Technical Options for Improving the Fuel Economy of U.S. Cars and Light Trucks by 2010–2015

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EXECUTIVE SUMMARY

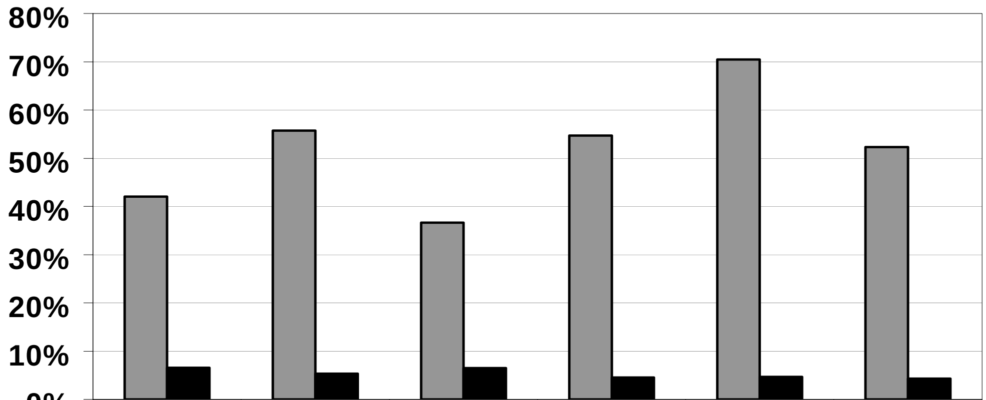
Technology progresses continually in the automotive industry. Engineering and design abilities have expanded greatly in recent years, stimulated by the computer, electronics, and materials revolutions; public policies; and the industry's recognition of the need for technological solutions to meet future market and societal challenges. At the same time, growing income and wealth create seemingly insatiable demands for customer-satisfying amenities that command designers' priorities and product planners' budgets. Just what is the automobile industry's capability to redesign cars and light trucks for higher fuel economy as a way to address concerns about global warming and petroleum dependence? Answering this question involves not only identifying technical options available to automotive engineers, but also addressing how such options can be applied to raise fuel economy as well as enhance other vehicle amenities.

Our study estimates the car and light truck design outcomes feasible over the next 10–15 years if the industry's capabilities were redirected toward improving average fuel economy. We also estimate the corresponding impacts on vehicle price. Technical measures considered range from efficiency-optimized applications of current and emerging technologies to initial deployments of "next-generation" technologies such as advanced materials substitution and hybrid drive. We evaluated these options using computer simulations to examine the improvements feasible for a set of representative models spanning the principal vehicle classes. In order to evaluate designs at varying degrees of ambition, we defined technology *packages* that represent moderate to advanced evolutions of conventional powertrains as well as hybrid drive.

This summary highlights results for a fleetwide fuel economy scenario based on our Moderate Package of conventional technology improvements plus a small share of hybrid electric vehicles (HEVs). Figure ES-1 illustrates this Moderate Package applied to the set of representative vehicles. Fuel economy improvements range from 37% for a full-size pickup truck to 70% for a midsize, standard-performance sport utility vehicle (SUV). The associated retail price impacts amount to 4–7% of today's vehicle prices. The full-size pickup shows the greatest relative challenge, given the need to maintain torque and power capabilities; nevertheless, the Moderate Package brings the pickup’s fuel economy up to the level of today's midsize cars. We find that a midsize car can be improved by 56%, from 26 to 41 miles per gallon (mpg), at a 5% increase in price. Other technology packages provide greater efficiency improvements, as listed in Table ES-1. The first part of this table shows the representative vehicles we selected for analysis along with their baseline Model Year (MY) 2000 fuel economy and price. The relative cost/benefit pattern among vehicle types with other design packages is similar to that of the Moderate Package.

To extrapolate potential improvements for the overall new car and light truck fleet, we created *scenarios* that blend vehicles designed according to the different technology packages. Scenario A assumes a fleet of 98% Moderate Package vehicles with the remaining 2% being an average of mild and full hybrids (as defined below). This scenario implies potential for a 50% increase in average new light vehicle fuel economy, from the 2000 level of 24 to 36 mpg (EPA CAFE test values). The corresponding average new vehicle price increase is $1,300. Given the design changes included and the time needed to implement them across all model lines, this level of improvement is achievable fleetwide by 2010–2015. It would cut average vehicle carbon dioxide (CO_2) emissions by 34%, from the current average of 228 grams/kilogram (g/km) down to 151 g/km. For comparison, the European automakers' voluntary commitment aims for a 25% reduction, from 186 g/km down to 140 g/km by 2008, although these values are based on European test cycles.

Figure ES-1. Fuel Economy and Price Increase Estimates for Moderate Technology Package of Design Improvements Achievable by 2010–2015



	Small Car	Midsize Car	Full-Size Pickup	Minivan	Standard SUV	Perform-ance SUV
MPG increase	42%	56%	37%	55%	70%	52%
Price increase	6.6%	5.3%	6.5%	4.5%	4.7%	4.3%

Greater improvements are possible using other technology packages. The Advanced Package pushes conventional technology toward its limits using engine technologies already known to be capable of meeting upcoming emissions standards if put into widespread use. The results for representative vehicle types with the Advanced Package are also shown in Table ES-1. The Advanced Package improvements average 70% across the fleet, at an average 8% price increase. Hybrid vehicles go further yet, offering upwards of doubled fuel economy but at a greater cost, averaging 20–30% higher than current vehicle prices. However, hybrids are happening for reasons beyond direct fuel savings, so we incorporate some hybrids into all of our fleetwide scenarios. Scenario C assumes a fleet of 98% Advanced Package conventional vehicles and 2% hybrids, yielding a 72% fuel economy improvement overall, from 24 to 41 mpg. Scenario B is intermediate between A and C; all scenarios are described below when we discuss fleetwide energy consumption and carbon emissions results.

Technology Packages

Engineering simulation analysis of the representative vehicles was done for four technology packages: moderate and advanced conventional technology sets and mild and full hybrid electric vehicles built on platforms already improved to the advanced conventional technology level.

Table ES-1. Summary of Fuel Economy and Price Estimates by Vehicle Type

	Vehicle Type					
	Small Car	Midsize Car	Full-Size Pickup	Minivan	Standard SUV	Performance SUV
Baseline Vehicles (MY2000)	Chevy Cavalier	Ford Taurus SE	Silverado 1500 2wd	Grand Caravan	Explorer OHV V6	Explorer DOHC V6
Retail Price (MSRP)	$14,380	$19,535	$23,334	$33,065	$29,915	$34,470
Fuel Economy	30.8	26.2	21.0	22.3	20.3	20.4
Moderate Package						
Fuel Economy	43.7	40.8	28.7	34.5	34.6	31.0
Price Increase	$944	$1,036	$1,515	$1,500	$1,395	$1,485
Advanced Package						
Fuel Economy	48.4	45.8	33.8	41.3	40.1	44.0
Price Increase	$1,125	$1,292	$2,291	$2,134	$2,087	$2,458
Mild Hybrid						
Fuel Economy	56.3	52.6	39.2	48.4	47.4	42.5
Price Increase	$3,118	$3,522	$4,547	$4,169	$4,002	$4,343
Full Hybrid						
Fuel Economy	63.5	59.3	44.2	54.6	53.4	48.0
Price Increase	$4,331	$5,089	$6,526	$5,818	$5,472	$6,322

Note: Prices are 2000$; fuel economy values are unadjusted composite miles per gallon, 55% city, 45% highway (CAFE). Fleet scenario (as in Figure ES-2) HEV shares assume an average of mild and full hybrid characteristics.

In all cases, our technology packages as applied to different vehicle types were designed for enhancing fleetwide safety as well as fuel economy while holding size and performance largely constant. Mass reduction through improved design and substitution of lightweight materials is a fundamental efficiency improvement strategy. What is unique in our study is that we target the degree of mass reduction according to vehicle size, with today's heaviest vehicles loosing the most weight, rather than assuming across-the-board levels of mass reduction. Average vehicle size is fixed except for small cars, which we assume are wider (for better side-impact protection) and strengthened by focusing new materials and structural designs to enhance safety without adding weight. The result is a fleet that would be made safer overall by having improved the crash compatibility among vehicle types. Although formally modeling crash involvements is beyond the scope of this study, such a conclusion is supported by the literature on safety.

The ***Moderate Package*** entails the following measures:

- Mass reduction: zero net reduction for small cars; 10% for midsize cars; and 20% for minivans, pickups, and SUVs

- Aerodynamic streamlining, reduced tire rolling resistance, and accessory improvements
- High-efficiency, lightweight, low-friction, precision-controlled gasoline engine
- Integrated starter-generator (ISG) with 42 volt (V) system
- Improved transmissions depending on vehicle type

All of the technologies in this package are either already in use or slated for near-term production. The curb weight reductions range from 0–20% and average to a 14% reduction fleetwide. In addition to the mass reduction and high-efficiency engine, the ISG is a notable aspect of our redesign strategy. This device has multiple benefits, allowing the engine to be turned off during idling, smoothing torque to complement the high-efficiency engines and transmission, plus more and better vehicle accessories served by a 42 V electric subsystem (not all of its cost need be charged to fuel economy, although we do so here). Fuel economy improvement results vary with vehicle type, as illustrated earlier in Figure ES-1, and average 47% across the fleet.

The ***Advanced Package*** incorporates more ambitious refinements of conventional technologies. Some of these are already in early production and others, particularly the greater degrees of mass reduction, represent strategies now under intensive research and design (R&D), targeting production-readiness within a few years. This Advanced Package includes the following choices:

- Greater mass reduction: 10% for small cars, 20% for large cars, and 33% for light trucks; we also examine an advanced large sport wagon reflecting a 40% mass reduction for its size
- The same streamlining, tire, and accessory improvements as in the Moderate Package
- Gasoline direct-injection engine (GDI, stoichiometric) with 42 V ISG system
- Advanced transmissions, using efficiency-optimized shift schedules for all vehicles

This advanced technology set pushes the conventional gasoline, internal combustion vehicle toward its efficiency limit short of hybridization. Although results vary with vehicle type, it achieves an average added fuel economy benefit of 15% relative to the Moderate Package, for an average overall improvement of 70% compared to current technology.

In addition to the greater degree of mass reduction and optimized transmissions, use of gasoline direct-injection engines are a key feature of the Advanced Package. GDI engines are already being used in Europe and Japan, but these versions of the engine run with lean mixtures and cannot meet stringent U.S. tailpipe standards. The GDI engines we assume for our advanced case retain stoichiometric operation (air/fuel mixtures containing no more than the precise amount of oxygen needed for complete combustion of the fuel, enabling very thorough cleanup in a three-way catalytic converter). Their efficiency benefits are less than those of lean-burn GDI, but still significant, and GDI is also valuable for the superior powertrain controllability and optimization that become possible.

The Advanced Package entails an average 24% curb mass reduction, ranging from 10% for small cars to 33% for light trucks. In addition, this case examines an advanced sport wagon concept, using technologies that target a 40% mass reduction for a vehicle of a given size. Such options include aluminum-intensive design, or metal space frame designs using composite panels, along with computer-optimized structures and advanced materials use in interior components as well. This degree of mass reduction is facilitated by the advanced conventional powertrains we identify. Such engines and transmissions are very compact and lightweight for their capabilities, and create a "double synergy," or virtuous circle of sorts, simultaneously enabling and being enabled by mass-efficient structural design techniques.

An Advanced Alternative to the Sport Utility Vehicle

The rising popularity of SUVs has brought environmental problems (due to their higher emissions and lower fuel economy) and safety problems (due their aggressivity to other vehicles and propensity to roll over). We focused extra analytic attention on SUVs and also developed an alternative design conceptualized with high efficiency and improved safety in mind. Two findings are of note:

- High performance detracts from the fuel economy gains achievable at a given level of technology, and so the trend toward high-performing SUVs is eroding the potential to control fuel use and CO_2 emissions.
- A large, advanced technology "sport wagon" built on a lightweight platform could counter these trends, more than doubling fuel economy while providing better safety and preserving or enhancing functionality.

Many SUVs have high performance levels, and so in addition to modeling a standard midsize SUV (based on a Ford Explorer XLT), we also modeled a high-performance SUV (based on a Ford Explorer "Eddie Bauer" edition). Both have an average test fuel economy of 20 mpg. The more refined SOHC engine already used to provide this higher performance leaves less room for improvement to the technology levels of our design packages (holding performance fixed in each case, as measured by 0–60 miles per hour [mph] acceleration time). Thus, our Moderate Package improves the high-performance SUV's fuel economy by only 52%, to 31 mpg, compared to a 70% improvement, to 35 mpg, for the standard SUV.

Rethinking the design of a vehicle intended to have good carrying capacity, 4-wheel drive, and other attributes that make SUVs popular can lead to much greater opportunities for improvement. Such design trends have already started, evidenced on one hand by emerging "sport wagon" styles such as the Subaru Outback and Volvo Cross Country, and on the other by unit-body SUV designs that are now migrating from luxury segments (such as the Lexus LX470 and Mercedes ML430) into mainstream segments (as for the Pontiac Aztek and Toyota Highlander). If executed with lightweight materials, attention to safety and compatibility with smaller vehicles, and a high-efficiency conventional powertrain, the result would be a very fuel-efficient vehicle that provides copious interior space, excellent performance, and a body structure that would be more stable, more streamlined, and safer for both its own occupants and other road users. This is the approach we took in defining an advanced large sport wagon concept.

With our Advanced Package, the standard SUV's fuel economy doubles, to 40 mpg, while the high-performance conventional SUV improves 78%, to 36 mpg. But the advanced sport wagon would achieve 44 mpg, a fuel economy that is better by a factor of 2.2 compared to a high-performance midsize SUV of today.

We developed the concept by benchmarking it to a set of current SUVs, wagons, new sport wagons, and concept vehicles. We assumed a ground-up design on a car-like platform using materials, structural, and interior components that achieve a 40% mass reduction for a given size vehicle. The advanced sport wagon has a wider track and is a bit lower than today's standard SUVs. It is streamlined to a drag coefficient (C_{D}) of 0.30 and uses best-practice packaging to maximize its interior space. A compact, high-output GDI engine is mated to an ISG and electronic motorized gear-shift (or perhaps a toroidal continuously variable transmission [CVT]) to provide the ultimate level of powertrain efficiency short of hybrid drive. We estimate an incremental cost of $2,500, well in line with the trends that have been underway in the SUV segment and clearly a bargain given the environmental and safety benefits that would be achieved.

The ***Hybrid Packages*** incorporate what is the most exciting technology now entering the market. Hybrid electric drive combines an electric motor, battery, and sophisticated controls with a combustion engine, offering very high efficiency and smooth, responsive operation. Hybrid propulsion can take many forms, from slight degrees of hybridization (perhaps using an ISG) to designs that drive the wheels only electrically. We analyze two versions:

- Mild Hybrid — drawing less than 25% of its total power from the electric drive system, allowing idle-off and some regenerative braking, but no significant electric-only driving

- Full Hybrid — drawing 30–50% of its total power from electric drive, for added efficiency and some electric-only driving but no real electric-only trip range

The Honda Insight can be considered an example of a mild hybrid and the Toyota Prius an example of a full hybrid. None of the HEV designs we analyze would plug-in to recharge. All of their energy comes from the gasoline, but the battery buffers power use to let the engine operate more efficiently and to restore power foregone by engine designs that trade-off power to achieve higher efficiency. Again, results vary by vehicle type and hybrid version, but on average we find net efficiency benefits of 23% over the conventional Advanced Package.

We assume that HEVs are built on vehicle platforms already improved to the level of our Advanced Package given the 2010–15 time frame we consider. Available data suggest that HEV costs will still be relatively high, so we assume only a 2% share for two of our scenarios (this is a level that might be stimulated by the zero-emission vehicle [ZEV]credit programs in California and some other states). We also examine higher HEV shares, reaching about 6% of the market, or 1 million new hybrids in MY2012, for example. Given the efficiency benefits of hybrids relative to our modest package, a 6% HEV share boosts new fleet average fuel economy by about 3% compared to a fleet with only 2% HEV share.

Fleetwide Fuel Economy Results

To compute fleetwide results, we weighted redesigned representative vehicles by market shares of their respective classes, and blended small shares of HEVs into fleets still dominated by improved conventional vehicles. We assume a 50/50% mix of mild and full hybrids for the HEV share of the overall fleet. Three main scenarios span a range of possibilities:

A. A fleet of largely Moderate Package vehicles with a small HEV share

B. A blend of equal shares of Moderate and Advanced vehicles with a small HEV share

C. A fleet of largely Advanced Package vehicles with a small HEV share

Scenario A has two variants, A_1 with the 2% HEV share and A_2 with a 6% HEV share. Scenario A_1 yields a 51% fleet fuel economy increase for a 5.8% average price increase (compared to a 47% mpg improvement for a 5.5% price increase with a fleet of Moderate Package vehicles only, without HEVs). Achieving this improvement in roughly 10 years implies a rate of progress for the whole fleet similar to the 25% improvement over 5 years that the Ford Motor Company has voluntarily committed to for its SUV fleet. The more aggressive Scenario C, based on our Advanced Package of technologies, yields a 72% fuel economy improvement for an 7.8% increase in average vehicle price. Scenario B is an intermediate case with the larger HEV share, for a fleet of 47% Moderate, 47% Advanced, and 6% Hybrid vehicles. Its results fall between those of scenarios A and C, for a 62% fleetwide mpg improvement at a 7.4% average price increase.

For all scenarios, the average cost of conserved energy ranges 70–80¢/gal (adopting a societal cost/benefit perspective with a 12 year lifetime and 5% real discount rate). Thus, the new vehicle price increase, amortized over a vehicle lifetime of fuel savings, is less than the expected pre-tax price of gasoline (about $1.00/gal) and well below the consumer price (about $1.35/gal) expected through 2015. This degree of cost-effectiveness, with lifetime fuel savings more than covering the up-front cost of technology improvements, means that CO_2 reductions are achieved at net savings. Under the economic assumptions made here, these savings are on the order of $100 per metric ton of carbon (carbon-mass basis counting only the direct CO_2 emissions from fuel combustion at the vehicle).

Neither diesel engines (nor hybrid powertrains, for that matter) are needed to achieve the 50–70% improvements we identify for fleetwide fuel economy. The advanced technology case does assume the use of GDI engines, but tuned to maintain ultra-low emissions. Higher efficiency levels could be achieved with GDI engines tuned to operate lean, which we did not analyze, and neither did we analyze diesel engine options. Breakthroughs in emissions control for either lean GDI or diesel would enable the attainment of fleetwide efficiency levels 10–20% higher than those identified here.

Breakthroughs could also occur in cost-reducing approaches for hybrid vehicles. Perhaps more significantly, hybrid drive offers benefits besides fuel efficiency, enabling it to provide customer value beyond that associated only with fuel savings. HEVs would have high-power onboard electrification capabilities and offer the possibility for new levels of powertrain responsiveness and controllability. Coupled with the strategic interest in moving toward electric drive in the long term (perhaps using fuel cells instead of a combustion engine), automakers may have reasons to increase HEV production beyond the levels assumed here. If deployed on efficient platforms and in ways that emphasize fuel economy, the result could be fuel economy levels even higher than those of our most advanced scenario. As for the ISG, the broader benefits of hybrid technology suggest that not all of its cost need be allocated to its fuel economy benefit, although that is the approach taken here absent data to support a different allocation.

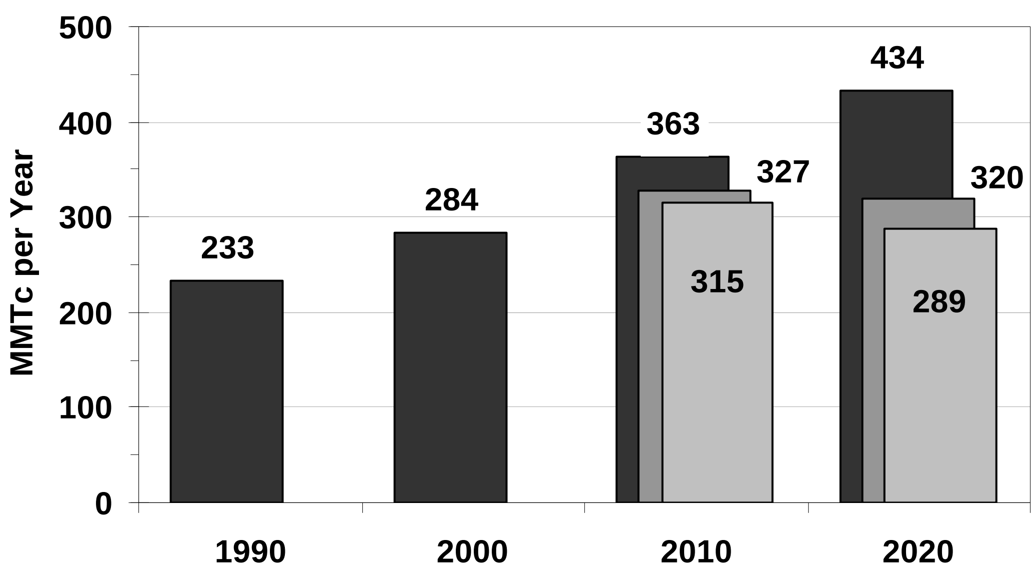
Energy and Carbon Impacts

Using the new fleet average fuel economy scenarios as input to a model representing turnover of the vehicle stock (all cars and light trucks, new and used) yields projections for nationwide fuel consumption and CO_2 emissions. What has been a "business-as-usual" baseline of flat fuel economy may be changing in light of the Ford and GM promises to improve SUV and light truck fuel economy. Nevertheless, flat efficiency plus ongoing increases in vehicle miles of travel (VMT) still provide a good baseline for comparison. Under such assumptions, total U.S. light vehicle fuel consumption would reach nearly 10 million barrels per day (Mbd) by 2010 and nearly 12 Mbd by 2020. For reference, consumption was 6.3 Mbd in 1990 and (preliminary estimate) 7.7 Mbd in 2000 (the latter value equals 118 billion gallons of gasoline per year). Parallel growth will occur in greenhouse gas emissions, certainly in the near term, since no nationally significant fuel substitution is plausible over the next decade, and probably even through 2020.

We examined linear ramp-ups of new fleet average fuel economy starting in 2003 and reaching our scenario levels by 2012. This decade-long time frame is long enough for automakers to redesign their cars and trucks in the course of routine reinvestments in upgrading their products. Based on market share weighting of our representative vehicles, our 2012 targets are: 36 mpg level for Scenario A, 39 mpg for Scenario B, and 41 mpg for Scenario C. The associated fleet-average retail price increases are roughly $1300, $1700, and $1800 (2000$). For Scenario A, the nationwide fuel savings are 1.0 Mbd by 2010 and 3.1 Mbd by 2020, when the improved technologies will have almost fully permeated the vehicle stock. Figure ES-2 shows these results in terms of projected light vehicle CO_2 emissions; compared to the baseline, fuel consumption and CO_2 emissions are reduced 10% in 2010 and 26% in 2020.

Greater reductions are, of course, achieved for the higher fuel economy scenarios. For Scenario C based on the Advanced Package of technologies, the savings are 1.3 Mbd (13% below baseline growth) in 2010 and 3.9 Mbd (33% below baseline growth) in 2020. These scenarios examine only the effects of improving the fleet to the designated technology-based levels; we did not examine what would happen if the rates of fuel economy improvement could be continued by drawing upon future technological progress. Thus, none of the scenarios suffice to return U.S. light vehicle fuel consumption or CO_2 emissions to their 1990 values. As shown in Figure ES-2, Scenario C comes close to returning consumption and emissions to the 2000 level (7.7 Mbd, 284 million metric tons carbon-equivalent [MMTc]), pulling them down to 7.8 Mbd (289 MMTc) by 2020. Not shown here are longer-term projections; however, barring additional efficiency improvements, consumption under all our scenarios turns upward again shortly after 2020, once the fuel economy improvements have largely permeated the on-road stock and VMT growth again starts to dominate.

Figure ES-2. U.S. Car and Light Truck Carbon Emissions: Baseline Growth vs. Scenario A, Moderate Package with 2% HEVs (middle bars), and Scenario C, Advanced Package with 2% HEVs (lower bars)



A critical question is the extent to which these technical capabilities can be applied to address the concerns that motivate fuel economy policy. By our reckoning, the direct costs are low, but so is market interest, which to date has valued technology improvement mainly for delivering customer benefits other than higher fuel economy. A key challenge is that of providing the policy guidance and leadership needed to harness the technical options identified here in ways that improve the fuel economy of cars and light trucks in the marketplace.

INTRODUCTION

In the United States, the average fuel economy of new light duty vehicles in model year 2000 was 24.0 mpg,[1] its lowest point in 19 years (Heavenrich & Hellman 2000). Yet this level is still 70% higher than the 14 mpg average of the early 1970s. Following the 1973 oil crisis and the 1975 passage of Corporate Average Fuel Economy (CAFE) standards, new fleet fuel economy rose rapidly through 1982 and then gradually peaked at 25.9 mpg in 1987–88. These improvements in fuel economy were almost entirely technology based (DOE 1995). What downsizing and de-powering that did occur in the late 1970s to early 1980s was largely undone by 1990, and more than undone by 2000.

New light vehicle fuel economy has declined since 1988 due to a shift from vehicles classified as cars to those classified as light trucks, the latter being held to a lower fuel economy standard. Light truck sales share was 19% in 1975, 28% in 1987, and reached 46% in 2000. The average new vehicle entering the stock is now less efficient than the average vehicle being scrapped, as reflected by the generally declining stock average on-road fuel economy in recent years (FHWA 1998 and previous editions). The only indication that such trends might not persist is the July 2000 promise by the Ford Motor Company, followed shortly with a similar pledge by General Motors, to voluntarily raise the fuel economy of their sport utility vehicles 25% by 2005. A generous interpretation of these pledges implies a 6.6% increase in fleetwide fuel economy,[2] not quite sufficient to reverse the 7.3% decline experienced since 1988.

Absent fuel economy increases, the light vehicle share of energy consumption and its associated oil dependence and greenhouse gas emissions impacts grow with vehicle miles of travel. Both decoupling VMT from economic growth and decoupling motor vehicle energy use from petroleum are difficult challenges. Although programs and policies for VMT reduction and alternative fuel vehicles (AFVs) have been pursued for several decades (albeit perhaps unevenly), no clear evidence exists demonstrating an ability to affect such decouplings at national scales. The possibilities of shifting fuels away from petroleum and shifting travel away from private vehicles should not be discounted and are arguably key parts of a balanced transportation energy strategy (DeCicco & Mark 1998). However, both are dependent on long-lived infrastructures and so are likely to be significantly achievable only on time scales much longer than the roughly 15-year usage lifetime of light vehicles. Moreover, both past experience and knowledge of markets suggest that policies to directly regulate new vehicle fuel economy are an effective means of controlling transportation energy use (Greene 1998).

Background

The question of what is the potential for raising new vehicle fuel economy has been regularly examined ever since it was thrust onto the national stage during the 1973 oil crisis. Through 1999, at least twenty major studies have examined the issue (see Greene & DeCicco 2000 for a review). Most studies indicate that some significant degree of improvement is possible at modest cost given adequate lead time. Many issues are involved in addressing transportation energy consumption. Nevertheless, quantifying the ability to improve fuel economy through vehicle design changes is crucial for informing other considerations of the problem. Periodically updating such analyses is valuable in light of ever-evolving market conditions and the ever-advancing technological frontier.

One lineage of studies is rooted in the view that policy-makers are best informed by analyses that reveal technically optimal applications of technologies within the constraints of affordability. That is the approach taken here, as in previous work by Ross & Williams (1981),[3] Ledbetter & Ross (1990), and DeCicco & Ross (1993, 1996). Less optimal targets may be deemed suitable after weighing other considerations. But a balanced assessment should be informed by a full range of cost-effective design changes, which is what we gauge here.

Overview

Following the methodology description below, the next major section reviews the technologies available for improving fuel economy over the coming decade and discusses how we grouped them for application to vehicles. The third section presents our results, starting with baseline vehicle characterizations followed by our technology packages and the resulting estimates of fuel economy and vehicle price impacts. The fourth section aggregates the vehicle-specific fuel economy and price estimates into scenarios of new fleet averages and shows the resulting implications for U.S. transportation energy use and greenhouse gas emissions.

METHODOLOGY

A variety of approaches can be used to assess the potential for improving automotive fuel economy.[4] We choose a system simulation approach, which applies a state-of-art computer simulation tool to model an entire vehicle system, including vehicle body, transmission, engine, power accessories and exhaust after treatment sub-systems. Advantages include:

- Detailed ability to mimic how vehicles are built and driven.
- Flexibility with respect to vehicle and technology type, enabling assessment of cars, SUVs, and trucks with different combinations of body types, engines, and transmissions.
- Sensitivity to driving cycle, enabling estimates to be made under various test cycles such as the U.S. Federal Test Procedure, high power cycles, and Japanese and European cycles.

We use a vehicle system simulation tool, the Modal Energy and Emissions Model (MEEM), developed by two of the authors and others (see Appendix A; also An et al. 1997 and NCHRP 2001), to assess the benefits of technology packages applied to a set of vehicles representing the major U.S. light duty vehicle (LDV) classes. MEEM has the advantage of a strong physical representation of vehicle systems, making it well suited to examine the effects of substantial changes in technology as well as sensitivity to driving cycle. The model has been extensively reviewed and applied for transportation air quality analyses and its results are closely consistent with those of other simulation tools such as the U.S. Department of Energy's (DOE) ADVISOR model.

Elements of the approach taken here are highlighted in the box on the next page. We analyze five contemporary vehicles representing the classes that now dominate the U.S. LDV vehicle fleet. Each representative vehicle is modeled at four different technology levels, using what we term technology *packages*. These packages represent approaches to ground-up, efficiency-optimized redesign of each vehicle type; we emphasize that what we are positing in each case is a thorough redesign appropriate for the vehicle type, rather than a variation of the

Elements of the Analytic Approach	
Representativ e Vehicles	Five existing vehicles are chosen to represent major classes, with variants examined for the SUV class; engineering simulation is used to model each vehicle in detail for the different technology packages.
Technology Packages	Four technology packages — Moderate and Advanced conventional technology, plus Mild and Full Hybrid Packages with electric vehicles — represent levels of redesign possible by combining available and emerging technologies.
New Fleet Scenarios	Scenarios (designated A, B, C) of future new car and truck fleet average fuel economy are constructed as weighted averages of the representative

base vehicle with incremental technology modifications. The design changes for each vehicle are based on a literature review and our engineering judgment about technologies that will be available, affordable, and meet expected tailpipe emissions requirements over the coming decade. Cost estimation is performed for each package, expressed as a retail-price equivalent (RPE) new car consumer cost impact (all values are in 2000$).

Safety considerations also dictate the design changes for each vehicle type, although neither a safety technology analysis nor a formal model of safety and crash involvement were attempted. Such analyses would be needed for a thorough examination of safety questions but were beyond the scope of this study. Our approach is informed by a recent companion study that examined the literature and statistical evidence on safety and vehicle weight (Ross & Wenzel 2001), as well as by prior studies that highlighted the importance of compatibility[5] effects for understanding this issue (as noted by NRC 1992, among others). Statistical work to date has failed to find compelling evidence that vehicle mass *per se*, independently of size, is a determining factor in overall safety. On the other hand, mass is a powerful factor in determining the relative risk in two-vehicle crashes; geometric and structural factors are also important, but mass has a dominant effect (Gabler & Hollowell 1998; Joksch 1998). By targeting greater mass reductions to heavier vehicles, we can exploit the benefits of improved compatibility to construct scenarios that have a high likelihood of improving fleetwide safety while obtaining the fuel efficiency benefits of mass reduction. Our redesign packages also allow for other structural changes that can enhance the crashworthiness of all vehicles; we assume that many opportunities exist to make vehicles safer on which engineers can draw during the redesign process.

In light of these considerations, our packages leave vehicle size unchanged except for the small car, which is made larger to build in greater side-impact crush space and to position the occupants higher for better crash compatibility. Thus, we assume that the small car has zero (Moderate Package) or 10% (Advanced Package) mass reduction, assuming application of the materials and structural advances to improve occupant protection and accommodate the larger size. Heavier vehicles are targeted for greater mass reductions, as specified below in Table 1. For the Advanced Package, we also model a new, large "sport wagon" design, with unit body construction using advanced lightweight materials and dimensional traits chosen to provide a safer and more fuel-efficient alternative to traditional SUVs. We restrict ourselves to identifying this strategy as a technical option; developing the policy guidance that might be needed to pursue it is an issue for future work.

To project aggregate fuel economy and fuel consumption outcomes, weighted mixes of the modeled vehicles are constructed to define *scenarios* of differing degrees of technology advancement. Scenario A combines Moderate Package conventional technology improvements with limited hybrid electric vehicle shares, representing our estimates of the minimum level of fleetwide fuel economy we believe to be achievable, given concerted policy guidance, over the study's 10–15 year time horizon. Finally, based on estimated fuel economy levels and an assumed ramp-up accounting for typical product cycles, nationwide fuel consumption and carbon dioxide emissions are projected based on turnover of the on-road vehicle stock. The estimated vehicle price impacts are used to calculate cost-effectiveness indicators, including simple payback by vehicle type, and fleetwide costs of petroleum savings and CO_2 emissions reduction.

Table 1. Weight Reduction Assumptions by Vehicle Type

Vehicle Class	Moderate	Advanced
Small Car	0	10%
Midsize Car	10%	20%
Minivan, Pickup, SUV	20%	33%

TECHNOLOGY ASSESSMENT

Technologies for improving fuel economy are continually evolving. Measures already in production can be used more widely or more efficiently and further refined for fuel economy purposes. Most opportunities over the next decade fall into this category. Emerging technologies, now in late stages of development, will be introduced soon and see increasing use as time goes on. Finally, advanced technologies now being researched could become available over the course of the decade-long horizon considered here. In all cases, cost is a critical factor, and "availability" ultimately means affordability. What follows first is an overview of technologies likely to be available for improving fuel economy over the coming decade. (These technologies are further described in Appendix B.) We then describe how we grouped these technologies into packages oriented toward improving fuel efficiency based on progressively more optimistic assumptions regarding market-readiness and affordability of the newer and more advanced options.

TECHNICAL OPTIONS FOR EFFICIENCY IMPROVEMENT

Technical options for improving vehicle efficiency fall into two fundamental categories: powertrain technologies include engines, transmissions, and the integrated starter-generator; load reduction technologies include mass reduction, streamlining, tire efficiency, and accessory improvements. Hybrid drive creates a whole new category for even further improvement of powertrain efficiency while providing other benefits of electric drive and enhanced onboard electric power capacity.

Conventional vehicles are achieving ever-higher performance and reliability while meeting stricter emissions and safety standards. The petroleum-fueled internal combustion engine will continue to improve, as will the entire powertrain through transmission improvements that enable a greater engine-transmission synchronization for higher efficiency. A key opportunity we invoke is a smaller, lighter, low-friction, high-output engine that operates as much as possible at low speeds, using control strategies to maintain smooth and responsive driving. Because of this change in engine and transmission operation, it is not fully clear that our vehicles are completely "transparent" in terms of driving experience, even though peak performance capabilities are maintained in our analysis. Shifting would become more frequent; our view is that improved control strategies and the torque smoothing abilities of the integrated starter-generator (see below) will enable designers to preserve or even enhance the driving experience with a powertrain of greatly improved fuel efficiency.

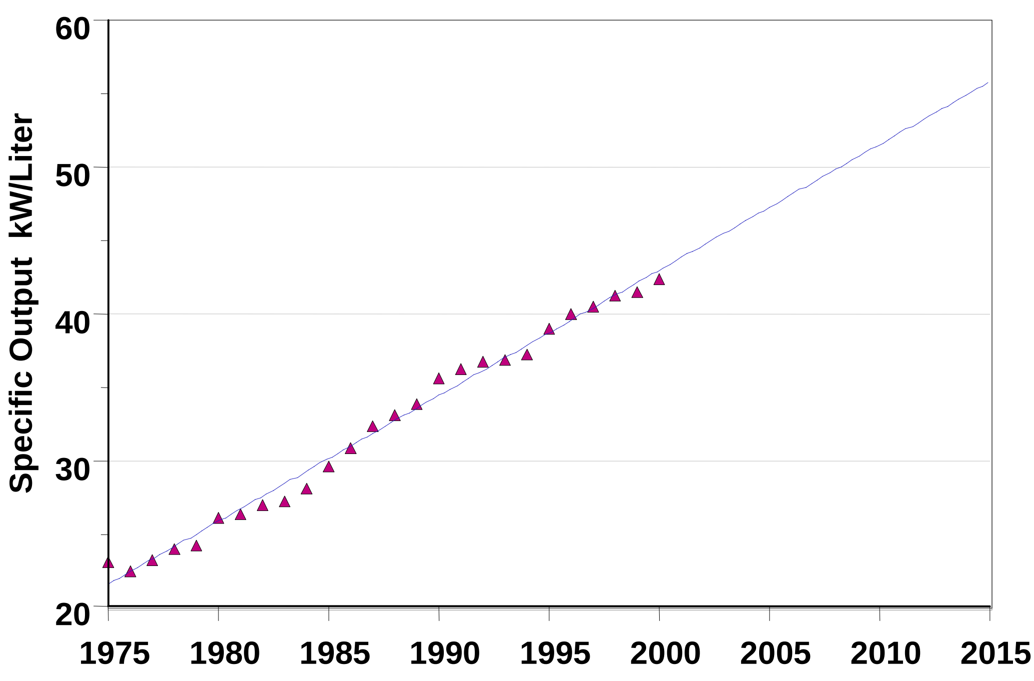
Powertrain Efficiency

High-efficiency gasoline powertrains will be able to meet very stringent[6] emissions requirements through the use of sensors and precise microprocessor control of the air-fuel ratio, durable and rapid-acting catalytic converters, and low-sulfur fuel that enables advanced catalysts to function with very high degrees of cleanup effectiveness. This revolution in emissions control — born of over two decades' experience in applying closed-loop catalytic control to meet progressively tighter standards — has not yet been achieved for diesel engines or gasoline engines using lean combustion. Both such engines, and particularly the diesel, offer added fuel economy benefits, but breakthroughs are needed before they can meet the stringent emissions standards that phase in starting in 2004. Cleanup is especially difficult for diesels, which we do not analyze here. We do consider direct-injection gasoline engines, which provide significant benefits even without the lean operation that bedevils pollution cleanup.

High Specific Power and Low Friction

Much of the efficiency improvement over the last two decades has come indirectly from increasing the engine's specific power (the maximum power per unit of displacement, e.g., in horsepower or kilowatts per liter). As shown in Figure 1, average light vehicle engine specific power has nearly doubled over the past 20 years. This achievement enabled a 58% engine downsizing and a 26% reduction in average zero-to-sixty mph (Z60) acceleration time. Engine downsizing also implies reduced engine friction and weight. Specific power was increased by adding valves, fuel injection, improved controls, low-friction and lightweight materials, application of numerical analysis techniques to optimize engine processes, precision manufacturing, and greatly improved quality control.

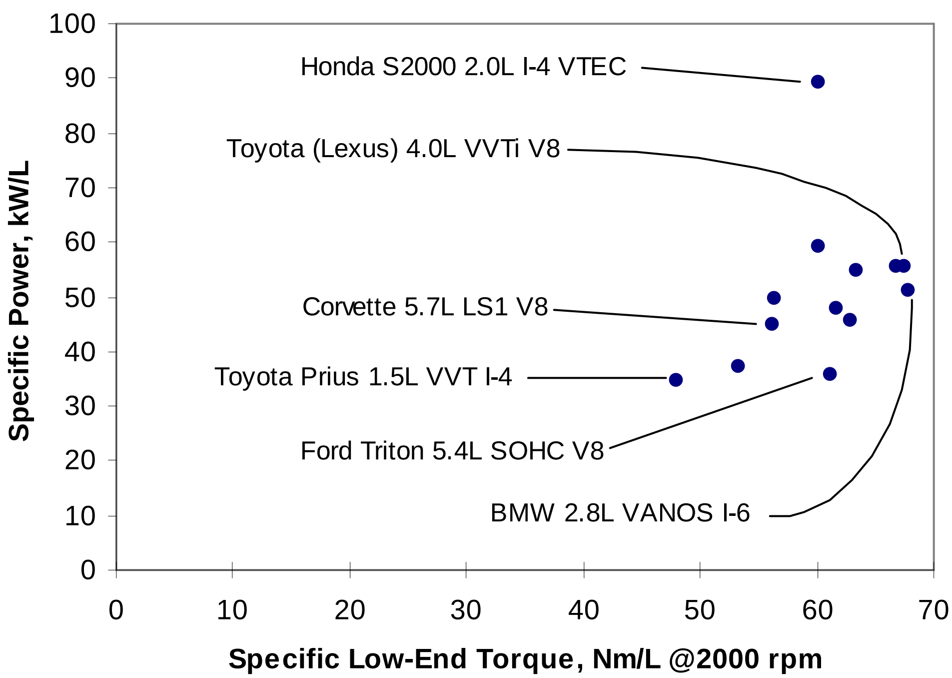
Figure 1. Engine Specific Output Trends for U.S. Light Duty Vehicles



Sources: Heavenrich & Hellman (2000); author's linear fit with slope of 0.86 kW/L per year

The opportunity to continue increasing specific power is excellent. Trend extrapolation from Figure 1 is corroborated by the specifications from today's state-of-the-art engines. Figure 2 shows specific power (in kilowatts/liter [kW/L]) and torque specs for some leading-edge contemporary engines. Ford's new Duratec HE engine series is another example, with the just-introduced 2.3L version for the Ranger pickup providing 135 horsepower (hp), for a specific output of 50 kW/L, compared to the 36 kW/L of the 119 hp, 2.5L engine it replaces (Jost 2001). The average of all MY2000 cars and light trucks was 43 kW/L. The 115 hp, 1.6L engine used in a Honda Civic HX has a specific output of 54 kW/L. In addition to 4 valves per cylinder, this engine has variable valve control (VVC, with Honda's "VTEC" design), aluminum block and heads, and numerous refinements that cut friction and improve the efficiency of induction and exhaust processes. A key aspect of recent improvements, aided by increasing use of electronic monitoring and control of engine process, is individual cylinder control of air/fuel mixtures. Such refinements and others are being deployed by all automakers.

Figure 2. Specific Power and Torque of Selected Gasoline Engines



Sources: Ward's 1999, 2000a, 2001

The engines we assume for the Moderate Package produce 50 kW/L. This level of output is 18% better than the 2000 average but not as good as today's best non-sports car engines and still a far cry from the levels achieved by high-performance engines from which many refinements "trickle down" to the mass market. Technically inclined readers can see some of the efficiency benefits of our assumed engines by comparing the baseline engine map of Appendix A's Figure A-2 with that of the improved engine shown in Figure A-3. The top curve of the map represents the peak brake mean effective pressure (bmep, which determines the torque delivered by the engine). The improved design is higher across the board, and notably so at low revolutions per minute (RPM), which allows responsive driving in more efficient engine modes. The "island" of minimum brake specific fuel consumption (bsfc, how much fuel is burned per unit of energy output) is not only lower, corresponding to higher peak efficiency, but also covers a broader portion of the map, meaning higher efficiency throughout the driving cycle.

For the Advanced Package, we assume a output of 55 kW/L, combining further degrees of refinement with the added benefits of gasoline direct-injection technology (see below). In both cases, a key issue is how the higher specific power levels are utilized. Our analysis assumes application for higher fuel economy, in contrast to the largely performance-enhancing emphasis that characterizes most recent introductions of improved engines. Given the continuing advance of the frontiers of engine performance, and the availability of boosting options and further efficiency-enhancing designs such as variable displacement (neither of which we explicitly include in our technology packages), the engine efficiency levels we identify do not preclude automakers' abilities to offer a full range of products, including high-performance vehicles and light trucks with ample load-bearing capacity.

Direct-Injection Engines

Another big step forward in engine efficiency will be the gasoline direct-injection engine, versions of which are already used in Japan and Europe. With a fuel spray directly into the cylinder, fueling can be controlled separately from valve timing and controlled cycle to cycle. This further leap in control capability will yield significant benefits. Even when operated stoichiometrically to meet stringent emissions standards, GDI offers greater efficiency and a higher compression ratio than port-injected engines. It also enables lower emissions and additional efficiency benefits due to improved cold start performance; mixture control, including ability to use high levels of exhaust-gas recirculation (EGR); charge air cooling; and reduced heat loss to engine block due to greater charge stratification. We do not separately model these efficiency benefits, but consider GDI to be part of an Advanced Package engine modeled using the level of downsizing enabled by a 55 kW/L specific output along with best-practice low-end torque for VVC controlled contemporary engines. We assume stoichiometric operation for all engines, and so exclude the greater benefits possible with lean-operating GDI engines due to their uncertain ability to meet stringent emissions standards (see discussion in Appendix B).

Advanced Transmissions

Very substantial progress in transmission efficiency can also occur. Three types of design improvements are: (1) added gears in conventional transmissions, e.g., 5- and 6-speed automatics; (2) motor-driven gear shifting ("powershift"); and (3) continuously variable transmissions. Additional gears enable the engine to run at a lower average speed over the range of vehicle speed and acceleration conditions, resulting in reduced engine friction. The ultimate in optimizing engine speed over driving conditions is the very wide span and "infinite" number of gears afforded by the continuously variable transmission (CVT).

Five-speed automatics and six-speed manuals have already been adopted in several production vehicles. Six-speed automatics are becoming available. Fully capturing the benefits of any multi-speed automatic transmission requires an efficiency-optimized shift schedule. Our simulation model specifies the shift schedule and enables use to accurately represent the engine/transmission interaction that determines fuel use over the course of a driving cycle, and so captures the benefits of adding gears and modifying the shift schedule.

Motor-driven gears (known as "motorized gear shift" or "powershift" transmissions) are being adopted in production vehicles starting in Europe. The motorized gear shift is an evolution of the manual transmission that not only automates for driver convenience,[7] but opens the opportunity for detailed programming of shifting, enabling fast shifting and the possibility of very smooth shifting without a torque converter. We modeled the powershift transmission as part of our analysis, assuming its use for the advanced sport wagon concept (see below). Although we did not model it for other vehicles, we consider it another way to achieve or exceed the efficiency levels of optimized 6-speed conventional automatic transmissions.

In many applications, the continuously variable transmission enables a broad span of gear ratios and low frictional loss compared to today's automatic transmissions (Markus 2000a). While a number of mechanical designs are possible for a CVT, a belt-driven design has seen most extensive light vehicle applications to date. More recently, a toroidal design has been introduced in Japan, and new variants of both belt and toroidal CVT designs appear to be close to introduction. Belt-driven CVTs face torque limitations, so we restrict their use to cars, not assuming them in use for light trucks in our analysis. A new design just entering the market is the toroidal CVT. Lacking sufficient data, we do not model it but consider it a promising advanced-case alternative to 6-speed conventional automatics, particularly for larger vehicles such as pickups and SUVs.

Another promising opportunity is elimination of the torque converter. This device has high frictional losses, particularly in urban driving when a lockup mechanism cannot be engaged, but is needed for its ability to smooth out start-ups and shift transitions. Until recently, most CVTs in production still used a torque converter, but improvements in automated shift actuation devices, new clutch designs, and precise electronic control of engine-transmission interactions can allow smooth operation without a torque converter (as demonstrated on the Honda Civic HX, for example). A direct-injection engine and integrated starter-generator also enhance the ability of any advanced automatic transmission, either CVT or geared, to minimize use of, downsize, or even eliminate the torque converter.

The Integrated Starter-Generator

Automobile electrical systems have evolved only slowly over the years in spite of steady growth in electrical loads. The traditional alternator has a capacity of 2–4 kW; it is a low-cost device but has poor efficiency. A new approach about to enter widespread use is the crankshaft-mounted, ISG powering an electrical system designed for 42 V operation with a 36 V battery. The ISG will allow conversion of a number of accessories to more efficient, electrically driven versions (described below, under *Vehicle Accessories*). The higher voltage allows smaller size wiring, saving weight and cost, as well as cutting resistive (I^2R) energy losses. Vehicles will even be able to offer 110 V outlets for plugging in devices designed for household current. There will, however, be transition costs in moving toward 42 V architecture. Although cost savings will dominate in the long run, initial elements of the new systems can be more costly than long-established 12 V commodity components (Khan 1998). Some automakers may retain a 12 V subsystem for lights and other items during the transition; initial vehicles may need two batteries (12 V and 36 V) or a battery module designed for dual voltage.

From a fuel economy point of view, the ISG provides numerous benefits, including: high efficiency, ability to turn the engine off during idle (engine start/stop), and torque augmentation for power boosting and reduced engine vibration. The ISG can permit the transmission to operate more frequently in lockup mode, increasing efficiency by 2–3% over traditional torque converter lockup. It can also be used to aid launch and smooth shift transitions enough to help dispense with the torque converter when combined with some of the advanced transmission designs noted above. Ford is using the ISG on an improved version of the Explorer slated for release in MY2004 as part of the approach to meet its SUV fuel economy improvement goals. We assumed use of a 42 V ISG for all technology cases except where it is superceded by hybrid drive. Our modeling found 2–3% fuel economy gains for an ISG without idle-off, and 7–10% with idle-off and launch assist (which we use for our results). Further gains of 10–15% can be had for an ISG that provides hybrid functionality (supplementing engine power throughout a drive cycle and regenerative braking), but we do not incorporate such 42v hybrids in our analysis, which assumes high-voltage designs for all HEVs.

Load Reduction

A load is any ultimate use of energy on a vehicle; tractive loads are those associated with the motion of the vehicle. Vehicle mass is the most important determinant of total tractive load; aerodynamic drag and tire friction are other factors. Accessory loads are those associated with running other devices on the vehicle, such as the air conditioner, heating and defrosting systems, lighting, power steering, active suspensions, other devices, and electronic equipment.

Mass Reduction

Although average car and light truck weight has been rising since 1987,[8] the substitution of lightweight materials has been ongoing. For example, aluminum use in vehicles has been growing at a rate of 7%/yr.[9] Were it not for such technical improvements, partly motivated by the need to meet CAFE standards, today's vehicles would arguably be even heavier given their size, safety requirements, performance, luxury, and other features. As for engine refinements, the issue is not so much of whether load reduction technologies are available and affordable — their deployment is in fact already underway. Rather, it is a question of whether they will be applied to yield fuel economy increases rather than to offset the effects of adding other features to vehicles.

Actual net mass reductions are achievable by redirecting product design priorities and taking advantage of more marked materials changes, such as aluminum-based structures, and new ways to design components and structures, such as composite panels on space frames. Automakers have identified approaches to achieve as much as 40% mass reduction, and are working on ways to bring down the cost. These approaches target not only body structures, but also suspensions and other chassis parts as well as closures and interiors. Some of the options for achieving given levels of mass reduction in major components are reviewed in Appendix B; however, the scope of this study did not permit a detailed analysis of specific materials and design changes. The amount of mass reduction we assume is inferred from our knowledge of the trade press and research literature on mass reduction through improved materials and design.

We assume different degrees of mass reduction for different vehicles, as shown in Table 1. For the Moderate Package, small car weight is unchanged in spite of upsizing and component additions to accommodate safety improvements. In this case, we allow for increased door and bodyside width and strengthening to protect against side impacts, raised sill and overall height for improved compatibility, improved restraint systems (side air bags, air belts, 4-point belts, etc.), and other passive safety enhancements. These changes can all be accommodated using the materials substitution, packaging, efficient powertrain, and computer-aided design techniques that provide engineers with substantial abilities for mass-efficient vehicle design. For larger vehicles, the larger base structures lessen the challenge of improving crashworthiness relative to those faced in small cars. Lightweight materials and design techniques can be applied to yield net weight reductions. For the Moderate Package, we assume that the midsize car has a 10% mass reduction and light trucks have a 20% reduction compared to baseline models.

The Advanced Package provides for greater mass reduction, but still targets the greatest weight loss (33%) for today's heaviest designs. In this case, the mass distribution of the fleet is greatly condensed, with the range of curb weights for the small car to the base full-size pickup decreasing from 2,800 lb to 4,000 lb, respectively, today down to 2500 lb to 2900 lb. Although we do not model what are today's largest "light" vehicles (large SUVs such as the Expedition or Suburban that weigh in at 4,800–5,400 lb depending on configuration), a 33% mass reduction would take these vehicles down to 3,200–3,600 lb. We do model a large, advanced sport wagon, capable of providing the carrying capacity of most of today's large SUVs but at 2,700 lb curb weight (see Appendix B). This design assumes much better packaging as well as advanced lightweight structural design and materials, such as those now being developed under R&D efforts that target a 40% curb weight reduction compared to conventional designs.[10]

Streamlining

Aerodynamic drag can be reduced through streamlining. Drag is proportional to the product of a vehicle's frontal area and a dimensionless drag coefficient (C_D) related to a vehicle's shape. Frontal area cannot be much reduced without downsizing the vehicle, so the technical opportunity is for ongoing streamlining to reduce C_D. In Germany the demand for low drag is so strong because of the lure of high-speed driving on autobahns, that not only is low C_D sought, but narrow cars are common. In the United States, as for other fuel-efficiency measures, streamlining benefits have been partly offset by the increased frontal area due to vehicle upsizing. Current C_D values are 0.30–0.35 for cars and 0.40–0.45 for light trucks.

Four General Motors cars are among the leaders in low C_D: a C_D of 0.26 characterizes the Opel Calibra in Germany, a conventional production car; among minivans, GM's Chevy APV had a C_D of 0.33 in the early 1990s. The C_D is 0.19 for the EV1, GM's two-seater electric car (it is somewhat easier to achieve low drag in an electric vehicle because the powertrain cooling load is small). A C_D of 0.16 was achieved for GM's Precept Partnership for a New Generation of Vehicles concept, an aerodynamic *tour de force* with a smooth flat underbody, rear vision achieved with cameras instead of mirrors, air scoops (for cooling) behind the rear wheels, rear wheel covers, and an overall shape determined through extensive software and wind tunnel trials. Other PNGV prototypes have C_D values near 0.20; for comparison, the C_D is 0.25 for the Honda Insight and 0.29 for the Toyota Prius.

Fleetwide C_D has decreased about 2.5%/yr over the past two decades[11] and it is not uncommon to see a 15% reduction when a vehicle is redesigned. Given the low C_D values of today's best designs and the even lower values demonstrated in concept cars, it seems likely that this rate of improvement can continue for at least another decade. We assume a roughly 10% reduction in drag coefficient for the current representative vehicles we analyze and posit a C_D of 0.30 for our advanced sport wagon.

Tire Rolling Resistance

Tire rolling resistance, represented by the coefficient C_R, can be reduced though new materials and design. Lower-energy tires continue to be introduced as original equipment to help meet CAFE standards, although shifts toward larger tires for reasons of performance and image partly offset the benefits. The sensitivity of fuel consumption to rolling resistance ranges 0.16–0.20, so that a 20% reduction in C_R offers up to a 3–4% improvement in fuel economy. Reductions in C_R through improved rubber compounds and design do not compromise safety and handling. The potential for such improvements over a decade time frame is 15–30% (DeCicco and Ross 1996; IWG 1997). We assume a 20% C_R reduction for the vehicles we analyze. Some of this reduction could occur at cost savings by foregoing tires that are (for styling and image reasons as is now the case on many SUVs) wider than really needed for safe handling and good traction.

Tire rolling resistance can also be reduced by increasing the pressure. The relationship is that resistance is roughly inverse to the square root of tire pressure. So if the pressure is doubled, tire drag is reduced about 40%. Such high pressures are used for electric vehicles that address California's Zero Emissions Vehicle mandate, because load reduction is critical to the range of an electric vehicle. A concern is that at high pressure the footprint of a tire becomes smaller and the ability of the tire to grip the road under some conditions may be reduced. Conversely, lower pressure increases tire drag. Since most people do not keep their tires inflated to their ideal pressure, measures such as pressure sensors to monitor tire pressure offer the potential for real-world efficiency improvements, although their benefits would not be captured on fuel economy test procedures. We do not analyze these devices here, but would recommend specifying them as a practical fuel-saving (and safety-enhancing) measure for future vehicles.

Vehicle Accessories

The largest vehicle accessory load is the belt-driven air conditioner; for a midsize car, its load is approximately 4 kW when running. Some other typical electrical accessory requirements are 120 W for the rear window defroster, 120 W for headlamps, and 60–90 W for wipers. Many of these loads are not measured in the regulatory test procedures that determine rated fuel economy (air conditioning loads are partly counted). Electrification of accessories as well as refinements of conventional components can reduce accessory loads. High-power accessories could all become electrical, including air conditioning. Today's hydraulic power steering systems are a direct drag on the engine, and a move to electric power steering is another way to improve efficiency (Badawy, Bolourchi, & Gaut 1997).

Hybrid Propulsion

Hybrid electric vehicles combine a combustion engine with a supplemental motor and an energy storage device such as a battery. Hybrid propulsion improves efficiency because it allows the engine to be downsized, operated in its most efficient zone, and turned off when not needed, and also enables braking energy to be recovered. Hybrid vehicles entered the automotive market with the December 1997 launch of the Toyota Prius in Japan. The Honda Insight went on sale in the United States in early 2000 and the Prius in July 2000. Nissan has been selling its Tino HEV in Japan since 2000 as well. All major automakers have promised HEV launches over the next several years.

In principle, hybrid propulsion can take many forms, from slight degrees of hybridization (perhaps using an ISG) to designs that drive the wheels only electrically. HEVs can be classified according to the portion of their total propulsion power provided by electric drive:

- Mild hybrid — less than about 25%; idle-off and some regenerative braking, but no significant electric-only driving (example: Honda Insight).

- Power hybrid — 30–50%; some electric-only driving but no real trip range, and battery not designed for plug-in recharging (example: Toyota Prius).

- Energy hybrid — 50–100%; a useful all-electric driving range (50 miles or more) and plug-in recharging ability.

Of course, given the newness of the technology and the flexibility it affords, such categories cannot be viewed rigidly. A power hybrid can be called a "full" hybrid, which is the term we will use here. Energy hybrids are also known as "charge depletion" hybrids. The larger batteries they require add to cost and detract from efficiency; no energy hybrids have been announced for production and we do not model them. At the low end of the mild hybrid range, some hybrid functionality can be provided by 42 V ISG-type systems, what might be termed "minihybrids," as recently announced by several automakers.

Table 2 lists some key specifications of the Prius and Insight. An et al. (2001) analyzed these vehicles to breakdown the elements of their efficiency improvement. Compared to vehicles with already efficient (VVC, 4 valve) conventional engines, the Prius demonstrates a 54% fuel economy improvement and the Insight a 66% improvement when counting mass reduction and streamlining effects. Isolating the net efficiency benefits of hybridization yields estimates of 25% for the Insight and 41% for the Prius (counting the benefits of the lean-burn VTEC engine, which is significantly enabled by the Insight's hybrid system, would push its estimated benefit to 31%). We model hybridization at two levels, representing the "mild" and "full" HEV design strategies, and adopt the respective 25% (Insight) and 41% (Prius) improvements as the basis for estimating the benefits in other vehicles. Our analysis accounts for interactions, so the net mpg benefits of HEVs are typically lower than these values, as indicated in our results below. Although we do not analyze the production-intent HEVs that have been announced, since only limited specifications are available to date, they are reviewed in Appendix B to provide examples of other hybrid vehicle design directions.

Table 2. Selected Specifications of the Toyota Prius and Honda Insight

Attribute	Prius	Insight
Fuel economy: City/Hwy label, CAFE (mpg)	52 / 45, 58	61 / 70, 76
Engine: size, power (hp) / torque (lb•ft)	1.5L, 70 / 82	1.0L, 67 / 66
Electric drive: power (hp) / torque (lb•ft)	44 / 258	13 / 36
Electric drive share of total power	39%	18%
Weight: curb / test (lb)	2765 / 3125	1856 / 2125
Peak total power/weight ratio (kW/tonne)	62	66

Peak total torque/weight ratio (Nm/tonne)	339	136
Performance index, 0–60 mph time (s)	12.5	10.6

VEHICLE REDESIGN PACKAGES

To examine the impacts of fuel-efficient design changes, we combine the technologies reviewed above into several packages representing combinations of measures that an automaker might use to achieve a higher fuel economy target. These packages vary somewhat by vehicle class. For example, a continuously variable transmission is used on lighter vehicles where the torque loads fit within the CVT's likely limitations. On heavier vehicles, other transmissions are used, such as 5- or 6-speed automatics or the motorized gear shift.

During the course of this study, we examined and modeled many different technology combinations. But our main results highlight three packages representing combinations of technologies that we judge to be suitable for achieving varying degrees of fuel economy improvement among the types of vehicles we examine. We term these packages Moderate, Advanced, and Hybrid Drive, with technologies specified as follows. A summary of how we applied them for various vehicles is given in Table 3, which also lists some options we considered but did not incorporate into our final packages. A key point is that none of our packages are exhaustive in terms of relatively low-cost measures available over the next decade, and that alternative choices are available that could yield similar levels of fuel economy improvement.

Table 3. Technologies Considered for Fuel-Efficient Design Packages

Technology and Characteristics	Design Package Applications		
	Moderate	**Advanced**	**Hybrid**
Mass reduction (see Table 1)	All but S	All	All
Other load reduction: C_D910%, C_R920%, more efficient accessories	All	All	All
Engine options:	All		
VVC, 4-valve, at 50 kW/L	All		
GDI, VVC, 4-valve at 55 kW/L		All	All
Individual cylinder control	All	All	All
Boosting (super-/turbo-charging)			
Variable displacement			
Transmission options:			
Continuously variable (CVT)	S, M	S, M	*
5-speed automatic	P, U, V		
6-speed automatic with optimized shifting		P, U, V	
5-speed powershift (automated manual)		W	*
Integrated Starter-Generator, 42-volt:			
With only idle-off and torque smoothing	All	All	
Adding regenerative braking and power assist			
Hybrid-electric drive, high-voltage systems providing power assist, idle-off, and regenerative braking			All

Vehicle Application Codes: H = High-performance SUV, M= Midsize car, P = Pickup truck, S = Small car, U = standard SUV, V = Van (minivan), W = advanced sport Wagon.

*Mild hybrids will still need a transmission; full hybrid may not, e.g., using a planetary gearset as in the Prius.

Moderate

The Moderate Package represents improvements achievable through a fuel-efficiency-oriented application of current trends in automotive technology, including developments that have already been entering production whether or not for raising fuel economy as analyzed here. It involves the following technology choices:

- Mass reduction according to the moderate percentages given in Table 1
- Streamlining, lower tire rolling resistance, and more efficient accessories
- High-efficiency, lightweight, low-friction, gasoline engine (50 kW/L)
- Integrated starter-generator with 42 V system
- Improved transmissions: CVT for cars, 6-speed automatics for light trucks

These design improvements include technologies that are either already in use or slated for near-term production. The mass reduction, ranging from none for the small car to 20% for the larger vehicles, is achievable by using current best practice materials use and packaging techniques (compare weight changes in Table A-2 vs. Table A-1). Size is unchanged for all but the small car, which gets 8.6 cm (3.4") wider and 3.8 cm (1.5") higher to accommodate safety enhancements as discussed above. Frontal area increases about 5% for the small car and remains unchanged for the other vehicles. Other load reduction entails streamlining for a 10% cut in drag coefficient, a 20% cut in tire rolling resistance, and use of the most efficient accessories now becoming available.

The engine represents a current best-practice design, integrating a set of features providing high specific output with low friction and a high degree of controllability (short of direct injection). Specific output is 50 kW/L, or 16% better than the 2000 average of 43 kW/L. Features include an overhead camshaft, 4 valves per cylinder with variable lift and phasing, and multipoint injection with timing and mixture individually controlled for each cylinder through the use of sensors and fully computerized logic. Improved cylinder linings, low-friction rings, and high-precision machining allows use of low-viscosity oil (5W-20) for further friction reduction. The engine is coupled to an integrated starter-generator, providing benefits including idle-off and torque smoothing (but not regenerative braking or other HEV functionality). Transmissions are electronically controlled, with a CVT used for the cars and an advanced, 6-speed conventional automatic used for the light truck class vehicles. However, we assume conventional shift schedules (road-load curves) for geared transmissions, and do not assume the lowest possible average engine speed for the CVTs, reserving full optimization for the advanced case.

Advanced

The Advanced Package includes the following choices:

- The higher, advanced level of mass reduction shown in Table 1
- The same streamlining, tire, and accessory improvements as in the Moderate Package
- Advanced direct-injection gasoline engine (stoichiometric, 55 kW/L)
- Integrated starter-generator with 42 V system
- Advanced transmissions, using efficiency-optimized shift schedules for all vehicles

This package takes three added steps forward in efficiency: a greater degree of mass reduction; a, even higher output gasoline direct-injection engine; and high-efficiency transmissions with optimized shift schedules. Advanced Package specifications for the representative vehicles are detailed in Table A-3. For small and large cars, the technology requirements for the 10–20% curb weight reduction are comparable to those used for the light trucks in the previous cases. The 33% mass reduction in the pickup, minivan, and traditional SUV is premised on more substantial use of new materials, as discussed earlier. An even more advanced, lightweight structure is used for the advanced sport wagon, which we model only for this case.

The GDI engine is coupled with an integrated starter-generator and fully optimized transmission, enabling an unprecedented degree of control over all key aspects of powertrain performance, including responsiveness, smoothness, avoidance of less efficient operating points, idle-off, and ultra-low emissions. As in the Moderate case, belt-driven CVTs are assumed for the small and large cars; electronically controlled 6-speed automatics are assumed for the other vehicles, with the advanced sport wagon assumed to use either a powershift or toroidal design. Achieving a fully optimized road-load curve is primarily a control (programming) change that can be accomplished with little hardware change compared to the moderate case, although more precise mechanisms may be needed. This advanced GDI powertrain would be very compact and have a high power density, contributing to the general reductions in vehicle weight.

Hybrid Electric

We model hybrid powertrains as being used with Advanced Package levels of load reduction and engine efficiency. Using the HEV technologies on low-mass platforms helps hold down the system cost, and hybridization has an excellent synergy with the highly controllable GDI engine. With its aluminum body, the Honda Insight is built on what we would term an "Advanced Package" platform. The hybrid powertrains introduced over the next few years will be coupled with a variety of other technology changes, initially perhaps closer to those of our Moderate Package. Nevertheless, given our 2010–15 horizon, we assume that advanced platforms will be the likely choice for high-volume HEVs.

As discussed earlier, a wide range of hybrid design choices is feasible. Our results are reported for two types of electric hybrid systems:

- Mild, for which we assume electric drive provides 15% of peak propulsion power

- Full, for which we assume electric drive provides 40% of peak propulsion power

The benefits of hybridization depend on the driving cycle, and for a given driving cycle, they depend on a vehicle's performance level. Adjusting for interactions with other powertrain improvements, the net fuel economy benefits are 15–18% for a mild hybrid and 29–33% for a full hybrid, relative to vehicles having Advanced Package engines and transmissions.

ANALYSIS AND RESULTS

The first part of our analysis involved selecting vehicles to model and calibrating the simulation model. This step provided our baseline results to which the results of our Moderate, Advanced, and Hybrid Packages of technology can be compared. Details of model runs are given in Appendix A. Table A-1 provides the baseline results, comparing the simulated fuel economy to test values for the representative models (they match within 0.4 mpg).We use the simulated values as the basis of comparison for results and they are the values identified as "Baseline" in other tables.

Vehicles Modeled

Representative baseline vehicles were chosen from five vehicle categories:

- Small cars — two-seater, mini-compact, compact, subcompact, and corresponding wagons
- Large cars — midsize and large classes and corresponding wagons
- Pickup trucks — for all pickup truck classes
- SUVs — medium and large sport utility vehicles
- Minivan — passenger vans

Table 4 lists some average attributes of these five classes (from Heavenrich & Hellman 2000). The large and small car classes averaged 10% and 28% higher, respectively, than the overall average MY1999–2000 fuel economy of 24 mpg. Minivans, pickups, and SUVs averaged 8, 16, and 20% lower, respectively, than the overall new fleet average.

Table 4. Average Attributes of Five Representative Vehicle Classes

Vehicle Class	*Sales (million)*	*Fuel Economy (mpg) city*	*hwy*	*55/45*	*Weight IWT (lb)*	*Liters*	*Engine HP*	*kW/L*	*0-60 time*
Small car	3.475	25.7	39.8	30.6	3066	2.3	143	47	10.8
Midsize car	4.148	21.8	35.6	26.3	3505	3.2	185	44	10.1
Pickup	2.380	17.6	25.7	20.1	4386	4.2	198	35	11.0
Minivan	1.511	18.6	28.9	22.0	4344	3.7	185	38	11.4
SUV	2.631	16.6	24.5	19.2	4642	4.3	205	36	11.0

Sources: Heavenrich & Hellman (2000), statistics for Model Year 1999

To select a representative vehicle within each class, we considered the following criteria:

- A baseline model should be among the top five best sellers in its class.
- Its key attributes should be close to its corresponding class averages

- Key vehicle attributes include (in the order of descending importance) fuel economy, vehicle weight, engine displacement, and rated engine power.

- The selected models should not be concentrated among only one manufacturer.

The result is the set of vehicles shown in Table 5. For the SUV class, two Ford Explorer models were chosen, a 160 hp "standard" version and a 210 hp "performance" version, in order to examine the sensitivity of fuel economy projections to different levels of engine technology in the baseline vehicle. In this class, the performance level (indicated by Z60 time) of the standard SUV is close to the class average (compare Tables 4 and 5) while that of the performance SUV is 19% quicker. Since 72% of MY2000 SUVs had 4-wheel drive, we assume 4wd for both versions of the SUV. For pickups, we select a 2wd Chevy Silverado; 2-wheel drive accounted for 62% of the full-size pickup truck market in 2000. For the small car class, our baseline model, the Chevy Cavalier, has a significantly lower performance metric (61 W/kg) than its EPA vehicle class average (76 W/kg), in part because the small car class includes many sporty cars and performance coupes as well as some luxury coupes. The Cavalier is at the economy end of this class. Examining the sensitivity of the projections relative to the standard vs. high output versions of the SUV class provides an indication of the general sensitivity to the issue without the additional effort needed to model all types of vehicles within every class.

For most light trucks, we emphasize improvements suitable for models used primarily as passenger vehicles. Most light trucks now substitute for cars; such is the case for nearly all SUVs and minivans, as well as roughly 75% of pickup trucks. Although we do not analyze commercial-use light trucks, we note that traditional versions, such as pickup trucks used by tradesmen and farmers, had power performance and comfort/convenience appointments, and relative prices well below those that have become commonplace today. For minivans and SUVs, we model our improvement packages to preserve zero-to-sixty mph (Z60) time, a metric that emphasizes peak power abilities. For the full-size pickup truck, we model improvements while preserving zero-to-thirty mpg (Z30), which gives greater emphasis to low-end torque availability, as needed for load hauling. Thus, this vehicle gives an example of the efficiency improvements achieved without compromising the "truck" functionality needed for work vehicles.

Table 5. Baseline Traits of Representative Vehicles from 5 Major Classes

	Sales	*Fuel Economy (mpg)*			*Weight*		*Engine*		*0-60*
	(' 000)	*city*	*hwy*	*55/45*	*IWT (lb)*	*Liters*	*HP*	*kW/L*	*time*
Small Car Chevy Cavalier Sedan 2.2L I4 L4	272	26	40	30.8	3125	2.2	115	39	11.2
Midsize Car Ford Taurus SE Sedan 3.0L V6 L4	368	22	36	26.2	3625	3.0	155	39	10.0
Pickup Chevy Silverado 1500 4.8L V8 L4, 2wd	644	18	26	20.6	4750	4.8	270	42	8.8
Minivan Dodge Grand Caravan 3.8L V6 L4, Awd	293	19	30	22.6	4500	3.8	180	31	10.1

SUV Ford Explorer XLT 4.0L,V6 L5	429	17	27	20.7	4250	4.0	160	30	10.7
Explorer Eddie Bauer 4.0L SOHC V6 L5		18	26	20.7	4500	4.0	210	39	8.9

As noted earlier, rather than restricting ourselves to established vehicle classes when it is clear that the market is in flux, we also analyze an advanced "sport wagon" inspired by recent trends. We examine a mid–large vehicle using unibody construction that can potentially replace some traditional SUVs and minivans in a high-volume, popular price segment. In this case, rather than take an early example already on the market, most of which are either small or luxury models, we developed a composite model by benchmarking to a set of current SUVs, wagons, new sport wagons, and a few concept vehicles (Citadel, Powerbox, Multisport, and Varsity) as explained in Appendix B. The resulting vehicle has a 120" wheelbase and 66" track, with overall dimensions of 192" length, 76" width, and 63" height. It could hold the proverbial 4'x8' sheet of plywood with rear seats folded down; we assume best-practice packaging to yield a spacious 177 ft^3 of total interior volume. We estimate an implied mass from the current vehicle sample, and then assume that the use of advanced lightweight materials techniques could be applied to yield a 40% cut in curb weight. The resulting advanced large sport wagon concept has a curb weight of 2,650 lb (1200 kg), and we evaluate it at a 3,000 lb inertial test weight.

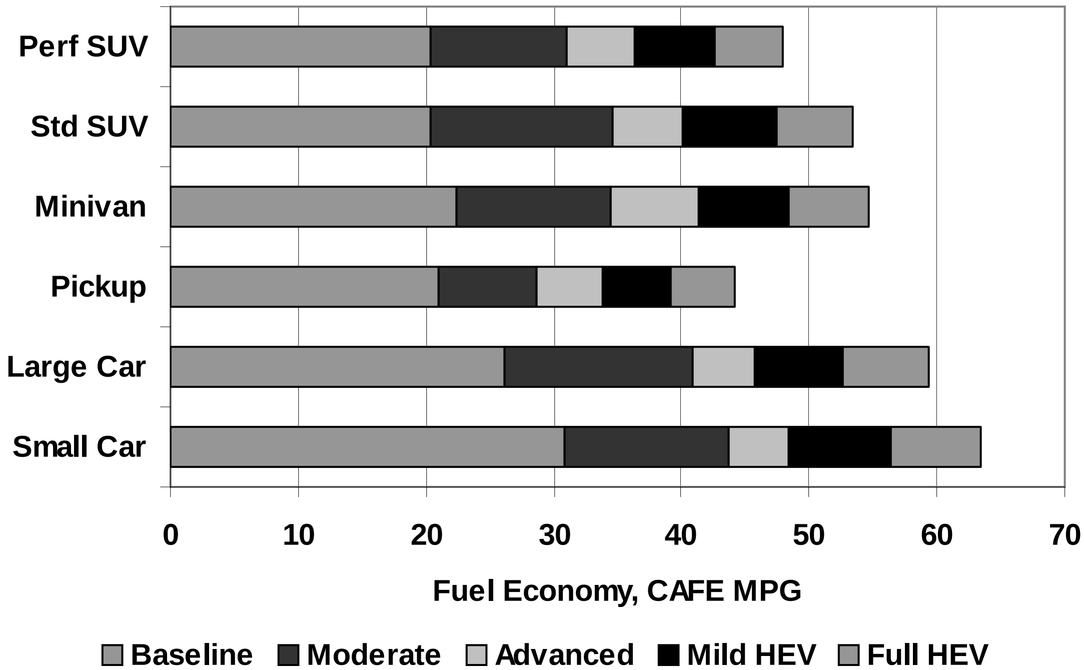
FUEL ECONOMY RESULTS

Table 6 summarizes our results, showing fuel economy estimates for each vehicle for the technology packages we analyzed. Further details are provided in Appendix A, Tables A-2 and A-3 for the Moderate and Advanced Packages of technology, respectively. The results are illustrated graphically in Figure 3.

Table 6. Fuel Economy Modeling Results

Vehicle	Fuel Economy (MPG) and Improvements over Baseline *(%)*								
	Baseline	Moderate		Advanced		Mild HEV		Full HEV	
Small car	30.8	43.7	*42%*	48.4	*57%*	56.3	*83%*	63.5	*106%*
Midsize car	26.2	40.8	*56%*	45.8	*75%*	52.6	*101%*	59.3	*126%*
Full size pickup	21.0	28.7	*37%*	33.8	*61%*	39.2	*86%*	44.2	*110%*
Minivan	22.3	34.5	*55%*	41.3	*85%*	48.4	*117%*	54.6	*145%*
Standard SUV	20.3	34.6	*70%*	40.1	*98%*	47.4	*133%*	53.4	*163%*
Performance SUV	20.4	31.0	*52%*	36.3	*78%*	42.5	*109%*	48.0	*135%*
Advanced sport wagon	n/a	—		44.0		—		—	

Figure 3. Summary of Fuel Economy Estimates by Vehicle Type and Technology Package



The Moderate Package yields improvements ranging from 37 to 70%, with the largest relative improvement being for the standard SUV. The high-performance SUV, with its already more refined base engine, obtains only a 52% fuel economy improvement at the moderate technology level since it has already absorbed some of the technologies to provide greater performance. The performance SUV has a 17% quicker Z60 time than the standard version, a edge that is preserved under our analytic assumptions. In the baseline, the better engine technology has all gone into performance and other amenities since the SOHC version (Explorer Eddie Bauer Edition) has essentially the same fuel economy as the OHV version (Explorer XLT). The pickup truck shows the smallest relative improvement, 37% above the baseline, since engine downsizing was limited by the need to preserve low-end torque (modeled by holding constant its 3.5 second Z30 time). However, this degree of improvement does suffice to raise the pickup's fuel economy to a level matching that of today's average passenger cars.

The Advanced Package yields substantially greater efficiency improvements, obtained by pushing conventional (non-diesel and non-hybrid) technology toward its limits. A good portion of the higher fuel economy is due to the greater degrees of mass reduction. Another substantial portion is due to the transmissions being greatly improved in terms of both their own mechanical efficiency and shift-schedule optimization that then enhances the engine's mechanical efficiency. The highly efficient, compact GDI engine provides added benefits as well. Improvements range from 57% for the small car to as much as 98%, an essential doubling of fuel economy, for the standard SUV. In this case, the small car shows the least improvement because it has the smallest degree of mass reduction. Even with a 33% reduction in curb mass, the pickup truck improves but 61%, again due to the lesser degree of engine downsizing permitted.

COSTS

The cost estimates for our scenarios are summarized here in Table 7, with some specific assumptions given in the table's notes and further details provided in Appendix B. In all cases, the cost estimates are retail price equivalent values given in 2000$. Thus, they represent consumer price impacts, based on normal costing assumptions that apply markups to manufacturing costs to cover the various industry overheads, sales and distribution costs, and profits. In general, we assume high-volume manufacturing status for all technologies. The exception is hybrid drive, which is too new to view as an evolution over known designs as is the case for other technologies. We do assume that HEV component costs will fall significantly by 2010–15 compared to present estimates, given ongoing R&D progress and moving to higher production volumes while gaining a decade of manufacturing experience.

Engines

The main costs associated with improved engine specific power are largely those associated with the more complex cylinder heads and valve train. Shifting to overhead cams itself can cut costs, but variable valve timing apparatus involves more complex mechanisms and control hardware. The RPE impacts for the Moderate Package (50 kW/L) engines are $270 and $360 for 4- and 6-cylinder versions, respectively (performance of our modeled vehicles is maintained without 8-cylinder engines because of both engine improvements and vehicle mass reduction). The 55 kW/L GDI engines of our Advanced Package are yet more expensive due to the added costs of high-pressure fuel injection systems. Based on EEA (1998a), the added RPE impacts are $180 and $270 for 4- and 6-cylinder GDI engines, although costs would be higher when the engines are first introduced before mature, high-volume component production is reached. Further discussion of engines, and our rationale for assuming no net long-run cost for ongoing detail refinements such as friction reduction and higher compression ratios, are given in Appendix B.

Table 7. Estimated Consumer Price Impacts of Technology Packages

	Vehicle Type					
Moderate Package	Small Car	Mid Car	Pickup	Minivan	Std SUV	Perf SUV
Mass reduction(a)	0	0	223	210	198	198
Other load reduction (b)	174	176	182	180	178	178
High-efficiency engine(c)	270	360	360	360	270	360
Integrated starter-generator(d)	500	500	750	750	750	750
TOTAL (2000$)	944	1,036	1,515	1,500	1,395	1,485
Advanced Package	Small Car	Mid Car	Pickup	Minivan	Std SUV	Adv. SW
Mass reduction(a)	0	166	801	756	711	1,080
Other load reduction(b)	175	176	180	178	176	178
Efficient GDI engine(e)	450	450	560	450	450	450
Integrated starter-generator(d)	500	500	750	750	750	750
TOTAL (2000$)	1,125	1,292	2,291	2,134	2,087	2,458
Hybrid Electric Vehicle (f)	Small Car	Mid Car	Pickup	Minivan	Std SUV	Perf SUV
Mild ($2000)	3,118	3,522	4,547	4,169	4,002	4,343
Full ($2000)	4,331	5,089	6,526	5,818	5,472	6,322

"Std SUV" is derived from OHV Explorer, "Perf(ormance) SUV" from DOHC Explorer, and "Adv SW" is the advanced sport wagon concept.

Notes

(a) Assume first 15% is no-cost (e.g., applying ULSA techniques), then $1.00/lb.

(b) Estimated as 144 + Mass Scale*32 (Tires II), where 144 = 64 (Drag III) + 80 (Access II + EPS) from EEA.

(c) For 4-6 cylinder engines, RPE estimated as $150-$200 for VVC plus $120-$160 for 4-valves/cylinder.

(d) We size ISGs at 8-12 kW rated output, with mogen at $25/kW ($200-$300), $100-$150 for electronics, and $300-$450 for battery (over lifetime), less $100-$150 for conventional starter and alternator.

(e) Long-term estimates from EEA (1998a) for Toyota design, less costs of lean-NOx control items, implying RPE of $180-$200 for 4-6 cylinders.

(f) Based on Delucchi (1999) and EEA (1998b) estimates as described in Appendix B, plus all other advanced package items except the ISG.

Transmissions

In short, we judge that the advanced transmissions assumed for our redesign packages will have zero price impact. This perhaps surprising result is based on a review of emerging transmission technology options, all of which promise to be ultimately less expensive than today's multi-speed automatics. For example, one transmission maker indicates that design improvements will enable its new 6-speed automatics to be lighter and simpler than existing 5-speeds (Automotive Engineering 2000), suggesting little or no cost impact in the long run.[12] The 6-speed designs also have a wider spread of gear ratios, potentially enabling elimination of the torque converter by using precisely controlled clutches and planetary gears (a step that will be further facilitated by ISGs). With electronic control, this evolved conventional transmission can have optimized shift schedules that begin to approach those obtainable with a CVT.

For powershift (motorized gearshift, or automated "manual") transmissions, one of the development motives has been the expectation that they will be less costly than conventional automatics. Cost estimates have not been available, but while electronic content is higher, overall complexity is less than that of conventional multi-speed automatics since powershift transmissions are mechanically similar to the smaller and lighter manual transmissions from which they are derived. Again, with an ISG, there would be a savings from elimination of the torque converter, and the additional electronic controls could be integrated into the engine control module. With such designs, there could even be a net long-run cost savings.

For our 10-year horizon, we estimate the incremental cost of a belt CVT compared to a conventional automatic at zero, even though there may well be a cost savings in the long run. Audi's Multitronic pull-belt CVT is now priced at only $100 more than their Tiptronic automatic. Cost information is not available on toroidal CVTs, but near-term premiums should give way to near-zero cost increments if the technology catches on in the long run. In any case, we expect an interesting competition between the "revolutionary" CVTs and the continuing evolution of geared transmissions, offering automakers several strategies for markedly improving transmission efficiency, with costs held down to those of the least expensive option for a given application.

ISGs

Integrated starter-generators are expected to initially run at 42 V (output) and have rated electrical capacities of 8–12 kW (though the motors will be capable of higher power bursts). The device will be a valuable way to serve many needs for both electrical capacity and higher efficiency. An ISG replaces both the starter and alternator, and can contribute to elimination of the torque converter when coupled with an advanced transmission. Costs would initially be relatively high; EEA (1999) estimates a retail price impact of $1,000. However, the motor/generators and electronics involved would see falling costs in what would be an competitive supplier market. As described in Appendix B, our total ISG system RPE impact estimates are $500 and $750 for nominal 8 and 12 kW systems, respectively (counting savings on starter/alternator, but not on torque converter). The ISG, however, offers value in ways that go beyond only fuel savings. A strong market driver is the need for greater onboard electrification to serve a variety of needs, and use of the ISG enables cost savings in other vehicles systems. Thus, the device may well "sell itself" and not all of its cost need be charged to its fuel economy benefits, although that is the assumption we make here lacking data to support a more sophisticated allocation.

Mass Reduction

A moderate degree of mass reduction can be obtained at no cost increase, with possibly even cost savings, by means of ongoing improvements in conventional design. For example, AISI (1998a, b) identifies steel assembly refinements yielding up to 20% body mass reductions depending on body type, along with improvements in crashworthiness and other structural performance metrics, at small net cost savings by using "ultralight steel" techniques. Similar or greater mass reductions have been identified for closures and chassis parts. For aluminum and plastics, cost-targeted component and product development strategies routinely yield lower-mass designs that cost less than older designs they replace. In general, ongoing materials and fabrication developments allow automakers to choose the best materials — from various metals and plastics — for a given application. Moreover, new applications are designed to meet targets including cost constraints combined with structural performance objectives. As noted earlier, a key issue for all such mass-saving refinements is how they are applied. We assume that the first 15% of mass reduction in our scenarios will have no net impact on vehicle price. In fact, if higher fuel economy targets serve to put a brake on the current upsizing trends, they might even help hold down overall costs.

For greater degrees of mass reduction, cost premiums are associated with the greater degree of material substitution. We assume an incremental RPE of $1.00/lb for mass reduction beyond 15% of each vehicle's baseline curb weight. This cost level is based on the "Materials Substitute III" cost assumption of EIA (2000b). It is slightly lower than the $1.12/lb estimate implied by EEA (1998c) for a high-volume aluminum spaceframe structure compared to a steel unibody.[13] Higher estimates for aluminum designs have been given, e.g., about $1,200 for a midsize car body.[14] However, further development of aluminum-optimized forming and assembly techniques is expected to cut the cost penalties compared to 1990s aluminum research designs on which current published estimates are based. For the advanced sport wagon, we estimate a materials price penalty of $1,080 compared to a vehicle built with current steel technology (see Appendix B). This cost is consistent with a halving of late 1990s estimates by the 2010–15 time frame we assume for our analysis. While we assume the level of mass reduction identified for aluminum-intensive vehicles, other mass-saving design approaches (combining various advanced materials and fabrication techniques) are likely to be available as well.

Hybrid Drive

The cost factors we use for hybrid vehicles are derived largely from EEA (1998b) and Delucchi (1999). Because the systems are so new and not just an evolution of conventional technology, costs are highly uncertain. While our estimates for other technologies reflect full-scale, mature costs, the estimates for HEV components may not reflect all of the opportunities for long-term cost reduction. As explained in Appendix B, our estimated price increases for full hybrid systems range from $3,700 for the small car to $5,000 for the pickup truck and performance SUV. This small car estimate is somewhat lower than the EEA (1998b) "Future 2005" estimate of $3,960 for a Prius-like hybrid system. For mild hybrids, the incremental price estimates range from $2,500 to $3,000. These values are only for the electric drive components (motors, power electronics, and power batteries); including Advanced Package technologies pushes net incremental prices to $3,100–4,500 for mild HEVs and $4,300–6,500 for full HEVs, depending on vehicle class.

The prospects for even lower HEV technology costs are good for motors and controllers, less so for batteries. Firms such as Lynx Mobility are developing highly integrated, modular motor systems with controllers packaged directly onto the device, promising to greatly cut the costs of such components. On the other hand, the HEV technology cost levels we use assume high-volume (200,000 unit) production, and while some of our scenarios involve HEV volumes of that level, it is not clear that our roughly one-decade time frame would suffice for manufacturers to actually gain the cost-reduction experience needed, since these components are still so new for the automotive sector. For HEV batteries, the NiMH technology that we assume is fairly well understood; other advanced battery technologies such as lithium still appear to have high costs and may not be competitive within the next decade (Anderman, Kalhammer, and MacArthur 2000).

Since the HEVs are assumed to be built on advanced, low-mass platforms chosen to narrow the mass distribution of the fleet, it is possible that very high degrees of scale economy and design modularity might be achieved for the common components of hybrid electric drivetrains. Thus, the narrowing of the fleet mass distribution that we posit for safety reasons may well have manufacturing cost-saving benefits as well, as firms will need to make fewer variants of major components. This modularization will also be fostered by the fact that the HEV powertrain will be fully electronically controlled, allowing designers to achieve different kinds of driving performance simply by changing the software.

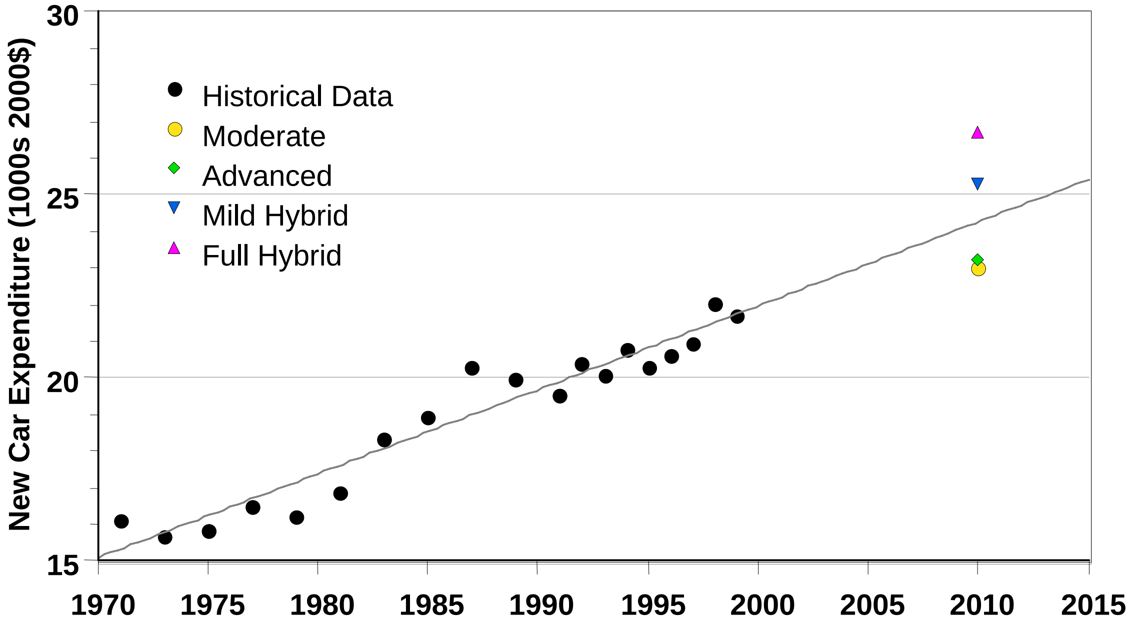
Note that while hybrid drive appears costly compared to conventional technology, its price impacts are within the range of trimline variations, particularly for light trucks. For example, the spread in 2000 MSRP for Ford Explorers is $14,000, from $20,495 for a 2-door, 2wd version to $34,900 for a fully loaded, 4-door, 4wd Limited Edition. Thus, if ways can be found to create appealing customer options packages with hybrid drive, it can pass the broader type of value test needed for marketability. Another way to look at this issue is that not all of the cost of a hybrid powertrain should be allocated to the fuel economy benefit, given the other types of benefits (smoothness, quiet, and high onboard electrical capacity) the technology can provide. Of course, HEVs are already on the market and more are announced; we therefore include them in our aggregate vehicle mixes even though modeling how many and what kinds of HEVs are likely to enter the market is not feasible here.

Overall Package Costs

The resulting cost estimates for each of our technology packages are given as the total lines in Table 7. Rounded to the nearest $100, our Moderate Package costs $900–1,500 depending on the type of vehicle. The Advanced Package costs $1,100–2,500, with the high-end cost being that of the large advanced sport wagon using more expensive materials. Costs jump further for hybrid drive, with mild HEV systems adding $3,100–4,500 to vehicle price depending on size class, and full HEVs adding $4,300–6,500.

Before examining formal metrics of cost-effectiveness, it is useful to put these price impacts in perspective. Figure 4 plots the past 30 years' trend in new car price, adjusted to constant 2000$. The trend is fairly linear (with apparent business cycle effects) and reflects increases in content for both customer features and regulatory requirements as well as evolving consumer income and spending patterns. Following this trend suggests an increase of $2,300, to $24,300 (2000$) by 2010, nearly 11% over the 2000 level of $22,000. Thus, the price impacts of our technology packages seem likely to be readily accommodated from an affordability perspective. Shown on the plot are the average of our small and midsize car price estimates for our four technology packages. The $300 difference between our Moderate and Advanced Packages is "in the noise" over the long-term trend, and their implication of an average 6% price increase falls 5% below the trend for 2010. Estimated hybrid car price impacts are above the 2010 trend, by 6% for a mild hybrid and 14% for a full hybrid. The mild hybrid would be essentially right on the trend for 2015. These are, of course substantial price impacts, but as noted earlier they still fall within the range of trimline variability. Thus, for HEVs, a key question is how well the technology can be "option-packaged" in ways that deliver an overall value falling within consumers' willingness to pay for features. On the other hand, the evolved conventional fuel economy improvement packages leave ample room for other costs without getting out of line with observed vehicle pricing trends.

Figure 4. Prices of Improved Cars vs. Average New Car Price Trend



Source: Historical statistics from Ward's (2000b, p. 65) inflated to 2000$ using CPI-U; trend fit is: Price (2000$) = $15,130 + ($229/yr)(Year - 1970)

COST-EFFECTIVENESS

The costs estimates can be combined with estimates of fuel and CO_2 savings to indicate the cost-effectiveness of the technology improvements for higher fuel economy. We do not attempt a full economic analysis, which would consider various other factors. In general, however, the larger analysis would still be dominated by the fundamental issues of technology cost and fuel savings (Greene and Duleep 1993). Table 8 summarizes the results in comparison to baseline vehicle prices and fuel economy.

The Moderate and Advanced Packages both have modest price impacts. It is important, however, to keep in mind our underlying premise of constant performance and optimal application of technological capability to improve fuel economy. That circumstance has not been an outcome of an unregulated market, which has a vast capacity to absorb technological progress to provide customer amenities other than fuel economy. A different cost picture could emerge as one folds in various assumptions about market acceptance or the opportunity costs of foregoing amenities that might otherwise command the attention of product designers. Thus, our estimates are best interpreted as representing the price impacts that might be seen if a determined, and most probably policy-guided, effort were made to raise fuel economy to address the public concerns about transportation energy consumption.

That being said, the fuel economy improvement achievable by pushing conventional technology forward is a very cost-effective means of cutting fuel consumption and CO_2 emissions. Simple paybacks range 3.4–5.9 years for the Moderate Package and 3.9–6.3 years for the Advanced Package. The pickup truck has the longest payback time since it has the lowest relative fuel economy improvement as explained above. Simple payback times can exceed vehicle lifetimes for HEVs, 7–10 years for mild hybrids, and 9–13 years for full hybrids.

Table 8. Summary of Fuel Economy, Cost, and CO_2 Emissions by Vehicle Type

Baseline	**Base Cavalier**	**Taurus SE**	**Silverado 1500 2wd**	**Grand Caravan**	**Explorer OHV V6**	**Explorer DOHC V6**
Model Year 2000 MSRP	$14,380	$19,535	$23,334	$33,065	$29,915	$34,470
CAFE fuel economy, mpg	30.8	26.2	21.0	22.3	20.3	20.4
CO_2 emissions rate, g/km	178	209	260	245	270	269
Moderate Package	**Small Car**	**Mid. Car**	**Pickup**	**Minivan**	**Std SUV**	**Perf SUV**
Price Increase, 2000$	$944	$1,036	$1,515	$1,500	$1,395	$1,485
CAFE fuel economy, mpg	43.7	40.8	28.7	34.5	34.6	31.0
CO_2 emissions rate, g/km	125	134	191	159	158	176
Annual fuel cost savings	$195	$277	$257	$320	$413	$341
Simple payback, years	4.9	3.7	5.9	4.7	3.4	4.4
Cost of conserved energy, $/gal	0.74	0.57	0.90	0.71	0.51	0.66
Cost of avoided carbon, $/tonne	(109)	(179)	(43)	(119)	(202)	(141)
Advanced Package	**Small Car**	**Mid. Car**	**Pickup**	**Minivan**	**Std SUV**	**Adv SUV**
Price Increase, 2000$	$1,125	$1,292	$2,291	$2,134	$2,087	$2,458
CAFE fuel economy, mpg	48.4	45.8	33.8	41.3	40.1	44.0
CO_2 emissions rate, g/km	113	119	162	132	136	124
Annual fuel cost savings	$240	$331	$364	$416	$493	$534
Simple payback, years	4.7	3.9	6.3	5.1	4.2	4.6
Cost of conserved energy, $/gal	0.71	0.60	0.96	0.78	0.64	0.70
Cost of avoided carbon, $/tonne	(119)	(169)	(17)	(92)	(148)	(125)
Mild Hybrid	**Small Car**	**Mid. Car**	**Pickup**	**Minivan**	**Std SUV**	**Perf SUV**
Price Increase, 2000$	$3,118	$3,522	$4,547	$4,169	$4,002	$4,343
CAFE fuel economy, mpg	56.3	52.6	39.2	48.4	47.4	42.5
CO_2 emissions rate, g/km	97	104	140	113	115	129
Annual fuel cost savings	$299	$388	$446	$488	$571	$519
Simple payback, years	10.4	9.1	10.2	8.5	7.0	8.4
Cost of conserved energy, $/gal	1.59	1.38	1.55	1.30	1.07	1.28
Cost of avoided carbon, $/tonne	246	159	229	124	29	115
Full Hybrid	**Small Car**	**Mid. Car**	**Pickup**	**Minivan**	**Std SUV**	**Perf SUV**
Price Increase, 2000$	$4,331	$5,089	$6,526	$5,818	$5,472	$6,322
CAFE fuel economy, mpg	63.5	59.3	44.2	54.6	53.4	48.0
CO_2 emissions rate, g/km	86	92	124	100	102	114
Annual fuel cost savings	$339	$431	$504	$536	$620	$573

Simple payback, years	12.8	11.8	12.9	10.8	8.8	11.0
Cost of conserved energy, $/gal	1.95	1.80	1.97	1.65	1.35	1.68
Cost of avoided carbon, $/tonne	394	332	402	271	145	284

Notes

Base MSRP includes destination charge, from *Automotive News Market Data Book* 2000.

Carbon and CO_2 values represent direct emissions only, for gasoline CO_2 emissions factor of 8800 g_{CO2}/gal; tonne refers to metric ton (1000 kg, 2204.6 lb, or 1.102 short tons).

Cost-effectiveness metrics are based on a 5% real "societal" discount rate, 12 year life, 12,000 mile average annual travel, retail and pre-tax gasoline prices of $1.35 and 1.00 per gallon, respectively, and 20% fuel economy shortfall.

However, as noted earlier and elaborated below, one must be wary of too narrow a perspective on HEV costs.

For other indicators of cost-effectiveness, we adopt a societal perspective by considering the fuel saved over the life of the vehicle, rather than just by the first owner, and by using a low discount rate. (We do not attempt to represent consumer decisions regarding fuel savings, and so claim no behavioral meaning for the cost-effectiveness indicators. It is amply clear that fuel economy has been nowhere close to being significantly valued among the myriad factors that capture new car buyers' attention when shopping.) Our amortization of incremental technology costs assumes a 12-year, average 12,000 mi/yr, vehicle lifetime and a 5% real discount rate. Calculated in this manner, the cost of conserved energy for the Moderate and Advanced Packages (ranging roughly 50–90¢/gal) is below the price of gasoline, indicating cost-effectiveness in terms of net aggregate benefits to all consumers over the life of a vehicle. Again, this does not mean to imply that vehicle purchasers themselves would feel economically motivated to demand efficiency improvements of the magnitude and cost identified here.

Carbon Reductions Can Be a Bonus

Table 8 also shows the corresponding CO_2 emissions rates in grams per kilometer (g/km). The numbers are nominal values of direct (not full fuel cycle) emissions based on CO_2 (not carbon) mass and unadjusted EPA test cycle (not in-use) fuel economy. The implied cost of avoided CO_2 emissions is shown in 2000$ per metric tonne, in this case on a carbon mass basis for consistency with climate policy work. These avoided carbon costs are based on the difference between the cost of conserved energy and the pre-tax price of gasoline. The "costs" are negative for the evolved conventional vehicles since fuel savings more than offset technology costs. Thus, society pays for cost-effective fuel savings through higher vehicle prices, and the excess savings are a bonus associated with the CO_2 reductions from reduced fuel use. For the Moderate Package, the net savings to society is $40–200/tonne of avoided carbon emissions; the range is $20–170/tonne for the Advanced Package. In the case of hybrids, there is a net cost for carbon reduction since the cost of conserved energy is higher than the pre-tax price of gasoline. The range is rather broad, from $30/tonne to $400/tonne in some cases, depending on the type of vehicle and type of hybrid.

Hybrids Need a Strategic View

Given the higher technology costs for hybrids, the cost-effectiveness does not appear as good as that of the Moderate and Advanced Packages of conventional technologies. Since we combine technologies into integrated packages, we did not evaluate the marginal cost of HEVs as a step above the advanced case. If we had, the marginal costs would be much higher than what are the average costs of a hybrid powertrain packaged with an underlying advanced design.

As can be seen in Table 8, hybridization cost-effectiveness appears weakest for the small car, a marked contrast with the fact the world's first production hybrids are small cars. The reason is two-fold: (1) there is a fixed-cost component for HEV drive that is comparable in magnitude to the portion of cost that varies with powertrain size; and (2) our modeling indicates a relatively fixed percentage fuel economy benefit for the hybrid drive and so, at the already higher fuel economy of a small car, the amount of fuel saved is smaller than for a large vehicles. But this reasoning neglects many factors that can explain initial targeting of small cars, particularly for low-volume production. One such factor is that the market value of fuel economy varies greatly with segment; in the U.S. market, in fact, *only* the small car segment places a notable value on fuel economy (OSAT 1998). Another factor is that the costs of smaller systems are simply lower, and so lessen the financial impact of initial designs built at low volume to gain experience and establish leadership. Other factors undoubtedly come into play in so complex a decision as introducing such a radical technology in which there is a long-term strategic interest.

Because of the cost and lack of technology maturity, and perhaps the longer-term threat of fuel cells, hybrids seem unlikely to achieve large market shares within the 10–15 year time frame examined here. Yet all automakers have announced further HEV introductions. Beside the new possibilities for appealing packages of customer amenities, this interest in HEVs is motivated by a variety of other reasons (DeCicco 2000):

- Increasing technical capabilities for executing hybrid designs
- Growing customer appreciation for advanced technology and environmental friendliness
- Anticipation of future fuel economy needs due to environmental and resource concerns
- The focus on hybrids under the R&D efforts of the PNGV
- The regulatory push of the California ZEV mandate

Therefore, it would be overly narrow to evaluate the economics of hybrids only on the basis of fuel savings. Clearly, automakers themselves are taking a broader view, and as described below, all of our scenarios include some hybrids.

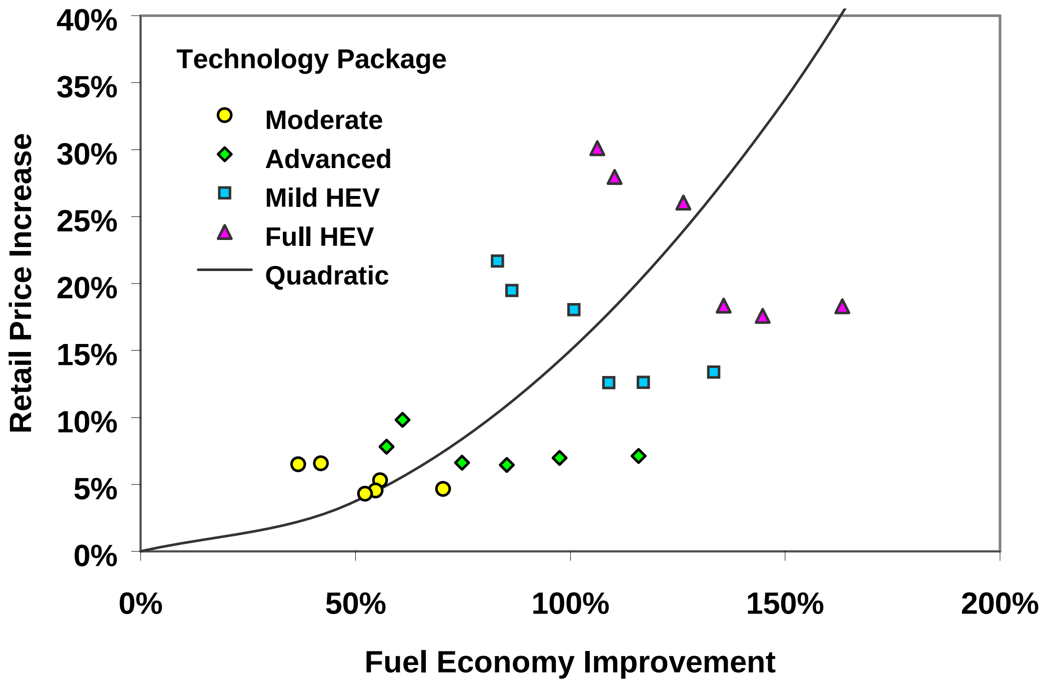
General Cost Picture

The general cost picture that emerges from our analysis is illustrated in Figure 5. This graph plots the estimated percent RPE against the percent fuel economy improvement, with the points marked differently by technology package.

The conventional packages deliver a range of 36–116% efficiency improvements for 4–10% increases in vehicle price. What is striking are the differences in how much fuel economy a given relative price impact will buy; the "value" depends on vehicle type. For example, the performance constraints we placed on the pickup truck make its fuel savings the most costly to achieve. For midsize cars, on which most previous studies have focused either explicitly or implicitly (since midsize class typically matches a fleetwide analysis outcome), the value points (efficiency benefit, price increase) are (56%, 5.3%) for our Moderate Package and (75%, 6.6%) for our Advanced Package. These levels are consistent with past studies (DeCicco & Ross 1993). The Moderate Package’s results compare favorably to the recent MIT "2020" study, which found points of (55%, 4.6%) for a "evolutionary" car (Weiss et al. 2000). However, that study's advanced gasoline vehicle was at (77%, 13%), an efficiency improvement similar to our Advanced Package but at twice the cost since our mass reduction cost estimates are much lower. Although our technology specifications are updated, results for SUVs are consistent with those of Mark (1999), for whom we provided the underlying fuel economy analysis and who used the same simulation model (MEEM) as used here.

Again, the hybrid vehicles (which are built upon advanced platforms using advanced engines) offer improvements of nearly 100% to over 150% (1.8x to 2.6x depending on vehicle type) at price impacts of 13% to 30%, although the uncertainties in these estimates are surely larger than those for the conventional technologies.

Figure 5. Percentage Increases of Price vs. Fuel Economy



Within each technology category, however, one can see similar relative cost patterns, most strongly in the HEV cases. The lower rightmost point of each package group is the standard SUV, which has good opportunities for improvement along with a high baseline vehicle price, implying a low relative cost. In all cases, the two upper leftmost points are the small car, with its low base price, and the pickup truck, with its relatively low potential for fuel economy improvement. In spite of the notable scatter due to these patterns, the cost picture can be coarsely approximated by a simple quadratic:

$$(\Delta P/P) = (0.15)\bullet(\Delta E/E)^2$$

where ΔP is the price increase and ΔE is the fuel economy increase. This curve passes through the (100%, 15%) point so that a doubling of fuel economy can be had for about a 15% increase in price, and the relationship is very roughly quadratic for lower and higher levels.

PROJECTED FLEETWIDE IMPACTS

To translate our model-specific results to project the potential fuel economy levels of the overall light vehicle fleet, we aggregate the estimates according to assumptions about the mix of vehicles by class (small car, large car, minivan, pickup, and SUV). We assume that the relative efficiency improvement found for the representative models (as given in Table 6) can be translated to each class as a whole; for SUVs, we average the improvement levels found for the standard and performance versions. Once new fleet average fuel economy levels are determined, it is straightforward to project the implications for overall light vehicle energy use and greenhouse gas emissions by using a stock model.

This step, of extrapolating technology packages analyzed for specific vehicles to scenarios of fleetwide fuel economy improvement, does interject another level of uncertainty. Ideally, one would either analyze a set of vehicles that characterized the fleet on a finer grid, so to speak (to capture the diversity in existing technology levels and design emphases), or use a fleetwide technology utilization approach (as has been done in previous assessments by ourselves and others, and is commonly used by DOE policy analysts). Such steps are beyond the scope of this study, however, so we rely on our representative vehicles being close to class average in terms of performance and weight as well as fuel economy. The sensitivity to baseline technology level is reflected in our results for the performance vs. standard SUV, but we note that the standard SUV is more representative, and so vehicles having lower performance also exist and would offer an even greater potential for improvement. Also, our conventional technology packages in particular did not incorporate all available low- to moderate-cost technology options. Although further analysis is needed to validate this assumption, we believe the results are sufficiently representative for extrapolation to fleetwide fuel economy potential.

As noted earlier, HEV availability over the coming decade is likely to remain limited by costs and competition from ongoing refinements to conventional powertrains. (However, the opportunity to create appealing new sets of customer amenities coupled with ongoing innovations could enhance the value of HEVs and reduce costs, leading to more extensive deployment.) Our analysis does not have an explicit economic model to justify widespread use of HEVs. We posit one HEV market share case based on the regulatory driver of California's Partial Zero Emission Vehicle (PZEV) credit program, including its likely effects in other states. In this case, we assume that HEVs achieve a 2% share nationwide by 2010–15.[15] We posit a more ambitious case, assuming 6% nationwide share or roughly 1 million new HEVs, based on the possibility that automakers invest heavily in hybrids for strategic and customer value reasons, accelerating technology maturation and cost declines for electrodrive systems.

New Vehicle Fuel Economy

Table 9 summarizes how we determined a set of market shares for aggregating our estimates and then projected new fleet improvements relative to the MY2000 average. For the SUV class, we used the average of results for the standard and high-performance versions to estimate the class average fuel economy potential. This approach lends a degree of conservatism to our results since the MY2000 class average performance index (Z60 time) of 10.9 seconds (s) is closer to the 10.7 s index of the standard Explorer than it is to the 8.9 s index of the high-performance (SOHC base engine) version.

In part (a) of Table 9, the first set of columns give values aggregated from EPA statistics (Heavenrich & Hellman 2000). The second set of columns, headed "Representative Vehicles," gives fuel economy and test weight values of our representative models (from Table A-1) along with "remix" market shares chosen so that the weighted average miles per gallon of the representative models matches the overall MY2000 average of 24.0 mpg. The remix average test weight is 2% higher than the actual MY2000 average and is consistent with a modest further overall shift to light trucks. Our remix has car/truck shares of 49/51%, compared to the actual MY2000 shares of 54/46% according to the EPA statistics.

Part (b) of Table 9 summarizes application of the mass reductions and fuel economy improvements (see Table 6) to the remix given in part (a), yielding average values for the various technology levels. Also shown are the corresponding average test weights. The "Overall" line in Table 9(b) represents fleet mix averages of vehicles from each class improved to a given technology level, with the last line indicating the change relative to the actual MY2000 light duty fleet average. The Moderate Package achieves a 47% improvement in average fuel economy, from 24 to 35 mpg, with an average 12% reduction in test weight (14% average cut in curb weight).

Table 9. Average Fuel Economy by Technology Level

(a) Base year fleet, and remix of representative vehicles that matches average MPG

	MY2000 Statistics				Representative Models		
Class	Sales (Million)	Market Share	Test wt (lb)	MPG	Remix Share	Test wt (lb)	MPG
Small car	3.979	24.8%	3088	30.3	21.8%	3125	30.8
Midsize car	4.654	29.1%	3642	26.5	26.8%	3625	26.2
Van	1.471	9.2%	4326	22.5	10.0%	4500	22.6
Pickup	2.689	16.8%	4464	20.1	18.2%	4750	21.0
SUV	3.221	20.1%	4456	20.0	23.2%	4250	20.7
Overall	16.014	100.0%	3868	24.0	100.0%	3954	24.0

(b) Projected vehicle weight and fuel economy, class averages and overall fleet

	Test Weight (lb)		Fuel Economy (MPG)			
Class	Moderate	Advanced	Moderate	Advanced	Mild Hybrid	Full Hybrid
Small car	3088	2809	43	48	55	62
Midsize car	3308	2974	41	46	53	60
Pickup	3625	3084	28	32	38	42
Van	3521	2997	35	42	49	55
SUV	3631	3090	32	37	44	50
Overall	3414	2988	35	41	47	53
vs. MY2000	***-12%***	***-23%***	***+47%***	***+70%***	***+97%***	***+122%***

The Advanced Package, pushing conventional gasoline powertrain technology toward its limits and invoking substantial mass reduction for the larger classes, achieves a 70% improvement in fleetwide fuel economy, to a new car and light truck fleet average of 41 mpg, with an average reduction of 23% in test weight (26% in curb weight). We do not explicitly consider the advanced sport wagon in the mix; rather, we treat it as an alternative design that achieves a fuel economy level (44 mpg, see Table 6) greater than that of either Advanced Package version of a conventional midsize SUV and even the midsize car. Thus, a mix substituting such vehicles would be more efficient than what is shown here.

Fleet Efficiency, CO_2 Emissions, and Price Impacts

Hypothetical new light vehicle fleets that would be technologically feasible and economically practical in a 2010–2015 time frame can be constructed by combining vehicles of the technology levels identified here. The new fleet scenarios and resulting fuel economy, CO_2 emissions, and average price impact values are listed in Table 10. For simplicity, we incorporate HEVs in our fleet scenarios by assuming average characteristics of mild and full hybrids. The scenarios are as follows:

Table 10. Scenarios of New Fleet Average Fuel Economy

	Scenario			
	A_1	A_2	B	C
Fleet fractions by technology level				
Moderate	98%	94%	47%	0
Advanced	0	0	47%	98%
Average Hybrid	2%	6%	6%	2%
Results				
Fleet fuel economy improvement	51%	52%	62%	72%
New fleet average fuel economy, MPG	36	37	39	41
New fleet average CO_2, g/km	151	149	140	132
Average vehicle price increase (2000$)	$1,311	$1,447	$1,685	$1,807
Average percent vehicle price impact	5.8%	6.5%	7.4%	7.8%
Cost-Effectiveness Indicators				
Annual fuel savings, gallons/vehicle	210	215	240	262
Average simple payback, years	4.6	5.0	5.2	5.1
Cost of conserved energy, $/gallon	0.70	0.76	0.79	0.78
Cost of avoided carbon, $/tonne	(123)	(100)	(87)	(93)

Scenario Definitions:
A_1. Moderate technology level throughout the fleet except HEVs at 2% nationwide market share.
A_2. Moderate technology level throughout the fleet except HEVs at 6% nationwide market share.
B. Even blend of moderate and advanced technology with HEVs at 6% nationwide market share.
C. Advanced technology level throughout the fleet except HEVs at 2% nationwide market share.

Cost-effectiveness indicators assume a 5% real discount rate; 12 year vehicle life; 12,000 mile average annual travel; 20% fuel economy shortfall; retail and pre-tax gasoline prices of $1.35 and $1.00 per gallon, respectively; and a direct carbon emissions factor of 19.2 MMTc/Quad (8.8 kg_{CO2}/gallon).

A_1. Moderate technology level throughout the fleet, except for HEVs achieving 2% nationwide market share as might be driven by the California ZEV program

A_2. Moderate technology level with HEVs achieving 6% nationwide share (1 million new vehicles) as might be seen under a strategic push by automakers

B. Combination of 47% moderate and 47% advanced conventional technology levels with 6% HEV market share

C. Advanced technology level throughout the fleet except 2% HEV market share

Of course, any number of technology combinations might be hypothesized. It is difficult to judge that any particular combination is clearly more "cost-effective" than another since analytically tractable definitions of cost-effectiveness do not capture all of the factors pertinent to a policy decision regarding appropriate automotive fuel economy targets. HEV technologies are the high-cost items in any scenario but have a small market share; thus, for all but the last scenario, identical new fleet averages could be constructed at lower cost with other combinations of improved conventional technologies alone.

The "A" scenarios are based on our Moderate Package, with two levels of HEV penetration given to assess the potential impacts of HEVs on what would otherwise remain a conventional gasoline internal combustion engine fleet. Scenario A_1 provides a 51% increase in new fleet average fuel economy, from 24 to 36 mpg, at a retail price impact of $1,300, or about 5% of average new vehicle price. New fleet average CO_2 emissions are cut by 34%, from 228 to 151 g/km. Scenario A_2 reflects the increased HEV share, adding 1 mpg to the new fleet average. Differencing the price increases of Scenarios A_1 and A_2 indicates that the higher HEV share would cost an average of $136 if spread over the entire new fleet, suggesting that automakers could probably afford to cross-subsidize HEV introductions at this level if they wished. Scenario B essentially represents a 50/50 combination of the Moderate and Advanced Packages with the larger, 6% HEV share assumption. The resulting 39 mpg overall new fleet, a 62% improvement over the 2000 level, would have a price impact of about $1,700. Scenario C is based on the Advanced Package of technologies and pushes the new fleet to 41 mpg, an 72% improvement, with a price impact of about $1,800.

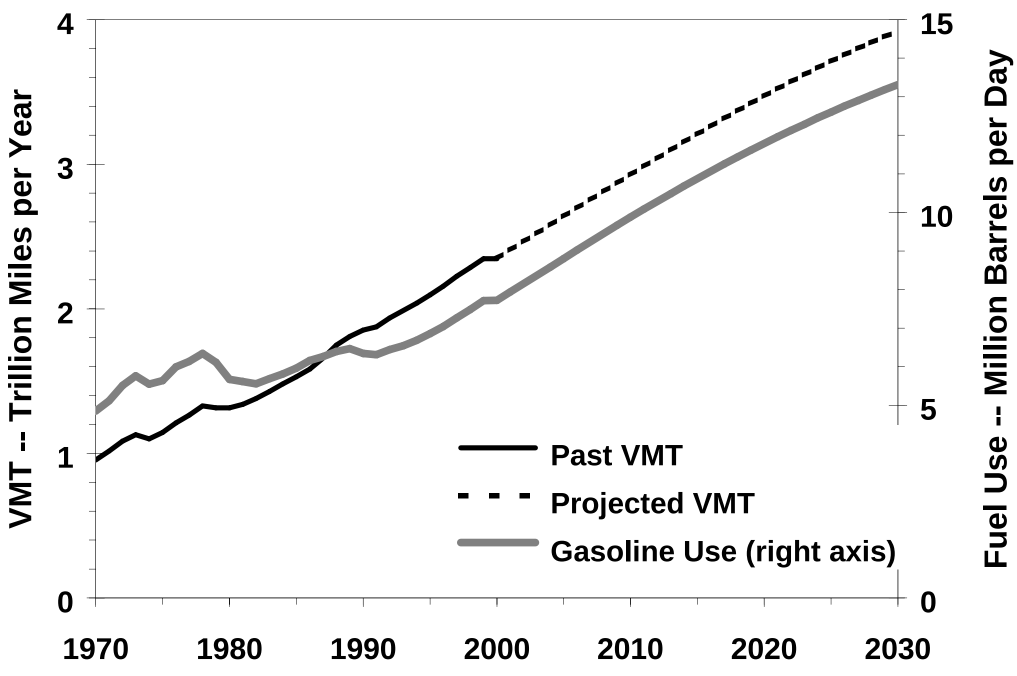
For all three scenarios, the average cost of conserved energy is in the range of 70–80¢/gal (with assumptions of 12-year lifetime and 5% real discount rate). In other words, the new vehicle price increase, amortized over the life of the vehicle per gallon of fuel saved, is less than the average pre-tax price of gasoline (about $1.00/gal) expected through 2015, and well below the expected consumer fuel price (about $1.35/gal according to EIA 2000a).[16] This degree of cost-effectiveness, with lifetime fuel savings more than covering the up-front cost of technology improvements, means that CO_2 reductions are achieved at net savings. Under the economic assumptions made here, these savings are on the order of $100 per metric tonne of greenhouse gases reduction (on a carbon mass basis counting only the direct CO_2 emissions from fuel combustion at the vehicle).

Aggregate Fuel Consumption and CO_2 Emissions

Using the new fleet average fuel economy values developed in Table 10 as input to a stock model yields projections for aggregate nationwide fuel consumption and CO_2 emissions. For context, Figure 6 shows historical vehicle miles of travel (in trillion [10^{12}] miles per year) and light vehicle fuel consumption (in million barrels per day gasoline-equivalent) along with projections assuming no increase in fuel economy from the 24.0 mpg new fleet average in 2000. However, we note that "business-as-usual" is already changing, given the recent commitments by Ford and GM to improve SUV and light truck fuel economy. Nevertheless, we are not in a position to speculate on the extent of such competitively induced fuel economy improvements, which are a striking new development in what has otherwise been a marketplace showing no net interest in higher fuel economy over the past 15 years.

VMT growth averaged 2.5%/yr over 1989–1999, but with the fuel price spike as well as some severe weather in 2000, early statistics show a drop in vehicle travel (by 0.1%) for the first time in 20 years. However, barring an economic downturn, we expect recent travel growth trends to resume. Consistent with EIA (2000a), our projection assumes VMT growth in excess of 2%/yr through 2010 and then tapering off to lower growth as time goes on. Absent increases in fuel economy, light vehicle gasoline consumption will track VMT. This baseline scenario is illustrated by the gray curve, plotted against the right-hand axis, in Figure 6. Overall U.S. car and light truck fuel consumption was 6.3 Mbd (gasoline energy basis) in 1990 and in 1999–2000 is estimated to have reached 7.7 Mbd (this value amounts to 118 billion gallons of gasoline per year).[17] Given the VMT trend and no increase in fuel economy, it would reach nearly 10 Mbd by 2010 and nearly 12 Mbd by 2020.

Figure 6. Past and Projected Nationwide Light Duty VMT and Fuel Use

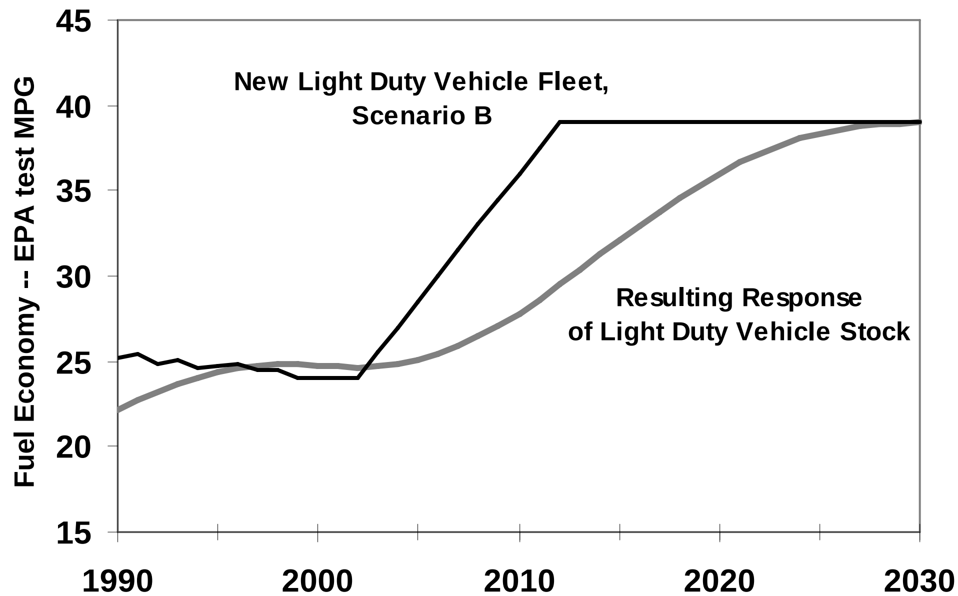


Sources: Historical VMT derived from FHWA Highway Statistics; projections assume 2001 growth of 2.45%/yr ramping down to 2%/yr by 2010, and growth rate continuing a similar decline through 2030. Historical gasoline use derived from ORNL Transportation Energy Data Book, with projections using author's stock model and an assumption of new light duty fuel economy frozen at 24 mpg.

To represent a phase-in of technology improvements to the levels identified here, we assume a linear ramp-up of new fleet average fuel economy between 2002 and 2012. This decade-long time frame is sufficient for both product development and staggered product cycles that would enable automakers to substantially redesign their products.[18] For each scenario, we then hold future new fleet fuel economy constant through the 2030 time horizon modeled. Thus, for our moderate technology case (Scenario A), the 36 mpg level is targeted for 2012; the 2012 level is 39 mpg for the intermediate case (Scenario B), and 41 mpg for the advanced case (Scenario C). Lags in stock turnover result in more than a decade delay before the benefits of new fleet fuel economy improvement permeate the entire vehicle stock (all light vehicles in use, new and used).[19] The response is illustrated in Figure 7 for Scenario B. In this case, 90% of the fuel economy improvement, targeted for the new fleet in 2012, is achieved in the overall stock by 2023, or 11 years later.

The resulting projections for overall U.S. light vehicle fuel consumption under all three scenarios are shown in Figure 8. The post-1990 portion of baseline fuel consumption (as in Figure 6) is shown for comparison. The 1990 level of 6.3 Mbd corresponds to 233 MMTC (direct emissions on a carbon-mass basis). Ramping up fuel economy to the levels we identify as technically feasible and affordable would not only control what has been steady growth in car and light truck fuel consumption, but within a few years begin to turn it around. Our Moderate Package justifies a 4%/yr improvement in fuel economy over the coming decade or so, enough to counter balance expected VMT growth in the 2%/yr range. Nationwide gasoline savings reach 1 Mbd by 2010 and rapidly compound to over 2 Mbd by 2015. In light of the recent gasoline price volatilities (due to both oil cartel action and tight refining capacity), such cuts in gasoline demand would have a substantial dual benefit of both direct consumer fuel savings and a dampening effect on fuel prices. Greater savings accrue for the more ambitious scenarios, approaching 4 Mbd by 2020 for Scenario C. In contrast to investments in oil fields, which have a finite lifetime, investments in fuel economy technology create a permanent shift in the demand structure, although the full dividends, so to speak, are not realized for over a decade due to the stock replacement lag.

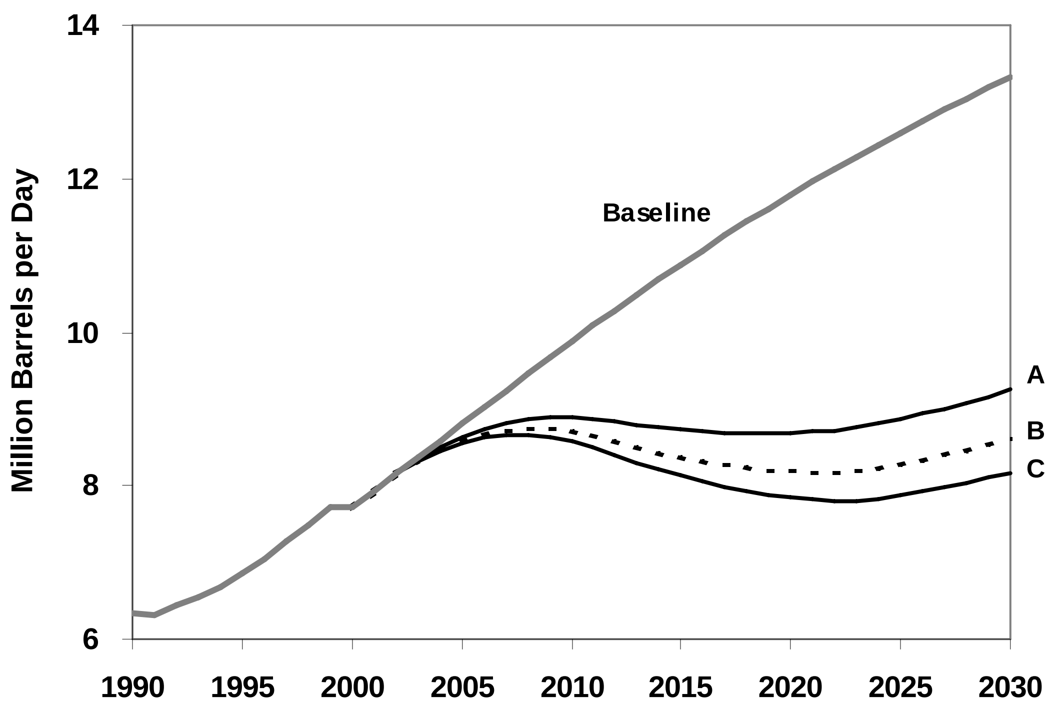
Figure 7. Response of the Light Duty Vehicle Stock to an Increase in New Fleet Fuel Economy



Sources: New fleet (EPA composite test MPG) uses historical statistics through 2000 from Heavenrich & Hellman (2000), then Scenario B, with new fleet fuel economy increasing starting in 2003 and reaching 39 mpg by 2012. Vehicle stock fuel economy values, including quasi-historical 1990-2000 values, are derived from stock model.

Because all of our scenarios examine only the effects of improving the fleet to the designated technology-based levels, none suffice to return light vehicle fuel consumption or CO_2 emissions to their 1990 values. Scenario C, relying on the Advanced Package, comes close to returning things to the 2000 level (7.7. Mbd, or 284 MMTc, about 22% higher than in 1990), pulling CO_2 emissions down to 287 MMTc by 2022 before they turn upward again. In all cases, consumption begins to rise again once fuel economy improvements fully permeate the stock. With fuel efficiency again stagnating, VMT growth is no longer offset. While the scenarios given here do start to control fuel consumption and CO_2 emissions, even more advanced technologies are clearly needed. Also needed, of course, are effective means to control VMT growth and shift to low-net-carbon or renewable fuels that would reduce CO_2 emissions per unit of fuel consumed.

Figure 8. U.S. Light Vehicle Fuel Consumption by Technology Scenario



Scenarios (refer to Table 11):

Baseline assumes fuel economy fixed at 24 mpg. Scenarios represent new fleet fuel economy increases to (A) 36 mpg, (B) 39 mpg, and (C) 41 mpg by 2012, and frozen thereafter.

N.B. Direct carbon emissions may be estimated using the factor 36.8 MMTc per Mbd. The 1990 level corresponds to 6.3 Mbd, or 233 MMTc.

CONCLUSION

Examining the technical options for improving automotive fuel economy reveals a rich and growing set of measures that automakers could use to redesign their vehicles with efficiency in mind. We combined options for improving the vehicle structure, engine, and transmission, plus emerging technologies such as the integrated starter generator and hybrid electric drive, into design packages applicable to representative vehicles spanning the U.S. light duty fleet. Engineering simulation was used to calculate the fuel economy achievable through such redesign. The resulting benefits varied by vehicle type, but overall demonstrate a capability to affordably improve average U.S. car and light truck fuel economy by 50–70% over the coming decade. The technology packages would add 6–8% to average vehicle price, but the fuel economy increases are cost-effective if viewed from a societal perspective over a vehicle lifetime.

Hybrid electric drive is among the options incorporated into our analysis, but it is more costly than the other measures and we assumed that its market share would remain limited (2–6%) over the 10–15 year horizon we examine. Most of improvement we identify comes from ongoing refinements of conventional technology, provided those refinements can be directed toward saving fuel rather than further increasing power performance, capacity, and other amenities. Not included in our analysis are diesel or lean-burn engines, which still face emissions issues; if clean-enough versions became available, even higher fuel economy levels could be achieved. Reducing weight (through materials substitution and improved packaging without downsizing) is an important option, but how it is done across the fleet has implications for safety. We assumed weight reduction targeted toward the heaviest vehicles to improve the crash compatibility of the fleet and thereby enhance overall safety. Further work is needed to specify the policy guidance suitable for motivating the joint safety-efficiency redesign strategy that we identify.

Table 11. Nationwide Fuel Saving and Carbon Reduction Projections

	Baseline 24 mpg	**Scenario A** 36 mpg by 2012		**Scenario B** 39 mpg by 2012		**Scenario C** 41 mpg by 2012	
Gasoline (Mbd)	Use	Use	(Save)	Use	(Save)	Use	(Save)
1990	6.3						
2000	7.7						
2010	9.9	8.9	(1.0)	8.7	(1.2)	8.6	(1.3)
2015	10.9	8.7	(2.1)	8.4	(2.5)	8.1	(2.7)
2020	11.8	8.7	(3.1)	8.2	(3.6)	7.8	(3.9)
Carbon (MMTc/yr)							
1990	233						
2000	284						
2010	363	327	(36)	320	(43)	315	(48)
2015	400	321	(79)	308	(92)	299	(101)
2020	434	320	(114)	301	(133)	289	(145)

Source: Author's stock model projections for new light vehicle fleet fuel economy improvement scenarios starting in 2003 and reaching target levels by 2012, then fixed thereafter. Baseline is frozen at 24 mpg.

Fuel use and savings are given in million barrels gasoline per day (Mbd) gasoline energy-equivalent.
Carbon emissions and reductions are in million metric tonnes per year (MMTc/yr) carbon-equivalent, counting only the direct CO_2 emissions from fuel combustion at the vehicle.

A question facing policy makers is the extent to which these technical capabilities can be tapped to address the persistent concerns associated with transportation energy use. The direct costs are low, but it is clear that the market does not pull these capabilities into the fleet in ways that improve fuel economy. Thus, the remaining challenge is one of providing the policy direction and leadership needed to harness this substantial technical ability in ways that improve the fuel economy of cars and light trucks in the marketplace.

ENDNOTES

[1] Unless otherwise noted, fuel economy values cited here are composite miles per gallon, 55% city, 45% highway average of EPA unadjusted test values; light duty vehicles comprise passenger cars and light trucks of up to 8,500 lb gross vehicle weight. Fleet statistics cited throughout the report are from Heavenrich & Hellman (2000).

[2] As of 1999, Ford and GM light trucks comprised 26.3% of the U.S. light vehicle market with an average fuel economy of 20.5 mpg. Improving the miles per gallon of this light truck population by 25% implies a 6.6% increase in overall light duty vehicle miles per gallon provided that it is accomplished without a further shift from cars to light trucks. Note that such an improvement is beyond the letter of Ford's promise. On the other hand, the impact could be larger if these pledges stimulate competitive improvements in other automakers' light truck fleets.

[3] Chapter 9 of Ross & Williams (1981), "Toward the 60-MPG Car," identified technical changes for boosting vehicle efficiency, following principles that still apply even though the specific technology set has evolved considerably.

[4] See Greene & DeCicco (2000) for an in-depth discussion of the approaches that can be taken and the associated methodological issues.

[5] *Compatibility* in the context of auto safety refers to how vehicles of differing designs interact in a two-vehicle collision. Elements of compatibility include the differing velocity changes related to differences in mass, structural effects related to the relative rigidity and energy absorption characteristics of colliding parts of the structure, and geometric effects related to where occupants are positioned and where parts of one structure strike another. It is a complex and challenging area of automotive engineering, but addressing compatibility offers important opportunities to improve safety (Vander Lugt, Connolly, & Bhalsod 1999). A broader view of compatibility would include all possible crash interactions of a vehicle (e.g., including pedestrians and cyclists).

[6] "Very stringent" refers to levels such as the California SULEV standard and low bins of the Federal Tier 2 regulations.

[7] See Neff (1999) and BorgWarner (2000).

[8] Average new light duty fleet test weight rose 20%, from 3,220 lb to 3,868 lb, from 1987 to 2000 (Heavenrich & Hellman 2000), implying a 22% increase in curb weight.

[9] DeCicco (1998) reviews trends in automotive materials use and issues associated with opportunities for mass reduction.

[10] Through the Partnership for a New Generation of Vehicles (PNGV) and in their own proprietary work, U.S. automakers have reported research and shown design concepts targeting a 40% curb weight reduction for the entire vehicle system — body as well as chassis, powertrain, and interior components. Different companies have used different materials emphases, but all have expressed determination to reach these mass reduction (and other streamlining and efficient accessory) goals at low cost. DaimlerChrylser in particular has stated the intent to achieve the mass reduction targets at eventual cost savings in order to offset the inherently higher costs of a hybrid powertrain, and has shown a series of prototypes with steadily declining cost increments, with the expectation that the lightweight designs would be made affordable by 2003. Ford has reported mass breakdowns for separate vehicle systems that tally to a 40% reduction overall for its P2000 concept series.

[11] Derived from statistics reported in IWG (1997, 5.8).

[12] EIA (2000b) assumes an incremental cost of $325 (RPE, 1990$) for a 5-speed automatic. However, based on Lindgren & Jones (1990), the total cost of a 4-speed automatic for a midsize car is $650 (RPE, 1989$). We find it implausible that the incremental cost of adding a gear should cost half as much again as an entire base transmission. Consistently with the new information about cost-saving designs for 6-speed automatics, we therefore assume zero cost impact for improved conventional transmissions, provided that the changes are made in the context of retooling for normal product cycles at high-volume production levels.

[13] EEA (1998c) developed a range of cost estimates for compact vehicle bodies; for a 200,000 unit/yr production level, it found that an aluminum space frame would be less costly than an aluminum unibody for a similar (40%) level of mass reduction, with an incremental manufacturing cost level of $1.23/kg; doubling that to reflect consumer price impact yields $2.46/kg or 1.12/lb.

[14] Sylvan (1995) estimated a cost increase of $500 for a vehicle combining the best, then-current auto aluminum applications; Politis (1995) estimated a $650 increase based on modeling various car bodies. Both of these estimates were for manufacturing costs, so doubling them yields a $1,000–1,300 RPE range. Stodolosky, Vyas, and Cuenca (1995) estimated $1,200 incremental price impact for an aluminum-intensive vehicle (AIV) achieving a 33% overall curb weight reduction, based on early 1990s Ford AIV work; however, significant refinements in terms of both further weight reduction and manufacturing optimization have been since reported (Cornille, Weishaar, and Young 1998). Aluminum costs about 5x steel per unit mass; typical prices of $0.30 for steel and $1.50 for aluminum and a 50% mass savings for simple substitution imply a penalty of $0.90 per pound saved. Aluminum companies and automakers are working on techniques to enable designs that would be competitive and cost-effective for aluminum-intensive vehicles; see Aluminum Association (1999).

[15] Hwang (2001) estimates California-only sales of roughly 100,000 HEVs per year based on credit requirements of the ZEV mandate by 2013. Given related requirements in Northeastern states and a likely sharing of some production elsewhere, we triple this estimate, implying 300,000 HEVs nationwide, or about 2% of a 17 million unit national light vehicle market.

[16] EIA (2000a), Table A12, foresees little change in average retail gasoline prices, with projections rising to $1.36/gal by 2010 and falling to $1.33/gal by 2020 (1999$), based on average world oil prices not exceeding $22 billion barrels over this period.

[17] A 7.71 Mbd value for 1999 light vehicle consumption results from our stock model, which is calibrated to 1990 estimates for car and light truck (under 8,500 lb gross vehicle weight) stock; this value closely matches the 1999 estimate of 7.76 Mbd from EIA (2000a), Table A7. Although preliminary FHWA statistics (see March 7, 2001 posting on www.fhwa.dot.gov/ohim/) indicate a 0.1% drop in VMT from 1999–2000, news reports based on API statistics indicate a slight rise (but well below recent trends) in gasoline consumption, consistent with stock fuel economy falling due to the ongoing permeation of the car-to-truck shift. Our model shows a 0.2% rise in light duty vehicle gasoline consumption in 1999–2000; a better picture will emerge as final statistics are reported (FHWA highway statistics are typically finalized in the fall of the following year).

[18] See the review of automaker product cycles in DeCicco and Ross (1993, pp. 46–50); if anything, competitive product cycles are likely to have shortened somewhat since the late 1980s through early 1990s experience reviewed there.

[19] The stock model incorporates recently updated statistics on the lengthening life of the U.S. vehicle stock as reported in Davis (2000). The model treats the light duty fleet in aggregate, using an average of car and light truck scrappage rates; its fuel consumption projections also assume a 10% "rebound" effect (see Greene 1992).

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APPENDIX A: DETAILS OF MODELING ANALYSIS

This appendix provides a general description of the vehicle simulation model used to conduct our analysis. It includes tables providing more detailed output than given in the summary tables of the main text. Tables A-1 through A-3 list vehicle parameters and simulation results for our main conventional technology cases. Table A-4 summarizes predicted technical efficiency levels for the transmission, engine, and overall powertrain. Table A-5 lists the predicted fuel economy and incremental gains for individual technology measures used in our redesign packages.

Modal Energy and Emission Model (MEEM)

The Modal Energy and Emissions Model (MEEM) is a physical, power-demand model based on a parameterized analytical representation of fuel consumption and emissions production. In this model, the emission process is broken down into different components or modules that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary based on several factors, such as vehicle/technology type, fuel delivery system, emission control technology, vehicle age, etc. Because these parameters typically correspond to physical values, many of the parameters are stated as specifications by the vehicle manufacturers, and are readily available (e.g., vehicle mass, engine size, aerodynamic drag coefficient, etc.). Other key parameters relating to vehicle operation and emissions production must be determined from a testing program, described in the model calibration procedure (see NCHRP 2001).

The complete modal energy and emissions model is composed of six modules, as indicated by the six square boxes in Figure A-1: 1) engine power demand; 2) engine speed; 3) fuel/air ratio; 4) fuel-rate; 5) engine-out emissions; and 6) catalyst pass fraction. The model as a whole requires two groups of input, indicated by the rounded boxes in Figure A-1: A) input operating variables; and B) model parameters. The output of the model is tailpipe emissions and fuel consumption.

There are also four operating conditions in the model, shown by the ovals in Figure A-1: (a) variable soak time start; (b) stoichiometric operation; (c) enrichment; and (d) enleanment. Hot-stabilized vehicle operation encompasses conditions (b) through (d); the model determines in which condition the vehicle is operating at a given moment by comparing the vehicle power demand with two power demand thresholds. For example, when the vehicle power demand exceeds a power enrichment threshold, the operating condition is switched from stoichiometric to enrichment. The model does not inherently determine variable soak time; rather, the user (or integrated transportation model) must specify the time the vehicle has been stopped prior to being started. The model does determine when the operating condition switches from a cold start condition to fully warmed-up operation. Figure A-1 also shows that the operating conditions have direct impacts on fuel/air ratio, engine-out emissions, and catalyst pass fractions.

The vehicle power demand (1) is determined based on operating variables (A) and specific vehicle parameters (B). All other modules require the input of additional vehicle parameters determined based on dynamometer measurements, as well as the engine power demand calculated by the model.

The fuel/air equivalence ratio, ϕ, is approximated only as a function of power, and is modeled separately in each of the four operating conditions (a) through (d). (ϕ is the ratio of the stoichiometric air/fuel mass ratio [14.7 for gasoline] to the instantaneous air/fuel mass ratio.) The core of the model is the fuel rate calculation (4). It is a function of power demand (1), engine speed (2), and fuel/air ratio (3). Engine speed is determined based on vehicle velocity, gear shift schedule and power demand.

MEEM development was originally funded between 1994 and 1998 by the National Cooperative Highway Research Program (NCHRP) Project 25-11, "Development of a Comprehensive Modal Emissions Model," at the University of California, Riverside, and the University of Michigan (NCHRP 2001). Argonne National Laboratory (ANL) has supported continuing development of MEEM. To assist in the model development, more than 350 in-use vehicles, ranging from early model year small cars to recent model year SUVs, as well as some medium-sized diesel trucks, were recruited. Testing of the vehicles was conducted in the University of California, Riverside Emission Laboratory, with a single-roll, 48-inch dynamometer over the FTP, US06, and a specially designed Modal Emissions Cycle (MEC01). The model was then calibrated against these tested vehicles on a second-by-second basis. Since MEEM is a physical model, it does not use steady-state engine performance maps; thus, adjustments for engine size, enrichment, and other technological improvements can be readily achieved.

For the purposes of this fuel economy study, we mainly use the fuel consumption estimates produced by the model. As shown in Table A-1, modeled CAFE values match certification test values within 0.4 mpg (±2%) for the representative vehicles. Since we are assuming stoichiometrically operated gasoline engines with advanced (Tier II / LEV II) emissions control systems and catalysts, emissions predictions are not of concern here; there are no barriers to such vehicles meeting applicable standards.

The model has been used to generate simulated engine performance maps for more traditional engine-map based simulation models such as NREL's ADVISOR and ANL's PSAT (PNGV System Analytic Toolkits) (An, 2001a). Some modeling comparisons between MEEM and ADVISOR are given by reference (An et al. 2001). To improve PSAT modeling capability, MEEM has also been integrated into PSAT (An and Rousseau 2001). Figures A-2 and A-3 show two engine maps generated by MEEM. As described in the main text (Technology Assessment, Powertrain Efficiency section), these maps illustrate some of the key efficiency improvements underpinning our results and how we obtained them. Tables A-2 and A-3 list our Moderate and Advanced technology package modeling results for the representative vehicles.

Figure A-1. Modal Energy and Emissions Model Structure

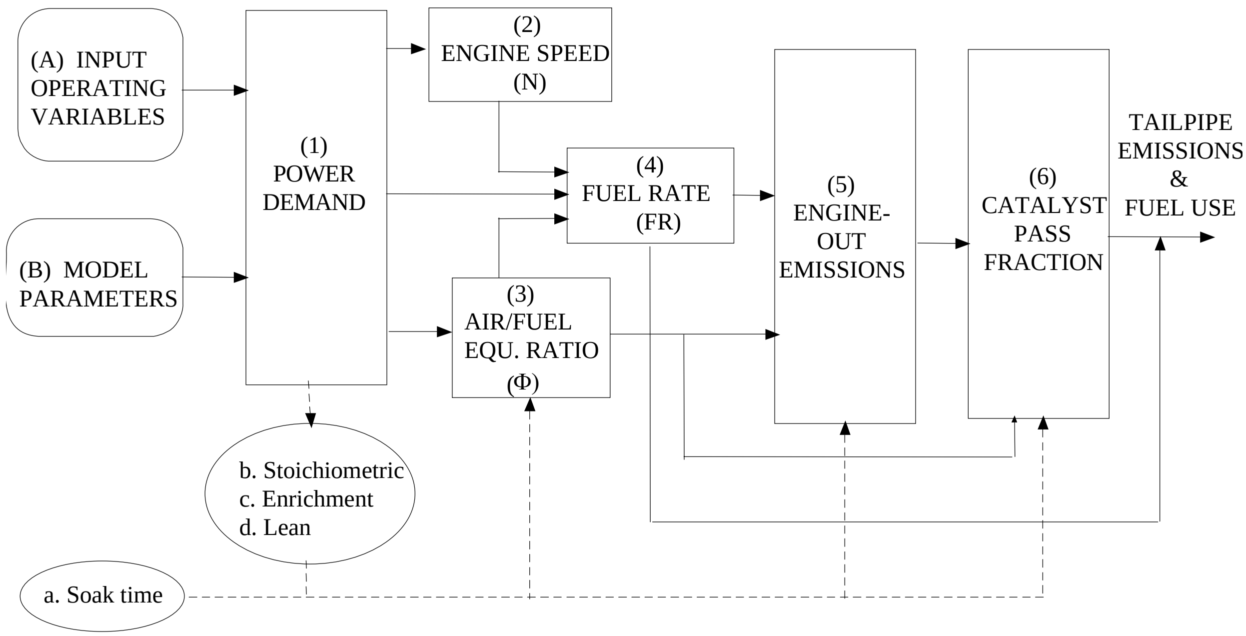

Figure A-2. Baseline Taurus Engine Map as Generated by MEEM (brake-specific fuel consumption [bsfc] contours in g/kWh)

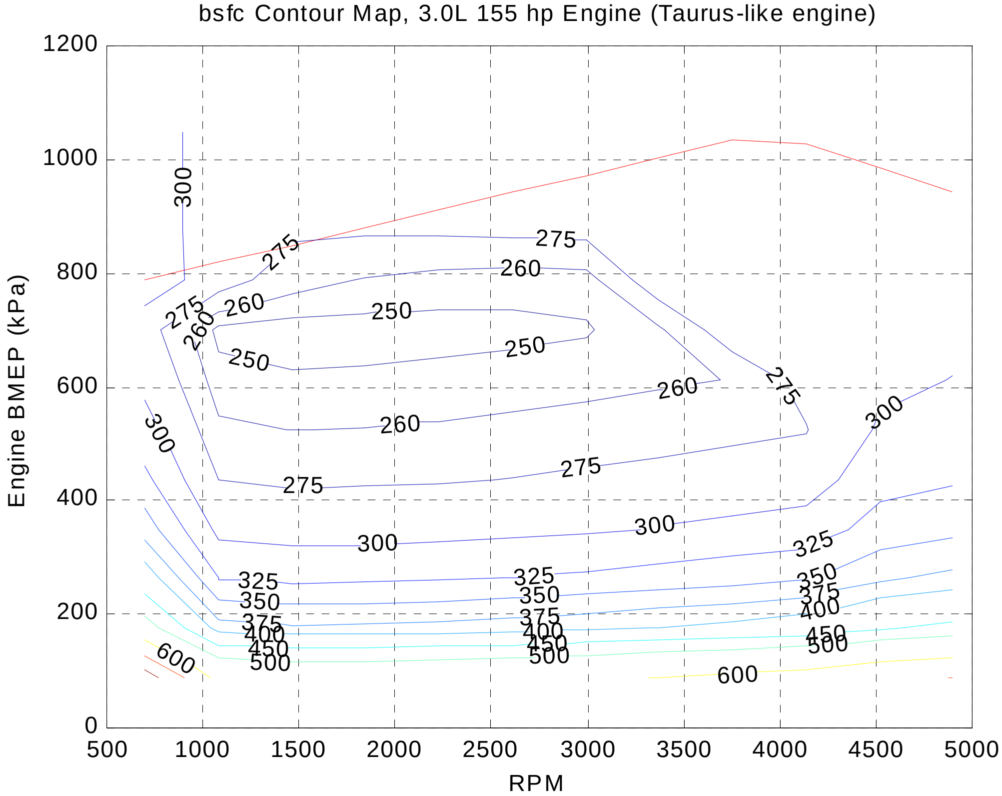

Figure A-3. Map for a Variable Valve Control Engine as Generated by MEEM (brake-specific fuel consumption [bsfc] contours in g/kWh)

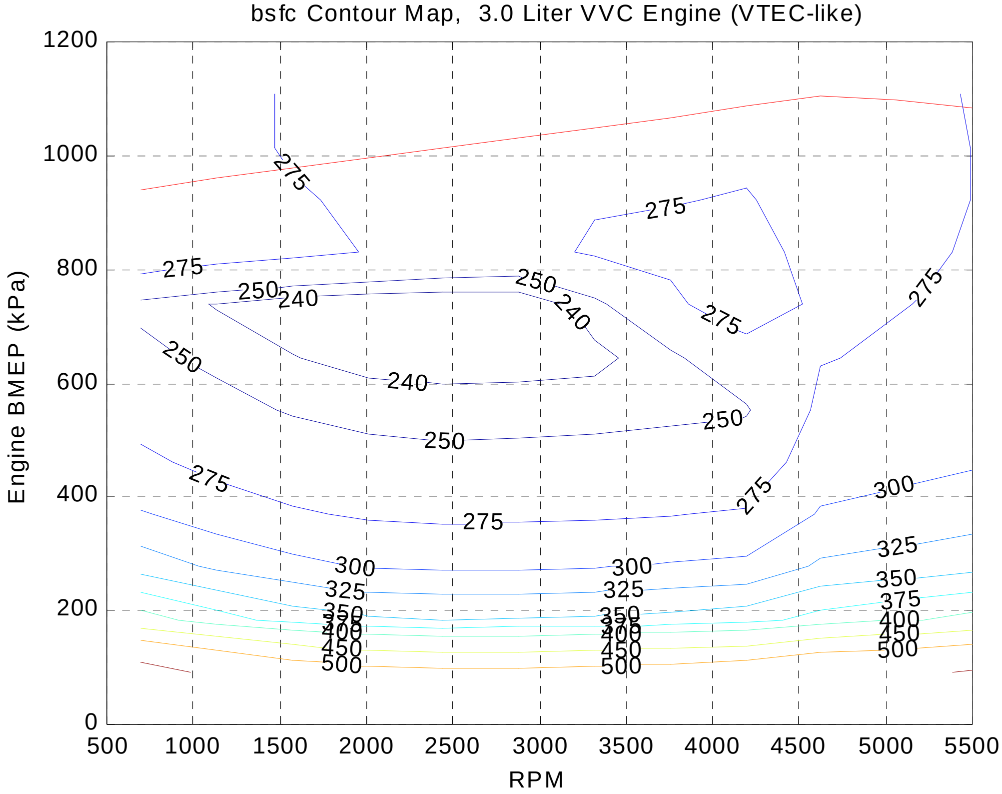

Table A-1. Baseline Vehicle/Engine Characteristics and Model Calibration Parameters

Table A-2. Moderate Technology Package: Vehicle/Engine Characteristics and Results

Table A-3. Advanced Technology Package: Vehicle/Engine Characteristics and Results

Table A-4. Modeled Energy Efficiencies by Vehicle Type and Technology Package

Vehicle Type / Technology Package	Average Engine RPM	Efficiencies: Trans-mission	Efficiencies: Engine Part-Load	Efficiencies: Engine Peak	Efficiencies: Overall Powertrain	Powertrain Efficiency Gain
Small Car						
Baseline	1700	79.2%	67.8%	34.9%	18.5%	—
Moderate	1608	83.5%	73.5%	35.6%	20.8%	12%
Advanced	1610	83.5%	76.2%	36.1%	21.3%	15%
Midsize Car						
Baseline	1675	79.2%	62.5%	34.3%	16.7%	—
Moderate	1603	83.5%	68.6%	35.5%	19.3%	16%
Advanced	1603	83.5%	71.4%	36.0%	20.3%	22%
Full Size Pickup						
Baseline	1320	81.4%	69.3%	35.0%	19.9%	—
Moderate	1457	81.4%	67.0%	35.8%	20.1%	1%
Advanced	1368	81.4%	71.3%	36.4%	21.6%	9%
Minivan						
Baseline	1484	82.7%	66.0%	34.8%	19.0%	—
Moderate	1780	82.7%	68.0%	36.0%	21.1%	11%
Advanced	1532	82.7%	73.2%	37.0%	22.8%	20%
Standard SUV						
Baseline	1784	81.4%	63.7%	33.8%	17.6%	—
Moderate	1781	81.4%	70.7%	37.0%	21.8%	24%
Advanced	1800	81.4%	73.7%	37.0%	22.9%	30%
Performance SUV						
Baseline	1784	81.4%	64.9%	34.3%	18.3%	—
Moderate	1781	81.4%	66.4%	36.3%	20.1%	10%
Advanced	1647	87.5%	69.2%	35.0%	21.4%	17%

Terminology:

Peak efficiency is the maximum registered over the driving cycle simulation; it is related to but somewhat lower than the engine's indicated efficiency.

Part-load efficiency is the ratio of cycle-average net engine efficiency to peak efficiency; it is related to but need not match the engine's mechanical efficiency.

Note that all efficiencies are driving cycle averages, and so while instantaneous overall efficiency is the product of the constituent transmission, part-load, and peak efficiencies, the listed cycle-average overall powertrain efficiency does not match the product of the average constituent efficiencies.

Powertrain efficiency gain is given relative to the baseline vehicle.

Table A-5. Stepwise Estimates of Midsize Car Fuel Economy Gains by Technology

Technology Step		Average	Efficiencies (%)					MPG increase	
Driving cycle	MPG	RPM	Max	E.Mech	P. load	Trans	Overall	vs.Base	by Step
Base vehicle: Ford Taurus 3.0L. 155 hp engine									
City	21.5	1534	34.3	54.4	37.7	69.3	12.9		
Hwy	35.5	1847	34.2	72.4	62.2	91.4	21.3		
CAFE	26.2	1675	34.3	62.5	48.7	79.2	16.7		
Basic streamlining									
City	22.0	1527	34.2	52.2	35.6	69.3	12.2	2.1%	2.1%
Hwy	38.2	1846	34.2	68.8	58.5	91.4	20.0	7.7%	7.7%
CAFE	27.2	1671	34.2	59.7	45.9	79.2	15.7	3.9%	3.9%
Weight reduction (10%) and displacement reduction with base engine technology									
City	24.1	1527	34.3	53.0	36.0	69.3	12.3	12.0%	9.7%
Hwy	41.0	1846	34.2	70.4	59.7	91.4	20.4	15.6%	7.4%
CAFE	29.6	1671	34.3	60.8	46.7	79.2	15.9	13.2%	9.0%
Improved engine technology: 2.34L VVC DOHC									
City	28.1	1705	36.1	58.5	39.8	69.3	14.4	30.4%	16.4%
Hwy	43.1	2068	36.0	70.5	59.8	91.4	21.5	21.6%	5.2%
CAFE	33.3	1868	36.1	63.9	48.8	79.2	17.6	27.3%	12.5%
Individual Cylinder Air/Fuel Control									
City	29.5	1705	36.5	60.7	41.3	69.3	15.1	37.0%	5.1%
Hwy	44.8	2068	36.4	72.4	61.4	91.4	22.4	26.4%	3.9%
CAFE	34.9	1868	36.5	66.0	50.3	79.2	18.4	33.3%	4.7%
Continuously Variable Transmission									
City	31.4	1604	35.5	60.6	45.2	83.5	16.0	45.5%	6.2%
Hwy	44.7	1601	35.6	80.6	62.7	83.5	22.3	26.0%	-0.3%
CAFE	36.2	1603	35.5	69.6	53.1	83.5	18.8	38.4%	3.9%
Integrated Starter-Generator (w/o idle-off)									
City	32.2	1604	35.5	59.4	46.4	83.5	16.5	49.5%	2.7%
Hwy	45.8	1601	35.6	79.9	64.2	83.5	22.8	29.0%	2.4%
CAFE	37.2	1603	35.5	68.6	54.4	83.5	19.3	42.0%	2.6%
Idle-off									
City	37.0	1604	35.5	59.4	46.4	83.5	16.5	71.6%	14.8%
Hwy	46.7	1601	35.6	79.9	64.2	83.5	22.8	31.6%	2.0%
CAFE	40.8	1603	35.5	68.6	54.4	83.5	19.3	55.9%	9.8%
Advanced weight reduction (20%) and 2.1L VVC engine (with ISG & idle-off)									
City	40.4	1604	35.5	60.0	46.7	83.5	16.6	87.6%	14.3%
Hwy	49.8	1601	35.6	81.2	65.1	83.5	23.2	40.4%	1.8%
CAFE	44.1	1603	35.5	69.5	55.0	83.5	19.6	68.8%	9.3%
More advanced engine, 1.9L VVC engine (with ISG & idle-off)									
City	42.1	1604	36.0	62.2	48.4	83.5	17.4	95.6%	4.3%
Hwy	51.2	1601	36.0	82.6	66.2	83.5	23.9	44.5%	2.9%
CAFE	45.8	1603	36.0	71.4	56.4	83.5	20.3	75.0%	3.7%
Motorized gear shift (6-speed) with optimal control, 1.7L VVC									
City	46.2	1417	35.4	66.2	54.2	79.2	19.2	114.7%	9.8%
Hwy	58.6	1659	35.7	81.6	76.4	97.6	27.3	65.2%	14.4%
CAFE	51.1	1526	35.5	73.1	64.2	87.5	22.8	95.3%	11.6%

APPENDIX B: REVIEW OF TECHNOLOGIES

As noted in the main text, technologies for improving fuel economy can be viewed on a continuum, but the status of technologies along this continuum is not fixed. Changes in market and regulatory conditions can change the prospects for options not now considered commercially worthwhile. Our approach allows for such changes in status. For example, we discusses options (such as transmission optimizations) that are technically feasible and inexpensive (and which indeed have been feasible for some time), but which automakers have not considered valuable under market conditions that place little value on higher fuel economy. Changing conditions could well make such options cost-effective ways for automakers to meet design targets requiring higher fuel economy. Similarly, improvements in fuel quality may advance the prospects for direct-injection engines that have already been deployed in Japan and Europe but which may require added development to meet emissions standards in the United States.

This appendix first reviews major technology options we consider for our analysis, discussing their efficiency benefits, costs, and other issues involved in deploying them. A final section of the appendix describes how we developed the advanced sport wagon specifications, benchmarking to recent vehicles and concepts and then invoking some of the advanced mass reduction technologies that are becoming available.

IMPROVED CONVENTIONAL VEHICLE TECHNOLOGIES

Conventional vehicles are achieving ever-higher performance and reliability while meeting stricter emissions and safety standards. And the petroleum-fueled internal combustion (piston) engine will continue to be improved, as will the entire piston-engine based powertrain as advanced transmission technologies enable a greater degree of engine-transmission synchronization for high efficiency. At the same time, the power requirements for driving can be reduced through lightweight body structures, ongoing streamlining and tire efficiency improvements, and more efficient accessories.

Engines

Although the topic of this report is fuel economy, criteria emissions are an important consideration for engines. A recent technological surprise is that gasoline engines can be made extraordinarily clean in actual use. Three improvements are responsible. First, a proliferation of sensors coupled to the microprocessor that manages the engine permits very precise and reliable control of the air-fuel ratio, the variable to which catalytic exhaust clean-up is most sensitive. Second, more durable and rapid acting catalytic converters have been developed, using coatings that degrade less at high temperature; as a result, a small catalytic converter can be placed next to the exhaust manifold where it heats up quickly, converting much of the pollution in cold start. Third, low-sulfur fuel enables the advanced catalysts to function with very high degrees of effectiveness. In addition to these technology changes, automakers, in meeting a regulatory requirement for on-board diagnostic equipment, have learned much more about how their emissions controls function in the real world, enabling them to refine the systems for greater effectiveness and reliability.

This revolution in emissions control — borne of over two decades experience in applying closed-loop catalytic control to meet progressively tighter tailpipe standards — has not yet been achieved for diesel engines or gasoline engines involving lean combustion. Both such engines, and particularly the diesel, offer added fuel economy benefits. However, as elaborated below, further emissions control progress is needed before they see widespread use given the upcoming California (LEV-2) and U.S. Federal (Tier 2) emissions standards that phase-in starting in 2004. Cleanup is especially difficult for diesels, which we do not incorporate into our analysis. We do consider gasoline direct-injection engines, which can provide efficiency benefits even without the lean operation that bedevils pollution cleanup.

Higher Specific Power and Lower Friction

Much of the efficiency improvement achieved in the last two decades has come indirectly from increasing the engine's specific power (the maximum power per unit of displacement, e.g., in horsepower per cubic inch). Over the past 20 years average gasoline engine specific power has nearly doubled. This achievement enabled a 58% engine downsizing and a 26% reduction in 0-to-60 mph acceleration time (in the average vehicle). Engine downsizing also implies reduced engine friction and weight. Specific power was increased by adding valves, fuel injection, improved controls, low-friction and lightweight materials, application of numerical analysis techniques to optimize engine processes, precision manufacturing, and greatly improved quality control. Of course, lower friction directly improves efficiency. Sensors and electronics will permit individual cylinder air-fuel mixture control, with multiple benefits yielding higher efficiency and facilitating emissions control. Improved engine controls also permit lower idle speeds, for further fuel savings (we assume idle speed reductions down to 500–600 rpm for the engines we model in our analysis).

As illustrated in Figures 1 and 2 of the main text, the opportunity to continue increasing specific power is excellent. For example, the 2000 Honda Prelude's 2.2L engine provides 200 hp, or 68 kW/liter, while the average of all model year 2000 cars and light trucks was 43 kW/liter. A more mainstream application is the 115 hp, 1.6L engine used in a Honda Civic HX, with a specific output of 54 kW/L. In addition to 4-valves per cylinder, this engine has variable valve control (Honda's VTEC system), aluminum block and heads, and numerous small refinements that reduce friction and improve the efficiency of induction and exhaust processes. Such refinements and others are being deployed by a number of automakers. Examples include BMW's variable-valve controlled ("VANOS") engines at over 50 kW/L, Nissan's non-VVC Sentra 1.8L and Maxima 3.0L engines at 52 and 56 kW/L, the Toyota Corolla and Echo VVTi engines at 51 and 54 kW/L, respectively, among others. GM's new Vortec 4200 inline six, producing 270 hp with 4.2L as announced for use in MY2002 SUVs such as the Chevy Trailblazer, features an aluminum block, DOHC, 4-valve per cylinder, and a VVC design for adjusting the cam phasing of the exhaust valves; the result is specific output of 48 kW/L, compared to the typically 40 kW/L output of current GM truck V8 engines which the new inline six could potentially replace (Broge 2001). We assume that the improved engines in our modeled vehicles produce 50 kW/L, or 18% better than the 2000 average but not as good as today's best non-sports car engines. Today's highest performance indices, such as the 90 kW/L of the Honda S2000 (naturally aspirated) or the 67 kW/L levels achieved by European turbocharged engines, suggest that our assumed levels are not at the boundary of internal combustion engine refinement.

When downsizing engines to take advantage of improved specific power, one needs to still provide adequate torque, especially for "low-end" (low rpm) response. Torque is fundamentally dependent on displacement and in-cylinder pressure, and there is much less scope to improve these parameters than engine speed, which multiplies torque to yield power. One can partially compensate by changing gear ratios, letting engine speed rise to provide the necessary power at lower torque; we adjust these ratios in our modeling. We are also helped because variable valve timing provides about 15–20% higher low-end torque than in a conventional engine. However, another new technology, the integrated starter-generator (ISG) discussed below, provides even greater compensation. The ISG can greatly augment engine torque, supplementing the power available for acceleration. It has the electric motor's advantages of high torque at startup and throughout the low speed range when piston engine torque is lowest. For example, a 10 kW (13 hp) motor (such as the permanent magnet version in the Honda Insight) can add 49 N•m (36 lb•ft) of torque. The Honda Insight system is a high-voltage (144v) device, used to provide hybrid drive capability. The ISG approach announced by Ford for some of its light trucks uses a 42v system.

To estimate costs of improved engines, we reviewed both our earlier work (DeCicco and Ross 1993, 1996) and earlier EEA estimates (Greene and Duleep 1993), as well as EEA's more recent estimates as used in EIA (2000) and in EEA (1998a) for the case of gasoline direct injection engines. We assume that shifting to overhead cams can cut costs (Lindgren and Jones 1990; NRC 1992), but do not take credit for it. While EEA assumes increased cost for successive detail improvements, such as friction reduction, our view is that such refinements are absorbed in routine engineering development, which typically takes costs out while improving a design. Thus, there is neither a variable manufacturing cost nor retail price impact for such refinements. We do not believe that an appropriate cost base is "yesterday's engine" developed with today's (or future) design and manufacturing skills, which is what some analysts effectively assume in continually increasing costs of various detail refinements (this issue pertains to other vehicle components, such as tires, aerodynamics, and accessories, as well).

Costs are increased due to the more complex cylinder heads and valvetrain. For example, variable valve timing apparatus involves more complex mechanisms and control hardware, ranging from minor for cam phasing on a single shaft to more extensive for greater degrees of variable control. Based on DeCicco & Ross (1996), we estimate retail price impacts of $120–$160 for upgrading to 4-valve per cylinder technology and $150–$200 for variable valve control in 4–6 cylinder engines, respectively. These estimates are generally consistent with EEA estimates as in Greene & Duleep (1993), but the 4-valve values are half those used in EIA (2000); given the growing experience with and use of 4-valve designs (which have now been used for many years by Japanese automakers), we feel that the older, lower cost estimate is more appropriate. For our Moderate Package (50 kW/L) engines, we add only costs for VVC and 4-valve technology, yielding estimates of $270–$360 for 4–6 cylinders. For our Advanced Package (55 kW/L) engines, we add costs of gasoline direct injection systems (the technology is elaborated below); the added costs are those of high-pressure fuel injection systems, which we base on EEA (1998a) estimates for a Toyota GDI design, implying $180–$200 for 4–6 cylinders.

Direct-Injection Engines

Engine fuel efficiency improvement is a more difficult challenge than after-treatment of the exhaust. The laws of physics make it more difficult, and so does the absence of new regulatory pressure. Nevertheless, powerful energy-saving technologies are being adopted and are in development. An example is the gasoline direct-injection (GDI) engine. With a fuel spray directly into the cylinder, fueling can be controlled separately from valve timing and controlled cycle to cycle. This leap in control capability will yield significant benefits. Even when operated stoichiometrically, GDI offers greater volumetric efficiency and higher compression ratio than port-injected engines. Such engines also enable lower emissions and some additional efficiency benefits due to improved cold start performance and mixture control while meeting the tightest upcoming emissions standards (which require very low sulfur fuel in any case).

Because of cost and engineering development needs, we assume GDI engines only for the Advanced Package. Since this package already assumes an increase of specific output to 55 kW/L, we do not model further efficiency gains from GDI *per se* (we did not have a GDI map with to model this engine and are not aware of a published comparison of stoichiometric GDI to an advanced VVC engine, as would be the appropriate basis for our context). This assumption is probably conservative since even retaining stoichiometric operation, several points of efficiency gain are likely.

Much of the attention on GDI, particularly in Europe and Japan, has been on versions that operate with lean mixtures. Direct injection facilitates a stratified charge that allows reliable combustion even with very lean fuel-air mass ratios. (With a uniform static mixture, the flame goes out if the air/fuel ratio is over roughly 21:1.) This lean combustion has further efficiency benefits, with as much as a 25% efficiency improvement in urban driving. There is, however, a downside to lean burn: reduction of nitrogen oxides (NOx) in oxygen-rich exhaust is difficult; absent a really inventive solution, lean burn probably won't be acceptable for widespread use in the United States. Direct-injection diesels offer even better efficiency, as much as 40% improvement over today's gasoline engines. However, with petroleum-based diesel fuels there are many particles in the exhaust (see below). Although particles can be cleaned up with catalytic traps, these further compound the DI diesel's cost over a gasoline engine. NOx cleanup remains very difficult in the diesel, also requiring new inventions to achieve degrees of control that will be expected in future years. Moreover, efforts to reduce NOx production in diesel engine combustion chambers generally cause higher particle generation.

Comment on ultrafine particles. Small particles are a serious public health concern and the effort to reflect their damage in air quality regulations is really just beginning. Such fine particulate matter (PM), perhaps coated with toxic fuel components, can lodge in the lungs, causing major health problems. However, the knowledge is woefully incomplete, in part because there are several types of particles with different causes. In addition, those from engines likely to be of greatest health significance are "ultrafine" particles a few tens of nanometers in size. Existing air quality standards and their derived regulations are stated in terms of the mass of particles. Therefore, they emphasize control of much larger particles (e.g., traditional PM_{10} standards addressed the mass of particles at least 10 μm in diameter). Particle traps (filters) are effective at removing both small (including ultrafine) and "large" (order of 10 μm) particles. Nevertheless, the very small particles that appear to be the most damaging are not explicitly monitored or regulated.

Some size distribution studies suggest that as diesel engines are being designed to meet stricter particle-mass regulations, the number of small particles emitted is increasing, with potentially adverse impacts on health. Fine particles may also be a problem for gasoline engines. Badly needed is fast, on-line measurement technology which can count particles in different size ranges. Although particle trap aftertreatment can control fine PM, it increases cost and can decrease engine efficiency, partly offsetting the value of using diesel engines to improve light vehicle fuel economy. But PM control is not the main emissions barrier for diesels or lean DI gasoline engines; it is the more fundamental and as yet unmet challenge of adequate lean NOx control that remains the "show-stopper," precluding use of such engines as a fuel economy improvement option in this analysis.

Transmissions

As outlined in the main text, a number of opportunities exist for substantial gains transmission efficiency. Key principles that designers are pursuing are adding gears for a broader range of ratios that allows the engine to operate in efficient modes more frequently; avoiding use of a torque converter and friction-based couplings by using direct (manual-transmission-like) gear shifting under precision electronic control; and continuously variable transmissions that offer both a broad range of ratios and a smoothly varying coupling of engine to the wheels. Fully capturing the benefits of any of these options requires an efficiency-optimized shift schedule, which we assume for the Advanced technology package.

Five-speed automatics are already being adopted and six-speed automatics are becoming available. In terms of cost, one transmission maker suggests that overall design improvements may enable new six-speed automatics to actually be lighter and simpler than existing 5-speeds (Auto Engr 2000), suggesting little or no cost impact in the long run. EIA (2000) assumes an incremental cost of $325 (RPE, 1990$) for a 5-speed automatic. However, based on Lindgren & Jones (1990), the total cost of a 4-speed automatic for a midsize car is $650 (RPE, 1989$). We find it implausible that the incremental cost of adding a gear should cost half as much again as an entire base transmission. Consistent with the new information about cost-saving designs for 6-speed automatics, we assume zero cost impact for improved conventional transmissions, provided that the changes are made in the context of normal product cycle retooling at high-volume production levels.

The motorized gear shift ("powershift") transmissions is an evolution of the manual transmission which not only automates for driver convenience, but opens the opportunity for detailed programming of shifting, enabling fast shifting and the possibility of very smooth shifting without a torque converter (Ward's 1999, 44). Specific information on the costs of powershift are not readily available. While the electronic content is higher, the overall complexity is not greater than that of conventional multi-speed automatics, and there would be savings from elimination of the torque converter. The additional electronic control functions could be integrated onto the engine control module, so we assume a negligible long-run net cost impact compared to conventional automatics.

The continuously variable transmission (CVT) offers both a broad span of gear ratios and lower frictional losses than today’s fluid-coupled automatics (Markus 2000a). While a number of mechanical designs are possible for a CVT, a belt-driven design has seen most extensive light vehicle applications to date. More recently, a toroidal design has been introduced in Japan, and new variant of both belt and toroidal CVT designs appear to be close to introduction.

The first belt-driven CVT to see production used a steel compression belt patented by a Dutch company, Van Doorne. The design has been licensed by a number of automakers and suppliers starting with Subaru in the mid-1980s and is now coming into more extensive use.

Honda uses such a CVT for the automatic versions of its Civic HX coupe, allowing it to attain best-in-class fuel economy for automatic transmissions vehicles in its class with an 87 kW (117 hp) engine. However, the compression belt is limited in the amount of torque it can handle. One maker (ZF, who will be supplying CVTs to Ford among others) offers versions for up to 250 N•m (184 lb•ft) of torque at 6500 rpm, suitable for vehicles with up to 140 kW (185 hp) engines (ZF 1997). More recently, Audi has introduced a new, pull-belt CVT, dubbed "Multitronic," as an option in the European version of the A6 sedan. This CVT is rated at 280 N•m (207 lb•ft). Notably, the Audi Multitronic CVT does not need a torque converter because of its very wide (6:1) ratio spread. It yields city fuel economy 2% better than a *manual* transmission and has been priced at $100 more than Audi's Tiptronic 5-speed conventional automatic (Markus 2000a). In any case, we restrict belt CVTs to our modeled small car and the large car after mass reduction. Because the dominant belt CVT design to date has been licensed from one company holding key patents, costs have been high, even though the inherent manufacturing costs of a CVT are likely to be lower than those for conventional multi-speed automatic transmissions (Lindgren & Jones 1990). These costs will drop as patents expire and competing designs, such as Audi's, become more widely available. For our 10-year horizon, we estimate the incremental cost of a belt CVT compared to a conventional automatic at zero, even though there may well be a cost savings in the long run.

The toroidal CVT is an old concept, considered for automotive transmissions as early as the 1920s. It has been used in some industrial drive applications over the years. However, materials limitations restricted its reliability and capability for cars until relatively recently, as advances in tribology, metallurgy, and special traction fluids have enabled the development of a modern toroidal CVT. An advantage of the toroidal design is that it does not face torque limitations as restricting as those for belt CVTs. In 2000, Nissan introduced their "Extroid" version of this device as an option for the low-volume Cedric/Gloria luxury sedans in Japan (Yamaguchi 2000). This vehicle couples the toroidal transmission to a high-output turbocharged 3.0L V-6 engine rated at 208 kW (280 hp) and 386 N•m (285 lb•ft). Fuel economy improvement is reported at 10%, similar to that for a belt-driven CVT in smaller vehicles. Kruger & Long (1999) report that toroidal CVT have overall efficiencies of 91% with improvements possible to nearly 93%, clearly superior to any other type of automatic transmission including belt-driven CVTs. Toroidal designs experience a marked efficiency drop off at low torque (viz., below 50 N•m for a device rated at 300 N•m), suggesting a good synergy with an ISG providing torque assist capability. Cost information is not available, except the that, as usual, initial costs are high. Nissan now offers it as a luxury sedan option, where the CVT's attributes of smoothness and rapid response to high power needs are appealing. Lacking sufficient data, we do not model the toroidal CVT, but consider it a promising advanced-case transmission alternative to 6-speed conventional or powershift automatics with efficiency-optimized shift schedules, particularly for larger vehicles such as pickups and SUVs.

A most promising opportunity for all high-efficiency transmissions is elimination of the torque converter. This device has high frictional losses, particularly in urban driving when a lockup mechanism cannot be engaged, but is needed for its ability smooth out start-ups and shift transitions. Until recently, most CVTs in production still use a torque converter, but improvements in automated shift actuation devices, new clutch designs, and precise electronic control of engine-transmission interactions can allow smooth operation without a torque converter (as is the case for the Honda Civic HX CVT). Improved engine controllability and the integrated starter-generator also work synergistically with advanced transmissions, either CVT or geared, to either minimize use of or eliminate the torque converter. Even with a more conservative designs, such as a 6-speed conventional automatic, the wider gear ratios can allow elimination of the torque converter by using precisely controlled clutches and planetary gears; and with electronic control, this evolution of the conventional design can have optimized shift schedules that begin to approach those obtainable with a CVT. Thus, we expect to see an interesting competition between the "revolutionary" CVTs and a continuing evolution of geared transmissions, offering automakers several strategies for achieving marked improvements in transmission efficiency. Costs will be saved by eliminating the torque converter and transmission costs will be held down to those of the least expensive option for a given vehicle application. Since we see several of the advanced transmission options as having no net long-run cost, we assume zero vehicle price increase for transmissions improvements to the levels of both our Moderate and Advanced technology packages.

Integrated Starter-Generators

At present, automobile electrical systems are somewhat primitive, as has been justified by the low electrical loads. The basic design of the electrical system has evolved only very slowly over the years, in spite of the steady growth of electrical accessories. The generator, or alternator, is energized via a belt from the crankshaft. The alternator is a light, low-cost device that is much less efficient than typical electric generators and has a traditional power capabilities of roughly 2-4 kW. With refinements to and the use of step-up converters, conventional alternators can raise capacity to about 6 kW, but costs increase and electrical efficiency is poor over the load range (Bischof, Gröter, and Schenk 1999).

A new approach, first developed by VW and Continental in Germany but now being engineered by several major automakers and suppliers worldwide, appears ready to see wide adoption. In this form, the electrical system will move to 36 volts (often called 42, the output rating of the new generators) instead of 12 volts. All vehicle accessories will be electrical, including air conditioning, and power take-off may be offered for emergency use in buildings and for outdoor uses such as camping. The innovative device is an on-crankshaft integrated starter-generator ("ISG") and its efficiency benefits are multifold:

1. The generator has a much higher efficiency, and better load range, than the conventional alternator. Conventional alternators have about 60% efficiency at low speeds and efficiency falls as engine speed increases. The ISG can provide at least 80% efficiency over a broad speed range.

2. Accessories can be converted to electricity, so that they can be much better controlled as well as not having always-on belt drives. A 42v system will enable far more efficient power steering and air conditioning, for example.

3. Smaller size wiring can be used for many electrical loads, saving both weight and cost.

4. When integrated onto the back of an engine in place of a flywheel, the combined starter-generator is more compact than the flywheel, starter and alternator it replaces.

5. The ISG permits idle-off (engine start/stop), offering up to a 6–10% fuel economy benefit (absent separate measures to decrease idle speed).

6. The integrated motor can help with torque augmentation and control, for power boosting and reduced engine vibration.

For example, in a drivetrain using a transmission having a torque converter, the ISG can permit more frequent operation in lockup mode, increasing fuel economy by 2-3% over traditional torque converter lockup. It also be used to aid launch and smooth shift transitions enough to help dispense with the torque converter when combined with some of the advanced transmission designs noted above. Ford has announced use of the ISG as a key part of its strategy for improving SUV fuel economy and will be using it on an improved version of the Explorer slated for release in MY2004.

Volkswagen has demonstrated the Siemens ISG on a version of the Golf. VW's experience with such a device for engine start-stop functionality dates back to the 1980s, when a small fleet of diesel engine start-stop vehicles was tested. Commercialization was delayed because of challenges on cost, electronics, and the need for engineering development, and because other strategies were sufficient for meeting the past decade's relatively low expectations for raising fuel economy. Cost issues still remain, of course, and with smaller vehicles using transverse-mounted engines, space can be a constraint. (The small car widening we assume for safety reasons may help accommodate an ISG in this regard.) Over the coming decade, and with pressure to improve fuel economy, the ISG is likely to be a cost-effective way of serving many needs for both electrical capacity and higher efficiency. The device also enables a degree of regenerative braking and provides an evolutionary manufacturing and market path toward mild levels of hybrid propulsion, although we do not model such applications of the technology here. We size ISGs for cars and light trucks at 8 kW and12 kW, respectively, for nominal rated output, noting that they are capable of short bursts of higher motor output. Since the motor of an ISG replaces both the conventional starter and alternator, there are cost savings as well; in our advanced case, we assume that use of the ISG with advanced powershift or continuously variable transmissions also enable elimination of the torque converter.

We assume that the ISGs use AC induction motors, at a high-volume RPE factor of $25/kW, implying $200–$300 for 8–12 kW sizes respectively. Additional costs include the power electronics and battery. To provide up to 15 kW at 36 volt operation, the electronics would have to handle about 400 amps. Based on power electronics reviewed by Moor (2000), we add $100–$150 for electronics including packaging, but we subtract $100–$150 for the conventional starter and alternator, so these aspects of cost cancel out. For batteries, we assume lead-acid, at an incremental price of $120–$180 over existing ignition batteries. However, lead-acid batteries have poor lifetimes; we multiply these costs by a factor of 2.5 to represent discounted lifetime consumer price impacts, yielding battery costs of $300–$450. The resulting total ISG system RPE impact is then $500–$750 for the nominal 8–12 kW ISG systems, respectively. We note that higher costs on the order of $1000 have been cited (e.g., EEA 1999), but we are assuming a 2010 timeframe, beyond the initial introductions over the next few years, by when the motor/generators and electronics can see rapidly falling costs in what would be an extensive, competitive components supplier market.

Vehicle Mass

A great deal of progress can also be made in technologies that cut vehicle load: reduced mass, air drag, tire rolling resistance, and accessory loads. Although the vehicle fleet has been gaining mass over the past decade, weight reduction still presents the best opportunity for load reduction; as with other aspects of technology, it is a question of how the industry's capabilities are utilized. Lighter materials, especially high-strength steel, plastics and aluminum, are taking increasing shares. Automakers have identified approaches to achieve as much as 40% mass reduction, and are working on ways of bringing down the costs. Our technology packages assume different degrees of mass reduction to different vehicles, as shown earlier in Table 1, in order to improve fleetwide crash compatibility and allow for extra safety improvements in small cars.

A moderate degree of mass reduction can be obtained at no cost increase or even cost savings by means of ongoing improvements in conventional design. For example, AISI (1998a,b) identifies steel refinements yielding up to 20% body mass reductions depending on body type, along with improvements in crashworthiness and other structural performance metrics, at small net cost savings by using "ultralight steel" techniques. Similar mass reductions have been identified for closures and chassis parts. For aluminum and especially plastics, cost-target-constrained component and product development strategies routinely yield lower-mass designs that cost less than the older designs they replace. In general, ongoing materials developments allow auto designers to choose the best materials — from among various metals and plastics — for a given application, typically at reduced cost and improved performance. As noted earlier, the real issue is one of how such potentially mass-saving refinements are applied. We assume that the first 15% of mass reduction has no net impact on vehicle price. In fact, if higher fuel economy targets serve to put a brake on the current upsizing trends, they may well help hold down consumer prices overall.

For greater degrees of mass reduction, we assume cost premiums associated with a greater degree of material substitution. We assume a cost (incremental RPE) of $1.00/lb for mass reduction beyond 15% of each vehicles baseline curb weight. This cost level is based on the "Materials Substitute III" cost assumption of EIA (2000). It also similar to the $1.12/lb estimate implied by EEA (1998c) for a high-volume aluminum spaceframe structure compared to a steel unibody. Examining a range of cost estimates for compact vehicle bodies, EEA found that, at a 200,000 unit/yr production level, an aluminum space frame would be less costly than an aluminum unibody for a similar (40%) level of mass reduction. Their resulting incremental manufacturing cost estimate was $1.23/kg; doubling that to reflect consumer price impact yields $2.46/kg or 1.12/lb. Higher estimates for substituting aluminum bodies for steel have been given, e.g., $1000–$1300 for a midsize car body. For example, Sylvan (1995) estimated a cost increase of $500 for a vehicle combining the then-best current practice for aluminum components. Politis (1995) estimated a $650 based on modeling various car bodies; both of these are in manufacturing cost terms, so doubling them yields the rough $1000–$1300 RPE range noted here. Aluminum costs about 5x steel per unit mass; typical prices of $0.30 for steel and $1.50 for aluminum and a 50% mass savings for simple substitution imply a material cost penalty of $0.90 per pound saved. This value can be taken as a ceiling on manufacturing costs, from which lower costs can be obtained through use of aluminum-optimized design, fabrication, and assembly techniques. We root our mass reduction costing in estimates made for aluminum designs because the information is available, while acknowledging that designers will chose the most cost-effective approaches from a range of materials strategies.

HYBRID PROPULSION

Hybrid electric drive is one of the highlights of new technology advances as the automobile enters the 21st century. Engineers have long been fascinated by the potential to build powertrains that couple the energy and power density of combustion engines with the efficiency and responsiveness of electric motors. However, the electronic systems and computerized design capabilities needed to implement such concepts proved elusive until very recently. Higher costs are inherent in a system that essentially combines two drive systems into one powertrain. Although mechanical or hydraulic devices have been proposed for a hybrid powertrain's supplemental system, automaker efforts have focused on hybrid electric vehicles (HEVs), utilizing electric motors/generators and batteries or ultracapacitors as storage devices. Electric designs have a good potential for cost reduction in most components as well as high degrees of controllability, smoothness, and quietness.

The efficiency benefits of hybrid drive follow from four main factors. First, the electric motor supplements engine power, allowing downsizing or fuel-efficient de-rating of the engine. Second, hybridization allows an engine to run at its most efficient operating points even more frequently than is feasible with the optimized engine/transmission designs described above. Third, hybrids can recover (regenerate) a portion of the energy that is otherwise lost to braking. Finally, hybrid drive is one way to reduce idling losses by turning the engine off when tractive power is not needed. Hybrid electric drive systems offer added consumer benefits through their greater capability for supplying on-board electric power and their smooth, responsive driving experience under many common urban/suburban driving conditions. The technology is relatively less beneficial for steady cruise conditions, although the hybrid drive's ability to add back performance compensates for engine downsizing and tuning optimizations that can boost efficiency during highway driving. Note that idle-off and some degree of regenerative braking are feasible with ISGs, so that not all of the hybrid's benefits are unique.

Two technical points are useful to keep in mind when considering hybrids. First, the battery for a hybrid is quite different from that in an all-electric vehicle. High power rather than energy density is needed; and that is an easier target for electrochemistry than high energy density. Although battery costs are still a major issue, a much smaller and very differently designed battery is needed for a hybrid, so that the efficiency penalty due to battery mass is much lower in a HEV than in a pure EV. Second, there is a strong advantage to turning a combustion engine off at low power; the frictional work in a conventional 80 kW engine at normal engine speed is about 7 kW. With a motor-inverter-battery system, the power loss at low output is only about 1 kW. However, hybridization is not the only way to achieve these energy savings, which can also be achieved with a start-stop system using an ISG, for example.

Types of HEVs

HEVs can be designed in ways, from using slight degrees of hybridization (perhaps with an ISG) to approaches that drive the wheels only electrically, reserving the combustion engine for running an onboard generator (this is, in fact, how modern diesel locomotives work). Researchers have often classified HEVs according to component arrangements (e.g., "series" vs. "parallel"). In fact, the world's first production hybrid, the Toyota Prius, is really a bit of both. Ronning (2000) suggests vehicle mission-oriented classifications based on the portion of a vehicle's total propulsion power provided by the electric drive system:

- Mild hybrid — less than about 25%
- Power hybrid — 30–50%
- Energy hybrid — 50–100%

Mild HEVs provide idle-off and some regenerative braking, but no electric-only driving mode (the combustion engine restarts whenever powered driving is underway). Power HEVs can offer some electric-only driving, such as electric-only launch, but provide no real "ZEV" trip range and are not designed for plug-in recharging. Power HEVs have also been called a "full" hybrids, which is the term we will use here. Energy HEVs (also called "charge depletion hybrids") do have a useful all-electric driving range (e.g., 50 miles or more) and plug-in recharging ability. No energy hybrids have been announced for mass production; automakers seem very reluctant to mechanically decouple the engine from the wheels. One reason may be that battery technologies remain too limited to provide adequate combinations of efficiency and performance even when supplemented by an engine-powered generator. Batteries are certainly a major cost factor for all hybrids, and so like pure EVs, energy hybrids will carry a very substantial cost premium for the foreseeable future.

HEV Examples

Guidance on practical HEV designs is provided by the first mass-produced HEVs, the Toyota Prius and the Honda Insight, which can be termed full and mild hybrids, respectively; some of their key specifications were presented in Table 2.

When the Toyota Prius was first announced in 1997, it touted a rating of 28 km/liter (66 mpg) on the Japanese city cycle, representing a 2x fuel economy improvement over a similarly sized Corolla. However, fuel economy is very sensitive to driving cycle, and hybridization sees its greatest benefits in the low-load, stop-and-go patterns of congested urban driving. The first-generation Japanese Prius had an U.S. EPA composite fuel economy of 49 mpg, representing a 65% improvement over the average 3000 lb weight class vehicle and a 45% improvement adjusted for performance (Hellman et al. 1998). An et al. (1999) compared the first-generation Japanese Prius and a 1997 Corolla. Separating out the effects of hybridization, they estimated a 23% CAFE cycle benefit relative to a Corolla-like vehicle with performance adjusted downward (14 s 0–60 time). Efficiency benefits are quite sensitive to the assumed performance level, with a greater benefit from hybridization for vehicles having better performance. Adjusting the modeled HEV characteristics to match those of the standard Corolla (11s 0–60 time), An et al. found a 41% CAFE benefit.

The U.S. version of the Prius, as listed in Table H, is the second-generation design in terms of hybrid componentry. Notable improvements include a more compact, lighter-weight battery pack than the first-generation model, and the powertrain was also recalibrated for optimal performance on U.S. driving cycles. The Prius 1.5L, 70 hp engine has VVC and uses an efficient Atkinson cycle, with a longer expansion stroke and high (13:1) compression ration, along with several friction reduction refinements. Optimized for efficiency, the Prius engine has a low specific power, 47 hp/L, enabled because the electric drive adds another 44 hp, and can deliver 258 lb•ft of torque. The Prius incorporates some tactive load reduction measures, with improvements in packaging, incremental materials changes, and low drag (C_D = 0.29). The

Toyota Echo, with a similar body style and a VVC engine, provides one simple basis of comparison. The total interior volume of the two cars is the same, but the Prius is wider and has more passenger room; it has less trunk space than the Echo because the battery pack takes up space behind the rear seat. Compared to the Echo's MPG values of 39.4 CAFE, 31 city and 38 highway label, the Prius appears to offer efficiency improvements of 68% on the city cycle, 18% on the highway, and 46% on average.

Honda provided a breakdown for the 85% efficiency city cycle improvement for the Insight over a Civic Hatchback (an imperfect comparison, since the Insight is a two-seater while the Civic is a subcompact coupe). They attributed 30% of the MPG improvement to the Insight's streamlined, lightweight aluminum body, another 30% to the high-efficiency lean-burn engine, and the remaining 25% to the hybrid drive system. However, all of these items are synergistic; in particular, hybrid drive clearly enables use of a smaller engine. Although a fully adjusted comparison has not yet been published, an idea of the benefits of the Insight's hybrid mechanism can be had by subtracting, from the 85% total benefit, 30% for load reduction plus half of the 30% engine efficiency contribution (i.e., attributing a 15% fuel economy improvement to VVC and friction reduction techniques). This approach leaves an approximately 40% efficiency gain attributable to hybridization, including its contributions of idle-off, regeneration, and the additional increases in part-load efficiency enabled by the hybrid mechanism.

Ford has not year released many details on its Escape HEV hybrid sport utility vehicle, promised for introduction in 2003, but it appears to be what we would term a full hybrid design. Its target city fuel economy is 40 mpg, compared to 20 mpg (test) for the 3.0L V6 automatic version of the Escape. A rough average improvement factor of 1.6 is implied by the vehicle's doubled city fuel economy if assuming a highway cycle improvement similar to that of the Prius. The Escape HEV will also incorporate other efficiency measures, such as engine refinements and further load reduction. The Escape appears to fall into the "full" hybrid category. Ford has also announced production of what might be termed "minihybrid" designs (Bradsher 2001) using 42 volt systems, slated for use on the Ford Explorer beginning in 2004.

GM's recently announced "ParadiGM" hybrid concept uses dual AC induction electric motors with a 42 volt system powered by lead-acid batteries to provide 32 hp (13%) of a total 252 hp propulsion system. The base engine for such a HEV would be a 220 hp V6 (unspecified displacement), and the company has said that a 6-speed powershift type of transmission would be used. GM is targeting a 35 mpg for a 2004 production version of this system in a high-performance (7.3 s Z60 time) midsize SUV design.

For the Durango HEV, DaimlerChrysler has stated a 20% fuel economy improvement relative to the 5.9L V8 4wd version of the Durango. The concept version demonstrated in early 2000 couples a 89 hp AC induction motor to a 3.9L, 175 hp V6 engine, for a total of 264 hp (34% from the electric motor). Compared to the 245 hp V8, with gets 14 mpg, the HEV Durango will get 17 mpg. The concept version used 24, 12-volt lead-acid battery modules as part of the HEV system, but DaimlerChrysler is evaluating lighter, lithium-ion batteries for possible use in a production version of the vehicle (Markus 2000b). On a technical note, these Durango engines have specific power indices of 31 kW/L for the V8 and 33 kW/L for the V6 (compare to Figure 1). Upgrading the engine to the 50 kW/L level we assume for our analysis would, at fixed displacement, boost the power available by just as much as the 50% boost provided by the HEV Durango's electric motor. Of course, torque ability would not be the same, but it seems quite likely that a design using a state-of-the-art engine and a smaller electric motor emphasizing torque assist would make for a more technically efficient, lighter weight, and less costly package.

HEV Cost Estimation

Cost factors for hybrid vehicles are derived largely from Delucchi (1999) and EEA (1998b). At this point, because the systems are so new and not just an evolution of conventional technology, costs are highly uncertain. While our estimates for other technologies reflect full-scale, mature costs, the estimates for HEV components may not reflect all of the opportunities for long-term cost reduction.

The basic estimates for hybrid motor plus electrodrive power electronics costs were based on a slope+intercept formula derived from Delucchi (1999, 34):

Manufacturing Cost = $700 + $17.3/kW (1997$)

This estimate is for high-volume (200,000+ units per year) production. It assumes systems using permanent magnet motors, as is the case for Insight and Prius. The resulting estimate for a small car hybrid system is $1,384, slightly lower than the EEA (1998b) estimate of $1,500 for the "future" cost of Prius-like motor/generator and power electronics.

The size of mild and full HEV systems is scaled based on the peak engine power requirements for our advanced package conventional powertrains. The calculations are detailed here in Table B-1. We add costs for ancillary electrodrive components (system controls, cooling, and high-power wiring harness) amounting to $200 (EEA 1998b, 3-6). We assume transmission manufacturing cost savings of $150 for mild hybrids (elimination of torque converter) and $350 for full hybrids (greatly simplified gearbox; see EEA 1998b, 3-5). We assume no engine cost savings for mild hybrids. For full hybrids, we use the EEA (1998b, 3-6) engine savings estimate of $100 for the small car and scale it up by vehicle peak power requirement for other vehicles. These are manufacturing costs, which we markup by a factor of 1.8 to estimate RPE, as given at the bottom of Table B-1 and incorporated into Table 7.

AN ADVANCED SPORT WAGON CONCEPT

As noted in the main text, rather than restrict ourselves to established vehicle classes when it is clear that the market is in flux, we also model an advanced "sport wagon" inspired by recent trends. Rather than take an early example already on the market, most of which are either small or luxury models, we developed a composite model by benchmarking to a set of current models and concepts. Vehicles examined included currently popular SUVs (Explorer, Blazer) and luxury SUVs (Lexus RX300, Acura MDX), wagons and sport wagons (PT Cruiser, Subaru Outback, Volvo Cross Country), and concept vehicles (Citadel, Powerbox, Multisport, Varsity).

Relevant specifications for the vehicles examined are shown here in Table B-2. Figure B-1 shows scatter plots of some of the gross dimensional and mass-related traits. Plots of footprint vs. mass and overall box volume (see below) vs. mass show how the newer designs are more "efficient" in terms of packaging and space utilization. To develop our composite vehicle, we proceeded as follows:

(1) Choose an overall length (OL = 192" — similar to Explorer/Astro/Durango) to place the vehicle in a size category between current mid-size SUVs and large SUVs/minivans.

(2) Track width was then selected, to be significantly wider than current SUVs of this length, benchmarking to the Acura MDX (TR = 66"), to offer stability as well as good interior cargo space (the vehicle could arguably carry the proverbial 4×8 sheet of plywood between wheel wells if rear seating is folded down). Based on track width, an overall width (OW = 76") was projected by comparison to current OW-TR differences, assuming modest (not too fat) tires.

Wheelbase (not really needed for our analysis) is estimated as WB = OL - 72" = 120" based on lower end of differences in current vehicles; this wheelbase is similar to that of large minivans, allowing for more interior space and also implying a shorter hood line. Frame height would be lower than that of today's midsize and large SUVs; a contemporary sport-wagon like undercarriage would allow good ground clearance (8"–9" as for Volvo Cross Country wagon) without a high step-up height and the aggressivity risks of a high frame. This vehicle is not designed to be an "off-road" machine, but rather functionally matched to the urban/suburban, and even rural road, driving conditions in which most SUVs are used.

(3) Existing relations between shadow (SH = OL x OW) and gross volume of enclosing box (Box = OL x OW x OH) were used to project a box volume = 15.9 m^3. However, the height was lowered about 10% from existing trend, for a more wagon-like, less SUV-like shape, yielding a target box volume of 15.0 m^3. This value implies an overall height of OH = 63".
(4) Existing relations between gross box volume and official interior volume were examined. Most SUVs and a few sedans had ratios of around 28% (i.e., interior volume = 28% of gross box volume). A new, efficiently packaged small wagon, the Ford Focus Wagon, had a ratio of 36%. We assume 33% for our advanced sport wagon, reflecting improvements in packaging well above traditional SUVs, but short of small wagons. This ratio implies an interior volume of 5 m^3 (177 ft^3), which is quite spacious (larger than Acura MDX's 162 ft^3). The resulting shape would be somewhere between wagon-like and van-like.

(5) Existing relations between box volume and mass were examined; a base mass was taken from the trend line of the current sample, implying 1954 kg curb weight for a 15.0 m^3 box. Advanced weight reduction (material substitution, e.g., to aluminum intensive design or space frame with composite panels, with corresponding reductions in interior components and other vehicle systems) was assumed to cut 40% from curb weight, implying 1172 kg. Rounding this up yields a 1200 kg (2646 lb) vehicle, which we nudge further to assume a 3000 lb inertial test weight.

For cost estimation purposes, the weight savings for a vehicle this size would be 782 kg (1,723 lb) compared to a current design with a steel body and conventional interior and chassis components. Following the approach described in Table 6, and assuming that the first 15% of mass savings are obtainable at no net cost by optimally using ongoing design progress, and evaluating the rest at an RPE penalty of $1/pound, implies a cost of $1,080, which is what we assume. Note that automakers are developing weight-saving strategies for all vehicle systems that target achievement of weight savings on the order of 40% with little cost penalty. For example, with the composite panels on frame approach being pursued by DaimlerChrysler in its ESX PNGV series, the company claims to be drastically cutting costs with each revision of their development concepts. They are planning an "affordable" design by 2004 which could conceivably be put into production by 2007. Price impacts have not been described, but

DaimlerChrysler has said that their hope is that ultimately, the lightweight vehicle structures can be made at net savings, helping to offset the inherently higher costs of electric powertrains (hybrid or fuel cell).

Because this advanced sport wagon is a hypothetical composite vehicle, there is no baseline reference vehicle to which to calibrate the simulation model. We projected results for various powertrain options applied to this advanced platform that can be compared to existing vehicles and concepts. With other elements of our Advanced technology package, the resulting vehicle has powertrain specifications as shown in the last column of Table A-3. The resulting composite (CAFE) fuel economy is 44 mpg, 2.2 times higher than a baseline 20 mpg SUV of today and 2 times higher than a baseline 22 mpg large minivan. As tallied in Table 7, the incremental cost of the advanced sport wagon concept is about $2,500 higher than that of a baseline midsize SUV such as today's Ford Explorer.

Table B-1. Cost Estimation for Hybrid Electric Powertrains
(for reference to Table 7 of main text; 2000$ unless otherwise noted)

HEV Cost Calculations	Small Car	Large Car	Pickup	Minivan	Std SUV	Perf SUV
Design peak vehicle power, kW	85	104	127	109	99	127
Mild hybrid drive, kW	13	16	19	16	15	19
Full hybrid drive, kW	34	42	51	44	40	51
Mild HEV battery mass, lb	38	46	56	48	44	56
Full HEV battery mass, lb	100	122	149	128	116	149
Mild motor/controller mfr $	989	1,042	1,104	1,054	1,027	1,104
Full motor/controller mfr $	1,384	1,527	1,693	1,560	1,488	1,693
Mild battery mfr $	347	425	516	443	404	516
Full battery mfr $	925	1,133	1,375	1,181	1,076	1,375
Engine savings mfr $	100	122	149	128	116	149
Mild systems subtotal, RPE $	2,764	3,000	3,276	3,055	2,936	3,276
Full systems subtotal, RPE $	4,516	5,147	5,883	5,294	4,975	5,883
Mild HEV net RPE $	2,494	2,730	3,006	2,785	2,666	3,006
Full HEV net RPE $	3,706	4,296	4,985	4,434	4,136	4,985

Parameters

Hconst	700	$, HEV motor+controller cost constant, from Delucchi (1999), in 1997$
Hslope	17.3	$/kW, HEV motor+controller cost slope, from Delucchi (1999)
CPI0097	1.073	for inflating Delucchi 1997$ to 2000$
Markup	1.8	mfr cost to RPE for electrodrive components (low value from EEA 1998b)
BattSize	1.33	kg of NiMH battery per kW electrodrive capacity
NiMH	19	$/kg mfr cost, from Delucchi (1999, p. 36) (1997$)
Hmisc	200	$, cost of controls, wiring harness, and cooling, from EEA (1998b, 3-6)
Esave	100	$, saving on engine (EEA 1998b, 3-6), for scaling up by engine size
MHsave	150	$, savings on transmission for mild HEV, assumed for losing torque converter
FHsave	350	$, savings on transmission for full HEV, from EEA (1998b, 3-5)

Table B-2. Specifications and Indices for Vehicles used to Benchmark an Advanced Large Sport Wagon Concept

Figure B-1. Scatter Plots of SUV and Wagon Attributes
(see Table B-2 for letter codes representing vehicles)