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The Benefits and Costs of New Fuels and Engines for Cars and Light Trucks

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EXECUTIVE SUMMARY

Concerns about high gas prices, global climate change, and the risks of oil dependence are spurring interest in new engines and fuels for passenger cars and light trucks. Automakers are considering new propulsion systems for vehicles, while the U.S. Congress and many states are considering new legislation to reduce oil use in the transport sector of the economy.

This report examines the benefits and costs of three alternatives to the gasoline-powered internal combustion engine for the 2010–2020 period: gasoline-electric hybrid technology, advanced diesel technology, and vehicles powered continuously by a mixture of 85% ethanol and 15% gasoline (E85), where the ethanol is produced from corn. Each technology is compared to a gasoline-powered vehicle (with otherwise comparable features) from both a consumer and societal perspective, with results expressed on a per-vehicle basis for a new mid-sized car, a mid-sized sport utility vehicle (SUV), and a large pickup truck. The key numeric output of the analysis is the net present value (NPV) of a technology expressed in 2005 dollars.

The nominal results from the consumer perspective account only for technology cost, fuel savings, mobility, and performance. For the passenger car, the private NPV was $198 for the hybrid, $460 for the diesel, and –$1,034 for the vehicle that runs on E85. For the SUV, the NPV was $1,066 for the hybrid, $1,249 for the diesel, and –$1,332 for E85. For the pickup truck, the NPV was $505 for the hybrid, $2,289 for the diesel, and –$1,632 for E85. These results assume fuel prices of $2.50 per gallon for gasoline, $2.59 per gallon for diesel fuel, and $2.04 per gallon for E85 (including the current 51-cent tax credit for use of ethanol in motor fuels).

The results of the private analysis are sensitive to fuel-price assumptions. In a high gas-price scenario ($3.50 per gallon), the diesel retains an advantage over the hybrid for pickup trucks, but the hybrid is preferred for cars and SUVs. The NPV of the E85 vehicle also improves in the high gas-price scenario. It has positive NPV for all three vehicle types, and the size of the NPV is larger than the NPV of the hybrid and diesel for passenger cars. A low gas price ($1.79 per gallon) hurts all three alternate technologies: Hybrids and E85 have negative NPV in each vehicle type; diesels are unattractive for cars but retain a positive NPV for SUV and pickup applications.

The societal perspective includes a much larger range of considerations such as conventional tailpipe pollutants, greenhouse gas emissions, and energy security. Despite the added complexity of the societal analysis, the results are similar to those reported for the consumer perspective. For the passenger car, the NPV is –$317 for the hybrid, $289 for the diesel, –$1,046 for E85. For the SUV, the NPV is $481 for the hybrid, $1,094 for the diesel, and –$1,500 for E85. For the pickup truck, the NPV is $132 for the hybrid, $2,199 for the diesel, and –$2,049 for E85. The absolute magnitudes of the societal results are influenced by the exclusion of transfer payments (e.g., fuel taxes).

The societal results are also sensitive to future fuel prices (see attached summary table). At expected long-run fuel prices ($2.50 per gallon), public policies that accelerate the diffusion of diesels and hybrids may, depending on the balance of existing policies, enhance social welfare to a greater extent than policies that enlarge the use of E85 based on corn-based ethanol. But if the cost of producing ethanol for E85 declines significantly or if gasoline prices remain very high ($3.50 per gallon), then E85 has positive NPV and can compete favorably with diesels and hybrids. If the cost of gasoline should fall significantly and stay low ($1.79 per gallon), then the only promising measures are some limited application of advanced diesel engines in large pickup trucks.

In order to provide context for these analytic results, the report discusses a variety of market developments and public policies that are influencing the rate of penetration of these technologies. Ideally, public policy should focus on setting the correct incentives for market participants and allowing the best portfolio of technologies to emerge through market competition.

Table ES-1: NPV of Hybrid, Diesel, and E85: Alternative Oil and Ethanol Prices (2005$)

Passenger Car

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV by Ethanol Price		
			Low	Nominal	High
Low	–$1,205	–$374	–$207	–$2,110	–$3,143
Nominal	–$317	$288	$1,336	–$1,045	–$2,370
High	$935	$1,219	$4,117	$1,113	–$627

Sport Utility Vehicle

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV by Ethanol Price		
			Low	Nominal	High
Low	–$636	$264	–$379	–$2,936	–$4,347
Nominal	$477	$1,092	$1,669	–$1,504	–$3,290
High	$2,044	$2,257	$5,341	$1,368	–$950

Large Pickup Truck

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV by Ethanol Price		
			Low	Nominal	High
Low	–$1,007	$1,162	–$568	–$4,005	–$5,925
Nominal	$135	$2,207	$2,171	–$2,046	–$4,438
High	$1,742	$3,679	$7,019	$1,792	–$1,272

Note: See text at p. 16 for explanation and Appendix A at p. 25 for details.

Section 1: Introduction

Rising world oil prices, coupled with concerns about global climate change, are forcing a reconsideration of the fuels and engines that are used in the transport sector of the U.S. economy. How to propel cars and light trucks is of special interest because these "light-duty" vehicles account for approximately 60% of oil use in the U.S. transport sector and total oil demand for these vehicles is projected to rise by almost 20% between now and 2020 (EIA, 2007). A similar dilemma is facing leaders in other regions of the world, including the European Union, China, India, and Japan.

The purpose of this paper is to provide information to investors, advocates, public policymakers, and the public about the relative promise of different engines and fuels in the 2010 to 2020 time frame. Benefit-cost analysis is used to compare different technological options.

Using the gasoline-powered internal combustion engine as a baseline for comparison, the benefits and costs of alternative engines and fuels are estimated for new light-duty passenger vehicles in the United States. Based on explicit screening criteria, the scope of the alternatives is restricted to gasoline-electric hybrid technology, advanced diesel technology, and dedicated vehicles that run continuously on 85% ethanol and 15% gasoline. Net-benefit estimates are computed on a per-vehicle basis. Separate estimates are provided for applications to passenger cars, sport utility vehicles, and large pickup trucks.

For analytic purposes, we assume in this paper that market and policy trends cause each of the three alternative technologies to be used in at least 1 million U.S. vehicles. We focus not on the benefits and costs of the policies that might produce this outcome but on the marginal benefits and costs of a dedicated E85 vehicle, hybrid, or advanced diesel, after the transitional process has expired and an equilibrium is reached. This is a steady-state assumption that focuses on the long-run marginal benefits and costs of each technology under a condition of substantial economies of scale. The same steady-state assumption is made for all three technologies, although the economic cost and political will necessary to bring each technology to the steady-state condition may not be equal. We also omit any inefficiencies associated with policies (tax preferences or regulations) that may be necessary to ensure the penetration of the three technologies to 1 million units per year. For example, analysts argue that tighter federal fuel economy standards cause more inefficiency than higher gasoline taxes (Austin and Dinan, 2005; West and Williams, 2005)

We examine each of the three alternatives using two perspectives: a "private" perspective that considers only those benefits and costs likely to be incurred by the vehicle owner, and a "societal" perspective that considers various externalities (e.g., climate change and energy security impacts) as well as private benefits and costs to vehicle owners. The societal perspective is favored in welfare economics and was applied in the pioneering studies of this issue (Hahn, 1995; Lave et al., 2000).

The key outcome measure is the net present value (NPV), defined as the present value of benefits minus the present value of costs (2005$). We examine the robustness of the NPV estimates by exploring how these estimates change with plausible yet different assumptions about key input values. In order to provide further context for the NPV estimates, we also summarize recent market and policy trends in the United States that appear to be affecting the penetration of the three alternatives, including a variety of qualitative factors that we were not able to incorporate into the numeric benefit-cost analysis.

This report contributes to a small but growing body of benefit-cost literature on new propulsion systems for cars and light trucks, including previous work by Lave et al. (2000), Lave and MacLean (2002), National Research Council (2002), MacLean and Lave (2003), and Lipman and Delucci (2006). National Research Council (2002) examines primarily improvements to the gasoline engine, with little analysis of hybrid and diesel technology and no analysis of E85. Studies that examine hybrid engines have reached conflicting conclusions, such as Lave and MacLean (2002) versus Lipman and Delucci (2006). The most comprehensive assessment of technologies is provided by Lave et al. (2000) and refined by MacLean and Lave (2003), but their primary assumptions about fuel prices ($1.50 per gallon), diesel emission control, and hybrid technology costs predate recent developments in the industry.

The strengths of the present study include application of a consistent analytic framework to four different technologies, a lifecycle perspective, updated inputs based on recent economic and technological developments, and extensive sensitivity analysis of results based on plausible changes to input values. The study also summarizes recent trends in the marketplace and public policy.

Section 2 of the report introduces and applies the screening criteria that support the selection of the three potential alternatives to gasoline-powered vehicles. Sections 3 and 4 present benefit-cost estimates from the private and societal perspectives, respectively. Section 5 presents results of various sensitivity analyses of key inputs to the calculations. Section 6 summarizes recent market and policy developments. The appendices to the report provide input values used in the analysis, their relevant sources, and further results not included in the main text.

Section 2: Alternatives to the Gasoline-Powered Internal Combustion Engine

The U.S. market for new light-duty vehicles—now about 17 million units per year—is currently dominated by the gasoline-powered internal combustion engine. A wide range of fuel/engine combinations have been suggested as alternatives: advanced diesel technology, electric vehicles, fuel cells, liquid fuels derived from coal, ethanol, biodiesel, compressed natural gas, liquefied natural gas, propane, gasoline-electric hybrid technology, diesel-electric hybrid technology, and plug-in hybrid technology.

In order to restrict the analysis to a manageable number of alternatives, we applied three screening criteria to each fuel/engine alternative: (1) Will the alternative help reduce U.S. oil consumption? (2) Will the alternative help reduce the emissions of greenhouse gases implicated in global climate change? (3) Could the alternative have significant market penetration (at least 1 million units of production per year) in the U.S. transport sector by the early part of the next decade (2010–2020)? We selected for analysis only those alternatives where a "yes" answer seemed appropriate for all three questions, based on our literature reviews and discussions with relevant specialists.

To illustrate how we applied the screening criteria, consider liquid fuels from coal and plug-in hybrid technology. The former would increase greenhouse gas emissions without technology to sequester the emissions. Sequestration technology is not commercially available at present, and its commercial prospects within the timeframe of this study remain uncertain. In the case of plug-in hybrids, there is considerable disagreement within the industry as to whether the market-penetration criterion can be met (CARB, 2007). Toyota, for example, has recently delayed significantly the company's plans for introduction of plug-in hybrids with lithium-ion battery technology due to safety concerns (Shirouzu, 2007). The company is giving more emphasis to increasing hybrid sales than accelerating the introduction of plug-in hybrids (White, 2007b).

The three chosen alternatives are (1) full gasoline-electric hybrid technology, such as the system offered as standard equipment on the Toyota Prius or the system offered as an option by Ford Motor Company on the Escape SUV; (2) advanced diesel technology, such as the systems sold widely in Europe coupled with low-sulfur diesel fuel and recent advances in control technology that minimize tailpipe emissions of particulates and nitrogen dioxide (e.g., particulate traps and nitrogen dioxide catalysts coupled with low-sulfur diesel fuel); and (3) vehicles that can operate on a mixture of gasoline and up to 85% ethanol, such as the 5 million vehicles already on the road in the United States that were produced by General Motors Corporation, Ford Motor Company, and Chrysler Corporation. We acknowledge that some of the rejected alternatives also hold considerable promise (e.g., plug-in hybrids) and are worthy of future benefit-cost studies, even though their near-term market penetration may be slight.

Even for the three selected alternatives to the gasoline engine, meeting the market penetration criterion will not be easy or costless—even though 1 million vehicles per year is a small fraction of the 17 million U.S. vehicles sold each year. Producing and fueling 1 million diesel-powered light-duty vehicles per year would require transitional costs at engine suppliers (domestic and foreign), vehicle assembly lines, refineries, and refueling stations. For hybrid technology, a major expansion of the supplier network for batteries and other inputs would be required. Although producing 1 million E85 vehicles per year is quite plausible, fueling those vehicles would require major changes in infrastructure (e.g., pumps at refueling stations) and efforts (information and incentives) to persuade consumers to use the fuel. Our focus in this paper is not on the transition process but on the marginal benefits and costs of the technologies once the transition is accomplished.

Concerning the three selected alternatives, we excluded some variants that may ultimately prove to be promising. A variety of "mild" hybrid systems are now being offered by

General Motors Corporation and other vehicle manufacturers (Greene et al., 2004; Truett, 2007a). A "mild" hybrid is less expensive than a "full" hybrid but also offers less gain in fuel economy (Greene et al., 2004). Moreover, the electric arm of the hybrid engine can be married with a diesel engine as well as a gasoline-powered engine. Ethanol can be made from switchgrass or wastes ("cellulosic ethanol") as well as from corn, and in Brazil there are some vehicles powered by pure (99+%) ethanol made from sugarcane (Goldemberg, 2006). Although each of these variants on the three chosen alternatives has some promise, we have excluded them from the main analysis because we believe that they are unlikely to satisfy the market-penetration criterion. We acknowledge that application of the screening criteria entails a considerable amount of subjective judgment.

Section 3: Net-Benefit Estimates: Private Perspective

We begin with a simple analysis in which a hypothetical consumer faces a choice between a gasoline-powered internal combustion engine, a gasoline-electric hybrid vehicle, an advanced diesel-powered vehicle, or a vehicle that runs continuously on E85. The consumer's choice is analyzed separately assuming that a mid-sized passenger car, a mid-sized SUV, and a large pickup truck (or a large SUV) is under consideration.

For the nominal assumptions about technology costs, fuel efficiency, and performance in Table 1 (below), we rely primarily on estimates prepared by analysts in the federal government: Greene et al. (2004), NHTSA (2005), and EPA (2005) for hybrids and diesels and IMF (2007), EPA (2007), and EIA (2007) for corn-based ethanol and E85. In the sensitivity analyses, we consider a variety of estimates from different viewpoints. Appendices A and B discuss the inputs in greater detail.

The gasoline-electric hybrid engine is the most costly of the four systems but is also the most fuel-efficient and offers some performance benefit compared to the gasoline-powered engine. The diesel engine is more expensive than the gasoline engine but less expensive than the hybrid. The diesel is assumed to offer better performance (measured by torque) than the two other alternatives but is not quite as fuel-efficient as the hybrid. Note that the performance comparison excludes acceleration, which, though quantifiable, varies largely by make and model and less as a result of the particular engine technology or fuel. The E85 vehicle, which is also likely to have flex-fuel capability, has a small incremental vehicle cost compared to the gasoline engine. Yet the E85 vehicle generates the largest fuel expenses because ethanol, which is assumed to be corn-based, is more expensive to produce than gasoline after adjusting for differences in energy content.

Table 1: Nominal Vehicle Assumptions about Fuel Economy, Technology Cost, and Torque

Private Inputs	**Passenger Car**	**SUV**	**Large Pickup Truck**
Fuel Economy Assumptions			
Hybrid	+40%	+40 %	+30%
Advanced Diesel	+27%	+27%	+27%
E85	–25%	–25%	–25%
Technology Cost Assumptions			
Hybrid	$3,500	$4,200	$5,040
Advanced Diesel	$2,300	$3,000	$3,500
E85 (Flex Vehicle)	$100	$150	$175
Torque Increase Assumptions			
Hybrid	+20%	+20%	+15%
Advanced Diesel	+25%	+25%	+25%
E85	0%	0%	0%

The prices of the fuels (gasoline, diesel, and E85), which play a key role in the analysis, are presented in Table 2. The average price of gasoline over the vehicle's life is assumed to be $2.50 per gallon (federal and state taxes included), which is based on the International Monetary Fund's world oil-price projections (approximately $65 per barrel in the long term) and standard EIA estimates of refining/distribution costs and taxes. The cost of diesel fuel is slightly higher. The nominal cost of E85 is assumed to be $2.42 per gallon based on IMF's (2007) and EPA's (2007) estimates for corn-based ethanol. The low and high estimates of the fuel costs are used in sensitivity analyses and are therefore discussed in Section 4. The tax credit referred to in Table 2 is the 51-cent-per-gallon tax credit paid to fuel blenders for each gallon of ethanol blended into the fuel supply. This provision is known as the Volumetric Ethanol Excise Tax Credit (VEETCH) and is scheduled to expire under current law in 2010. We follow EIA's assumption in their analysis that the tax credit will persist through the period considered in this study.

Table 2: Fuel Price Assumptions

	Low Value	Nominal Value	High Value
World oil price (2005$/barrel)	35	65	107
Gasoline price (2005$/gallon)	1.79	2.50	3.50
Diesel price (2005$/gallon)	1.87	2.59	3.59
E85 price (2005$/gallon)	1.70	2.42	3.04
E85 price (2005$/gall gas equiv)	2.27	3.23	4.05
E85 price w/ tax credit (2005$/gallon)	1.32	2.04	2.66
E85 price w/ tax credit (2005$/gall gas equiv)	1.76	2.72	3.55

Diesel and hybrid engines are assumed to create a mobility benefit. They induce more travel by reducing the fuel expenditures necessary to operate the vehicle for a specified distance. E85 is associated with a mobility disbenefit because the E85's lower energy value causes an effective increase in the fuel expenditures necessary to operate the vehicle. The impact of fuel-efficiency changes on miles traveled is sometimes called "the rebound effect." Our nominal estimate is that 15% of the fuel savings projected for a more fuel-efficient engine will be nullified by induced travel (Greening et al., 2000). The monetary value of the mobility benefit is computed according to what economists call a "revealed preference": The mobility is valued as the sum of the extra fuel expenses plus the non-fuel variable costs of travel such as vehicle maintenance expenses, crash risks, and time spent in transit, which are assumed to be 30% of the fuel expenses. Even with the 30% adjustment, the mobility benefits—which have considerable psychological value to motorists—are probably underestimated. The net fuel savings estimated for each technology are adjusted to account for the rebound effect. The adverse social impacts from the rebound effect (e.g., congestion and pollution) are excluded from the private perspective but included below in the societal perspective.

We assume that the consumer cares only about the cost of the engine technology, any performance gain or detriment, any mobility impacts, and the net fuel savings over the projected life of the vehicle (see Table 1). The vehicle life is characterized by a survival rate, an annual rate of miles driven that declines steadily as the vehicle ages, and a maximum lifespan of 25 years. We also assume that the consumer applies a 7% real discount rate to any future benefits and costs, and compares the alternatives according to their net present value of monetized savings, where savings can be positive (good) or negative (bad). The 7% rate is near the effective interest rate that consumers pay on loans for vehicle purchases, 6% for new cars and 9% for used cars (Federal Reserve Board, 2007). NHTSA (2006b) argues that the proper weighted average of the two loan rates is quite close to 7%.

The results from the private perspective are displayed in Table 3. For all three vehicle types, the diesel has the largest positive savings ($460 for the car, $1,249 for the SUV, and $2,289 for the pickup truck). The hybrid has small positive savings for the passenger car ($198), larger savings for the SUV ($1,066) and somewhat smaller savings for the large pickup ($505). The E85 vehicle has consistently negative NPV (–$1,034 for cars, –$1,332 for SUVs, and –$1,632 for large pickups), primarily due to the higher fuel expenditures.

The impacts of the four components (fuel consumption, technology cost, performance, and mobility) on the private results are also reported in Table 3. A key insight is that while the hybrid saves more fuel than the diesel, the overall advantage of the diesel arises from the assumptions about lower technology costs and improved performance. The performance benefit from increased torque is adapted from a recent econometric analysis of vehicle prices (Crandall et al., 2004).

Table 3: NPV Estimates from Private Perspective

	NPV Fuel Savings	Technology Cost	Performance Benefit	Mobility Benefit	NPV Savings
Hybrid					
Passenger Car	$2,441	–$3,500	$567	$690	$198
Sport Utility Vehicle	$3,030	–$4,200	$1,346	$890	$1,066
Large Pickup Truck	$3,110	–$5,040	$1,530	$905	$505
Diesel					
Passenger Car	$1,520	–$2,300	$708	$532	$460
Sport Utility Vehicle	$1,880	–$3,000	$1,683	$686	$1,249
Large Pickup Truck	$2,380	–$3,500	$2,550	$859	$2,289
E85					
Passenger Car	–$740	–$100	$0	–$194	–$1,034
Sport Utility Vehicle	–$930	–$150	$0	–$252	–$1,332
Large Pickup Truck	–$1,150	–$175	$0	–$307	–$1,632

A distinct choice we have not analyzed in detail is whether vehicles should be produced to run only on E85 (a so-called dedicated E85 vehicle) or on gasoline or E85 (the “flex-fuel” or “dual fuel” vehicle). Once the vehicle manufacturer modifies a vehicle to run on E85, the incremental cost of dual-fuel capability (i.e., E85 or gasoline) is negligible.

In some regions of the country where E85 is more widely available (e.g., Minnesota), owning a flex-fuel vehicle might be especially advantageous in the event of long gas lines. Yet energy economists argue that long gas lines like those experienced in the United States in 1973–1974 are unlikely in the future due to the growing fungibility of the world oil market and the removal of price controls that contributed to long waiting times (Toman, 1993). We have not quantified any incremental benefit to the consumer of owning a vehicle that can operate on two fuels instead of one.

For purposes of this analysis, we assume that at least 1 million vehicles are being fueled continuously by E85, even if the relative costs of gasoline are lower than the energy-equivalent costs of E85. This usage obviously would not occur voluntarily if the relative price of E85 is higher, which is why our analysis should not be interpreted as projecting levels of any alternative fuel use. Expanded E85 usage would require other steps, such as larger subsidies or mandates for renewable fuels use. Countries such as Brazil and Sweden have already taken such steps to promote substantial use of E85, and policymakers in the corn-producing states of the United States and in the U.S. Congress are considering pro-E85 policies (Fialka, 2007).

Our technology cost estimates do not necessarily include all of the transitional and one-time costs associated with each of the alternatives. If some refineries need to shift their mix of products towards diesel fuel instead of gasoline, there will be some one-time capital expenses at the refinery associated with the shift. If auto-assembly lines shift from making gasoline engines to hybrids or diesels, there will be some one-time costs associated with the conversion (Hammett et al., 2004). And if E85 is used to power 1 million vehicles, there will be some one-time costs associated with upgrading distribution, storage facilities, and pumps at retail outlets—though some of these one-time costs (e.g., capital costs of ethanol plants) are already incorporated into the marginal cost estimates we are using.

For hybrid and diesel engines, our cost estimates may appear smaller or larger than the prices of some optional packages now on the market in the United States or Europe. The pricing of low-volume, optional packages is not a good indicator of long-run marginal costs because vehicle manufacturers price some low-volume options below costs and other options above costs, depending on corporate objectives.

The positive NPV results for hybrids and diesels assume no improvements in the fuel efficiency of the gasoline-powered internal combustion engine. The baseline fuel efficiencies are assumed to be 28.3 miler per gallon (mpg) for the mid-sized passenger car, 22.7 mpg for the mid-sized SUV, and 17.3 for the large pickup truck. We developed these assumptions, which do not apply to any specific vehicles, based on estimates in the literature and in consultation with industry experts (EPA, 2007; NHTSA, 2006b).

We examined an alternative scenario in which creative engineers are able to identify modifications to the gasoline engine that can achieve a 25% increase in baseline fuel efficiency at no net cost to the consumer. Some specialists would regard this scenario as implausible, since many low-cost improvements to the gasoline engine have already been implemented. But if the hypothetical improved gasoline engine is used as the baseline, the NPV results for diesels and hybrids are less favorable, whereas the results for E85, though negative, are not quite as unfavorable as before (see Table 4). Some experts argue that underutilized, fuel-saving, cost-saving technologies are available for vehicle manufacturers to apply to the gasoline engine (National Research Council, 2002; Power and Walker, 2007). A new National Research Council study is underway to provide an updated estimate of the technological opportunities available to vehicle manufactures, suppliers, and consumers.

Table 4: NPV Estimates, Assuming Fuel-Economy Improvements in Gasoline Engine

	Hybrid NPV	Diesel NPV	E85 NPV
Passenger Car	–$1,789	–$1,744	–$851
Sport Utility Vehicle	–$1,370	–$1,501	–$1,075
Large Pickup Truck	–$1,695	–$1,228	–$1,426

The addition of the federal income tax credit for purchasing a hybrid or diesel engine is analyzed in Table 5 from a consumer perspective. The size of the hybrid credit is based on recent IRS determinations (e.g., $2,100 for passenger car, $1,950 for SUV, and $1,500 for a large pickup truck) while the diesel credit is assumed to be $1,000 per vehicle. No diesel-powered vehicle has yet been certified for a tax credit. With the benefit of these tax credits, both hybrids and diesels are significantly more attractive to the consumer.

Table 5: NPV Estimates, Including Federal Income Tax Credits for Hybrids and Diesels

Private NPV	Hybrid	Diesel	E85
Passenger Car	$2,298	$1,460	–$1,034
SUV	$3,016	$2,249	–$1,332
Large Pickup Truck	$2,005	$3,289	–$1,632

For urban consumers, the hybrid is more attractive than our nominal estimates suggest because the hybrid produces larger fuel savings in urban traffic. (The gasoline engine is highly inefficient in stop-and-go city traffic, whereas the hybrid can use electric power—harnessed by regenerative braking—as well as the gasoline engine). If we take the extreme case of an urban consumer who will use a car entirely in city traffic, the NPV of a hybrid car increases substantially (see Table 6 for calculations based on data for the 2008 Honda Civic). Thus, it is not surprising that the Toyota Prius and Honda Civic (hybrid version) have attracted significant interest among urban commuters on the coasts of the United States (Rechtin, 2007). This interest is only accentuated in states or regions where owners of hybrid vehicles gain special access to high-occupancy vehicle (HOV) lanes or city parking and typically face fuel prices above the national average.

Table 6: NPV Estimates for an Urban Consumer

	MPG	City/Hwy	NPV Savings
Conventional Car	25/36	100/0	Baseline
Hybrid Car	40/45	100/0	$1,671

For new-car buyers with a short planning horizon, the extra up-front cost of the diesel or hybrid engine will weigh more heavily than the small annual fuel savings that occur over the long lifetime of a vehicle. For example, under our nominal assumptions, a new-car consumer with a 3-year time horizon will perceive negative NPV for both a hybrid and diesel engine, except for the large pickup truck (see Table 7). Some analysts argue that consumers do not respond to higher gas prices because of the short time horizon (National Research Council, 2002; Gallagher et al., 2007); others argue that there is increasing evidence that consumers are responsive to fuel savings, especially as fuel prices increase (Espey and Nair, 2005; McManus, 2006; Sterner, 2007).

Table 7: NPV Estimate for Consumers with a 3-Year Time Horizon

	Hybrid NPV	Diesel NPV	E85 NPV
Passenger Car	–$1,551	–$693	–$515
SUV	–$1,150	–$209	–$667
Large Pickup Truck	–$1,695	$503	–$834

Some analysts argue that the diesel engine will hold its resale value better than hybrids because the diesel engine is highly durable, whereas the hybrid may need an expensive battery replacement. However, the durability of the diesel's advanced emission-control system remains an open question, while the longevity of the battery packs in hybrid vehicles has been impressive (AllianceBernstein, 2006). We assume that neither the diesel nor the hybrid has a comparative advantage in holding resale value.

In assessing the overall results from the private perspective, it is important to recognize that the net savings for diesels and hybrids are small compared to the overall purchase cost of a new light-duty vehicle, which can range from $20,000 to $50,000 per vehicle and even higher. Our inference is that, assuming fuel prices stabilize at $2.50 per gallon, market forces alone are unlikely to induce a powerful shift away from the gasoline-powered internal combustion engine, especially since steady improvements in the gasoline engine will compete with advanced diesels and hybrids. Among those consumers with a very strong interest in fuel efficiency or performance, hybrid and diesel offerings will find some enthusiastic buyers. In contrast, E85 appears to have no appeal from a consumer perspective (given our nominal assumptions) because corn-based ethanol is more costly to produce than gasoline after adjusting for the energy content of the fuels.

Section 4: Net-Benefit Estimates: Societal Perspective

Our societal analysis introduces the following complications: (1) the impact of lowered U.S. oil consumption on U.S. energy security is quantified and monetized, (2) the lifecycle impacts of emissions of conventional tailpipe pollutants and greenhouse gas emissions are quantified and monetized, and (3) the indirect effect of each alternative on vehicle miles of travel through the "rebound effect," including pollution, congestion and other externalities, is quantified and monetized. Fuel prices are treated net of taxes and credits in the societal case because taxes and credits are considered to be transfers (i.e., they produce no net change in well-being for society as a whole). Since the societal analysis includes consideration of impacts on everyone, not just the vehicle owner or user, it is the most relevant perspective for public policy deliberations.

The key inputs used for the societal perspective are displayed in Table 8. We discuss briefly below the rationale for introducing these complications, with additional discussion and references contained in Appendix C.

Table 8: Key Input Values for the Societal Perspective

	Low	**Nominal**	**High**
Rebound Factor	10%	15%	20%
Miles per year (before rebound)	10,000	15,000	20,000
Percentage urban driving (city/highway)	25/75	55/ 45	75/25
Externalities			
Greenhouse Gas Cost (US$ per ton CO_2)	0	5.50–15	100
Energy Security Cost (cents/gallon)	0	32	175
"Congestion Cost" (cents/mile)	2	7.5	10
Conventional Pollutant Costs			
Nitrogen Oxides (per ton)	$1,633	$1,633	$163,300
Carbon Monoxide (per ton)	$22.7	$22.7	$2,270
Volatile Organic Compounds (per ton)	$1,633	$1,633	$163,300
Particulate Materials (2.5) (per ton)	$13,083	$13,083	$1,308,300
Sulfur Dioxides (per ton)	$8,678	$8,678	$867,800
Discount Rate	3%	7%	11%

The energy-security analysis is based on two assumptions: reduced U.S. oil consumption will put downward pressure on the world price of oil, since the U.S. is such a large consumer of oil, and reduced U.S. oil consumption makes the U.S. economy less vulnerable to price volatility (Toman, 2002). The magnitudes of these effects that are reported in National Research Council (2002) are updated to reflect the projected world price of oil (IMF, 2007). We calculate lifecycle petroleum use for each of the fuels using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, which accounts for petroleum use in the extraction, transportation, and refining of fuels.

Conventional air pollution is examined on a lifecycle basis for multiple pollutants and then aggregated across pollutants using standard "shadow prices" (damage estimates) for the different pollutants. One of the reasons that diesel and hybrid engines have a lifecycle pollution benefit compared to gasoline is that they use less fuel, which means less air pollution occurs during drilling, oil shipment, refining, and transport to the blender (Brinkman et al., 2005). The pollution impacts of the rebound effect (more travel causes more pollution) have a significant effect, as do the inherent differences in the cleanliness of the different fuels and engines.

The climate analysis accounts for all greenhouse gases (e.g., carbon dioxide, methane, and nitrous oxide), weighted by their relative global-warming potential and expressed in units of "CO2 equivalents." Any climate impacts of black carbon are omitted, which may bias the climate analysis in favor of diesel, which is projected to have a higher rate of black-carbon emissions than E85, hybrids, or gasoline (Jacobson et al., 2007a). The shadow price of carbon dioxide, reflecting damages from climate change, is assumed to start relatively small ($5.45/ton in 2007) but rise steadily throughout the time horizon of the study ($14.85/ton in 2030). We base our assumptions on recent analysis in Nordhaus (2007) that shows the damages from climate change increasing over time.

Congestion enters the analysis because hybrids and diesels increase travel whereas E85 discourages travel. As travel increases, motorists experience more congestion and the rate of crashes increases. Standard damage estimates for congestion are drawn from regulatory analyses of federal fuel-economy standards (NHTSA, 2006b). Note that the congestion cost applies only to the rebound miles of travel, whereas the damages from pollution apply to all miles of travel.

The rebound effect has multiple ramifications in the societal analysis. For example, the rebound effect dampens the extent of fuel savings, pollution reductions, and greenhouse gas reductions attributable to the diesel engine and the hybrid engine. Interestingly, the external benefits of E85 are enhanced by the rebound effect because the higher energy-equivalent cost of E85 discourages travel, reduces greenhouse gases, and reduces congestion. But the mobility disbenefit hurts E85.

Despite the numerous complications that have been added to the societal perspective, the results are qualitatively similar to the results found for the private perspective. Measured by NPV, the diesel is the most promising alternative. The NPV for the hybrid is slightly negative for cars but positive for SUVs and pickups. The NPV of E85 is again uniformly negative. A careful look at Table 9 reveals an underlying pattern: The most important inputs appear to be fuel savings, technology cost, performance, and mobility, the same inputs that drive the private perspective. In other words, the externalities are relatively small compared to the private impacts (Parry et al., 2007).

Table 9: NPV Estimates from the Societal Perspective

	NPV Fuel Savings	Technology Cost	Performance Benefit	Mobility Benefit	Pollution Savings	Energy Security Savings	GHG Savings	Congestion Cost	**NPV Externality**	**NPV Savings**
Hybrid										
Passenger Car	$2,079	–$3,500	$567	$588	$21	$337	$103	–$512	**–$51**	**–$317**
Sport Utility Vehicle	$2,583	–$4,200	$1,346	$759	$23	$366	$115	–$511	**–$7**	**$481**
Large Pickup Truck	$2,650	–$5,040	$1,530	$771	$38	$423	$131	–$371	**$221**	**$132**

Diesel										
Passenger Car	$1,382	–$2,300	$708	$448	$52	$263	$81	- $345	**$51**	**$289**
Sport Utility Vehicle	$1,716	–$3,000	$1,683	$577	$33	$328	$102	- $345	**$118**	**$1,094**
Large Pickup Truck	$2,160	–$3,500	$2,550	$723	$57	$413	$128	- $332	**$266**	**$2,199**
E85										
Passenger Car	–$1,670	$100	$0	–$929	$25	$959	$92	$577	**$1,653**	**–$1,046**
Sport Utility Vehicle	–$2,070	–$150	$0	–$1,202	$42	$1,186	$116	$578	**$1,922**	**–$1,500**
Large Pickup Truck	–$2,610	–$175	$0	–$1,496	$31	$1,503	$144	$554	**$2,232**	**–$2,049**

Section 5: Sensitivity Analyses

In this section, we examine the robustness of our analytic results with respect to plausible changes in the assumed values of inputs. We begin with a sensitivity analysis of the results from the private perspective and then explore the societal perspective. Numerous sensitivity analyses were performed. We focus on those that affect the rank ordering of the technologies or are likely to be of significant interest to readers.

Robustness of Private Results

In the private case, the most interesting sensitivity analyses concern the projected fuel price, the technology costs and fuel-efficiency gains, and the time preferences of the consumer. The key insights are discussed here, with technical details presented in Appendix D.

As we look over the maximum 25-year lifetime of a light-duty vehicle, the anticipated price of fuel looms as a large unknown. For a low-price scenario, we assumed that the world oil price would decline sharply from its present levels and stabilize at a level that produced an average gasoline price of $1.79 per gallon for the time horizon of this study (EIA, 2007). This price may seem very low by the experience of recent years in the United States, but it remains higher than what U.S. motorists saw at the pump through most of the 1980s and 1990s. For a high-price scenario, we assumed $3.50 per gallon, which is much larger than EIA's upper-end, long-run forecast and larger than what U.S. motorists experienced after Hurricane Katrina and the unexpected shutdown of Gulf Coast refineries. The low- and high-price scenarios are intended to stretch the bounds of plausibility, thereby serving a useful bounding role. Thus, our sensitivity analysis covers a large range of potential fuel prices.

The results of the fuel-price analysis are reported in Table 10. At the low gasoline price ($1.79 per gallon), hybrids have negative NPV for all three vehicle types, but the NPV of the diesel remains positive for both SUVs and pickups. At the high gasoline price ($3.50 per gallon), both the hybrid and diesel have positive NPV for all three vehicle types, but the NPV of the hybrid is higher than the NPV of diesel in car and SUV applications. All of these analyses assume that gasoline and diesel fuel prices move together, with diesel priced slightly higher than gasoline. Since the world oil price is the primary driver of both gasoline and diesel fuel prices, we do not expect the two fuel prices to diverge in the long run.

The NPV of E85 is quite sensitive to the estimated cost of producing E85 from corn. At the low cost estimate ($1.70 per gallon), E85 has a positive NPV for all three vehicle types, higher than the NPV of the diesel or hybrid. At the high cost estimate ($3.04 per gallon), unfavorable results for E85 become more strongly unfavorable.

The low-cost ethanol scenario is based on EPA (2007), but some analysts question whether the cost of producing corn-based ethanol can really decline by 50% over the next decade. Progress is being made at the farm, where more corn is being grown with the same inputs, and at the ethanol plant, where more ethanol is being produced from a bushel of corn (Shapouri et al., 2002; Worldwatch Institute, 2006). Creative ways are also being explored to generate commercial value from the byproducts of corn-based ethanol production (Rosner, 2007). Despite these encouraging trends, continued growth in the price of corn could make the low-cost ethanol scenario completely implausible. A different interpretation of the low-cost scenario would be a breakthrough in cellulosic ethanol production or a removal of the tariff on imported ethanol from low-cost producers such as Brazil. A detailed analysis of these non-corn possibilities is beyond the scope of this paper.

The best fuel-price scenario for E85 is a combination of high world oil prices and low costs of producing E85. Under those conditions, the NPV of E85 is not only positive, it is larger than the NPV of both diesel and hybrid engines. But the probability of these two unlikely conditions occurring simultaneously for a decade or more is exceedingly small.

Table 10: NPV of Hybrid, Diesel, and E85: Alternative Oil and Ethanol Prices (Private Perspective

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$692	–$172	$39	–$2,929	–$4,720
Nominal	$198	$460	$2,155	–$1,034	–$3,008
High	$1,449	$1,390	$5,439	$1,870	–$290

Sport Utility Vehicle

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$48	$462	$15	–$3,697	–$5,930
Nominal	$1,066	$1,249	$2,667	–$1,332	–$3,800
High	$2,633	$2,417	$6,791	$2,304	–$405

Large Pickup Truck

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$633	$1,293	$69	–$4,638	–$7,471
Nominal	$505	$2,289	$2,237	–$1,632	–$4,755
High	$2,116	$3,761	$5,732	$3,002	–$432

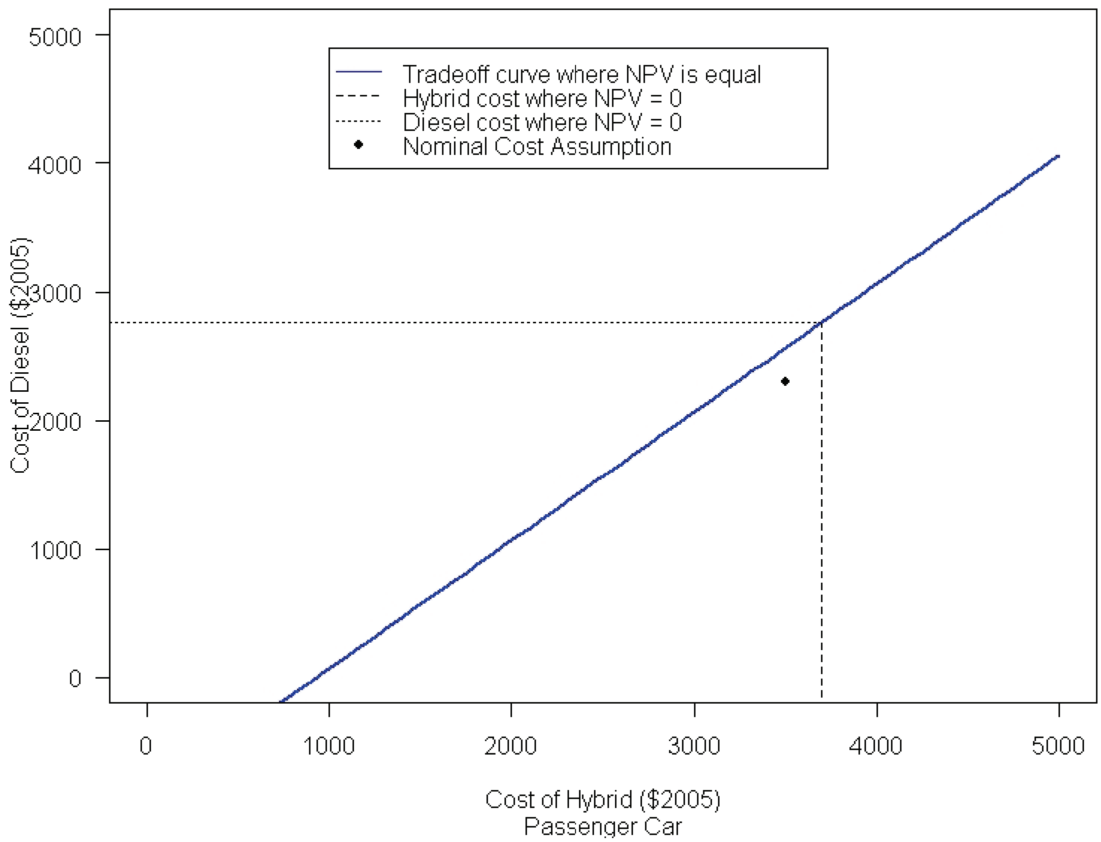
The costs of advanced diesel engines and the hybrid engine are also not known with certainty. Even the modern diesel engine, which is sold widely in Europe, must be augmented with new emission-control equipment (e.g., a particulate trap and NOx catalyst coupled with ultra low-sulphur diesel fuel) in order to be sold in the United States (especially in California and four other states). Our nominal cost assumption for the additional emissions control ($500 per vehicle plus a 3% fuel-economy penalty) may underestimate overall costs of advanced diesel emission controls (Hammett et al., 2004). In a sensitivity analysis, we considered a case in which advanced emission controls add an additional $1,000 to the cost of a diesel engine and attenuate the fuel-economy gain of the diesel by 5 percentage points. See Table D-1 of Appendix D. Despite these pessimistic assumptions for diesel emission control, the NPV of the diesel remains positive for SUVs and pickups. However, the NPV of diesel trails the hybrid engine in all three vehicle types.

Nor are the long-run costs of producing a full hybrid engine known with precision, especially for SUV and pickup applications, where the large volumes that reap substantial economies of scale in the auto industry have not yet been reached. Our cost estimates for the hybrid engine, for which we assume substantial scale economies, may prove to be optimistic, especially for SUV and pickup applications. We considered a case in which hybrid technology costs for SUVs and pickups are 30% higher and the mileage gain is 5 percentage points smaller than our nominal assumptions (NHTSA, 2005). See Table D-2 of Appendix D. Under these more pessimistic assumptions, hybrids have negative NPV for both SUVs and pickups.

On the other hand, the costs of both diesel and hybrid technology could decline significantly over time. Diesel engine costs could decline as advanced emission controls are refined and optimized with engine performance. Hybrid costs have already declined significantly and could decline further with breakthroughs in battery technology (AllianceBernstein, 2006). The future relative costs of the two technologies becomes a key issue, one that is perplexing many decisionmakers in the automotive industry.

In Figure 1, we display a sensitivity analysis for the passenger car using pairs of different technology cost estimates for diesel and hybrid vehicles. The relationship between relative technology costs and NPV is revealed. The vertical axis represents the additional cost for the diesel, while the horizontal axis represents the additional cost for the hybrid. The diagonal line across the middle of the graph shows all pairs of cost estimates for which the NPV of the two technologies are equal (holding all other input assumptions at their nominal values). For pairs above the diagonal, hybrids are superior to diesels; for pairs below the diagonal line, diesels are preferred to hybrids. The dashed horizontal line represents the breakeven technology cost for the diesel. If the cost of the diesel falls above this line, the diesel NPV will be negative; below the line, it is positive. The dashed vertical line, in turn, defines the breakeven points for the hybrid. The dashed line from each axis to the diagonal line shows where the NPV is equal to zero ($3,698 for hybrids and $2,760 for diesels in the case of passenger cars). In a separate calculation, we determined that the costs of the hybrid must fall below $3,238 in order for the NPV of the hybrid to exceed the NPV of the diesel (setting all other input values at our nominal assumptions). For SUVs and large pickups, those switchpoint values for the hybrid costs are $4,017 and $3,256, respectively. See Figures D-1 and D-2 in Appendix D.

Figure 1 – Sensitivity Analysis on Hybrid and Diesel Technology Costs on Private NPV



Finally, we consider different analytic treatments of the discount rate used to express future costs and benefits in present value. The nominal 7% rate has a solid justification in the market for car loans, but NHTSA (2006b) found that both higher and lower rates were urged by stakeholders in a public comment process on a federal fuel-economy rule. Table D-3 of Appendix D reports NPV estimates for a wide range of discount rates (3, 5, 7, 9, and 11%). As expected, lower rates help the diesel and hybrid engines (since their benefits are spread out over the long life of the vehicle) while larger rates help E85 when compared to hybrids and diesels.

Robustness of Societal Results

We report NPV sensitivities to fuel prices and each of the externality factors that play a role in the societal perspective. Those factors include conventional air pollution, greenhouse gases, the rebound effect, and the energy-security externality. Each of those factors is quite uncertain but, as we shall see, has surprisingly little impact on overall NPV results. Once again, the key uncertain variable is future fuel prices. We begin this section by again looking at the effects of fuel prices in Table 11.

Table 11: NPV of Hybrid, Diesel, and E85: Alternative Oil and Ethanol Prices (Societal Perspective)

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$1,205	–$374	–$207	–$2,110	–$3,143
Nominal	–$317	$288	$1,336	–$1,045	–$2,370
High	$935	$1,219	$4,117	$1,113	–$627

Sport Utility Vehicle

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$636	$264	–$379	–$2,936	–$4,347
Nominal	$477	$1,092	$1,669	- $1,504	–$3,290
High	$2,044	$2,257	$5,341	$1,368	–$950

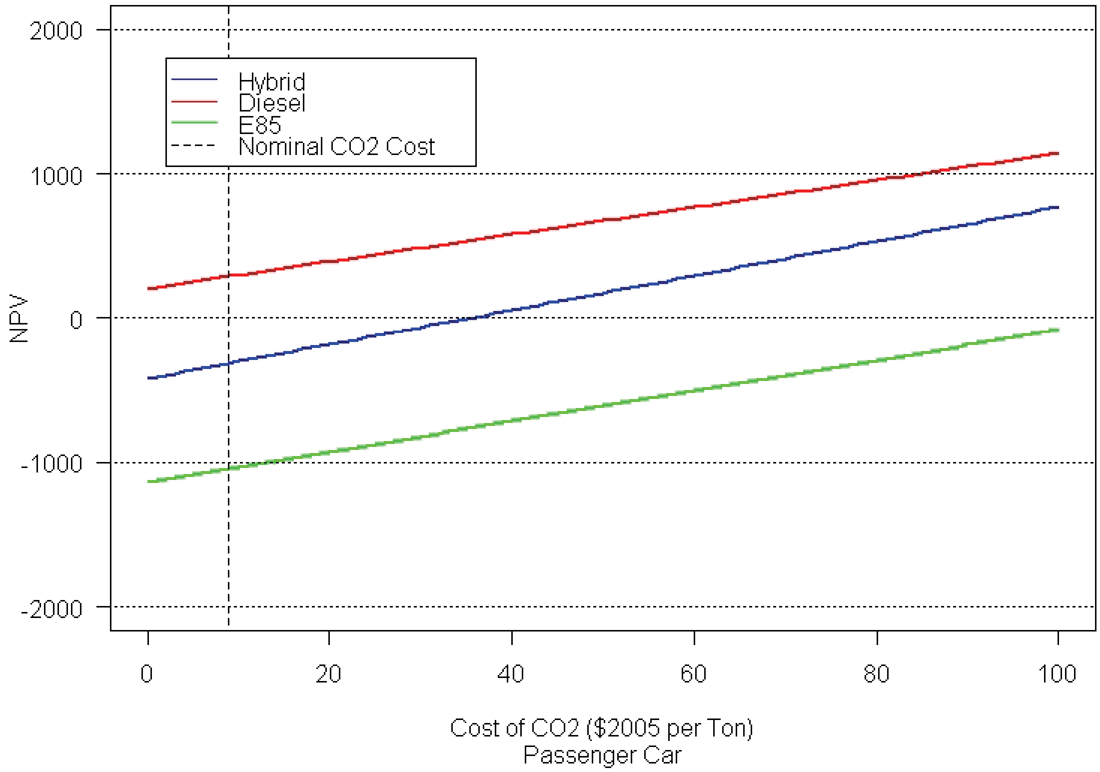
Large Pickup Truck

Oil Price Case	Hybrid NPV	Diesel NPV	E85 NPV		
			Low	Nominal	High
Low	–$1,007	$1,162	–$568	–$4,005	-$5,925
Nominal	$135	$2,207	$2,171	–$2,046	–$4,438
High	$1,742	$3,679	$7,019	$1,792	–$1,272

Table 11 shows that NPV increases as oil prices increase, which is expected. The most dramatic difference occurs with E85. Even with our nominal assumption about ethanol costs, the NPV of E85 becomes significantly positive in the high oil-price case and exceeds the NPV for hybrids in passenger cars and large pickup trucks. In the low-cost case for ethanol, E85 consistently has the highest NPV when oil prices equal or exceed the nominal assumption (except for large diesel pickup trucks under nominal and high oil prices). This shows that E85 has promise with a sustained rise in oil prices and declines in corn-based ethanol costs. Of course, under more pessimistic assumptions about E85, where oil prices decline or E85 costs rise over the nominal assumptions, then E85 has considerably negative NPV.

The damages from greenhouse gas emissions are not known with any certainty. In Figure 2, we report passenger-car NPVs using widely different estimates of the per-ton damages from carbon dioxide. The rank ordering of diesels, hybrids, and E85 holds unless the per-ton cost of carbon dioxide rises dramatically (our nominal assumption begins at $5.50 per ton and rises to $15 per ton in 2030). For SUV and pickup applications, the results (see Figures E-1 and E-2 in Appendix E) are even more robust with respect to differing environmental inputs.

Figure 2 – Sensitivity of Societal Results to Greenhouse Gas Costs



The reductions in greenhouse gas emissions from diesels and hybrids are due to the higher fuel economy, which decreases the amount of fuel used by the driver and the associated emissions that occur "upstream" (extraction, transport, and refining of oil). E85 greenhouse gas benefits are moderated by two facets of the current corn-based ethanol production process. A significant amount of emissions are associated with the fertilizer used to grow corn, and many of the ethanol plants rely heavily on coal as a fuel (Farrell et al., 2006).

Our nominal results assume a rebound effect of 15%. When we examined rebound effects ranging from 10% to 20% (see Appendix E), the rank ordering of the technologies did not change. Our reading of the literature suggests that if our 15% figure is incorrect, it is more likely to be overstated than understated if real household incomes continue to rise (Small and Van Dender, 2007).

The nominal estimate of the "energy security" externality is 33 cents per gallon and is based on the economic ramifications of U.S. oil dependence. This figure could easily be too high or too low by 30%, but differences of this magnitude do not change the rank ordering of the four technologies. In Figure 3, we show the sensitivity analysis of energy security costs for passenger cars.

Figure 3: Sensitivity of Societal Results to Energy Security Externality Cost Passenger Car

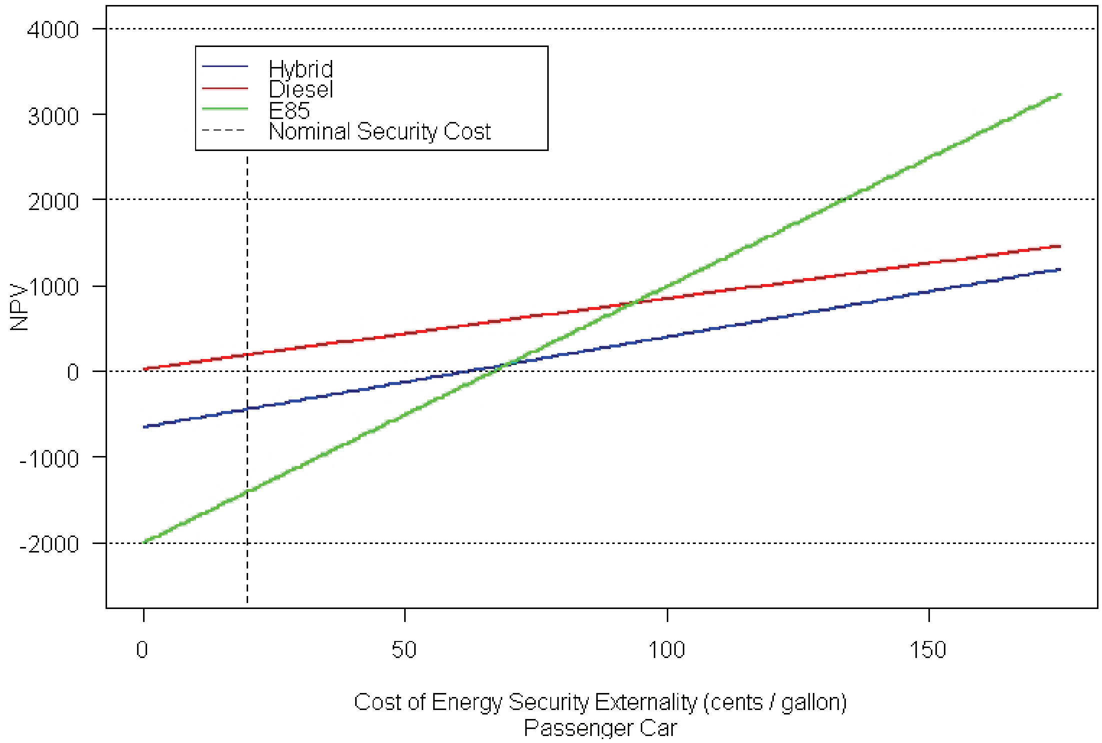


Figure 3 shows that the energy-security externality can significantly impact the results for E85. At a value of $0.67 per gallon, E-85 has a positive NPV. With an external cost of $0.94 per gallon, E85 NPV exceeds the two other technologies. These externality costs exceed most estimates of this value, but not all (Leiby, 2007). The figure also shows that, even with externality costs approaching $2 per gallon, hybrids do not gain an advantage over diesel.

Our approach to the energy-security externality does not account for any effect of U.S. oil consumption on U.S. military expenditures, U.S. flexibility in foreign policy, the financing of terrorists by oil-exporting regimes, or the financing of insurgents in Iraq by oil-exporting regimes. Some analysts argue that lowering U.S. oil consumption would drive down the price of world oil, which would reduce oil revenues to countries such as Iran, which are believed to be financing terrorists, insurgents in Iraq, and instability in the Middle East (ESLC, 2006; Copulos, 2006; Gallagher et al., 2007; Friedman, 2007)). A counterargument is that lowered world oil prices would also hurt moderate regimes that are sympathetic to U.S. interests in the Middle East and the world (e.g., Saudi Arabia and Mexico). Moreover, terrorism is such a low-cost activity that it is not clear that marginal reductions in U.S. oil consumption would have any discernible effect on the financing of terror, the strength of the insurgency in Iraq, the rate of U.S. military expenditures, or the conduct of U.S. foreign policy (Toman, 2002; Parry and Darmstadler, 2003).

Nonetheless, we prepared a sensitivity analysis that examined larger estimates of the energy-security externality. As the energy-security externality rises, the NPV of all three technologies improves, but the NPV of E85 improves disproportionately. The switchpoint value that makes E85 the preferred technology is $0.94 per gallon for the passenger car, $1.29 per gallon for the SUV, and $1.57 per gallon for the large pickup truck. See Appendix E for more detail on the switchpoint values.

With regard to conventional air pollution, our per-mile emission rates for the three alternatives are computed on a lifecycle basis using the GREET model, which we understand to be the state-of-the-art tool. Damage estimates for each pollutant reflect mid-range literature estimates, but we also examined how much NPV changes when we altered the input values for damages from conventional pollutants. The results (reported in Appendix E) do not reveal much sensitivity to pollution damage estimates. Qualitatively, larger damage estimates for particulate matter and nitrogen dioxide hurt the diesel engine relative to the hybrid engine (Jacobson et al., 2004). Larger damage estimates for carbon monoxide help the diesel engine relative to the hybrid engine. E85 is also hurt by larger damage estimates for nitrogen dioxide (Jacobson, 2007b). Given that new vehicles emit relatively few emissions for all four engine/fuel combinations, it is unlikely that alternative damage estimates would play a significant role in reordering the technologies. Although the diesel engine is often perceived as dirtier than the gasoline engine, the lifecycle analysis shows the advanced diesel to be cleaner than gasoline because the fuel savings from the diesel create pollution reductions through the entire process of producing, refining, and transporting diesel fuel.

In our societal analysis, we captured what were in our judgment the key social impacts from the technologies. However, as in any complex analysis, we could not include all possible effects. For instance, we have not quantified any water-pollution impacts that may occur from growing corn for ethanol production or mining nickel for use in hybrid batteries. Even in cases in which our NPV estimates for technologies are positive, there may be other uses of the consumed resources that would produce an even higher return for society (e.g., improved vehicle safety or engine performance). It has been observed that, historically, major improvements in vehicle fuel efficiency have been traded in vehicle design for enhancements to performance, vehicle size and weight, and vehicle features that consumers value (Lutter and Kravitz, 2003).

Finally, although the societal analysis is complicated by many more inputs and indirect effects, it turns out that the most important variables in the societal analysis are the same variables that drive the private analysis: the costs of the engine technologies and fuels, the assumed fuel efficiencies, the mobility benefits, and the performance assumptions. Keeping these variables in mind, we turn to an assessment of how the three technologies are faring in the U.S. market and in recent public policy developments.

Section 6: Recent Market and Policy Developments

At current fuel prices, our benefit-cost model ranks the alternatives as follows: diesels, hybrids, gasoline, and E85. In this section, we review what is actually happening in the marketplace and in public policy.

Advanced Diesel Technology

Advanced diesel technology has captured about 50% of the new light-duty market in Europe, but diesel offerings in the United States are currently quite limited (Greene et al., 2004). In 2006, diesels accounted for less than 350,000 sales in the US new light-duty vehicle market, or about 2% of the market. Most of these diesels are large pickups and large SUVs that are appealing to buyers because the diesel provides an advantage for towing, cargo-carrying, and other rugged applications (Healey, 2007). According to the California Air Resources Board, the $52,000 Mercedes E320 sedan was the only diesel passenger car certified for sale in California in 2007.

There are a variety of possible explanations for the huge difference in diesel penetration in the European and American new-vehicle markets. Tax policies in many European member states have for years kept the price of fuel very high, often double the $3.00 per gallon levels recently experienced by the U.S. consumer. Due to its greater fuel efficiency, the diesel will tend to sell better when pump prices are high than when pump prices are low. In some EU countries, the diesel has an added advantage because diesel fuel is taxed less aggressively than gasoline, creating a market incentive for diesels over gasoline-powered vehicles. There are also some EU member-state policies (e.g., governmental fleet purchases) that favor diesels over gasoline.

The tailpipe-emission standards applied to diesels by the U.S. EPA and California EPA, including the testing systems used to gauge compliance, are stricter than the EU standards (Warburton, 2007). (The California standards, which have also been adopted by four New England states, are actually somewhat stricter than the U.S. EPA standards). Recent advances in emission-control technology, coupled with the increased availability of low-sulfur diesel fuel, are now making it feasible for diesel-powered cars and light trucks to be certified for sale in all 50 U.S. states (Truett, 2007b).

The combined impact of higher U.S. fuel prices, expanded supplies of low-sulfur diesel fuel, and improved emission-control opportunities are causing vehicle manufacturers to reconsider the future of the diesel in light-duty passenger applications (Truett, 2007b; Healey, 2007). Volkswagen, which temporarily terminated U.S. diesel offerings, has announced plans to offer diesel-powered cars and SUVs in the United States with a cleaner engine. Before the recent sale of Chrysler, Daimler-Chrysler announced plans for diesel offerings in the U.S. market ranging from the two-seat Smart Car to the upscale Mercedes sedans and the Jeep Grand Cherokee SUV. BMW was initially reluctant to bring diesel technology to the U.S. market but reversed course in July 2006 with an announcement that diesel-powered cars will be offered in all 50 states. Honda also surprised the industry in 2006 with an announcement that it has patented a new method to control diesel exhaust that will permit certification and sale of diesel engines in all 50 states. Honda indicated that it sees diesels as especially attractive for SUV applications. And Nissan has announced it is developing its own diesel technology and will be offering diesel-powered cars in the United States and Asia by 2010 (Warburton, 2007).

GM and Ford are rapidly expanding diesel offerings for their pickups and larger SUVs but, until recently, appeared cautious about the application of diesel technology to passenger cars and car-like SUVs. In July 2006, GM announced the purchase of a 50% stake in the Italian diesel maker VM Motori from Penske Corporation, which analysts say gives GM more diesel technology and new engine-manufacturing capability. GM also indicated it is planning a range of diesel-powered passenger cars for the 2010 model year, while Ford has reportedly discontinued a plan to offer diesel-powered cars in the United States (Truett, 2007c).

Toyota offers diesel-powered cars elsewhere in the world, but Toyota has made no signs that it intends to offer diesels in the U.S. market. Even the new Toyota Tundra pickup truck, which was launched in competition with Ford and GM pickups that have a diesel option, is not yet available with a diesel engine. Yet Toyota clearly has the resources and agility to launch diesel offerings in the United States, and they recently purchased a 5.9% stake in Isuzu Motors Ltd. to gain better access to clean diesel technology (Shirouzu, 2007).

On the public policy front, recent developments have further encouraged diesel offerings. The U.S. Department of Transportation (DOT) has already raised mileage standards for light trucks through model year 2011 (NHTSA, 2006), and the U.S. Congress is considering much larger increases in mileage standards for both cars and light trucks. Analysts at DOT believe that diesel technology will play a significant role in the compliance decisions of vehicle manufacturers (NHTSA, 2006).

Consumer tax credits for diesels that meet stringent tailpipe and mileage requirements were authorized by Congress in 2005 and are scheduled to be available at least through 2010. These tax credits are large enough to offset a majority of the up-front cost of diesel technology. If the U.S. Congress were to also legislate a carbon-control program that further raises fuel prices, the case for investments in diesel technology would be further strengthened.

In summary, if fuel prices remain high, the rate of diesel penetration in the light-duty market should increase steadily and substantially. A variety of vehicle manufacturers and their suppliers are already signaling that light-duty offerings of the diesel engine will be expanded. Given the long lead times that characterize introduction of new propulsion systems for cars and light trucks, it will be at least five years before we know how large the revival of diesels will be in the U.S. market.

Gasoline-Electric Hybrid Technology

The commercial promise of hybrid technology has been a matter of sustained dispute in the automotive industry (Spector, 2007). Some see it as a fad or niche product, but the sales experience of recent years, partly supported by consumer tax credits and owner access to HOV lanes (UCS, 2007), is impressive (Romm and Frank, 2006). In 2006, U.S. sales of hybrid vehicles (252,000) nearly doubled compared to the 2005 level, and hybrid sales continued to grow rapidly in 2007 (Herman, 2007).

Honda was the first manufacturer to offer gas-electric technology in the U.S. market, starting with the two-seat Insight in 1999. Honda's Civic Hybrid was commercially more successful than the Insight, selling more than 25,000 units in 2006 (or about 8% of total Civic volume). The Insight never achieved U.S. sales over 2,000 units per year and was discontinued in 2006. Honda's Accord Hybrid was recently discontinued due to low sales volume (Associated Press, 2007).

Toyota offered the hybrid Prius in Japan in 1997 and followed Honda into the U.S. market in 2000. But Toyota rapidly surpassed Honda in both volume of hybrid sales and number of hybrid offerings. The Prius accounts for vast majority of Toyota's hybrid sales, but in 2006 Toyota made seven total hybrid offerings (including two under its Lexus brand) and accounted for 75% of U.S. hybrid sales. Toyota has ambitious plans to expand the number of Prius-like models (In Brief, 2007).

The Ford Escape Hybrid, introduced in 2004, was the first full hybrid offered on an SUV in the U.S. market and the first offered by the Big Three. In August 2005, Ford pledged to boost the company's production of hybrid vehicles to 250,000 by 2010, about ten times the 2005 sales volume. But Ford backed off this pledge in 2006 as the company's financial situation worsened. Sales of the Hybrid Escape started strong in 2005, but the Escape now has severe competition from hybrid versions of Toyota's Highlander and the Lexis Rx400h.

General Motors was initially pessimistic about hybrid technology but in recent years has launched a substantial hybrid development program (White, 2007a). By the summer of 2008, GM plans to offer eight hybrid models using three different systems. The 2008 Saturn Vue and Chevrolet Malibu are scheduled for introduction with mild hybrid technology, while the Chevrolet Tahoe and GMC Yukon are scheduled to be equipped with a full hybrid system. The more advanced GM hybrid system was co-developed with BMW and Daimler-Chrysler, which also plan to offer the system in 2008 (Wernle, 2007).

The extent of hybrid market penetration may depend on the success of suppliers in reducing the weight and the cost of the battery packs that support the electric system. Toyota already made significant cost reductions from the first- to the second-generation Prius (Greene et al., 2004; Romm and Frank, 2006). There is significant scientific interest in the application of lithium ion batteries as a substitute for the nickel-metal hydride batteries now in widespread use by vehicle manufacturers. However, if the progress is sufficient to make lithium ion batteries economical, the optimal step for vehicle manufacturers may be a plug-in hybrid system rather than an expansion of current hybrid offerings. There is disagreement within the automotive industry as to how long it will take to commercialize low-cost lithium ion batteries and achieve high-volume sales.

Consumer tax credits for hybrid purchasers have been available for several years (Stoffer, 2007). The size of the credit for Toyota's hybrid products has been reduced to zero because the manufacturer surpassed the 60,000-unit cap specified in the authorizing legislation. Honda is projected to reach the 60,000 cap by the end of 2007. Congress is considering authorization of more tax credits for hybrid technology, which could further stimulate sales volume. Hybrid sales have also been boosted in some urban areas by owner access to HOV lanes and government preferences in fleet purchases (e.g., the New York City taxi fleet).

Hybrids, like diesels, are also aided by tighter federal fuel-economy standards such as the requirements being considered by Congress in the summer of 2007. Even if Congress does not act, President Bush has instructed EPA and DOT to regulate carbon emission controls under existing Clean Air Act authority. And the carbon-control standards enacted by the State of California and 12 other states, if they survive litigation, are likely to spur compliance strategies that may include more hybrid as well as diesel offerings (CARB, 2004).

Ethanol

It was regulatory pressure rather than consumer interest that spurred development of ethanol as a motor fuel in the United States. The 1990 amendments to the Clean Air Act required urban areas to add oxygen to fuel, since Congress expected "oxygenated" products to reduce the air concentrations of carbon monoxide and ozone. On the east and west coasts of the country, the most cost-effective oxygenate is the chemical MTBE, which can be mixed with gasoline and shipped through oil pipelines with no risk of corrosion. In the Midwest, it was economical to produce corn-based ethanol and create a blend of up to 10% ethanol, sometimes called "gasohol." In 2006, gasohol accounted for about 50% of the gasoline produced in the United States.

The widespread use of MTBE led to contamination of surface and groundwater, since MTBE is highly persistent and flows rapidly in water. State and federal policies began to discourage use of MTBE, stimulating even more regulatory interest in ethanol. A combination of favorable tax breaks, regulatory policies, tariffs, and subsidies have caused an explosion of commercial interest in corn-based ethanol.

In the early 1990s, the federal excise tax on gasoline was 18.4 cents per gallon. In order to encourage ethanol use, Congress set the "gasohol" tax at only 13.2 cents per gallon, 5.2 cents per gallon less the rate assessed on pure gasoline (including gasoline blended with MTBE). The 2005 energy bill replaced the 5.2-cent advantage with a comparable tax credit for gasohol blenders based on the volume of ethanol they use. At least 20 states, predominantly those in the Midwest, also enacted tax breaks and subsidies to encourage ethanol production.

Ethanol production grew rapidly from 660 million gallons in 1996 to 1.1 billion gallons in 2002. In 2005 Congress required refiners to increase the volume of ethanol and other renewable fuels to 4 billion gallons by 2006 and 7.5 billion gallons by 2012. President Bush and ethanol proponents in Congress are now seeking an even larger mandate of renewable fuels extending through 2020.

If ethanol is to comprise more than 10% of motor fuel, the vehicle and engine must be modified to prevent damage from corrosion of parts and hardware. Even before the 2005 energy bill was passed, Congress passed legislation to encourage vehicle manufacturers to offer "flexible-fuel" vehicles that can run on either pure gasoline or up to 85% ethanol (E85). Such vehicles are already marketed widely in Brazil, where ethanol is made at low cost from sugarcane (Goldemberg, 2006). In Sweden, large refueling stations will soon be required to sell a specified minimum amount of E85 in order to stay in business.

Congress authorized DOT to provide fuel-economy compliance credits for new vehicles that are capable of running on E85. The credits are generous: A dual-fuel version of a Chevy S-10 that normally gets 25 miles per gallon is counted for federal compliance purposes as if it gets

40 miles per gallon (NHTSA, 2001). DOT offered the credits for model years 2004 to 2007, and in 2005 Congress extended permission for such credits through 2014.

Vehicle manufacturers responded to the incentive for more E85 vehicles (Fialka, 2007). In 2007 alone, almost 5% of the 17 million new light-duty vehicles sold in the United States were produced with dual-fuel capability, including 500,000 GM vehicles, 250,000 Ford vehicles, and 250,000 Chrysler vehicles. Toyota and Nissan have also pledged to offer flex-fuel vehicles, though Honda has decided against E85 vehicles as an investment priority. The modifications required cost less than $200 per vehicle, but currently entail making the fuel tank from stainless steel (to withstand corrosion) and may include a special sensor so that the engine spark timing and fueling can be adjusted for the different fuels.

A major obstacle to greater use of E85 has been the lack of availability of E85 at refueling stations (Meckler, 2007). Only about 1,000 of the 170,000 fueling stations in the United States, most of them in the Midwest, have E85 pumps for motorists. In 2005, Congress made fueling stations eligible for a tax credit through 2010 that equals up to 30% of the cost of installing E85 refueling stations (with a cap of $30,000). Owners of refueling stations argue that it can cost more than $200,000 to add an E85 pump. Congress is now considering additional legislation that would force or encourage more E85 pumps at refueling stations.

The big unknown is whether consumers will choose to use E85 over gasohol or pure gasoline. They do so in Brazil only because the price is controlled by the government to make it attractive to the consumer. In Sweden, owners of refueling stations will soon be required to make sure that E85 accounts for a certain percentage of their overall fuel sales.

If the price of E85 at the pump is not significantly lower than the price of gasoline or gasohol, cost-conscious consumers will not purchase it because it has diminished energy content (O'Dell et al., 2007). A vehicle has to use more E85 than gasoline to go the same distance.

In order to appreciate the public-policy interest in ethanol, it is necessary to acknowledge why some politicians support it: They see ethanol as a vehicle to stimulate economic development in the corn states, not just as a measure to promote energy security and protect the environment (Poncer, 2005). A clear indication of this distributional concern is that some of the U.S. demand for ethanol could be met by importing more of it from Brazil, where vast amounts are made from sugarcane at low cost. But Congress has retained a 54-cent-per-gallon tariff on imported ethanol from countries such as Brazil, despite a request from President Bush to advance consumer interests by removing the tariff.

A potentially lower-cost method is "cellulosic" ethanol, a process of producing the fuel not from corn but from crop residues, wood chips, switchgrass, or even municipal garbage. The U.S. Department of Energy is investing up to $385 million in a commercial demonstration project to build six cellulosic ethanol plants . Backed by federal loan guarantees, venture capitalists are also making significant investments in new ways to make ethanol (Wald and Barrionuevo, 2007). It is too early to assess how successful these efforts will be.

Looking to the future, gasohol use will continue to expand steadily due to regulatory requirements on refiners. But ethanol cannot be shipped through oil pipelines because water condensation contaminates the ethanol (API, 2007). Transport of ethanol for now is largely by rail, ship, and truck. The future of E85 hinges on whether there will be enough interest from consumers to be make it widely available or enough support from policymakers (subsidies and rules) to stimulate its widespread use. E85 does not appear promising from a cost-benefit perspective unless the costs of ethanol production decline significantly or the price of gasoline stabilizes near $3.50 gallon.

PORTFOLIO STRATEGY

Given the large degree of uncertainties and different consumer preferences revealed in this paper, it is not necessary for decisionmakers to choose only one of the alternative technologies. The United States is already pursuing a portfolio strategy, where each of the technologies is being implemented to some extent, and new decisions will be made as experience accumulates. More research is needed on the full range of government policies that are favoring or retarding diffusion of these technologies (GAO, 2000; CEC, 2004; Koplow, 2006; Metcalf, 2006). Ideally, public policy should focus on setting the correct incentives for market participants and allowing the best portfolio of technologies to emerge through competitive market responses. Future research should determine the cumulative impact of current federal and state policies, helping define a level playing field in the competition among technologies to achieve consumer, energy security, and environmental policy objectives.

APPENDIX A – FUEL PRICE CALCULATIONS

We estimate gasoline and diesel fuel prices, beginning with assumptions about world oil prices and then adding the costs of refining, distribution, and taxes. Our nominal world oil price assumption of $65 per barrel comes from the 2007 IMF World Economic Outlook. The low value in our range of assumptions is $35 per barrel. We derived this value from the average oil price in EIA's low world oil price scenario of the 2007 Annual Energy Outlook (AEO). In this scenario, they project oil prices to decline from their current level to near $30 per barrel, which is near the levels experienced in 2003 and 2004. Our high value corresponds to sustained gas prices slightly above the historical highs in 2007. We set a high gasoline price of $3.50 a gallon, which corresponds to an oil price of $107 per barrel. This scenario represents high prices sustained by tight conditions in the demand/supply balance and considerable uncertainty about political conditions in key oil-producing countries. Using these assumptions about world oil prices, we then used EIA 2007 AEO estimates of the costs of refining, distribution, and taxes, which we show in Table A-1.

Table A-1: Itemized Costs in Gasoline and Diesel Price Assumptions

Gasoline (2005$/gall)	Low Value	Nominal Value	High Value
Oil cost	0.83	1.55	2.55
Refining cost	0.46	0.46	0.46
Distribution cost	0.13	0.13	0.13
State tax	0.23	0.23	0.23
Federal tax	0.15	0.15	0.15
Retail price	**1.79**	**2.50**	**3.50**
Diesel (2005$/gall)			
Oil cost	0.83	1.55	2.55
Refining cost	0.47	0.47	0.47
Distribution cost	0.17	0.17	0.17
State tax	0.21	0.21	0.21
Federal tax	0.19	0.19	0.19
Retail price	**1.87**	**2.59**	**3.59**

The itemized costs are the average over EIA's projection period (see Table 102 in EIA, 2006). The first line for each product is the oil price in per-gallon terms. The next item is the cost of refining the petroleum product. Diesel costs are slightly higher than gasoline. The distribution costs are next, which are followed by state and federal taxes. Using these estimates, diesel fuel is consistently 9 cents greater than gasoline. We've used this approach to provide transparency in our fuel price assumptions. We believe this presents a defensible range for sustained fuel prices over the next 20 years.

We now turn to our assumptions about the costs of ethanol. As stated earlier in the paper, we assume that drivers will use E85 derived from corn-based ethanol. Similar to gasoline and diesel prices, we assume a range of plausible costs. We begin with assumptions about the production costs of ethanol that include all the variable costs of production. The nominal assumption also comes from the IMF's 2007 World Economic Outlook. The other ends of the range come from the EPA's recent Regulatory Impact Analysis (RIA) on the Renewable Fuels Standard (EPA, 2007). We add the costs of amortized capital to the production costs. Table A-2 shows our assumptions.

Table A-2: Itemized Costs in Ethanol Price Assumptions

Ethanol costs (2005$/gallon)	Low Value	Nominal Value	High Value
Ethanol production cost	0.88	1.60	2.08
Capital cost	0.16	0.16	0.16
Distribution cost	0.13	0.13	0.13

Total wholesale cost	1.17	1.89	2.37
Total wholesale cost ($2005/gas gall equiv)	1.75	2.82	3.54
Total wholesale cost w/ tax credit	0.66	1.38	1.86
Total wholesale cost w/ tax credit ($2005/gas gall equiv)	0.99	2.06	2.78

Our capital cost assumptions also come from EPA's report. They state that capital costs of a new dry mill corn ethanol plant are $101 million (2005$) with a nameplate capacity of 81 million gallons per year. We assume a 20-year economic life for the plant, a 10% return on investment, and 90% capacity factor in calculating the capacity costs. We then add a distribution cost, which comes from the EPA report. This reflects the cost of transporting ethanol from the plant to the terminal where it is blended. We use a national average for the distribution costs, which were estimated on a regional basis. We report the total wholesale costs, including and excluding the 51-cent tax credit for blending ethanol.

We report our estimates for E85 in the Table A-3.

Table A-3: Itemized Costs in E85 Price Assumptions

E85 ($2005/gallon)	Low Value	Nominal Value	High Value
Gas wholesale cost	1.29	2.00	3.00
Ethanol wholesale cost	1.17	1.89	2.37
Blended product cost	1.20	1.92	2.54
Distribution	0.13	0.13	0.13
State tax	0.23	0.23	0.23
Federal tax	0.15	0.15	0.15
Retail E85 price	1.70	2.42	3.04
Retail E85 price ($2005/gas gall equiv)	2.27	3.23	4.05
Retail E85 price w/ tax credit	1.32	2.04	2.66
Retail E85 price w/ tax credit ($2005/gas gall equiv)	1.76	2.72	3.55

The gasoline wholesale cost is the sum of the oil and refining costs. The ethanol wholesale cost is shown in Table A-3. We calculate the blended product cost using the average ethanol/gasoline mix reported by EIA, which is 74% ethanol and 26% gasoline. This is lower than 85%/15% because pure ethanol contains about 5% gasoline on average, which is added to help ethanol mix with gasoline at later stages in the production process. In addition, refiners vary the amount of ethanol in the summertime because of higher evaporative emissions from ethanol and the resulting air-quality concerns. The blended product cost is then the weighted average of gasoline and ethanol wholesale costs using the 74%/26% mix. The resulting mix has about 75% of the energy content of conventional gasoline. We finally add state and federal taxes with the distribution cost for an estimate of E85 retail prices. We also report the E85 retail price including the subsidy and the E85 price in energy equivalent terms to gasoline.

As you can see, our nominal assumptions result in E85 prices that are 73 cents more expensive than gasoline in energy-equivalent terms. Interestingly, our low-cost ethanol case implies that ethanol is less expensive than gasoline in the nominal and high oil-price cases. Such a low cost of ethanol represents a substantial reduction in current ethanol production costs, reflecting an unspecified major breakthrough in this process. The high-cost ethanol case reflects continued increases in the price of corn, which comprises about half the production cost of ethanol.

APPENDIX B – PRIVATE CASE INPUTS

In this appendix, we document the inputs to the private perspective, which also contribute to the societal perspective.

Baseline Fuel Economy

Our baseline MPG assumptions for conventional gasoline do not correspond to a specific vehicle in each of the three classes. We developed them from the following sources: EPA estimates for fuel economy by model/class, recent federal fuel-economy standards for light trucks (NHTSA, 2006), and correspondence with specialists in government and industry. We have assumed the following fuel economy values for each class:

- Passenger cars – 26 city / 31 highway – 28.3 combined
- Sport utility vehicles – 20 city / 26 highway – 22.7 combined
- Large pickup trucks – 15 city/ 20 highway – 17.3 combined

The combined fuel economy is calculated using EPA's assumption of 55% city driving and 45% highway driving for the average driver, and taking a weighted average of the fuel economy estimates (Model Year 2008 Fuel Economy Guide, EPA—available at www.fueleconomy.gov).

Fuel Economy Change

Although this paper analyzes new propulsion systems, we realize that vehicles may have other characteristics that affect emissions, fuel economy, etc. To the extent possible, we are only concerned with the potential gains from employing these technologies in a fuel-saving capacity.

The estimates for fuel-economy benefit are adapted from Greene et al. (2004). Greene et al. estimates the fuel-economy increase for "larger light trucks" at 35%, but we have modified this assumption to reflect the likely larger size of our "large pickup truck" vehicle class. The 3% fuel-economy penalty for the diesel is based on emission-control system impacts (EPA, 2005, pp.74-76). The fuel-economy assumption of the E85 vehicles is based on the energy content of the fuel. Pure ethanol has approximately two-thirds of the energy content of conventional gasoline. Since formulations of E85 typically vary across seasons, we use EIA's assumption that E85 on average contains 74% ethanol and 26% gasoline. E85 then contains 75% of the energy content of gasoline resulting in a 25% fuel economy decline.

Torque Increase

Our assumptions about the torque increases associated with each vehicle are also based on Greene et al. (2004). We found no literature suggesting that E85 provides the consumer with a measurable performance benefit or decline, and we thus attributed no change in performance to E85 vehicles.

Our assumptions about the monetary value of torque increases in diesel and hybrid vehicles are based on the econometric estimates of Crandall et al. (2004) for light trucks. Crandall et al.'s analysis estimates the marginal willingness to pay for various vehicle characteristics. In particular, they estimate that a 10% increase in torque increases the value of a light truck by 3.4%. We have adjusted Crandall's estimate in the following way: we assume 1/3 of this benefit for passenger cars, two-thirds for SUVs, and the full benefit (3.4%) for large pickup trucks based on vehicle price assumptions of $25,000, $30,000, and $30,000, respectively.

Driving Behavior

Based on EPA's assumptions used in measuring tailpipe emissions and fuel economy, we assume consumers drive 15,000 miles in the first year of a vehicle's life. We also follow EPA in assuming that the total mileage driven consists of 55% city driving and 45% highway driving (EPA, 2007).

We have assumed that driving (of a given vehicle) decreases over time as a result of normal driving habits. The decrease over time is not constant and follows a pattern reported by NHTSA (2006a,b) The mileage decreases are larger between years 1 and 6 and slowly decline to a nearly constant level of about 6,000 vehicle miles traveled per year. This trend varies slightly by vehicle class. In order to accommodate the initial vehicle miles traveled (VMT) assumption used by EPA for fuel economy estimates, we have extracted the trend from the NHTSA estimates and applied it to the initial year assumption. The initial assumption of VMT is 15,000 miles for each vehicle, but is then modified by the rebound effect before introducing the decreasing mileage trend (NHTSA, 2006a).

Vehicle Lifetime

The longevity of a vehicle is also likely to diminish as a result of car malfunctions and crashes that "total" the vehicle. Therefore, we adjust total miles driven by estimates of vehicle survival rates. We apply vehicle survival rates reported in (NHTSA, 2006a) to weight the number of miles driven in each year of our analysis. The maximum lifetime of a light truck is 25 years (20 years for passenger cars); however, after applying the survival rates, the expected lifetime is about 125,000 miles for cars and about 153,000 miles for light trucks (NHTSA, 2006a).

Rebound Effect

The rebound effect refers to the amount of fuel-consumption savings offset by an increase in driving after an improvement in vehicle fuel economy (Greening et al., 2000). The magnitude of the rebound effect is still debated in the literature.

We assume a nominal value of 15%. It is calculated in the following way (similar to NHTSA, 2006): The rebound factor adds additional miles to the baseline annual vehicle miles traveled (nominally 15,000), based on the number of gallons (and their cost) saved as a result of the new fuel-saving technologies. For example, in the first year, if the hybrid passenger car saves 300 gallons of fuel, then the rebound effect acts to reduce that fuel savings by 15%—and consequently adds those miles to the annual vehicle miles traveled. Note that this not only affects the NPV fuel savings, but decreases the reduction in carbon dioxide emissions, primary tailpipe pollutants, and energy-security benefit, which are based on vehicle miles traveled (we discuss the value of these externalities below).

We assume a range of 10% to 20% for the rebound effect, which is within the range of estimates identified by Greening et al. (2000) for the long-run rebound effect. In Greening et al.'s survey of the literature, they found a range of 10% to 30%. We've revised the upper end of the range downward to 20% based on recent analysis in Small and Van Dender (2007). They analyzed more recent data accounting for higher fuel prices and incomes (which have counteracting effects). In their analysis, which uses time series data from 1966–2001, the long-run rebound effect varies between 10% to 20%.

In the private case, the rebound effect reduces the fuel savings from the technologies that improve fuel economy. We also account for the benefits that accrue to individuals as a result of increased travel (mobility). While the monetary value of this is difficult to determine, we have assumed that the additional miles traveled are worth at least the fuel cost of traveling them. We then assume a 30% increase in value to the consumer to account for his valuation of the increased risk and non-fuel variable expenses of vehicle travel. This quantity enters the model as the “mobility benefit” and is discounted over time.

One final note is that the rebound effect sometimes works in reverse because E85 costs more than gasoline (adjusting for energy content differences). We decrease the amount of driving in this case, which saves fuel but reduces mobility benefits to the consumer.

APPENDIX C – SOCIETAL CASE INPUTS

Our societal case builds on the private results and incorporates the effects of externalities such as greenhouse gas emissions and congestion. In this appendix, we describe how we treat the costs of greenhouse gas emissions, oil consumption, primary pollutant emissions, and congestion.

Greenhouse Gas Emissions

We calculate changes in greenhouse gas emissions using the Greenhouse gases, Regulated Emissions, and Energy use in Transmission (GREET) model. GREET is a spreadsheet-based model developed by the Argonne National Lab (ANL) that performs lifecycle analysis of automobile engine and fuel combinations. The ANL provides this model to the public with regular updates (see www.transportation.anl.gov/software/GREET/). The model estimates the emissions of greenhouse gases during operation of the vehicle and the emissions that occur earlier in the lifecycle, such as the extraction, shipping, refining, and transportation of oil/gasoline or the growing corn for ethanol and transporting it to blenders. The estimates encompass emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_20). The final results are expressed in terms of the CO_2 equivalents, which adjust for the greater impacts of methane and nitrous oxide emissions on climate. Table C-1 shows the emissions intensity estimates from the GREET model for greenhouse gases:

Table C-1: Greenhouse Gas Emissions Intensity Estimates from GREET Model

Passenger Car

Emissions intensity (grams/mile)	Conventional Gas	E85	Hybrid	Advanced Diesel
CO_2	383	278	273	299
CH_4	0.46	0.48	0.32	0.33
N_20	0.02	0.16	0.02	0.01
Total GHG (g CO_2 equivalent/mi)	398	336	285	310
% GHG Reduction	-	–16%	–28%	–22%

Sport Utility Vehicle

Emissions intensity (grams/mile)	Conventional Gas	E85	Hybrid	Advanced Diesel
CO_2	477	347	353	372
CH4	0.57	0.59	0.42	0.41
N_20	0.02	0.19	0.02	0.01
Total GHG (g CO_2 equivalent/mi)	496	418	368	386
% GHG Reduction	-	–16%	–26%	–22%

Large Pickup Truck

Emissions intensity (grams/mile)	Conventional Gas	E85	Hybrid	Advanced Diesel
CO_2	626	455	481	489
CH_4	0.75	0.78	0.58	0.54
N_20	0.02	0.25	0.02	0.01

Total GHG (g CO_2 equivalent/mi)	649	548	500	505
% GHG Reduction	-	–16%	–23%	–22%

The results show that hybrid vehicles consistently have the largest greenhouse gas reductions, followed by advanced diesels, with E85 having the lowest decrease. Hybrid and diesel reductions are due to the fuel-economy improvements. Drivers use less fuel, which lowers greenhouse gas emissions from their car and reduces emissions that occur earlier in the lifecycle when oil is extracted, transported, and refined. E85 greenhouse gas emissions are affected by the use of fertilizers and coal as an energy source in the ethanol plant. The higher methane and N_20 emissions result from the fertilizers used in producing corn. Ethanol plants use natural gas and coal as a fuel source, which also moderates the greenhouse gas benefits of E85 (Farrell et al., 2006).

Recent research indicates these estimates may overstate the greenhouse gas reductions possible with advanced diesel and E85. Jacobson (2007) uncovers the potential climate-change impacts of particulate matter emitted from diesel vehicles, which is known as black carbon. The magnitude of this effect remains under debate and is currently excluded from the GREET model. Crutzen et al. (2007) highlight the greater emissions of N_20 during the production of corn, arguing that they outweigh any climate benefits from reduced carbon dioxide. In our results, Table 8 shows the NPV for each component in the analysis. The table shows that removing any greenhouse gas benefits for diesels and E85 would not change the substantive conclusions. Diesel NPV would remain positive and retain its advantage over hybrids. Removing this benefit would only exacerbate the negative results for E85.

We use an estimate of the social cost of greenhouse gas emissions from Nordhaus (2007). Nordhaus estimates the future social damages from climate change using a computable general equilibrium model know as DICE and finds that climate change damages increase over time. Accordingly, we assume an increasing social cost for greenhouse gas emissions. The social cost of CO_2 starts at $20/ton carbon ($5.45/ton CO_2) in 2007, and grows linearly to $54.50/ton carbon ($14.85/ton CO_2) by 2030. The sensitivity analysis considers a much wider range of values, but they do not change over time as in the nominal case.

Energy Security

The “energy-security” externality refers to two effects: monopsony power of the United States as a global oil consumer and the effects of oil price volatility on US GDP. Monopsony power refers to the ability of the United States to impact the world oil price by reducing aggregate consumption. The magnitude of these effects remains under debate in the literature, and we use a range in our sensitivity analysis to assess the impact of this factor. Our nominal assumption is based on the National Research Council (2002). They assume an externality of $0.12 per gallon in 2002 dollars. We adjust this value to account for inflation and then scale it upward to reflect the difference in oil prices at the time the study was published and our range of assumptions.

After accounting for inflation, the external cost is $0.13 in 2005$. The oil price in 2002 was $26.22 in 2005$ (EIA, 2007). Scaling the external cost by our assumptions about oil prices, our nominal value for energy security costs is $0.32 per gallon. At the low oil price, the externality value is $0.17 per gallon; at the high oil price value, it is $0.53 per gallon.

Congestion Cost

In our discussion of the private perspective, we described the rebound effect. In our societal analysis, we account for the external costs from the increase in driving as fuel economy improves. The increase in driving is associated with more congestion and accidents. We follow the assumptions of NHTSA (2006b). The congestion cost in our model is a composite consisting of 4.27 cents/mile for congestion, 2.30 cents/mile for crashes, and 0.06 cents/mile for noise. This estimate has been adjusted to reflect constant $2005 and only affects the "rebound miles" traveled by vehicles in our study.

It is also worth noting that E85 sometimes receives a congestion "benefit." The rebound effect is based on fuel savings—which are negative for the E85 vehicles. As such, it is likely that those drivers travel fewer miles than they would in a comparable gasoline powered vehicle.

Conventional Tailpipe Pollutants

We also use the GREET model to estimate lifecycle pollutant emissions for conventional tailpipe pollutants. Table C-2 shows urban emissions intensities for each vehicle type:

Table C-2: Pollutant Emissions Intensities for Criteria Pollutants

Passenger Car

Emissions intensity (grams/mi)	Conventional Gas	E85	Hybrid	Advanced Diesel
VOC	0.18	0.16	0.12	0.06
CO	2.35	2.34	2.34	0.35
NOx	0.13	0.12	0.11	0.12
PM10	0.03	0.02	0.02	0.02
PM2.5	0.01	0.01	0.01	0.01
SOx	0.04	0.03	0.03	0.02

Sport Utility Vehicle

Emissions intensity (grams/mi)	Conventional Gas	E85	Hybrid	Advanced Diesel
VOC	0.21	0.20	0.15	0.09
CO	2.46	2.45	2.45	0.27
NOx	0.20	0.18	0.16	0.22
PM10	0.03	0.02	0.03	0.03
PM2.5	0.02	0.01	0.02	0.02
SOx	0.04	0.03	0.03	0.03

Large Pickup Truck

Emissions intensity (grams/mi)	Conventional Gas	E85	Hybrid	Advanced Diesel
VOC	0.28	0.27	0.24	0.12
CO	2.69	2.68	1.99	0.20
NOx	0.35	0.33	0.27	0.33
PM10	0.04	0.03	0.03	0.03
PM2.5	0.02	0.02	0.02	0.02
SOx	0.06	0.05	0.04	0.04

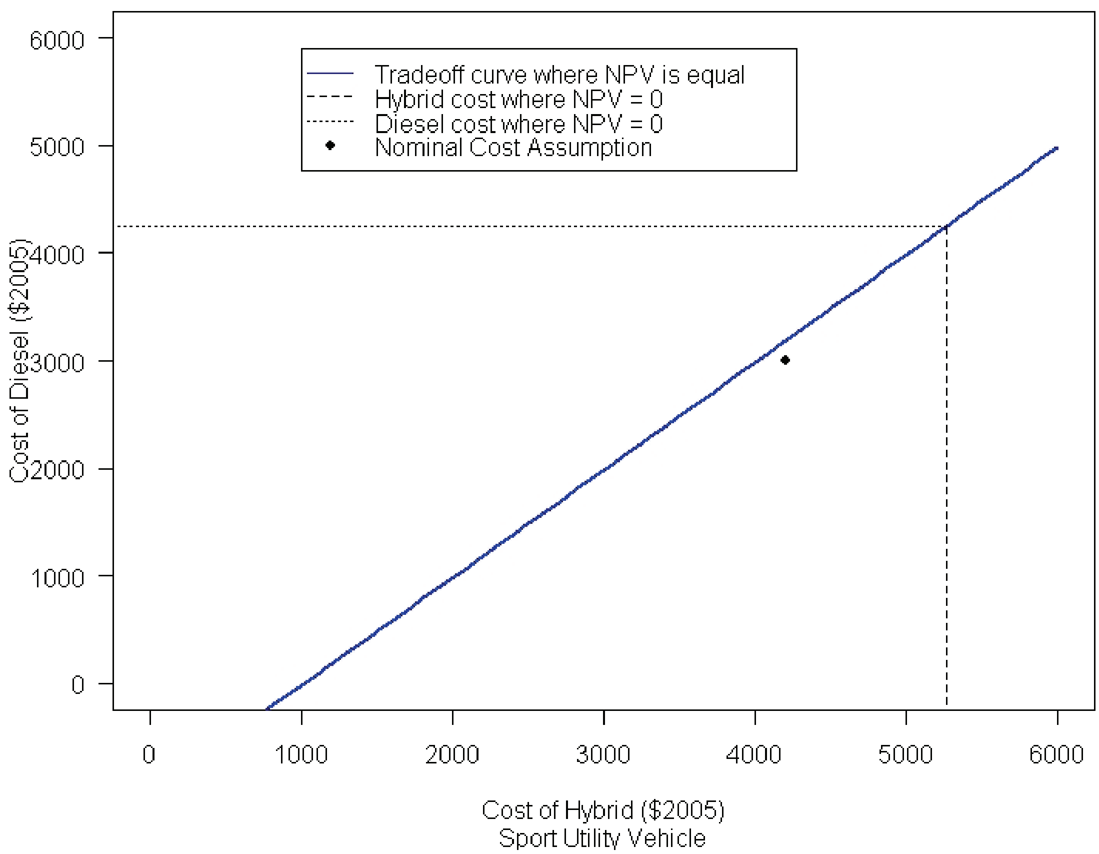
The GREET model assess lifecycle emissions for these pollutants. The lifecycle includes upstream emissions during extraction, shipping, refining, and transport to the refueling station as well as the tailpipe emissions. Overall emissions decline for hybrids and advanced diesels even though for some pollutants the tailpipe emissions for advanced diesels are greater (NOx and PM).

Our damage estimates for conventional tailpipe pollutants are based on NHTSA (2006b). The values are displayed in Table 8 in Section 4 of the paper.

APPENDIX D – SENSITIVITY ANALYSES IN PRIVATE CASE

We first show sensitivity analysis of the technology cost estimates for advanced diesel and hybrids (E85 technology costs are minor). Figures D-1 and D-2 display results for sport utility vehicles and large pickup trucks. These are the companion figures to Figure 1 in the text. These figures vary technology costs on each axis and the diagonal line across the graph shows all the combinations of costs where NPV for technologies are equal. The dashed lines show the points where NPV is zero for each technology. The region with technology costs lower than the dashed lines shows where NPV for both technologies are greater than zero. Finally, the area above the diagonal line is where NPV for hybrids is greater the diesels and the converse is true below the diagonal line.

Figure D-1: Technology Cost Sensitivity for Sport Utility Vehicle



The point plotted on the graph shows the nominal cost assumptions. In this case, NPV for both technologies is positive and diesel is slightly greater. Both NPV exceed $1,000.

Figure D-2: Technology Cost Sensitivity for Large Pickup Truck

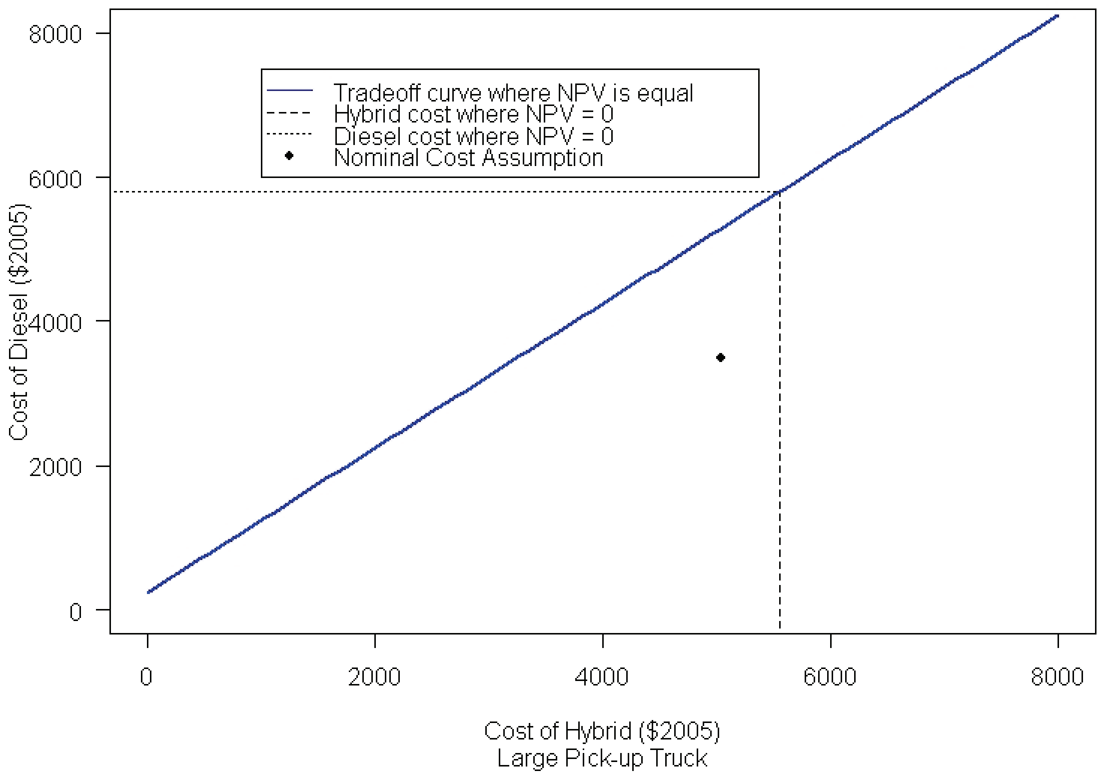


Figure D-2 shows that advanced diesel technology is more strongly favored over the hybrid for large pickup trucks. Hybrids still have positive NPV though.

Sensitivity Analysis of Diesel Emissions Control Costs and Fuel Economy

Figures D-1 and D-2 compare technology costs for diesel and hybrids over a broad range. The next sensitivity analysis looks at a specific scenario in which advanced diesel-emission controls are more costly than assumed and also incur a greater fuel economy penalty. We increase passenger car cost by $500 and the SUV and large pickup truck costs by $750—effectively doubling our initial estimate of emission control technology costs. We also reduce the fuel economy improvement for diesel by 5%. Table D-1 shows the results of this scenario.

Table D-1: Sensitivity Analysis of NPV Concerning Diesel Emissions Control Costs

	Hybrid NPV	Diesel NPV	E85 NPV
Passenger Car	$198	–$180	–$1,034
SUV	$1,066	$324	–$1,332
Large Pickup Truck	$505	$1,358	–$1,632

Under these assumptions, NPV for advanced diesels is lower than hybrids for the passenger car and SUVs. It still retains an advantage for large pickup trucks. Diesels also remain positive for SUVs and large pickup trucks despite the increase in costs and reduction in fuel savings.

Sensitivity Analysis of Hybrid Technology Cost and Fuel Economy

We also consider a case with higher hybrid technology costs for SUVs and large pickup trucks and lower fuel economy gains relative to our nominal assumptions. The table below shows results assuming technology costs 30% greater than our nominal assumption and 10% lower fuel economy gain.

Table D-2: Sensitivity Analysis of Hybrid Technology Cost and Fuel Economy

	Hybrid NPV	Diesel NPV	E85 NPV
SUV	–$949	$1,249	–$1,332
Large Pickup Truck	–$2,118	$2,289	–$1,632

In this case, we only consider SUVs and large pickup trucks because of the greater uncertainty about hybrid costs in these vehicle classes. Hybrid NPV is negative and considerably lower than advanced diesels under these assumptions. When comparing Tables D-1 and D-2, advanced diesel NPV remains positive for SUVs and large pickup trucks under the more conservative assumptions, whereas hybrid NPV becomes negative under more conservative assumptions.

Our final sensitivity analysis considers variation in the private results under different discount rates. Table D-3 shows these results.

Table D-3: Sensitivity of Private Results to the Discount Rate

Passenger Car NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$948	$957	–$1,260
5%	$535	$682	–$1,137
7%	$197	$458	–$1,037
9%	–$83	$273	–$953
11%	–$317	$119	–$884

SUV NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$2,077	$1,922	–$1,639
5%	$1,517	$1,550	–$1,471
7%	$1,065	$1,251	–$1,335
9%	$697	$1,007	–$1,224
11%	$392	$806	–$1,132

Large Pickup Truck NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$1,493	$3,092	–$1,984
5%	$950	$2,648	–$1,788
7%	$509	$2,289	–$1,629
9%	$147	$1,994	–$1,499
11%	–$154	$1,750	–$1,390

Our nominal assumption is a 7% discount rate. For hybrids and diesels, NPV increases at lower discount rates and decreases at higher values. This is expected because the consumer incurs a large cost when buying the vehicle and the benefits (fuel savings, reduced emissions, etc.) accrue over time. With a higher discount rate, the benefits that accrue over time receive less weight in the present. Under the nominal assumptions, E85 results have an opposite pattern. The incremental cost in the present for E85 is modest, but the consumer pays more every time he buys fuel. These losses decrease as the discount rate increases.

Diesel NPV remains positive across the range of discount rates in all but one case. The positive NPV of the hybrid generally does not hold up, even with only small increases to the discount rate.

APPENDIX E – SENSITIVITY ANALYSES IN SOCIETAL CASE

In this appendix, we display the results for sensitivity analyses on the externalities considered in the study and other influential factors such as discount rate and rebound effect. We begin by showing the sensitivity of societal results to changes in the discount rate.

Table E-1: Sensitivity of Societal Results to Discount Rate

Passenger Car NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$316	$745	–$1,330
5%	–$32	$493	–$1,171
7%	–$316	$288	–$1,045
9%	–$552	$118	–$945
11%	–$749	–$24	–$863

Sport Utility Vehicle NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$1,343	$1,721	–$1,916
5%	$863	$1,372	–$1,686
7%	$477	$1,092	–$1,504
9%	$162	$863	–$1,359
11%	–$99	$674	–$1,241

Large Pickup Truck NPV Savings

Discount Rate	Hybrid	Diesel	E85
3%	$1,030	$2,987	–$2,574
5%	$536	$2,556	–$2,280
7%	$135	$2,207	–$2,046
9%	–$195	$1,920	–$1,858
11%	–$468	$1,682	–$1,704

Similar to the private case, hybrid and diesel NPV decrease at higher discount rates, and E85 NPV increases. Diesel NPV remains positive through the entire range for all vehicle types except passenger cars. Hybrid NPV becomes negative at high discount rates in each vehicle class.

Rebound Effect

We also analyze the effects of varying our assumptions about the rebound effect, which exerts opposing effects on NPV (e.g., mobility benefit versus congestion cost).

Table E-2: Sensitivity of Societal Results to the Rebound Effect

Passenger Car

Rebound Factor	Hybrid NPV	Diesel NPV	E85 NPV
10%	–$191	$368	–$1,199
15%	–$317	$288	–$1,045
20%	–$443	$208	–$892

Sport Utility Vehicle

Rebound Factor	Hybrid NPV	Diesel NPV	E85 NPV
10%	$586	$1,158	–$1,637
15%	$477	$1,092	–$1,504
20%	$368	$1,026	–$1,371

Large Pickup Truck

Rebound Factor	Hybrid NPV	Diesel NPV	E85 NPV
10%	$197	$2,259	–$2,163
15%	$135	$2,207	–$2,046
20%	$72	$2,155	–$1,929

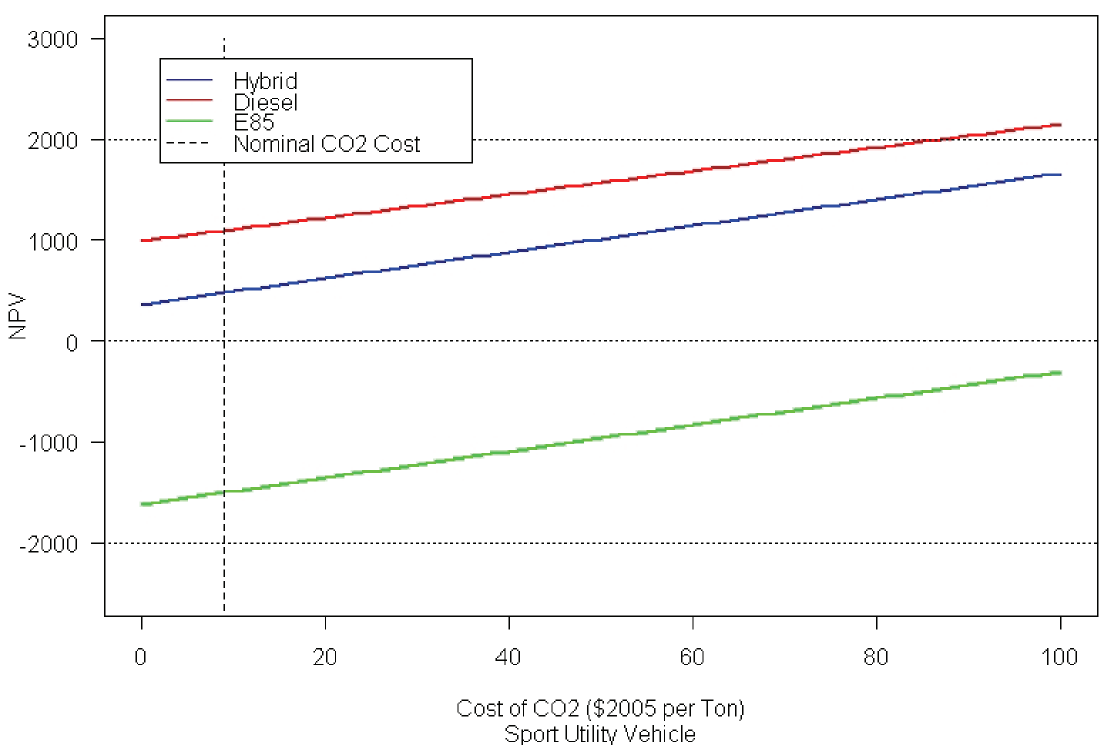
In general, the results are relatively robust to changes in the rebound effect. All of the results where NPV is negative at nominal assumptions remain negative across the entire range. The same is true for the positive results.

Greenhouse Gas Emissions

In the main text, Figure 2 shows the effects of varying the damages of greenhouse gas emissions for passenger cars. Figures E-1 and E-2 show the same sensitivities for SUVs and large pickup trucks.

Figure E-1: Sensitivity of Societal Results to Greenhouse Gas Emissions Costs

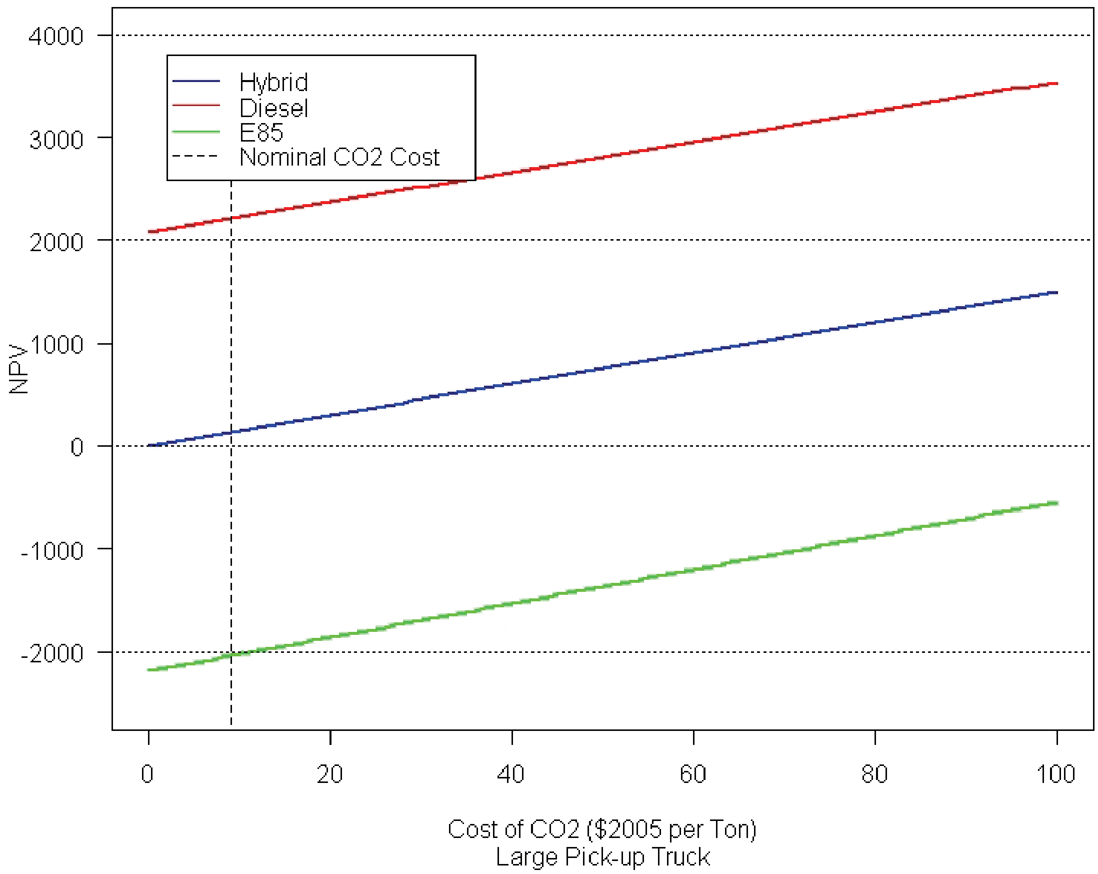
Sport Utility Vehicle



The graph shows that increasing the cost of greenhouse gas emissions improves NPV for each technology. Even at large cost values for this externality, E85 NPV does not become positive, and hybrid NPV does not exceed diesels. Figure E-2 shows the results for large pickup trucks.

Figure E-2: Sensitivity of Societal Results to Greenhouse Gas Emissions Costs

Large Pickup Truck



Similar to the case with SUVs, the greenhouse gas externality improves NPV for each technology. But even large values do not offset the higher fuel costs of E85 or improve the relative position of hybrids.

Energy-Security Externality

The next set of figures display sensitivity analysis of the energy-security externality. We find that the value of this externality does impact the results.

**Figure E-3: Sensitivity of Societal Results to Energy Security Externality Cost
Sport Utility Vehicle**

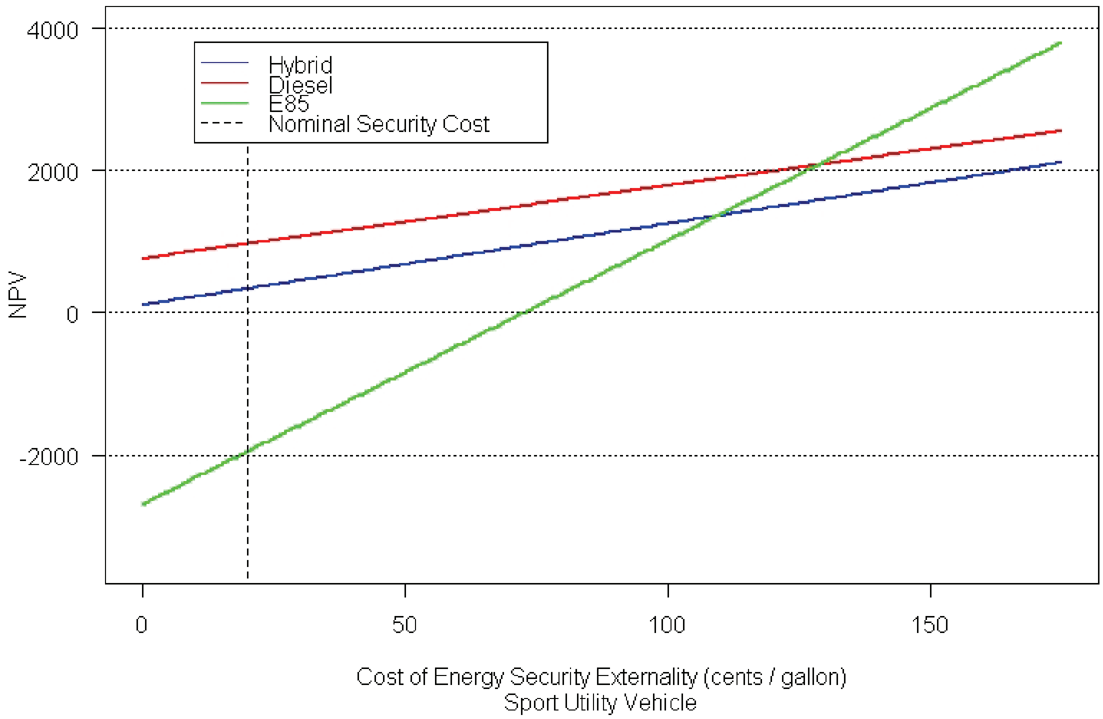
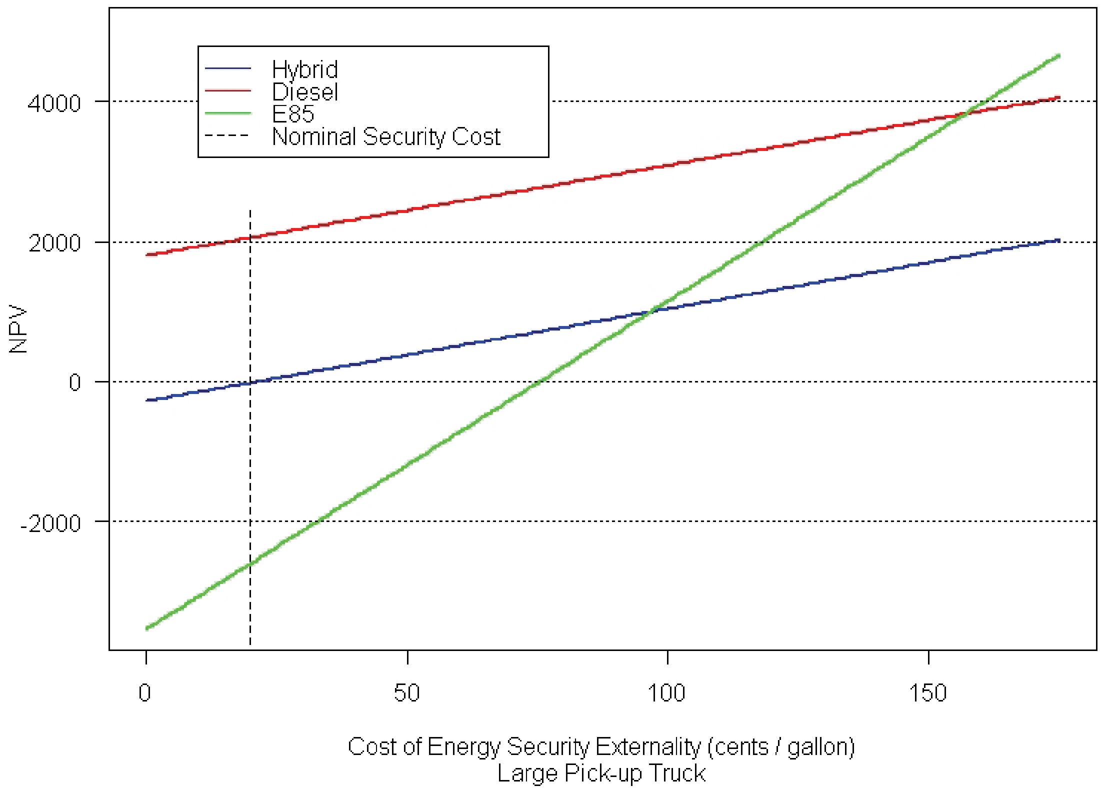


Figure E-3 shows the same pattern as the results for passenger cars. However, now the values necessary to change the NPV results for E85 are higher. The externality cost must exceed $0.73 per gallon for a positive result for E85 and exceed $1.29 per gallon for E85 to overtake the other technologies. Again, the NPV of the hybrid does not exceed diesel at any point in the range analyzed.

Figure E-4: Sensitivity of Societal Results to Energy Security Externality Cost
Large Pickup Truck



Again, Figure E-4 shows a similar result. The externality costs for oil consumption must now exceed $0.76 per gallon for E85 to have a positive result and be greater than $1.57 per gallon to make E85 the best option.

Table E-3 displays the switch points for the energy-security externality These are values for the energy-security externality where a negative result becomes positive or where the NPV of E85 exceeds the NPV of the other technologies.

Table E-3: Switch Points in NPV from Energy Security Externality Cost

	Hybrid	Diesel	E85	E85 Best Option
Passenger Car	63	0	67	94
SUV	0	0	73	129
Pickup Truck	22	0	76	157

The table shows that the externality needs to exceed $0.60 per gallon to change a negative result in all but one case. The externality needs to surpass about $1.00 per gallon for E85 to become the best option.

Conventional Air Pollutants

The final sensitivity analyses assess the impacts of damage estimated for air pollution on NPV. Figure E-5 shows the results for passenger cars. We use a range of damage costs up to 100 times the nominal values. As long as the damage estimates for each pollutant are raised proportionately, there is no change in the rank ordering of the technologies. If damages estimates were raised only for particulate matter, it would hurt diesels. It the damages were raised only for nitrogen dioxide, it would hurt E85 and diesels. And if it were raised only for carbon monoxide, it would help diesels. But the tailpipe emissions are so small for all the engine/fuel combinations that they do not drive the results. What is critical are the upstream emissions for all pollutants, which are reduced by hybrids and diesels relative to gasoline because less fuel is needed.

Figure E-5: Sensitivity of Societal Results to Conventional Pollutant Costs Passenger Car

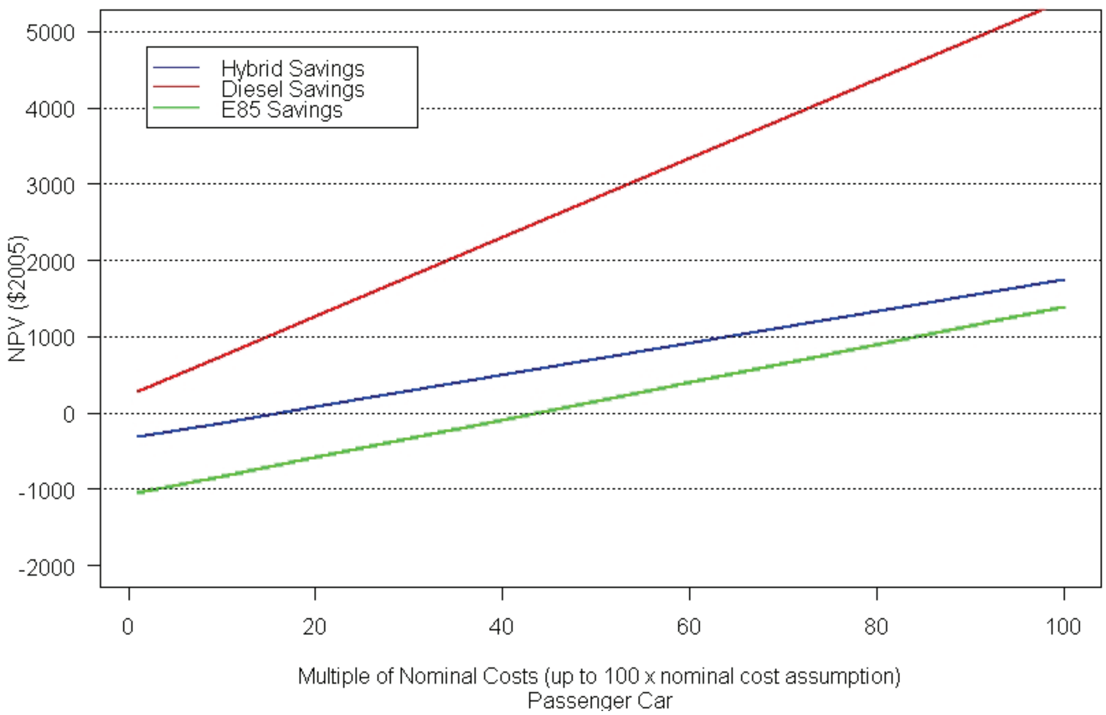


Figure E-6: Sensitivity of Societal Results to Conventional Pollutant Costs Sport Utility Vehicle

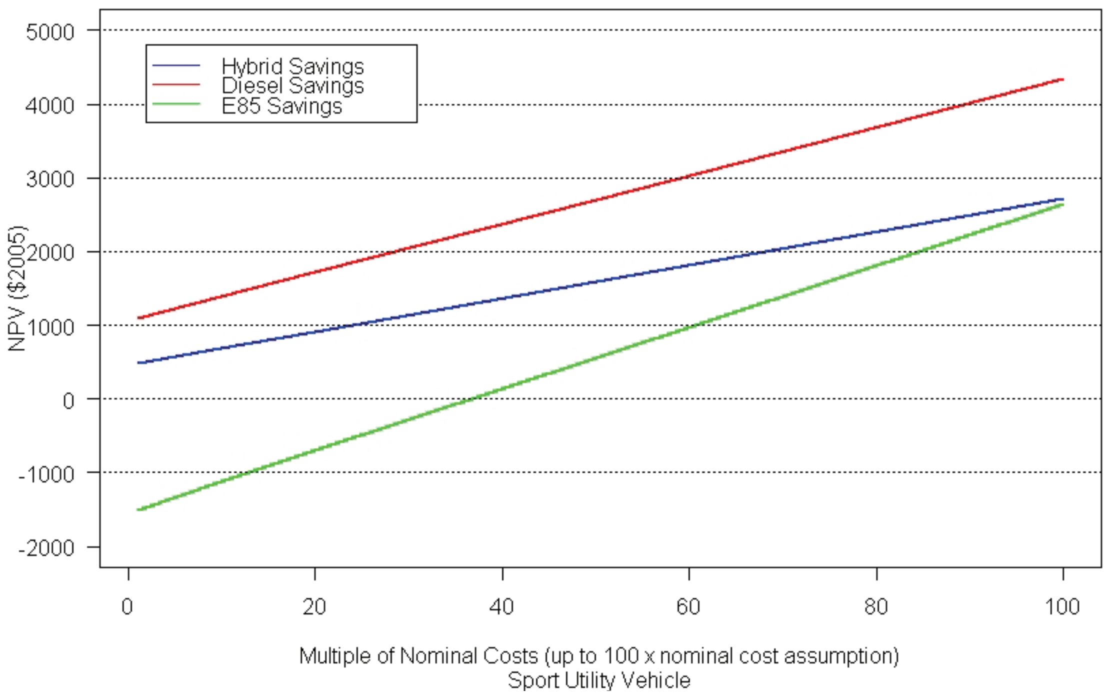
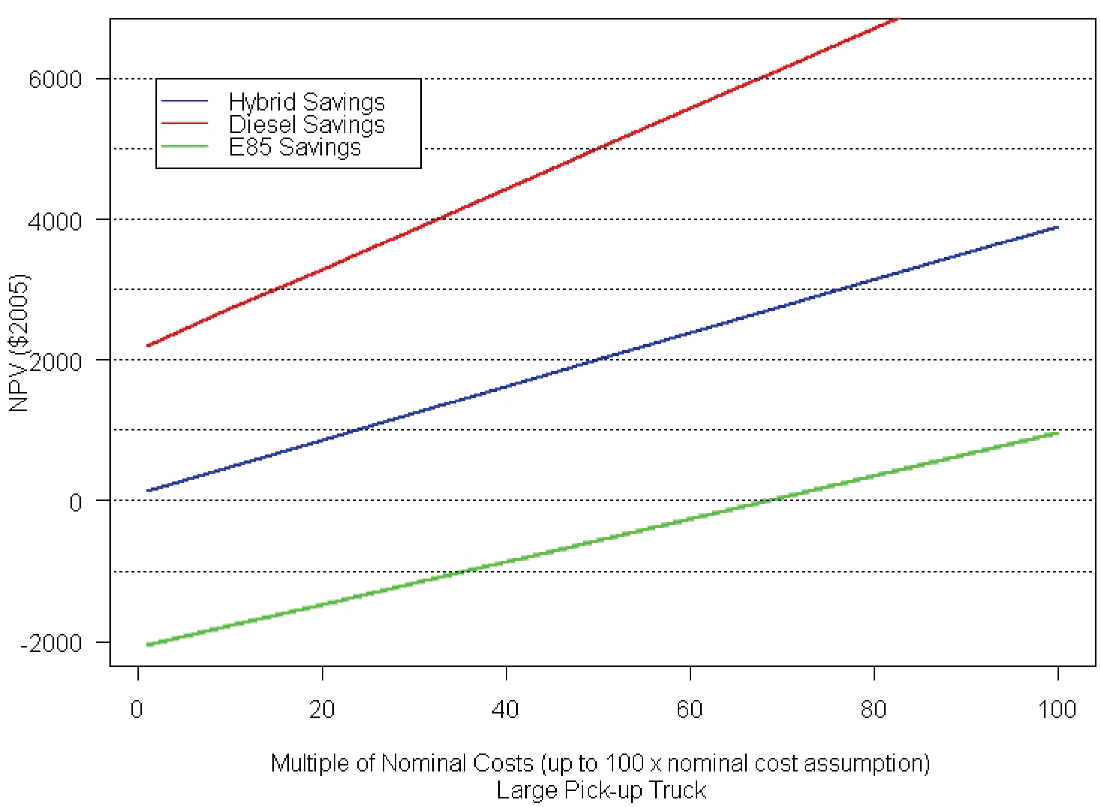


Figure E-7: Sensitivity of Societal Results to Conventional Pollutant Costs Large Pickup Truck



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