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Progress Report on Clean and Efficient Automotive Technologies Under Development at EPA

Interim Technical Report

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Interim Technical Report

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Report Availability

An electronic copy of this technical report is available for downloading from EPA's website:

http://www.epa.gov/otaq/technology.htm

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Abstract

This progress report summarizes the status of several automotive powertrain technologies under development in EPA's Clean Automotive Technology program: hydraulic hybrid drivetrains, clean diesel engines, and variable displacement engines.

The economic projections in this progress report are based on a longer-term, 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 will undoubtedly be higher during a transition period when economies of scale will be much lower and there will be a series of necessary up-front investments, but estimates of these temporary 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 truly achieves long-term market maturity, as that type of sustained market share would no doubt justify continued cost reduction that cannot be predicted at this time.

Various combinations of the new technologies included in this progress report could "payback" to the consumer in 1 to 10 years, depending on the personal vehicle type and technology package. All of these technology packages could provide net vehicle lifetime savings for consumers--ranging from $1000 to $3000 for most cases--as discounted operating savings over time more than offset higher initial vehicle prices. The maximum vehicle fuel economy improvement and lifetime savings are achieved with a clean diesel engine (with or without variable displacement) and a full hydraulic hybrid drivetrain with engine-off strategy. A central assumption in this analysis is that the addition of the new powertrain technologies do not change vehicle size, acceleration, or range. As no new lightweight materials are assumed, overall vehicle weights increased by from 30 to 250 kilograms due to the added components in the various technology packages.

In every case, these new automotive powertrain technologies payback for an owner of a larger personal vehicle more quickly than they do for an owner of a smaller personal vehicle. These new technologies would payback in large sport utility vehicle (SUV) applications with 4-wheel drive in 1-5 years and would payback in midsize car applications with 2-wheel drive in 3-10 years, based on current fuel prices.

Executive Summary

This progress report primarily addresses four technology approaches with which EPA has direct experience, due to active in-house projects under EPA's Clean Automotive Technology program:

> ➢ mild hydraulic hybrid drivetrain, with both engine-on (where the engine is always on unless shut off) and engine-off (with engine on and engine off cycling) strategies
> ➢ full hydraulic hybrid drivetrain, with both engine-on and engine-off strategies
> ➢ clean diesel engine
> ➢ variable displacement engine

Hydraulic hybrid drivetrains have been a core focus of EPA's Clean Automotive Technology program since the mid-1990s. EPA has cooperative research and development agreements (CRADAs) with Eaton Corporation, Parker-Hannifin, and the Ford Motor Company. Much of EPA's early research focused on the design of individual hydraulic hybrid components optimized for passenger vehicle applications (i.e., smaller, lighter, and more efficient), but more recently EPA has been working with its private sector partners to demonstrate complete hydraulic hybrid drivetrains in specific vehicle applications. For example, EPA recently built a mild hydraulic hybrid urban delivery vehicle that competed in the Michelin Bibendum Challenge in September 2003 and won a gold medal for fuel efficiency and a silver medal for acceleration performance. EPA is currently building a full hydraulic series hybrid urban delivery truck that will have further fuel economy and performance improvements.

Clean Diesel Combustion is a second core focus of EPA's in-house research and development program. EPA has demonstrated the lowest diesel engine-out nitrogen oxide emissions levels ever reported in the literature, and is in discussions with several private sector organizations on potential future partnerships to further develop this technology. Since it is premature to make cost projections for Clean Diesel Combustion, this report uses a combination of conventional diesel engine technology along with emissions aftertreatment technology (both for particulate matter and oxides of nitrogen emissions) as a basis for costing out clean diesel engine technology, and as a first-order surrogate for the costs that would be associated with Clean Diesel Combustion.

Variable displacement refers to a specific engine concept developed by EPA that divides the engine into two separate modules, each with its own crankshaft, that allows one-half of the engine to be shut down and the other half to be operated at a much more efficient level, during low-load vehicle operation. EPA is currently in the process of considering a prototype engine to further evaluate this concept.

EPA is also optimistic about the potential of electric hybrid and fuel cell vehicle technologies, but they are not included in this progress report because they are not part of EPA's Clean Automotive Technology research and development program. While there are some comparable

cost analyses that exist for hybrid electric vehicles (HEV)[1], EPA does not at this time have the ability to project future HEV costs with confidence. EPA is optimistic that the consumer payback of electric hybrid vehicles will continue to improve in the future. Honda and Toyota currently offer three hybrid electric models in the US market and reports suggest that owners have been pleased with the performance of these first-generation electric hybrids. Nearly every automobile manufacturer has announced plans to bring additional electric hybrid vehicles to the US market in the next few years which suggests that the industry believes that the economics of electric hybrids will continue to improve. EPA is actively seeking more updated information from automobile manufacturers on the cost and performance of electric hybrid vehicles. Fuel cell vehicles are the subject of intense research and development within both the industry and the federal government's FreedomCar project, but it is impossible at this time to project fuel cell vehicle cost with certainty.

In this progress report, a total of 40 modeling scenarios are analyzed, comprising 2 personal vehicle classes, 5 drivetrain configurations, and 4 engine packages. Two of these scenarios represent the "baseline" cases for the two personal vehicle classes, so there are 38 non-baseline scenarios evaluating vehicles with advanced technology packages. It should be emphasized that, because of the large number of technology packages evaluated in this study, it was not possible to optimize every design. The goal in this paper is to evaluate plausible designs, and it is expected that commercialization would yield optimization for all of the technology packages. A central assumption in this analysis is that the addition of the new powertrain technologies do not change vehicle size, acceleration, or range. As no new lightweight materials are assumed in this analysis, overall vehicle weights increased by from 30 to 250 kilograms due to the added components in the various technology packages. The two personal vehicle classes, chosen to represent the types of powertrains used in other high-volume vehicle classes as well, are:

> large SUV, 4-wheel drive (e.g., Ford Expedition, Chevrolet Suburban, Dodge Durango)
> midsize car, front wheel drive (e.g., Chevrolet Monte Carlo, Toyota Camry, Honda Accord)

The 5 drivetrain configurations are:

> conventional transmission (the baseline)
> mild hydraulic hybrid with engine-on strategy
> mild hydraulic hybrid with engine-off strategy
> full hydraulic hybrid with engine-on strategy
> full hydraulic hybrid with engine-off strategy

The 4 engine configurations are:

> conventional gasoline engine (the baseline)
> clean diesel engine
> gasoline variable displacement engine

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[1] One source of information on cost of electric hybrid powertrain components is "*Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*," a report published by the Electric Power Research Institute in 2001 (with contributions from a number of consulting firms, automobile companies, and governmental bodies).

> ➢ clean diesel variable displacement engine

For each of the 20 large SUV modeling scenarios, Table ES-1 projects the absolute fuel economy level in miles per gallon, as well as the fuel economy improvement, incremental cost, cost per % fuel economy improvement, cost payback period, and lifetime savings all compared to the baseline 4-wheel drive (4WD) large SUV with a conventional gasoline engine and conventional transmission.

Table ES-1: Key Projections for Large 4WD SUV Modeling Scenarios

Large Sport Utility Vehicle (4WD)	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	17.2	19.4	20.0	20.2	23.0
Clean Diesel Engine	23.6	27.0	27.6	27.2	32.0
Gasoline Variable Displacement Engine	19.7	22.5	22.8	22.8	24.1
Clean Diesel Variable Displacement Engine	26.8	30.9	31.3	31.2	34.6
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	base	13%	17%	18%	34%
Clean Diesel Engine	37%	57%	61%	59%	86%
Gasoline Variable Displacement Engine	15%	31%	33%	33%	40%
Clean Diesel Variable Displacement Engine	56%	80%	82%	82%	101%
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$1,321	$1,336	$552	$575
Clean Diesel Engine	$1,668	$2,983	$2,999	$2,217	$2,241
Gasoline Variable Displacement Engine	$532	$1,822	$1,838	$1,055	$1,084
Clean Diesel Variable Displacement Engine	$2,195	$3,487	$3,504	$2,721	$2,749
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$100	$81	$32	$17
Clean Diesel Engine	$45	$52	$49	$38	$26
Gasoline Variable Displacement Engine	$36	$59	$56	$32	$27
Clean Diesel Variable Displacement Engine	$39	$44	$43	$33	$27
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	4.9	4.4	2.0	1.2
Clean Diesel Engine	3.6	4.6	4.5	3.2	2.5
Gasoline Variable Displacement Engine	2.3	4.2	4.1	2.1	2.0
Clean Diesel Variable Displacement Engine	3.5	4.5	4.5	3.3	2.9
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	$955	$1,282	$2,159	$3,527
Clean Diesel Engine	$2,060	$2,733	$2,880	$3,559	$4,786
Gasoline Variable Displacement Engine	$1,175	$2,067	$2,202	$2,975	$3,472
Clean Diesel Variable Displacement Engine	$2,738	$3,318	$3,401	$4,145	$4,852

* Fuel economy values are laboratory values and are about 15% higher than real-world projections.

The large number of technology packages yields a broad range of projected fuel economy improvements. The new technologies could increase the fuel economy of a typical 4WD large SUV from 17.2 mpg to as little as 19.4 mpg (for the conventional engine with mild hydraulic hybrid and engine-on strategy) to as much as 34.6 mpg (for the clean diesel variable displacement engine with full hydraulic hybrid and engine-off strategy). This range reflects a fuel economy increase of 13-101% (all fuel economy values in this report are expressed as laboratory values, similar to the values used for CAFE compliance and are about 15% higher

than real world projections provided to consumers). The technologies that could yield these fuel economy increases would add $500-3500 to the cost of a new 4WD large SUV.

The incremental cost for any particular technology package reflects both the cost of any added components as well as the savings from any components of the conventional vehicle that can be deleted. For example, as shown in detail in Section 6, for the package involving a conventional gasoline engine with full hydraulic hybrid drivetrain in a 4WD large SUV, there are several components that can be deleted from a conventional 4WD SUV (most notably the automatic transmission and transfer case) that total approximately $2200 in supplier cost. This offsets a major portion of the additional cost of the hydraulic drivetrain in the 4WD large SUV, and is a major reason why the overall incremental cost is low and the consumer payback is so short for the 4WD large SUV.

It is very important to emphasize the underlying assumptions involved in the cost projections. The central assumption is that the cost projections are for a longer-term scenario where the economies of scale (component production volumes on the order of one million units per year) 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 other technology studies. These cost projections are not relevant to a transition period where the advanced technology is initially commercialized (and annual component production volumes might only be in the thousands or tens of thousands). During a transition period, there will be many relevant cost factors that will be nonexistent or negligible in a mature market, including but not limited to: recovery of research and development expenditures; initial investment in component manufacturing facilities, vehicle assembly plants, and dealer and maintenance infrastructure; engineering time for vehicle design modifications to accommodate the new technology; and higher per unit costs due to lower economies of scale. Accordingly, the transition costs would be higher than the long-term cost projections for the advanced technologies in this study. On the other hand, it is also a basic tenet of automotive production that, once a technology achieves market maturity, there is overwhelming economic incentive to continue to invest in research to continually reduce cost. So it is also likely that the cost projections in this report underestimate the potential to reduce cost 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 first reach high levels.

Cost payback period to the consumer, or how many years it would take for the discounted fuel savings (and brake savings, for hydraulic hybrid drivetrains) to offset the higher initial vehicle cost, is the best single metric for identifying those technologies which will be most attractive to vehicle manufacturers and new vehicle buyers alike. Table ES-1 shows that, for 4WD large SUVs, the payback periods for the full range of new technologies analyzed in this report range from 1.2 years for a conventional gasoline engine and a full hydraulic hybrid drivetrain with an engine-off strategy (the consumer acceptance of the engine cycling frequency of this configuration is unknown), to 4.9 years for a conventional gasoline engine and a mild hydraulic hybrid drivetrain with an engine-on strategy. Most important, almost all of the twenty 4WD

large SUV scenarios yield paybacks of 4.5 years or less. Lifetime savings is the sum of the discounted fuel savings due to higher vehicle fuel economy and the discounted savings in brake maintenance (only for the hydraulic hybrid powertrains due to regenerative braking) minus the higher initial technology cost. By definition, any scenario that has payback less that the typical 14-year vehicle lifetime will also show a positive lifetime savings, and Table ES-1 shows that owners of 4WD large SUVs with advanced technologies could reap discounted lifetime savings up to $5000 per vehicle.

Table ES-2 projects the absolute fuel economy level, fuel economy improvement, incremental new vehicle cost, cost per % fuel economy improvement, cost payback period, and lifetime savings for the 20 midsize car scenarios.

Again, the large number of technology packages yields a broad range of projected fuel economy improvements. The new technologies could increase the fuel economy of a typical midsize car from 29 mpg to as little as 32.4 mpg (for the conventional engine with mild hydraulic hybrid and engine-on strategy) to as much as 64.3 mpg (for the clean diesel variable displacement engine with full hydraulic hybrid and engine-off strategy). This range reflects a fuel economy increase of 12-122%. The technologies that could yield these fuel economy increases would add $400-2700 to the cost of a new midsize car.

Table ES-2 shows that, for midsize cars, the payback periods for the full range of new technologies analyzed in this report range from 2.9 years for a variable displacement engine and a conventional transmission, to 9.6 years for a conventional gasoline engine and a mild hydraulic hybrid drivetrain with an engine-on control strategy. All of the remaining midsize car scenarios yield paybacks of 4-7 years. Owners of midsize cars with advanced technologies could reap lifetime vehicle fuel savings as much as $1400 per vehicle.

Table ES-2: Key Projections for Midsize Car Modeling Scenarios

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	29.0	32.4	34.1	36.0	43.5
Clean Diesel Engine	39.8	48.5	50.2	50.0	59.9
Gasoline Variable Displacement Engine	35.4	40.7	42.0	44.1	45.4
Clean Diesel Variable Displacement Engine	46.9	57.5	59.3	58.7	64.3
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	base	12%	18%	24%	50%
Clean Diesel Engine	37%	67%	73%	73%	107%
Gasoline Variable Displacement Engine	22%	41%	45%	52%	57%
Clean Diesel Variable Displacement Engine	62%	99%	105%	103%	122%
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$998	$1,009	$1,114	$1,133
Clean Diesel Engine	$1,206	$2,182	$2,195	$2,307	$2,330
Gasoline Variable Displacement Engine	$412	$1,373	$1,386	$1,493	$1,525
Clean Diesel Variable Displacement Engine	$1,613	$2,567	$2,581	$2,692	$2,722
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$83	$57	$46	$23
Clean Diesel Engine	$32	$32	$30	$32	$22
Gasoline Variable Displacement Engine	$19	$34	$31	$28	$27
Clean Diesel Variable Displacement Engine	$26	$26	$25	$26	$22
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	9.6	6.5	6.1	4.2
Clean Diesel Engine	6.7	6.9	6.5	7.1	6.0
Gasoline Variable Displacement Engine	2.9	6.0	6.0	6.0	5.8
Clean Diesel Variable Displacement Engine	6.2	6.7	6.5	7.1	6.4
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	$70	$320	$525	$1,381
Clean Diesel Engine	$583	$817	$933	$808	$1,403
Gasoline Variable Displacement Engine	$756	$862	$982	$1,101	$1,182
Clean Diesel Variable Displacement Engine	$895	$1,045	$1,129	$986	$1,231

Fuel economy values are laboratory values and are about 15% higher than real-world projections.

All of the above results in Tables ES-1 and ES-2 are for a "base roadload" case where aerodynamic drag and tire rolling resistance are assumed to be equivalent to typical production levels today. Appendix A gives a perspective for the same 40 vehicle technology packages for a "reduced roadload" case where average roadload due to aerodynamic drag and tire rolling resistance is reduced by 20 percent due to assumed future improvements in vehicle design and tires. In general, the reduced roadload scenarios summarized in Tables A-1 and A-2 of Appendix A yield higher percentage fuel economy improvements, higher incremental vehicle costs, lower payback periods, and higher net consumer savings relative to the base roadload results in Tables ES-1 and ES-2.

Appendix O contains a second sensitivity analysis focused on the cost projections for the 32 technology packages involving hydraulic hybrid drivetrains and based on alternative cost assumptions for hydraulic components provided by one reviewer. This sensitivity case increases the initial cost (and reduces the lifetime savings) of various technology packages involving hydraulic hybrid drivetrains by between $270 and $670, and increases the payback periods of most of these technology packages by 1-2 years.

1.   Introduction

The purpose of this progress report is to describe to the public the status of, and to provide a basis for setting priorities among, various technologies under development in EPA's Clean Automotive Technology program.

This report has six additional sections. Section 2 describes the individual automotive technologies which are the subject of this report. Section 3 describes in some depth the key design features associated with the hydraulic hybrid vehicle technology scenarios. Section 4 groups the individual technologies into the 40 vehicle technology scenarios which are modeled and evaluated later in the report. Section 5 projects the fuel economy improvement potential for the vehicle technology scenarios. Section 6 projects the likely cost increases associated with the advanced technologies. Finally, Section 7 projects the consumer "payback" periods and associated lifetime savings.

There is a series of appendices following the body of the report. Appendix A provides a sensitivity analysis for the key fuel economy and economic projections in the body of the report based on an alternative set of assumptions related to lower vehicle roadload (aerodynamic drag and tire rolling resistance). Appendices B through N provide more detailed technical information to support the fuel economy and economic projections made in the body of the report.

A preliminary draft of this study was distributed to, and comments were received from, six external organizations for their technical review. Appendix O summarizes the most important comments received during the review process, and includes a sensitivity analysis for the cost projections for hydraulic hybrid drivetrains based on a series of alternative cost assumptions provided by one reviewer.

2. Overview of Individual Technologies

There are a large number of technologies now being developed and evaluated which can improve personal vehicle fuel economy beyond that already achieved by today's "conventional" vehicles. The National Academy of Sciences (NAS) report "Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards," published in January 2002, evaluated those "existing and emerging" technologies which it believed had the greatest likelihood of being integrated into commercial vehicles in the next 10-15 years.[i] The technologies included in the NAS report are technologies that can generally be described as "incremental" improvements to the conventional gasoline engine/transmission powertrain, which has been the standard powertrain for personal vehicles in the United States for the last century.

This progress report examines several technologies which were not included in the above NAS report, and which would tend to involve somewhat greater changes in the design of automotive powertrains than those evaluated by NAS. This report focuses on those technologies for which EPA has first-hand experience, because of active in-house R&D as part of EPA's Clean Automotive Technology development program.

This report evaluates the following basic technology approaches:

- ➢ mild hydraulic hybrid drivetrain
- ➢ full hydraulic hybrid drivetrain
- ➢ clean diesel engine
- ➢ variable displacement engine

As will be discussed later, various combinations of these individual technologies can be included in a single powertrain. The following subsections briefly describe these four individual technologies, as well as two additional technologies also under development at EPA but which are not as advanced in development and thus are not evaluated in detail.

2.1   Mild Hydraulic Hybrid Drivetrain

A mild hydraulic hybrid vehicle (which is also referred to as Hydraulic Launch Assist by Eaton Corporation, Hydraulic Power Assist by Ford Motor Company, or as a parallel hydraulic hybrid vehicle) has both a conventional vehicle powertrain (e.g., gasoline engine with conventional transmission) and a hydraulic secondary energy storage system that captures and stores a large fraction of the energy normally wasted in vehicle braking and uses this energy to help propel the vehicle during the next vehicle acceleration. The primary hydraulic components are two hydraulic accumulator vessels (a high-pressure accumulator capable of storing hydraulic fluid compressing inert nitrogen gas and a low-pressure accumulator) and a hydraulic pump/motor unit which both "pressurizes" the high-pressure accumulator by pumping in greater volumes of hydraulic fluid during braking and, in the opposite direction, utilizes the high-pressure hydraulic fluid to generate and supply additional torque to the driveshaft during acceleration.

Hydraulics have, of course, been used on a number of stationary and non-road vehicle applications for decades. Sporadically, researchers have investigated hydraulics for on-highway vehicle applications. General Motors investigated hydraulics some time ago, and Professors Beachley and Fronczak led a longtime program on hydraulics for vehicle applications at the University of Wisconsin. Several years ago, a consortium that included VOAC and FIBA Canning, outfitted hydraulic systems on several urban buses and refuse trucks in Canada and Japan. Currently, researchers at FEV of America and Southwest Research Institute have carried out hydraulics research under contract to EPA, and EPA currently has cooperative research and development agreements (CRADAs) with Ford Motor Company, Eaton Corporation, and Parker-Hannifin. Eaton Corporation and PermoDrive are now offering commercial applications of hydraulic retrofit systems.

Section 3 provides a detailed description of the mild hydraulic hybrid vehicle designs that will be evaluated in subsequent sections.

Hydraulic launch assist can be viewed as an "add on" to a conventional powertrain that does not require any fundamental changes to the way the powertrain operates. When the vehicle brakes, the hydraulic pump/motor uses the kinetic energy of the braking event to charge hydraulic fluid from a low-pressure accumulator into a high-pressure accumulator, increasing the pressure of the nitrogen gas in the high-pressure accumulator up to 5000 pounds per square inch. During the next vehicle acceleration, the hydraulic pump/motor unit uses the high-pressure hydraulic fluid to generate torque, sending the fluid back to the low-pressure accumulator, which is transferred to the driveshaft.

One issue with a mild hydraulic hybrid vehicle is whether the engine would ever be shut off to save fuel in those modes where engine power is not required (e.g., idle or deceleration) or where the hydraulic launch assist alone is able to provide sufficient power. This study will consider both "engine-on" and "engine-off" approaches. With an engine-on strategy, the engine would only be shut down when the driver turns the engine off, usually at the end of a trip. With an engine-off strategy, engine operation will be shut down whenever the vehicle is not moving.

One major benefit of a hydraulic hybrid vehicle is the ability to capture a large percentage of the energy normally lost in vehicle braking. In urban stop-and-go driving, as much as one-half of all of the energy available at the vehicle wheels is lost in braking and a mild hydraulic design can capture and re-use a large portion of this otherwise wasted energy. The specific fuel economy improvement associated with a mild hydraulic hybrid vehicle is dependent upon vehicle driving cycle, i.e., there will always be a larger improvement for those vehicles with a high amount of stop-and-go driving. While a mild hydraulic hybrid does require the addition of several components not on conventional powertrains, these components are made from conventional materials, and are relatively straightforward to manufacture.

Compared to mild electric-battery hybrid systems, hydraulics have a much higher power density (and can capture a significantly higher percentage of braking energy). The main challenges are noise and packaging, but these engineering issues are expected to be solvable. In January 2002, Eaton Corporation, a major automotive component supplier, stated that the system "could be readied for commercial introduction by mid-decade." [ii] EPA recently built a mild hydraulic

hybrid urban delivery truck that competed in the Michelin Bibendum Challenge in September 2003 and won a gold medal for fuel efficiency and a silver medal for acceleration performance. Hydraulic hybrid technology has perhaps the greatest commercial potential for a wide range of medium-duty vehicles such as urban delivery trucks, but this study evaluates its potential for sport utility vehicles and other personal vehicles as well.

2.2   Full Hydraulic Hybrid Drivetrain

A full hydraulic hybrid vehicle represents a second-generation or second-phase hydraulic hybrid vehicle. While a first-generation mild hydraulic hybrid vehicle essentially adds on a hydraulic energy storage system to a conventional vehicle powertrain, a full hydraulic hybrid vehicle is designed to maximize the benefits of a hydraulic powertrain. The nature of a full hydraulic hybrid vehicle, where there is almost an infinite number of unique designs and control systems, makes it difficult to specify one design that is preferable to others. However, Section 3 lays out plausible designs for the full hydraulic hybrid vehicles that will be evaluated in subsequent sections. While the basic hydraulic components in a full hydraulic hybrid vehicle are similar to those used in a mild hydraulic hybrid, a full hydraulic hybrid opens up several interesting possibilities with respect to powertrain design, including for example, a greater potential for more frequently shutting the engine off and/or operating the engine at or near its peak efficiency.

However, whether the engine would ever be shut off to save fuel, at those times where the vehicle is not in motion or where there is sufficient hydraulic energy to power the vehicle, is also an important design issue for a full hydraulic hybrid vehicle. As with the mild hydraulic hybrid drivetrain discussed above, this study will consider both engine-on and engine-off approaches. With a full hydraulic hybrid vehicle with engine-off strategy, the engine will be cycled on and off in a manner to optimize overall vehicle efficiency. It is important to note that the consumer acceptance of frequent engine cycling is unknown.

There are two primary efficiency benefits of a full hydraulic hybrid system. One, as with a mild hydraulic hybrid, is the ability to capture a large percentage of the energy normally lost in vehicle braking. Based on EPA data, a full hydraulic hybrid can capture and re-use up to 80% of this otherwise wasted braking energy. Two, the full hydraulic hybrid design permits much greater use of engine-off strategies and maximizes the operation of the engine at or near its peak efficiency. A full hydraulic hybrid drivetrain also allows the possibility of downsizing the engine (which is assumed in this study), which is relatively more important with an engine-on strategy than with an engine-off strategy, since with the latter the engine is already operating at or near its peak efficiency point most of the time. Compared to a mild hydraulic hybrid vehicle, a full hydraulic hybrid will require a more sophisticated powertrain control system, but can also allow the deletion of the traditional mechanical transmission.

EPA work on full hydraulic hybrid technology has been a primary emphasis in the Clean Automotive Technology program since the early 1990s. EPA has proven the basic feasibility of full hydraulic hybrids with a series of test chassis that were built and evaluated. For example, one of the EPA full hydraulic hybrid proof-of-concept test chassis, equipped with a small state-of-the-art diesel engine and tested at rolling resistance and aerodynamic drag values of 0.006 and 0.2 respectively, has already achieved over 80 mpg over the Federal Test Procedure on diesel

fuel, at a 3800-pound test weight. EPA is now in the process of building a full hydraulic hybrid urban delivery truck that will allow a fuller demonstration and evaluation of the technology.

As with mild hydraulic hybrid vehicles, two challenges for full hydraulic hybrids are noise and packaging. A challenge more unique to the full hydraulic hybrid vehicle, with its more sophisticated control system that will likely involve a different engine operating strategy than with a conventional vehicle or with mild hydraulic hybrids, is making the system transparent to the driver. However, ongoing EPA work suggests these challenges will be solvable and that full hydraulic hybrids will be a serious competitor for future vehicles where maximizing fuel economy improvement is a primary objective. As with mild hydraulic hybrids, the most compelling initial application may be in medium-duty vehicles with a very high frequency of urban stop-and-go operation, but again this analysis only considers the potential for full hydraulic hybrids in sport utility vehicles and other personal vehicle applications. The increased torque and torque response available from a full hydraulic hybrid, without the fuel economy tradeoffs usually associated with high performance vehicles, may very well be the most important early commercialization driver for full hydraulic hybrid vehicles, considering the price premium currently paid for such enhanced performance by many consumers.

2.3   Clean Diesel Engine

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. In the US market, the relative attributes of gasoline and diesel engines have resulted in gasoline engines capturing over 99% of the personal vehicle market (the only personal vehicles available with a diesel engine option are the Volkswagen New Beetle, Golf and Jetta) and diesel engines representing the entire line-haul, Class 8 over-the-road truck market. Medium-duty trucks have seen more of a direct competition between the two engines, with the tendency in recent years for diesel vehicles to be taking greater market share.

There has been a vigorous, ongoing debate about the environmental merits of diesel engines in the US. By far the most obvious environmental benefit of diesel engines is the high-efficiency characteristic. As will be discussed in more detail later in this study, all other things being equal, today's diesel engines are projected to achieve about 37% higher fuel economy than today's gasoline engines, which is equivalent to about a 27% savings in fuel consumption. This projection is similar to recent statements from the industry: General Motors has reported that diesel engines use about 30% less fuel than gasoline engines (equivalent to about 43% higher fuel economy) and DaimlerChrysler has recently stated that its diesel-powered Liberty sport utility vehicle, slated for introduction in the US market in late 2004, is expected to provide up to a 30% improvement in fuel economy.[iii][iv] Even recognizing that diesel fuel contains about 16% more energy and carbon than an equal volume of gasoline, a vehicle mile traveled with a diesel engine that has 37% higher fuel economy should reduce vehicle energy consumption and carbon emissions by about 15%. On a life-cycle basis, the benefit of diesel engines is likely even

greater due to the fact that US refineries are designed to optimize gasoline production, yielding higher per gallon energy losses for gasoline production than for diesel fuel production. There are other environmental advantages of diesel engines as well: near-zero evaporative hydrocarbon emissions due to the extremely low vapor pressure of diesel fuel, low cold start emissions, and low in-use emissions deterioration.

On the other hand, diesel combustion has in the past resulted in high levels of oxides of nitrogen (NOx) and particulate matter (PM) emissions. High 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. In order to permit diesel engines to compete for even its small (generally less than 1%) part of the personal vehicle market, in the past Congress and EPA permitted diesel vehicles to emit higher levels of NOx and PM emissions than gasoline vehicles. This will change as EPA's Tier 2 emission standards phase in beginning in 2004 when gasoline and diesel vehicles are subject to the same set of emission classification bins and all gasoline and diesel vehicles must meet an average NOx standard. EPA regulations require a huge reduction in diesel fuel sulfur levels beginning in 2006. This will not only reduce emissions from the millions of heavy-duty trucks and buses powered by diesel engines already on the road, but will also facilitate the development of the next generation of clean diesel engines that may be considered for personal vehicle applications.

There is increasing evidence that automakers will be able to design diesel vehicles that can comply with the Tier 2 emission standards later this decade. 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 have as much as 50% of the new personal vehicle market in some European countries. Today's small European diesel engines have greatly improved performance and environmental characteristics compared to diesel engines of just a few years ago. US and Japanese-based automobile companies are also investing in diesel engine R&D, driven in part by the demand for diesels in Europe but also by the possibility that diesel engines may return to the US personal vehicle market. At this time, the primary path towards compliance with EPA's Tier 2 standards in the future involves advances in diesel emissions control aftertreatment. There has been considerable progress with oxides of nitrogen adsorption catalyst technology, as well as with catalyzed particulate matter trap technology with active regeneration control to ensure regeneration even under extreme conditions. In April 2002, EPA tested a prototype Toyota Avensis, a compact diesel car that Toyota is developing for the European market, possibly as early as 2004.[v] The vehicle uses a DPNR (diesel particulate-NOx reduction) emission aftertreatment system which includes both a particulate trap and a NOx adsorber. This prototype met the Tier 2 bin 5 emission levels of 0.07 grams per mile NOx and 0.01 grams per mile particulate matter. While challenges remain with respect to meeting EPA Supplementary Federal Test Procedure (SFTP) emission standards, there appear to be no fundamental barriers to the development and introduction of advanced diesel emission control technology like DPNR to a broad range of personal vehicle applications.

In addition to diesel vehicle and fuel regulations, under its Clean Automotive Technology R&D program, EPA is also evaluating unique diesel engine concepts with a goal of identifying a Clean Diesel Combustion concept that could simultaneously be extremely efficient, clean, and cost effective. EPA first publicly discussed this work at a diesel workshop at MIT in November

2002.[vi] EPA has now demonstrated lower engine-out nitrogen oxide emissions levels than anything reported in the literature, and this suggests the potential for a diesel engine design, using innovative air, fuel, and combustion management and conventional particulate matter trap aftertreatment, that might be able to achieve Tier 2 bin 5 NOx levels without the need for NOx aftertreatment. EPA is currently in the process of discussing this technology in technical forums with the goal of setting up a consortium of one or more interested private sector companies to carry this research forward.

Of course, whether diesel engines will enter the US personal vehicle market will depend on more than just environmental issues, there are also issues of consumer acceptance and cost. Historically, diesel engines have always been more costly than gasoline engines. We will return to this important issue in Section 6.

2.4   Variable Displacement Engine

A variable displacement engine is an engine that can be operated at multiple displacements by varying the cumulative volume swept by the pistons. The concept of variable displacement has received attention for many years because of its obvious potential to increase vehicle fuel economy. In a conventional vehicle where the engine is the only source of on-board power, the engine must be sized to accommodate the maximum power requirements for rapid acceleration, hill climbing, and/or towing. The efficiency of an internal combustion engine is highest at relatively high loads. Unfortunately, engine efficiency is much poorer at low and moderate loads, and most people operate their vehicles at lower engine loads much more frequently than they do at high engine loads (for example, maintaining a constant 70 miles per hour during highway driving places only a moderate load on the engine). The net result is that the average overall efficiency of a conventional gasoline engine (typically between 15% and 20%) is much lower than its peak efficiency (typically between 30% and 35%). If the displacement of the engine could be varied, then the engine could be operated at or near its peak efficiency much more often, leading to a large increase in the average overall efficiency of the engine. Appendix B has a more in depth discussion of the potential efficiency benefits available from increasing the average engine load factor.

There has been considerable research into ways to vary engine displacement. Probably the most well known approach is to simply shut down one or more engine cylinders, generally referred to as cylinder deactivation. There are several ways to shut down cylinders, most based on denying fuel and air to selected cylinders. General Motors has been a leading proponent of what they call "Displacement-on-Demand." Its approach automatically closes both intake and exhaust valves for half of the engine cylinders during light load operation when power demands are low. General Motors has stated that its Displacement-on-Demand technology can boost fuel economy by an average of about 8% and as high as 25% in certain real world driving conditions. General Motors has announced that it will introduce Displacement-on-Demand in 2004 on over 150,000 of its Vortec V-8 engines, and that it expects to increase production of this technology to nearly 1.5 million units by 2007, including both pickup truck and sport utility vehicle applications.[vii] The recent NAS study included cylinder deactivation in its "production-intent" technology scenarios, postulating a 3-6% fuel economy improvement at a cost of $112-$252 per vehicle.[viii] Cylinder deactivation has the primary advantage of being a relatively straightforward approach

to variable displacement, minimizing necessary changes to conventional engine design, but has the drawback of retaining the friction losses involved in a moving piston acting against a "gas spring."

There is an alternative approach to variable displacement that may well have the potential to be a more cost effective approach for improving vehicle fuel economy. One critical feature of the EPA concept, shown in Figure 2-1, is that it involves two crankshafts, one for each of the two engine "modules." Each engine module/crankshaft acts as an independent unit. The "base" engine module would be sized to be able to provide sufficient power for most vehicle operation, and during these times the first engine module will generally have a relatively

Figure 2-1: EPA Variable Displacement Engine Concept
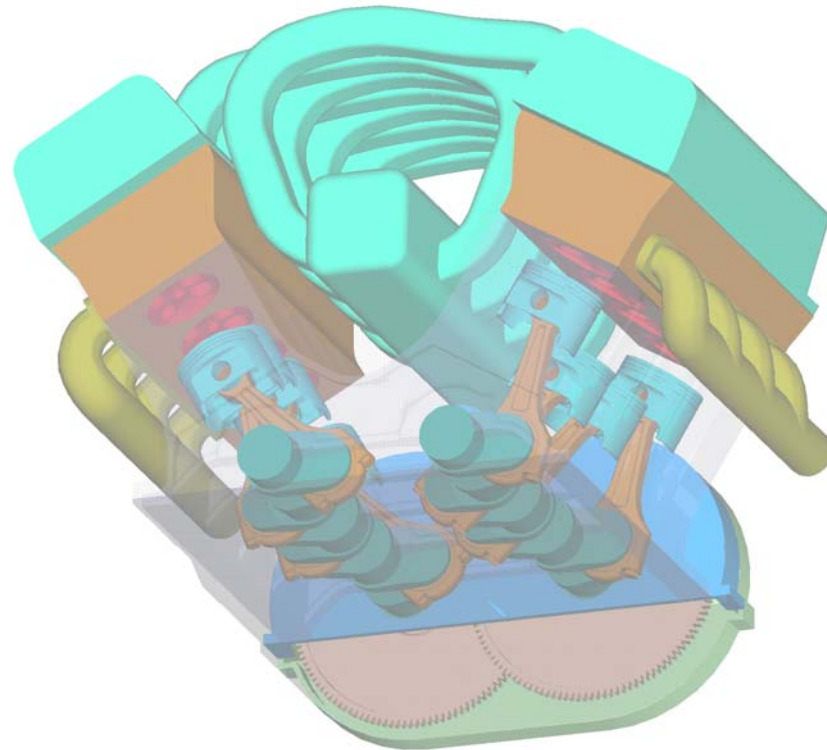
high load factor and efficiency, while the second engine module does not operate at all. Because of the independent crankshafts, when the second engine module is not operated, not only is combustion inhibited but the pistons in the second engine module do not move either, which means no friction losses whatsoever. This is a primary advantage of this design. During high power needs, such as acceleration, hill climbing, and/or towing, the second engine module is quickly started and the control system adjusts the individual power levels of the two engine modules to optimize overall powertrain efficiency. Appendix C contains more details about EPA's variable displacement design.

One operational challenge that must be addressed relates to rapid and seamless start-up of the second engine module. It is important that the second engine be able to move from being off to full power within 0.3 seconds or less. Frequent starting of the second engine module also raises issues of driver "feel", noise, emissions and durability, so engine startup, control, and power balancing are essential elements of this engine design.

Specific efficiency and cost projections will be made in later sections, but it appears that this variable displacement concept has the potential to be more cost effective than cylinder deactivation and other variable displacement concepts that have been discussed in the literature to date.

Sections 2.1 through 2.4 describe the four technologies under development at EPA that are evaluated in detail later in this report. Sections 2.5 and 2.6 describe two additional technologies

which are at a more preliminary stage of development at EPA and therefore cannot be evaluated in detail at this time.

2.5   Variable Compression Engine

A variable compression engine is an engine that can be operated at different compression ratios. As with variable displacement, the general concept of variable compression has received attention for many years due to its potential to increase vehicle fuel economy. In a conventional vehicle where the engine is the only source of on-board power, the engine design is compromised with a single compression ratio that provides acceptable combustion under all vehicle and engine operating modes. In general, raising compression ratios higher than those typically used in today's gasoline engines (8:1 or 9:1 with regular gasoline and 10:1 or 10.5:1 with premium gasoline) would increase engine efficiency. But, at high engine loads, compression ratios higher than these levels generally lead to excessive peak cylinder pressures and pre-ignition. The basic concept of a variable compression engine fueled with gasoline is that compression ratios would be increased to, say, 13:1 or 14:1 during most vehicle and engine operating modes, where efficiency would be increased with no negative side effects, and then lowered during the intermittent high power modes where high compression is not desired. Such a design could potentially yield a large increase in the average overall engine efficiency.

There has been much research into variable compression engines, with several such operating engines. Saab has a prototype variable compression engine that appears to be one of the most advanced concepts.[ix] The Saab Variable Compression (SVC) engine is a 1.6-liter, 5-cylinder engine. The mechanism for the varying compression is "tilting" the monohead of the engine through the use of hydraulic actuators. This is turn varies the volume of the combustion chambers and the resulting compression ratio from 8:1 to 14:1. Saab states that its SVC engine, without downsizing the engine, increases fuel economy by about 4%. With a smaller engine and supercharging, the fuel economy increase can be as high as 30%. Saab has not announced any formal commercialization plans. The NAS study included variable compression engines in its "emerging" technology scenarios (i.e., 10-15 years), postulating a 2-6% fuel economy improvement at a cost of $210-$490 per vehicle.[x]

EPA has developed a variable compression engine concept that also appears to have promise. The EPA concept achieves two unique compression ratios, without changing the overall length of the engine cylinder or the length of the connecting rod/piston assembly, by using a "piston-within-piston" mechanism. Figure 2-2 shows a detailed drawing of this "piston within a piston." During times of low and moderate power demand that typify most driving modes, the top of the inner piston is flush

Figure 2-2: EPA's Variable Compression Engine Concept
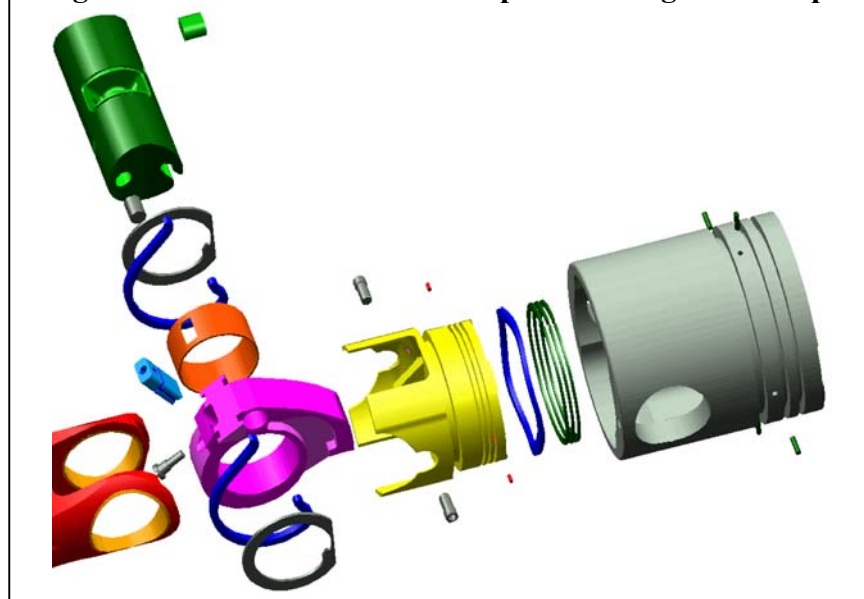
with the top of the outer piston, yielding a compression ratio higher than those used in conventional vehicles and improving efficiency. When vehicle power demand increases to the point where this compression ratio might lead to pre-ignition or durability concerns, a command signal causes the inner piston to recede to the second position within the outer piston, thereby increasing the total clearance volume and reducing the compression ratio to prevent pre-ignition and/or durability concerns. One important feature of this design is it will require fairly simple engine design changes. A second important feature of this design is that good fuel-air mixing and combustion is retained under both compression modes because the piston bowl resides within the receding inner piston and therefore the outer piston squish height (the distance between the piston at top dead center and the cylinder head) does not change. The only change is the distance of the piston bowl from the cylinder head. Appendix D contains a more detailed description of the "piston within a piston" design.

As with all variable compression engine concepts, there are several challenges that remain to be addressed. The biggest challenge with EPA's variable compression engine concept is the reliability and durability of the inner piston mechanism.

The likely cost and efficiency of variable compression engines are unknown at this time, though it is likely that they will be similar to those of variable displacement engines.

2.6   Homogeneous Charge, Compression Ignition Engine

In terms of fundamental combustion, a homogeneous charge, compression ignition (HCCI) engine can be considered a hybrid between a conventional gasoline engine (which premixes the fuel and air before combustion and uses a spark to initiate combustion) and a conventional diesel

engine (which does not premix the fuel into the air and which uses the injection of fuel into the hot, compressed charge-air to initiate combustion). An HCCI engine premixes the fuel and air (like a conventional gasoline engine) and uses control of compressed charge-air temperature as the primary means to initiate combustion (somewhat like a conventional diesel engine). HCCI engines have the potential to be able to combust a wide variety of fuels including gasoline (high octane and low cetane), diesel (high cetane and low octane), and many alternative fuels. The primary challenge for HCCI engines, and the primary reason they have not been commercialized in the past, is that the design and operational features of previous engines made it extremely difficult to control the combustion process, particularly in terms of ignition timing and combustion rate. But the major advances in computerized controls of the last two decades and breakthroughs in new engines have greatly improved the potential for successful development of HCCI engines.

The primary driving force for interest in HCCI engines has been their potential environmental performance. Gasoline engines, particularly in combination with sophisticated three-way catalysts, can yield extremely low criteria emissions but have relatively low overall efficiency. Diesel engines provide much higher efficiency than gasoline engines, but have historically had high emissions, particularly of particulate matter and oxides of nitrogen (NOx). In effect, HCCI engines offer the best of both worlds: the potential to equal or possibly exceed diesel efficiencies with emissions as low as or likely lower than gasoline engines. In fact, the extremely high air-fuel ratios of HCCI engines suggest the likelihood of engine-out NOx emission levels so low that NOx emissions aftertreatment will likely not be needed to meet Tier 2 levels, a situation that will not be possible with either conventional gasoline or conventional diesel engines. The air-fuel premixing minimizes the formation of particulate matter, so particulate traps are not needed either. Engine-out levels of hydrocarbons and carbon monoxide are sufficiently high that oxidation catalysts will be needed to bring these emissions down to Tier 2 levels. But, the cost of a simple oxidation catalyst is much lower than that of today's three-way catalysts used on conventional gasoline vehicles and much lower than the NOx adsorbers and particulate traps that are likely to be needed on conventional diesel engines.

HCCI engines are the subject of considerable research and development by industry, government, and academic researchers throughout the world. To our knowledge, EPA has been able to achieve what no other researcher has yet reported: the ability to run a 4-cylinder HCCI engine over a broad engine map with acceptable combustion control and engine performance. EPA has demonstrated engine operation that yields efficiencies very similar to today's best diesel engines, NOx emissions at levels of below 0.2 grams per kilowatt-hour, and near-zero particulate matter emissions.[xi]

As with any advanced engine concept, there are challenges that remain to be overcome. Like diesel engines, HCCI engines achieve higher cylinder peak pressures than do conventional gasoline engines, which must be addressed in engine design. HCCI engines require high boost levels, which will require a turbocharger and/or supercharger, which raises cost and packaging issues. And HCCI engines have high air charge cooling requirements, which will likely require an intercooler, which raises packaging issues.

The likely cost of HCCI engines is unknown. Relative to a conventional diesel engine, HCCI engines have some elements that will increase costs (the need for higher boost and cooling, more sophisticated engine control system) and some elements that will decrease costs (a relatively inexpensive fuel injection system, a simpler emissions aftertreatment system). Similarly, precise estimates of HCCI engine efficiency are not possible pending further research and development. At this time, our best estimate is that the cost and efficiency of HCCI engines will be similar to those of clean diesel engines.

3.   Key Design Features for Hydraulic Hybrid Vehicle Technology Packages

The purpose of this section is to describe key components in a hydraulic hybrid vehicle (HHV), demonstrate the feasibility of integrating these systems into a large sport utility vehicle (SUV) and a midsize car, and estimate the mass increase of the hydraulic drivetrains included in this study over conventional drivetrains. A separate section on hydraulic hybrid vehicle design features is appropriate because hydraulic hybrid drivetrains involve a wider range of changes than replacing one engine design with another, and because there is much less in the existing literature on hydraulic hybrid designs. The section is organized into two parts. Subsection 3.1 describes the key individual components used in some or all of the hydraulic hybrid designs, and Subsection 3.2 describes specific, plausible mild and full hydraulic hybrid system designs for the SUV and midsize car scenarios.

The analysis assumes base vehicle specifications and components similar to a 1999 Ford Taurus and a 1999 Ford Expedition. The Taurus and Expedition were chosen because previous EPA hybrid drivetrain development programs focused on these vehicles. The rear suspension system for the large SUV is assumed to be an independent design similar to the 2003 Ford Expedition, rather than the live axle used in the 1999 Expedition. Table 3-1 summarizes some specifications for the base SUV and midsize car used in the analysis.

Table 3-1: Base Conventional Vehicle Specifications

Component	SUV	Midsize Car
Engine	5.4L V8 gasoline	3.0L V6 gasoline, 2v/cyl
Transmission	4R100 4-speed automatic	AX4S 4-speed automatic
Front differential final ratio	3.55	3.77
Rear differential final ratio	3.73	-
Rear suspension	Independent	-
Transfer case	Modes: Automatic 4WD, 4WD high, 4WD low	-
Curb weight	5700 lb.	3350 lb.
Fuel Tank size	28 gallon	16 gallon

3.1   Key Components of a Hydraulic Hybrid Vehicle

The key components of a hydraulic hybrid vehicle include:

➢ pump/motor(s) with integral valves
➢ accumulators with integral valves

> ➤ hydraulic fluid
> ➤ an oil conditioning system
> ➤ a hydraulic power steering system (for some configurations only)
> ➤ a unique battery, alternator, and starter system
> ➤ general hydraulic fittings and hoses

Each of these components is described in this subsection and form the basis for estimating the mass of the four specific hydraulic hybrid configurations in Subsection 3.2. Component mass for each vehicle configuration is a key input in the methodology for projecting incremental cost in Section 6.

3.1.1   Pump/Motor with Integral Valves

Hydraulic pump/motor (P/M) units are energy conversion devices. In the pump mode, the P/M converts kinetic energy from vehicle motion into hydraulic energy, which is stored in an accumulator. In the motor mode, the P/M converts hydraulic energy stored in the accumulator into vehicle kinetic energy as the vehicle accelerates. Hydraulic P/Ms are analogous in function to electric generators and electric motors used in electric hybrid vehicles. P/M designs used in high fluid pressure applications are typically of the bent-axis or swashplate (in-line) type. In a bent-axis design, the pistons reciprocate on an axis that is "bent" on an angle relative to the input/output shaft. In a swashplate unit, the pistons reciprocate on an axis that is in-line with the input/output shaft. Bent-axis P/Ms achieve higher efficiencies than swashplate units, which make them more attractive for high fuel economy HHV applications.

For this reason, the P/M used in this analysis is a high efficiency, variable displacement bent-axis unit. It has an integrated flow control valve and proportional electro hydraulic displacement actuator providing infinitely variable control between zero and maximum displacement. The P/M is made primarily of cast iron and steel, with some bronze and aluminum components. Manufacturing complexity for a P/M, which contains pistons, connecting rods, cylinder bores, rotating shafts, roller and bronze bearings, and electronic components and sensors associated with displacement and mode control, is similar to that found in automotive engines. High and low-pressure ports with face seals connect the P/M to the accumulator through hoses and tubing. The P/M case is designed to handle the maximum pressure from the low-pressure accumulator (1.4 MPa or 200 psi), eliminating the need for a separate leakage recovery system.

The estimated mass of a stand-alone 110 cc/rev unit with SAE standard 4-bolt mounting flange and splined input shaft is 37 kg, based on a unique EPA P/M design. Other size units scale roughly proportional to displacement; therefore a 55 cc/rev unit is projected to weigh half that of the 110 cc/rev unit (18.5 kg). The P/M was designed to handle pressures of 48.3 Mpa (7000 psi), although all projections in Section 5 assume a maximum P/M inlet pressure of 34.5 Mpa (5000 psi) to allow for a safety margin. Since a lighter P/M could be designed for the 34.5 MPa application analyzed in this study, the above P/M mass estimate is conservative.

Depending on application in the drivetrain (engine pump, front drive unit, etc.), the P/M mount geometry will differ from the SAE 4-bolt mount, although the mass will be similar. Changes to

the base mass of 37 kg due to mounting or integration with other components will be addressed within the discussion of each hybrid configuration.

3.1.2 Accumulators with Integral Valves

Hydraulic hybrids utilize accumulators to store energy. In this way, accumulators are similar in function to the battery pack of an electric hybrid vehicle. However, unlike batteries, accumulators have extremely high power densities (kW/kg) and can operate over a wide range of power at very high efficiency. On the other hand, energy density (kJ/kg) is relatively low compared to an electric battery. Thus, accumulators are better suited for short bursts of power rather than for sustained energy delivery. Accumulators are used to store energy from vehicle braking, and depending on the vehicle configuration, they can be used to allow the engine to run at a near steady-state output independent of drive power demand.

The type of hydraulic accumulators used for the HHVs in this analysis are hydro-pneumatic accumulators — they store energy in a gas spring. The oil in a hydraulic hybrid vehicle is essentially non-compressible, and therefore cannot store energy. Instead energy is stored in a gas (nitrogen) that is compressed by incoming oil. A movable barrier (such as a rubber bladder, metal-lined plastic bag, bellows, or piston) separates the oil from the gas as the accumulator fills with oil, keeping the gas inside the accumulator and preventing it from spreading throughout the hydraulic system. Within the gas side of the accumulator is flexible open-celled foam that increases accumulator efficiency by reducing heat losses.

All of the hydraulic hybrid configurations in this analysis require one high-pressure and one low-pressure accumulator. The difference in pressure between the high and low-pressure accumulators, when connected to the inlet and outlet ports of a P/M, is transformed into shaft torque to be used to accelerate or decelerate the vehicle or absorb engine power. Both the high and low-pressure accumulators have composite shells made from carbon and e-glass fiber with an epoxy matrix. EPA contractors have fabricated and successfully tested several sizes of carbon/e-glass fiber composite accumulators.   The basic components of the accumulators are shown in Figure 3-1 and described below.

Figure 3-1: Accumulator Components
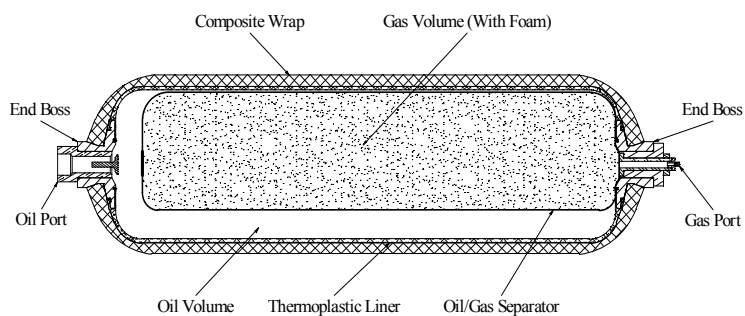
High-Pressure Accumulator Shell

The high-pressure accumulator shell is constructed of carbon fiber and e-glass with an epoxy matrix. The carbon fiber provides most of the vessel's strength, while the e-glass provides impact strength. The high-pressure accumulator could be reinforced entirely of carbon fiber (no

e-glass) to reduce mass, but costs would likely increase. EPA chose a reasonable balance between cost and mass for its design.

The high-pressure accumulator has a maximum service pressure of 35 MPa (5000 psi), and is designed to have a burst pressure safety factor of 3.0 (i.e., the burst pressure is 105 MPa or 15,000 psi). The vessel is constructed with a sacrificial outer layer to provide abrasion protection. The high-pressure accumulator has steel end bosses that are molded into the molded thermoplastic liner with threaded bosses for insertion of the oil and gas end ports. The total mass of a 56.8 L (15 gallon) high-pressure accumulator shell is 38.0 kg.

Reducing the safety factor with respect to a burst pressure of 2.25 could reduce the mass of the accumulator shell. This is the same value utilized by the natural gas vehicle industry. This would likely reduce the mass of the carbon, e-glass and epoxy by fifteen to twenty percent, for a total shell mass of 32.6 to 34.0 kg. Additional mass could likely be removed from the end bosses and liner in a mass production design. The vessels this data are based on were development prototypes utilizing existing tooling when possible.

Low-Pressure Accumulator Shell

The low-pressure accumulator is used to store and contain the oil when it is not in the high-pressure accumulator. It also provides sufficient inlet pressure to the hydraulic pumps to avoid cavitation, a condition arising in pumps when inlet pressure falls low enough to cause bubbles to form in the fluid. An atmospheric reservoir could be used in place of the low-pressure accumulator, but additional charge pumps would be required to boost inlet pressures to the main pumps. This would increase mass, complexity, and energy losses of the system.

The low-pressure accumulator is designed for a maximum service pressure of 1.4 MPa (200 psi), and has a burst pressure safety factor of 5 (i.e., the burst pressure is 7 MPa or 1000 psi). It is constructed of a glass fiber and epoxy matrix. The recommended safety factor with respect to stress rupture is higher for glass fiber composite pressure vessels than for carbon fiber vessels. A lower mass carbon/e-glass shell could be constructed at higher cost, but this was not the approach used by EPA. The low-pressure accumulator has aluminum end bosses molded into the thermoplastic liner that have threaded bosses to allow the insertion of oil and gas end fittings. The total mass of a 56.8 L (15 gallon) low-pressure accumulator shell is 13.0 kg. Additional mass could likely be removed from the end bosses and liner in a mass production design. The vessels this data are based on were development prototypes utilizing existing tooling when possible.

Nitrogen

Nitrogen, the gas typically used to charge hydro-pneumatic accumulators, is non-reactive and inexpensive due to its abundance in the atmosphere. The high-pressure accumulator is pre-charged with nitrogen to a level that both maximizes the energy storage in the accumulator and keeps the minimum system pressure high enough to deliver the required torque from the P/Ms. A 56.8 L (15 gallon) high-pressure accumulator is charged with 7.5 kg of nitrogen to obtain a

pre-charge of 12.4 MPa (1800 psi). A 56.8 L (15 gallon) low-pressure accumulator is charged with 0.3 kg of nitrogen to obtain a pre-charge of 0.5 MPa (70 psi).

Accumulator Foam

When the oil flows into the accumulator and the gas is compressed, heat is generated and transferred to the oil and the shell of the accumulator. When the oil flows back out of the accumulator, the nitrogen expands and cools and heat transfers back to the gas from the oil and the shell of the accumulator. Some of this heat is irreversibly lost in the process, decreasing the efficiency of the accumulator.

To reduce the heat loss, open-cell foam is placed inside the oil-gas separator along with the nitrogen. The foam reduces the heat loss by providing a heat sink, and providing a large surface area for heat transfer to occur over small differential temperatures. The foam used for the HHV accumulators is polyurethane foam with a density of 96 kg/m^3. It is reaction injection molded in place inside the oil-gas separator using a two-component curing foam, not unlike that used in automotive seat fabrication. A 56.8 L (15 gallon) accumulator has 5.2 kg of polyurethane foam cast into each bag, for a total of 10.4 kg for both accumulators.

Oil-Gas Separator

The oil and gas sides of the accumulator are separated to prevent the nitrogen charge gas from going into solution in the oil. This can result in the gas coming back out of solution when the oil is brought to a lower pressure, turning the single-phase relatively non-compressible oil to a two-phase mixture of gas and oil that is highly compressible. Gas bubbles in the oil can lead to extreme cavitation wear on pump components and can also cause noise as the bubbles are collapsed in the pump.

Conventional bladder accumulators utilize an elastomeric rubber bladder to separate the nitrogen and oil. Bladders perform well in many respects, but nitrogen permeation rates through the rubber material are considered too high for automotive applications where a "fill for life" specification is highly desirable. Thus, it is assumed that an HHV will utilize a permeation-free barrier similar to concepts currently under development at EPA. The mass of these barriers is expected to be similar to the mass of conventional bladders, with approximately 50 percent higher cost.

To prevent the bag from being herniated out of the accumulator oil port, an anti-extrusion valve is necessary. It is a step valve that is depressed to seal off the accumulator to prevent further expulsion of oil and rupture of the bag. The permeation-free barrier bag has a metal plate bonded to the end to make contact with the anti-extrusion valve.

In order to charge the accumulator with nitrogen, a nitrogen charge valve is affixed to the end of the oil-gas separator bag. This is a steel fitting bonded to one end of the oil-gas separator, with a schraeder valve for filling. The nitrogen gas port has 0.5 kg of steel for the high-pressure accumulator and 0.2 kg of aluminum for the low-pressure accumulator, for a total of 0.7 kg.

Integral Valve

Both the high-pressure and low-pressure accumulators utilize one valve that is integrated with the fluid port (see Figure 3-2). The valve has three main functions. The first, as mentioned earlier, is to prevent the bladder from herniating out the fluid port when oil is fully drained from the accumulator. The second is to function as a flow fuse in the event of a catastrophic hydraulic line failure. The valve automatically closes if the flow rate out of the accumulator exceeds a predetermined level. Finally, the valve can function as a leak free shut-off. When the vehicle is parked or being serviced, the valve can keep the majority of hydraulic oil in the system trapped indefinitely. The steel high-pressure valve has a mass of 4.3 kg, and the low-pressure valve has a mass of 2.9 kg.

Figure 3-2: Accumulator Integral Valve
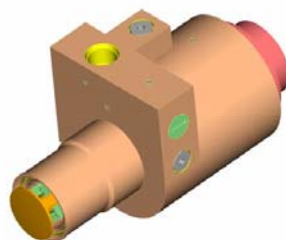
Accumulator Summary

Table 3-2 presents a summary of the component masses for 56.8 L (15 gallon) high-pressure and 56.8 L (15 gallon) low-pressure accumulators. The mass of other size accumulators required for the hybrid configurations discussed in Subsection 3.2 is extrapolated from this prototype design.

3.1.3   Hydraulic Fluid

The two main criteria for selecting an acceptable hydraulic fluid for use in hydraulic hybrid vehicles are 1) high and low-temperature performance, and 2) service life.

Table 3-2: Accumulator Component Mass Summary

Component	Low-pressure Accumulator Mass (kg)	High-pressure Accumulator Mass (kg)
Composite Shell		
Carbon Fiber		16.1
E-Glass Fiber	5.7	3.4
Epoxy Matrix	1.6	7.6
Liner	4.4	4.4
End Bosses	2.1	6.0
Gas Valve	0.2	0.5
Bag	1.0	1.0
Foam	5.2	5.2
Nitrogen	0.3	7.5
Shutoff Valve	2.9	4.3
Total	**23.5**	**56.0**

The fluid must provide sufficient lubrication at continuous service temperatures of 93 $^{\circ}$C (200 $^{\circ}$F), with extreme intermittent operating temperatures of up to 121 $^{\circ}$C (250 $^{\circ}$F). At the same time, the fluid must be able to flow at -40 $^{\circ}$C (-40 $^{\circ}$F) without causing harmful cavitation at the pump inlet. Viscosity breakdown and fluid oxidation must be minimal, such that oil changes will not be necessary between 150,000-mile service intervals.

The most cost-effective hydraulic fluids that meet these design criteria for the hydraulic system are blends of synthetic Poly-Alfa-Olefin (PAO) or high-grade mineral oil (Group III) base stocks. These possess a high viscosity index (i.e., their viscosity changes relatively little with temperature), and provide long service lives without unacceptable degradation in performance. The estimated density of this type of fluid is 0.84 kg/L.

The majority of the oil in a HHV is in the accumulators. When "full" of oil, approximately 50 percent of the interior volume of an accumulator is oil. This is done to maximize the energy storage of the accumulator (based on the gas change-of-state equation for nitrogen) and is related to the nitrogen pre-charge pressure chosen. Some oil is also present in the P/M cases, hydraulic lines, valve blocks, oil cooler and filter. The oil present in these components is estimated based on the interior dimensions of EPA prototype hardware and adjusted based on the vehicle configurations analyzed in the following subsections.

3.1.4 Oil Conditioning System

In a hydraulic hybrid, the oil needs to be kept clean and its temperature controlled to prevent excessive weaR&Damage to the components in the system. This is accomplished using a filter, an air-to-oil cooler, and valves to control oil flow. The size of the filter, cooler, and valves will vary depending on the size of the hydraulic system in the HHV. A schematic of the system is shown in Figure 3-3.

Figure 3-3: Oil Conditioning System

When the front drive motor is motoring, oil flows from the high-pressure accumulator to the low-pressure accumulator. At this time low low-pressure oil is directed through a filter and air-to-oil cooler. If the back-pressure exceeds a predetermined level, a relief valve opens, and flow can bypass the filter and cooler. If the oil temperature is low, a thermostatic valve opens to bypass the cooler.

When the drive motor is pumping, oil flows from the low-pressure accumulator to the high-pressure accumulator. Oil is prevented from back-flushing the filter by a check valve and is instead directed around the filter and cooler. This redirection of flow also minimizes the pressure drop from the low-pressure accumulator to the front drive motor and helps prevent cavitation.

3.1.5 Hydraulic Power Steering System

In a full hydraulic hybrid (FHH) vehicle, the engine is mechanically decoupled from the road. Therefore, it does not have to be running while the vehicle is propelled forward or in reverse. In turn, the engine is not always available to drive the power steering pump as in conventional vehicles, so an alternative system must be used to provide power steering. Since high-pressure

hydraulic oil is always available, the obvious solution is to take advantage of this source of power. Simply connecting a conventional rack and pinion assembly to the high-pressure accumulator will not work, however, because conventional systems are a "flow through" design. When steering assist is not needed, oil flows freely through the system. This type of system would quickly deplete the accumulator pressure.

An alternative to conventional power steering, which is better suited to a FHH vehicle, is an on-demand hydraulic assist system which allows fluid to flow to the rack only when power assist is needed. This type of system is used on the 1975-1991 Citroën CX, which utilizes hydraulic fluid stored in an accumulator at a pressure of 1000 psi for power steering, ride height adjustment, and power assist brakes. The Citroën's power steering system uses a rack and pinion similar to conventional systems combined with a pressure control mechanism to adjust pressure to the rack based on steering wheel input.

In order to find the mass difference between the conventional system and the on-demand system, any components which are not common to both systems are weighed and the difference is calculated. The conventional system consists of a pump, fluid reservoir, hydraulic lines, and steering gear assembly. The on-demand system uses a control mechanism, hydraulic lines, pressure control valve, and steering gear assembly. The hydraulic lines for the two systems are similar, so their mass is ignored. The control valve mechanism from the Citroën is a relatively old design, and has not been optimized for mass reduction. A mass reduction of 1 kg is assumed based on an analysis of similar components.

The Ford Expedition uses a recirculating ball steering gear rather than the rack and pinion used in the Citroën. A power steering system for a FHH Expedition has not yet been developed, but the recirculating ball steering gear could be modified to operate in the same manner as the Citroën rack and utilize the same control mechanism. The Expedition steering gear incorporates a control valve mechanism in the housing that is not needed for a FHH, so the mass of the steering gear has been reduced by 2.5 kg to account for this.

A conventional system is designed to operate at 1000 psi, while a FHH will have fluid available at a minimum of 2000 psi. The mass shown for the FHH steering gear has been reduced by 0.6 kg to account for the smaller forcing piston that would be allowed by the higher pressure. Overall, a mass reduction of 2.7 is estimated by replacing the conventional power steering system of the Expedition with an on-demand power steering system (see Table 3-3).

Table 3-3: Large SUV Power Steering System

System Type	Power Steering Component	Mass (kg)
Conventional Power Steering	Pump, Reservoir, and Fluid	4.1
	Steering Gear	13.2
	Total	**17.3**
On-Demand Power Steering	Control Mechanism	5.1
	Steering Gear	10.0
	Pressure Regulator	0.5
	Total	**15.6**

Similar reductions could be realized in a midsize car. The Ford Taurus uses a rack and pinion steering gear that can be modified to work with the Citroen control valve assembly. Because the Taurus rack and pinion assembly includes control valves, the mass was reduced for this analysis by 1.4 kg. Also, because the Taurus system operates at 1000 psi and the fully integrated hydraulic hybrid will have operate at a minimum of 2000 psi, the forcing piston can be reduced in size, resulting in a mass savings of 0.58 kg. Overall, replacing the conventional power steering with an on-demand hydraulic power steering system on a midsize car is estimated to result in a mass reduction of 0.5 kg (see Table 3-4).

Table 3-4: Midsize Car Power Steering System

System Type	Power Steering Component	Mass (kg)
Conventional Power Steering	Pump, Reservoir, and Fluid	3.8
	Steering Gear	8.5
	Total	**12.3**
On-Demand Power Steering	Control Mechanism	5.1
	Steering Gear	6.2
	Pressure Regulator	0.5
	Total	**11.8**

The mild hydraulic hybrid (MHH) vehicle analyzed in this study does not decouple the engine from the road. Hence, like a conventional vehicle, the engine must be running when the vehicle is propelled forward or in reverse. Although a MHH vehicle could use an on-demand power steering system like that described for the FHH, it is assumed for this analysis that a conventional power steering system will be retained primarily to minimize changes to the baseline conventional vehicle. Engine shut-off should not negatively affect power steering performance because the engine will start in a fraction of a second after the brake pedal is released, and generate hydraulic pressure for power steering as the vehicle begins to move. For parallel parking maneuvers, where several engine stops may occur, an operating mode to keep the engine idling could be selected using the automatic shift lever.

The advantages of using an on-demand system in a MHH would be seamless operation and reduced parasitic losses. Calculations show that a high-pressure accumulator in a MHH would provide adequate fluid for the power steering even if the steering wheel is turned from lock to lock repeatedly while the vehicle is not moving.

3.1.6 Battery, Alternator, and Starter System

Because the engine can be shut off in a HHV during typical operation, some means of driving the alternator to maintain battery charge must be added for certain hybrid configurations. In addition, more frequent engine starting, if accomplished using a conventional starter, would require a larger battery to handle the higher usage. However, the need for accessory drive modifications depends on the exact hybrid configuration, with some requiring no change at all from the conventional system.

For MHHs or FHHs using a strategy where the engine runs at all times (engine-on strategy), no change is required for the battery, alternator, or starter. The alternator is driven directly by the engine and the battery requirements and starter usage are the same as in a conventional vehicle.

It is possible to reduce the size of the battery and starter in FHHs because the engine P/M is available to help start the engine. However, this analysis conservatively assumes that the battery and starter in a FHH are the same size as that used in the conventional vehicle.

For MHH vehicles with "engine off" strategies, there is an increased demand on the battery to restart the engine. Based on the 1994 Volkswagen Golf Ecomatic, which featured an engine-off strategy, it is estimated that a 25 percent larger battery would be required. Since the engine duty cycle is still high for a MHH vehicle even with on/off operation, no change is required of the alternator. The stock starter is retained and used as in a conventional vehicle, although with a higher frequency of starts.

For the FHH vehicles with engine-off strategies, the engine duty cycle (the amount of time the engine runs compared to total vehicle drive time) is significantly reduced. Depending on the engine used, engine duty cycle can be as low as 20 percent during city driving. For low engine duty cycle configurations, a hydraulically driven alternator is added to keep the battery charged. The hydraulically driven alternator combines a conventional alternator with a fixed displacement hydraulic motor controlled by a pulse-width modulated flow control valve. The alternator mount for the hydraulically motor and valve is offset by elimination of the pulley from the conventional alternator.

Engine starting in a FHH vehicle is accomplished using either the electric starter or the engine P/M or both. The conventional starter is retained because there may occasionally be insufficient pressure in the high-pressure accumulator to start the engine. In this case, the electric starter kicks the engine and the hydraulic motor helps the starter to reduce amperage draw. If system pressure is high enough, the engine P/M starts the engine on its own. Using this strategy to reduce battery draw during frequent starts, the battery can be kept the same size as in the conventional vehicle. In fact, because the P/M is available to help the electric starter, it is likely that the battery size and starter size could be reduced in FHH configurations with engine-off strategies. However, this study conservatively assumes no reduction in the battery or starter size for the FHH vehicles.

3.1.7   General Hydraulic Fittings And Hoses

The hydraulic oil in a HHV is contained and directed to the pumps, motors, valves and accumulators by hoses, tubes and fittings. Tubes are steel lines with brazed or flared end connections. Hoses are rubber conduits, reinforced with fibers or steel wire or braids. Fittings are connectors, adapters, and end pieces for the hoses and tubes. It is desirable to keep the number of fittings and connections in the vehicle low because each connection adds complexity and cost to the vehicle and is a potential leak point.

To keep pressure drops to an acceptable level for high efficiency and to minimize mass, cost, and space allocated to the oil conduits, 1" ID lines are used for the high-pressure P/M connections, and 1.25" ID lines are used for the low-pressure P/M connections. The mass of these lines is 2.2 kg/m for the high-pressure lines and 1.2 kg/m for the low-pressure lines. Because the number and type of fittings is highly dependent on the configuration, mass estimates of total fittings used will be given for each vehicle configuration below.

3.2   Four Hydraulic Hybrid Configurations

This subsection describes four hydraulic hybrid configurations.   These are 1) Full Hydraulic Hybrid SUV (FHHSUV), 2) Mild Hydraulic Hybrid SUV (MHHSUV), 3) Full Hydraulic Hybrid Car (FHHCAR), and 4) Mild Hydraulic Hybrid Car (MHHCAR). For each configuration, a vehicle layout is presented detailing hydraulic component sizes and function. In addition, unique features of the configuration are described and mass estimates are given for conventional components removed and HHV components added. The mass estimates are used to project incremental costs for the hybrid technology packages later in Section 6. It is important to emphasize that there are a large number of possible designs for each of the four configurations. Plausible designs have been chosen based on EPA experience, but it is likely that further improvements would be made if and when hydraulic hybrid designs are commercialized.

3.2.1   Full Hydraulic Hybrid SUV

A FHHSUV could be configured in many unique ways depending on the tradeoffs associated with packaging, cost, fuel economy, acceleration performance, etc. This analysis focuses on one plausible configuration that EPA believes is representative of the various options available. The configuration was designed to have similar launch feel, 0 – 60 mph acceleration time, and towing capability as the baseline conventional vehicle. Figure 3-4 presents the basic FHHSUV configuration used for this analysis.

Figure 3-4: FHHSUV Configuration
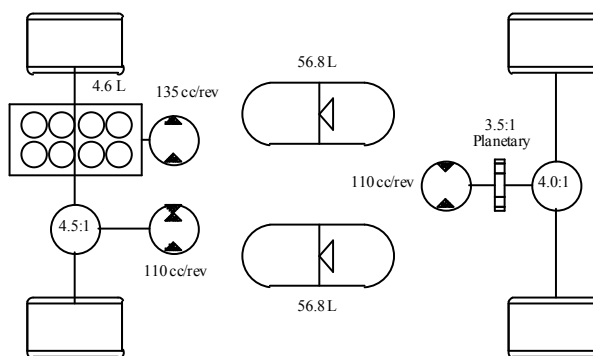
In this configuration, the automatic transmission is replaced with a hydraulic hybrid drivetrain. A 4.6 L gasoline engine replaces the baseline 5.4 L engine. (For the diesel full hydraulic hybrid, a 3.8 L engine replaces the original diesel engine.) This is possible because the hydraulic drivetrain with the 4.6 L engine provides comparable 0-to-60 mph acceleration. In addition, high-power towing can be handled with the smaller engine because peak engine output can be delivered at any vehicle speed in a FHH, while engine power is somewhat limited by discrete ratios inherent in conventional transmissions.

The engine is coupled to a 135 cc/rev hydraulic pump/motor (P/M), which operates as a pump to supply hydraulic power to the drive motors and/or to fill the high-pressure accumulator as needed. The engine P/M can also be used to start the engine when operated as a motor.

A 110 cc/rev hydraulic P/M is integrated into the front differential. The front P/M is operated in a motor mode to accelerate the vehicle, in a pump mode to slow the vehicle down by capturing kinetic energy, and in a reverse mode for vehicle reverse. The various modes are accomplished through the use of a flow control valve integrated into the P/M housing.

A 110 cc/rev motor is integrated into a rear drive assembly which also includes a two-speed gearbox and a differential. The rear motor operates in a motor mode to accelerate the vehicle and in a reverse mode for vehicle reverse; it is not used for regenerative braking. The rear motor/gearbox/differential (discussed in greater detail below) is capable of delivering significantly greater torque than the front drive unit to give the vehicle good launch acceleration. The front and rear units can be used independently or together to provide the most efficient transfer of energy to the wheels.

Front Pump/Motor/Differential Assembly

The front power unit combines a P/M and the differential into a common housing. The assembly consists of a 110 cc/rev unit and differential with a 4.5:1 final drive ratio. P/M speed at a vehicle speed of 161 km/hr (100 mph) is estimated to be 4700 rpm. The layout of the system is illustrated in Figure 3-5. Alternatively, a helical gear set could be used for the differential in place of the conventional hypoid gear set shown. Combining the P/M into the same housing as the differential eliminates the front drive shaft from the conventional 4WD SUV, which has a mass of 5.0 kg.

Figure 3-5: Front Pump/Motor/Differential Assembly
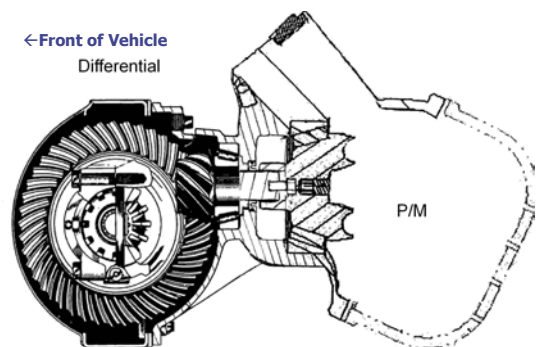
To estimate the mass increase of adding a P/M to the front base front differential, the mass of the stand alone SAE 4-bolt flange 110 cc/rev hydraulic unit was adjusted down to account for the savings from integrating the P/M with the differential housing. It is estimated that the P/M mass could be reduced by 8 kg (from 37.2 kg to 29.2 kg) by: 1) eliminating the drive flange, front bearing, and part of the pinion shaft from the base differential, 2) eliminating the SAE mount, front bearing, and a portion of the input shaft from the stand-alone P/M, and 3) adding housing to combine the two components together.

The front drive unit is designed to efficiently provide torque for moderate accelerations and decelerations typical of normal driving. Heavy accelerations are accomplished by using both the front and rear hydraulic power units. The front power unit decelerates the vehicle when operating as a pump to capture energy normally lost to friction brakes in a conventional vehicle. The unit is sized to capture energy from normal, moderate braking events (deceleration events of less than 0.15 g), and is supplemented by friction brakes for more aggressive braking.

Rear Motor/Gearbox/Differential Assembly

The basic components of the rear assembly envisioned by EPA include a motor, gear reduction, clutch out mechanism, and a differential. Depending on the size of the motor and the gearing option chosen, a FHHSUV can be configured to provide limited 4WD capability (low speeds only for lower costs) or full 4WD performance similar to that offered on current SUVs. For this analysis, a rear drive system with full 4WD capability was chosen to allow comparison with a conventional 4WD SUV. The system consists of a 110 cc/rev P/M, a 2-speed planetary gearbox with two forward ratios and a geared neutral, and differential with 4.0:1 final drive. The components are integrated into one combined housing as part of an independent rear suspension.

The overall layout of the system is given in Figure 3-6. Alternatively, a helical gear set could be used for the differential instead of the hypoid arrangement shown.

In low gear, a planetary ratio of 3.5:1 gives the same launch torque as the conventional SUV. In high gear, the planetary ratio is 1:1, which lowers motor speeds for 4WD use at highway speeds. The geared neutral operating mode of the planetary is used to reduce spin losses from the motor at highway speeds for increased fuel efficiency when 4WD is not selected.

Figure 3-6: Rear Motor/Gearbox/Differential Assembly

The motor portion of the integrated system is approximately 37 kg, nearly the same as the base stand-alone motor described in Subsection 3.1.1. For this analysis, the motor flow control valve is designed to allow both forward and reverse operation. However, depending on the overall gearing approach used, a geared reverse may be the more cost-effective design.

The motor bearings support the sun gear of the planetary, while the ring and carrier are supported by the differential pinion gear bearings. The three modes of operation in the planetary are obtained using a band clutch on the ring gear and a multi-disk clutch between the ring gear and carrier. The mass of the planetary section of the system, including planetary gears, clutches, clutch actuation valves, and housing is estimated to be 10 kg. The differential portion of the assembly remains largely unchanged from the baseline vehicle, except for the elimination of the drive shaft flange, which was taken into account in the above estimate. The motor section of the assembly is based on the prototype EPA design, and is included in the mass summary table for the FHHSUV (Table 3-8). Mounts for the system are similar in mass to the mounts for the base differential, with one large mount integrated into the differential cover (not shown in the figure) and a second mount near the large bearing of the motor to react the wheel torque.

Engine Pump Mount

The engine P/M mount is an aluminum bell housing bolted to the block. The bell housing accepts the 4-bolt flange of the base P/M and the splined shaft of the P/M fits directly into the

crankshaft. A second rear mount (similar to the rear mount for the base automatic transmission) is present on the P/M to stabilize the engine and P/M. Thus, there no mass increase associated with the rear mount P/M mount. The mass of the bell housing for the main 4-bolt mount is estimated to be 5.3 kg.

Battery/Alternator/Starter and Power Steering Systems

As explained in Subsection 3.1.6, the FHHSUV will utilize a hydraulically driven alternator for all engine-off strategy engine options. The hydraulically driven alternator allows the battery to charge when engine duty cycle is too low, which would occur during extended periods of city driving. The hydraulically driven alternator adds 4 kg for a 4 cc hydraulic motor and 0.5 kg for a PWM control valve, for a total of 4.5 kg over the base conventional vehicle's alternator system. The battery size and starter remain unchanged.

The conventional power steering system is replaced with an on-demand power steering system fed by the high-pressure accumulator (as described in Subsection 3.1.5). The mass of the on-demand power steering system is projected to be 1.7 kg less than the base conventional system.

Hydraulic Circuit

Figure 3-7 presents the hydraulic circuit diagram for the FHHSUV. The line lengths in the diagram are used to estimate the mass of lines and hoses, fittings, and oil contained in the system. The line length and hose routing estimates are based on dimensions of a 1999 Ford Expedition. Table 3-5 gives mass estimates for the fluid conduits used to carry fluid throughout the system. Tables 3-6 and 3-7 provide estimates of the amount of oil in the hydraulic circuit, and the mass of the oil conditioning system, respectively.

Figure 3-7: FHHSUV Hydraulic Circuit Diagram
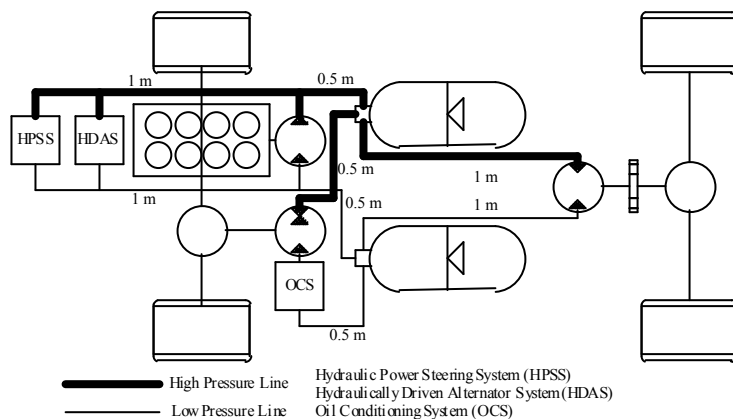
Table 3-5: FHHSUV Fluid Conduit Mass Summary

Component	High Pressure Length (m)	High Pressure Mass (kg)	Low Pressure Length (m)	Low Pressure Mass (kg)
Main Loop Hose/Tube	2	4.4	2.0	2.4
Accessory Loop Hose/Tube	1	0.5	1.0	0.1
Fittings/Hose ends		17.4		8.5
Sub Totals		**22.3**		**11.0**
			Total:	**33.3**

Table 3-6: FHHSUV Oil Mass Summary

Component	Volume (L)	Mass (kg)
Accumulator	28.4	23.8
Pumps	12.1	10.2
Oil Conditioning System	3.0	2.5
Fluid Conduits	2.7	2.3
Total:	**46.3**	**38.8**

Table 3-7: FHHSUV Oil Conditioning System Mass Summary

Component	Mass (kg)
Filter	2
Oil to Air Cooler	4
Valves and Manifold	2.5
Mount	1
Total:	**9.5**

FHHSUV Mass Summary

Table 3-8 summarizes the mass of components added and removed for the FHH SUV configuration. The component mass will be grouped into categories of similar manufacturing complexity to estimate cost in Section 6.

Table 3-8: FHHSUV Mass Summary
Gas Engine with Engine Off Strategy

Category	Component	Mass (kg)
P/Ms	135 cc engine pump motor (w/ mounting flange and bearing)	45.7
	110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2
	110 cc motor for rear power unit	37.2
Accumulators	15 gal composite accumulator (high pressure)	56.0
	15 gal composite accumulator (low pressure)	23.4
Gearbox	2 speed planetary (w/housing) for rear power unit	15.0
Hydraulic circuit	oil cooler and filter loop (front motor low side) + mount	9.5
	fitting and hoses	33.3
	fluid in HP accumulator, fittings, hoses, oil conditioner	38.8
Accessories	hydraulic driven alternator	4.5
	on-demand power steering system	15.6
Brackets & Mounts	accumulator mounting brackets	6.0
	engine/PM coupling and fasteners	5.3
Components Removed	engine downsize	-31.0
	automatic transmission	-106.0
	transfer case	-47.3
	net downsize of fuel tank	-2.4
	rear drive shaft	-9.8
	front drive shaft	-7.3
	transmission cooler and lines	-1.8
	transmission fluid	-11.8
	power steering system (pump, reservoir, steering gear)	-17.3
	TOTAL MASS ADDED	**84.8**

3.2.2 Mild Hydraulic Hybrid SUV

Figure 3-8 presents the MHHSUV assumed in this analysis. The configuration was designed to have similar launch feel, 0 – 60 mph acceleration time, and towing capacity as the baseline conventional vehicle. In this configuration, the base 5.4 L engine and automatic transmission are retained. In addition, a 110 cc/rev hydraulic P/M is integrated into the 4WD transfer case along with a 1.35:1 helical gear set.

Figure 3-8: MHHSUV Configuration

The P/M is operated in a motor mode to assist the transmission in accelerating the vehicle, and operated in a pump mode to slow the vehicle down by capturing kinetic energy. The P/M modes are accomplished through the use of a flow control valve integrated into the P/M housing. The speed of the P/M is 5000 rpm at 161 km/hr (100 mph).

The P/M is used primarily to capture vehicle kinetic energy. The energy is stored in a 26.5 L (7 gallon) accumulator and reused during the next acceleration. The system operates exactly like the base conventional system whenever the P/M is off line.

Integrated Transfer Case and Pump/Motor

A 110 cc/rev P/M is integrated into the transfer case housing through a 1.35:1 gear ratio. The layout shown (Figure 3-9) assumes that the electronic shift servo is repositioned slightly and the transfer case housing strengthened somewhat to accommodate the addition of the P/M. Overall, it is estimated that the gear set and housing additions would add 3.5 kg to the individual mass of the base transfer case and stand-alone P/M. A vehicle mount is attached to the P/M to supplement the existing transfer case mount at the transmission interface, adding 1.0 kg, for an overall addition of 4.5 kg.

Figure 3-9: Integrated Transfer Case and P/M
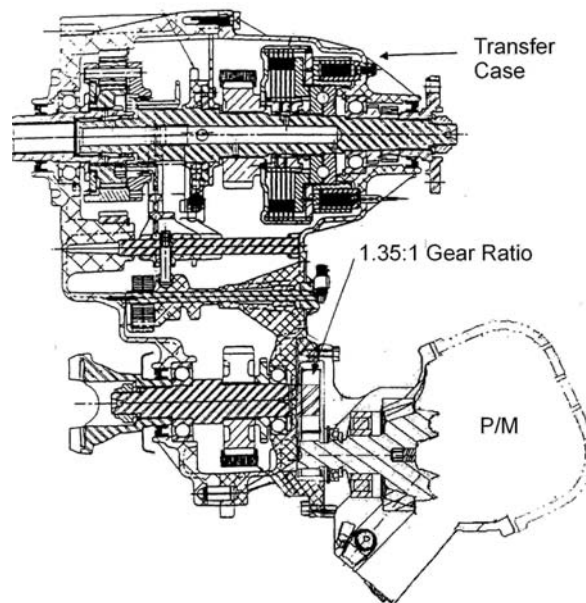
A more integrated package could be achieved using a 148 cc/rev unit with no gear reduction. However, overall mass would be roughly equal to that in the layout shown in Figure 3-9, as savings from greater integration would be offset by the increased mass of the P/M.

Battery/Alternator/Starter and Power Steering System

As discussed in Subsection 3.1.6, a MHHSUV with an engine-off strategy requires 25 percent greater battery capacity to handle the increase starter load, resulting in a battery mass increase of 5.2 kg. No change is required for the alternator because the engine shuts off only at zero vehicle speed, keeping engine duty cycle high enough to charge the battery using the conventional charging system. The stock starter is retained and used as in a conventional SUV, although with a higher frequency of starts.

The MHHSUV uses a conventional power steering system to keep changes to the base conventional vehicle to a minimum. Optionally, an on-demand power steering system (as described in Subsection 3.1.5) could be used to take advantage of the hydraulic pressure in the accumulator and reduce parasitic losses. The choice between power steering options may vary depend on the vehicle application and anticipated sales volume of the MHHSUV in relation to the conventional configuration.

Hydraulic Circuit

Figure 3-10 contains the hydraulic circuit diagram for the MHHSUV. The diagram is used to estimate the mass of lines and hoses, fittings, and oil contained in the system. The line length and hose routing estimates are based on dimensions of a 1999 Ford Expedition. Table 3-9 summarizes the mass of the fluid conduits for the MHHSUV. Table 3-10 gives the amount of oil in the hydraulic circuit, and Table 3-11 present the mass estimates for oil conditioning system. Descriptions of these components are given in Subsection 3.1, as it applies to the MHHSUV.

Figure 3-10: MHHSUV Hydraulic Circuit Diagram
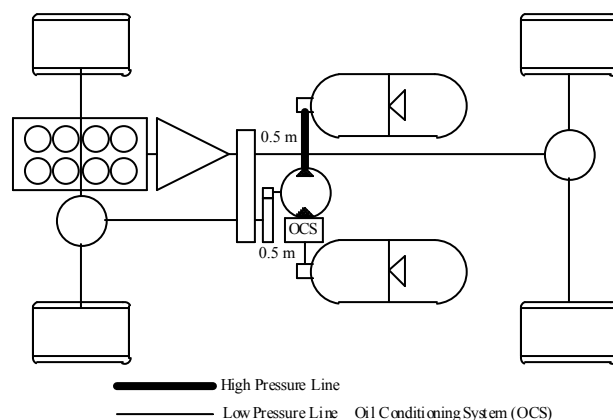
Table 3-9: MHHSUV Fluid Conduit Mass Summary

Component	High Pressure Length (m)	High Pressure Mass (kg)	Low Pressure Length (m)	Low Pressure Mass (kg)
Main Loop Hose/Tube	0.5	1.1	0.5	0.6
Accessory Loop Hose/Tube	0	0.0	0.0	0.0
Fittings/Hose ends		4.2		2.1
Sub Totals		**5.3**		**2.7**
			Total:	**8.1**

Table 3-10: MHHSUV Oil Mass Summary

Component	Volume (L)	Mass (kg)
Accumulator	12.8	10.7
Pumps	3.8	3.2
Oil Conditioning System	2.5	2.1
Fluid Conduits	0.6	0.5
Total:	**19.7**	**16.5**

Table 3-11: MHHSUV Oil Conditioning System Mass Summary

Component	Mass (kg)
Filter	2
Oil to Air Cooler	3
Valves and Manifold	2.5
Mount	1
Total:	**8.5**

MHHSUV Mass Summary

Table 3-12 summarizes the mass of components added and removed for the MHHSUV configuration. The component mass will be grouped into categories of similar manufacturing complexity to estimate cost in Section 6.

Table 3-12: Mass Summary for MHHSUV Gas Engine with Engine Off Strategy

Category	Component	Weight (kg)
P/Ms	110 cc pump motor (w/mounting flange for transfer case)	37.7
Accumulators	7 gal composite accumulator (high pressure)	32.3
	7 gal composite accumulator (low pressure)	14.3
Gearbox	1.4 gearset integrated into transfer case	3.5
Hydraulic circuit	oil cooler and filter loop (front motor low side)	8.5
	fitting and hoses	8.1
	fluid in HP accumulator, fittings, hoses, oil conditioner	16.9
Accessories	Battery upsize	5.2
Brackets & Mounts	accumulator mounting brackets	4.5
	pump motor isolation mount (in addition to transfer case mount)	1.0
Components Removed	net downsize of fuel tank	-1.3
	TOTAL MASS ADDED	**130.7**

3.2.3   Full Hydraulic Hybrid Car

Similar to the FHHSUV, a FHHCAR can be configured many different ways depending on tradeoffs associated with packaging, cost, fuel economy, acceleration performance, etc. A front-wheel drive configuration is shown in Figure 3-11. In this configuration, all the P/Ms are located in the front of the vehicle in a single combined housing. Alternatively, a FHHCAR could be configured in an all-wheel drive arrangement, with one motor connected to the rear wheels through a differential. For this analysis, the front-wheel drive layout was chosen to compare directly to the baseline midsize car.

Figure 3-11: FHHCAR Configuration
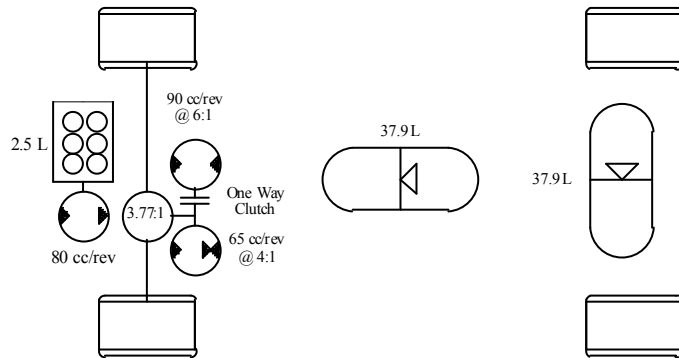
The key components are sized to provide performance equivalent to the baseline conventional vehicle while maximizing fuel efficiency. Energy stored in the hydraulic accumulators and engine operation flexibility possible in a hydraulic powertrain allow the baseline 3.0 L V6 engine to be downsized to a 2.5 L gasoline engine. (For the diesel full hydraulic hybrid, a 2.3 L engine replaces the original diesel engine.) In addition, the torque converter and automatic transmission of a conventional car are replaced with an integrated hydraulic transaxle including an engine P/M, one drive P/M, one drive motor, and a one-way clutch.

The P/Ms are used in a manner similar to the FHHSUV described earlier in Subsection 3.2.1. The 80 cc/rev engine P/M is used to start the engine and then operates as a pump to supply hydraulic power. The 65 cc/rev drive P/M is used to propel the vehicle, in forward and reverse, and brake the vehicle. This P/M delivers a large majority of the energy to and from the wheels during typical driving. The 90 cc/rev motor can deliver significantly more torque to the wheels and is used to provide good acceleration for the vehicle in forward and reverse. This motor is coupled with a one-way clutch to reduce the introduction of parasitic losses to the drivetrain when it is not being used. Finally, for energy storage there is a 37.9 L (10 gallon) high-pressure accumulator and a 37.9 L (10 gallon) low-pressure accumulator.

Integrated Hydraulic Transaxle

All of the P/Ms and the clutch are integrated into one hydraulic transaxle. Each drive motor has its own pinion gear to provide a unique ratio with the ring gear of the differential. A potential layout of the system is shown in Figure 3-12. The overall layout is similar in size to the baseline conventional automatic transmission. To minimize complexity, the hydraulic transaxle is connected to accumulators through one high and one low-pressure hose/line. Individual fluid conduits connect the individual P/Ms within the transaxle. The estimated mass of the transaxle excluding the P/Ms is 41.3 kg. The estimate is based on a prototype layout designed by an EPA contractor.

Figure 3-12: FHHCAR Integrated Hydraulic Transaxle
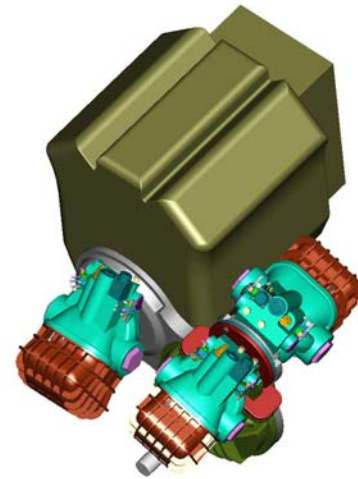
Battery/Alternator/Starter and Power Steering Systems

The FHHCAR is similar to the FHHSUV with regards to the battery/alternator/starter and power steering systems. A hydraulically driven alternator, which combines a 3 cc hydraulic unit, a control valve, and an alternator, adds 3.5 kg compared to the base alternator system. The mass of the on-demand power steering system is projected to be roughly the same (see Subsection 3.1.5) as the base conventional system.

Hydraulic Circuit

Figure 3-13 contains the hydraulic circuit diagram for the FHHCAR. The diagram is used to estimate the mass of lines and hoses, fittings, and oil contained in the system. The line length and hose routing estimates are based on dimensions of a 1999 Ford Taurus. Tables 3-13, 3-14, and 3-15 give a summary of mass estimates for these components.

Figure 3-13: FHHCAR Hydraulic Circuit Diagram
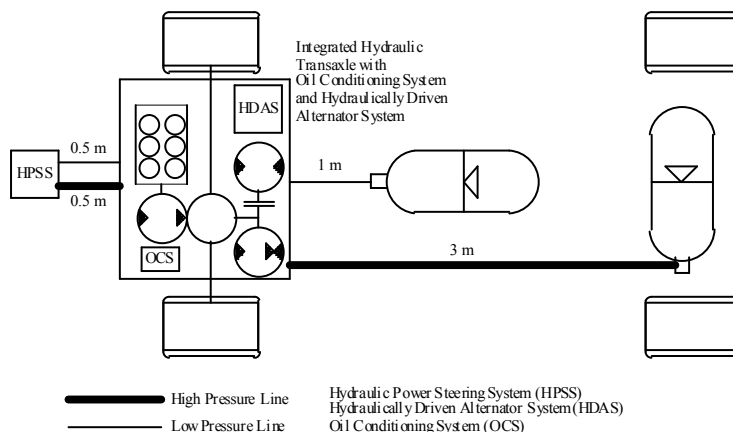
Table 3-13: FHHCAR Fluid Conduit Mass Summary

Component	High Pressure Length (m)	High Pressure Mass (kg)	Low Pressure Length (m)	Low Pressure Mass (kg)
Main Loop Hose/Tube	3	6.6	1.0	0.8
Accessory Loop Hose/Tube	0.5	0.3	0.5	0.1
Fittings/Hose ends		4.5		2.2
Sub Totals		**11.4**		**3.0**
			Total:	**14.4**

Table 3-14: FHHCAR Oil Mass Summary

Component	Volume (L)	Mass (kg)
Accumulator	18.9	15.9
Pumps	7.7	6.5
Oil Conditioning System	2.5	2.1
Fluid Conduits	2.1	1.8
Total:	**31.2**	**26.2**

Table 3-15: FHHCAR Oil Conditioning System Mass Summary

Component	Mass (kg)
Filter	1
Oil to Air Cooler	3
Valves and Manifold	1.5
Mount	0.5
Total:	**6**

FHHCAR Mass Summary

Table 3-16 summarizes the mass of components added and removed for the FHHCAR configuration.

Table 3-16: Mass Summary for FHHCAR

Category	Component	Mass (kg)
P/Ms	80 cc pump motor	27.1
	65 cc drive motor	22.0
	80 cc drive motor	27.1
Accumulators	10 gal composite accumulator (high pressure)	41.7
	10 gal composite accumulator (low pressure)	18.1
Gearbox	integrated transmission (w/o motors)	41.3
Hydraulic circuit	oil cooler and filter loop (front motor low side)	6.5
	fitting and hoses	14.4
	fluid in HP accumulator, fittings, hoses, oil conditioner	24.1
Accessories	hydraulic driven alternator	3.5
	on-demand power steering system	11.8
Brackets & Mounts	accumulator mounting brackets	6.0
Components Removed	engine downsize	-21.0
	automatic transmission	-85.0
	net downsize of fuel tank	-4.1
	transmission fluid	-10.0
	power steering system (pump, reservoir, steering gear)	-12.3
	TOTAL MASS ADDED	**111.1**

3.2.4 Mild Hydraulic Hybrid Car

Figure 3-14 presents the Mild Hydraulic Hybrid Car (MHHCAR) configuration assumed in this analysis. The configuration was designed to have similar launch feel and 0 to 60 mph acceleration time as the baseline conventional vehicle. In this configuration, the baseline 3.0 L engine and automatic transmission are retained and a 55 cc/rev hydraulic P/M is integrated into the transmission. The P/M is sized to capture the energy from normal braking and weighs 18 kg. For comparison, the AX4N automatic transmission used in the Ford Taurus weighs approximately 85 kg (dry). There is a 1.27:1 gear reduction from the P/M to the transmission. This reduction, coupled with a final drive ratio of 3.77:1 produces an overall ratio of 4.79:1. Therefore the P/M can provide or absorb over 1400 N-m of torque at the wheels. Finally, for energy storage there is a 15.1 L (4 gallon) high-pressure accumulator and a 15.1 L (4 gallon) low-pressure accumulator.

Figure 3-14: MHHCAR Configuration
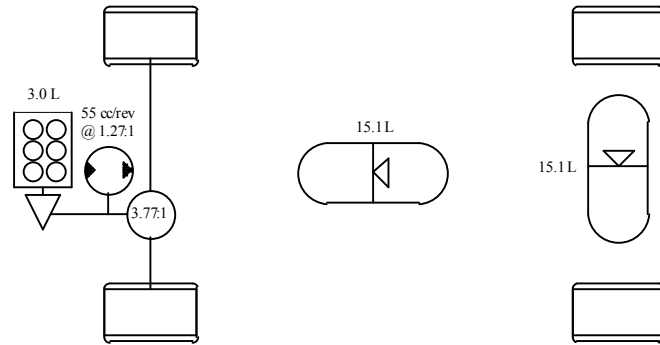
Integrated P/M and Automatic Transmission

The layout of the integrated P/M and automatic transmission system is presented in Figure 3-15. The P/M is oriented with its drive shaft parallel to the transmission axle shafts. The connection between the P/M and transmission is accomplished through the use of a chain drive similar to the chain between the input shaft and main transmission shaft in the Taurus AX4N transmission and many other front wheel drive automatics. A P/M mount is added to the automatic transmission and housing strength is increased to support the additional mass of the P/M. Also, the transmission is slightly longer to accommodate the extra gear & chain assembly that connects the P/M to the transmission. The estimated mass increase over the baseline automatic transmission resulting from the addition of the chain drive and P/M mount is 8.3 kg.

Figure 3-15: MHHCAR Transaxle
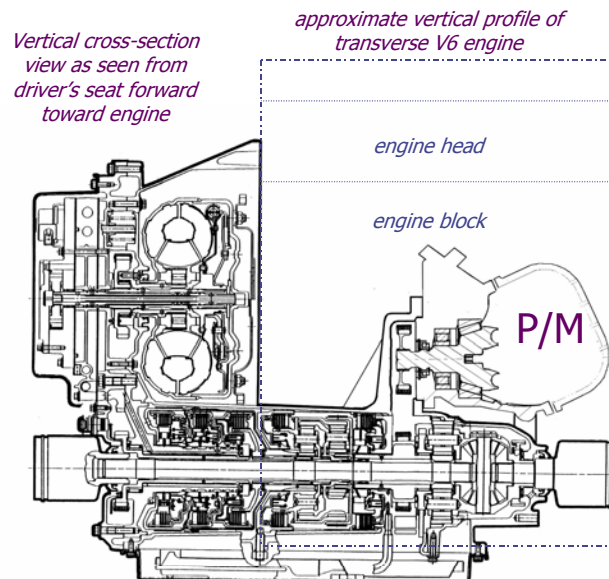
Battery/Alternator/Starter and Power Steering System

Similarly to a MHHSUV, a MHHCAR with an engine-off strategy requires 25 percent greater battery capacity to handle the increase starter load, resulting in a battery mass increase of 4.6 kg. No change is required for the alternator or starter (see Subsection 3.1.6). A conventional power steering system is used on the MHHCAR as described in Subsection 3.1.5 to keep changes to the base conventional vehicle to a minimum.

Hydraulic Circuit

Figure 3-16 contains the hydraulic circuit diagram for the MHHCAR. The schematic is used to estimate the mass of lines and hoses, fittings, and oil contained in the system. The line length and hose routing estimates are based on dimensions of a 1999 Ford Taurus. Tables 3-17, 3-18, and 3-19 give a summary of mass of the hydraulic components for the MHHCAR.

Figure 3-16: MHHCAR Schematic
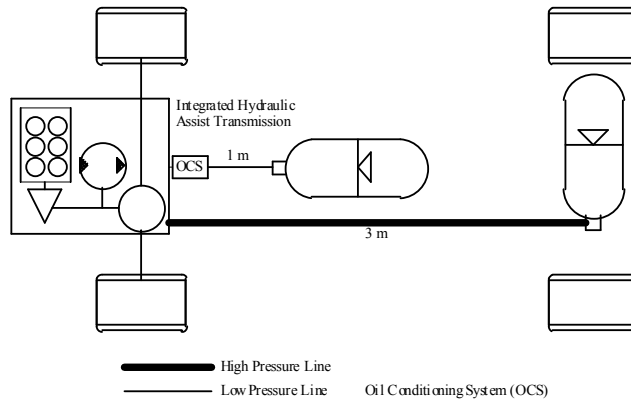
Table 3-17: MHHCAR Fluid Conduit Mass Summary

	High Pressure		Low Pressure	
	Length	Mass	Length	Mass
Component	**(m)**	**(kg)**	**(m)**	**(kg)**
Main Loop Hose/Tube	3	6.6	1.0	0.8
Accessory Loop Hose/Tube	0	0.0	0.0	0.0
Fittings/Hose ends		4.2		2.1
Sub Totals		**10.8**		**2.9**
			Total:	**13.8**

Table 3-18: MHHCAR Oil Mass Summary

	Volume	Mass
Component	**(L)**	**(kg)**
Accumulator	7.6	6.3
Pumps	1.9	1.6
Oil Conditioning System	2.5	2.1
Fluid Conduits	2.0	1.7
Total:	**14.0**	**11.7**

Table 3-19: MHHCAR Oil Conditioning System Mass Summary

Component	Mass (kg)
Filter	1
Oil to Air Cooler	3
Valves and Manifold	2
Mount	1
Total:	**7**

MHHCAR Mass Summary

Table 3-20 summarizes the mass of components added and removed for the MHHCAR configuration.

Table 3-20: MHHCAR Mass Summary

Category	Component	Weight (kg)
P/Ms	55 cc pump motor	18.6
Accumulators	4 gal composite accumulator (high pressure)	24.0
	4 gal composite accumulator (low pressure)	11.2
Gearbox	additional input to final drive of trans, extra housing, mounts, chain	8.3
Hydraulic circuit	oil cooler and filter loop (front motor low side)	5.0
	fitting and hoses	13.8
	fluid in HP accumulator, fittings, hoses, oil conditioner	9.6
Accessories	battery upsize	4.6
Brackets & Mounts	accumulator mounting brackets	4.0
Components Removed	net downsize of fuel tank	-1.8
	TOTAL MASS ADDED	**97.3**

4. Vehicle Technology Packages and Modeling Scenarios

This progress report evaluates four basic technology approaches that could improve vehicle fuel economy: mild hydraulic hybrid drivetrains, full hydraulic hybrid drivetrains, clean diesel engines, and variable displacement engines. As will be explained below, these individual technologies, when grouped into reasonable packages, leads to a total of 40 vehicle technology packages defined by three different dimensions:

- ➢ 2 vehicle classes
- ➢ 5 drivetrain configurations
- ➢ 4 engine configurations

4.1 Two Vehicle Classes

Midsize cars with front wheel drive and large sport utility vehicles (SUVs) with 4-wheel drive are the two vehicle classes chosen to simplify this analysis. In EPA's Fuel Economy Trends report, one classification methodology for new vehicles involves dividing the fleet into 16 different classes: two-seater cars, minicompact cars, subcompact cars, compact cars, small station wagons, midsize cars, midsize station wagons, large cars, small SUVs, mid SUVs, large SUVs, minivans, small pickups, midsize pickups, large pickups, and large vans. (Some analyses also include medium-duty passenger vehicles, the largest SUVs and passenger vans in excess of 8500 pounds gross vehicle weight rating, as a 17th personal vehicle class.) Carrying out this technology evaluation for all 16 or 17 vehicle classes, rather than the 2 chosen vehicle classes, would greatly increase the number of vehicle technology scenarios. Instead, EPA staff chose to focus on two vehicle classes which, because of their high sales volumes and relatively low fuel economies, have the potential to yield large aggregate fuel and carbon savings: midsize cars (e.g., Chevrolet Monte Carlo, Toyota Camry) and large SUVs (e.g., Dodge Durango, Ford Expedition). These two classes alone represent about one-quarter of the overall personal vehicle market and a higher proportion of overall fuel use and carbon emissions. The baseline midsize car uses front wheel drive, while the baseline SUV uses 4-wheel drive. The impact of various technology packages on fuel economy and cost for these high-volume classes will "carry over" to other vehicle classes in varying degrees, but it seemed most appropriate to focus initially on high-volume vehicle classes with relatively low fuel economies.

4.2 Five Drivetrain Configurations

There are 5 transmission/hydraulic hybrid drivetrain configurations. The first simply involves the conventional transmission that is standard on nearly all personal vehicles today. The second and third cases involve mild hydraulic hybrid drivetrains, differing only in whether the powertrain strategy never shuts the engine off except when the driver explicitly does so (i.e., engine-on strategy) or does in fact shut the engine off during times when the engine power is not needed and when overall vehicle efficiency can be increased by shutting the engine down (engine-off). The fourth and fifth scenarios involve full hydraulic hybrid drivetrains, again with both engine-on and engine-off approaches. Hydraulic hybrid drivetrains in general are briefly

described in Section 2 and specific hydraulic hybrid vehicle designs are described in greater detail in Section 3. It is important to note that consumer acceptance of the frequent engine cycling associated with the engine-off strategy is unknown at this time.

4.3   Four Engine Configurations

There are 4 engine technology configurations. The first is simply the conventional gasoline engine that is used on nearly all personal vehicles today. The second configuration is a clean diesel engine able to meet Tier 2 emission standards. The third is a variable displacement gasoline engine. The fourth is the one engine configuration that involves two changes: both a clean diesel engine and variable displacement. This configuration makes technical sense because the diesel cycle improves basic combustion efficiency over the full range of engine operating conditions, while variable displacement increases the frequency of engine operation at or near the regions of peak efficiency.

Table 4-1 shows the 40 vehicle technology packages, of which 2 are baselines (i.e., represent today's vehicles with conventional gasoline engines and conventional transmissions) and the remaining 38 are the technology packages evaluated in this study.

Table 4-1: 40 Vehicle Technology Packages

Large Sport Utility Vehicle (4WD)

*Fuel Economy (MPG) ***

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Conventional Gasoline Engine	(base)	x	x	x	x
Clean Diesel Engine	x	x	x	x	x
Gasoline Variable Displacement Engine	x	x	x	x	x
Clean Diesel Variable Displacement Engine	x	x	x	x	x

Midsize Car (2WD)

*Fuel Economy (MPG) ***

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Conventional Gasoline Engine	(base)	x	x	x	x
Clean Diesel Engine	x	x	x	x	x
Gasoline Variable Displacement Engine	x	x	x	x	x
Clean Diesel Variable Displacement Engine	x	x	x	x	x

* Fuel economy values are laboratory values and are about 15% higher than real-world projections.

5.   Projection of Fuel Economy Improvement Potential

5.1   <u>Overview</u>

EPA staff developed a new modeling tool called the Stored Hydraulic Energy Research Platform Analyzer (SHERPA), using Matlab and Simulink on a desktop personal computer, to project likely fuel economy levels for the 40 vehicle technology scenarios. The model is designed to be able to simulate operation of vehicles with all of the unique engine and drivetrain designs included in the 40 vehicle technology configurations. For each scenario and driving cycle studied, the model produces a summary file including statistics for each of the vehicle's components and an energy balance table to show where the fuel energy was consumed either by internal losses or vehicle propulsion.

The major inputs to the model are the vehicle roadload specification, vehicle mass, the efficiency maps of the engines and hydraulic components, the control strategy, and the driving cycles.
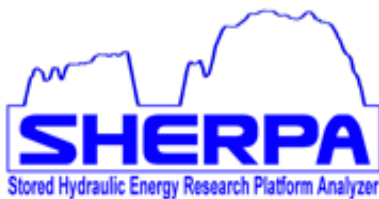
The vehicle roadload specification determines the amount of force required to propel the vehicle as a function of vehicle speed. The baseline 4WD large SUV had a test weight of 5563 pounds and the baseline midsize car had a test weight of 3517 pounds. For modeling scenarios involving changes to the powertrain, the masses of component packages were added to or subtracted from the baseline vehicle to estimate the total mass for each configuration. With respect to two other important components of vehicle roadload, EPA assumed that vehicle aerodynamic drag and tire rolling resistance were similar to today's production vehicles. Automobile manufacturers provide roadload equations to EPA as part of the vehicle emissions certification and fuel economy testing programs, and EPA generated representative values for the modeling scenarios by performing a simple sales-weighted analysis of the roadload equations for the top-selling vehicles in both the large SUV and midsize car classes.

To model the various engines, representative engine maps (fuel energy efficiency as a function of load and RPM) based on manufacturer or in-house data were used, scaled to match the vehicle's power and torque requirements. Appendix E gives the 4 basic engine maps that are used in this report: for the base gasoline and diesel engines for both the large SUV and the midsize car applications. Maps for the variable displacement engines were modifications of these engine maps. Appendix F gives the efficiency maps for the hydraulic pump/motors, which were based on efficiency data from prototype units developed and tested by EPA.

The control strategies are fairly straightforward, based on first-order approaches to hydraulic hybrid vehicle operation and direct EPA experience with in-house hydraulic hybrid vehicle test chassis. It should be noted that for the large number of fuel economy modeling scenarios it was not possible to optimize the control strategy for each in the time available for this study. For this reason, there are only relatively minor changes in strategy for each fuel economy modeling

scenario. Any production vehicle would have an optimized strategy that would likely produce higher fuel economy than the results projected in our modeling.

The driving cycles used are the standard Federal Test Procedure (FTP) city and highway cycles used to measure the fuel economy and emissions of conventional vehicles. These driving cycles are used to generate the fuel economy test data that is then adjusted (to better reflect what consumers will achieve in real world driving) to provide the fuel economy label values displayed on showroom vehicles and in the EPA/DOE Fuel Economy Guide. The city label number is 90% of the city test result and the highway label number is 78% of the highway test result. Unless noted otherwise, the fuel economy values shown in this report are unadjusted, combined city/highway fuel economy test values, which are approximately 15% higher than the projected real-world values on new car labels and in the Fuel Economy Guide.

Figure 5-1 is a diagram of the top level for the fuel economy modeling of a mild hydraulic hybrid vehicle showing the basic flow of information among the different parts of the model. The model is a "forward" model for which results flow from a driver torque request to a vehicle response. The model "driver" compares the actual vehicle speed with the vehicle speed desired by the driving cycle and requests positive or negative torque at the wheels as required. This modeling method is computationally expensive (i.e. not as fast as we might like) but has the advantage of following the same basic principles as an actual vehicle and driver.

Figure 5-1: Mild Hydraulic Hybrid Fuel Economy Modeling Diagram
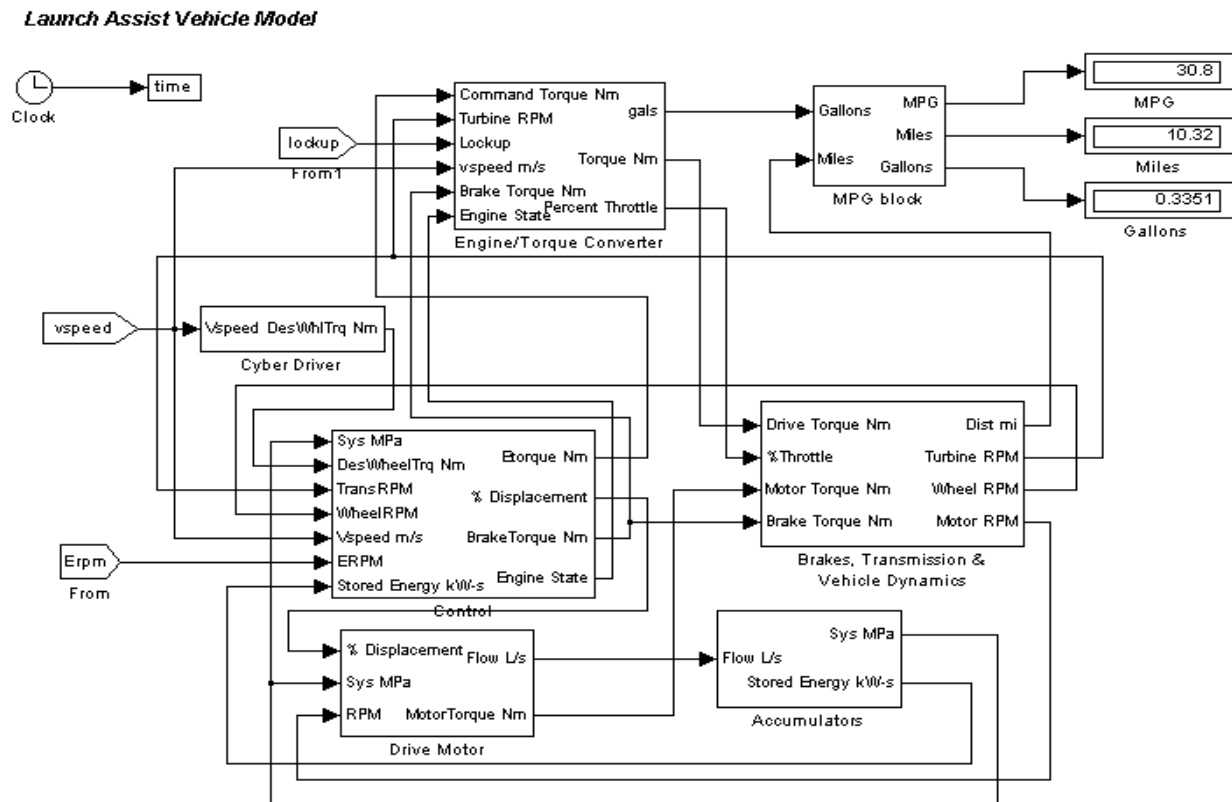
As an initial test of the validity of the model, we compared the fuel economy modeling results for the base conventional engine/transmission vehicles with actual fuel economy test data for conventional vehicles obtained from the formal EPA fuel economy database. Appendix G shows the data that was used for this comparison.

For a group of top-selling large SUVs, the sales-weighted average city/highway fuel economy from EPA's federal fuel economy database (based on formal testing of prototype vehicles by EPA and industry) is 14.5/21.3 mpg (combined value of 16.9 mpg), with a range of 12.8 to 15.4 mpg city and 19.1 to 22 mpg highway. Our model projected city/highway fuel economy, for a representative large SUV with a 5.4-liter gasoline engine and conventional transmission, of 14.9/21.2 mpg (combined value of 17.2 mpg). For a group of top-selling midsize cars the sales-weighted average city/highway fuel economy from the official EPA fuel economy database is 24.2/37.8 mpg (combined value of 28.9 mpg), with a range of 22.2 to 25.8 mpg city and 35.4 to 39.2 mpg highway. Our model projected city/highway fuel economy, for a representative midsize car with a 3.0-liter engine and conventional transmission, of 24.3/37.9 mpg (combined value of 29.0). SHERPA projections are within 3% of the average city, highway, and combined city/highway test results for both large SUVs and midsize cars from the EPA fuel economy database and so SHERPA is very good at predicting the fuel economy of vehicles with conventional powertrains. Likewise, model results for some of the full hydraulic hybrid configurations have also been compared to actual test data from EPA's full hydraulic hybrid proof-of-concept test chassis with good correlation.

5.2   Example

To illustrate the fuel economy modeling process, the following is a brief case study of the design process and key design assumptions that were made for one of the 40 unique fuel economy modeling scenarios–the large SUV with conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy. The design parameters assumed for the engine, hydraulic pump/motors, and hydraulic accumulators for this example powertrain configuration are described below. It should be noted that for every technology package there are many reasonable alternative assumptions that could be made. In this context, the assumptions and results of the fuel economy modeling should be viewed as reasonable and plausible, but not necessarily optimized. If any of these technology packages were to be commercialized, it is likely that optimization would yield different, and most likely higher, fuel economy levels.

The design process begins with the selection of the engine and determination of the engine pump capacity based on the engine operating strategy. Next the drive motor gearing and capacities are chosen. Zero to sixty performance of the system is the modeled and compared with the baseline performance. If necessary, the engine and/or pump/motors are reconfigured to obtain a vehicle configuration of equal performance.

5.2.1   Engine

For the full hydraulic hybrid vehicle as modeled with stop/start engine operation, the basic strategy is to run the engine at a high efficiency "minimum efficient power" or shut it off. There are many possible variations on this theme, but this is one of the simplest. If the driver demands

a higher power, then the engine will run along a line to a higher power point, but the engine will never run below its minimum efficient power.

Frequent engine shutdown results, for the city cycle, in the engine being restarted 21 times and the engine being on for 27% of the time. Over the highway cycle, the engine is restarted 9 times and on for 79% of the time. The consumer acceptability of this amount of engine cycling is unknown. In order to account for the fact that gasoline engines are more inefficient during startup, we assessed a 2% absolute fuel economy penalty at the peak engine efficiency point (and proportionally lower efficiency penalties at other points on the engine map). For the variable displacement gasoline engine, a smaller fuel economy penalty was assumed since the engine is on more often and the restart involves a smaller engine displacement.

Based on a 5.4-liter engine map, the peak engine efficiency is 33.5% at approximately 40 kW at 1500 RPM, which implies a torque of about 250 Nm. For start/stop engine operation, the higher the minimum power the lower the total duty cycle and the shorter the average run time.

5.2.2 Hydraulic Pump/Motors

Based on experience with in-house proof-of-concept test chassis and looking at the torque required at the minimum vehicle operating pressure, a 160 cc/rev engine hydraulic pump was initially considered (but a smaller unit was ultimately selected for the modeling of this design, as will be discussed below). For a minimum system pressure (high pressure minus low pressure) of 2000 PSI, a 160 cc/rev pump can absorb approximately 350 Nm of torque, which is more than required to match the 250 Nm needed for the chosen operating point and allows absorption of full engine power at minimum system pressure.

Next we must choose the size of the drive motor(s) and gear ratio(s). Again, we have a choice of many configurations. For the purposes of this study we decided on a simple two-motor arrangement. The secondary unit incorporates a one-way clutch and is only used for driving, not regenerative braking. This is similar to an arrangement we have on an in-house test chassis. The second unit may or may not incorporate a torque converter for low-speed launch and drives the rear wheels for an all wheel drive configuration. For this configuration we assume a two-speed planetary gearbox without torque converter between the rear pump/motor and the final drive. The goal then is to size the primary unit to be able to provide most or all of the necessary drive energy and to absorb all of the kinetic energy during regenerative braking.

For this chassis, a 110 cc/rev primary motor was chosen with a gear ratio of 4.5:1. This is similar to an arrangement we have on an in-house test chassis. Over the city cycle, this combination provides 99.4% of the required drive energy. Over the highway cycle, this configuration provides 100% of the required drive energy. The 4.5:1 ratio allows the use of full pump displacement at 90 MPH and implies a maximum (RPM limited) speed of 121 MPH.

The secondary motor and gear ratio are sized for vehicle performance during acceleration with the goal of matching the performance of the conventional vehicle. For this vehicle we chose a 110 cc/rev secondary motor with a 4.0:1 axle ratio and two-speed planetary with ratios of 3.5:1 and 1:1. For a starting system pressure of 3000 PSI this results in a modeled 0-to-60 mph

acceleration time of approximately 8.0 seconds, which is faster than the modeled base vehicle acceleration time of about 8.8 seconds.

Since the common ground for all configurations is equal performance based on 0-to-60 mph acceleration time, the engine is downsized by 15% to a 4.6L engine. The new acceleration time is then 8.9 seconds, which compares favorably to the baseline vehicle's acceleration time.

Downsizing the engine requires re-examining the choice of engine "sweet spot", which becomes 30 kW at 1500 RPM. The engine pump is also downsized, from the 160 cc/rev unit originally considered, by the same percentage to 135 cc/rev.

It is important to emphasize that this configuration has the primary benefits of being simple and low-cost, but has the corresponding drawback of not being as optimized for fuel economy as a more complex configuration. Based on our in-house laboratory experience, we are confident that a higher-cost design could yield significantly higher fuel economy values. EPA in fact is working with industry partners to better identify the tradeoffs associated between simplicity and cost, on the one hand, with fuel economy optimization.

5.2.3 Hydraulic Accumulators

The next major decision is the capacity of the two accumulators. The vehicle has one high-pressure (roughly 2000 to 5000 PSI) accumulator to store energy and one low-pressure (roughly 100 to 300 PSI) accumulator to provide the necessary minimum inlet pressure to the hydraulic units during pumping. For this vehicle a 15 gallon capacity (for each accumulator) was chosen. It should be noted that this is larger than the 7 gallon capacity required for the mild hydraulic hybrid configuration because the high-pressure accumulator must not only store energy from regenerative braking but must also act as a buffer for the engine start/stop operation. A smaller accumulator will result in more frequent, shorter engine runs and a larger accumulator will result in less frequent, longer engine runs. As long as the accumulator can absorb the required regenerative braking energy and provide some engine buffering, accumulator size makes little difference to fuel economy (other than as a weight penalty) but has a large effect on the engine operating characteristics.

These were the major assumptions involved with this particular technology package. A similar approach, each with its own set of assumptions, was carried out for the other 39 fuel economy modeling scenarios.

5.3 Results

EPA staff used the SHERPA model to project the fuel economy for the 40 different fuel economy modeling scenarios shown in Table 4-3. The results of fuel economy modeling exercise are shown in Table 5-1 in two different metrics.

The first fuel economy metric is simply the vehicle mpg value. For both the 4WD large SUV and midsize car matrices, the top set of data gives the projected combined city/highway fuel economy value for each of the various technology packages. For example, the 4WD large SUV

with conventional gasoline engine and conventional transmission has a projected fuel economy value of 17.2 mpg and the midsize car with conventional gasoline engine and conventional transmission is projected to have a combined fuel economy of 29.0 mpg. These two technology packages represent the baseline values for calculating the percent improvement of the other vehicle technology packages.

Table 5-1: Fuel Economy Modeling Results

Large Sport Utility Vehicle (4WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	17.2	19.4	20.0	20.2	23.0
Clean Diesel Engine	23.6	27.0	27.6	27.2	32.0
Gasoline Variable Displacement Engine	19.7	22.5	22.8	22.8	24.1
Clean Diesel Variable Displacement Engine	26.8	30.9	31.3	31.2	34.6
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	base	13%	17%	18%	34%
Clean Diesel Engine	37%	57%	61%	59%	86%
Gasoline Variable Displacement Engine	15%	31%	33%	33%	40%
Clean Diesel Variable Displacement Engine	56%	80%	82%	82%	101%

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	29.0	32.4	34.1	36.0	43.5
Clean Diesel Engine	39.8	48.5	50.2	50.0	59.9
Gasoline Variable Displacement Engine	35.4	40.7	42.0	44.1	45.4
Clean Diesel Variable Displacement Engine	46.9	57.5	59.3	58.7	64.3
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	base	12%	18%	24%	50%
Clean Diesel Engine	37%	67%	73%	73%	107%
Gasoline Variable Displacement Engine	22%	41%	45%	52%	57%
Clean Diesel Variable Displacement Engine	62%	99%	105%	103%	122%

* Fuel economy values are laboratory values and are about 15% higher than real-world projections.

The second fuel economy metric in Table 5-1, shown in the bottom set of data for the 4WD large SUV and midsize car classes, is the percent fuel economy improvement over the baseline vehicles described above. Typically, the percent fuel economy improvement is the easiest way to compare the relative fuel economy improvement potential of various technology packages.

As Table 5-1 shows, the 4WD large SUV conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy is projected to be 34% more efficient than the base SUV, raising the large SUV fuel economy from 17.2 mpg to 23.0 mpg. As discussed earlier, the specific design of this configuration was optimized for simplicity and low cost, rather than maximum fuel economy, and this value could be significantly higher if the design were optimized for maximum fuel economy. For the full range of vehicle technology packages, fuel economy is projected to improve by from 13-101% for the 4WD large SUV, and from 12-122%

for the midsize car. It should be noted that rounding can sometimes lead to some slight differences between the values in tables such as Table 5-1 and some of the spreadsheet values shown in the appendices as well as some of the sample calculations.

Several trends are apparent from Table 5-1:

> the single change of replacing a conventional gasoline engine with a clean diesel engine is projected to increase fuel economy by 37% for both 4WD large SUVs and midsize cars
> the single change of replacing a conventional gasoline engine with a variable displacement engine is projected to increase fuel economy by 15-22%
> changing from a conventional engine to an engine with the dual characteristics of clean diesel and variable displacement is projected to increase fuel economy by 56-62%
> the single change of adding a mild hydraulic hybrid drivetrain is projected to increase fuel economy by 12% (midsize car with engine-on strategy) to 18% (midsize car with engine-off strategy)
> the single change of moving to a full hydraulic hybrid vehicle is projected to increase fuel economy by 18% (4WD large SUV with engine-on strategy) to 50% (midsize car with engine-off strategy)
> the mild hydraulic hybrid drivetrain with engine-on strategy, the mild hydraulic hybrid drivetrain with engine-off strategy, and the full hydraulic hybrid drivetrain with engine-on strategy all yield fairly similar fuel economy improvements; the full hydraulic hybrid drivetrain with engine-off strategy gives the highest fuel economy improvements for any of the hydraulic-only drivetrains
> there is a relatively small fuel economy benefit of adding a variable displacement engine to a vehicle that has a full hydraulic hybrid drivetrain with engine-off strategy (there would be additional benefits associated with reduced engine on/off and off/on cycling and a less costly accessory drive system)
> the maximum improvement for the 4WD large SUV is a 101% improvement for the technology package involving an engine with both clean diesel and variable displacement and a full hydraulic hybrid drivetrain with engine-off strategy
> the maximum improvement for the midsize car is a 122% improvement for the technology package involving an engine with both clean diesel and variable displacement and a full hydraulic hybrid drivetrain with engine-off strategy

The table in Appendix H reports the fuel economy modeling results for the city and highway test cycles separately, which is of particular interest for hydraulic hybrid drivetrains which typically achieve much greater fuel economy improvement in city driving.

Comparisons can be made between these modeling results and the literature for 5 of the 40 technology scenarios: the baseline conventional gasoline engine and conventional transmission for both large SUVs and midsize cars, the clean diesel engine for both large SUVs and midsize cars, and the mild hydraulic drivetrain with engine-on strategy for large SUVs. As discussed earlier in this section, the model results for the combined city/highway fuel economy values for the baseline large SUV and midsize car of 17.2 and 29.0 mpg, respectively, compare favorably with the sales-weighted values of 16.9 and 28.9 mpg that were calculated for large SUVs and midsize cars from the formal EPA fuel economy certification data base. The projected fuel

economy improvements for clean diesel engines of 37% for both large SUVs and midsize cars are in line with industry statements that diesel vehicles are typically 30-40% more fuel efficient than comparable gasoline vehicles.[xii][xiii] Finally, Ford Motor Company has reported a 24% fuel economy improvement over the EPA city driving cycle for a large SUV with a conventional gasoline engine and a mild hydraulic drivetrain with engine-on strategy.[xiv] This compares well with the model projection of a 26% improvement for this same configuration (see Appendix H for the separate urban and highway fuel economy projections).

6.   Projection of Incremental Vehicle Cost

6.1   <u>Overview</u>

This section projects the cost increases that would likely be associated with the vehicle technology packages, identified in Section 4 and modeled for fuel economy impacts in Section 5.

It is very important to emphasize the underlying assumptions involved in the cost projections. The central assumption is that the cost projections are for a longer-term scenario where the economies of scale (component production volumes of one million units per year) 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 other technology studies. These cost projections are not relevant to a transition period where the advanced technology is initially commercialized (and annual component production volumes might only be in the thousands or tens of thousands). During a transition period, there will be many relevant cost factors that will be nonexistent or negligible in a mature market, including but not limited to: recovery of research and development expenditures; initial investment in component manufacturing facilities, vehicle assembly plants, and dealer and maintenance infrastructure; engineering time for vehicle design modifications to accommodate the new technology; and higher per unit costs due to lower economies of scale. Accordingly, the transition costs would be higher than the long-term cost projections for the advanced technologies in this study. On the other hand, it is also a basic tenet of automotive production that, once a technology achieves market maturity, there is overwhelming economic incentive to continue to invest in research to continually reduce cost. So it is also likely that the cost projections in this report underestimate the potential to reduce cost 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 first reach high levels.

For the advanced engine technologies (clean diesel engines and variable displacement engines), we rely on cost analyses and projections provided by FEV Engine Technology, Inc., a major engine design and consulting company headquartered in Germany and with a US office in Auburn Hills, Michigan. For diesel engine emission control systems, we rely on projections from EPA engineers involved in our in-house technology assessment program. For the advanced drivetrain technologies (mild hydraulic hybrids and full hydraulic hybrids), we use system designs from EPA engineers who have been leaders in hydraulic hybrid research and development for the last decade, and we utilize a methodology based on changes in component mass and complexity relative to baseline vehicles. For vehicle technology packages that involve both engine and drivetrain changes, we combine the projections from FEV and EPA engineers.

6.2   <u>Clean Diesel Engines</u>

FEV was contracted to project the incremental cost of a diesel engine compared to a

conventional gasoline engine for this study. The three most important assumptions underlying FEV's analysis were:

> the analysis only included changes directly and indirectly associated with the engine and did not, for example, include any potential incremental costs associated with diesel emissions aftertreatment

> the analysis assumed a mature diesel engine production environment where there are equal economies of scale for diesel engines and gasoline engines, and where the relative profit from diesel engines are equal to that from gasoline engines

> the diesel and gasoline vehicles are designed to have equal performance in general, and equal 0-to-60 mph acceleration times and equal vehicle ranges in particular

FEV's cost estimates for a clean diesel engine are described in the report *Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks* (see Appendix I). For both the large SUV and the midsize car, the primary incremental costs associated with the diesel engine are due to high-pressure common rail fuel injection and a variable geometry turbocharger. As shown in Table 10 of Appendix I, FEV projected the incremental cost of the fuel injection system for a large SUV to be $735. (Taking into account a projected gasoline SUV fuel injection system cost of $245, FEV projects a total diesel fuel injection cost of $980 for a large SUV. Similarly, adding a gasoline midsize car fuel injection cost of $165 to the $465 shown in Table 9 of Appendix yields a total diesel fuel injection cost of $630 for a midsize car.) FEV estimated the mature incremental manufacturing costs of a clean diesel engine to be $1042 for a large SUV and $739 for a midsize car.

It is generally accepted that, based on current state-of-the-art engine technologies, emissions control systems for diesel vehicles to meet Tier 2 emission levels will be more expensive than those for comparable gasoline vehicles. There is a major industry effort underway to develop viable and cost-effective diesel engine emission control systems, and it is impossible at this time to project the likely cost impacts of such systems with any precision. Nevertheless, based on the best information regarding emission control technology at this time, EPA engineers provided projections of this incremental cost: $282 for large SUVs and $218 for midsize cars. EPA assumes that there would be no fuel economy penalty associated with diesel emissions control systems. EPA is monitoring progress in this area and will modify these projections as more information becomes available.

An aggregate incremental retail cost to the consumer will include the incremental engine cost plus the incremental emissions control cost plus a retail markup factor. In regulatory development, EPA uses a retail price equivalent (RPE) mark-up factor of 1.26 to adjust a manufacturing price increase to a retail price increase. This factor accounts for manufacturer overhead and profit. The total incremental retail cost to the consumer for a large SUV, assuming no change in fuel tank size, is the $1042 incremental engine cost plus the $282 incremental emissions control cost, times the 1.26 markup factor, or a total of $1668. The total incremental retail cost to the consumer for a midsize car, assuming no change in fuel tank size, is the $739 incremental engine cost plus the $218 incremental emissions control cost, times the 1.26 markup factor, or a total of $1206.

6.3   Variable Displacement Engines

FEV was also contracted to project the incremental cost of a variable displacement engine compared to a conventional gasoline engine for this study. The key underlying assumption in this analysis was that there would be no other changes in engine design or performance other than those necessary to allow the engine to operate as a variable displacement engine.

FEV estimated the incremental manufacturing cost of a 5.0-liter, V-8 variable displacement engine, relative to a conventional gasoline engine of the same displacement, in the report *Variable Compression Ratio and Variable Displacement Engine Cost* (see Appendix J). For conventional drivetrains, FEV estimated the mature incremental manufacturing cost of the 5.0-liter variable displacement engine to be $431 ($278 for incremental changes to the engine itself plus an additional $153 due to the more complex control system plus associated parts). This estimate for a 5.0-liter, V-8 engine is assumed to be applicable to the slightly larger 5.4-liter, V-8 engine used for the large SUV scenario in this report. Applying the EPA RPE markup of 1.26 to FEV's projected incremental manufacturing cost for a variable displacement engine yields incremental consumer costs of $543 for a large SUV with no change in fuel tank size. Adjusting fuel tank size for equivalent range, the total incremental cost of a variable displacement engine in a large SUV with a conventional transmission drops by $11 to $532. For hydraulic drivetrains, where two intermediate bearing assemblies could be deleted, the FEV estimate is $406 for the manufacturing cost of a variable displacement engine for a large SUV. The retail price equivalent for the variable displacement engine only in combination with the hydraulic drivetrain for a large SUV is $512.

FEV did not project the cost of a variable displacement engine for the midsize car scenario. EPA calculated a projected cost for a 3.0-liter, V-6 variable displacement engine based on the FEV projection for the 5.0-liter, V-8 engine discussed above. EPA assumed that most of the incremental costs for modifying a conventional engine to be a variable displacement engine would be proportional to engine weight, but that certain costs (e.g., control system plus associated parts) would remain the same regardless of displacement. One additional issue with a variable displacement V-6 engine is whether a balance shaft or some other modification will be necessary for NVH reasons, particularly vibration. In fact, it may be possible that variable compression is a preferred engine design for a midsize car application, and FEV projected a lower incremental cost for a variable compression car engine than for a variable displacement car engine. Nevertheless, assuming a variable displacement engine without a balance shaft, EPA calculated a projected incremental manufacturing cost of $340 for a 3.0-liter, V-6 engine for the midsize car scenario. Applying the 1.26 retail price equivalent markup factor yields a consumer cost of $428 assuming equal fuel tank size. Adjusting fuel tank size for equivalent range yields a total incremental cost for a variable displacement engine in a midsize car with a conventional transmission of $412. The consumer cost for a variable displacement engine only in combination with a hydraulic hybrid drivetrain is again slightly lower, or $396.

6.4   Hydraulic Hybrid Drivetrains

For hydraulic hybrid drivetrains, EPA employed a simple first order cost methodology that was patterned after what we were able to project as the estimated cost of similar vehicle chassis, engine and transmission components. Others have employed similar cost methodologies that are

somewhat more detailed. These analyses specifically breakout individual component manufacturing costs and then try to identify and apply the appropriate overhead, profit and mark-up costs (such as in the EPRI study – *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, July 2001). However, since we did not have access to proprietary data for overhead, profit and markup (as adjusted for COLA, manufacturing improvements and current material costs), we projected component system cost values for three vehicle subsystems (transmission, engine, and chassis) using detailed vehicle cost data from a typical 1990 Big-Three vehicle scaled to 2002 retail costs. These component costs were then adjusted to retail price by applying the same retail price equivalent (RPE) factor, 1.26, that we use when implementing new emission regulations. The RPE factor accounts for manufacturer overhead and profit. While a more rigorous analysis may give more "precise" costs for individual components, we felt that when aggregated together this method would work well to show the magnitude of the incremental cost changes.

The key input for the EPA cost projections is the detailed description of the hydraulic hybrid drivetrains in Section 3. That section described in considerable detail plausible designs for four hydraulic hybrid configurations: full hydraulic hybrid 4WD SUV, mild hydraulic hybrid 4WD SUV, full hydraulic hybrid car, and mild hydraulic hybrid car. Specifically, for each of these hydraulic hybrid configurations, Section 3 provided a comprehensive list of every component that would be added to the baseline vehicle and every component that could be deleted from the baseline vehicle, as well as the mass for each of these components.

It is important to emphasize that, particularly for a 4WD large SUV with full hydraulic hybrid drivetrain, several components can be deleted from the conventional vehicle (most notably the automatic transmission and transfer case), which greatly reduces the incremental cost that would otherwise be associated with a hydraulic drivetrain.

The individual mass values for each of these components, both those added to and those deleted from the baseline vehicles, provides the starting point for the cost analysis in this section. The supplier price of each component is estimated from the weight of the component multiplied by price per unit of weight. The price per unit weight varies depending on the complexity of the component. There are three major price per weight figures used in this analysis, based on components that are used in three major vehicle subsystems: transmission, engine, and chassis.

For some components that are not in a conventional vehicle, such as a hydraulic pump/motor, we examined the overall manufacturing complexity, the material composition, and the design in order to group this component in one of the three major vehicle subsystems. For example, the hydraulic pump/motors are made primarily of cast iron and steel, with some bronze and aluminum components. The manufacturing complexity for a pump/motor, which contains pistons, connecting rods, cylinder bores, rotating shafts, roller and bronze bearings, and electronic components and sensors associated with displacement and mode control, is similar to the complexity found in automotive engines. Therefore, we used the engine price per weight factor for estimating the cost of the hydraulic pump/motors.

Specific price per weight values for these three vehicle subsystems (transmission, engine, and chassis) were derived using cost data from a typical 1990 Big-Three vehicle adjusted to 2002

costs *[vehicle configuration specs: 3.0L, V6, 4-speed automatic, fuel injected, front wheel drive]*. Appendix K shows the original cost by component for the 1990 vehicle. The cost and weights for the three component systems of interest were taken from Appendix K and are provided below in the first two columns of Table 6-1. The 1990 costs were adjusted to a 2002 model year vehicle by multiplying by the ratio of 1990 to 2002 Manufacturer's Suggested Retail Price (MSRP). The sample vehicle's MSRP is $12,944 while a 2002 version of that model has an estimated MSRP of $20,000. The resulting price per kg by component system for a current vehicle is listed in the last column of Table 6-1. The complexity category based on transmission components is the most complex, with a price of $10.45 per kg, the category based on engine components uses a value of $9.11 per kg, and the category based on chassis components is the least complex at a price of $7.19 per kg.

Table 6-1: Price per Weight ($/kg)

Component System	Weight kg	1990 Manufacturer Cost	2002 Manufacturer Cost	$/kg
Total Transmission	64	$431	$666	$10.45
Total Engine	274	$1616	$2497	$9.11
Total Chassis	527	$2453	$3790	$7.19

For each of the hydraulic hybrid drivetrains, most of the components (whether added to or deleted from the baseline vehicle) were grouped into one of these three "complexity categories" based on the three price per mass factors above. However, a few components such as hydraulic accumulators and various fluids were considered unique enough that separate cost projections are developed. The prices per kg of hydraulic and transmission fluids are based on publicly available cost information. EPA engineers who are experienced in the design and development of hydraulic systems provided the price per kg for accumulators. The accumulator costs assume high volume production and are optimized for lighter materials as discussed in Section 3.

All components, both those added to and those deleted from baseline vehicles, were grouped into the three main complexity categories based on engineering judgment. The changes in mass were then multiplied times the price per unit mass for each component added or deleted from the baseline vehicle, allowing a total incremental cost projection for each of the cost scenarios.

6.5   Adjustment in Fuel Tank Size

As was shown in Table 5.1, all of the vehicle technology packages in this study have fuel economy values higher than the base large SUV and base midsize car equipped with conventional gasoline engines and conventional mechanical transmissions. Therefore, if fuel tank size were held constant for the large SUV and midsize car scenarios with advanced vehicle technologies, all of the advanced technology vehicles would have higher vehicle range (miles that can be driven on a full tank of fuel). Designs were chosen that would have comparable vehicle range, so the fuel tank could be somewhat smaller. The reduction in fuel tank size and weight was calculated as proportional to the increase in projected fuel economy for each vehicle technology package. Since fuel tanks are a very small fraction of a vehicle's total weight, the resulting cost benefits were small.

6.6   Example

The cost modeling example focuses on the same technology package used previously in Section 5—the 4WD large SUV with conventional gasoline engine and full hydraulic hybrid drivetrain with engine off strategy.

Table 3-8 lists all of the components that would be added to and removed from a baseline 4WD large SUV in order to transform the design into a 4WD large SUV with conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy. The major additions are:

> 3 pump motors (one 135 cc unit and two 110 cc units) - engine, front axle, rear axle
> 2 accumulators (each 15 gallons) - high pressure, low pressure
> a 2-speed planetary gearbox
> all of the fluids, fittings, hoses, etc. in the hydraulic circuit

The major component deletions for the 4WD large SUV are:

> conventional transmission
> transfer case
> downsized engine

The calculation of the cost of the 135 cc pump motor unit is illustrated below. The pump motor has a mass of 45.7 kg. Pump motors are considered to be similar to engines in terms of the complexity of manufacturing. Therefore, $9.11 is used as the price per kg for a pump motor. The supplier or manufacturing price of the pump motors is calculated as:

Supplier's Price = 45.7 kg * $ 9.11 per kg = $ 416

A similar process is followed for all the components listed in Table 3-8 for the 4WD SUV's full hydraulic hybrid drivetrain. Table 6-2 gives the total supplier price for the removed and added components. The total supplier's price is then multiplied by the RPE factor. Based upon this method of calculation, the total retail cost increment of the hydraulic hybrid components is $575 ($3,352 for the additional hybrid components minus $2777 for the conventional transmission that is deleted).

Table 6–2: Incremental Costs for Large 4WD SUV with Full Hydraulic Hybrid Drivetrain and Engine-Off Strategy

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
power steering system (pump, reservoir, steering gear)	-17.3	$9.11	-$158
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system	15.6	$9.11	$142
hydraulic driven alternator	4.5	$9.11	$41
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.4	$7.19	-$17
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**84.8**		**$457**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$575**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**31.6%**
base mpg	14.63

6.7   Results

Table 6-3 provides a summary of the incremental new vehicle costs for the 38 new technology scenarios along with the cost per percent fuel economy improvement, a metric often used in the industry.

Table 6-3: Incremental New Vehicle Costs

Large Sport Utility Vehicle (4WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$1,321	$1,336	$552	$575
Clean Diesel Engine	$1,668	$2,983	$2,999	$2,217	$2,241
Gasoline Variable Displacement Engine	$532	$1,822	$1,838	$1,055	$1,084
Clean Diesel Variable Displacement Engine	$2,195	$3,487	$3,504	$2,721	$2,749
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$100	$81	$32	$17
Clean Diesel Engine	$45	$52	$49	$38	$26
Gasoline Variable Displacement Engine	$36	$59	$56	$32	$27
Clean Diesel Variable Displacement Engine	$39	$44	$43	$33	$27

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$998	$1,009	$1,114	$1,133
Clean Diesel Engine	$1,206	$2,182	$2,195	$2,307	$2,330
Gasoline Variable Displacement Engine	$412	$1,373	$1,386	$1,493	$1,525
Clean Diesel Variable Displacement Engine	$1,613	$2,567	$2,581	$2,692	$2,722
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$83	$57	$46	$23
Clean Diesel Engine	$32	$32	$30	$32	$22
Gasoline Variable Displacement Engine	$19	$34	$31	$28	$27
Clean Diesel Variable Displacement Engine	$26	$26	$25	$26	$22

Several key trends from Table 6-3 are:

➢ the lowest-cost advanced technology packages involve either the single change of replacing a conventional gasoline engine with a variable displacement engine in either the 4WD large SUV or midsize car, or the single change of replacing the conventional transmission of a 4WD large SUV with a full hydraulic hybrid drivetrain (either engine-

on or engine-off strategy), all of which have incremental costs between $412-$575

➤ the single change of replacing a conventional gasoline engine with a clean diesel engine is projected to cost $1206 (midsize cars) to $1668 (large SUVs)

➤ changing from a conventional engine to an engine with the dual characteristics of clean diesel and variable displacement is projected to increase cost by $1613 (midsize cars) to $2195 (large SUVs)

➤ the single change of adding a mild hydraulic hybrid drivetrain is projected to increase cost by approximately $1000 (midsize car) to $1300 (large SUV)

➤ the single change of moving to a full hydraulic hybrid is projected to increase new vehicle cost by from about $600 (4WD large SUV) to $1100 (midsize car); the reason the incremental cost is less for the larger vehicle is that much more expensive components can be deleted from the 4WD large SUV baseline vehicle with the addition of a full hydraulic hybrid design

➤ for 4WD large SUVs, the full hydraulic hybrid package always has a lower incremental cost than the mild hydraulic package, again because more expensive components can be deleted; on the other hand, for midsize cars, the full hydraulic package is always slightly more expensive than the mild hydraulic hybrid package

➤ the highest-cost advanced technology package for the 4WD large SUV is the clean diesel with variable displacement engine and mild hydraulic hybrid drivetrain, with an incremental cost of approximately $3500; the highest-cost advanced technology package for the midsize car is the clean diesel with variable displacement engine and full hydraulic hybrid drivetrain, with an incremental cost of about $2700

➤ the cost per percent fuel economy improvement ranges from $17 (4WD large SUV with conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy) to $100 (4WD large SUV with conventional gasoline engine and mild hydraulic hybrid drivetrain with engine-on strategy)

Appendix L contains the full spreadsheets for each of the 38 new technology cost scenarios. Some of the values in the body of the report will differ slightly from values in the spreadsheets due to rounding.

7. Projection of Payback Period and Lifetime Savings

7.1   Overview

Payback refers to the number of years that it takes for one or more consumers to offset in operating savings the extra cost that they paid for the new technology when they bought the vehicle. Lifetime savings is the total net savings in dollars (total operating savings minus higher initial new vehicle cost) that consumers will realize over the typical lifetime of a vehicle. The operating savings associated with the advanced technology powertrains in this study are primarily fuel savings due to higher vehicle fuel economy, plus brake maintenance savings with hydraulic hybrid drivetrains (there may be other operating costs and/or savings associated with advanced technologies, but no others are included here).   The calculation of both consumer payback and lifetime savings are relatively straightforward, and relies heavily on the results of the fuel economy modeling and the cost projections discussed previously. While these calculations require spreadsheet calculations, they do not require sophisticated modeling.

Two of the key inputs into the calculation of consumer payback and lifetime savings are the fuel economy of the base vehicle without the new fuel economy technology and the fuel economy of the vehicle with the new fuel economy technology. The projected fuel economies for all the vehicle technology packages, in mpg, are shown in Table 5-1 (the values in Table 5-1 are unadjusted fuel economy values, and are adjusted downward by about 15% for purposes of the payback analysis in this section to account for laboratory-to-road shortfall, to better reflect the fuel economy that a consumer would achieve in the real world).

A third input is a profile of miles traveled per year as consumer payback with a fuel economy technology will be much quicker and lifetime savings will be greater for a consumer that drives high annual mileage than for a consumer that drives low annual mileage. For the midsize car scenario, this analysis uses the official annual miles traveled profile for cars from EPA's MOBILE6 emissions model used for motor vehicle emission regulation and air quality analyses. This profile projects that the typical car travels about 14,900 miles in its first full year of operation and then travels fewer miles in each succeeding year, falling to 12,200 miles in the fifth year, 9500 miles in the tenth year, and 7700 miles in year 14. For the large SUV scenario, this analysis uses the MOBILE6 profile for light-duty trucks, which projects about 20,000 miles for the first year of operation, dropping to 15,300 miles in the fifth year, 11,000 miles in the tenth year of operation, and 8400 miles in the 14th year.

A fourth input is fuel price, as payback will be quicker and lifetime savings will be greater at a higher fuel price than at a lower price. Predicting future fuel prices is, of course, a difficult task. Just in the last three years, consumers in many parts of the country have paid as little as $1.00 per gallon and as much as $2.00 per gallon for gasoline. As this report is being written, average nationwide gasoline price is approximately $1.50 per gallon. Diesel fuel is typically somewhat cheaper than gasoline. This paper uses a flat $1.50 per gallon for both gasoline and diesel fuel. Obviously, lower future fuel prices would raise the payback periods and decrease lifetime savings and higher future fuel prices would lower the payback periods and increase lifetime savings.

A fifth input is an appropriate discount rate. The rationale for use of a discount rate is that a dollar is worth more to a consumer today than 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 benefit from fuel and/or brake savings over time, use of a discount rate in the calculations of payback and lifetime savings is appropriate. For this analysis, EPA uses the 7% annual discount rate that is recommended by the Office of Management and Budget (OMB) for monetary costs and savings associated with motor vehicle emissions regulations. Based on OMB guidance, savings in the first year of vehicle operation are not discounted. The savings in the second year are reduced by 7%, the savings in the third year are reduced by approximately 14%, etc.

The final inputs, which are relevant only for hydraulic hybrid powertrains, relate to the frequency and cost of brake maintenance. Because hydraulic hybrid vehicles will utilize regenerative braking for the majority of their braking, as opposed to friction braking on conventional vehicles, owners of hydraulic hybrid vehicles will need far less brake maintenance. See Appendix M for a detailed description of the methodology used to project brake savings. The key assumption is that brake maintenance will be reduced by 70% for a vehicle with a hydraulic hybrid drivetrain.

A spreadsheet was developed that uses the above factors to calculate the annual discounted fuel savings each year associated with each vehicle technology package. The "payback year" is then the first year during which the cumulative, discounted operating savings exceeds the initial cost increase associated with the fuel economy technology. Lifetime savings are the net savings over the life of the vehicle, i.e., operating savings minus the higher initial vehicle cost.

7.2   Example

This section shows how the payback year and lifetime savings are calculated for the same case study as used in previous sections: the 4WD large SUV with conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy.

MOBILE6 projects that a truck travels 19,978 miles in its first year of operation. We assume that 55% of this travel will entail city driving, or 10,988 miles. From Table H-1, a "base" 4WD large SUV with conventional engine and conventional transmission is projected to have a laboratory city fuel economy value of 14.9 mpg. This laboratory value must be reduced by 10% to yield a real world city fuel economy value, so the 14.9 mpg yields a real world city fuel economy value of 13.4 mpg. A typical consumer traveling 10,988 miles with a fuel economy of 13.4 mpg would consume 820 gallons of gasoline. The remaining 45% of miles, or 8990 miles, is assumed to be highway driving. From Table H-1, the laboratory highway fuel economy value for the base 4WD large SUV is 21.2 mpg. Reducing this highway value by 22% yields a real world highway fuel economy value of 16.5 mpg. A typical consumer traveling 8990 miles with a fuel economy of 16.5 mpg would consume 545 gallons of fuel. So, total city plus highway fuel consumption in the first year would be 820 plus 545 gallons or 1365 gallons. At $1.50 per gallon and no discounting in the first year, the consumer would have a total fuel cost of $2048. So, the owner of a "base" 4WD large SUV would spend $2048 on fuel in the first year.

The same set of calculations for a large SUV with full hydraulic hybrid drivetrain and engine-off strategy yields a first-year fuel consumption of 1040 gallons of gasoline in the first year. At $1.50 per gallon and no discounting in the first year, the consumer would have a total fuel cost of $1560.

The fuel savings due to the addition of the full hydraulic hybrid drivetrain with engine-off strategy for a 4WD large SUV is the difference between the $2048 a consumer would spend with the "base" vehicle and the $1560 the consumer would spend with the full hydraulic hybrid drivetrain with engine off. This difference is $488 for the first year of operation. This value is slightly different than the $492 value shown in the spreadsheet table in Appendix N due to rounding.

Table 6-3 shows that the incremental cost of the conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy for the 4WD large SUV is $575. Carrying out the same calculations above for the second year shows that the owner of a 4WD large SUV would accrue cumulative fuel savings of $575 sometime during the third month of the second year, and therefore would achieve consumer payback in 1.2 years.

Since payback was achieved after just 1.2 years in this example, prior to the time when any brake savings would be realized, there was no need to take brake maintenance into account for this payback calculation.

This is the only one of the advanced technology packages that offers payback as early as during the second year. For each of the other cases, the discounted fuel savings and brake savings, if any, are calculated for each succeeding year, added to the savings of the previous years, and compared to the incremental cost until such time that the cumulative discounted operating savings exceed the incremental cost, and that is the "payback year."

For the calculation of lifetime savings, we must sum lifetime fuel savings, lifetime brake savings (if any), and higher vehicle cost. For the 4WD large SUV with full hydraulic hybrid and engine off strategy, we show above that the first-year fuel savings would be $488. The fuel savings for each succeeding year is smaller and smaller, both because the annual vehicle miles traveled is less each year and because future savings are discounted by 7% per year. For example, the discounted fuel savings for this 4WD large SUV with a full hydraulic hybrid drivetrain with engine-off strategy drops to just $86 in the fourteenth year, the last year in our analysis. For the 14 years, the owner(s) of such a vehicle would save $3319 in discounted fuel savings.

Because of the full hydraulic hybrid drivetrain, brake wear would be reduced by approximately 70%. This means that pads and rotors will need less frequent service. For a typical large SUV, this means less brake maintenance at four different times over its lifetime. Based on the methodology in Appendix M, the sum of these discounted brake savings for a 4WD large SUV with a full hydraulic hybrid drivetrain is $783. Total operating savings is the $3319 in discounted fuel savings plus the $783 in discounted brake savings, or a total of $4102. The lifetime savings is this $4102 in operating savings minus the $575 in higher vehicle cost, or $3527.

7.3   Results

Table 7-1 shows the payback year and lifetime savings for the 38 new technology scenarios. The units for payback are years, the units for lifetime savings are dollars.

Table 7-1: Projected Payback Years and Lifetime Savings

Large Sport Utility Vehicle (4WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	4.9	4.4	2.0	1.2
Clean Diesel Engine	3.6	4.6	4.5	3.2	2.5
Gasoline Variable Displacement Engine	2.3	4.2	4.1	2.1	2.0
Clean Diesel Variable Displacement Engine	3.5	4.5	4.5	3.3	2.9
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	$955	$1,282	$2,159	$3,527
Clean Diesel Engine	$2,060	$2,733	$2,880	$3,559	$4,786
Gasoline Variable Displacement Engine	$1,175	$2,067	$2,202	$2,975	$3,472
Clean Diesel Variable Displacement Engine	$2,738	$3,318	$3,401	$4,145	$4,852

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	9.6	6.5	6.1	4.2
Clean Diesel Engine	6.7	6.9	6.5	7.1	6.0
Gasoline Variable Displacement Engine	2.9	6.0	6.0	6.0	5.8
Clean Diesel Variable Displacement Engine	6.2	6.7	6.5	7.1	6.4
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	$70	$320	$525	$1,381
Clean Diesel Engine	$583	$817	$933	$808	$1,403
Gasoline Variable Displacement Engine	$756	$862	$982	$1,101	$1,182
Clean Diesel Variable Displacement Engine	$895	$1,045	$1,129	$986	$1,231

Some key trends from Table 7-1 are:

➢ The best payback is 1.2 years for the 4WD large SUV with a conventional gasoline engine and full hydraulic hybrid drivetrain with engine-off strategy; the worst payback is nearly 10 years for the midsize car with conventional gasoline engine and mild hydraulic hybrid drivetrain with engine-on strategy
➢ the maximum lifetime savings are nearly $5000 for those 4WD large SUV packages with both clean diesel engines and full hydraulic hybrid drivetrains with engine-off strategies

- for every technology package, the 4WD large SUV has a lower payback period and higher lifetime savings than the midsize car
- all of the 4WD large SUV technology packages payback in 1-4 years, except for those large SUV packages with mild hydraulic hybrid drivetrains, and these latter all have paybacks of 4-5 years; every 4WD large SUV package yields lifetime savings of at least $900 and many large SUV packages yield lifetime savings of $3000 or more
- the best payback for the midsize car is 2.9 years for the variable displacement engine with conventional transmission; nearly all of the other midsize car packages payback in 4-7 years; most of the midsize car packages provide lifetime savings of $500-1400

Appendix N gives the spreadsheets with the data underlying the results shown in Table 7-1.

End Notes - References

[i] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Research Council, 2002.

[ii] Eaton Corporation Unveils Breakthrough Fuel Savings Technology at 2002 North American International Auto Show, Eaton Corporation Press Release, January 7, 2002.

[iii] Clean Diesels Dispel Outdated 'Dirty' Image, General Motors website at www.gm.com, July 30, 2002.

[iv] Diesel Finds Liberty in North America, Automotive Engineering Magazine, January 2003.

[v] 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.

[vi] Assessing New Diesel Technologies, presentation by Charles L. Gray, Jr., U.S. Environmental Protection Agency, at MIT Light Duty Diesel Workshop, November 20, 2002.

[vii] GM's 'Displacement on Demand' V8 Engine Improves Truck Fuel Economy, General Motors website at www.gm.com, July 30, 2002.

[viii] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Research Council, 2002.

[ix] Saab Reveals Unique Engine Concept That Offers High Performance and Low Fuel Consumption, Saab website at www.saabnet.com, March 2000.

[x] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Research Council, 2002.

[xi] An HCCI Engine: Power Plant for a Hybrid Vehicle, R.Sun, R. Thomas and C. Gray, Jr., U.S. Environmental Protection Agency, Society of Automotive Engineers Paper 2004-01-0933 (to be released at the SAE Congress in March 2004).

[xii] Clean Diesels Dispel Outdated 'Dirty' Image, General Motors website at www.gm.com, July 30, 2002.

[xiii] Diesel Finds Liberty in North America, Automotive Engineering Magazine, January 2003.

[xiv] Hydraulic Power Assist – A Demonstration of Hydraulic Hybrid Vehicle Regenerative Braking in a Road Vehicle Application, R.P. Kepner, Ford Motor Company, Society of Automotive Engineers Paper 2002-01-3128.

Appendices

Appendix A: Sensitivity Analysis with Reduced Roadload Scenarios

A number of factors contribute to the overall energy demand of a vehicle. The three most important parameters are the weight of the vehicle, the aerodynamic drag of the vehicle, and the tire rolling resistance. Vehicle weight is an overt variable in the modeling discussed throughout this report, and unique vehicle weights were projected and utilized for each of the vehicle technology packages. Vehicle aerodynamic drag and tire rolling resistance are the other two major factors in the roadload force equation, which gives the amount of force required to propel a vehicle as a function of vehicle speed. All of the results in the body of this report assume "base roadload" values representing today's top-selling production vehicles. This Appendix presents a sensitivity analysis for "reduced roadload" where projections for each of the 40 vehicle technology scenarios are made assuming that roadload values are approximately 20% lower than today's production levels.

The base roadload case was defined in Section 5 as the sales-weighted average roadload specifications for today's top-selling vehicles in the large SUV and midsize car classes. The automobile manufacturers supplied the base roadload equations to EPA as part of the submission for the 2002 vehicle emissions certification program. For the reduced roadload case, the base roadload specifications were lowered by 20%.

The cost of a 20% reduction in the roadload specifications was approximated by using a cost estimate for the reduction in both vehicle coefficient of drag and tire rolling resistance by the National Academy of Sciences/National Research Council (NAS/NRC). In *Effectiveness of Corporate Average Fuel Economy (CAFE) Standards*, the NAS/NRC estimated an average cost of $105 to reduce both coefficient of drag and tire rolling resistance by 10% (this cost already included NAS' retail price equivalent markup factor and no further adjustment was made for this analysis).[2] This estimate was doubled to $210 for this sensitivity analysis to approximate the costs of a nominal 20% reduction in aerodynamic drag and rolling resistance.

Tables A-1 and A-2 provide summaries of the absolute fuel economy, fuel economy improvement, incremental new vehicle cost, payback and lifetime savings for the reduced roadload scenarios for large SUV and midsize car classes. These tables are in the same format as those for the base roadload scenarios in the Executive Summary. Though there are a few exceptions, in general the reduced roadload scenarios yield higher absolute fuel economy levels, higher fuel economy improvements, higher incremental vehicle costs, lower payback periods, and higher lifetime savings relative to the base roadload results in Tables ES-1 and ES-2.

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[2] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Research Council, 2002.

Table A-1:
Key Projections for Large 4WD SUV Modeling Scenarios with Reduced Roadload

Reduced Roadload Case

Large Sport Utility Vehicle (4WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	18.6	21.5	22.3	22.9	27.2
Clean Diesel Engine	25.7	30.1	30.8	31.4	38.2
Gasoline Variable Displacement Engine	22.0	25.7	26.2	26.5	28.7
Clean Diesel Variable Displacement Engine	29.7	35.3	35.9	36.4	41.2
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	8%	25%	30%	33%	58%
Clean Diesel Engine	50%	75%	80%	83%	123%
Gasoline Variable Displacement Engine	28%	50%	53%	54%	67%
Clean Diesel Variable Displacement Engine	73%	106%	109%	112%	140%
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	$210	$1,531	$1,546	$762	$785
Clean Diesel Engine	$1,878	$3,193	$3,209	$2,427	$2,451
Gasoline Variable Displacement Engine	$742	$2,032	$2,048	$1,265	$1,294
Clean Diesel Variable Displacement Engine	$2,405	$3,697	$3,714	$2,931	$2,959
Consumer Cost Payback (Years)					
Conventional Gasoline Engine	1.3	4.1	3.6	1.6	1.1
Clean Diesel Engine	3.2	4.3	4.2	2.8	2.3
Gasoline Variable Displacement Engine	1.8	3.3	3.2	1.9	1.7
Clean Diesel Variable Displacement Engine	3.2	4.2	4.1	3.0	2.7
Vehicle Lifetime Savings ($) to Consumer					
Conventional Gasoline Engine	$888	$1,945	$2,328	$3,372	$4,931
Clean Diesel Engine	$2,723	$3,434	$3,602	$4,544	$5,827
Gasoline Variable Displacement Engine	$2,267	$3,222	$3,367	$4,261	$4,885
Clean Diesel Variable Displacement Engine	$3,431	$4,104	$4,192	$5,057	$5,778

Table A-2:
Key Projections for Midsize Car Modeling Scenarios with Reduced Roadload

Reduced Roadload Case

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
Fuel Economy (MPG) *					
Conventional Gasoline Engine	30.7	34.8	36.8	39.7	50.2
Clean Diesel Engine	42.6	52.8	55.5	55.5	68.9
Gasoline Variable Displacement Engine	38.2	45.1	46.7	50.4	52.3
Clean Diesel Variable Displacement Engine	50.9	64.4	66.9	66.6	74.2
Fuel Economy Improvement (%)					
Conventional Gasoline Engine	6%	20%	27%	37%	73%
Clean Diesel Engine	47%	82%	92%	92%	138%
Gasoline Variable Displacement Engine	32%	56%	61%	74%	81%
Clean Diesel Variable Displacement Engine	76%	122%	131%	130%	156%
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	$210	$1,208	$1,219	$1,324	$1,343
Clean Diesel Engine	$1,416	$2,392	$2,405	$2,517	$2,540
Gasoline Variable Displacement Engine	$622	$1,583	$1,596	$1,703	$1,735
Clean Diesel Variable Displacement Engine	$1,823	$2,777	$2,791	$2,902	$2,932
Consumer Cost Payback (Years)					
Conventional Gasoline Engine	4.8	8.0	6.1	6.0	3.8
Clean Diesel Engine	6.6	6.8	6.4	6.8	6.0
Gasoline Variable Displacement Engine	3.2	6.0	5.7	5.3	5.1
Clean Diesel Variable Displacement Engine	6.2	6.6	6.4	6.8	6.3
Vehicle Lifetime Savings ($) to Consumer					
Conventional Gasoline Engine	$179	$268	$545	$820	$1,774
Clean Diesel Engine	$702	$939	$1,089	$989	$1,618
Gasoline Variable Displacement Engine	$969	$1,117	$1,244	$1,438	$1,540
Clean Diesel Variable Displacement Engine	$1,009	$1,197	$1,287	$1,173	$1,427

* Fuel economy values are laboratory values and are about 15% higher than real-world projections.

Appendix B: Discussion of Efficiency Benefits of and Design Options for Increasing Average Engine Load Factor

In the design of a motor vehicle, an onboard source of motive power must be provided in order to propel the vehicle in a manner responsive to the wishes of the driver. The demands of normal driving call for a wide range of power demands and speeds. In a conventional automotive powertrain design, an internal combustion engine (ICE) is employed as the source of motive power. The ICE may act through a speed reducing gearbox of various sorts, but the power demanded of the ICE is directly linked to road load demand. While the average power demanded by normal driving is quite small, intermittent events such as rapid acceleration, passing, and hill climbing demand power outputs far in excess of the average. Therefore, owing to the situation of the ICE in this type of powertrain, the ICE must be sized to accommodate the maximum anticipated intermittent power demand rather than the average power demand.

The sizing of the ICE to the maximum power demand results in a powertrain of relatively poor efficiency. ICEs create mechanical work from fuel energy by combusting the fuel over a thermodynamic cycle consisting typically of four cycles, namely intake, compression, expansion, and exhaust. The best energy conversion efficiency of an ICE is experienced over only a relatively narrow range of loads and speeds. Specifically, efficiency tends to be better at high load than at low load, and better at moderate speed than at either low speed or high speed. An automotive ICE that is sized to the maximum intermittent power demand will operate at low to moderate power levels the vast majority of the time, where efficiency is relatively poor. This results in a much lower fuel economy than could potentially be achieved.

One approach to improving fuel utilization would call for operating the ICE within its most efficient operating range over a larger fraction of the typical driving cycle. The most obvious approach would simply reduce the power rating of the ICE closer to the average power demand, so that the peak efficiency range of the engine more frequently matches the power demanded by the driver. However, the ability to meet peak power demands would then be compromised, leading to unacceptable performance, driver confidence, and safety. Successfully utilizing the efficient portion of the operating range would require a more sophisticated approach that would also include a means to provide for intermittent bursts in power that are required by normal driving.

Several broad strategies for achieving this outcome have been attempted with varying levels of success.

> *Approach 1: Load-Leveling a Prime Mover*

An auxiliary power unit (APU) might be added to provide intermittent assistance to the ICE. This "load-leveling" strategy would allow average power demands to be met by a relatively low power ICE having a peak efficiency near the average road load power demand, while the APU supplements the ICE to meet larger power demands. Such an APU can take many forms. For example, an electric motor and battery, or hydraulic pump/motor and accumulator, could be employed as the APU. These particular technologies offer an added benefit because they offer

the possibility of a two-way power flow between the ICE and the APU. This strategy allows continued operation of the ICE at a high load, high efficiency state even when road power demand falls below its efficient operating range. Energy taken from the wheels during braking may also be reclaimed and reused with such a system. The main drawback of this load-leveling approach is the added complexity of the powertrain. APUs that offer a two-way power flow cannot be internal-combustion devices, meaning that the APU represents an additional subsystem that would otherwise not be present, adding complexity and cost.

Approach 2: Primary and Secondary Engines

Another approach could discard the idea of a two-way APU and instead adopt a second ICE as the APU. This would create a multiple-engine powertrain. In such a system, the additional engine(s) might normally be inactive but be intermittently engaged to provide power bursts at times when a primary engine, sized to an average power demand, is not adequate to meet such demands. Alternately, each engine could be sized to serve a specific range of demands at which their respective efficiency is greatest. A general shortcoming of such a powertrain is the need to frequently start and stop the various engines. Prevailing ICE technologies, if used in such a system, would encounter some efficiency losses and increased emissions as a result of frequent restarting. Driver confidence might also be negatively influenced if the driver perceives the frequent starting and stopping of the engines as a reliability risk.

Approach 3: Variable Displacement

The multiple-engine powertrain discussed previously may be described more broadly as one form of a variable-displacement powertrain. That is, a sort of variable displacement is achieved by switching the various engines on or off. Variable displacement has more commonly been achieved by changing the displacement of a single engine, perhaps by variably switching one or more of its cylinders on or off. Many approaches have been used to control the participation of the various cylinders, including the selective feeding of fuel to each cylinder, variable control of exhaust and intake valves, and physical disconnection of cylinders or their parts. All of these methods have drawbacks. If the piston of a non-participating cylinder continues to reciprocate within its cylinder, friction losses will be significant. Even if compression forces are minimized by selectively opening the valves, there is still a price to be paid in terms of friction, pumping losses, and inertial effects for each cylinder that is not producing power at a given time.

Approach 4: Low Speed Operation

Friction is a significant cause of inefficiency in a piston-based ICE. Because friction loss per unit power delivered is greatest at higher engine speeds, operating the engine at a relatively low average speed may improve efficiency by reducing the influence of friction. If such a low-speed engine were properly designed, peak power demands could be met by intermittent operation at higher speeds. Low-speed engines have not been a popular approach in the prior art in part because current engine and drivetrain designs do not respond well to low speed operation. At low engine speeds, torque pulses on the crankshaft are more distinctly felt on the output shaft. Conventional gearboxes would tend to transmit these pulses to the vehicle, resulting in less comfort and reduced component durability. Optimum fuel injection timing is also very critical at

low speed operation, requiring more sophisticated control. Also, the relatively slow piston stroke would allow more time for heat to be lost to the surroundings during the expansion stroke, and more opportunity for leakage of gases past the rings during the compression stroke. Combustion processes might also be negatively affected by stroke speed and cycle length, reducing mixing efficiency and combustion quality. Finally, because the kinetic energy of the crankshaft varies with velocity squared, reducing the speed beyond a certain point will dramatically increase the risk of stalling on the compression stroke. A heavier flywheel could alleviate this problem, but it would make the drivetrain less responsive, especially at higher speeds.

Approach 5: Switching Between Four-Stroke and Two-Stroke Operation

Another method would selectively switch between four-stroke and two-stroke operation. The four-stroke cycle has been preferred in automotive applications because it provides better efficiency and emissions than a two-stroke cycle. However, a two-stroke cycle, having twice as many power strokes per cycle, could theoretically double the power output of an engine of given size. Thus the ability to switch between four-stroke and two-stroke operation would allow a small four-stroke engine to meet average power demands at optimum efficiency and minimum emissions, while a two-stroke mode could be engaged to meet peak power demands intermittently. A primary drawback of this approach is the difficulty of achieving acceptable emissions and efficiency in two-stroke mode. Conventional two-stroke operation relies on an imperfect "scavenging" process that takes the place of separate intake and exhaust strokes and results in the escape of unburned fuel with the exhaust, resulting in high hydrocarbon emissions and loss of fuel efficiency. A dramatic boost in power is achieved as the scavenging process approaches 100% efficiency (owing to the purity of the fresh air in the mixture), but nearly perfect scavenging is elusive. There are several approaches to "scavenging" including cross-scavenging, loop-scavenging, and uniflow methods, but none are perfect. Generally, scavenging may be improved with variations in porting and piston shaping, the clutching in of a supercharger, or a 4-valve design. The combustion chamber of such an engine would also be designed to have peak efficiency in four-stroke operation while providing maximum scavenging in two-stroke operation. The two-stroke mode would call for direct cylinder fuel injection and full flexibility of fuel injection timing. Switching between modes would require total control of intake and exhaust valve mechanisms, not the mechanical valve control typically employed.

Approach 6: Variable Compression Ratio

Perhaps the most practical way to improve engine efficiency is to increase the compression ratio (CR) of the engine. The compression ratio is simply the ratio of expanded cylinder volume to compressed cylinder volume in one cycle of the reciprocating piston. According to thermodynamic laws, a greater degree of compression relative to the expanded volume corresponds to greater efficiency of the thermodynamic cycle and hence greater efficiency of the engine. Unfortunately, a large compression ratio promotes several undesirable side effects. An increased level of friction and higher peak cylinder pressures are two results of a high compression ratio. Under these conditions, if the fuel is introduced with the fresh charge air, there is a potential for knocking or pre-ignition at high power output. For this reason, if the compression ratio of a normal engine were simply increased without other allowances being made, the efficiency at low power output might improve, but operation at higher power outputs

would be compromised by severe knocking. This would not only reduce efficiency significantly but could potentially lead to engine damage.

These problems could be avoided if a high-compression engine could selectively reduce its compression ratio at times when high power output is needed. Ideally, one would desire to employ a high compression ratio at normal load, and shift to a lower compression ratio for intermittent high loads. In this way the high efficiency associated with a high compression ratio could be achieved over normal ranges of operation, while higher power output could be achieved without fear of pre-ignition by invoking a lower compression ratio.

Appendix C: Description of EPA's Variable Displacement Engine Design

EPA's variable displacement engine design varies displacement by use of a multiple-crankshaft engine design in which two distinct crankshafts are contained within a single engine block. The crankshafts are independent so that each can rotate singly or in combination. For example, a first crankshaft operates pistons which represent, for example, two liters of displacement, and a second crankshaft operates pistons which represent an additional two liters of displacement or a different displacement. When relatively low power is needed, the first crankshaft unit is operated alone at a higher relative load than if all crankshaft units were operating, thus allowing it to operate at a higher relative efficiency. When higher power is commanded than can be supplied by the first crankshaft unit, the second crankshaft unit is activated, and together the two crankshaft units supply the commanded power.

EPA's variable displacement engine design provides several advantages necessary for commercial practicality and acceptance: 1) uninterrupted accessory drive; 2) low cost of manufacture, including operability with conventional automotive components, and minimal duplication of components (starting, cooling, lubrication, accessories, and other support systems); 3) smooth transitioning among units of displacement; 4) good lifetime and reliability; and 5) an option for multiple output shafts for use with unconventional hybrid drive systems.

Uninterrupted Accessory Drive

The EPA variable displacement engine design utilizes a unique means to allow a zero displacement mode without interrupting power to accessories that require a direct power drive. One option provides a separate power drive accessories system which operates the accessories with a drive motor (e.g., electric or hydraulic) independent of either crankshaft unit. This option allows the accessories to be driven at a speed that is optimum for the demands being placed on the accessories. In a second configuration, this drive system is mounted to the engine with drive attachments (through clutch means) to each crankshaft, and in this configuration the separate drive motor drives through clutch means as well. When either crankshaft unit is operating, the accessories are directly driven by power from the operating crankshaft(s). When neither crankshaft unit is operating, the drive motor drives accessories through its clutch drive means. A third option for satisfying accessory needs is to insure at least one crankshaft unit will be operating when accessory needs exist, and the separate drive motor of the previous configuration can be deleted.

Low Cost of Manufacture

Low cost of manufacture includes maintaining operability with conventional automotive components and minimal duplication of components.

The EPA variable displacement engine design utilizes a single starter to start both displacement units. One option includes a single starter which can engage a first crankshaft unit to start it and then when more power is commanded than the first crankshaft unit can supply alone, the starter

engages a second crankshaft unit to start it. In a second option the first crankshaft unit is started with a dedicated starter and the second unit is started by activating its clutch to rapidly raise its speed to that of the first crankshaft unit.

By integrating the separate crankshafts into a common block, each displacement unit shares the same cooling system and lubrication system.

Compatibility of the power plant with existing automotive components would be assured by (a) providing means as described above to drive conventional power drive accessories without interruption, allowing off-the-shelf components to be used without substantial redesign; and (b) delivering a single output shaft for attachment to conventional transmissions by means of a unique clutching and gearing system.

It would also be possible to designate one displacement unit as a secondary unit that receives intermittent use, which allows it to be constructed less expensively than the primary unit.

Smooth Transitioning

Smooth transitioning among various units of displacement can be achieved by adopting an operating strategy in which one displacement unit is designated as a permanent secondary unit and its flywheel is eliminated, allowing it to spin up faster.

Reliability and Lifetime

Reliability and lifetime would be improved when the two displacement units may interchangeably serve as primary or secondary displacement units, which acts to reduce the potential for uneven wear, and guarantees that a first increment of displacement is always available for emergency use even when one of the units has failed.

Option for Multiple Output Shafts

It is also possible to provide separate crankshaft outputs to provide certain advantages for powertrains which transmit power to the drive wheels by electric or hydraulic motors.

Appendix D: Description of EPA's Variable Compression Ratio Engine Design

The EPA variable compression ratio engine design achieves a two-stage variation in compression ratio by use of a piston-within-piston mechanism that varies the combustion and mixing volume provided within the piston crown, thereby regulating the net clearance volume at top dead center (TDC) without changing the main piston squish height.

In normal operation (during low to moderate power demands), the top of an inner piston is flush with the top of an outer piston, defining a normal high compression ratio mode. The relatively high compression ratio in this mode provides excellent thermodynamic efficiency in this normal operating range. When power demand increases to the point where this high compression ratio might cause performance problems such as pre-ignition or knocking, a command signal causes the inner piston to recede to a second position within the outer piston, thereby increasing the total clearance volume and reducing the compression ratio sufficiently to prevent pre-ignition or knocking. Good mixing and combustion is retained in both modes because the piston bowl resides within the receding inner piston and therefore does not change shape, only changing its relative distance from the top of the cylinder head at TDC.

The inner piston is located in either the normal high CR position or the intermittent low CR position by the rotation of a rotary cam-like actuator which pivots about a wrist pin residing in the outer piston. The rotary actuator is comprised of a rotary hydraulic piston and fluid chamber that are integrated with the wrist pin, and a cam which pivots around the wrist pin in reaction to movement of the hydraulic rotary piston. Movement of the hydraulic rotary piston and cam assembly is caused by the presence or absence of a hydraulic command signal consisting of a pulse of pressurized hydraulic fluid, in conjunction with inertial forces created by reciprocation of the piston assembly in an engine cylinder. The issuance of the command signal activates the intermittent low-CR mode. Withdrawal of the command signal allows a spring mechanism and inertial forces to restore a normal high-CR mode.

Appendix E: Engine Maps

This appendix provides the four engine maps that were used in the fuel economy modeling of the various vehicle technology packages that were discussed in Section 5. These maps show fuel energy efficiency (shown in the "islands" in the middle of the charts) as a function of engine load (torque, the vertical axis) and engine speed (revolutions per minute, or rpm, on the horizontal axis).

Figure E-1: SUV Baseline GAS Engine
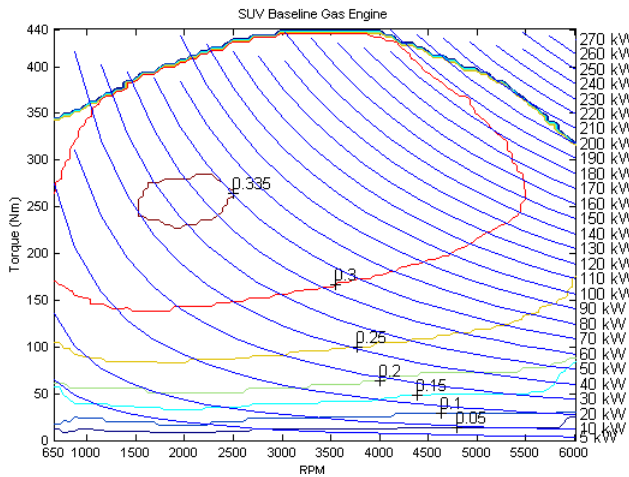
Figure E-2: SUV Baseline Diesel Engine
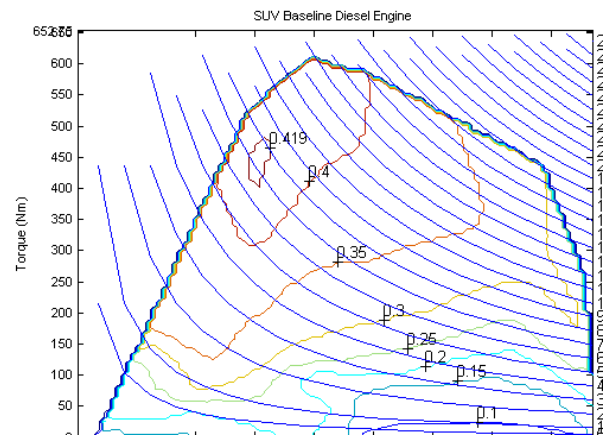
Figure E-3: Car Baseline Gasoline Engine
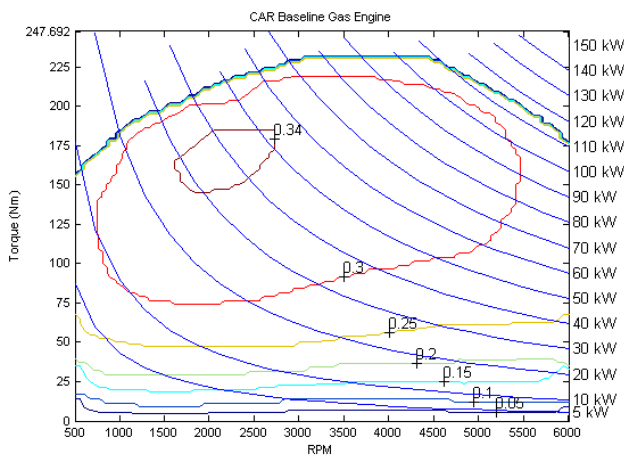
Figure E-4: Car Baseline Diesel Engine
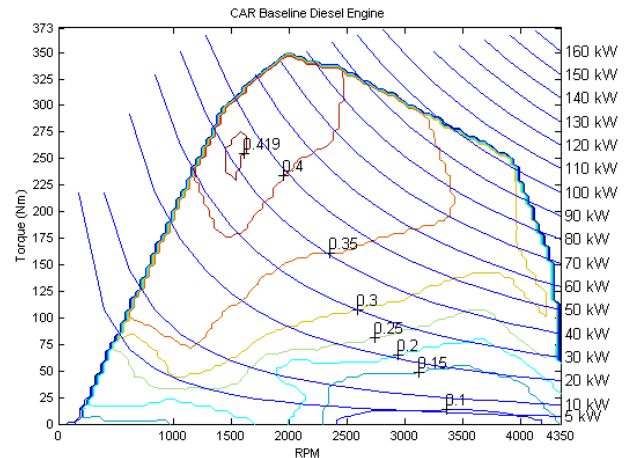
Appendix F: Hydraulic Pump/Motor Maps

This appendix provides the five hydraulic pump/motor maps that were used in the fuel economy modeling of the various hydraulic hybrid vehicle technology packages that was discussed in Section 5. These maps show pump/motor efficiency (shown in the "islands" and lines in the middle of the charts) as a function of displacement (the vertical axis) and pump/motor speed (revolutions per minute, or rpm, on the horizontal axis). The maps represent a high-efficiency unit tested at five different pressures.

Figure F-1:   2000 PSI

Figure F-2:   2500 PSI

Figure F-3:   3000 PSI

Figure F-4:   3500 PSI

Figure F-5: 4000 PSI

Gen 2 4000 PSI
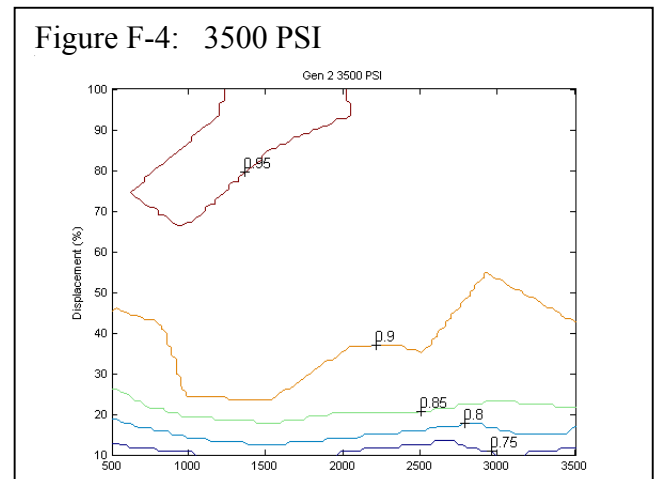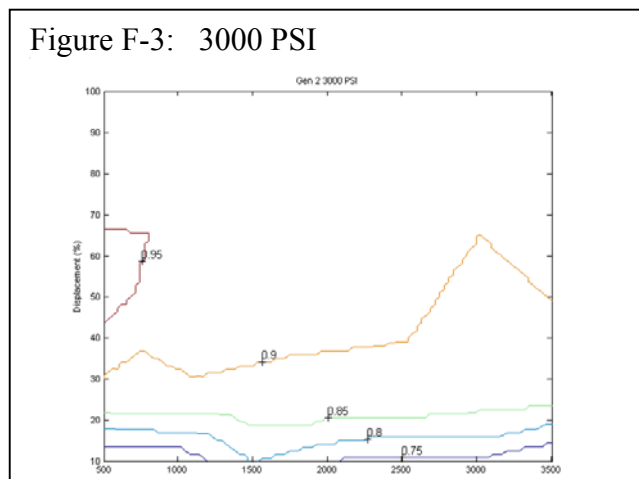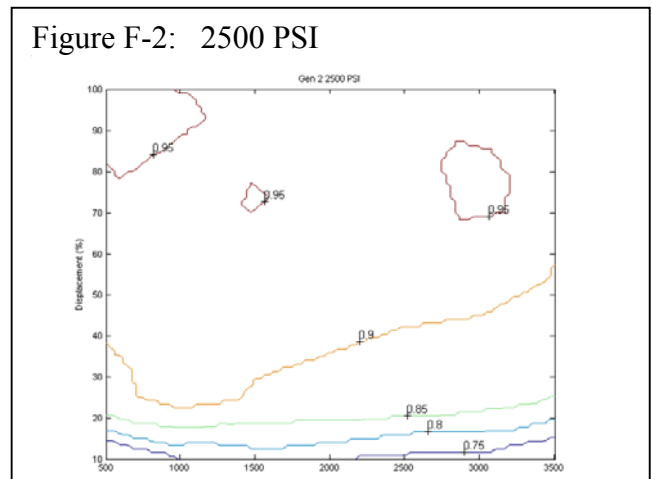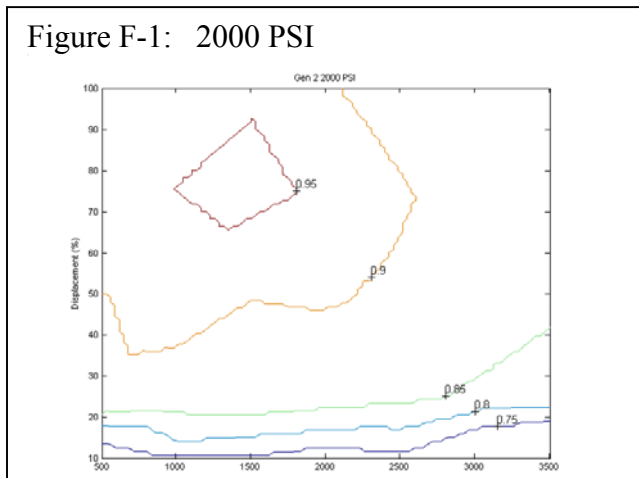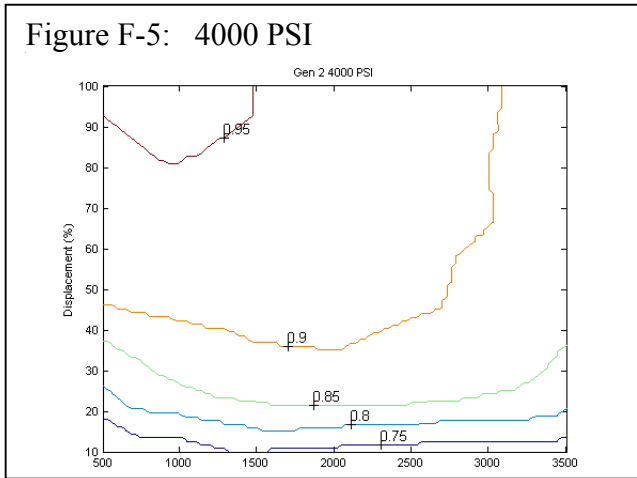
Appendix G: Derivation of Base Roadload Specifications

Appendix G provides the background material on the base roadload specifications that are one of the major inputs to the fuel economy modeling described in Section 5. The base roadload is calculated as the sales-weighted average roadload specifications for today's top-selling vehicles in the large SUV and midsize car classes. The automobile manufacturers supplied roadload equations to EPA as part of their submission for emissions certification of 2002 model year vehicles. Table G-1 provides the roadload specifications for top selling 2002 models in the large SUV and midsize car classes. These were weighted together to form the base roadload specifications for the body of this report. For the reduced roadload case supplied in Appendix A, the base roadload specifications were lowered by 20 %.

Table G-1

Emissions/Fuel Economy Test Cars - Track Roadload Coefficients, Curb Weight, ETW
2002 Models - Representative Models
Top Selling Model Lines within Selected Classes

LARGE SUV

| MAKE | MODEL LINE | ENG/ETW | MODEL | TRACK COEFF | | | CURB WT | ETW | CITY | HWY |
				A lbs	B lbs/mph	C lbs/mph^2	lbs	lbs	mpg	mpg
Chevy	Tahoe	5.3 L/6000	4WD	58.57	1.1649	0.03022	5049	6000	14.9	21.9
Chevy	Suburban	5.3 L/6500	4WD	61.33	1.1653	0.03202	5142	6500	14.7	21.5
GMC	Yukon	4.8 L/6000	4WD	41.65	1.2249	0.02792	5103	6000	15.4	21.5
GMC	Yukon Denali XL	6.0 L/6000	AWD	56.02	1.2954	0.02872	5820	6000	12.8	19.1
Ford	Expedition	5.4 L/6500	4WD	52.63	1.5779	0.03069	5449	6500	13.4	21
Toyota	Sequoia	4.7 L/6000	4WD	53.33	0.59261	0.03497	5295	6000	15.4	22
Sales Weighted Average				**56.69**	**1.1514**	**0.03121**	**5263**			

MID-SIZE CARS

| MAKE | MODEL LINE | ENG/ETW | MODEL | TRACK COEFF | | | CURB WT | ETW | CITY | HWY |
				A lbs	B lbs/mph	C lbs/mph^2	lbs	lbs	mpg	mpg
Ford	Taurus	3.0 L/3625	SE	29.72	0.2625	0.0182	3336	3625	22.2	35.4
Toyota	Camry	2.4 L/3500	XLE	28.621	0.09621	0.01964	3219	3500	25.3	39.2
Honda	Accord	2.4 L/3375	LX Sedan	26.01	0.4918	0.01591	3097	3375	25.8	38.8
Buick	Century	3.4L/3625	Custom	25.43	0.5118	0.01634	3368	3625	22.3	36.7
Sales Weighted Average				**27.52**	**0.31624**	**0.01771**	**3240**			

Appendix H: Detailed City/Highway Fuel Economy Results

The body of the report uses composite fuel economy values where the city and highway values are harmonically averaged and weighted 55% city/45% highway. The table in this appendix provides the individual city and highway fuel economy modeling results for each of the vehicle technology packages.

	city mpg	hwy mpg	comb mpg											
SUV Target from EPA Database	15.0	21.0	17.2											

Conventional Transmission | **Mild Hydraulic Hybrid, Engine On** | **Mild Hydraulic Hybrid, Engine Off**

SUV--Base Roadload	city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine	14.9	21.2	**17.2**			18.7	20.4	19.4	13		19.7	20.5	20.0	17	
Gasoline Var Disp Engine	18.0	22.2	19.7	15		23.6	21.3	22.5	31		24.2	21.3	22.8	33	
Clean Diesel Engine	20.9	27.8	23.6	37		27.2	26.9	27.0	57		28.2	26.9	27.6	61	
Diesel Var Disp Engine	24.2	30.7	26.8	56		32.0	29.6	30.9	80		32.7	29.7	31.3	82	
SUV--Reduced Roadload	city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine	15.7	24.1	**18.6**	8	8	20.3	23.2	21.5	16	25	21.6	23.3	22.3	20	30
Gasoline Var Disp Engine	19.4	26.3	22.0	18	28	26.3	25.1	25.7	38	50	27.2	25.1	26.2	41	53
Clean Diesel Engine	22.2	31.9	25.7	38	50	29.6	30.7	30.1	62	75	30.8	30.8	30.8	66	80
Diesel Var Disp Engine	26.1	36.0	29.7	60	73	36.0	34.6	35.3	90	106	36.8	34.9	35.9	93	109

Full Hydraulic Hybrid, Engine On | **Full Hydraulic Hybrid, Engine Off**

SUV--Base Roadload						city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine						19.9	20.5	20.2	18		25.6	20.6	23.1	34	
Gasoline Var Disp Engine						23.8	21.7	22.8	33		26.8	21.5	24.1	40	
Clean Diesel Engine						27.7	26.6	27.2	59		35.9	28.2	32.0	86	
Diesel Var Disp Engine						33.3	29.0	31.2	82		38.7	30.6	34.6	101	
SUV--Reduced Roadload						city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine						22.0	24.0	22.9	23	33	29.9	24.5	27.2	46	58
Gasoline Var Disp Engine						26.9	26.0	26.5	42	54	31.2	26.1	28.7	54	67
Clean Diesel Engine						31.1	31.9	31.4	69	83	41.8	34.6	38.2	105	123
Diesel Var Disp Engine						37.7	34.9	36.4	96	112	45.4	37.1	41.2	122	140

	city mpg	hwy mpg	comb mpg											
Car Target from EPA Database	24.0	38.0	28.8											

Conventional Transmission | **Mild Hydraulic Hybrid, Engine On** | **Mild Hydraulic Hybrid, Engine Off**

Car--Base Roadload	city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine	24.3	38.0	**29.0**			29.6	36.7	32.4	12		32.1	36.8	34.0	18	
Gasoline Var Disp Engine	30.5	43.8	35.3	22		39.9	41.8	40.7	41		42.1	41.8	42.0	45	
Clean Diesel Engine	33.1	52.7	39.8	37		46.5	51.2	48.5	67		49.3	51.3	50.2	73	
Diesel Var Disp Engine	39.7	60.5	46.9	62		57.0	58.2	57.5	99		60.1	58.4	59.3	105	
Car--Reduced Roadload	city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine	25.2	41.8	**30.7**	6	6	31.2	40.6	34.8	13	20	34.0	41.1	36.8	20	27
Gasoline Var Disp Engine	32.1	49.8	38.2	25	32	43.0	47.8	45.1	47	56	45.8	47.9	46.7	52	61
Clean Diesel Engine	34.7	59.2	42.6	39	47	49.6	57.3	52.8	72	82	53.8	57.6	55.5	81	92
Diesel Var Disp Engine	42.0	68.7	50.9	66	76	62.6	66.8	64.4	110	122	66.8	66.9	66.9	118	131

Full Hydraulic Hybrid, Engine On | **Full Hydraulic Hybrid, Engine Off**

Car--Base Roadload						city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine						33.4	39.7	36.0	24		45.3	41.5	43.5	50	
Gasoline Var Disp Engine						44.2	44.1	44.1	52		47.2	43.5	45.4	57	
Clean Diesel Engine						48.0	52.6	50.0	72		62.4	57.0	59.9	107	
Diesel Var Disp Engine						58.6	58.7	58.7	103		67.2	61.1	64.3	122	
Car--Reduced Roadload						city mpg	hwy mpg	comb mpg	% Gain(loss)		city mpg	hwy mpg	comb mpg	% Gain(loss)	
Conv Gasoline Engine						36.0	45.4	39.7	29	37	51.4	48.9	50.2	64	73
Gasoline Var Disp Engine						49.1	52.0	50.4	64	74	52.8	51.7	52.3	70	81
Clean Diesel Engine						52.2	60.1	55.5	81	92	70.3	67.2	68.9	124	138
Diesel Var Disp Engine						64.6	69.1	66.6	117	130	75.4	72.8	74.2	142	156

Appendix I: FEV Report - Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks

This appendix contains a report written by FEV to estimate the cost for a clean diesel engine.

FEV

Engine Technology

FEV01-505P3 Rev. 1 Final Report

**Engine and Vehicle Development
and Engineering Support**

**Contract No. 68-C-01-155
Work Assignment 0-2 Amendment 2**

**Cost and Fuel Economy Comparison
of Diesel and Gasoline Powertrains in
Passenger Cars and Light Trucks**

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April 23, 2003

A. Executive Summary

Fuel economy and production cost differences for gasoline and diesel powered vehicles are compared. Similar production volumes for gasoline and diesel engines and vehicles are assumed, with the result that the economies-of-scale for the diesel engine and the gasoline engine are equal. Furthermore, it is also assumed that the base vehicles' architecture will have been initially designed to accept either engine. No effort was made to assess the relative difference in exhaust aftertreatment systems. A "low-risk" approach to technology was taken whereby engine and vehicle technology widely available in the 2002 world automotive market is assumed.

A detailed vehicle simulation model was used to assess the relative fuel economy difference between gasoline and diesel powered passenger cars and SUV's. The passenger car comparison is based on vehicles in the mid-sized 5-passenger car class typified by the Ford Taurus and Toyota Camry. Full-size SUV's typified by the Chevrolet Tahoe and Ford Expedition are also compared. Vehicle performance with gasoline engines was predicted in both vehicle classes and compared with published results for these vehicles. These values were then used as a baseline for further comparisons. The diesel engine displacement and output were adjusted to achieve parity in 0-60 mph acceleration between gasoline and diesel engine powered vehicles. Fuel economy on the U.S. Federal fuel economy cycles (city and highway) and vehicle performance using several metrics were predicted and compared. Fuel economy figures that result from EPA test procedures are reported in miles per gallon. The primary engine fuel consumption maps, which strongly influence the fuel economy results, were developed independently and were not produced from vehicle manufacturer-supplied data.

Estimated production cost and weight differences between gasoline and diesel engine powered versions of the comparison vehicles were detailed. The primary factor leading to the increased cost and weight of the diesel powertrain is the diesel engine, which is strongly influenced by the cost of the high pressure diesel fuel injection system.

Table ES1 summarizes the fuel economy, production cost, and weight differences for the two (2) comparison vehicles with gasoline and diesel engines.

	Passenger Car		Full-Size SUV	
	Gasoline	**Diesel**	**Gasoline**	**Diesel**
City Fuel Economy	24.8 mpg	36.7 mpg	14.7 mpg	21.4 mpg
City FE Improvement	Baseline	48%	Baseline	45%
Highway Fuel Economy	41.0 mpg	51.3 mpg	21.0 mpg	28.1 mpg
Highway FE Improvement	Baseline	25%	Baseline	33%
Combined Fuel Economy	30.2 mpg	42.1 mpg	17.0 mpg	24.0 mpg
Combined FE Improvement	Baseline	39.5%	Baseline	41%
Vehicle Test Weight	3550 lbs	3643 lbs	5563 lbs	5752 lbs
Mature Production Cost Estimate (2002 $)	Baseline	+ $739	Baseline	+ $1042
Current Production Cost Estimate (2002 $)	Baseline	+ $1063	Baseline	+ $1537

Table ES1: Overall Results of the Study

For both passenger car and SUV diesel engines, high pressure common rail fuel injection systems were assumed. The estimated cost for the common rail diesel fuel injection system alone contributes $735 to the total difference of $1063 between the gasoline and diesel engine powered passenger car using current cost estimates. Because common rail diesel fuel injection technology is relatively new, initial development and capitalization costs may significantly impact the estimated current production cost. FEV estimates that the mature production cost of the complete fuel injection system could be reduced by approximately 30% from the current cost estimate under the boundary conditions of the study. For similar arguments, FEV estimates that the mature production cost of a variable geometry turbocharger can also be reduced 30% from current estimate. These estimates reduce the cost differential between gasoline and diesel engine powered vehicles.

Table of Contents

Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks

B. Introduction

For the US market, diesel engines are proposed as a means to improve the fuel economy of new passenger cars and light trucks.

In contrast to the US where diesel engine powered vehicles make up just 0.1% of new light vehicle sales[1,2,] vehicles with diesel engines make up an increasingly large portion of the new passenger car and light commercial vehicle fleet in the European market. The fuel consumption advantage, price disparity between gasoline and diesel fuel in many countries, along with rapidly advancing technology of high speed direct injection diesel engines by European automakers, has increased the market penetration of diesel engines. European Union emission standards also grant diesel powered cars and light commercial vehicles different emissions requirements. The percentage of diesel engine powered light vehicles in the European market has increased steadily over the last 30 years and rapidly in the last 5 years, as shown in Table 1.

Year	Diesel %
1973	2.5
1994	22.7
2000	34.9
2001	35.8

Table 1. Percentage of new car registrations in Europe with diesel engines [3]

This study compares estimated production cost (without economic inflation) and simulated fuel economy of two classes of vehicles with gasoline and diesel engines for the US light vehicle market. Vehicle models that are typical to the US automotive market are studied. It is projected that by the year 2010, vehicles could be developed for use with gasoline or diesel engines in similar production quantities. It is assumed that vehicle designs would be completed with both engine options fully engineered, rather than initially developed with the gasoline engine and then modified for a diesel engine after the platform is already designed.

In this study, the technology level associated with each powertrain is already in mass production in the 2002 world automotive market. For example, the baseline passenger car gasoline engine assumes a primarily aluminum construction spark-ignited, homogeneous charge engine with variable intake valve timing. A conventional 4-speed automatic transmission is also applied to every vehicle in the study. The diesel engine technology is typical of 2002 model European diesel engines, including common rail fuel injection,

variable geometry turbocharging, and electronic EGR control. Evolution in the development of both gasoline and diesel engines that could improve engine performance and fuel economy is not considered.

Two vehicle comparisons are considered. The first is a 5-passenger sedan typified by the 2002 model year Ford Taurus, Chrysler Sebring, Saturn LS, Honda Accord, and Toyota Camry. This class of vehicles makes up the largest segment of the passenger car market in the US. A full size SUV typified by the 2002 model year Chevy Tahoe, Ford Expedition, and Toyota Sequoia is the second comparison vehicle. Large SUV's represent a vehicle class with low fuel economy ratings and growing market penetration, so the difference in fuel use in gallons per year for this class of vehicle would be anticipated to be relatively large and potentially growing.

This study does not consider the exhaust aftertreatment system necessary to allow either gasoline or diesel vehicles to meet US emissions standards in the 2010 time frame. The cost and fuel economy implications must be applied in addition to the final findings of this study. Such an approach should be taken cautiously, because the engine cost may be impacted by the need to meet very low emissions requirements. Further, it is FEV's experience that the exhaust aftertreatment system technology necessary to meet a challenging emissions level must be developed in conjunction with the base engine in a complete systems approach.

This study does not consider the impact of other technologies on the relative fuel consumption and cost of either gasoline or diesel engine system. It is expected that 42V electrical systems, advanced transmissions, and hybrid powertrains can be analyzed relative to gasoline and diesel engines on a cost/benefit basis.

C. Vehicle Performance and Fuel Economy Simulation

Detailed simulation models of gasoline and diesel powered vehicles were prepared and evaluated. Parameters chosen for simulation, including engine maps, were determined independently and were not developed utilizing vehicle manufacturer-supplied data. Actual engine and vehicle calibrations could differ significantly from those assumed under this study.

Vehicle performance simulation was performed using a computer simulation program developed internally by FEV. FEV's vehicle simulation model has capabilities similar to those of commercial vehicle performance simulation models such as GT-Drive from Gamma Technologies or the proprietary software used by automakers. FEV has correlated simulation model predictions to measured vehicle performance to validate the model capabilities.

Using this model, vehicle performance can be predicted for a time sequenced vehicle speed profile (e.g. FTP75) to predict performance on prescribed cycles. It is also possible to assess vehicle acceleration performance times between prescribed speeds (e.g. 0-60 mph, 30-50 mph).

Vehicle properties are entered including engine torque curve and primary engine fuel rate map as a function of engine speed and load. Engine fuel rate maps are based on engine test data measured on competitive engines from the world automotive market. All data used in this study is based on engines in mass production during the 2002 model year.

Equivalent vehicle acceleration performance for each comparison set of vehicles was required. Zero to 60 mile per hour acceleration time was chosen as the key performance metric. The diesel engine output curve and final drive ratio were selected to achieve parity in 0-60 mph acceleration performance for gasoline and diesel versions in each comparison vehicle class. The engine torque curves were determined using base engine performance measured on existing production engines from the world automotive market. To achieve performance parity of the comparison vehicles, the engine displacement was scaled to increase or decrease total engine output. Fundamental transmission characteristics such as gear efficiencies and vehicle properties were unchanged from gasoline to diesel vehicles.

The primary differences in the gasoline and diesel vehicle simulation models are the peak engine output curve and the engine fuel consumption map, which contains tabulated fuel consumption rates as a function of engine speed and output torque. The final drive ratio was adjusted for the diesel engine to optimize the vehicle fuel economy while achieving equivalent acceleration performance. For all vehicles, the automatic transmission shift map was estimated. The fuel consumption map used in this study for the passenger car with a gasoline engine is shown in Figure 1.

**Passenger Car Gasoline Engine
Fuel Consumption Map [g/bkW-hr]**
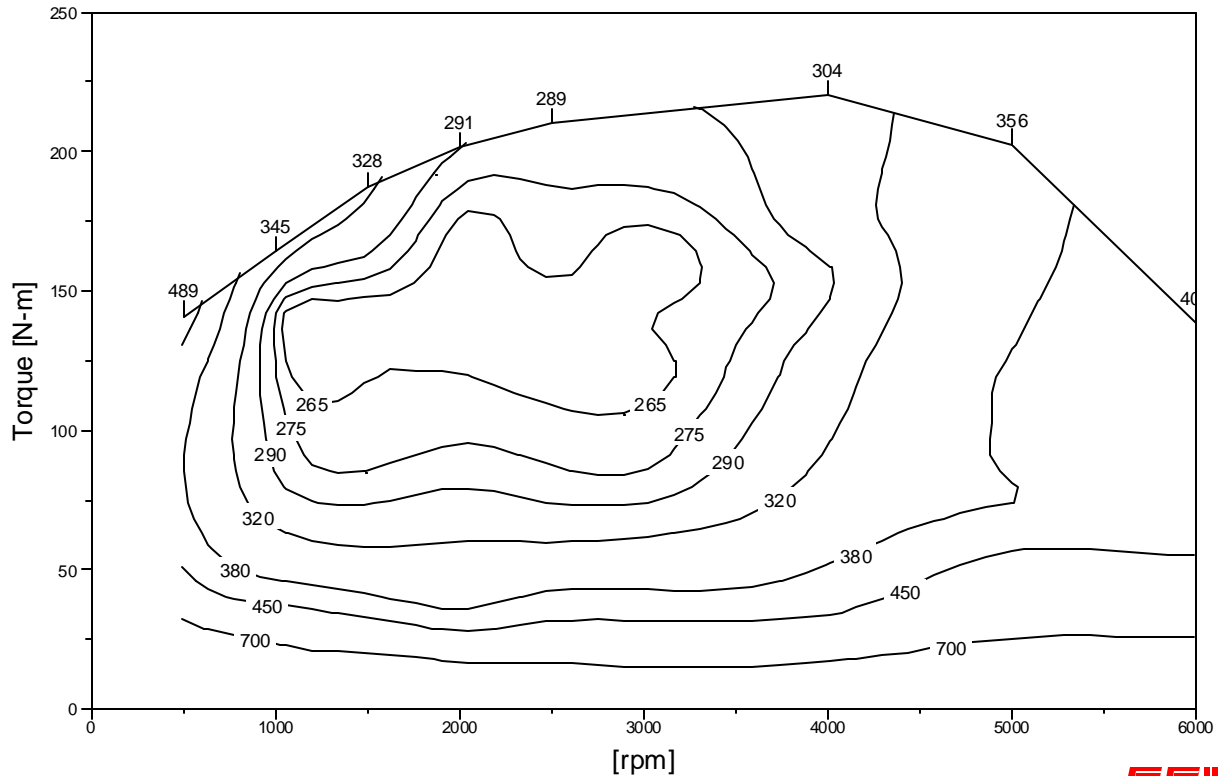
Figure 1. Passenger car gasoline engine fuel consumption map

The diesel engine fuel consumption maps are typical of diesel engines available on the European market in 2002. The diesel engine fuel consumption map used in this study for the passenger car is shown is Figure 2.

For both gasoline and diesel engines, no improvement in engine fuel consumption over today's engines is assumed or implemented in the vehicle simulation models.

**Passenger Car Diesel Engine
Fuel Consumption Map [g/bkW-hr]**
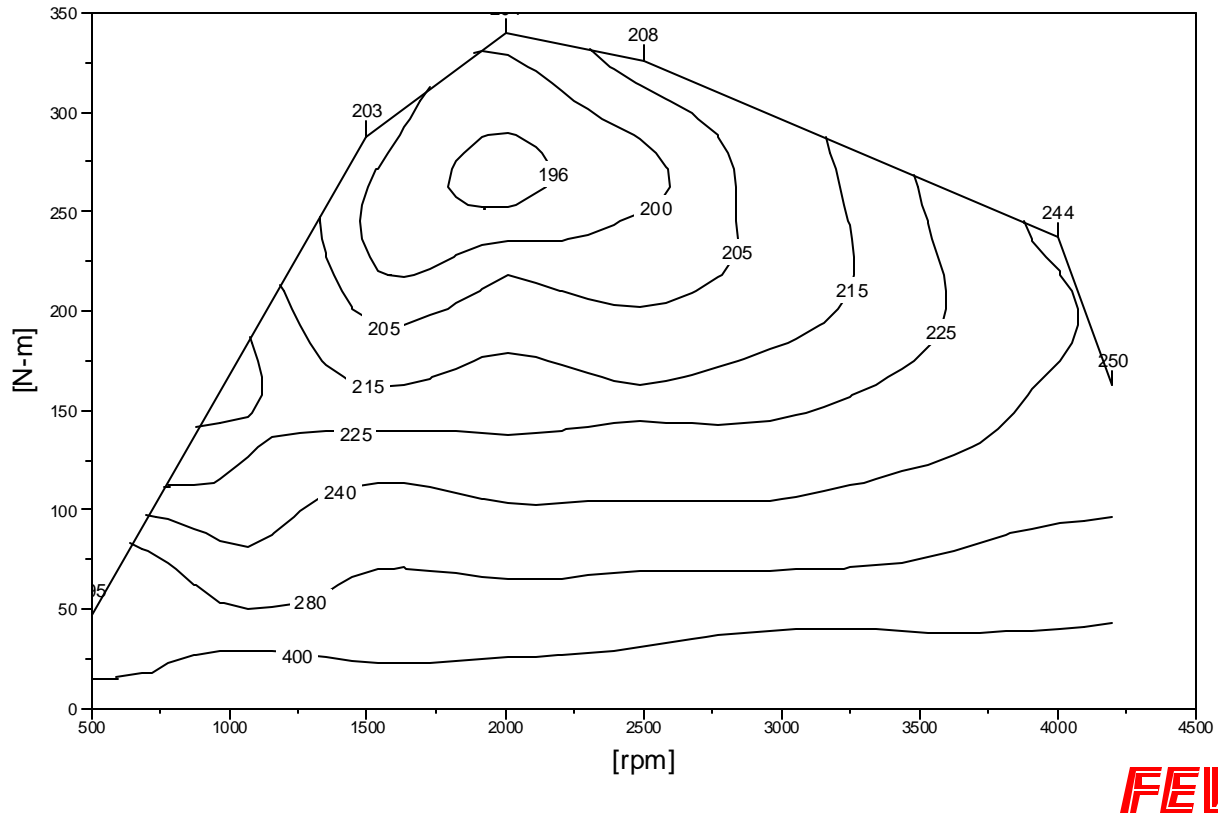
Figure 2. Passenger car diesel engine fuel consumption map

Using the developed simulation models, fuel economy and other performance metrics were then evaluated. Fuel economy figures quoted in this study represent the miles per gallon figure that can be achieved on EPA laboratory tests. Fuel economy figures are reported in miles traveled per gallon of respective fuel consumed.

The different economy results are not adjusted for fuel density. A gallon of diesel fuel typically weighs about 10% more than a gallon of gasoline. The fuel density assumed for this study is shown in Table 2.

Fuel	Specific Gravity
Gasoline	0.764
Diesel	0.85

Table 2. Gasoline and diesel fuel specific gravity assumed for this study

City and highway fuel economy figures were obtained using the vehicle simulation models on the prescribed vehicle speed cycles. Combined fuel economy was calculated using the following relationship:

$$\text{Combined FE} \ = \ \frac{1}{(0.55 \,/\, \text{City FE}) + (0.45 \,/\, \text{Highway FE})}$$

Acceleration performance from 0-60 miles per hour was assessed using a specific vehicle test procedure. The vehicle is idled with the automatic transmission selector in drive. At time zero, the accelerator pedal is depressed from 0 to 100% in less than 100 msec. The time when the vehicle passes 60 mph is measured to determine total accumulated acceleration time. The simulation procedure matches FEV's vehicle test procedure to measure acceleration time. Automotive enthusiast magazines report shorter acceleration times, but the test procedure is not equivalent.

Baseline results for the gasoline powered vehicles were compared to data which FEV obtained from EPA testing for city and highway fuel consumption values and zero to sixty mph times FEV had measured in actual vehicle road tests. These values were used to "tune" model parameters and act as validation for the parameter sets.

The engine torque output map for gasoline engines was taken from measured engine performance tests. The necessary output from the diesel engine was estimated to achieve equivalent vehicle acceleration from 0-60 mph. The engine torque curve and fuel economy map was then scaled from actual measured engine data. Figures 3 and 4 illustrate the maximum engine performance from the passenger car gasoline and diesel engines included in this study.

Passenger Car Engine Power
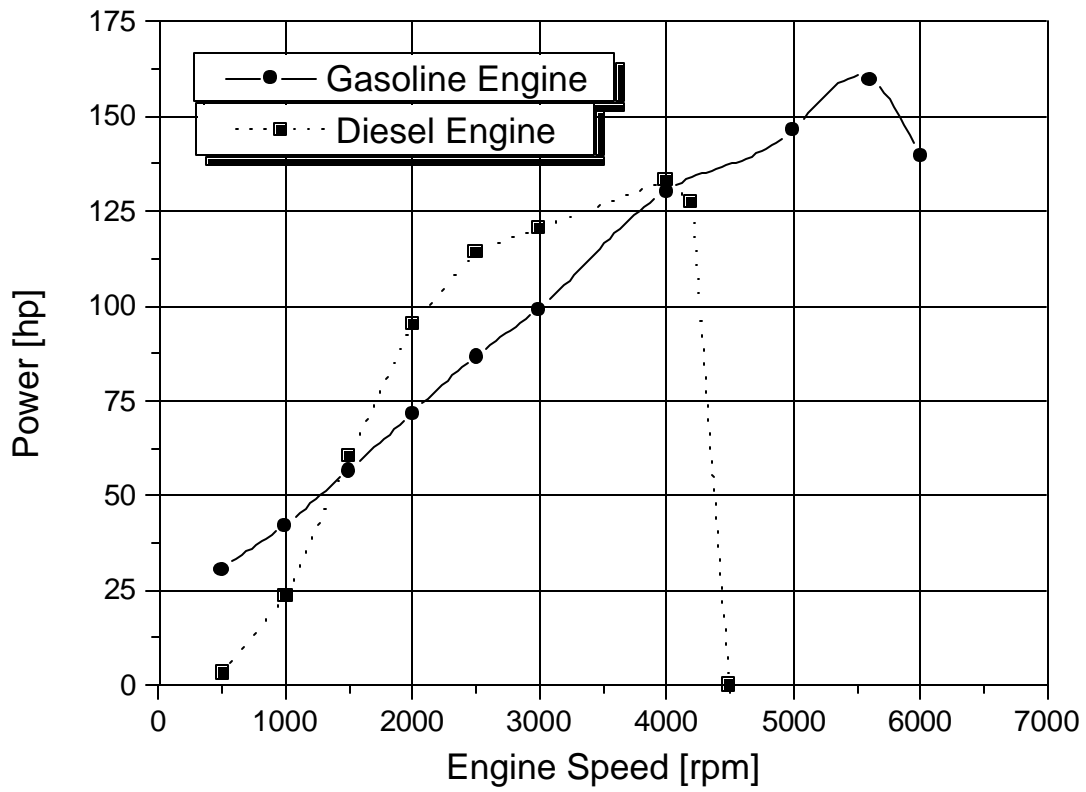
Figure 3. Gasoline and diesel engine maximum power output

Passenger Car Engine Torque
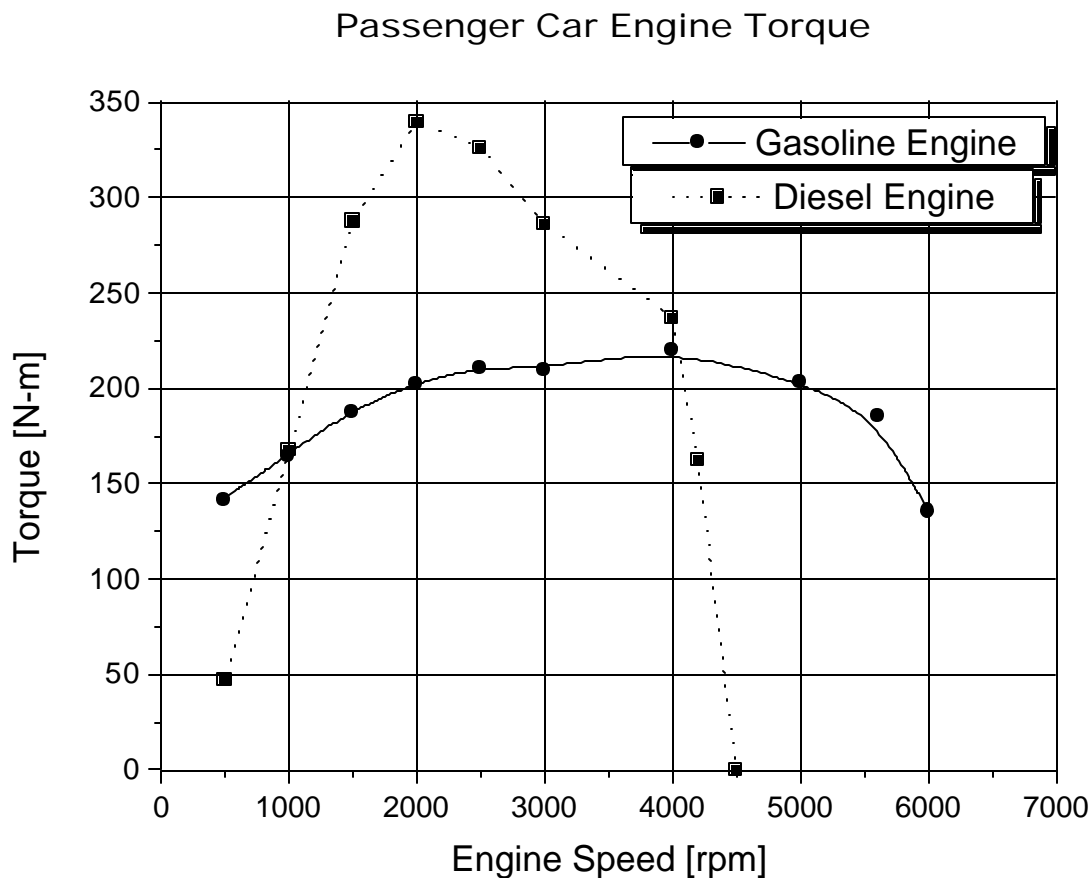
Figure 4. Gasoline and diesel engine maximum torque output

The simulation portion of the study quantified the displacement, output, and configuration of diesel engine needed to achieve equivalent vehicle acceleration. This information was needed to provide a boundary for the cost portion of the study.

For SUV and passenger cars with gasoline engines, the vehicle test weight used in the simulation model was based on average manufacturer data for equivalent 2002 model year vehicles. The vehicle test weight is equivalent to the vehicle curb weight plus 300 pounds for driver and instrumentation. Although it is possible that vehicle weight will decrease by the year 2010 through the continued increase in use of lighter materials and advanced structural optimization methods, some increase in weight is also possible because of the increased use of safety equipment in cars. It was therefore decided to maintain vehicle weight at values typical for the vehicle class in the 2002 model year.

The diesel powertrain is expected to add weight to the vehicle. To evaluate the comparison vehicles fairly, FEV also estimated the weight penalty that a diesel powertrain would add to the comparison vehicles. The weight of fuel included in the test weight of each vehicle was adjusted for gasoline or diesel. The fuel tank capacity of gasoline and diesel comparison vehicles was changed to produce equivalent vehicle range (using combined city/highway

fuel economy). The vehicle test weight includes an assumption that the tank is half full, and the difference in fuel density is taken into account. Table 3 summarizes the difference in vehicle weight attributed to the fuel.

	Passenger Car		Full-Size SUV	
	Gasoline	**Diesel**	**Gasoline**	**Diesel**
Combined fuel economy	30.2 mpg	42.1 mpg	17.0 mpg	24.0 mpg
Range (miles)	513 miles	513 miles	442 miles	442 miles
Fuel tank capacity (gallons)	17 gal	12.2 gal	26 gal	18.4 gal
Half tank capacity (gallons)	8.5 gal	6.1 gal	13 gal	9.2 gal
Weight of 1 gallon of fuel	6.4 lbs	7.1 lbs	6.4 lbs	7.1 lbs
Total fuel contribution to Vehicle Test Weight (lbs)	54.5 lbs	43.3 lbs	83.2 lbs	65.4 lbs
Weight reduction for diesel	Baseline	(11.2 lbs)	Baseline	(17.8 lbs)

Table 3: Difference in fuel weight for equivalent range

The modeled drag coefficient for passenger cars and SUV's was relatively unchanged from best-in-class vehicles available in 2002. No change in drag coefficient for gasoline and diesel engine powered vehicles was assumed. The frontal area is typical of 2002 model year vehicles and was not varied within the comparison vehicle classes. Overall rolling resistance, which represents the input of many components including tires, was typical of vehicles sold in 2002.

Using estimates developed in conjunction with the cost comparison, the passenger car weight difference between a gasoline and diesel engine powered vehicle was estimated to be 93 lbs.

Table 4 summarizes the vehicle level content assumptions for the comparison passenger car vehicles with gasoline and diesel engines.

Passenger Car	Gasoline	Diesel
Engine displacement and configuration	2.4L I-4	2.2L I-4
Boost pressure	0	15 psi
Maximum power (hp @ rpm)	157 @ 5600 rpm	133 @ 4000 rpm
Maximum torque (lb-ft @ rpm)	162 @ 4000 rpm	250 @ 2000 rpm
Transmission	4-speed auto	4-speed auto
1st gear ratio	3.94	3.94
2nd gear ratio	2.92	2.92
3rd gear ratio	1.4	1.4
4th gear ratio	1	1
Final drive ratio	2.74	2.68
Tire size	215/60R-16	215/60R-16
Vehicle test weight	3550 lbs	3643 lbs
Drag coefficient	0.28	0.28

Table 4. Passenger car comparative vehicle data

Table 5 summarizes the vehicle level content assumptions for the SUV vehicles. Using estimates developed in conjunction with the cost comparison, the SUV weight difference between a gasoline and diesel engine powered vehicle was estimated to be 180 lbs.

SUV	Gasoline	Diesel
Engine displacement and configuration	5L V8	4L V8
Boost pressure	0	15 psi
Maximum power (hp @ rpm)	232 @ 4000 rpm	246 @ 4000 rpm
Maximum torque (lb-ft @ rpm)	380 @ 2500 rpm	462 @ 2000 rpm
Transmission	4-speed auto	4-speed auto
1st gear ratio	2.84	2.84
2nd gear ratio	1.55	1.55
3rd gear ratio	1	1
4th gear ratio	0.7	0.7
Final drive ratio	3.73	3.43
Tire size	265/70R-17	265/70R-17
Vehicle test weight	5563 lbs	5743 lbs
Drag coefficient	0.41	0.41

Table 5. SUV comparative vehicle data

D. Cost and Weight Predictions

With reasonable predictions of the relative engine size and vehicle characteristics necessary to achieve parity in performance, the vehicle level content for gasoline and diesel engine versions was formed in detail. Assumptions for the relative technology content of the engines were made using vehicle technology in mass production in 2002.

Using the vehicle information determined to achieve equivalent vehicle acceleration performance, a detailed summary of the cost and weight differences between the gasoline and diesel engine versions of the passenger cars and SUV's was prepared. The following major areas account for most of the estimated cost and weight differences in the vehicles, so a discussion of each system is detailed in the following sections.

- Engine, including engine mounted fuel injection system and turbocharger
- Vehicle fuel system, including evaporative emissions and ORVR systems
- Air induction system including intercooler for diesel engines
- Vehicle electrical system including battery and starter
- Powertrain mounting system

Cost estimates represent assumed relative production cost increases for diesel vehicles and do not assume a "retail price equivalent" factor.

A detailed summary of the complete cost and weight comparisons for passenger car and SUV vehicles is included in section D.8 as Table 9 (passenger car) and Table 10 (SUV).

D.1 Gasoline and Diesel Engine

The majority of the cost and weight difference between gasoline and diesel comparison is the engine.

The majority of the cost penalty of the diesel engine is the fuel injection system. FEV estimates that the cost difference between the gasoline fuel injection system and the diesel fuel injection system is currently $735 for the passenger car and $1155 for the SUV. The elimination of the gasoline engine ignition system and throttle body costs are relatively small when compared to the overall diesel engine costs. Using the mature production assumptions consistent with this study, the estimated cost difference for the diesel fuel injection system is $465 and $735 for passenger car and SUV respectively.

Several factors contribute to the higher cost of the diesel fuel injection system. First and most influential, a diesel fuel injection system must meter fuel directly into the combustion chamber at high pressure. Typical automotive diesel fuel injection systems

operate with peak injection pressures of 1350 to 1600 bar (19,600 to 23,200 psi), while gasoline port fuel injection systems typically operates with system pressures of 3 to 5 bar (44 to 72 psi). The high pressure requirement for the diesel system requires the use of more expensive high strength materials for all components and for the high pressure connecting tubes to contain the fuel pressure.

The second factor that contributes to the higher cost of diesel fuel injection equipment is the lack of feedback control of fuel quantity. Typical electronic gasoline fuel injection systems operate using closed-loop control of fuel quantity through an oxygen sensor mounted in the exhaust system. Opening and closing the throttle plate on a gasoline engine adjusts the amount of air entering the engine. The amount of gasoline injected into the cylinder can be electronically adjusted to achieve the correct air-fuel mixture properties. The correct amount of fuel is metered and controlled with feedback depending on the amount of oxygen measured in the exhaust stream. A diesel engine operates primarily without a throttle; thus, the amount of air entering the cylinder is unregulated. The engine output is regulated by the amount of fuel injected into the cylinder. Therefore, the system must be deterministic in the amount of fuel injected. Accordingly, diesel fuel injectors are manufactured under strict tolerances. Also, a diesel fuel injection system operates without feedback control of fuel quantity.

A third factor that also contributes to the higher cost of diesel fuel injection equipment is fundamentally related to the noise produced by a diesel engine. Conventional diesel combustion noise is high because of a very high rate of cylinder pressure rise during the initial combustion phase when the initial pre-mixed amount of fuel is quickly burned upon auto-ignition. New common rail diesel fuel injection systems that are becoming extremely popular with European consumers, have the capability to introduce more than one injection event per cycle. With such a fuel injection system, an initial small injection quantity is added to the combustion chamber early. A short time later, the main fuel charge is injected. Because the early injection quantity is small, the initial combustion phase occurs more slowly and the noise produced by the initial combustion is reduced. Proper control of the tolerances of the quantity and relative timing of the early injection is critical to achieving low noise and low exhaust emissions. The capability to provide multiple injection events that occur close to each other also makes the diesel fuel injection system more expensive. Further, the tolerances of the components that can reliably inject the necessary small fuel injection quantity in a separate pulse add to the cost of the injector components.

Because the assumed common rail fuel injection system is a relatively new technology, current production costs may reflect significant development and capitalization costs. Further, the current market for light automotive common rail diesel fuel injection systems currently has only four suppliers: Bosch, Siemens, Delphi, and Denso. Bosch currently produces more systems than other suppliers in this rapidly growing market. As the market for diesel fuel injection systems stabilizes, more competition may result. The fuel

injectors themselves, which account for about half of the price of the complete system, may become more of a commodity just as gasoline port fuel injectors have become. Given the boundary conditions of this study – mature products produced in large volumes by several companies – FEV estimates that mature pricing for a diesel fuel injection system may be reduced by 30% from the 2002 price estimate. Mature production cost estimates use 2002 production cost estimates with 30% lower costs for the entire fuel injection system.

Beyond the injection system, other factors add to the cost of the diesel engine. The base mechanical engine represents a relatively small portion of the cost difference. As summarized in Table 6, the base engine differences are estimated to add between $30 and $40 to the cost of a diesel engine compared to a gasoline engine of similar output.

Other components that add cost to a diesel engine relative to a gasoline engine include the turbocharger, EGR valve, and vacuum pump. The turbocharger is required on the diesel engine to achieve competitive power density. For both comparison diesel engines in this study, variable geometry turbochargers are assumed. Because currently variable geometry turbochargers are in relatively low volume production, FEV also estimates that the turbocharger production cost may be reduced in a more competitive market conditions assumed by this study. FEV estimates that the turbocharger production cost may be reduced 30% compared to today's cost estimate.

To meet present NOx emissions standards in Europe or the US, a fast response, large flow EGR system is necessary. For these comparison vehicles, the passenger car is assumed to have a direct acting solenoid activated EGR valve with feedback control using a mass air flow sensor. The SUV is also assumed to have such a valve, but because of the higher vehicle weight, the SUV system should also include an EGR cooler. For both diesel vehicles, a simple intake throttle valve is also required to provide intake-to-exhaust manifold pressure drop to achieve high EGR rates. This EGR system content is typical of vehicles with diesel engines to meet current 2002 emissions standards.

Because the diesel engine produces little if any vacuum, a pump is required to provide the necessary vacuum to power the vacuum power-assisted brakes and provide a form of energy to actuators in the vehicle Heating Ventilation Air Conditioning (HVAC) system and vacuum modulated valves in the powertrain control system. For the purposes of this study, vacuum assisted brakes and components are still assumed to be typical for the classes of vehicle studied.

Component	Modifications for Base Diesel Engine	Estimated Incremental I-4 Cost (2002 $)	Estimated Incremental V-8 Cost (2002 $)
Cylinder block	Increased stiffness, provision for piston cooling jets	3	4
Main bearing caps	Increase stiffness, better material	2	3
Crankshaft	Increase stiffness, forged material instead of cast iron for I-4 gasoline engine	16	1
Main bearings	No change	0	0
Connecting rods	Larger piston pin, tapered top	3	6
Rod bearings	Premium material	2	4
Piston	Heavier	1	2
Rings			
Cylinder head	Increase stiffness, premium alloy material	3	6
Valvetrain	Reduced heat and engine speed	(3)	(4)
Piston cooling jets	Necessary to cool piston	5	6
Oil pump	Larger capacity, lower engine speed	0	0
Oil filter	Larger capacity	1	1
Intake manifold	No injector mounting, simpler design	(2)	(4)
Vibration damper	Dual mode	7	8
Total, Base Engine		**$38**	**$33**

Table 6. Base (mechanical) diesel engine component and cost difference

In this study the accessory drive is included in the engine assembly. Because the crankshaft speed variations on a diesel engine are higher than on a gasoline engine, it is expected that the alternator will require an over-running clutch for acceptable accessory drive belt durability. Further, the belt and belt tensioner will be of higher material cost with larger range of adjustment. The A/C compressor and power steering pump are not expected to change in weight or cost for either engine. The alternator is not expected to change in output.

For the classes of vehicles considered, an acoustic engine cover is typically included on a diesel engine to reduce cabin-level combustion and injector noise.

The gasoline engine must include an ignition system and throttle body, which are not necessary on the diesel engine.

Using current estimates, the cost increase of a diesel engine for the passenger car application vehicle is $910. For the SUV application, the cost penalty of the diesel engine is estimated to be $1365. Under the boundary conditions of this study, the mature production cost differences are estimated to be $586 and $870 for the passenger car and SUV diesel engines respectively. Table 7 summarizes the primary contributors to the cost difference between the gasoline and diesel engines for the passenger car application.

Component Modification for Diesel Powertrain	Current Estimated Cost Increment (2002 $)	Mature Estimated Cost Increment (2002 $)
Base engine mechanical	38	38
Fuel injection	735	465
Ignition	(75)	(75)
Turbocharger, variable geometry	180	126
Throttle body	(27)	(27)
Vacuum pump	10	10
EGR valve	20	20
Engine acoustic cover	12	12
Alternator (drive pulley clutch)	10	10
Accessory drive belt/tensioner	7	7
Total	**$910**	**$586**

Table 7. Passenger car diesel engine component cost difference

A complete summary of the engine cost and weight differences for the comparison vehicles is included in section D.8 as Table 9 (passenger car) and Table 10 (SUV).

D.2 Vehicle Fuel System

The vehicle fuel system for the gasoline engine includes an electric fuel pump with pre-filter, a variable output fuel pump control system, evaporative emissions content including carbon canisters to collect hydrocarbon vapors, and a purge valve to allow the engine to consume any collected vapors. The diesel fuel injection system includes a mechanically driven fuel pump; no electric fuel pump in the fuel tank is necessary on most diesel systems. Further, because the fuel is less volatile, diesel engine powered vehicles are not required to meet similar standards for evaporative emissions. Diesel engine powered

vehicles are not required to meet Onboard Refueling Vapor Recovery (ORVR) requirements of gasoline vehicles.

The diesel fuel filter is larger in capacity and must meet smaller filtration requirements than for gasoline engines. The tighter requirements are necessary because of the closer tolerances and higher loads of the diesel fuel injection equipment. A heated fuel filter is not expected to be required.

Because the amount of fuel required to provide a vehicle with equivalent range is smaller for a diesel, the tank volume can be reduced for a diesel passenger car. In this study, the size of the fuel tank was changed to achieve the same vehicle range for gasoline and diesel vehicles based on combined city/highway fuel economy predictions. The actual test weight difference between the two vehicles was calculated using the higher density of diesel fuel, smaller tank volume for the diesel, and assuming the fuel tank is half full at measured test weight.

D.3 Air Induction System

The air induction system for the diesel engine includes an intercooler, which is vital to achieving the power density of the turbocharged diesel engines. Because the Mass Air Flow (MAF) sensor on the diesel engine is used for emissions-critical EGR control, the MAF sensor for a diesel has a smaller tolerance band and higher cost than for a gasoline engine.

D.4 Powertrain Control System and Vehicle Electrical System

The relative complexity of the engine control system including the primary engine control unit, sensors, and wiring is similar for both gasoline and diesel engines. A comparison of the input/output devices for gasoline and diesel engines is made in Table 8.

The number of devices reveals that the relative complexity of the systems for gasoline and diesel engines is nearly equivalent. It is FEV's opinion that the complexity of engine management software and calibration effort needed for either engine can be considered approximately equivalent.

The starter motor must be upsized to provide the rotation torque necessary to start a diesel engine with a typical compression ratio of 18:1 compared to a compression ratio of typically 10:1 for a gasoline engine. Along with the larger starter motor, the diesel engine is also equipped with glow plugs to aid cold starting performance. Together, these two features require a substantially larger battery to provide equivalent starting capability at low ambient temperatures.

Gasoline	Diesel
Injectors (1 per cylinder)	Injectors (1 per cylinder)
Ignition (1 per cylinder)	None
Knock sensor	Acoustic sensor (optional)
EGR valve	EGR valve
Mass Air Flow (MAF) sensor	Mass Air Flow (MAF) sensor
Manifold Absolute Pressure (MAP) sensor	Manifold Absolute Pressure (MAP) sensor
Crank angle position sensor	Crank angle position sensor
Cam phase sensor	Cam phase sensor
Fuel pressure sensor	Fuel pressure sensor
Fuel pressure regulator	Fuel pressure regulator
Coolant temperature sensor	Coolant temperature sensor
Intake air temperature sensor	Intake air temperature sensor
Exhaust gas oxygen sensor(s)	None
Catalyst monitor sensor(s)	None
None	Fuel temperature sensor
Throttle position sensors (2)	Accelerator pedal sensors (2)
None	Atmospheric pressure sensor
None	Turbocharger actuator
Cooling fan controls	Cooling fan controls
A/C compressor control	A/C compressor control

Table 8. Engine control unit input/output list

Catalyst monitors are required for OBD monitoring of gasoline engine catalysts. For the SUV application, multiple catalysts (each with a monitoring sensor) are assumed. The diesel vehicles are assumed not to require sensors to monitor the catalysts in the exhaust system.

D.5 Powertrain Mounting System

Automotive diesel engines are typically turbocharged and operate at higher compression ratios than gasoline engines. The engine structure is designed for higher peak cylinder pressure levels that result from high boost pressure and high engine compression ratio.

Further, a diesel engine also operates without the need for significant throttling. For all these reasons, a diesel engine produces substantially higher engine shaking forces than a gasoline engine of comparable configuration and output. To achieve similar vehicle level noise and vibration levels with a diesel engine, it is therefore essential to enhance the isolation performance of the powertrain mounting system with the diesel engine.

For the two vehicle comparisons in this study, FEV has assumed a relative step in technology and isolation in the engine mounting system. Hydromounts are assumed for the gasoline vehicles, while switchable hydromounts are assumed for the diesel vehicles. The switching technology is available in mass-production in 2002 on several vehicles. Other forms of active or semi-active engine mounts are available but not currently produced in large volume.

D.6 Transmission and Drivetrain System

For the increased torque of the diesel engine, the transmission components are assumed not to change dramatically. Within the vehicle simulation, only the final drive ratio was changed for the diesel engine. FEV estimates that the transmission for the diesel engine will be upgraded to handle the higher engine torque. Premium bearing materials, added clutches to clutch packs with improved material, and upgraded gear surface treatment are the only substantial changes assumed. No weight increase is expected for these changes. The transmission cost increase associated with these upgrades is estimated to be $25 for both vehicle classes in this study.

D.7 Other Contributors

To provide comparable noise and vibration levels in the passenger compartment, the sound insulation package of the vehicle with a diesel engine will be upgraded. Higher density foam and thicker insulation is necessary for critical areas.

Because the engine operates more efficiently, the diesel engine produces less passenger compartment heating capacity. It is typical for vehicles with diesel engines to be equipped with supplemental heaters to provide passenger compartment heat. For this study, a supplemental coolant heater is assumed for both diesel vehicles. It is FEV's experience that such devices are necessary to meet federal requirements for windshield defrost time, and to meet consumer expectations. For the passenger car, an electric resistance heater in line with the coolant supply to the heater core is assumed. For the larger passenger volume of the SUV, a large supplemental heater that combusts fuel to provide increased heat to the coolant is assumed. The cost of these devices is estimated to be $15 for the passenger car and $50 for the SUV.

The diesel and gasoline engine exhaust systems are assumed to be nearly equivalent in content and cost for similar production volumes.

Because the engine heat rejection is somewhat less, the radiator can be modestly downsized for the diesel engine. Other cooling system content is assumed equivalent.

D.8 Cost and weight prediction summary

The predicted weight difference between gasoline and diesel vehicles was estimated and used in the vehicle simulation model to assess the vehicle performance. The cost differential between gasoline and diesel vehicles is summarized in Table 9 (passenger car) and Table 10 (SUV).

In both classes of vehicles, the primary cost and weight increase is due to the diesel engine itself.

Component	Modifications for Diesel Powertrain	Current Estimated Cost Increment (2002 $)	Mature Estimated Cost Increment (2002 $)	Estimated Weight Increment (lbs)
Engine	Sum	$910	$586	66 lb
	Base engine	38	38	
	Fuel injection	735	465	
	Ignition	(75)	(75)	
	Turbocharger, variable geometry	180	126	
	Throttle body	(27)	(27)	
	Vacuum pump	10	10	
	EGR valve	20	20	
	Engine acoustic cover	12	12	
	Alternator (drive pulley clutch)	10	10	
	Accessory drive belt/tensioner	7	7	
Air Induction	Sum	$55	$55	11 lb
	Intercooler and ducts	50	50	
	MAF sensor	5	5	
Exhaust	Sum	$0	$0	0 lb
Transmission	Sum	$25	$25	0 lb
Engine Electronic Control and Vehicle Electrical System	Sum	$20	$20	19 lb
	Engine electronic control unit	0	0	
	Exhaust gas oxygen sensor(s)	(30)	(30)	
	Battery, larger for diesel	15	15	
	Starter, 2 kW for diesel	20	20	
	Glow plugs / relay	15	15	
Powertrain Mounting System	Sum	$107	$107	1 lb
	Mounts, switchable hydromounts	100	100	
	Vacuum control valves, hoses	7	7	
Cooling System	Sum	($4)	($4)	0 lb
	Radiator			
Body	Sum	$10	$10	11 lb
	NVH package			
HVAC System	Sum	$15	$15	1 lb
	Supplemental coolant heater			
Chassis Fuel System	Sum	($75)	($75)	(16 lb)
	Fuel tank, mounting	(10)	(10)	
	Electric fuel supply pump, controller	(40)	(40)	
	Fuel filler and cap	(2)	(2)	
	Evaporation canisters / valves	(25)	(25)	
	Fuel filter	4	4	
	ORVR requirements	(6)	(6)	
Totals		**$1063**	**$739**	**93 lb**

Table 9. Passenger car production cost and weight increments for diesel

Component	Modifications for Diesel Powertrain	Current Estimated Cost Increment (2002 $)	Mature Estimated Cost Increment (2002 $)	Estimated Weight Increment
Engine	Sum	$1365	$870	132 lb
	Base engine	33	33	
	Fuel injection system	1155	735	
	Ignition system	(120)	(120)	
	Turbocharger, variable geometry	250	175	
	Throttle body	(33)	(33)	
	EGR cooler	20	20	
	Vacuum pump	10	10	
	EGR valve	20	20	
	Engine acoustic cover	12	12	
	Alternator (drive pulley clutch)	10	10	
	Accessory drive belt/tensioner	8	8	
Air Induction	Sum	$80	$80	11 lb
	Intercooler and ducts	75	75	
	MAF sensor	5	5	
Exhaust	Sum	$0	$0	0 lb
Transmission	Sum	$25	$25	21 lb
	Transmission			
Engine Electronic Control and Vehicle Electrical System	Sum	$12	$12	17 lb
	Engine electronic control unit	0	0	
	Exhaust gas oxygen sensor(s)	(60)	(60)	
	Battery, larger for diesel	25	25	
	Starter, 3 kW for diesel	20	20	
	Glow plugs / relay	27	27	
Powertrain Mounting System	Sum	$87	$87	2 lb
	Mounts, switchable hydromounts	80	80	
	Vacuum control valve, hoses	7	7	
Cooling System	Sum	($13)	($13)	0 lb
	Radiator			
Body	Sum	$25	$25	12 lb
	NVH package			
HVAC System	Sum	$50	$50	8 lb
	Supplemental coolant heater			
Chassis Fuel System	Sum	($94)	($94)	(23 lb)
	Fuel tank, mounting	(13)	(13)	
	Electric fuel supply pump	(55)	(55)	
	Fuel filler and cap	(2)	(2)	
	Evaporation canisters / valves	(30)	(30)	
	Fuel filter	6	6	
	ORVR requirements	(8)	(8)	
Total		**$1537**	**$1042**	**180 lb**

Table 10. SUV production cost and weight increments for diesel

E. Results

FEV performed simulation of two representative vehicles to assess the fuel consumption and performance difference for diesel engines compared to baseline gasoline engines. Simulation models of vehicles with gasoline engines were adapted to include diesel engines. Along with the engine, the final drive ratio was optimized, and the vehicle weight was increased. The required peak engine performance necessary to achieve performance parity with the gasoline vehicle was determined.

The weight increase from a diesel powertrain was estimated using detailed summaries of the component differences shown in Tables 9 and 10 in Section D.8. The primary contributor to the increase in vehicle weight is the diesel engine itself. Other components including the battery and starter are also considered.

Fuel economy and performance of the vehicles with gasoline and diesel engines were compared using the simulation model. Results are summarized in Table 11 for the passenger car and Table 12 for the SUV. For both vehicle classes with equivalent zero to 60 mile per hour acceleration, the combined fuel economy in miles per gallon improved by about 40% with the diesel engine.

Passenger Car	Gasoline	Diesel
Vehicle Weight (test)	3550 lbs	3643 lbs
0-60 mph Acceleration	11.5 sec	11.5 sec
City Fuel Economy	24.8 mpg	36.7 mpg
Highway Fuel Economy	41.0 mpg	51.3 mpg
Combined Fuel Economy	30.2 mpg	42.1 mpg
30-50 mph Acceleration	4.8 sec	5.8 sec
50-70 mph Acceleration	9.8 sec	7.3 sec
Top Speed	133 mph	122 mph
55 mph Steady State Fuel Economy	44.9 mpg	49.8 mpg
Current Production Cost Estimate (2002 $)	Baseline	+ $1063
Mature Production Cost Estimate (2002 $)	Baseline	+ $739

Table 11. Passenger car comparative results

The cost increase from a diesel powertrain was estimated using detailed summaries of the component differences shown in Tables 9 and 10 in Section D.8. The primary contributor to the increase in vehicle cost is the diesel engine itself.

SUV	Gasoline	Diesel
Vehicle Weight (test)	5563 lbs	5743 lbs
0-60 mph Acceleration	10.3 sec	10.3 sec
City Fuel Economy	14.7 mpg	21.4 mpg
Highway Fuel Economy	21.0 mpg	28.1 mpg
Combined Fuel Economy	17.0 mpg	24.0 mpg
30-50 mph Acceleration	4.5 sec	4.8 sec
50-70 mph Acceleration	15.3 sec	15.0 sec
Top Speed	119 mph	119 mph
55 mph Steady State Fuel Economy	19.9 mpg	27.5 mpg
Current Production Cost Estimate (2002 $)	Baseline	+ $1537
Mature Production Cost Estimate (2002 $)	Baseline	+ $1042

Table 12. SUV comparative results

The current estimated production cost of the common rail fuel injection system on the diesel engine was estimated for both vehicle classes. Because some current technology is new and the production volumes are rapidly growing, the current system prices may fall significantly as market competition increases. The production cost of gasoline port fuel injectors fell as the number of suppliers and market penetration increased. FEV estimates that a 30% reduction in common rail diesel fuel injection total system cost could be achieved under the boundary conditions of this study. FEV further estimates that the production cost of a variable geometry turbocharger may also be sensitive to market competition. A reduction in production cost of 30% was estimated for the turbocharger component on both vehicles. With these assumptions, estimates of the diesel powertrain system costs were made.

The cost increment for the diesel powertrain is also summarized for passenger car and SUV in Tables 11 and 12 using current cost estimates and mature cost estimates.

Based on direction from the EPA Project Officer, the relative cost and weight differences of exhaust aftertreatment systems for gasoline and diesel vehicles are not included in this study.

F.   Appendix A – References

[1] National Automobile Dealers Association, 2002 NADA Data

[2] USA Today, May 15, 2001, "Diesel-Sippers Win Fans as Gas Prices Soar"

[3] VDA (Verband der Automobilindustrie e.V.) Auto 2002 Annual Report

Appendix J: FEV Report - Variable Compression Ratio and Variable Displacement Engine Cost

This appendix contains a report written by FEV to estimate the costs for a variable compression ratio engine and a variable displacement engine.

Appendix J

FEV
Engine Technology
Draft Report Rev. 2   FEV02-622F

Variable Compression Ratio and
Variable Displacement Engine Cost

Engine and Vehicle Development with Production Intent
Contract No. 68-C-02-036
Work Assignment 0-1

Development of Various Unique Engines

Prepared for:

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January 29, 2003

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Variable Compression Ratio and Variable Displacement Engine Cost

A. Introduction and Program Objectives

EPA has utilized FEV to provide design concepts for Variable Compression Ratio (VCR) and variable displacement engines under previous EPA contracts. The objective of this project was to conduct additional analysis to estimate the incremental cost of each concept applied to the base engines utilized in FEV's study titled *Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks* submitted under contract 68-C-01-155 WA 0-2.

The VCR concept has been incorporated into a 2-cylinder Boxer engine utilizing a piston within a piston design, which is hydraulically actuated and incorporated into a 70 mm diameter bore, under previous contract work scopes. Components have been designed, fabricated and initial development testing performed for this application, which provides the component designs as shown in Figure A.1 for the VCR cost study. The variable displacement engine concepts were developed as a twin crankshaft concept of a V-8 engine as shown in Figure A.2, as the basic architecture for a family of variable displacement Twin Crank engines ranging from 6-cylinders to 12-cylinders.

The technical details of both concepts are contained in previous reports and presentations. This report addresses the cost aspects.
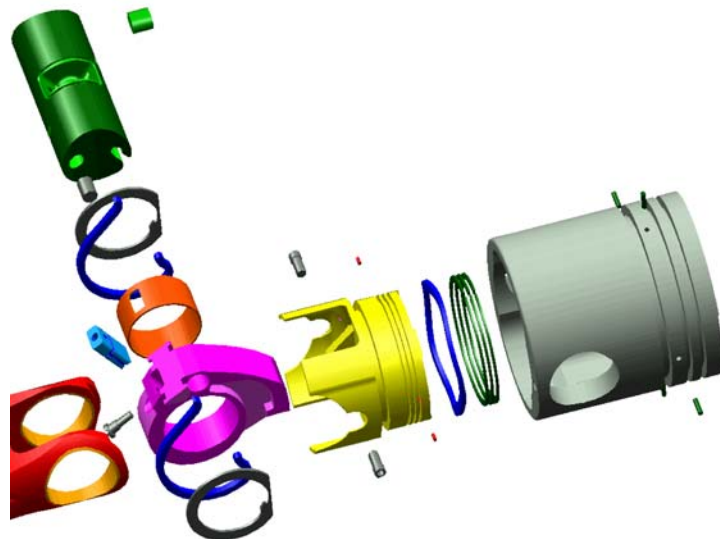
Figure A.1: Component Designs for the VCR Cost Study
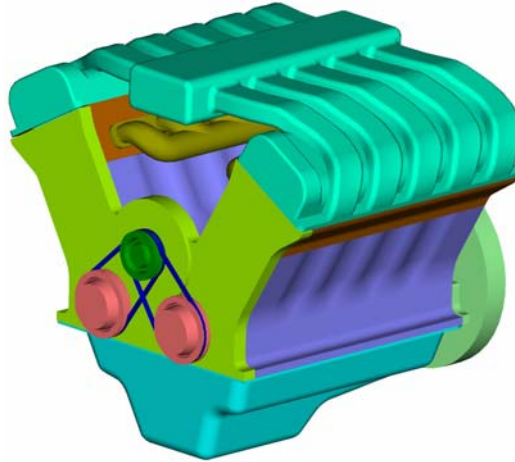
Figure A.2: Variable Displacement Twin Crank V-8 Engine Concept

B. Methodology

The cost estimates were performed using the following methodology and are based on a production volume of 250,000 units annually:

1. Each affected component was reviewed and a percentage increment was estimated for material and processing cost, i.e., 5% decrease in raw casting cost and 15% increase in machining cost. The incremental change in assembly and subassembly cost was also estimated.

2. Using a detailed production engine cost bill of material (from another program) the percent increments were calculated as dollar values.

3. The same detailed engine cost bill of material was feature-normalized to the base engine being used in the *Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks* report and the total engine cost so adjusted.

4. The final cost differential was calculated by multiplying the cost from Step 2 by the ratio of the adjusted detail cost from Step 3 to the cost of the base engine used in the *Cost and Fuel Economy Comparison of Diesel and Gasoline Powertrains in Passenger Cars and Light Trucks* report.

B.1   Variable Compression Ratio Engine

The cost estimate uses a 2.4L I-4 engine typified by a Toyota Camry. The cost includes weight added to the balance shafts to compensate for the increased piston weight. The cost increase should be doubled for a 5.0 L V-8 engine, although balance shafts are not required, additional weight would be required on the crankshaft counterweight and the crankcase would be expanded for the larger counterweights. Details of the costing are listed in Table B.1.1. Additional costs for high pressure oil supply, control actuators and electronics were not included in the total costs.

VCR Piston in Piston	
Outer Piston	Material cost, 70% of same size production piston
	Machining cost, 50% increase over standard piston
	Hard coat inside bore, 20% increase in finished cost
Inner Piston	Material, aluminum
	Material and machining cost, same as production piston of same size
	Add 10% for skirt coating
	Add inner piston rings and spring washer
Small Piston Pins	With retention feature, both pins same as one large pin
Forked Connecting Rod	Material, forged solid 25% increase
	Machining, forked end and oil drilling 150% increase
	2 partial bushings, 50% over single bushing
Piston Pin	Material, 15% increase
	Machining, 300% increase
Actuating Cam	Add powder metal parts, cost/cam same as oil pump rotor set
	Bushing, same as conn rod pin bushing
Springs	50% cost of valve spring each
Fasteners	6 pins, clips, keys = $0.60
Oil Passages	Rod and main bearings - add cost difference between upper and lower to each
	Block, add 2% to casting cost and 10% to machining cost
	Crank, add 15% to machining cost
Not Costed:	
Control Valve	
High Pressure Oil Supply	
Integration into Block	

Table B.1.1: Component Cost Considerations–Variable Compression Ratio

B.2   Variable Displacement Engine:

The cost estimate was conducted for a 5.0L Twin Crank V-8 engine. Details of the costing are listed in Table B.2.1. The output gear drive, clutches, accessory drive, modified starter and electronics control module were not included being specific to the power output arrangement. A suitable strategy for a variable displacement Twin Crank 4-cylinder engine has not be identified due to balance issues, therefore no cost estimates were performed for this option. Concept designs have been completed for a Twin Crank 6-cylinder, 10-cylinder, and 12-cylinder engine but were not costed for this study.

Twin Crank	
Cylinder block	Casting add 12% due to weight increase
	Machining add 15% for oil gallery, added caps, and misc. fasteners
Main bearing caps	Add 5 caps plus fasteners plus 100%
Crankshaft	Replace V-8 with 2 4's plus 90% material and 80% machining
Timing drive	Crank sprocket plus 100%
	Tensioner plus 100%
	2 short chains instead of long chain plus 75%
Front cover	Larger plus 10% material
Crank seals	Front and rear plus 100%
Flywheel	Add one plus 100%
Oil pan	Larger and more fasteners plus 20%
Oil pump	Replace with 2 smaller plus 90%
	Oil pickup plus 100%
Intake manifold	Two 4's replace one 8, plus 40% material and 80% machining
	Add throttle body plus 80%
Sensors	Crank plus 100%
	Cam plus 100%
	Oil pressure plus 100%
Engine wiring	Plus 40%
Engine assembly	Plus 35%

Table B.2.1: Component Cost Considerations–Twin Crank V-8 Engine

C. Results

The incremental costs for the VCR 2.4L I-4 engine are summarized in Table C.1. The cost includes $45.55 for modifications to existing components and $43.24 for new additional components totaling $88.79. A VCR 5.0L V-8 engine would be twice this amount totaling $177.58.

Modified Parts	Cost	Added Parts	Cost
Pistons (4)	$21.60	Inner pistons (4)	$25.00
Piston pins (4)	$2.70	Small piston pins (4)	$3.40
Cylinder block	$9.06	Inner piston rings (4 sets)	$2.52
Crankshaft	$9.19	Springs (4 sets)	$0.96
Balance shafts (2)	$3.00	Actuating cams (4)	$10.00
		Fasteners (4 sets)	$0.60
		Actuating cam bushings (4)	$0.76
Sub Total	**$45.55**	**Sub Total**	**$43.24**
		Total	**$88.79**

Table C.1: Incremental Cost – 4-cylinder VCR Engine

The incremental costs for the variable displacement Twin Crank 5.0L V-8 Engine are summarized in Table C.2. The cost includes $102.85 for modifications to existing components and $174.99 for new additional components totaling $277.84.

Modified Parts	Cost	Added Parts	Cost
Engine assembly	$47.18	Crankshaft sprocket	$1.17
Timing belt cover	$3.37	Cam sensor	$6.91
Cylinder block	$36.79	Crankshaft bearing caps	$16.34
Oil pan and gasket	$3.82	Main bearings	$5.19
Engine wiring	$22.44	Crankshaft	$122.43
Crankshaft	($10.75)	Crankshaft vibration damper	$10.10
		Crankshaft & camshaft seals	$12.85
Sub Total	**$102.85**	**Sub Total**	**$174.99**
		Total	**$277.84**

Table C.2: Incremental Cost – Twin Crank V-8 Engine

Figure C.1 from the EPA shows the inclusion of the conventional mechanical power output option for the variable displacement Twin Crank 5.0L V-8 Engine. This option would add $53.40 (or $153.40 with the control system), to the total cost. Table C.3 shows a breakdown of the components.
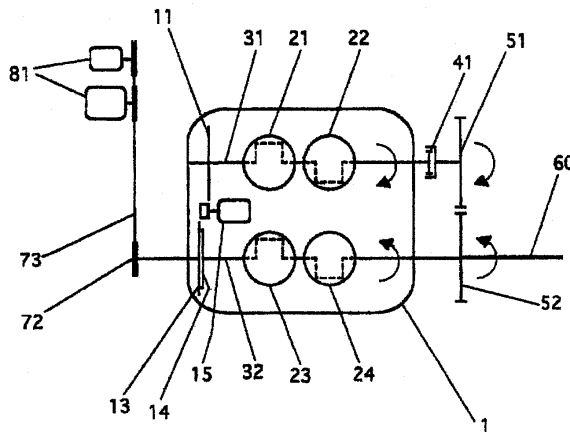
Figure C.1: Conventional Mechanical Power Output Option

Conventional	Cost
Output one-way clutch	$9.00
Output gear x 2	$16.00
Flywheel with ring gear	$8.00
Added starter cost	$18.00
Larger flywheel housing	$2.40
Sub Total	**$53.40**
Control System	**$100.00**
Total	**$153.40**

Table C.3: Incremental Cost – Twin Crank V-8 Engine

Conventional Option

Figure C.2 from the EPA shows the variable displacement Twin Crank 5.0L V-8 Engine for the hydraulic hybrid application incorporating two (2) hydraulic units.   Each hydraulic unit is assumed to be capable of withstanding crankshaft loads, therefore eliminating the need for two (2) intermediate bearing assemblies.   This option would add $28.30 (or $128.30 with the control system), to the total cost.   Table C.4 shows a breakdown of the components.
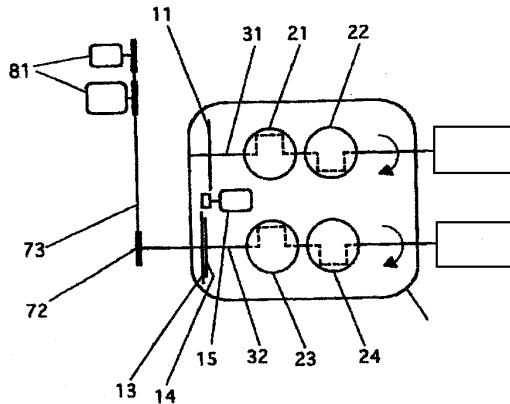
Figure C.2: Hydraulic Hybrid Option

Hydraulic Hybrid	Cost
Flywheel with ring gear	$8.00
Added starter cost	$18.00
Block additions/fasteners	$2.30
Sub Total	$28.30
Control System	$100.00
Total	$128.30

Table C.4: Incremental Cost – Twin Crank V-8 Engine

Hydraulic Hybrid Option

D.   Recommendations

The incremental costs provided in this analysis are estimates based on actual manufactured costs of comparable components.   Additional accuracy can be realized with costing obtained from production suppliers and completion of detailed designs for the Twin Crank Engine concept.

Appendix K: Price Factors: Price per Unit Weight by Component System

As discussed in Section 6, the manufacturing cost of each hardware component is estimated from the weight of the component multiplied by price per unit weight. The price per unit weight varies depending on the complexity of manufacturing the component. Appendix K gives the source data used to derive the complexity price factors. There are three major price per weight figures used in this analysis, based on components that are used in three major vehicle subsystems: transmission, engine, and chassis. Price per weight values for these three vehicle subsystems were derived using cost data from a typical 1990 Big-Three vehicle adjusted to 2002 costs. Table K-1 gives the original cost by component for the 1990 vehicle. Further explanation of the development of the price factors is discussed in Section 6.

Table K-1
Vehicle Manufacturing Costs
1990 Car - V6, 3.0L, 4 Speed Auto, FI, FWD

Subsystem	Finished Wt (lbs)	Material Used	Cost/ Pound	Material Costs	Labor Hours	Labor Rate	Labor Cost	Overhead Labor Rate	Overhead Labor Cost	Total Labor Cost	Total Mfr Cost	Total Div. Cost
Body												
Body in White	826	926	$0.40	$370.40	10.84	$9.50	102.98	250%	$257.45	$360.43	$730.83	
How Int & Ext	33	33	$0.42	$13.86	0.59	$9.51	5.61	100%	$5.61	$11.22	$25.08	
Elect. Components	23	23	$0.78	$17.94	0.52	$9.50	4.94	100%	$4.94	$9.88	$27.82	
Molding Panels	30	33	$1.10	$36.30	0.37	$9.51	3.52	150%	$5.28	$8.80	$45.10	
Trim & Insulation	207	210	$1.00	$210.00	4.03	$9.50	38.29	150%	$57.44	$95.73	$305.73	
Seats	107	110	$1.10	$121.00	1.73	$9.50	16.44	150%	$24.66	$41.10	$162.10	
Glass	81	81	$1.10	$89.10	1.37	$9.50	13.02	200%	$26.04	$39.06	$128.16	
Safety Equipment	21	21	$1.00	$21.00	0.55	$9.51	5.23	100%	$5.23	$10.46	$31.46	
Coatings	10	10	$0.50	$5.00	0.07	$9.57	0.67	200%	$1.34	$2.01	$7.01	
Total Body	**1338**	**1447**	**$7.40**	**$884.60**	**20.07**	**$9.50**	**$190.70**		**$387.99**	**$578.69**	**$1,463.29**	**$2,268**
Engine												
Base Engine	444	464	$0.60	$278.40	13.11	$9.50	$124.55	250%	$311.38	$435.93	$714.33	
Engine Comp. Access	160	180	$0.40	$72.00	2.40	$9.50	$22.80	150%	$34.20	$57.00	$129.00	
Eng. Assembly	0	0	$0.00	$0.00	6.00	$9.50	$57.00	250%	$142.50	$199.50	$199.50	
Total Engine	**604**	**644**	**$1.00**	**$350.40**	**21.51**	**$9.50**	**$204.35**		**$488.08**	**$692.43**	**$1,042.83**	**$1,616**
Transmission												
Clutch & Controls	6.5	8	$0.40	$3.20	0.05	$9.60	$0.48	150%	$0.72	$1.20	$4.40	
Transmission	134	140	$0.40	$56.00	4.30	$9.50	$40.85	150%	$61.28	$102.13	$158.13	
Trans Assembly	0	0	$0.00	$0.00	3.47	$9.50	$32.97	250%	$82.43	$115.40	$115.40	
Total Transmission	**141**	**148**	**$0.80**	**$59.20**	**7.82**	**$9.50**	**$74.30**		**$144.42**	**$218.72**	**$277.92**	**$431**
Chassis												
Eng Electrical	38	38	$0.75	$28.50	0.53	$9.51	$5.04	100%	$5.04	$10.08	$38.58	
FI Emission System	30	32	$3.00	$96.00	0.70	$9.50	$6.65	100%	$6.65	$13.30	$109.30	
Final Drive	110	115	$0.40	$46.00	1.52	$9.50	$14.44	150%	$21.66	$36.10	$82.10	
Frame	99	110	$0.32	$35.20	1.30	$9.50	$12.35	150%	$18.53	$30.88	$66.08	
Suspension	153	160	$1.40	$224.00	2.00	$9.50	$19.00	150%	$28.50	$47.50	$271.50	
Steering	60	65	$0.40	$26.00	1.17	$9.50	$11.12	150%	$16.68	$27.80	$53.80	
Brakes	154	160	$0.55	$88.00	3.20	$9.50	$30.40	150%	$45.60	$76.00	$164.00	
Wheels/Tires/ Tools	181	190	$0.55	$104.50	6.40	$9.50	$60.80	200%	$121.60	$182.40	$286.90	
Exhaust	33	35	$0.60	$21.00	1.40	$9.50	$13.30	100%	$13.30	$26.60	$47.60	
Catalytic Convertor	30	33	$3.00	$99.00	0.60	$9.50	$5.70	250%	$14.25	$19.95	$118.95	
Fuel System	24	27	$0.30	$8.10	0.50	$9.50	$4.75	150%	$7.13	$11.88	$19.98	
Fender Shields Bumper	90	93	$0.90	$83.70	1.80	$9.50	$17.10	150%	$25.65	$42.75	$126.45	
Chassis Elect Battery	41	41	$0.30	$12.30	1.76	$9.50	$16.72	100%	$16.72	$33.44	$45.74	
Fluids	115	115	$0.70	$80.50	2.70	$9.50	$25.65	150%	$38.48	$64.13	$144.63	
Accessories Equip.	4	4	$1.10	$4.40	0.10	$9.50	$0.95	150%	$1.43	$2.38	$6.78	
Total Chassis	**1162**	**1218**	**$14.27**	**$957.20**	**25.68**	**$9.50**	**$243.97**		**$381.20**	**$625.17**	**$1,582.37**	**$2,453**
Vehicle Assembly	0	0	$0.00	$0.00	35.00	$9.50	$332.50	250%	$831.25	$1,163.75	$1,163.75	$1,803
Total Vehicle	**3245**	**3457**	**$23.47**	**$2,251.40**	**110.08**	**$9.50**	**$1,045.82**		**$2,232.93**	**$3,278.75**	**$5,530.00**	**$8,571**

	MSRP	**$12,944**

Tecnology Improvement Incremental Cost Analysis , Easton Consultants for

Committee on Fuel Economy of Automobiles and Light Trucks Workshop, July 1991

Appendix L: Incremental Cost Calculations by Technology Scenario

Appendix L provides the detailed incremental cost data for each of the 40 technology scenarios considered in the body of this report. There is one table for each technology. Each of the tables in the Appendix provides the list of components added or subtracted from the base vehicle technology to form the new technology. For each listed component within a technology, the component weight in kg, the price per kg, the supplier price and the retail price equivalent (RPE) is given. The weight and price of components whose function is replaced by other hardware are noted in red as subtractions from the incremental cost calculation. The net change in cost is the total incremental cost provided near the bottom of each table. The total incremental costs of the technology along with the change in fuel economy and brake savings are used in the calculation of payback and vehicle lifetime savings.

Similar tables for the sensitivity case with reduced roadload have not been provided in the report. As discussed in Appendix A, the cost of reducing roadload by 20% is estimated to be $210 for all the technologies. There is no need to recreate all these tables for the simple addition of $210 to the total incremental cost of each technology.

Tables L1-1 through L1-20 contain cost data for SUV configurations.

Tables L2-1 through L2-20 contain cost data for Car configurations.

Table L1-1: Base Case Incremental Cost
4WD SUV Gas, Conventional Transmission

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Totals	**0.0**		**$0**

Table L1-2: Incremental Cost
4WD SUV   Clean Diesel

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for diesel engine	81.6	-	$1,324
net downsize of fuel tank		$7.19	$0
Totals	**81.6**		**$1,324**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,668**

Table L1-3: Incremental Cost
4WD SUV   Gas, Variable Displacement

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for variable displacement engine	43.1	-	$431
net downsize of fuel tank	-1.2	$7.19	-$9
Totals	**41.9**		**$422**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$532**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**14.1%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	16.69
improved consumption (gpm)	0.0599
consumption reduction	**-12.4%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	24.5	(3.5)
fuel tank weight (kg)	10.0	8.7	(1.23)

Table L1-4: Incremental Cost
4WD SUV   Clean Diesel, Variable Displacement

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for diesel engine	81.6	-	$1,324
cost increase for variable displacement engine	43.1	-	$431
net downsize of fuel tank	-3.6	$7.19	-$13 *
Totals	**121.2**		**$1,742**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,195**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**55.4%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	22.74
improved consumption (gpm)	0.0440
consumption reduction	**-35.6%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	18.0	(10.0)
fuel tank weight (kg)	10.0	6.4	(3.56)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-5: Incremental Costs
4WD SUV Gas, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-1.1	$7.19	-$8
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**125.8**		**$1,048**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,321**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**12.1%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	16.40
improved consumption (gpm)	0.0610
consumption reduction	**-10.8%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	25.0	(3.0)
fuel tank weight (kg)	10.0	8.9	(1.08)

Table L1-6: Incremental Costs
4WD SUV Clean Diesel, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	81.65	-	$1,324
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-3.6	$7.19	-$13 *
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**204.9**		**$2,367**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,983**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**55.4%**	
base mpg	14.63	
base consumption (gpm)	0.0684	
improved mpg	22.74	
improved consumption (gpm)	0.0440	
consumption reduction	**-35.6%**	

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	18.0	(10.0)
fuel tank weight (kg)	10.0	6.4	(3.56)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-7: Incremental Costs

4WD SUV Gas, Variable Displacement, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for variable displacement engine	43.09	-	$406
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.2	$7.19	-$16
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**167.7**		**$1,446**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,822**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**29.0%**	
base mpg	14.63	
base consumption (gpm)	0.0684	
improved mpg	18.87	
improved consumption (gpm)	0.0530	
consumption reduction	**-22.5%**	

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	21.7	(6.3)
fuel tank weight (kg)	10.0	7.7	(2.24)

Table L1-8: Incremental Costs
4WD SUV Clean Diesel, Variable Displacement, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	81.65	-	$1,324
cost increase for variable displacement engine	43.09	-	$406
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.3	$7.19	-$18 *
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**247.2**		**$2,768**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$3,487**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**77.2%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	25.92
improved consumption (gpm)	0.0386
consumption reduction	**-43.6%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	15.8	(12.2)
fuel tank weight (kg)	10.0	5.6	(4.35)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-9: Incremental Costs
4WD SUV Gas, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-1.3	$7.19	-$10
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
Initial fuel tank size (gals)	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
Battery upsize	5.2	$2.70	$14
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**130.7**		**$1,060**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,336**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**15.3%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	16.87
improved consumption (gpm)	0.0593
consumption reduction	**-13.3%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	24.3	(3.7)
fuel tank weight (kg)	10.0	8.7	(1.32)

Table L1-10: Incremental Costs
4WD SUV Clean Diesel, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	81.65	-	$1,324
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-3.7	$7.19	-$13 *
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
Battery upsize	5.2	$2.70	$14
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**210.0**		**$2,380**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,999**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**58.4%**	
base mpg	14.63	
base consumption (gpm)	0.0684	
improved mpg	23.17	
improved consumption (gpm)	0.0432	
consumption reduction	**-36.9%**	

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	17.7	(10.3)
fuel tank weight (kg)	10.0	6.3	(3.68)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-11: Incremental Costs
4WD SUV Gas, Variable Displacement, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for variable displacement engine	43.09	-	$406
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.3	$7.19	-$17
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
Battery upsize	5.2	$2.70	$14
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**172.8**		**$1,459**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,838**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**30.8%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	19.14
improved consumption (gpm)	0.0523
consumption reduction	**-23.5%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	21.4	(6.6)
fuel tank weight (kg)	10.0	7.6	(2.35)

Table L1-12: Incremental Costs
4WD SUV Clean Diesel, Variable Displacement, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor (per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
1.4 gearset integrated into transfer case	3.5	$10.45	$37
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	81.65	-	$1,324
cost increase for variable displacement engine	43.09	-	$406
110 cc pump motor (w/mounting flange for transfer case)	37.7	$9.11	$343
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.4	$7.19	-$19 *
fitting and hoses	8.1	$7.19	$58
oil cooler and filter loop (front motor low side)	8.5	$7.19	$61
accumulator mounting brackets	4.5	$7.19	$33
pump motor isolation mount (in addition to transfer case mount)	1.0	$7.19	$7
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	16.9	$3.00	$51
Battery upsize	5.2	$2.70	$14
7 gal composite accumulator (high pressure)	32.3	$10.00	$323
7 gal composite accumulator (low pressure)	14.3	$10.00	$143
Totals	**252.4**		**$2,781**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$3,504**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**79.4%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	26.25
improved consumption (gpm)	0.0381
consumption reduction	**-44.3%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	15.6	(12.4)
fuel tank weight (kg)	10.0	5.6	(4.42)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-13: Incremental Cost
4WD SUV: Gas, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
power steering system (pump, reservoir, steering gear)		$9.11	$0
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-1.4	$7.19	-$10
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**83.0**		**$438**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$552**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**16.2%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	17.00
improved consumption (gpm)	0.0588
consumption reduction	**-13.9%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	24.1	(3.9)
fuel tank weight (kg)	10.0	8.6	(1.39)

Table L1-14: Incremental Cost
4WD SUV Clean Diesel, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for diesel engine	81.6	-	$1,324
power steering system (pump, reservoir, steering gear)		$9.11	$0
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-3.6	$7.19	-$13 *
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**162.5**		**$1,759**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,217**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**56.5%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	22.90
improved consumption (gpm)	0.0437
consumption reduction	**-36.1%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	17.9	(10.1)
fuel tank weight (kg)	10.0	6.4	(3.60)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-15: Incremental Cost
4WD SUV Gas, Variable Displacement, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for variable displacement engine	43.1	-	$406
power steering system (pump, reservoir, steering gear)		$9.11	$0
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.3	$7.19	-$17
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**125.2**		**$837**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,055**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**30.7%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	19.12
improved consumption (gpm)	0.0523
consumption reduction	**-23.5%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	21.4	(6.6)
fuel tank weight (kg)	10.0	7.6	(2.34)

Table L1-16: Incremental Cost
4WD SUV Clean Diesel, Variable Displacement, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for diesel engine	81.6	-	$1,324
cost increase for variable displacement engine	43.1	-	$406
power steering system (pump, reservoir, steering gear)		$9.11	$0
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.4	$7.19	-$19 *
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**204.8**		**$2,160**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,721**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**78.6%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	26.13
improved consumption (gpm)	0.0383
consumption reduction	**-44.0%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	15.7	(12.3)
fuel tank weight (kg)	10.0	5.6	(4.39)

*An adjustment was made to this value to account for the partial credit already
taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-17: Incremental Cost
4WD SUV: Gas, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
power steering system (pump, reservoir, steering gear)	-17.3	$9.11	-$158
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system	15.6	$9.11	$142
hydraulic driven alternator	4.5	$9.11	$41
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.4	$7.19	-$17
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**84.8**		**$457**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$575**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**31.6%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	19.25
improved consumption (gpm)	0.0519
consumption reduction	**-24.0%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	21.3	(6.7)
fuel tank weight (kg)	10.0	7.6	(2.40)

Table L1-18: Incremental Cost
4WD SUV   Clean Diesel, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for diesel engine	81.6	-	$1,324
power steering system (pump, reservoir, steering gear)	-17.3	$9.11	-$158
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system	15.6	$9.11	$142
hydraulic driven alternator	4.5	$9.11	$41
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.5	$7.19	-$19 *
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**164.4**		**$1,778**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,241**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**82.3%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	26.67
improved consumption (gpm)	0.0375
consumption reduction	**-45.1%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	15.4	(12.6)
fuel tank weight (kg)	10.0	5.5	(4.51)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L1-19: Incremental Cost
4WD SUV   Gas, Variable Displacement, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for variable displacement engine	43.1	-	$406
power steering system (pump, reservoir, steering gear)	-17.3	$9.11	-$158
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system	15.6	$9.11	$142
hydraulic driven alternator	4.5	$9.11	$41
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.7	$7.19	-$20
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**127.6**		**$860**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,084**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**37.5%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	20.12
improved consumption (gpm)	0.0497
consumption reduction	-27.3%

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	20.4	(7.6)
fuel tank weight (kg)	10.0	7.3	(2.72)

Table L1-20: Incremental Cost
4WD SUV Clean Diesel, Variable Displacement, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-106.0	$10.45	-$1,108
transfer case	-47.3	$10.45	-$494
2 speed planetary (w/housing) for rear power unit	15.0	$10.45	$157
Complexity Level #2 (like an Engine)			
engine downsize	-31.0	$9.11	-$282
cost increase for diesel engine	81.6	-	$1,324
cost increase for variable displacement engine	43.1	-	$406
power steering system (pump, reservoir, steering gear)	-17.3	$9.11	-$158
135 cc engine pump motor (w/ mounting flange and bearing)	45.7	$9.11	$416
110 cc pump motor (combined frt power unit saves 8 kg est.)	29.2	$9.11	$266
110 cc motor for rear power unit	37.2	$9.11	$339
on-demand power steering system	15.6	$9.11	$142
hydraulic driven alternator	4.5	$9.11	$41
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.9	$7.19	-$22 *
rear drive shaft	-9.8	$7.19	-$70
front drive shaft	-7.3	$7.19	-$52
transmission cooler and lines	-1.8	$7.19	-$13
fitting and hoses	33.3	$7.19	$239
accumulator mounting brackets	6.0	$7.19	$43
oil cooler and filter loop (front motor low side) + mount	9.5	$7.19	$68
engine/PM coupling and fasteners	5.3	$7.19	$38
Other Complexity Levels			
transmission fluid	-11.8	$0.75	-$9
fluid in HP accumulator, fittings, hoses, oil conditioner	38.8	$3.00	$116
15 gal composite accumulator (high pressure)	56.0	$10.00	$560
15 gal composite accumulator (low pressure)	23.4	$10.00	$234
Totals	**207.0**		**$2,181**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,749**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**97.3%**
base mpg	14.63
base consumption (gpm)	0.0684
improved mpg	28.86
improved consumption (gpm)	0.0346
consumption reduction	**-49.3%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	14.2	(13.8)
fuel tank weight (kg)	10.0	5.1	(4.92)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-1: Base Case Incremental Costs
Car: Gas, Conventional Transmission

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Totals	**0.0**		**$0**

Table L2-2: Incremental Costs
Car: Clean Diesel

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for diesel engine	42.2	-	$957
net downsize of fuel tank		$7.19	$0
Totals	**42.2**		**$957**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,206**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**37.5%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	34.03
improved consumption (gpm)	0.0294
consumption reduction	**-27.3%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	20.4	(7.6)
fuel tank weight (kg)	10.0	7.3	(2.72)

Table L2-3: Incremental Costs
Car: Gas, Variable Displacement

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for variable displacement engine	28.9	-	$340
net downsize of fuel tank	-1.8	$7.19	-$13
Totals	**27.1**		**$327**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$412**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**21.7%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	30.12
improved consumption (gpm)	0.0332
consumption reduction	**-17.8%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	23.0	(5.0)
fuel tank weight (kg)	10.0	8.2	(1.78)

Table L2-4: Incremental Costs
Car: Clean Diesel, Variable Displacement

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
cost increase for diesel engine	42.2	-	$957
cost increase for variable displacement engine	28.9	-	$340
net downsize of fuel tank	-3.8	$7.19	-$17 *
Totals	**67.3**		**$1,280**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,612**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**62.0%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	40.10
improved consumption (gpm)	0.0249
consumption reduction	**-38.3%**

	Initial	Final	full tank delta
fuel tank size (gals)	28.0	17.3	(10.7)
fuel tank weight (kg)	10.0	6.2	(3.82)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-5: Incremental Costs
Car: Gas, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-1.3	$7.19	-$9
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**93.2**		**$792**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$998**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**11.2%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	27.52
improved consumption (gpm)	0.0363
consumption reduction	**-10.1%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	14.4	(1.6)
fuel tank weight (kg)	12.7	11.4	(1.28)

Table L2-6: Incremental Costs
Car: Clean Diesel, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	42.2	-	$957
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-5.0	$7.19	-$26 *
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**131.7**		**$1,732**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,182**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**65.4%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	40.94
improved consumption (gpm)	0.0244
consumption reduction	**-39.5%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	9.7	(6.3)
fuel tank weight (kg)	12.7	7.7	(5.02)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-7: Incremental Costs
Car: Gas, Variable Displacement, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
cost increase for variable displacement engine	28.9	-	$314
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-3.5	$7.19	-$25
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**119.9**		**$1,089**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,373**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**38.7%**		
base mpg	24.75		
base consumption (gpm)	0.0404		
improved mpg	34.33		
improved consumption (gpm)	0.0291		
consumption reduction	**-27.9%**		

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	11.5	(4.5)
fuel tank weight (kg)	12.7	9.2	(3.54)

Table L2-8: Incremental Costs
Car: Clean Diesel, Variable Displacement, Mild Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price	
Complexity Level #1 (like a Transmission)				
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87	
Complexity Level #2 (like an Engine)				
cost increase for diesel engine	42.2	-	$957	
cost increase for variable displacement engine	28.9	-	$314	
55 cc pump motor	18.6	$9.11	$169	
Complexity Level #3 (like a Chassis)				
net downsize of fuel tank	-6.2	$7.19	-$35	*
fitting and hoses	13.8	$7.19	$99	
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36	
accumulator mounting brackets	4.0	$7.19	$29	
Other Complexity Levels				
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29	
4 gal composite accumulator (high pressure)	24.0	$10.00	$240	
4 gal composite accumulator (low pressure)	11.2	$10.00	$112	
Totals	**159.4**		**$2,037**	
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,567**	

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**95.8%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	48.46
improved consumption (gpm)	0.0206
consumption reduction	**-48.9%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	8.2	(7.8)
fuel tank weight (kg)	12.7	6.5	(6.21)

*An adjustment was made to this value to account for the partial credit already
taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-9: Incremental Costs
Car: Gas, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-1.8	$7.19	-$13
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
battery upsize	4.6	$2.70	$12
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**97.3**		**$800**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,009**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**16.4%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	28.81	
improved consumption (gpm)	0.0347	
consumption reduction	**-14.1%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	13.7	(2.3)
fuel tank weight (kg)	12.7	10.9	(1.79)

Table L2-10: Incremental Costs
Car: Clean Diesel, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price	
Complexity Level #1 (like a Transmission)				
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87	
Complexity Level #2 (like an Engine)				
cost increase for diesel engine	42.2	-	$957	
55 cc pump motor	18.6	$9.11	$169	
Complexity Level #3 (like a Chassis)				
net downsize of fuel tank	-5.3	$7.19	-$28	*
fitting and hoses	13.8	$7.19	$99	
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36	
accumulator mounting brackets	4.0	$7.19	$29	
Other Complexity Levels				
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29	
battery upsize	4.6	$2.70	$12	
4 gal composite accumulator (high pressure)	24.0	$10.00	$240	
4 gal composite accumulator (low pressure)	11.2	$10.00	$112	
Totals	**136.0**		**$1,742**	
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,195**	

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**70.9%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	42.30
improved consumption (gpm)	0.0236
consumption reduction	**-41.5%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	9.4	(6.6)
fuel tank weight (kg)	12.7	7.4	(5.27)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-11: Incremental Costs
Car: Gas, Variable Displacement, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
cost increase for variable displacement engine	28.9	-	$314
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-3.8	$7.19	-$27
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
battery upsize	4.6	$2.70	$12
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**124.2**		**$1,100**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,386**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**42.7%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	35.32
improved consumption (gpm)	0.0283
consumption reduction	**-29.9%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	11.2	(4.8)
fuel tank weight (kg)	12.7	8.9	(3.80)

Table L2-12: Incremental Costs
Car: Clean Diesel, Variable Displacement, Mild Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
additional input to final drive of trans, extra housing, mounts, chain	8.3	$10.45	$87
Complexity Level #2 (like an Engine)			
cost increase for diesel engine	42.2	-	$957
cost increase for variable displacement engine	28.9	-	$314
55 cc pump motor	18.6	$9.11	$169
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-6.4	$7.19	-$36 *
fitting and hoses	13.8	$7.19	$99
oil cooler and filter loop (front motor low side)	5.0	$7.19	$36
accumulator mounting brackets	4.0	$7.19	$29
Other Complexity Levels			
fluid in HP accumulator, fittings, hoses, oil conditioner	9.6	$3.00	$29
battery upsize	4.6	$2.70	$12
4 gal composite accumulator (high pressure)	24.0	$10.00	$240
4 gal composite accumulator (low pressure)	11.2	$10.00	$112
Totals	**163.8**		**$2,048**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,581**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**101.6%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	49.90
improved consumption (gpm)	0.0200
consumption reduction	**-50.4%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	7.9	(8.1)
fuel tank weight (kg)	12.7	6.3	(6.40)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-13: Incremental Costs
Car: Gas, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
power steering system (pump, reservoir, steering gear)		$9.11	$0
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-2.4	$7.19	-$17
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**109.8**		**$884**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,114**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	23.2%
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	30.49
improved consumption (gpm)	0.0328
consumption reduction	-18.8%

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	13.0	(3.0)
fuel tank weight (kg)	12.7	10.3	(2.39)

Table L2-14: Incremental Costs
Car: Clean Diesel, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price	
Complexity Level #1 (like a Transmission)				
automatic transmission	-85.0	$10.45	-$888	
integrated transmission (w/o motors)	41.3	$10.45	$432	
Complexity Level #2 (like an Engine)				
engine downsize	-21.0	$9.11	-$191	
cost increase for diesel engine	42.2	-	$957	
power steering system (pump, reservior, steering gear)		$9.11	$0	
65 cc drive motor	22.0	$9.11	$200	
80 cc drive motor	27.1	$9.11	$246	
80 cc pump motor	27.1	$9.11	$246	
on-demand power steering system		$9.11	$0	
hydraulic driven alternator		$9.11	$0	
Complexity Level #3 (like a Chassis)				
net downsize of fuel tank	-5.2	$7.19	-$28	*
fitting and hoses	14.4	$7.19	$104	
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47	
accumulator mounting brackets	6.0	$7.19	$43	
Other Complexity Levels				
transmission fluid	-10.0	$0.75	-$8	
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72	
10 gal composite accumulator (high pressure)	41.7	$10.00	$417	
10 gal composite accumulator (low pressure)	18.1	$10.00	$181	
Totals	**149.1**		**$1,831**	
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,307**	

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**70.4%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	42.17	
improved consumption (gpm)	0.0237	
consumption reduction	**-41.3%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	9.4	(6.6)
fuel tank weight (kg)	12.7	7.5	(5.25)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-15: Incremental Costs
Car: Gas, Variable Displacement, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
cost increase for variable displacement engine	28.9	-	$314
power steering system (pump, reservior, steering gear)		$9.11	$0
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.2	$7.19	-$30
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**136.8**		**$1,185**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,493**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**50.1%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	37.15
improved consumption (gpm)	0.0269
consumption reduction	**-33.4%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	10.7	(5.3)
fuel tank weight (kg)	12.7	8.5	(4.24)

Table L2-16: Incremental Costs
Car: Clean Diesel, Variable Displacement, Full Hydraulic Hybrid, Engine On

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
cost increase for diesel engine	42.2	-	$957
cost increase for variable displacement engine	28.9	-	$314
power steering system (pump, reservoir, steering gear)		$9.11	$0
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system		$9.11	$0
hydraulic driven alternator		$9.11	$0
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-6.3	$7.19	-$36 *
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**176.9**		**$2,137**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,692**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**99.6%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	49.40	
improved consumption (gpm)	0.0202	
consumption reduction	**-49.9%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	8.0	(8.0)
fuel tank weight (kg)	12.7	6.4	(6.34)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-17: Incremental Costs
Car: Gas, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
power steering system (pump, reservoir, steering gear)	-12.3	$9.11	-$112
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system	11.8	$9.11	$107
hydraulic driven alternator	3.5	$9.11	$32
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.1	$7.19	-$29
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**111.1**		**$899**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,133**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**47.4%**
base mpg	24.75
base consumption (gpm)	0.0404
improved mpg	36.48
improved consumption (gpm)	0.0274
consumption reduction	**-32.2%**

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	10.9	(5.1)
fuel tank weight (kg)	12.7	8.6	(4.08)

Table L2-18: Incremental Costs
Car: Clean Diesel, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
cost increase for diesel engine	42.2	-	$957
power steering system (pump, reservior, steering gear)	-12.3	$9.11	-$112
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system	11.8	$9.11	$107
hydraulic driven alternator	3.5	$9.11	$32
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-6.4	$7.19	-$36 *
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**150.9**		**$1,849**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,330**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**103.0%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	50.24	
improved consumption (gpm)	0.0199	
consumption reduction	**-50.7%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	7.9	(8.1)
fuel tank weight (kg)	12.7	6.3	(6.44)

*An adjustment was made to this value to account for the partial credit already taken for fuel tank downsize in the above cost of changing to a diesel engine.

Table L2-19: Incremental Costs
Car: Gas, Variable Displacement, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
cost increase for variable displacement engine	28.9	-	$314
power steering system (pump, reservoir, steering gear)	-12.3	$9.11	-$112
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system	11.8	$9.11	$107
hydraulic driven alternator	3.5	$9.11	$32
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-4.5	$7.19	-$32
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**139.6**		**$1,211**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$1,525**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**54.1%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	38.14	
improved consumption (gpm)	0.0262	
consumption reduction	**-35.1%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	10.4	(5.6)
fuel tank weight (kg)	12.7	8.2	(4.46)

Table L2-20: Incremental Costs
Car: Clean Diesel, Variable Displacement, Full Hydraulic Hybrid, Engine Off

Component	Weight (kg)	Price Factor ($ per kg)	Supplier Price
Complexity Level #1 (like a Transmission)			
automatic transmission	-85.0	$10.45	-$888
integrated transmission (w/o motors)	41.3	$10.45	$432
Complexity Level #2 (like an Engine)			
engine downsize	-21.0	$9.11	-$191
cost increase for diesel engine	42.2	-	$957
cost increase for variable displacement engine	28.9	-	$314
power steering system (pump, reservior, steering gear)	-12.3	$9.11	-$112
65 cc drive motor	22.0	$9.11	$200
80 cc drive motor	27.1	$9.11	$246
80 cc pump motor	27.1	$9.11	$246
on-demand power steering system	11.8	$9.11	$107
hydraulic driven alternator	3.5	$9.11	$32
Complexity Level #3 (like a Chassis)			
net downsize of fuel tank	-6.9	$7.19	-$39 *
fitting and hoses	14.4	$7.19	$104
oil cooler and filter loop (front motor low side)	6.5	$7.19	$47
accumulator mounting brackets	6.0	$7.19	$43
Other Complexity Levels			
transmission fluid	-10.0	$0.75	-$8
fluid in HP accumulator, fittings, hoses, oil conditioner	24.1	$3.00	$72
10 gal composite accumulator (high pressure)	41.7	$10.00	$417
10 gal composite accumulator (low pressure)	18.1	$10.00	$181
Totals	**179.4**		**$2,160**
Increment in Vehicle Consumer Retail Price (Supplier Price x RPE of 1.26)			**$2,722**

Calculation of fuel tank downsize (included above)

fuel efficiency improvement	**117.9%**	
base mpg	24.75	
base consumption (gpm)	0.0404	
improved mpg	53.93	
improved consumption (gpm)	0.0185	
consumption reduction	**-54.1%**	

	Initial	Final	full tank delta
fuel tank size (gals)	16.0	7.3	(8.7)
fuel tank weight (kg)	12.7	5.8	(6.87)

*An adjustment was made to this value to account for the partial credit already
 taken for fuel tank downsize in the above cost of changing to a diesel engine.

Appendix M: Methodology for Brake Savings

A conventional vehicle accomplishes disc braking by converting the kinetic energy of the vehicle to heat through friction between the brake pad and the rotor. This friction between the brake pad and the rotor wears both surfaces and these parts will eventually need to be replaced.

During a typical braking event on the hydraulic hybrid vehicle more than 90 percent of the energy that is dissipated as heat in a conventional vehicle will be recovered and stored in the accumulator. Although a hydraulic hybrid vehicle will also require a friction braking system, the reduction in the energy that must be absorbed by the friction braking system greatly reduces the wear on the brake pads and rotors. This analysis assumes the overall brake wear on a hydraulic hybrid vehicle will be reduced by 70% in comparison to a conventional vehicle.

This analysis also assumes that the friction braking system on a hydraulic hybrid vehicle would be exactly the same as the friction braking system on a similar conventional vehicle. The friction braking system was not downsized to guarantee that hydraulic hybrid vehicle will be capable of at least the same braking performance as a conventional vehicle in all situations.

The maintenance schedules for a number of conventional passenger cars and sport/utility vehicles call for the brake system to be inspected at regular intervals. However, no part of the brake system appears to have a mileage limit or a suggested replacement interval. That is, in part, because brake wear is a function of both driving conditions and driving style. For example, if one drives for long periods of time in stop-and-go traffic, drives in the mountains or carries heavy loads, the brake system will likely need maintenance sooner than if most of one's driving is on the highway.

At a May 15, 2001 Brake Symposium sponsored by Pro-Cut International, Daimler-Chrysler engineers stated that the target front brake life for Jeep products was at least 25,000 miles for a heavily loaded vehicle in the city driving test.

An internet article entitled "Tech Forum: Brakes"[3] states that "Many times, a set of front disc brake pads may be all that is needed when a vehicle has its first brake job. If a brake system only has 30,000 to 40,000 miles on it, chances are the rest of the system is still in relatively good condition and needs little attention. ... By the time a vehicle is ready for its second or third brake job, the situation is usually entirely different. By this time the vehicle has 60,000 to 80,000 or more miles on it, numerous brake components may need to be replaced."

For the purposes of this analysis it has been assumed that a conventional vehicle under typical driving conditions will need brake maintenance at 40,000 mile intervals according to the following schedule. This maintenance schedule also assumes that the front brakes bear twice the burden of slowing the vehicle as do the rear brakes.

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[3]   http://www.babcox.com/editorial/cm/cm80226.htm

Maintenance Schedule

Mileage	_Front Brakes_	Rear Brakes
40,000	Replace pads, machine rotors	
80,000	Replace pads and rotors	Replace pads, machine rotors
120,000	Replace pads, machine rotors	
160,000	Replace pads and rotors	Replace pads and rotors

The cost of brake maintenance is a function of parts cost, labor hours required to perform the maintenance and the hourly shop rate.

Ford Parts Cost[4]

Part	2000 Taurus	2000 Expedition 4WD
Front Brake Pad	$59.70	$95.16
Front Rotor	$99.98	$91.33
Rear Brake Pad	$67.57	$81.12
Rear Rotor	$88.20	$124.13

Parts costs vary. OEM parts tend to cost more. Aftermarket parts tend to cost less than OEM parts, sometimes a lot less.

Aftermarket Parts Cost

Part	2000 Taurus	2000 Expedition 4WD
Front Brake Pad[5]	$30.99	$50.99
Front Rotor[6]	$31.99	$34.99
Rear Brake Pad[3]	$31.99	$49.99
Rear Rotor[4]	$21.49	$58.99

The number of labor hours charged to complete a job also depends upon the work to be done as well as the type of facility doing the work.

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[4]   http://fordpartsnetwork.com
[5]   http://www.autozone.com
[6]   http://www.napaonline.com

Dealership Flat Rate Labor Hours

Maintenance	**Passenger Vehicle**	**Sport/Utility Vehicle**
Replace front pads, machine rotors	2.0	2.0
Replace front pads and rotors	1.6	1.6
Replace rear pads, machine rotors	2.8	2.8
Replace rear pads and rotors	2.4	2.4

Dealerships tend to charge more for these services because they have more overhead, their mechanics generally have more certifications so they have to pay them more and they have more sophisticated diagnostic equipment than independent repair establishments. This analysis assumes that dealerships allocate about 10% more labor for brake maintenance than do either independent repair facilities or franchises.[7]

Independent Repair Shop Flat Rate Labor Hours[8]

Maintenance	**Passenger Vehicle**	**Sport/Utility Vehicle**
Replace front pads, machine rotors	1.8	1.8
Replace front pads and rotors	1.4	1.4
Replace rear pads, machine rotors	2.5	2.5
Replace rear pads and rotors	2.2	2.2

Franchise Flat Rate Labor Hours

Maintenance	**Passenger Vehicle**	**Sport/Utility Vehicle**
Replace front pads, machine rotors	1.8	1.8
Replace front pads and rotors	1.4	1.4
Replace rear pads, machine rotors	2.5	2.5
Replace rear pads and rotors	2.2	2.2

Shop rates vary by region of the country as well as whether the repair facility is a franchise, independent or part of a dealership. Dealership shop rates tend to be higher. This analysis uses two shop rates: $49.80[9] for franchises and independent repair facilities and $75.00 for dealerships.

To summarize, this analysis postulates three types of repair facilities with the work divided among them: franchises (40%), independent repair shops (40%) and dealerships (20%). Franchises and independent repair facilities are assumed to use the less expensive parts;

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7   Based on personal communication between Varsity Ford, Ann Arbor, MI 41830 and Julie Schaefer.
8   ALLDATA DIY: Individual Online Diagnostic and Repair Information for the Automotive Enthusiast.
    http://www.alldata.com/
9   Brake & Front End 2001 Service and Repair Survey, Babcox Research, Akron, Ohio
    http://www.aftermarketnews.com/01brkservice.pdf

dealerships are assumed to use OEM parts. Franchises and independent repair facilities are assumed to charge the same shop rate; dealerships are assumed to charge a higher shop rate. Franchises and independent repair facilities are assumed to estimate the time it takes to perform a job that is about 10% lower than that listed in the flat rate manual; dealerships are assumed to estimate the time it takes to perform a job that is equal to the flat rate manual.

This analysis also assumes that cars accumulate 153,000 miles during the first 14 years, that sport/utility vehicles accumulate 188,000 miles, and that future costs are discounted at the rate of 7% per year[10]. Seven percent is the discount rate used in EPA's regulatory analyses and is based on OMB guidance.

Mileage Accumulation Rates[11]

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Cumulative MOBILE6 LDV VMT	Cumulative MOBILE6 LDT VMT
1	14,910	19,978	14,910	19,978
2	14,174	18,695	29,084	38,674
3	13,475	17,494	42,559	56,168
4	12,810	16,371	55,369	72,538
5	12,178	15,319	67,547	87,857
6	11,577	14,335	79,125	102,192
7	11,006	13,414	90,130	115,607
8	10,463	12,553	100,593	128,159
9	9,947	11,746	110,540	139,905
10	9,456	10,992	119,996	150,897
11	8,989	10,286	128,985	161,183
12	8,546	9,625	137,531	170,808
13	8,124	9,007	145,655	179,814
14	7,723	8,428	153,378	188,242

Discount Factors

Age	Cumulative MOBILE6	Cumulative MOBILE6	Discount Factor

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[10] OMB Circular A-94 Revised http://www.whitehouse.gov/omb/circulars/a094/a094.html **Special Guidance for Regulatory Impact Analysis**. Additional guidance for analysis of regulatory policies is provided in *Regulatory Program of the United States Government* which is published annually by OMB. (See "Regulatory Impact Analysis Guidance," Appendix V of *Regulatory Program of the United States Government* for April 1, 1991 to March 31, 1992.)

[11] U.S. Environmental Protection Agency, MOBILE6 Emissions model

(years)	LDV VMT	LDT VMT	7%
2.08		40,000	0.93
2.81	40,000		0.88
4.49		80,000	0.79
6.08	80,000		0.71
7.35		120,000	0.65
10.00	120,000		0.54
10.89		160,000	0.51
8.44		133,333	0.60
11.47	133,333		0.49

Dealership Discounted Cost

Mileage	2000 Taurus	2000 Expedition 4WD
40,000	$185.52	$227.94
80,000	$466.06	$544.12
120,000	$114.05	$159.53
160,000		$464.76
Total	$765.62	$1,396.35

Independent Repair Facility Discounted Cost

Mileage	2000 Taurus	2000 Expedition 4WD
40,000	$106.73	$130.76
80,000	$229.89	$290.79
120,000	$65.61	$91.51
160,000		$239.88
Total	$402.22	$752.94

Franchise Discounted Cost

Mileage	2000 Taurus	2000 Expedition 4WD
40,000	$106.73	$130.76
80,000	$229.89	$290.79
120,000	$65.61	$91.51
160,000		$239.88
Total	$402.22	$752.94

Weighted Average Discounted Cost

Mileage	2000 Taurus	2000 Expedition 4WD
40,000	$122.48	$150.19
80,000	$277.12	$341.46
120,000	$75.30	$105.12
160,000		$284.85
Total	**$474.90**	**$881.62**

Several brake repair facilities in the Ann Arbor, Michigan area were called on October 12, 2002 to obtain estimates on the cost of replacing the front brake pads and resurfacing the front brake rotors.[12] A summary of these telephone calls follows:

Local Franchise Cost

Facility	1999 Taurus	1999 Expedition
Midas	$99.99	$99.99
Tuffy	$110.00 - $120.00	
Speedy	$140.00	
Mr. Muffler		$110.00

These costs correspond to the 40,000 mile <u>estimated</u> franchise cost - before applying the 7% OMB discount - of replacing the front brake pads and machining the front rotors of $120.63 for cars and $140.63 for light trucks.

We project that hydraulic hybrid vehicles will reduce brake wear by 70%. That means that the first and only brake maintenance expense would occur at 133,333 miles.

Weighted Average Discounted Cost

Mileage	2000 Taurus	2000 Expedition 4WD
133,000	$67.99	$97.64

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[12] Based on personal communication between listed local repair facilities and Tony Tesoriero. October 12, 2002

Even if brake wear were reduced by only 50% for hybrid cars and 60% for hybrid light trucks, only one brake maintenance expense would be expected in the first 14 years of a vehicle's life.

Discounted Net Savings

2000 Taurus	2000 Expedition 4WD
$407	$784

Conclusion

Hybrid vehicles are expected to require significantly less brake maintenance over the first 14 years of their life, saving, in today's dollars, more than $400 for cars and almost $800 for light trucks.[13]

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[13] The savings for any particular calendar year depend upon the fraction of the fleet that needs brake maintenance in that year and the discounted cost of those repairs.

Appendix N: Calculations of Payback by Technology

Appendix N provides the detailed payback data for each of 80 technology scenarios, 40 base roadload scenarios presented in the body of the report and 40 reduced roadload scenarios presented in Appendix A. For this Appendix, the 80 scenarios are arranged in groups defined by vehicle type (midsize car or large SUV), drivetrain (conventional or hydraulic), and roadload (base or reduced). Each of the tables in the Appendix provides the amount of discounted savings due to improved fuel economy and reduced brake maintenance. These savings are presented by vehicle age (the first column of each set of tables) and are compared to the incremental cost of the technology. The final column in each technology table gives the age at which the breakeven point or payback occurs.

Tables N1-1 through N1-10 contain cost data for SUV configurations.

Tables N2-1 through N2-10 contain cost data for Car configurations.

Table N1-1: Large 4WD SUV Conventional Transmission

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	Base	Base	Base	$552	$552		$253	$253		$731	$731	
2	14,174	18,695				$483	$1,035		$221	$474		$639	$1,370	
3	13,475	17,494				$422	$1,457		$193	$667	2.3	$559	$1,929	
4	12,810	16,371				$369	$1,826	3.6	$169	$836	*	$489	$2,418	3.5
5	12,178	15,319				$323	$2,149	*	$148	$984	*	$427	$2,845	*
6	11,577	14,335				$283	$2,432	*	$129	$1,113	*	$374	$3,219	*
7	11,006	13,414				$247	$2,679	*	$113	$1,226	*	$327	$3,546	*
8	10,463	12,553				$216	$2,895	*	$99	$1,325	*	$286	$3,832	*
9	9,947	11,746				$189	$3,084	*	$87	$1,412	*	$250	$4,082	*
10	9,456	10,992				$165	$3,249	*	$76	$1,488	*	$219	$4,301	*
11	8,989	10,286				$145	$3,394	*	$66	$1,554	*	$191	$4,492	*
12	8,546	9,625				$126	$3,520	*	$58	$1,612	*	$167	$4,659	*
13	8,124	9,007				$111	$3,631	*	$51	$1,663	*	$146	$4,805	*
14	7,723	8,428				$97	$3,728	*	$44	$1,707	*	$128	$4,933	*
						$3,728			$1,707			$4,933		

Table N1-2: Large 4WD SUV Conventional Transmission Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$162	$162		$682	$682		$446	$446		$865	$865	
2	14,174	18,695	$142	$304	1.3	$596	$1,278		$390	$836	1.8	$756	$1,621	
3	13,475	17,494	$124	$428	*	$521	$1,799		$341	$1,177	*	$661	$2,282	
4	12,810	16,371	$109	$537	*	$456	$2,255	3.2	$298	$1,475	*	$578	$2,860	3.2
5	12,178	15,319	$95	$632	*	$399	$2,654	*	$261	$1,736	*	$506	$3,366	*
6	11,577	14,335	$83	$715	*	$349	$3,003	*	$228	$1,964	*	$442	$3,808	*
7	11,006	13,414	$73	$788	*	$305	$3,308	*	$199	$2,163	*	$387	$4,195	*
8	10,463	12,553	$64	$852	*	$267	$3,575	*	$174	$2,337	*	$338	$4,533	*
9	9,947	11,746	$56	$908	*	$233	$3,808	*	$153	$2,490	*	$296	$4,829	*
10	9,456	10,992	$49	$957	*	$204	$4,012	*	$133	$2,623	*	$259	$5,088	*
11	8,989	10,286	$43	$1,000	*	$178	$4,190	*	$117	$2,740	*	$226	$5,314	*
12	8,546	9,625	$37	$1,037	*	$156	$4,346	*	$102	$2,842	*	$198	$5,512	*
13	8,124	9,007	$33	$1,070	*	$136	$4,482	*	$89	$2,931	*	$173	$5,685	*
14	7,723	8,428	$28	$1,098	*	$119	$4,601	*	$78	$3,009	*	$151	$5,836	*
			$1,098			$4,601			$3,009			$5,836		

Appendix N
Calculations of Payback by Technology

Table N1-3: Large 4WD SUV Mild Hydraulic Hybrid - Engine On

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$221	$221		$731	$731		$460	$460		$892	$892	
2	14,174	18,695	$193	$414		$639	$1,370		$403	$863		$780	$1,672	
2.08			$150	$564		$150	$1,520		$150	$1,013		$150	$1,822	
3	13,475	17,494	$169	$733		$559	$2,079		$352	$1,365		$682	$2,504	
4	12,810	16,371	$148	$881		$489	$2,568		$308	$1,673		$597	$3,101	
4.49			$341	$1,222		$341	$2,909		$341	$2,014	4.2	$341	$3,442	
5	12,178	15,319	$129	$1,351	4.9	$427	$3,336	4.6	$269	$2,283	*	$522	$3,964	4.5
6	11,577	14,335	$113	$1,464	*	$374	$3,710	*	$235	$2,518	*	$456	$4,420	*
7	11,006	13,414	$99	$1,563	*	$327	$4,037	*	$206	$2,724	*	$399	$4,819	*
7.35			$105	$1,668	*	$105	$4,142	*	$105	$2,829	*	$105	$4,924	*
8	10,463	12,553	$87	$1,755	*	$286	$4,428	*	$180	$3,009	*	$349	$5,273	*
8.44			-$98	$1,657	*	-$98	$4,330	*	-$98	$2,911	*	-$98	$5,175	*
9	9,947	11,746	$76	$1,733	*	$250	$4,580	*	$157	$3,068	*	$305	$5,480	*
10	9,456	10,992	$66	$1,799	*	$219	$4,799	*	$138	$3,206	*	$267	$5,747	*
10.89			$285	$2,084	*	$285	$5,084	*	$285	$3,491	*	$285	$6,032	*
11	8,989	10,286	$58	$2,142	*	$191	$5,275	*	$120	$3,611	*	$234	$6,266	*
12	8,546	9,625	$51	$2,193	*	$167	$5,442	*	$105	$3,716	*	$204	$6,470	*
13	8,124	9,007	$44	$2,237	*	$146	$5,588	*	$92	$3,808	*	$179	$6,649	*
14	7,723	8,428	$39	$2,276	*	$128	$5,716	*	$81	$3,889	*	$156	$6,805	*
			$2,276			$5,716			$3,889			$6,805		

Table N1-4: Large 4WD SUV Mild Hydraulic Hybrid - Engine On Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$399	$399		$866	$866		$662	$662		$1,040	$1,040	
2	14,174	18,695	$349	$748		$757	$1,623		$579	$1,241		$909	$1,949	
2.08			$150	$898		$150	$1,773		$150	$1,391		$150	$2,099	
3	13,475	17,494	$305	$1,203		$662	$2,435		$507	$1,898		$795	$2,894	
4	12,810	16,371	$267	$1,470		$579	$3,014		$443	$2,341	3.3	$695	$3,589	
4.49			$341	$1,811	4.1	$341	$3,355	4.3	$341	$2,682	*	$341	$3,930	4.2
5	12,178	15,319	$233	$2,044	*	$506	$3,861	*	$387	$3,069	*	$608	$4,538	*
6	11,577	14,335	$204	$2,248	*	$443	$4,304	*	$339	$3,408	*	$532	$5,070	*
7	11,006	13,414	$179	$2,427	*	$387	$4,691	*	$296	$3,704	*	$465	$5,535	*
7.35			$105	$2,532	*	$105	$4,796	*	$105	$3,809	*	$105	$5,640	*
8	10,463	12,553	$156	$2,688	*	$339	$5,135	*	$259	$4,068	*	$407	$6,047	*
8.44			-$98	$2,590	*	-$98	$5,037	*	-$98	$3,970	*	-$98	$5,949	*
9	9,947	11,746	$137	$2,727	*	$296	$5,333	*	$227	$4,197	*	$356	$6,305	*
10	9,456	10,992	$119	$2,846	*	$259	$5,592	*	$198	$4,395	*	$311	$6,616	*
10.89			$285	$3,131	*	$285	$5,877	*	$285	$4,680	*	$285	$6,901	*
11	8,989	10,286	$104	$3,235	*	$227	$6,104	*	$173	$4,853	*	$272	$7,173	*
12	8,546	9,625	$91	$3,326	*	$198	$6,302	*	$152	$5,005	*	$238	$7,411	*
13	8,124	9,007	$80	$3,406	*	$173	$6,475	*	$133	$5,138	*	$208	$7,619	*
14	7,723	8,428	$70	$3,476	*	$152	$6,627	*	$116	$5,254	*	$182	$7,801	*
			$3,476			$6,627			$5,254			$7,801		

Table N1-5: Large 4WD SUV Mild Hydraulic Hybrid - Engine Off

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$272	$272		$755	$755		$483	$483		$907	$907	
2	14,174	18,695	$238	$510		$660	$1,415		$422	$905		$793	$1,700	
2.08			$150	$660		$150	$1,565		$150	$1,055		$150	$1,850	
3	13,475	17,494	$208	$868		$577	$2,142		$369	$1,424		$693	$2,543	
4	12,810	16,371	$182	$1,050		$505	$2,647		$323	$1,747		$607	$3,150	
4.49			$341	$1,391	4.4	$341	$2,988		$341	$2,088	4.1	$341	$3,491	
5	12,178	15,319	$159	$1,550	*	$442	$3,430	4.5	$282	$2,370	*	$530	$4,021	4.5
6	11,577	14,335	$139	$1,689	*	$386	$3,816	*	$247	$2,617	*	$464	$4,485	*
7	11,006	13,414	$122	$1,811	*	$338	$4,154	*	$216	$2,833	*	$406	$4,891	*
7.35			$105	$1,916	*	$105	$4,259	*	$105	$2,938	*	$105	$4,996	*
8	10,463	12,553	$106	$2,022	*	$295	$4,554	*	$189	$3,127	*	$355	$5,351	*
8.44			-$98	$1,924	*	-$98	$4,456	*	-$98	$3,029	*	-$98	$5,253	*
9	9,947	11,746	$93	$2,017	*	$258	$4,714	*	$165	$3,194	*	$310	$5,563	*
10	9,456	10,992	$81	$2,098	*	$226	$4,940	*	$144	$3,338	*	$271	$5,834	*
10.89			$285	$2,383	*	$285	$5,225	*	$285	$3,623	*	$285	$6,119	*
11	8,989	10,286	$71	$2,454	*	$198	$5,423	*	$126	$3,749	*	$237	$6,356	*
12	8,546	9,625	$62	$2,516	*	$173	$5,596	*	$110	$3,859	*	$208	$6,564	*
13	8,124	9,007	$54	$2,570	*	$151	$5,747	*	$97	$3,956	*	$182	$6,746	*
14	7,723	8,428	$48	$2,618	*	$132	$5,879	*	$84	$4,040	*	$159	$6,905	*
			$2,618			$5,879			$4,040			$6,905		

Table N1-6: Large 4WD SUV Mild Hydraulic Hybrid - Engine Off Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$458	$458		$893	$893		$686	$686		$1,055	$1,055	
2	14,174	18,695	$400	$858		$781	$1,674		$600	$1,286		$923	$1,978	
2.08			$150	$1,008		$150	$1,824		$150	$1,436		$150	$2,128	
3	13,475	17,494	$350	$1,358		$683	$2,507		$525	$1,961		$807	$2,935	
4	12,810	16,371	$306	$1,664	3.6	$597	$3,104		$459	$2,420	3.2	$706	$3,641	
4.49			$341	$2,005	*	$341	$3,445	4.2	$341	$2,761	*	$341	$3,982	4.1
5	12,178	15,319	$268	$2,273	*	$522	$3,967	*	$401	$3,162	*	$617	$4,599	*
6	11,577	14,335	$234	$2,507	*	$457	$4,424	*	$351	$3,513	*	$540	$5,139	*
7	11,006	13,414	$205	$2,712	*	$400	$4,824	*	$307	$3,820	*	$472	$5,611	*
7.35			$105	$2,817	*	$105	$4,929	*	$105	$3,925	*	$105	$5,716	*
8	10,463	12,553	$179	$2,996	*	$349	$5,278	*	$269	$4,194	*	$413	$6,129	*
8.44			-$98	$2,898	*	-$98	$5,180	*	-$98	$4,096	*	-$98	$6,031	*
9	9,947	11,746	$157	$3,055	*	$306	$5,486	*	$235	$4,331	*	$361	$6,392	*
10	9,456	10,992	$137	$3,192	*	$267	$5,753	*	$205	$4,536	*	$316	$6,708	*
10.89			$285	$3,477	*	$285	$6,038	*	$285	$4,821	*	$285	$6,993	*
11	8,989	10,286	$120	$3,597	*	$234	$6,272	*	$180	$5,001	*	$276	$7,269	*
12	8,546	9,625	$105	$3,702	*	$204	$6,476	*	$157	$5,158	*	$241	$7,510	*
13	8,124	9,007	$92	$3,794	*	$179	$6,655	*	$137	$5,295	*	$211	$7,721	*
14	7,723	8,428	$80	$3,874	*	$156	$6,811	*	$120	$5,415	*	$185	$7,906	*
			$3,874			$6,811			$5,415			$7,906		

Appendix N
Calculations of Payback by Technology

Table N1-7: Large 4WD SUV Full Hydraulic Hybrid - Engine On

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$286	$286		$740	$740		$481	$481		$901	$901	
2	14,174	18,695	$250	$536		$647	$1,387		$421	$902		$788	$1,689	
2.08			$150	$686	2.0	$150	$1,537		$150	$1,052		$150	$1,839	
3	13,475	17,494	$218	$904	*	$566	$2,103		$368	$1,420	2.1	$689	$2,528	
4	12,810	16,371	$191	$1,095	*	$495	$2,598	3.2	$322	$1,742	*	$603	$3,131	3.3
4.49			$341	$1,436	*	$341	$2,939	*	$341	$2,083	*	$341	$3,472	*
5	12,178	15,319	$167	$1,603	*	$433	$3,372	*	$281	$2,364	*	$527	$3,999	*
6	11,577	14,335	$146	$1,749	*	$378	$3,750	*	$246	$2,610	*	$461	$4,460	*
7	11,006	13,414	$128	$1,877	*	$331	$4,081	*	$215	$2,825	*	$403	$4,863	*
7.35			$105	$1,982	*	$105	$4,186	*	$105	$2,930	*	$105	$4,968	*
8	10,463	12,553	$112	$2,094	*	$289	$4,475	*	$188	$3,118	*	$353	$5,321	*
8.44			-$98	$1,996	*	-$98	$4,377	*	-$98	$3,020	*	-$98	$5,223	*
9	9,947	11,746	$98	$2,094	*	$253	$4,630	*	$165	$3,185	*	$308	$5,531	*
10	9,456	10,992	$85	$2,179	*	$221	$4,851	*	$144	$3,329	*	$270	$5,801	*
10.89			$285	$2,464	*	$285	$5,136	*	$285	$3,614	*	$285	$6,086	*
11	8,989	10,286	$75	$2,539	*	$194	$5,330	*	$126	$3,740	*	$236	$6,322	*
12	8,546	9,625	$65	$2,604	*	$169	$5,499	*	$110	$3,850	*	$206	$6,528	*
13	8,124	9,007	$57	$2,661	*	$148	$5,647	*	$96	$3,946	*	$180	$6,708	*
14	7,723	8,428	$50	$2,711	*	$129	$5,776	*	$84	$4,030	*	$158	$6,866	*
			$2,711			$5,776			$4,030			$6,866		

Table N1:8 Large 4WD SUV Full Hydraulic Hybrid - Engine On Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$496	$496		$917	$917		$703	$703		$1,067	$1,067	
2	14,174	18,695	$434	$930	1.6	$802	$1,719		$615	$1,318	1.9	$934	$2,001	
2.08			$150	$1,080	*	$150	$1,869		$150	$1,468	*	$150	$2,151	
3	13,475	17,494	$380	$1,460	*	$701	$2,570	2.8	$537	$2,005	*	$816	$2,967	3.0
4	12,810	16,371	$332	$1,792	*	$613	$3,183	*	$470	$2,475	*	$714	$3,681	*
4.49			$341	$2,133	*	$341	$3,524	*	$341	$2,816	*	$341	$4,022	*
5	12,178	15,319	$290	$2,423	*	$536	$4,060	*	$411	$3,227	*	$624	$4,646	*
6	11,577	14,335	$254	$2,677	*	$469	$4,529	*	$359	$3,586	*	$546	$5,192	*
7	11,006	13,414	$222	$2,899	*	$410	$4,939	*	$314	$3,900	*	$478	$5,670	*
7.35			$105	$3,004	*	$105	$5,044	*	$105	$4,005	*	$105	$5,775	*
8	10,463	12,553	$194	$3,198	*	$359	$5,403	*	$275	$4,280	*	$418	$6,193	*
8.44			-$98	$3,100	*	-$98	$5,305	*	-$98	$4,182	*	-$98	$6,095	*
9	9,947	11,746	$170	$3,270	*	$314	$5,619	*	$240	$4,422	*	$365	$6,460	*
10	9,456	10,992	$149	$3,419	*	$274	$5,893	*	$210	$4,632	*	$319	$6,779	*
10.89			$285	$3,704	*	$285	$6,178	*	$285	$4,917	*	$285	$7,064	*
11	8,989	10,286	$130	$3,834	*	$240	$6,418	*	$184	$5,101	*	$279	$7,343	*
12	8,546	9,625	$114	$3,948	*	$210	$6,628	*	$161	$5,262	*	$244	$7,587	*
13	8,124	9,007	$99	$4,047	*	$183	$6,811	*	$141	$5,403	*	$214	$7,801	*
14	7,723	8,428	$87	$4,134	*	$160	$6,971	*	$123	$5,526	*	$187	$7,988	*
			$4,134			$6,971			$5,526			$7,988		

Appendix N
Calculations of Payback by Technology

Table N1-9: Large 4WD SUV Full Hydraulic Hybrid - Engine Off

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$492	$492		$925	$925		$559	$559		$1,010	$1,010	
2	14,174	18,695	$430	$922	1.2	$809	$1,734		$489	$1,048		$883	$1,893	
2.08			$150	$1,072	*	$150	$1,884		$150	$1,198	2.0	$150	$2,043	
3	13,475	17,494	$376	$1,448	*	$707	$2,591	2.5	$427	$1,625	*	$772	$2,815	2.9
4	12,810	16,371	$329	$1,777	*	$619	$3,210	*	$374	$1,999	*	$676	$3,491	*
4.49			$341	$2,118	*	$341	$3,551	*	$341	$2,340	*	$341	$3,832	*
5	12,178	15,319	$288	$2,406	*	$541	$4,092	*	$327	$2,667	*	$591	$4,423	*
6	11,577	14,335	$251	$2,657	*	$473	$4,565	*	$286	$2,953	*	$517	$4,940	*
7	11,006	13,414	$220	$2,877	*	$414	$4,979	*	$250	$3,203	*	$452	$5,392	*
7.35			$105	$2,982	*	$105	$5,084	*	$105	$3,308	*	$105	$5,497	*
8	10,463	12,553	$192	$3,174	*	$362	$5,446	*	$219	$3,527	*	$395	$5,892	*
8.44			-$98	$3,076	*	-$98	$5,348	*	-$98	$3,429	*	-$98	$5,794	*
9	9,947	11,746	$168	$3,244	*	$316	$5,664	*	$191	$3,620	*	$346	$6,140	*
10	9,456	10,992	$147	$3,391	*	$277	$5,941	*	$167	$3,787	*	$302	$6,442	*
10.89			$285	$3,676	*	$285	$6,226	*	$285	$4,072	*	$285	$6,727	*
11	8,989	10,286	$129	$3,805	*	$242	$6,468	*	$146	$4,218	*	$264	$6,991	*
12	8,546	9,625	$113	$3,918	*	$212	$6,680	*	$128	$4,346	*	$231	$7,222	*
13	8,124	9,007	$98	$4,016	*	$185	$6,865	*	$112	$4,458	*	$202	$7,424	*
14	7,723	8,428	$86	$4,102	*	$162	$7,027	*	$98	$4,556	*	$177	$7,601	*
			$4,102			$7,027			$4,556			$7,601		

Table N1-10: Large 4WD SUV Full Hydraulic Hybrid - Engine Off Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$731	$731		$1,110	$1,110		$799	$799		$1,178	$1,178	
2	14,174	18,695	$639	$1,370	1.1	$971	$2,081		$699	$1,498	1.7	$1,031	$2,209	
2.08			$150	$1,520	*	$150	$2,231		$150	$1,648	*	$150	$2,359	
3	13,475	17,494	$559	$2,079	*	$849	$3,080	2.3	$611	$2,259	*	$901	$3,260	2.7
4	12,810	16,371	$489	$2,568	*	$743	$3,823	*	$535	$2,794	*	$788	$4,048	*
4.49			$341	$2,909	*	$341	$4,164	*	$341	$3,135	*	$341	$4,389	*
5	12,178	15,319	$427	$3,336	*	$650	$4,814	*	$468	$3,603	*	$689	$5,078	*
6	11,577	14,335	$374	$3,710	*	$568	$5,382	*	$409	$4,012	*	$603	$5,681	*
7	11,006	13,414	$327	$4,037	*	$497	$5,879	*	$358	$4,370	*	$527	$6,208	*
7.35			$105	$4,142	*	$105	$5,984	*	$105	$4,475	*	$105	$6,313	*
8	10,463	12,553	$286	$4,428	*	$434	$6,418	*	$313	$4,788	*	$461	$6,774	*
8.44			-$98	$4,330	*	-$98	$6,320	*	-$98	$4,690	*	-$98	$6,676	*
9	9,947	11,746	$250	$4,580	*	$380	$6,700	*	$273	$4,963	*	$403	$7,079	*
10	9,456	10,992	$219	$4,799	*	$332	$7,032	*	$239	$5,202	*	$353	$7,432	*
10.89			$285	$5,084	*	$285	$7,317	*	$285	$5,487	*	$285	$7,717	*
11	8,989	10,286	$191	$5,275	*	$291	$7,608	*	$209	$5,696	*	$308	$8,025	*
12	8,546	9,625	$167	$5,442	*	$254	$7,862	*	$183	$5,879	*	$270	$8,295	*
13	8,124	9,007	$146	$5,588	*	$222	$8,084	*	$160	$6,039	*	$236	$8,531	*
14	7,723	8,428	$128	$5,716	*	$194	$8,278	*	$140	$6,179	*	$206	$8,737	*
			$5,716			$8,278			$6,179			$8,737		

Appendix N
Calculations of Payback by Technology

Table N2-1: Midsize Car Conventional Transmission

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Conv Gas Engine Cum $	Conv Gas Engine Paybk Age	Clean Diesel Engine $/Age	Clean Diesel Engine Cum $	Clean Diesel Engine Paybk Age	Gas Var Disp Engine $/Age	Gas Var Disp Engine Cum $	Gas Var Disp Engine Paybk Age	Clean Diesel Var Disp Engine $/Age	Clean Diesel Var Disp Engine Cum $	Clean Diesel Var Disp Engine Paybk Age
1	14,910	19,978	Base	Base	Base	$246	$246		$161	$161		$346	$346	
2	14,174	18,695				$219	$465		$143	$304		$307	$653	
3	13,475	17,494				$195	$660		$127	$431	2.9	$273	$926	
4	12,810	16,371				$173	$833		$113	$544	*	$243	$1,169	
5	12,178	15,319				$154	$987		$100	$644	*	$216	$1,385	
6	11,577	14,335				$136	$1,123		$89	$733	*	$191	$1,576	
7	11,006	13,414				$121	$1,244	6.7	$79	$812	*	$170	$1,746	6.2
8	10,463	12,553				$108	$1,352	*	$70	$882	*	$151	$1,897	*
9	9,947	11,746				$96	$1,448	*	$63	$945	*	$134	$2,031	*
10	9,456	10,992				$85	$1,533	*	$56	$1,001	*	$119	$2,150	*
11	8,989	10,286				$76	$1,609	*	$49	$1,050	*	$106	$2,256	*
12	8,546	9,625				$67	$1,676	*	$44	$1,094	*	$94	$2,350	*
13	8,124	9,007				$60	$1,736	*	$39	$1,133	*	$84	$2,434	*
14	7,723	8,428				$53	$1,789	*	$35	$1,168	*	$74	$2,508	*
						$1,789			$1,168			$2,508		

Table N2-2: Midsize Car Conventional Transmission Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Conv Gas Engine Cum $	Conv Gas Engine Paybk Age	Clean Diesel Engine $/Age	Clean Diesel Engine Cum $	Clean Diesel Engine Paybk Age	Gas Var Disp Engine $/Age	Gas Var Disp Engine Cum $	Gas Var Disp Engine Paybk Age	Clean Diesel Var Disp Engine $/Age	Clean Diesel Var Disp Engine Cum $	Clean Diesel Var Disp Engine Paybk Age
1	14,910	19,978	$54	$54		$292	$292		$219	$219		$390	$390	
2	14,174	18,695	$48	$102		$259	$551		$195	$414		$347	$737	
3	13,475	17,494	$42	$144		$230	$781		$173	$587		$308	$1,045	
4	12,810	16,371	$38	$182		$205	$986		$154	$741	3.2	$274	$1,319	
5	12,178	15,319	$33	$215	4.8	$182	$1,168		$137	$878	*	$243	$1,562	
6	11,577	14,335	$30	$245	*	$162	$1,330		$121	$999	*	$216	$1,778	
7	11,006	13,414	$26	$271	*	$144	$1,474	6.6	$108	$1,107	*	$192	$1,970	6.2
8	10,463	12,553	$23	$294	*	$128	$1,602	*	$96	$1,203	*	$171	$2,141	*
9	9,947	11,746	$21	$315	*	$113	$1,715	*	$85	$1,288	*	$152	$2,293	*
10	9,456	10,992	$18	$333	*	$101	$1,816	*	$76	$1,364	*	$135	$2,428	*
11	8,989	10,286	$16	$349	*	$89	$1,905	*	$67	$1,431	*	$120	$2,548	*
12	8,546	9,625	$15	$364	*	$79	$1,984	*	$60	$1,491	*	$106	$2,654	*
13	8,124	9,007	$13	$377	*	$71	$2,055	*	$53	$1,544	*	$94	$2,748	*
14	7,723	8,428	$12	$389	*	$63	$2,118	*	$47	$1,591	*	$84	$2,832	*
			$389			$2,118			$1,591			$2,832		

Table N2-3: Midsize Car Mild Hydraulic Hybrid - Engine On

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$91	$91		$357	$357		$252	$252		$442	$442	
2	14,174	18,695	$81	$172		$317	$674		$224	$476		$393	$835	
2.81			$122	$352		$122	$1,024		$122	$759		$122	$1,240	
3	13,475	17,494	$72	$366		$282	$1,078		$199	$797		$349	$1,306	
4	12,810	16,371	$64	$430		$251	$1,329		$177	$974		$310	$1,616	
5	12,178	15,319	$57	$487		$223	$1,552		$157	$1,131		$275	$1,891	
6	11,577	14,335	$50	$537		$198	$1,750		$140	$1,271		$245	$2,136	
6.08			$277	$818		$277	$2,041		$277	$1,558	6.0	$277	$2,430	
7	11,006	13,414	$45	$859		$176	$2,203	6.9	$124	$1,672	*	$217	$2,630	6.7
8	10,463	12,553	$40	$899		$156	$2,359	*	$110	$1,782	*	$193	$2,823	*
9	9,947	11,746	$35	$934		$139	$2,498	*	$98	$1,880	*	$172	$2,995	*
10	9,456	10,992	$107	$1,041	9.6	$199	$2,697	*	$162	$2,042	*	$228	$3,223	*
11	8,989	10,286	$28	$1,069	*	$110	$2,807	*	$77	$2,119	*	$135	$3,358	*
11.51			-$68	$1,001	*	-$68	$2,739	*	-$68	$2,051	*	-$68	$3,290	*
12	8,546	9,625	$25	$1,026	*	$97	$2,836	*	$69	$2,120	*	$120	$3,410	*
13	8,124	9,007	$22	$1,048	*	$86	$2,922	*	$61	$2,181	*	$107	$3,517	*
14	7,723	8,428	$20	$1,068	*	$77	$2,999	*	$54	$2,235	*	$95	$3,612	*
			$1,068			$2,999			$2,235			$3,612		

Table N2-4: Midsize Car Mild Hydraulic Hybrid - Engine On Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$148	$148		$403	$403		$316	$316		$492	$492	
2	14,174	18,695	$131	$279		$358	$761		$281	$597		$437	$929	
2.81			$122	$495		$122	$1,141		$122	$922		$122	$1,365	
3	13,475	17,494	$116	$517		$318	$1,201		$250	$970		$388	$1,439	
4	12,810	16,371	$103	$620		$283	$1,484		$222	$1,192		$345	$1,784	
5	12,178	15,319	$92	$712		$251	$1,735		$197	$1,389		$306	$2,090	
6	11,577	14,335	$82	$794		$223	$1,958		$175	$1,564		$272	$2,362	
6.08			$277	$1,077		$277	$2,251		$277	$1,853	6.0	$277	$2,658	
7	11,006	13,414	$73	$1,144		$198	$2,433	6.8	$156	$1,997	*	$242	$2,881	6.6
8	10,463	12,553	$64	$1,208		$176	$2,609	*	$138	$2,135	*	$215	$3,096	*
9	9,947	11,746	$57	$1,265	8.0	$157	$2,766	*	$123	$2,258	*	$191	$3,287	*
10	9,456	10,992	$126	$1,391	*	$214	$2,980	*	$184	$2,442	*	$245	$3,532	*
11	8,989	10,286	$45	$1,436	*	$124	$3,104	*	$97	$2,539	*	$151	$3,683	*
11.51			-$68	$1,368	*	-$68	$3,036	*	-$68	$2,471	*	-$68	$3,615	*
12	8,546	9,625	$40	$1,408	*	$110	$3,146	*	$86	$2,557	*	$134	$3,749	*
13	8,124	9,007	$36	$1,444	*	$98	$3,244	*	$76	$2,633	*	$119	$3,868	*
14	7,723	8,428	$32	$1,476	*	$87	$3,331	*	$68	$2,701	*	$106	$3,974	*
			$1,476			$3,331			$2,700			$3,974		

Table N2-5: Midsize Car Mild Hydraulic Hybrid - Engine Off

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$127	$127		$375	$375		$270	$270		$455	$455	
2	14,174	18,695	$113	$240		$333	$708		$240	$510		$405	$860	
2.81			$122	$444		$122	$1,070		$122	$805		$122	$1,274	
3	13,475	17,494	$101	$463		$296	$1,126		$213	$845		$360	$1,342	
4	12,810	16,371	$89	$552		$263	$1,389		$190	$1,035		$319	$1,661	
5	12,178	15,319	$79	$631		$234	$1,623		$169	$1,204		$284	$1,945	
6	11,577	14,335	$70	$701		$208	$1,831		$150	$1,354		$252	$2,197	
6.08			$277	$983		$277	$2,123		$277	$1,642	6.0	$277	$2,492	
7	11,006	13,414	$63	$1,041	6.5	$184	$2,292	6.5	$133	$1,764	*	$224	$2,698	6.5
8	10,463	12,553	$56	$1,097	*	$164	$2,456	*	$118	$1,882	*	$199	$2,897	*
9	9,947	11,746	$49	$1,146	*	$146	$2,602	*	$105	$1,987	*	$177	$3,074	*
10	9,456	10,992	$119	$1,265	*	$205	$2,807	*	$169	$2,156	*	$232	$3,306	*
11	8,989	10,286	$39	$1,304	*	$115	$2,922	*	$83	$2,239	*	$140	$3,446	*
11.51			-$68	$1,236	*	-$68	$2,854	*	-$68	$2,171	*	-$68	$3,378	*
12	8,546	9,625	$35	$1,271	*	$102	$2,956	*	$74	$2,245	*	$124	$3,502	*
13	8,124	9,007	$31	$1,302	*	$91	$3,047	*	$65	$2,310	*	$110	$3,612	*
14	7,723	8,428	$27	$1,329	*	$81	$3,128	*	$58	$2,368	*	$98	$3,710	*
			$1,329			$3,128			$2,368			$3,710		

Table N2-6: Midsize Car Mild Hydraulic Hybrid - Engine Off Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$187	$187		$426	$426		$336	$336		$506	$506	
2	14,174	18,695	$166	$353		$378	$804		$298	$634		$450	$956	
2.81			$122	$475		$122	$926		$122	$756		$122	$1,078	
3	13,475	17,494	$148	$623		$336	$1,262		$265	$1,021		$400	$1,478	
4	12,810	16,371	$131	$754		$299	$1,561		$235	$1,256		$355	$1,833	
5	12,178	15,319	$117	$871		$265	$1,826		$209	$1,465		$315	$2,148	
6	11,577	14,335	$104	$975		$236	$2,062		$186	$1,651	5.7	$280	$2,428	
6.08			$277	$1,252	6.1	$277	$2,339		$277	$1,928	*	$277	$2,705	
7	11,006	13,414	$92	$1,344	*	$209	$2,548	6.4	$165	$2,093	*	$249	$2,954	6.4
8	10,463	12,553	$82	$1,426	*	$186	$2,734	*	$147	$2,240	*	$221	$3,175	*
9	9,947	11,746	$73	$1,499	*	$165	$2,899	*	$130	$2,370	*	$197	$3,372	*
10	9,456	10,992	$140	$1,639	*	$222	$3,121	*	$191	$2,561	*	$250	$3,622	*
11	8,989	10,286	$57	$1,696	*	$130	$3,251	*	$103	$2,664	*	$155	$3,777	*
11.51			-$68	$1,628	*	-$68	$3,183	*	-$68	$2,596	*	-$68	$3,709	*
12	8,546	9,625	$51	$1,679	*	$116	$3,299	*	$91	$2,687	*	$138	$3,847	*
13	8,124	9,007	$45	$1,724	*	$103	$3,402	*	$81	$2,768	*	$122	$3,969	*
14	7,723	8,428	$40	$1,764	*	$92	$3,494	*	$72	$2,840	*	$109	$4,078	*
			$1,764			$3,494			$2,840			$4,078		

Table N2-7: Midsize Car Full Hydraulic Hybrid - Engine On

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$170	$170		$373	$373		$302	$302		$451	$451	
2	14,174	18,695	$151	$321		$332	$705		$268	$570		$401	$852	
2.81			$122	$443		$122	$827		$122	$692		$122	$974	
3	13,475	17,494	$134	$577		$295	$1,122		$238	$930		$356	$1,330	
4	12,810	16,371	$119	$696		$262	$1,384		$212	$1,142		$316	$1,646	
5	12,178	15,319	$106	$802		$233	$1,617		$188	$1,330		$281	$1,927	
6	11,577	14,335	$94	$896		$207	$1,824		$167	$1,497	6.0	$250	$2,177	
6.08			$277	$1,173	6.1	$277	$2,101		$277	$1,774	*	$277	$2,454	
7	11,006	13,414	$84	$1,257	*	$184	$2,285		$148	$1,922	*	$222	$2,676	
8	10,463	12,553	$74	$1,331	*	$163	$2,448	7.1	$132	$2,054	*	$197	$2,873	7.1
9	9,947	11,746	$66	$1,397	*	$145	$2,593	*	$117	$2,171	*	$175	$3,048	*
10	9,456	10,992	$134	$1,531	*	$204	$2,797	*	$179	$2,350	*	$231	$3,279	*
11	8,989	10,286	$52	$1,583	*	$114	$2,911	*	$92	$2,442	*	$138	$3,417	*
11.51			-$68	$1,515	*	-$68	$2,843	*	-$68	$2,374	*	-$68	$3,349	*
12	8,546	9,625	$46	$1,561	*	$102	$2,945	*	$82	$2,456	*	$123	$3,472	*
13	8,124	9,007	$41	$1,602	*	$90	$3,035	*	$73	$2,529	*	$109	$3,581	*
14	7,723	8,428	$37	$1,639	*	$80	$3,115	*	$65	$2,594	*	$97	$3,678	*
			$1,639			$3,115			$2,594			$3,678		

Table N2-8: Midsize Car Full Hydraulic Hybrid - Engine On Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine			Clean Diesel Engine			Gas Var Disp Engine			Clean Diesel Var Disp Engine		
			$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age	$/Age	Cum $	Paybk Age
1	14,910	19,978	$240	$240		$427	$427		$377	$377		$506	$506	
2	14,174	18,695	$213	$453		$380	$807		$335	$712		$449	$955	
2.81			$122	$575		$122	$929		$122	$834		$122	$1,077	
3	13,475	17,494	$189	$764		$337	$1,266		$298	$1,132		$399	$1,476	
4	12,810	16,371	$168	$932		$300	$1,566		$264	$1,396		$355	$1,831	
5	12,178	15,319	$149	$1,081		$266	$1,832		$235	$1,631		$315	$2,146	
6	11,577	14,335	$133	$1,214		$237	$2,069		$209	$1,840	5.3	$280	$2,426	
6.08			$277	$1,491	6.0	$277	$2,346		$277	$2,117	*	$277	$2,703	
7	11,006	13,414	$118	$1,609	*	$210	$2,556	6.8	$185	$2,302	*	$249	$2,952	6.8
8	10,463	12,553	$105	$1,714	*	$187	$2,743	*	$165	$2,467	*	$221	$3,173	*
9	9,947	11,746	$93	$1,807	*	$166	$2,909	*	$146	$2,613	*	$196	$3,369	*
10	9,456	10,992	$158	$1,965	*	$223	$3,132	*	$205	$2,818	*	$250	$3,619	*
11	8,989	10,286	$73	$2,038	*	$131	$3,263	*	$116	$2,934	*	$155	$3,774	*
11.51			-$68	$1,970	*	-$68	$3,195	*	-$68	$2,866	*	-$68	$3,706	*
12	8,546	9,625	$65	$2,035	*	$116	$3,311	*	$103	$2,969	*	$138	$3,844	*
13	8,124	9,007	$58	$2,093	*	$103	$3,414	*	$91	$3,060	*	$122	$3,966	*
14	7,723	8,428	$51	$2,144	*	$92	$3,506	*	$81	$3,141	*	$109	$4,075	*
			$2,144			$3,506			$3,141			$4,075		

Table N2-9: Midsize Car Full Hydraulic Hybrid - Engine Off

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$291	$291		$458	$458		$317	$317		$489	$489	
2	14,174	18,695	$258	$549		$407	$865		$282	$599		$434	$923	
2.81			$122	$671		$122	$987		$122	$721		$122	$1,045	
3	13,475	17,494	$229	$900		$362	$1,349		$250	$971		$386	$1,431	
4	12,810	16,371	$204	$1,104		$322	$1,671		$222	$1,193		$343	$1,774	
5	12,178	15,319	$181	$1,285	4.2	$286	$1,957		$198	$1,391		$305	$2,079	
6	11,577	14,335	$161	$1,446	*	$254	$2,211		$176	$1,567	5.8	$271	$2,350	
6.08			$277	$1,723	*	$277	$2,488	6.0	$277	$1,844	*	$277	$2,627	
7	11,006	13,414	$143	$1,866	*	$226	$2,714	*	$156	$2,000	*	$240	$2,867	6.4
8	10,463	12,553	$127	$1,993	*	$200	$2,914	*	$139	$2,139	*	$214	$3,081	*
9	9,947	11,746	$113	$2,106	*	$178	$3,092	*	$123	$2,262	*	$190	$3,271	*
10	9,456	10,992	$176	$2,282	*	$233	$3,325	*	$185	$2,447	*	$244	$3,515	*
11	8,989	10,286	$89	$2,371	*	$141	$3,466	*	$97	$2,544	*	$150	$3,665	*
11.51			-$68	$2,303	*	-$68	$3,398	*	-$68	$2,476	*	-$68	$3,597	*
12	8,546	9,625	$79	$2,382	*	$125	$3,523	*	$86	$2,562	*	$133	$3,730	*
13	8,124	9,007	$70	$2,452	*	$111	$3,634	*	$77	$2,639	*	$118	$3,848	*
14	7,723	8,428	$62	$2,514	*	$99	$3,733	*	$68	$2,707	*	$105	$3,953	*
			$2,514			$3,733			$2,707			$3,953		

Table N2-10: Midsize Car Full Hydraulic Hybrid - Engine Off Reduced Roadload

Age	MOBILE6 LDV VMT	MOBILE6 LDT VMT	Conv Gas Engine $/Age	Cum $	Paybk Age	Clean Diesel Engine $/Age	Cum $	Paybk Age	Gas Var Disp Engine $/Age	Cum $	Paybk Age	Clean Diesel Var Disp Engine $/Age	Cum $	Paybk Age
1	14,910	19,978	$374	$374		$517	$517		$395	$395		$545	$545	
2	14,174	18,695	$332	$706		$460	$977		$351	$746		$484	$1,029	
2.81			$122	$828		$122	$1,099		$122	$868		$122	$1,151	
3	13,475	17,494	$295	$1,123		$408	$1,507		$312	$1,180		$430	$1,581	
4	12,810	16,371	$262	$1,385	3.8	$363	$1,870		$277	$1,457		$382	$1,963	
5	12,178	15,319	$233	$1,618	*	$322	$2,192		$246	$1,703		$340	$2,303	
6	11,577	14,335	$207	$1,825	*	$286	$2,478		$219	$1,922	5.1	$302	$2,605	
6.08			$277	$2,102	*	$277	$2,755	6.0	$277	$2,199	*	$277	$2,882	
7	11,006	13,414	$184	$2,286	*	$254	$3,009	*	$195	$2,394	*	$268	$3,150	6.3
8	10,463	12,553	$163	$2,449	*	$226	$3,235	*	$173	$2,567	*	$238	$3,388	*
9	9,947	11,746	$145	$2,594	*	$201	$3,436	*	$154	$2,721	*	$212	$3,600	*
10	9,456	10,992	$204	$2,798	*	$254	$3,690	*	$212	$2,933	*	$263	$3,863	*
11	8,989	10,286	$115	$2,913	*	$159	$3,849	*	$121	$3,054	*	$167	$4,030	*
12	8,546	9,625	$102	$3,015	*	$141	$3,990	*	$108	$3,162	*	$148	$4,178	*
11.51			-$68	$2,947	*	-$68	$3,922	*	-$68	$3,094	*	-$68	$4,110	*
13	8,124	9,007	$90	$3,037	*	$125	$4,047	*	$96	$3,190	*	$132	$4,242	*
14	7,723	8,428	$80	$3,117	*	$111	$4,158	*	$85	$3,275	*	$117	$4,359	*
			$3,117			$4,158			$3,275			$4,359		

Appendix O: Review by External Organizations

A preliminary draft of this progress report was distributed to six external organizations for their technical review: three private sector companies with which EPA has cooperative research and development agreements (Ford Motor Company, Eaton Corporation, and Parker-Hannifin), two private contractors which have contracts with EPA and which are experts on various aspects of the new technologies included in this report (FEV of America and Southwest Research Institute), and a professor at Michigan State University. These technical reviews were considered to be confidential to allow frank feedback, and this section will summarize the most important comments but will not link them to specific organizations.

1. The comments provided to EPA were generally very favorable. One of the more extensive reviews stated: "Good overall study/analysis. The approaches taken to the areas the study chooses to address are appropriate and probably sufficient for a generalized look at this topic in a mature state." Another commenter "found the document to be comprehensive and insightful." A third reviewer stated: "The conclusions reached regarding fuel efficiency improvements and reduced operating costs are based upon sound engineering approaches including modeling and simulation based upon real test data." No commenter suggested that EPA should not release the study.

2. One reviewer cited the report's assumption of a long-term, high economy-of-scale scenario for cost projections, and stated that: "The simplicity of a mature cost/payback (benefit) analysis as done by EPA leaves much of the practical considerations of moving to a hydraulic hybrid drivetrain un-studied and is therefore not a sufficient basis to justify the technology." A second commenter said that "[t]he report does not explicitly define what annual volumes are used as the basis for the cost estimates." In response to these comments, EPA has added text in the Abstract, Executive Summary, and Section 6 to clarify the underlying high economy-of-scale assumption (when annual component production volumes first reach one million units) and to recognize that the projections do not account for many costs that would be borne during a transition period.

3. One commenter suggested that the cost projections might be too conservative in the long run: "The projections for fuel economy improvement seem to be somewhat conservative considering the current level of technical development of the hardware. As with all automotive technologies, high volume production can be expected to yield significant additional improvements in efficiency and reduction in cost. The net results will be greater vehicle lifetime savings and reduced payback time." A second reviewer stated: "[t]he global marketplace, especially in the very competitive auto industry, is a place where cost optimization and reduction is the key to success….Significant advances in the technologies and manufacturing processes associated with these systems could yield lower costs and thus lower prices to the end user. Although it is not possible to accurately predict how many of these advances will occur and what their net effects will be, I am confident that advances will be made." In response to these comments, EPA has added text in the Abstract, Executive Summary, and Section 6 to recognize that the projections do not account for potential long-term cost savings if and when such technologies become mature and sustainable.

4. One reviewer stated that "[T]he addition of sensitivity analyses for the various options has the potential to add value to the understanding of their commercial viability." This same reviewer also offered a specific set of alternative cost assumptions (based on annual component production volumes of 500,000 per year) for hydraulic hybrid drivetrains that differed from EPA cost assumptions used in the body of the report (based on annual component production volumes of one million) in five areas that are summarized in Table O-1 below.

**Table O-1: Alternative Cost Assumptions for the
Hydraulic Hybrid Drivetrain Sensitivity Analysis**

| Hydraulic Hybrid Cost Area	Cost Assumption in Section 6	Alternative Cost Assumption Suggested by Reviewer	Rationale for Alternative Assumption
Pump Motors	$9.11/kg	$10.45/kg	Pump motor more like transmission ($10.45/kg) complexity than engine ($9.11/kg) complexity
Controls/Sensors	Included in pump motor cost	+$200 SUV & +$100 car	Reviewer assumed cost of controls and sensors not included. Also, more lengthy wiring harness is needed for hydraulic system than a normal transmission.
Accumulators	$10.00/kg	$13.00/kg	Based on current manufacturing techniques and aggressive "learning curve" for high volume.
Hoses/Fittings	100%	90% of EPA's cost	Higher mass than projected by EPA, but lower cost per unit mass.
Oil	$3.00/kg	$2.00/kg	Based on reviewer experience with fluids.

These alternative cost assumptions provide a basis for a sensitivity analysis of the cost projections for the technology packages involving hydraulic hybrid drivetrains. The one case where EPA modified the cost assumptions suggested by the commenter was with respect to controls and sensors. The reviewer stated that: "The inclusion of an electronic control and the required incremental sensors is not apparent in the report." EPA did include controls and sensors in the hydraulic hybrid designs described in Section 3, but for purposes of the sensitivity analysis, EPA included the full $200 cost increment suggested by the commenter for controls and sensors for the 4WD large SUV hydraulic hybrid designs and one-half of this, or a $100 cost increment, for controls and sensors for the midsize car hydraulic hybrid drivetrains. Table O-2 shows the projected incremental vehicle costs, cost per percent fuel economy improvement, consumer payback, and vehicle lifetime savings for the 4WD large SUV technology packages involving hydraulic hybrid drivetrains under this alternative scenario compared to the conventional 4WD large SUV that is used as the baseline 4WD large SUV throughout this report.

Table O-2: Key Economic Projections for Large 4WD SUV Under the Hydraulic Hybrid Drivetrain Sensitivity Analysis

Large Sport Utility Vehicle (4WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$1,784	$1,799	$1,218	$1,241
Clean Diesel Engine	$1,668	$3,446	$3,463	$2,883	$2,907
Gasoline Variable Displacement Engine	$532	$2,285	$2,302	$1,721	$1,750
Clean Diesel Variable Displacement Engine	$2,195	$3,950	$3,967	$3,387	$3,415
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$135	$109	$70	$36
Clean Diesel Engine	$45	$60	$57	$49	$34
Gasoline Variable Displacement Engine	$36	$74	$70	$53	$43
Clean Diesel Variable Displacement Engine	$39	$49	$48	$41	$34
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	9.8	6.9	4.2	2.5
Clean Diesel Engine	3.6	5.3	5.1	4.4	3.5
Gasoline Variable Displacement Engine	2.3	5.0	4.9	3.9	3.3
Clean Diesel Variable Displacement Engine	3.5	5.0	4.9	4.4	3.9
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	$492	$819	$1,493	$2,861
Clean Diesel Engine	$2,060	$2,270	$2,416	$2,893	$4,120
Gasoline Variable Displacement Engine	$1,175	$1,604	$1,738	$2,309	$2,806
Clean Diesel Variable Displacement Engine	$2,738	$2,855	$2,938	$3,479	$4,186

Table O-3 shows the differences in the key economic projections between this sensitivity case and the standard case summarized in Table ES-1 for 4WD large SUVs with hydraulic hybrid drivetrains.

Table O-3: Change in the Key Economic Projections for the Sensitivity Case Relative to the Standard Case for Large 4WD SUV

Large Sport Utility Vehicle (4WD)	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hydraulic (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$463	$463	$666	$666
Clean Diesel Engine	$0	$463	$464	$666	$666
Gasoline Variable Displacement Engine	$0	$463	$464	$666	$666
Clean Diesel Variable Displacement Engine	$0	$463	$463	$666	$666
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$35	$28	$38	$19
Clean Diesel Engine	$0	$8	$8	$11	$8
Gasoline Variable Displacement Engine	$0	$15	$14	$20	$17
Clean Diesel Variable Displacement Engine	$0	$6	$6	$8	$7
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	5	2.5	2.2	1.3
Clean Diesel Engine	0.0	0.7	0.6	1.2	1.0
Gasoline Variable Displacement Engine	0.0	0.8	0.8	1.8	1.3
Clean Diesel Variable Displacement Engine	0.0	0.5	0.4	1.1	1.0
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	-$463	-$463	-$666	-$666
Clean Diesel Engine	$0	-$463	-$464	-$666	-$666
Gasoline Variable Displacement Engine	$0	-$463	-$464	-$666	-$666
Clean Diesel Variable Displacement Engine	$0	-$463	-$463	-$666	-$666

For a 4WD large SUV, this alternative cost scenario adds about $460 for a mild hydraulic hybrid drivetrain, and about $670 for a full hydraulic hybrid drivetrain (and reduces the vehicle lifetime savings by the same amount). These higher incremental costs increase the cost per percent fuel economy improvement, and the consumer payback period, the latter generally on the order of about one year. The best payback for a 4WD large SUV hydraulic hybrid technology package in this alternative cost scenario, involving a conventional gasoline engine with full hydraulic hybrid drivetrain and engine-off strategy, is 2.5 years, compared to a payback of 1.2 years with the hydraulic hybrid cost assumptions in Section 6.

For the midsize car technology packages involving hydraulic hybrid drivetrains, Table O-4 shows the projected incremental vehicle costs, cost per percent fuel economy improvement, consumer payback, and vehicle lifetime savings under this alternative scenario compared to the conventional midsize car that is used as the baseline midsize car throughout this report.

Table O-4: Key Economic Projections for Midsize Car Under the Hydraulic Hybrid Drivetrain Sensitivity Analysis

Midsize Car (2WD)

	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$1,263	$1,274	$1,551	$1,570
Clean Diesel Engine	$1,206	$2,448	$2,461	$2,744	$2,767
Gasoline Variable Displacement Engine	$412	$1,639	$1,652	$1,930	$1,963
Clean Diesel Variable Displacement Engine	$1,613	$2,833	$2,847	$3,130	$3,159
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$105	$72	$64	$31
Clean Diesel Engine	$32	$36	$34	$38	$26
Gasoline Variable Displacement Engine	$19	$40	$37	$37	$34
Clean Diesel Variable Displacement Engine	$26	$29	$27	$31	$26
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	#N/A	12.1	11.9	6.0
Clean Diesel Engine	6.7	8.6	8.0	9.7	7.3
Gasoline Variable Displacement Engine	2.9	6.7	6.2	7.1	6.8
Clean Diesel Variable Displacement Engine	6.2	8.1	7.7	9.4	8.4
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	-$195	$55	$88	$944
Clean Diesel Engine	$583	$551	$667	$371	$966
Gasoline Variable Displacement Engine	$756	$596	$716	$664	$744
Clean Diesel Variable Displacement Engine	$895	$779	$863	$548	$794

Table O-5 shows the differences in the key economic projections between this sensitivity case and the standard case summarized in Table ES-2 for midsize cars with hydraulic hybrid drivetrains.

Table O-5: Change in the Key Economic Parameters for the Sensitivity Case Relative to the Standard Case for Midsize Car

Midsize Car (2WD)	Conventional Transmission	Mild Hydraulic Hybrid (eng on)	Mild Hydraulic Hybrid (eng off)	Full Hydraulic Hybrid (eng on)	Full Hydraulic Hybrid (eng off)
New Vehicle Cost Increase ($)					
Conventional Gasoline Engine	base	$265	$265	$437	$437
Clean Diesel Engine	$0	$266	$266	$437	$437
Gasoline Variable Displacement Engine	$0	$266	$266	$437	$438
Clean Diesel Variable Displacement Engine	$0	$266	$266	$438	$437
Cost Increase / FE Improvement ($ per %)					
Conventional Gasoline Engine	base	$22	$15	$18	$9
Clean Diesel Engine	$0	$4	$4	$6	$4
Gasoline Variable Displacement Engine	$0	$7	$6	$8	$8
Clean Diesel Variable Displacement Engine	$0	$3	$3	$4	$4
Cost Payback to Consumer(s) (Years)					
Conventional Gasoline Engine	base	#N/A	5.6	5.8	1.8
Clean Diesel Engine	0.0	1.7	1.5	2.6	1.3
Gasoline Variable Displacement Engine	0.0	0.7	0.2	1.1	1.0
Clean Diesel Variable Displacement Engine	0.0	1.4	1.2	2.3	2.0
Net Lifetime Savings to Consumer(s) ($)					
Conventional Gasoline Engine	base	-$265	-$265	-$437	-$437
Clean Diesel Engine	$0	-$266	-$266	-$437	-$437
Gasoline Variable Displacement Engine	$0	-$266	-$266	-$437	-$438
Clean Diesel Variable Displacement Engine	$0	-$266	-$266	-$438	-$437

For a midsize car, this alternative cost scenario adds about $270 for a mild hydraulic hybrid drivetrain, and about $440 for a full hydraulic hybrid drivetrain (and reduces the vehicle lifetime savings by the same amount). These higher incremental costs increase the cost per percent fuel economy improvement, and the consumer payback period, the latter generally on the order of about 1-2 years. The best payback for a midsize car hydraulic hybrid technology package in this alternative cost scenario, involving a conventional gasoline engine with full hydraulic hybrid drivetrain and engine-off strategy, is 6.0 years, compared to a payback of 4.2 years with the hydraulic hybrid cost assumptions in Section 6.

It now appears that future hydraulic hybrid designs will likely evolve toward operating pressures of 7000 pounds per square inch (psi). The designs described in Section 3 could accommodate pressures of 7000 psi, but were sized based on a maximum operating pressure of 5000 psi in order to be conservative. Operating at 7000 psi would reduce the size and cost of key hydraulic components (pump/motors and accumulators) on the order of 30 percent. In view of this likely evolution, as well as the likelihood of other unforeseen cost reductions driven by a sustained future market, EPA believes that the alternative cost scenario suggested by the reviewer (based

on annual component production volumes of 500,000) should be viewed as an upper bound with a high likelihood that sustained costs would be lower.

5. Two reviewers pointed out that there might be additional consumer operating costs associated with maintenance of hydraulic components such as pump/motors and accumulators. EPA recognizes this as a possibility, but there is not yet information on which to base such a projection, and any such maintenance costs are likely to be small relative to the primary cost factors of component cost, fuel savings, and brake maintenance savings. Accordingly, no changes were made in this regard. One reviewer also suggested that noise isolation and advanced braking designs might be necessary for hydraulic hybrids, which could add cost. EPA believes that these modifications may or may not be necessary, and because of this uncertainty EPA has not modified the cost analysis.

6. Two reviewers asked for more detail about the diesel aftertreatment cost projections, and one reviewer stated that: "Aftertreatment costs are expected to be significantly higher than EPA estimate, due to addition of DPF and NOx treatment with large volumes and precious metal requirements." EPA has retained the estimate of diesel aftertreatment costs in the draft report. There is a major industry effort underway to develop viable and cost-effective diesel emission control systems. There is great uncertainty as to the ultimate design and cost of such systems, and EPA believes its original estimates are still the best available at this time. EPA will refine its diesel aftertreatment cost estimates as more information becomes available.

7. One reviewer was skeptical of the use of a 1.26 retail price equivalent mark-up factor, and cited the use of a 1.4 factor in the National Academy of Sciences report on CAFE published in January 2002. The Office of Management and Budget has endorsed the use of the 1.26 mark-up factor in EPA motor vehicle regulatory development, and EPA considers it important to be consistent in the application of retail mark-up factors.

8. One commenter recommended the addition of a "$ per % fuel economy improvement" metric to the summary tables in the report. EPA has modified tables ES-1 and ES-2 to include this metric.

9. One reviewer "suggested that EPA consider providing copies of the modeling and simulations developed to aid in the technology transfer to industry." In response to this comment, EPA is prepared to share the models and simulations with outside parties that request them.

While these were the more important and/or comprehensive comments, many other helpful suggestions led to more minor improvements in the progress report. EPA appreciates the time and effort invested by all of the reviewers of the draft report, and the progress report is clearly improved because of the comments.