter stated that the 1.26 factor “*is low by most manufacturer standards. Some assessment of sensitivity or elasticity should be done*.”

We retained the RPE factor of 1.26 that EPA uses for regulatory development, but we did add a sensitivity analysis of payback using RPEs of 1.4 and 1.6. This analysis appears in Appendix D.

Maintenance costs

Several commenters pointed out that EPA accounted for one type of maintenance savings—reduced brake maintenance for hybrid vehicles—but did not account for additional maintenance costs that might be associated with new technologies. One commenter stated that the *“Assumption that maintenance will be the same or better for hybrids is not proven. Also, maintenance for diesel aftertreatment may be significantly higher.”* A second commenter raised the possibility that some hybrid vehicles might require replacement of the battery pack.

EPA agrees that this is a legitimate issue for further study, and text was added in Sections 1.4.7.2 and 1.4.7.4 to reflect this. Brake savings for hybrids are the one type of maintenance where the difference with conventional vehicles is both significant and certain. Other maintenance items are not well understood at this time, and were not included. EPA will continue to monitor real world data on this issue and will revise the analysis as appropriate.

Consumer value of less refueling time

One commenter noted that increased fuel economy would reduce frequency of refueling events (and a corresponding monetized time savings). The value to consumers of saving time refueling is not included in the analysis; however, as noted in Section 1.4.7.5, EPA will consider this in future analyses.

Selection of large SUV and midsize car classes

One commenter noted that the selection of vehicle class may influence the result of the study if the selected classes are more or less responsive to new technologies than a class that was not studied. *“…do some technologies work better for one class of vehicles that* *is not represented in the analysis…while others work better for another class of vehicle that is represented….?*” Naturally, some individual technologies benefit certain vehicle classes more than others. EPA’s analysis selected two high-volume classes that cover the range of vehicle classes, with the assumption that any technological advances could yield large aggregate fuel and carbon savings. It is acknowledged in Section 1.2 that the impact of various technologies on fuel economy and cost for these selected classes will translate to other vehicle classes in varying degrees.

E.2 Gasoline Vehicle Technology Packages

Sources for core technology projections

One concern was over *“the exclusive use of the NAS and NESCCAF study results for [advanced gasoline technology package] data….Technology developers conducted both studies, which raises conflict-of-interest issues and obvious bias in promoting high benefit estimates and low cost estimates for some new engine technologies they are developing. Referencing other studies, or providing some evidence of unbiased choice of technology cost-benefit estimates would be useful, especially since the actual benefit numbers for the technology packages are not likely to change significantly.”*

EPA selected the NAS and NESCCAF studies because we believe they are the most credible peer-reviewed analyses in the literature. The fact that technology developers authored both reports can be both a weakness and a strength, a weakness in terms of possible bias and a strength in terms of technology expertise. EPA will continue to monitor the literature, but at this time still considers these two studies to be the most authoritative on the subject.

Better description of NAS technology packages

Multiple commenters requested further clarification on how the technology content in the NAS cost-efficient gasoline packages (both Midsize Car and Large SUV) was established. EPA attempted to replicate the methodology used in the NAS study for determining these cost-efficient technologies. A more detailed description of the NAS cost-efficient methodology is available in Chapter 4 of the NAS report.

To clarify, the list of NAS technologies presented in this report (as Tables 2-3 and 2-4) are presumed to represent the cost-efficient packages established by NAS, and are merely illustrative for EPA’s purposes. All EPA economic analysis was performed on NAS fuel economy improvement and cost projections cited directly from NAS, Table 4-2.

E.3 Diesel Engines

Diesel vehicle technology uncertainties

One commenter strongly recommended that the report *“clearly note the uncertainty associated with all the technologies (particularly diesel and diesel hybrids)…huge uncertainty as to whether diesels can meet emission standards, and whether diesel hybrid costs and emissions can be reduced….we believe that it is widely accepted that significant hurdles toward Tier 2, Bin 5 compliance remain….Durability and in-use emissions performance are still unproven.”*

Based on monitoring of the progress by automakers, testing of automaker prototypes, the introduction of low-sulfur diesel fuel in 2006, and confidential discussions with automakers and other researchers, EPA is confident that diesel vehicles will be able to meet Tier 2, Bin 5 in the near future. Volkswagen recently announced plans to market a Tier 2, Bin 5 compliant Jetta in the U.S. by the 2007 model year.

Diesel engine costs

One reviewer suggested that the diesel cost estimates were fairly realistic: *"As far as the base engine cost estimate it looks like you have done a good job of comparing the gas vs diesel at a component level..."*

Diesel engine fuel economy projections

EPA received two comments. One reviewer asked that we *"cite the reference for the source of the claim that today's diesel engines achieve 40% higher fuel economy than today's gasoline engines."* A second commenter supported the range of 33-40% diesel fuel economy improvement, *"Actual certification data plotted across all gasoline and diesel vehicles sold in Europe provides technical proof of this benefit. Furthermore, as the vehicle weight increases, the percent improvement continues to increase, which suggests that the actual benefits in the U.S. could be more than 40%."*

The second commenter above responds to the first commenter. The sources for the 33-40% fuel economy improvement are the FEV and Oak Ridge National Laboratory studies referenced in Section 3 of the report. EPA continues to believe that these are credible projections for the fuel economy improvement associated with diesel vehicles, all other things being equal.

Diesel aftertreatment costs

Several reviewers took issue with the projected costs for diesel aftertreatment. One commenter stated, *"Of all of the information that I saw in your report, the one that was most striking to me was the underestimate of the aftertreatment. If you modify that, I believe you will be in line with where the diesel industry is today as it wrestles with reducing the aftertreatment costs.... I would say that the aftertreatment increase over a gas engine is at least $1000..."* Further communication with this commenter clarified that this estimate would be for "volumes up to 100,000 units," and that the commenter would expect lower costs at higher unit volumes. A second reviewer said *"This is an extremely low estimate. The precious metal alone will exceed this cost estimate. Such an overly optimistic [assumption] could appear biased toward diesel."*

EPA has added Appendix B to explain the methodology for the diesel aftertreatment cost projections. The manufacturer cost projections have been increased from $282 for the large SUV and $218 for the midsize car to $355 for the large SUV and $255 for the midsize car. With the 1.26 markup factor, these manufacturer cost projections translate to retail price projections of $447 for the large SUV and $321 for the midsize car. As discussed in Section 3.2.2, Tier 2 NOx emissions aftertreatment for diesels is an area of intense development and EPA is aware of cost estimates that are both higher and lower than the projections. EPA is monitoring the progress in this area closely and will update costs as the information becomes more solid.

Diesel aftertreatment fuel economy penalty

The same reviewers also challenged EPA's assumption that there would be no fuel economy penalty associated with diesel aftertreatment. One commenter stated unequivocally that, *"This is not true as even diesel particulate filters alone must be regenerated with somewhat rich operation, so there is always an influence on fuel economy which can be 1-5% in some cases."* Another said, *"Diesel aftertreatment systems are likely to reduce fuel economy."*

EPA has clarified the assumption that there will be no <u>overall</u> fuel economy penalty with diesel vehicles that have aftertreatment emission control systems. EPA believes it is likely that there will be some increase in fuel consumption related to the operation of diesel aftertreatment emission controls, but that overall diesel vehicle fuel economy, due to engine optimization and other changes, will be unchanged. EPA will monitor developments and make appropriate changes as more information becomes available.

Other fuel-saving technologies that could be included in the diesel vehicle package

One commenter questioned the lack of non-engine technologies, that were included in the gasoline vehicle technology packages, in the diesel technology packages. Technologies such as advanced transmissions, lower rolling resistance tires, and improved aerodynamics were not included in the diesel packages because they were not part of the FEV and Oak Ridge National Laboratory reports which were the primary sources for the core diesel technology projections. But, EPA agrees that non-engine technologies such as these could in fact be included in a broader diesel package, and EPA will consider including these technologies in future analyses.

E.4 <u>Gasoline / Electric Hybrids</u>

Gasoline hybrid fuel economy projections

One reviewer stated that the projections for fuel economy improvement for the midsize car *"look reasonable"* but that the 52% fuel economy improvement potential for large SUVs from the EPRI study *"is way too high"* and that the 35% improvement projection from the Oak Ridge National Laboratory (ORNL) study is *"still higher than OEMs expect."*

This is a significant comment, as it is clear that this reviewer believes that the fuel economy improvement potential for gasoline hybrids is much less for large SUVs than for midsize cars, but the reviewer provided no quantitative estimates. EPA uses the projections from the EPRI and ORNL studies, which provide the core technology projections for hybrid vehicles. EPA will continue to monitor new work in this area and will modify the fuel economy projections for hybrid vehicles as more information becomes available.

On-road hybrid vehicle fuel economy adjustment factor

Several reviewers noted that EPA used the same 0.85 fuel economy adjustment factor, to convert EPA laboratory fuel economy values to real world fuel economy estimates, for all technologies and suggested that this adjustment may be too generous for hybrid vehicles.

EPA has publicly announced that we are reviewing the current methodology for calculating fuel economy labels and we expect to propose a new methodology by the end of 2005. Once EPA adopts a new fuel economy labeling methodology, we intend to revise this analysis to be consistent with the new approach. It is also possible that further development and refinement of hybrid technology may be able to reduce any higher real world fuel economy shortfall that current hybrid owners may be experiencing.

Definition and classification of hybrid vehicle designs

One reviewer expressed concern with how EPA defined, classified, and named different types of hybrid vehicles and suggested alternative approaches.

EPA retained its hybrid vehicle definitions and classifications. EPA recognizes that different manufacturers use different definitions of what a hybrid vehicle is, and that there are debates over terms like “full,” “mild”, and “assist” hybrids. EPA tried to choose equitable terms that reflect the different perspectives in the industry, and encourages the individual manufacturers and industry associations to resolve these issues as soon as possible.

Other fuel-saving technologies that could be included in the hybrid vehicle package

One commenter pointed out that certain technologies (such as tires and aerodynamics) that were included in the gasoline vehicle technology packages could also be included in the hybrid technology packages. It is clear that many of the gasoline hybrids currently on the U.S. market in fact have some of these improvements. EPA agrees that non-engine technologies such as these could in fact be included in a broader hybrid package, and EPA will consider including these technologies in future analyses.

E.5 Diesel / Electric Hybrids

Diesel hybrid fuel economy projections

Two comments were received on this topic. One reviewer stated that *“this section seems much more optimistic than current information would suggest.....remember, there is still no product.”* A second reviewer inquired about the diesel hybrid fuel economy improvement projections made in the report, and how they compared to a recent study by MIT.

EPA recognizes that the projections for diesel hybrids are much more speculative than those for other technologies in the report, because of less research and development, much less information in the technical literature, and the lack of any diesel hybrid personal vehicles on the market. Interestingly, the diesel hybrid fuel economy improvements predicted by MIT were more optimistic than those estimated by EPA. See Section 5.2.1 for more discussion of this topic. EPA will monitor developments and make changes as appropriate in future analyses.