A Fuel Efficiency Horizon for U.S. Automobiles

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EXECUTIVE SUMMARY

Improving automotive fuel efficiency is an important way to address transportation oil demand and greenhouse gas (GHG, "carbon") emissions. In the United States, new light duty vehicle fuel economy rose nearly 70% after the 1970s energy crisis but then changed little over the 1985-2005 period. Recently, rises in oil prices and concerns about climate disruption have led to stricter fuel economy and automotive GHG emissions standards. The single national program finalized in April 2010 targets a 38% increase in fuel economy, for a projected new fleet average of 34 miles per gallon (lab-test mpg) by 2016 or a 27% decrease in energy intensity (energy use per distance driven) and tailpipe carbon dioxide (CO_2) emissions compared to 2005.

Fuel efficiency is only one element of a complete transportation sector climate policy, which must also address travel demand and the net carbon balance of fuel supply. Nevertheless, in light of its important role, a key question is just how far fuel efficiency can progress over the coming decades. Given a stock turnover period of roughly 15 years, the new fleet efficiency horizon for 2035 is relevant for helping meet mid-century GHG emissions targets. This study examines how far automobile efficiency can be taken if it is pursued with determination, using an analysis that assumes success in technology and design strategies that offer "revolution by evolution."

Many analyses highlight alternative technologies for replacing internal combustion engines and petroleum-based fuels, such as grid-based vehicle electrification, biofuels, hydrogen or natural gas. Others point to radical changes in vehicle materials and design. Proponents of these options marshal technological optimism in scenarios that show how their alternatives will revolutionize the automobile. While such options mature, it will be crucial to pursue evolutionary advances in existing systems, which can be greatly improved at cost, but at much less cost and with none of the other barriers faced by alternative technologies.

Harnessing Real-World Progress

This study focuses the lens of technological optimism on evolutionary changes in automobiles that still rely on internal combustion engines and largely steel-based structures. Technologies considered include turbocharged gasoline direct-injection engines, low-emission diesels, a range of hybrid drive options (but not "plugging in"), advances in lightweight steel and other mass-efficient material and design solutions. Assumed rates of progress are based on what has been observed historically in the auto market, where innovation is relentless even when not focused on fuel efficiency. The analysis assumes competitively driven advances in engineering, with cost reductions achieved through budget-constrained product development and productivity gains as witnessed in all aspects of vehicle manufacturing.

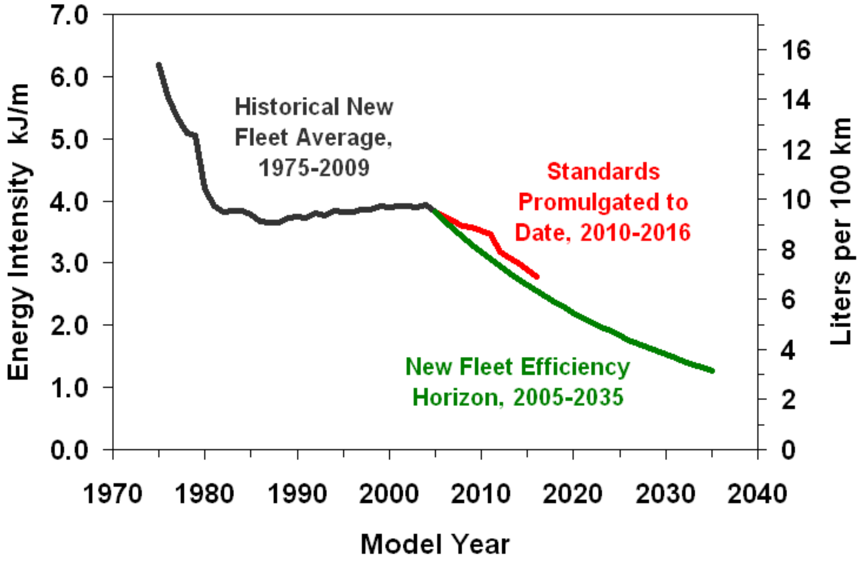
Automotive engineering has always seen continuous progress; at issue is the extent to which it is harnessed for fleetwide efficiency as opposed to other market outcomes. It is this factor -- the emphasis on reducing fuel consumption relative to different goals -- that more than any other will influence the direction of the fleet over the first half of the 21st century. In short, improving auto efficiency is as much a matter of design priority as it is one of technology change.

Many studies analyze the ways to improve vehicles along energy-related dimensions including powertrain efficiency and load reduction. This report does not perform new detailed engineering analysis, but rather synthesizes published results under an assumption that efficiency gains from evolutionary technology changes are maximized on a fleetwide basis. New features of this study include highlighting the role of efficiency-compatible product planning strategies in addition to the technology options usually analyzed; fitting historical technology changes to logistic curves to identify rapid but feasible adoption rates for key new technologies; and modeling costs using quadratic functions of energy consumption reduction that shift through time.

The conclusion is that a tripling of new fleet fuel economy is an ambitious but defensible horizon for 2035. Figure 1 shows the resulting trajectory in terms of new fleet average energy intensity (kilojoules per meter, kJ/m, similar to Btu/mile), with historical averages and the levels implied by recent regulations shown for comparison. The right-hand axis gives corresponding nominal fuel consumption rates (liters per 100 kilometers, L/100km, based on unadjusted lab tests), which fall from 9.5 L/100km to 3.2 L/100km over the 25 year horizon 2005-2035. Historically, a drop of comparable magnitude (roughly 6 L/100km) happened over 12 years, 1975-1987. In terms of nominal, lab-test fuel economy, this trajectory would take the new U.S. car and light truck fleet from 25 mpg in 2005 to 74 mpg in 2035, implying an improvement from 20 mpg to 60 mpg in terms of estimated on-road ("real world") fuel economy.

The assumed rates of technological progress, particularly for the degree of hybridization likely to be needed, are in line with those of some major automotive technology changes in the past. The challenge is cost, which rises steadily as greater use of advanced technology is required. Nevertheless, projected fuel savings greatly exceed upfront costs and this evolutionary horizon remains less costly than revolutionary changes in vehicles based on electric grid connection, hydrogen or other alternatives that entail extensive new infrastructure.

Figure 1. New fleet efficiency horizon in terms of energy intensity and fuel consumption rate compared to historical fleet averages and recent U.S. regulations



Energy intensity is estimated on-road value in kilojoules per meter (kJ/m) assuming 20% fuel economy shortfall for all years. Right axis gives nominal (lab-test) fuel consumption rate in liters per hundred kilometers (L/100km); convert to miles per gallon (mpg) by dividing L/100km into 235.2. See Table 1 for further details.

Table 1. Projected horizon for fuel efficiency, fuel savings and CO_2 emissions reductions for a U.S. light duty gasoline and diesel vehicle fleet

New Light Duty Fleet Averages and Per-Vehicle Estimates	Base & Current Year		Trajectory by Model Year			
	2005	2010	2020	2025	2030	2035
Energy intensity (on-road kJ/m)	3.81	3.52	2.20	1.83	1.53	1.27
reduction in energy intensity	0%	8%	42%	52%	60%	67%
Fuel economy (unadjusted mpg)	25	27	43	52	62	74
on-road (adjusted) mpg	20	22	34	41	50	60
CO_2 emissions (g/mi, with A/C)	358	330	192	157	128	104
Lifetime fuel savings (gallons)		590	3,264	4,039	4,696	5,254
Lifetime CO_2 reduction (tons)		5	29	36	42	47
Fuel savings benefits (2010$)			5,600	6,900	8,000	8,800
Technology costs (2010$)			2,600	3,400	4,000	4,200
Net Present Value (2010$)			3,000	3,500	4,000	4,600

Assumptions: shadow price of fuel $2.88/gal (2010$); 20% fuel economy shortfall; 7% discount rate; 10% rebound effect. The CO_2 emissions rate reflects subtraction of potential air conditioning (A/C) reductions starting in 2020. Lifetime fuel savings are undiscounted gallons of gasoline equivalent (gge) and CO_2 reductions are direct (tailpipe only) metric tons, both relative to the 2005 base year fleet; dollar values are rounded; see Table 5 for further details.

Although it may seem high, a tripled efficiency horizon can be viewed as having been validated by the Partnership for a New Generation of Vehicles (PNGV) program. The PNGV concept cars shown a decade ago demonstrated a factor of 2.6 increase in fuel efficiency with prototype diesel hybrid powertrains less advanced than today's. Since then many technologies have not only been developed, but also progressed into commercialization and its attendant stages of competitively driven refinement and cost reduction. Although performance has risen, so has technological capability. Thus, tripled efficiency is indeed attainable by 2035, a time frame more than three decades after the PNGV delivered proof-of-concept cars approaching that goal.

Getting from Here to There

Table 1 summarizes the results of a scenario leading to tripled efficiency by 2035. The analysis works forward from a 2005 base year fleet, with new fleet average energy intensity declining at a compound rate of 3.6% per year (a 3.7% per year fuel economy increase). By comparison, the recent Joint Rule for 2012-16 requires a fuel economy increase averaging 4% per year between now and 2016. By 2025, the trajectory shown here reaches a nominal 52 mpg, or a doubling of fuel economy compared to the 2005 fleet. For fleet average GHG emissions rates, given here after subtracting the reductions likely to be feasible with improved air conditioning systems, the trajectory implies 157 CO_2-equivalent grams per mile (g/mi) in 2025 and 104 g/mi in 2035.

To project this horizon, this analysis uses results from studies that assess particular technologies such as advanced engines and hybrid drive. As interpreted here, however, these options are used only as an existence proof of the potential for high fuel efficiency rather than as a literal technology pathway to be implemented. Thus, the view is technologically agnostic and reflects opportunities identified through engineering fundamentals.

That being said, extensive use of hybrid drive appears necessary for tripling fleet efficiency. High utilization of hybrids could be reached by 2035 if their adoption rate is greatly increased, with associated implications for increased cost. The hybrid adoption rate assumed here is faster than in MIT's studies but still mid-range among those observed historically (see Figure 10). Reliance on hybrids could be lower if greater progress is seen in mass reduction, other ways to reduce loads and recover energy, use of start-stop, additional refinements of gasoline and diesel engines (including lean emissions control) and other advanced combustion techniques.

A central assumption is that going forward, essentially all energy-related technology advances are focused on fuel efficiency rather than further boosting average acceleration performance. A sensitivity analysis shows that if performance instead rises in line with past trends, then the 2035 horizon drops to doubled rather than tripled fuel efficiency. Performance enhancement consumes technological capability and so achieving greater progress on fuel efficiency means redirecting market trends and customer preferences away from ever more mass and muscle.

Mindful of this challenge, it will be valuable for automakers to pursue what this study terms *efficiency-compatible* design strategies in addition to the technical efficiency improvements commonly considered. Compatible strategies are approaches for both individual vehicles and product plans that enhance customer value by emphasizing features that are not inherently fuel consumptive. Such options include intelligent systems content, matching performance to real-world driving needs, creative downsizing, interior packaging and styling -- in short, appealing to consumers in ways that are in line with, as opposed to work against, fuel efficiency.

Costs and Savings Estimates

To estimate the costs of pursuing the efficiency horizon given here, estimates from recent studies were synthesized into cost curves (Figures 13 and 14 in the main text). These curves were chosen to be quadratic in energy intensity reduction, reflecting an increasing marginal cost for each step of additional fuel savings. They were also modeled to shift rightward as time goes on, reflecting progress toward lower costs for achieving a given level of fuel savings overall.

The near-term curve was derived from costs estimated for the Model Year 2012-2016 Joint Rule. Long-term cost estimates were derived using a recent study by MIT, which reflects steady gains in efficiency by optimizing internal combustion engines and hybrid drive along with declining costs for advanced powertrain components. Those findings imply a long-term (2035) cost curve much lower than the near-term curve. Both near- and long-term curves were adjusted downward based on studies by the steel industry and Lotus Engineering. In interpreting those findings, this report assumes that evolutionary mass reduction (reaching 20% by 2035) can be obtained at no net cost, in contrast to a presumption that saving weight always adds cost.

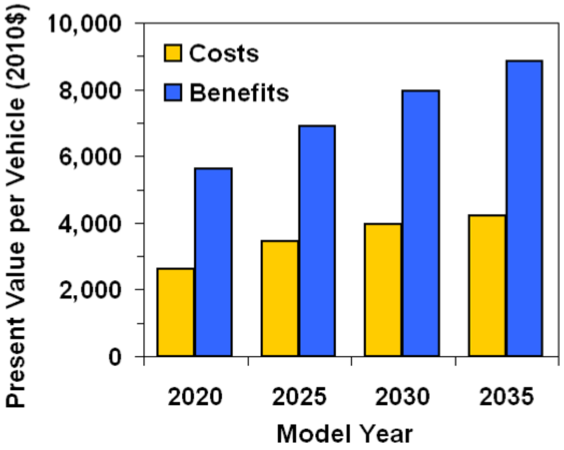
Figure 2 shows the incremental technology costs and discounted lifetime benefits for the new fleet by model year. Benefits related to fuel savings mainly depend on the pre-tax price of fuel, assumed to average \$2.50 per gallon. Benefits also include avoided CO_2 emission and oil import externalities valued at \$22/ton CO_2 and \$7.50 per barrel, respectively. The difference between benefits and costs is the net present value (NPV) listed in the last row of Table 1. NPV grows as time goes on, reaching \$3,500 in 2025 and \$4,600 by 2035 (all costs are given in 2010\$).

Base case technology costs are \$3,400 in 2025 and \$4,200 in 2035. Sensitivity cases with more and less optimistic assumptions yield costs ranging from \$3,200 to \$4,000 respectively in 2025 and ranging from $3,800 to $5,700 in 2035. The NPV results vary accordingly, though lifetime savings still significantly exceed costs in all cases (see Table 6 for details).

Large Benefits; Cost and Consumer Interest Challenges

The technology costs of achieving the fuel efficiency horizon projected here are large even though they are exceeded by the energy savings and also provide substantial non-monetary value in terms of reduced GHG emissions. Pursuing this trajectory may require ways to better reconcile the upfront costs, largely borne by automakers, with the substantial but diffuse benefits that accrue to consumers over vehicle lifetimes.

Figure 2. Technology costs and fuel savings benefits leading to a new fleet of tripled efficiency by 2035



The more that consumers can be interested in ongoing efficiency gains -- or at least have their interests pulled toward amenities that conflict less with fuel efficiency -- the easier it will be for automakers to invest in the technology and design changes needed. New efforts to engage consumers in fuel efficiency in spite of the vagaries of fuel prices will therefore be crucial. The auto market cannot expect to "have it all," that is, to see significant ongoing gains in power performance and other energy-impactful vehicle amenities while affordably achieving high levels of fuel efficiency.

A key implication of this analysis is that a great deal of progress can be made with evolutionary design and technology changes even though the exact mix of vehicle designs and technologies involved cannot be projected. Therefore, public efforts to foster interest in higher fuel efficiency should be technology neutral rather than promoting politically popular alternatives that are likely to be much less cost effective for reducing petroleum demand and limiting GHG emissions from the automotive fleet.

Attaining this fleetwide fuel efficiency horizon will entail a sustained effort to make efficiency improvement a high priority both in individual vehicle design and in automakers' overall product strategies as well as by consumers and policymakers. Policy guidance is clearly needed, although identifying the best set of policies is left for other work. Effective climate protection will also require greatly reducing the net GHG impact of fuel supply as well as attention to travel demand and other factors within the transportation sector and across the economy as a whole. In any case, if the fuel efficiency horizon identified here is achieved or even approached, the benefits will be substantial for both protecting the climate and reducing of oil dependence. ■

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A Fuel Efficiency Horizon for U.S. Automobiles

Introduction

Perennial concerns about energy security and growing concerns about climate disruption motivate measures to transform transportation energy use. Because it reduces fuel demand, improving vehicle energy efficiency is one way to address such issues. In the United States, automobiles (cars and light trucks) account for 60% of transportation energy use (Davis et al. 2009). Their dominance has made them a focus of efforts to improve efficiency and develop alternatives. Corporate Average Fuel Economy (CAFE) standards established in response to the 1973 oil embargo contributed to a near doubling of new car fuel economy by 1985.

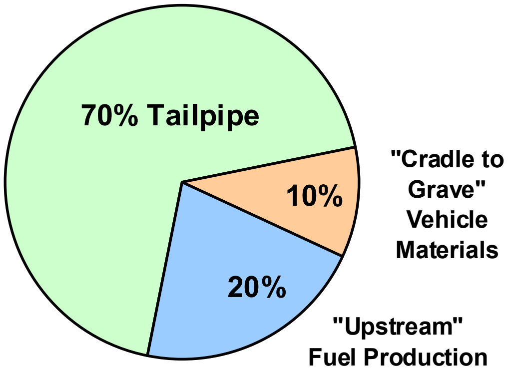
Market forces then worked against efficiency for most of the next two decades. The new fleet mix shifted from passenger cars to less fuel-efficient light trucks, which came to comprise half the fleet by 2004. Nevertheless, measured by estimated on-road fuel economy, the U.S. light vehicle stock was roughly 50% more efficient in 2005 than it had been in 1975. The new fleet in 2005 averaged 19.9 miles per gallon (mpg) according to EPA's adjusted estimates, barely more than the on-road stock average of 19.7 mpg estimated by FHWA (2006). In nominal (unadjusted lab-test) terms as used for regulatory purposes, the 2005 new light duty vehicle fleet stood at 24.8 mpg and 358 g/mi CO_2 (EPA 2009).

Fuel economy is the inverse of fuel consumption, which in turn maps to a travel activity-based measure of vehicle energy intensity such as Btu/mile or MJ/km. Important impacts of concern -- whether petroleum demand, CO_2 emissions or consumer operating cost -- scale with energy intensity, making it an ideal metric for analysis. Although fuel economy is commonly used in the United States, its inverse relationship to energy-related impacts can distort one's view. Thus, this report presents key results in terms of energy intensity, or "tank to wheels" consumption rate.

AUTO EFFICIENCY AND GHG EMISSIONS

The overall GHG emissions associated with motor vehicles result from two intersecting product lifecycles. One is the "cradle-to-grave" materials cycle for production and disposal of the vehicle and its components. The other is the "well-to-wheels" lifecycle for production and consumption of motor fuel. Figure 3 shows the breakdown for a typical U.S. light duty vehicle of today running on gasoline. About 70% of the combined lifecycle GHG emissions is from the tailpipe during vehicle operation (end use); 20% occurs upstream during fuel production; and 10% is associated with the materials cycle for the vehicle and its components.

Figure 3. GHG emissions breakdown for an average U.S. light vehicle



Source: Rounded values based on 20 mpg in-use fuel economy, 150,000 miles lifetime usage, and lifecycle estimates from Burnham et al. (2006).

For a given fuel, end-use emissions (largely tailpipe CO_2) depend on fuel chemistry and so are directly proportional to vehicle energy intensity. Upstream ("well to tank") emissions also scale with the rate of fuel consumption. Thus, 90% of the CO_2 emissions for today's vehicle-fuel system are tied to vehicle energy intensity and so represent the potential reductions that can be leveraged by improving automotive end-use efficiency.

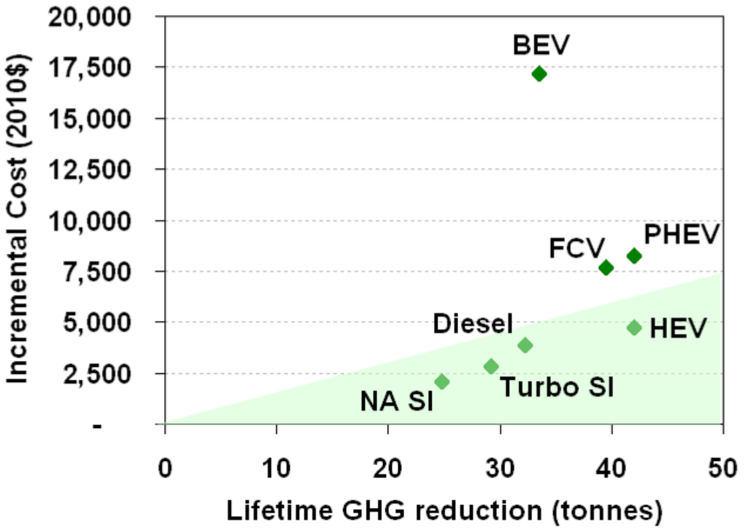
This report gives on-road ("real world") estimates for energy intensity in kilojoules per meter (kJ/m = MJ/km = 1.525 kBtu/mile). It also reports gasoline-equivalent fuel economy (mpg), fuel consumption (L/100 km) and tailpipe CO_2 emissions rates (g/mi), with these latter three metrics given using nominal values (as derived from EPA unadjusted 55% city, 45% highway driving cycle laboratory tests) unless otherwise stated. The historical fuel economy gain noted above took the new U.S. car and light truck fleet from 15.3 mpg in 1975 to 25.9 mpg by 1987 in terms of nominal fuel economy (EPA 2009, Table 1). The entire light duty stock saw a net gain from 13.3 mpg in 1975 to 19.7 mpg by 2005 in terms of estimated on-road fuel economy (DeCicco et al. 2007, Table A-1), corresponding to the 38% decrease in energy intensity from 6.2 kJ/m in 1975 to 3.8 kJ/m in 2005 as illustrated earlier in Figure 1.

Modest efficiency improvements may be acceptable, as they historically have been, in an energy security context. Energy conservation is part of a U.S. policy response that otherwise emphasizes measures oriented to energy supply, including military and diplomatic activities to secure access to foreign sources of petroleum and facilitate oil imports; expanding domestic petroleum production; tapping remote and unconventional fossil resources; and promoting alternatives such as biofuels, electricity and hydrogen. However, as climate protection rises in importance as a policy concern, the magnitude of the challenge related to unmitigated consumption of carbon-based fuels is amplified. Science-based targets for limiting GHG concentration imply ambitious goals, such as an 80% reduction in U.S. GHG emissions relative to recent levels by 2050 (USCAP 2007; White House 2009). Such goals indicate a need for much greater change in the transportation energy system along all dimensions, including vehicle efficiency.

To date, regulation to improve vehicle efficiency has proven to be both politically acceptable (though of uneven implementation) and measurably effective among the various options for addressing transportation energy use. NRC (2002) found that CAFE standards contributed to fuel savings that reached 2.8 million barrels per day (6.3 EJ) by 2000. These savings amounted to 25% of U.S. automobile fuel demand (the policy's direct target) and 12% of total U.S. petroleum demand. CAFE standards have also proven to be cost effective. As a leading analyst concludes, "although numerous hypothetical and theoretical objections to CAFE have been raised, tangible evidence of significant negative effects is lacking" (Greene 1998: 595).

As energy-related concerns returned to prominence in recent years, policymakers again turned to regulation, as seen in the recent California and Federal initiatives on GHG emissions and fuel economy respectively. Efforts converged in a single national program, the EPA & NHTSA (2010) Joint Rule for model years 2012-16, which requires a 27% average reduction in new light vehicle energy intensity from the 2005 level. The agencies recently announced a plan to develop a next round of standards to cover model years 2017-2025 (EPA 2010).

Figure 4. Projected per-vehicle incremental costs and GHG reductions for future automotive technologies in a 2035 time horizon, based on MIT (2008)



Source: MIT (2008), Table ES-1 and Figure ES-1(b). Area shaded (by author) covers options based on vehicle efficiency only that do not require major changes in fuel supply system. Technologies are: NA SI = naturally aspirated spark ignition; Turbo SI = turbocharged spark ignition; Diesel = turbocharged compression ignition; HEV = hybrid-electric vehicle with NA SI engine; PHEV = plug-in hybrid-electric vehicle with NA SI engine; FCV = hydrogen fuel cell vehicle; BEV = battery electric vehicle. All future options assume a streamlined, 20% mass-reduced vehicle platform. Costs (retain-price equivalent) and full vehicle+fuel lifecycle GHG reductions (metric tonnes) are shown relative to a 2006 midsize car (origin of axes).

EFFICIENCY IN THE CONTEXT OF OTHER OPTIONS

While clearly important, auto efficiency represents an incomplete focus for addressing energy and climate issues. Automobiles are but one mode of transportation, which is in turn but one sector of the economy. Efficiency is but one factor that determines oil demand and GHG emissions, others being travel demand and the fuel supply system. Most analyses include automobile efficiency improvement as one part of a broader set of opportunities to be pursued (Greene & Shafer 2003; Cambridge Systematics 2009). Particularly for climate protection, it is important to address regulations and other measures that target vehicle efficiency within a policy framework capable of linking vehicle efficiency needs to overall GHG limitation goals while balancing its benefits and costs against those of the other factors that determine emissions (DeCicco 2010).

In terms of the vehicle-fuel system, reducing the net carbon impact of fuel supplied is crucial. Biofuels encompass many options, but just what their net benefits are and even how to properly evaluate them in light of globally coupled energy and terrestrial systems remain open questions. Some analysts advocate all-electric drive, which is also seen as a basis for "reinventing" the car (Sperling 1996; Mitchell et al. 2010). Although expensive because of inherently high materials costs for batteries and other components, electrification improves end-use efficiency relative to current vehicles because thermodynamic losses are either shifted to the electric supply system (for grid-connected electric vehicles) or avoided (for fuel cell vehicles, though other losses occur). Such "carbon free" energy carriers are now more carbon intensive than petroleum-based fuels per unit of energy supplied. For current vehicles the efficiency of electric drive more than compensates. However, this advantage greatly narrows if internal combustion engine vehicles -- including grid-free hybrids -- see their efficiency greatly improve, as seen above in Figure 4 and further elaborated in this report.

Vehicle-fuel systems are commonly analyzed on a "well-to-wheels" basis, reflecting the effects of both vehicle efficiency and fuel carbon (GHG) intensity. For gasoline, a typical "well-to-tank" carbon intensity is 94 gCO_2eq/MJ, reflecting the 70% + 20% tailpipe + upstream portion of the breakdown shown in Figure 3. For electricity, the emissions all occur upstream during power distribution and generation. U.S. electricity remains half based on coal, resulting in a current average carbon intensity of 177 gCO_2eq/MJ (2010 extrapolation based on data from eGrid and Electric Power Annual [EPA 2010b; EIA 2010]). Although electricity is now nearly twice as carbon intensive as gasoline per unit of energy supplied, its GHG emissions intensity has been trending downward as generation efficiency improves and coal's share slowly declines. In contrast, the GHG emissions for gasoline production are creeping upward as supply turns to heavy crudes, oil sands and other unconventional resources (Brandt & Farrell 2007).

The MIT (2008) analysis applies assumptions for fuel cycle GHG emissions that are cautious and consistent across sectors, using EIA (2007) reference-case projections for electricity generation mix and natural-gas-based hydrogen production over the next 30 years. Over this horizon, MIT analysts see the potential for substantial (yet non-breakthrough-dependent) progress in gasoline internal combustion vehicles (including grid-free hybridization). Figure 4 plots the resulting estimates of incremental vehicle costs against lifetime reductions in GHG emissions. The point of reference (origin of graph) is a 2006 midsize car rated at 26.4 mpg (8.9 L/100km unadjusted; 3.6 kJ/m on-road) having lifetime GHG emissions of 69 tonnes (metric) and a retail price of $20,500 (2010$). Thus, the hybrid-electric vehicle (HEV) estimate, for example, is that a lifetime reduction of 42 tonnes (61%) would be achieved at an added vehicle cost of $4,700.

The shaded band in the lower portion of the graph highlights an evolutionary pathway that does not require major investments in fuel supply and distribution infrastructure. MIT's "apples-to-apples" comparison finds that improving efficiency is the least costly way to cut transportation GHG emissions for the foreseeable future. As seen in Figure 4, BEVs and FCVs offer no advantage over optimized grid-free HEVs as long as both the liquid and electric energy supply systems remain largely based on unmitigated use of fossil fuels. These results buttress this paper's focus on vehicle efficiency while leaving for other discussions the many issues surrounding alternatives (such as electricity, hydrogen and biofuels), which their proponents believe are essential for the future even if more costly at present.

OVERVIEW OF REPORT

The report provides context for the issue by reviewing past trends in fuel economy and related attributes. The achieved level of fleetwide efficiency results as much from design choices made about how to harness innovation as it is about technology innovation itself. Progress in automotive engineering is ongoing but often used to offer features other than higher fuel economy. This realization suggests a broader way to view options for improving efficiency. The concept of "efficiency compatible" solutions is introduced to complement the evaluation of technical solutions, emphasizing the perspective fact that vehicle efficiency improvement is as much a matter of design priority as it is of technology adoption.

With this perspective in mind, the report turns to a synthesis of previously published technology assessments in order to project a long-term (2035) efficiency horizon. The discussion distinguishes incremental versus fundamental approaches to analysis, relying on the latter to identify a large potential for efficiency gain through evolutionary technology change with a proviso that further gains in fleet-average performance are foregone. The analysis then examines rates of technology adoption, finding that the rate of hybridization likely to be needed is comparable to the rates at which some major technology changes occurred in the past. Although high utilization of hybrid drive is a part of the efficiency horizon "existence proof," the interpretation given here is technology neutral. While many studies identify specific technology "pathways," this study emphasizes that the technology mix should not be taken literally and that automotive engineering offers a range of solutions for realizing fundamental efficiency gain.

Turning to cost issues, the report draws on recent studies that reflect the reductions in cost available through evolutionary strategies. In keeping with the fundamental, technologically agnostic engineering assessment, costs are treated at a highly aggregate level using quadratic cost curves. Such curves fit previously published detailed cost estimates reasonably well while reflecting an assumption that marginal costs grow linearly as each next step of energy intensity reduction is sought. Technology costs are compared to benefits based on fuel savings evaluated over the lifetime of the new fleet. Although the lifetime benefits exceed costs, the fact that costs grow steadily raises questions regarding the extent to which automakers can recoup the upfront costs of technology improvement. A final section examines the sensitivity of the results to differing assumptions.

Compared to the prior literature on automotive efficiency, this report presents three new ways of thinking about the issue. One is highlighting the primacy of design priority in shaping the future of the fleet. If high priority is given to efficiency improvement, then efficiency-compatible product planning strategies should be considered in addition to the technology strategies usually analyzed, and high fuel efficiency levels identified by fundamental engineering analysis can be realized. Another contribution is applying logistic curves based on fits to historical technology change in order to develop ambitious but plausible rates of adoption for hybrid drive. A third new approach is modeling fleetwide costs using quadratic functions of energy savings that shift through time. The development of these curves is detailed in the report's Appendix.

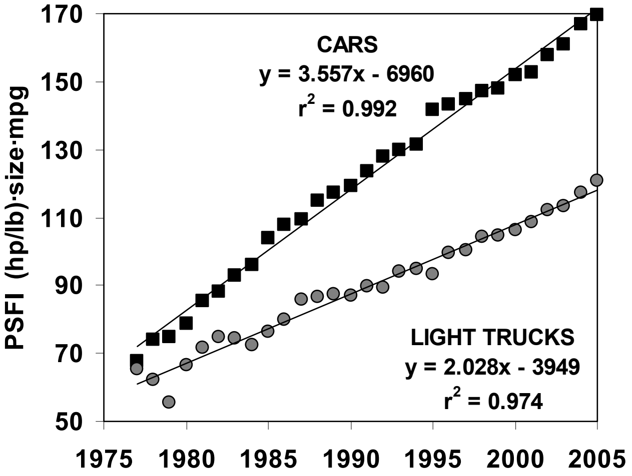
Past Efficiency-Related Trends

It is now well appreciated that until very recently, most of the past two decades' advances in automotive engineering went toward delivering faster performance, greater carrying capacity and numerous amenities in addition to lower tailpipe emissions of non-GHG pollutants and better crashworthiness. EPA's Fuel Economy Trends reports (EPA 2009 and earlier editions) document how car and light truck fleet characteristics evolved with increasing horsepower while new fleet fuel economy slowly declined from its 1987 peak until recent improvements started in 2005. Historical U.S. new fleet fuel economy was shown in Figure 1; more detailed charts of the trends are published by EPA (2009) and so are not repeated here.

STEADY GAINS IN TECHNICAL EFFICIENCY

This report uses *fuel efficiency* synonymously with *fuel economy*. The term *technical efficiency* is used here to denote the broader notion of how efficiently a vehicle provides other amenities such as carrying capacity and acceleration performance. While fuel efficiency did not improve for many years, technical efficiency did improve and historical data reveal that such improvements have been quite steady. To measure technical efficiency gains, An & DeCicco (2007) developed a Performance-Size-Fuel-economy Index (PSFI), which provided a strong linear correlation to historical data for these variables.

Figure 5. PSFI for new cars and light trucks, 1977-2005



Source: An & DeCicco (2007); PSFI = Performance - Size - Fuel Economy Index, with size measured as interior volume for cars and wheelbase for light trucks.

Figure 5 shows PSFI results for the new car and new light truck fleets. Relative to a 1977 base year, the index shows average rates of increase of 5.3% per year for cars and 3.1% per year for light trucks. These estimates average out to a historical technical efficiency gain of 4.2% per year for the light duty fleet as a whole.

The PSFI trends can be interpreted as revealing an intrinsic rate of technological progress on vehicle energy efficiency. Automakers appear to adopt efficiency-related technology at a steady rate whether or not that progress is used to achieve net gains in fuel economy. Such findings are in line with other analyses that examine the trade-offs between reducing fuel consumption and increasing other vehicle attributes such as weight and performance (Cheah et al. 2008).

EPA (2009) documents an ongoing gain in a weight-fuel economy metric (ton miles per gallon) and also examines the effects of weight, performance and vehicle size mix on potential fuel economy. For example, using 1981 weight and performance distributions, EPA calculated that 2005 cars and light trucks would have had fuel economy levels 26% and 34% higher, respectively, than actual 2005 values. Examining changes in new fleet mix, size, performance and weight, Greene & Fan (1994) found nearly linear technological progress equivalent to 0.6 mpg per year for cars, corresponding to a 3.8% per year rate of technical efficiency gain relative to a 1975 base. Referenced to 1980 levels and controlling for horsepower, torque and weight, Knittel (2009) estimated that light vehicle fuel economy could have been 50% higher in 2006 than it actually was.

These overall technical efficiency trends correspond to observed gains in engineering figures of merit. A key metric is engine specific power, or peak power per unit of engine displacement as measured in kilowatts per liter (kW/L), for example. It also exhibits a strikingly linear trend (see Figure 6 later in this report), with estimated rates of gain of 5.5% per year for cars and 4.3% per year for light trucks (An & DeCicco 2007). Lutsey & Sperling (2005) identified steady trends in progress for other efficiency-related engineering metrics, including aerodynamic drag and rolling resistance as well as engine performance.

An & DeCicco (2007) concluded that one implication of a linear PSFI trend is that higher levels of performance and size imply a lower level of potential fuel economy gain, at least as long as the intrinsic rate of progress is maintained at the historically observed rate. Mathematically, letting P = performance, S = size, F = fuel economy, and t = time, a linear PSFI trend can be represented as

$$\mathrm{PSFI}(t) = P(t)\cdot S(t)\cdot F(t) = \alpha t + \beta$$

where α and β are the slope and intercept of the trend line. Partial differentiation then yields

$$\partial F/\partial t = \alpha/(P\cdot S)$$

which implies that the rate of trend-consistent progress on fuel economy is inversely proportional to achieved levels of performance and size. In other words, ongoing gains in performance and size "use up" technical progress on vehicle efficiency, and so a significant portion of the intrinsic potential for improving fuel economy is lost.

PERFORMANCE'S EFFICIENCY PENALTY

The foregoing analysis underscores the efficiency-performance trade-off likely to be faced in the years ahead. For example, although the potential for fuel economy gain at constant size and performance was 4.2% per year relative to the 1977 new fleet, it falls to 2% per year relative to 2005 fleet levels of size and performance (based on An & DeCicco 2007, Table A1).

This effect is dominated by acceleration performance. Either technological progress more rapid than historically observed or a relaxation of fleet average performance levels is needed to realize fuel economy gains at rates similar to those based on past trends. Increasing the rate of technological progress suggests increasing costs, an inference borne out later in this report by the rising costs projected for advancing the fleet toward the efficiency horizon identified. Conversely, cost impacts would be moderated if performance expectations are moderated.

Rising acceleration performance penalizes potential fuel efficiency gain because it prevents advances in powertrain engineering from being utilized in ways that significantly improve the part-load efficiency of the engine-transmission system. Hybrid drive mitigates this trade-off, but also comes at a greater price than conventional powertrain refinements. Thus, speeding up the rate of fleetwide fuel economy gain through hybridization is consistent with the cost implications just noted.

The performance penalty can be seen in the lack of progress in automobile tractive efficiency, which is the fraction of fuel energy ultimately delivered to the wheels for overcoming the basic forces of vehicle motion. These forces -- in energy terms called tractive loads -- are aerodynamic drag, tire rolling resistance and the dissipation of kinetic energy through braking. The tractive efficiency of a typical late-model U.S. passenger car is only about 16% (for a 2006 midsize sedan; MIT 2008). A similar value of 17% is obtained for a late-model midsize SUV (derived from graphic in Ponticel 2010). These recent estimates match the 17% estimate made for an average car of the early 1990s (DeCicco & Ross 1994). As the EPA data show, the 1990-2006 period saw little gain in average fuel economy but a 35% increase in average power-to-weight ratio. Tractive efficiency had increased significantly in earlier years; it was estimated at 12% for an average 1980 car (Gray and von Hippel 1981). From 1980-1990, average new car fuel economy increased 18% and average power-to-weight ratio increased 25%.

A point of comparison is the brake efficiency of an engine, referring to the energy available at the engine's output shaft (input to the transmission) relative to the energy in the fuel. It reflects thermodynamic losses and other heat losses. Peak brake efficiency is attained at an engine's ideal operating conditions of wide-open throttle and relatively low RPM. For current gasoline engines peak efficiency is around 35%, or about double the average tractive load efficiency. If engine efficiency is improved through engineering refinements that reduce frictional losses under part-load conditions but performance continues to grow, the engine still largely operates at points well away from peak efficiency and little progress is made on tractive efficiency. That has been the situation since new fleet fuel economy peaked in 1987. Unless ongoing performance gains are moderated it will be difficult to increase fuel economy without either incurring much higher technology costs or making other trade-offs (such as a smaller vehicle mix).

Hybrid drive enables an advance in tractive efficiency by using the electric drive system to handle a much greater fraction of part-load operation, reserving the combustion engine for operating conditions closer to its peak efficiency. As MIT researchers point out,

> The difference in relative fuel consumption benefit from hybridization between different vehicles depends mainly on how efficiently the original engine was operating. A vehicle with a lower average engine load in its non-hybrid version will have lower average engine efficiency and will thus benefit more from using a hybrid powertrain. (Kasseris & Heywood 2007: 11)

Higher performance vehicles operate at lower average engine loads in ordinary driving. Kasseris & Heywood found that hybrid drive reduced fuel consumption by nearly 60% for a higher performance sedan versus 50% for a lower performance sedan.

Hybrid drive also enables recovering kinetic energy through regenerative braking. Therefore a more basic measure of tractive efficiency might count only the inherently dissipative forces of aerodynamic drag and rolling resistance. With such a convention, end-use efficiency would appear even lower; for example, only 9% of the fuel energy ultimately gets applied to overcome those two tractive loads for a current average car. Without delving further into possible definitions of vehicle energy efficiency, suffice it to say that the tractive efficiency metric noted above suggests ample opportunity for improvement, and that minimizing increases in power performance is likely to help minimize the costs for making such improvements.

Efficiency Opportunities

The basic principles for improving internal combustion engine vehicle fuel economy have been analyzed extensively since the issue was elevated by the 1970s oil crises. It comes down to minimizing the energy loads that must be met while maximizing the efficiency with which the powertrain (engine-transmission system) converts fuel energy into useful work for meeting the loads. Even as technology has been expended to improve technical efficiency as seen above, innovation yields new options to address the same basic challenges of decreasing vehicle loads and increasing powertrain efficiency.

Table 2. Design strategies for automotive energy efficiency

COMPATIBLE	TECHNICAL
• Creative downsizing and styling	• Load reduction
• Intelligent systems content	• Engine improvements
• Performance matching	• Transmission improvements
• Interior packaging efficiency	• Hybrid drive

The main development of significance in recent years is hybrid drive. While long known as an R&D opportunity, Toyota's 1997 introduction of the Prius placed hybrid drive squarely on the list of solutions available for evolutionary improvement of vehicle fuel efficiency. However, technology for efficiency -- which hybridization has come to epitomize -- cannot be evaluated in isolation from the market and design context that determines not only which technologies are used but also what benefits they deliver.

COMPATIBLE AS WELL AS TECHNICAL SOLUTIONS

Table 2 offers a holistic look at the ways that automotive product planners can address vehicle efficiency, identifying what are termed efficiency-*compatible* design strategies in addition to the *technical* strategies commonly analyzed.

Technical strategies entail engineering modifications that raise fuel efficiency while preserving other vehicle attributes. Compatible strategies involve rethinking design goals for both individual vehicles and the product mix while exploiting features to enhance customer value in ways that are less inherently fuel consumptive. Through product planning choices that avoid conflict with fuel efficiency, or facilitate the ability to apply engineering progress to efficiency rather than performance, compatible strategies can help automakers minimize the difficult-to-recover costs of adding technology to improve fuel efficiency beyond the levels that customers might choose on their own.

Most fuel economy assessments focus on technical options and assume that other vehicle attributes are constant. However, attributes have not been constant. Indeed, many years of changes in capacity and performance have been incompatible with fuel economy improvement. Such attribute changes increase energy loads or prevent powertrain refinements from closing the gap between peak and part-load engine efficiency. If improving efficiency becomes a priority -- expressed as a shared sense of direction among consumers, automakers and policymakers -- then all strategies are implicitly on the table even if there are ample technical opportunities to increase fuel economy without changing other attributes. While the fuel efficiency analysis horizon developed in this report adheres to the constant performance convention, this discussion highlights these issues in recognition of the challenges involved and just how much of a departure from past patterns it would be to redirect technological progress toward raising fuel efficiency instead of any further increase in fleet average performance.

Although his subject is very small vehicles, designer Robert Q. Riley offers a useful insight when he states that developing new paradigms through innovative design is "closer to the grasp of available technique than the technical solutions needed to double or triple the fuel economy of conventional vehicles" (Riley 1994: 356). Approaches that fight less against fuel efficiency are not just a matter of technological feasibility, but also of affordability. Large fuel efficiency gains in line with the need to limit GHG emissions will be less costly to achieve if the mix of vehicles sold is less massive than what resulted from design priorities that gave little importance to reducing consumption-related impacts. A resurgence in small car classes, the relative success of products such as the Mini Cooper (perhaps anticipated a decade ago by the Chrysler PT Cruiser, which sold even when gas prices were low and large SUVs were still on the upswing), and the proliferation of segment-defying designs on compact and midsize platforms: such trends illustrate the roles that creative downsizing and styling can play in product strategies compatible with the need to improve fuel efficiency.

Toward Virtual Performance

From a business perspective, degrading customer appeal is of course counterproductive. The challenge is finding ways to emphasize features, such information technology (IT) and styling, that might appeal to buyers with less recourse to design requirements that degrade fuel efficiency. The fact that IT is an ever-expanding area of opportunity for automobiles (as throughout the economy) opens up numerous possibilities for options compatible with greater fuel efficiency. What can be termed "virtual performance," measured by the types and quality of IT features as well as by technical metrics such as memory capacity and bandwidth, is beginning to compete for consumer dollars with traditional physical power metrics such as horsepower and engine displacement.

This trend will accelerate as demographics shift toward millenials ("Gen Y") and successive cohorts. Millenials now exceed one-quarter of the U.S. driving population and "have an insatiable appetite for digital technology," according to Ford President of the Americas Mark Fields (2008). Automakers are pursuing these opportunities as customers show an increasing willingness to pay. The average transaction price of the new Ford Focus, for example, was increased by $750 through optional purchase of the Sync® IT package, which was approaching 50% take rate (Fields 2008).

While caution is needed to avoid compromising safety when adding IT features, the category also includes driving and safety enhancements such as adaptive cruise control, stability control, parking assist, rear-view cameras and emerging crash-avoidance technologies. These virtual performance features help drivers deal with everyday road conditions better than performance capabilities than can often only be exercised on a race track. Such IT options are migrating from luxury segments into mainstream cars (Kranz 2006), providing automakers with opportunities to offer customer value in ways that displace strategies based on size and horsepower.

The Challenge of Performance Expectations

As new, efficiency-compatible content expands, automakers may have a chance to put traditional performance metrics into better balance with the concerns that motivate policy. In Table 2, *performance matching* refers to a pragmatic approach on power instead of ongoing power gains. Such a shift is yet to be seen statistically; at least for now, customers seem to value more of both virtual and physical performance. The view in automotive circles is that the horsepower war is far from over and that the market will see trade-offs in other attributes, such as size, before relinquishing further performance enhancement (Winter 2009a).

These sentiments underpin the prevailing approach on engine sizing as new, high-specific output options, such as turbocharged direct-injection gasoline engines, are scaled to exceed the power performance requirements of larger engines they replace. In the impressionistic world of car sales, automakers see enough challenge in convincing consumers that they will get good performance with, say, a 6- rather than 8-cylinder engine, let alone trying to convince them that they can have a great driving experience without a high power-to-weight ratio.

At least to some extent, the horsepower war is a cultural phenomenon, an interplay between car journalists and other market intermediaries attuned to subtleties of performance and handling. This dynamic promotes products that advance such metrics each year and at least implicitly pans products that lag in performance, even if this year's laggards perform at levels that would have earned them high marks in previous years. Praiseworthy performance gets benchmarked, for example, in a recent review of the Land Rover LR4 luxury SUV, which with its 5.0L, 375 hp V8 and 5,700 pound curb weight delivers "smooth and effortless acceleration" and "towed our 5,000-pound test trailer to 60 mph in an excellent 12.8 seconds" (*Consumer Reports,* April 2010: 55). A 12.8 second zero-to-sixty (Z60) time was the estimated average for all light duty vehicles -- unladen and trailerless -- in 1988, when average curb weight was under 3,000 pounds, gasoline was 91¢/gal ($1.66 in 2010$), sales were a robust 15 million units and the market was widely seen as having recovered from the detuned doldrums of the post-oil-shock early 1980s.

The customer experience of good performance is immediate and even visceral. This is in contrast to the benefits of fuel efficiency which -- unless fuel prices are high and awareness of higher fuel prices is strong -- are either unseen and societal (e.g., lower environment impacts) or take the form of deferred gratification through fuel savings experienced periodically when refueling and with marginally lower expenses over the period of ownership. The generally tepid interest in fuel economy in spite of the cumulative savings it offers can be explained by consumers' loss aversion and the perceived uncertainty of the fuel-saving benefits (Greene et al. 2009). Thus, it is no surprise that under most conditions to date, performance has trumped efficiency. While there are signs that fuel efficiency is becoming more of a selling point, how strong and durable that trend will be is yet to be seen.

In contrast, promotion of class-leading performance can be found in any market segment and featuring it is a time-honored automotive marketing and journalism idiom. Those attempting to advance green technologies, for example, electric cars such as the Tesla Roadster or promised Fisker Karma, feel compelled to market high performance and prove that their products are not underpowered "golf carts." The estimated new fleet average Z60 time has fallen to 9.5 seconds (EPA 2009) but exotic sports cars now clock in at under 4 seconds, indicating that the limit of fleetwide performance remains a long way off. Pursuing an efficiency-compatible performance matching product strategies would be a profound paradigm shift. However, failing to rethink the extent of design priority placed on performance enhancement may consign the industry to slower and more costly progress on higher fuel efficiency than might otherwise be necessary.

The last compatible strategy listed in Table 2 is packaging, which involves designing vehicle interiors to provide a given amount of usable, comfortable space within a given size overall structure. It is often mentioned among the technical options for mass reduction (as by Duleep

2010 and previous studies), but is distinguished here from engineering approaches that use new materials or structural and assembly techniques. Of course, boundaries blur among strategies for reducing mass; the larger point is that designers can find ways to meet spatial requirements while minimizing the amount of material needed for safety and amenity.

TECHNOLOGIES FOR EFFICIENCY

Technical options for fuel efficiency include two broad approaches: tractive load reduction and powertrain improvements. Both can increase fuel economy without significantly changing size, performance, carrying capacity and other customer amenities. Such strategies are the traditional focus of technology assessments as reviewed by Greene and DeCicco (2000), examined in the NRC (1992, 2002, 2008, 2010) studies and applied in regulatory analyses up to and including EPA & NHTSA (2010). Improving efficiency through technology was successful historically, with an estimated 80% of U.S. light vehicle fuel economy improvement since 1975 having been technological in nature (DOE 1995).

Fuel efficiency measures evolve continuously. Technologies already in production can be used more widely, implemented more optimally and see reductions in cost. Emerging technologies now in late stages of development are introduced and join the production refinement process as time goes on. Advanced technologies now in earlier stages of R&D will become available over the course of the 25 year time horizon considered here. Cost is always a critical factor: a technology is not ultimately available unless it is affordable. Of course, what cost levels are considered affordable is a key issue. The more expensive options, such as hybrid powertrains, may find their utilization limited by upfront costs even if the net present value of their fuel saving benefits minus costs is strongly positive.

Tractive Load Reduction

Reducing tractive loads, which refer to the energy needed to overcome inertia and the resistance due to aerodynamic drag and tire friction, is a highly leveraged option for improving vehicle fuel efficiency. Given that today's average powertrains have a net efficiency over U.S. driving cycles of 16%-17% (about one-sixth), a given reduction in tractive energy requirements can translate to a sixfold reduction in fuel energy requirements assuming that the powertrain is reoptimized for constant performance.

Mass reduction

A cornerstone of technical efficiency improvement is mass reduction without downsizing. In general, a 10% reduction in mass yields a 6.5% reduction in fuel consumption when the powertrain is reoptimized (EPA & NHTSA 2010 TSD: 3-76). The sensitivity is somewhat lower for hybrid vehicles where regenerative braking enables recovery of inertial energy (An & Santini 2004; Pagerit et al. 2007). Materials substitution and improved technique with existing materials have roles to play in reducing vehicle mass. Engine downsizing and the associated mass decompounding can also provide additional weight reduction.

The potential for mass reduction and its cost-effectiveness for improving efficiency are both substantial (Lutsey 2010). However, it has been inadequately treated in some studies such as NRC (2002 and its updates) and often underappreciated in policymaking circles. At issue have been the contentious and sweeping claims -- ultimately unsubstantiated scientifically -- about safety risks from mass reduction. Such allegations sparked a trenchant dissent in the NRC (2002) study; that discussion provides a rigorous, well-considered treatment of the topic (Appendix A by Greene & Keller in NRC 2002). It is prudent to leave unchanged an earlier conclusion that "concern for safety should not be allowed to paralyze the debate on the desirability of enhancing the fuel economy of the light-duty fleet" (NRC 1992: 7).

Some concept cars and a few production vehicles demonstrate major changes in materials use. Examples include aluminum-intensive structures of several Audi and Jaguar models, composite-based structures such as Chrysler's ESX concepts and the ultralight carbon-fiber bodies as proposed by Lovins et al. (1993). Aluminum and magnesium have seen steady increases in component level applications for several decades and competition among materials for cost-effective mass-saving solutions is ongoing (Ward's 2008; Winter 2009b). Plastics continue to see new uses and nanotechnology is enabling new formulations for saving weight while offering other benefits (Miel 2004, 2008). Plastics are beginning to make inroads for weight reduction in vehicle glazing (Weernink 2007).

Carbon fiber is perhaps the ultimate material for high strength plus low mass. BMW recently broke ground on a joint venture facility to produce carbon fiber for its upcoming Megacity vehicle (BMW & SGL 2010). Top carbon fiber producers in Japan, now largely oriented to supplying non-automotive uses, are steadily expanding their capacity for automotive applications (Greimel 2008). Nevertheless, although carbon fiber is seeing expanded use for components in mainly high-end vehicles, the materials revolution promoted by Lovins et al. (1993) has yet to materialize, as adoption remains slow due to still much higher cost (LeGault 2008).

For mainstream, high-volume production over the foreseeable future, most automakers will continue to take an evolutionary, "menu" approach to materials. Although the prospect of a major shift in materials has long been identified as a possibility, it still remains true that automotive materials changes are "distinctly evolutionary in nature" even though "the cumulative impact of a long series of minor innovations could allow an eventual thorough redesigning of vehicles" (Amendola 1990: 498). Automakers assess the range of options that are available and cost effective for given applications at a given time and select materials accordingly.

Established materials continue to evolve, narrowing the gap with alternative materials and doing so with little or no net cost impact (DeCicco 2005). Responding to PNGV work that aimed for substantial (order of 40%) mass reduction by emphasizing aluminum and composites, American Iron and Steel Institute (AISI) programs have demonstrated large reductions using advanced steel technologies. That work found that high-strength steels plus innovative design, forming and joining techniques can reduce auto body mass by 35%–40% (AISI 2002; Krupitzer 2008). Recent and near-term programs are obtaining 22%–30% weight savings in major structural assemblies, chasses and closures at no additional cost (Krupitzer 2009). Although the current fleet incorporates many such advances, AISI's Advanced Vehicles Concepts (AVC) and FreedomCAR-oriented Future Steel Vehicle analyses show that evolutionary progress using steel-based technologies still has a large potential for ongoing progress, targeting as much as 50% mass reduction at no additional cost (Krupitzer 2009).

Evolutionary change without higher cost

Under an evolutionary process, progressive mass reduction can be achieved over regular product development cycles at little or no added program cost if saving weight is made a high enough priority. A recent comprehensive study of structural, chassis, interior and ancillary components found that improved materials along with component integration and assembly techniques offer a near-term mass reduction potential of 21% at a 2% cost decrease and 38% at a 3% cost increase (Lotus 2010). The higher reduction target (which Lotus termed a "high development vehicle") involved a greater degree of materials change, but the aforementioned AISI studies suggest that similar reductions can be achieved still using largely steel-based structures.

Choices automakers make within cost-constrained vehicle programs will draw upon a range of options and exploit the competition among materials to hold costs down even as additional mass reduction is sought as long as the rate of reduction falls within the range of evolutionary change. This picture is quite different than that assumed in the NAS studies and recent regulations such as EPA & NHTSA (2010), which assumed a fixed cost of roughly $1.50 per pound of mass saved. That implies an RPE impact of roughly $1200 for 20% mass reduction in an average vehicle, a 4% increase in contrast to the 2% cost decrease found by Lotus (2010) and the cost savings implied by the AISI studies.

A 20% mass reduction, as assumed by the MIT (2008) study on which this report's efficiency horizon is based, would lower light duty fleet average curb weight by 760 lbs relative to the recent average of 3800 lbs. That would amount to trimming an average of 30 lbs per year over the 25 year horizon between now and 2035. By comparison, the light duty fleet gained an average of 44 lbs per year from 1987 to 2007 (weight gain has greatly slowed over the past three years; see EPA 2009, Table 2). Thus, the mass reduction assumptions used here fall well within an envelope of evolutionary change. Note that mass reduction need not, and perhaps should not, be uniform across the fleet: heavier vehicles can stand to lose more weight and vehicles that are already relatively small and light might not lose any or could even see incremental gains.

Aerodynamic and tire improvements

Similar themes apply to aerodynamic drag and tire rolling resistance. Drag coefficients (C_D) can be cut by 10% or more during redesign and have been declining steadily. However, when vehicles are upsized the increase in frontal area at least partly offsets the decrease in C_D and a net reduction in drag force may not be fully realized. Similarly, while tire compounding techniques enable lower rolling resistance (C_R), other design priorities for improving handling, off-road capability and performance -- as well as styling objectives that use large tires for reasons of appearance -- can negate the potential for net gains in tire efficiency.

On C_D, recent benchmark averages are 0.33 for sedans, 0.43 for SUVs and 0.48 for pickup trucks (Yang and Khalighi 2005). Given that passenger C_D levels on the order of 0.20 have already been demonstrated, and assuming a comparable degree of relative progress for other types of vehicles as well as a rebalancing of the fleet mix away from very boxy truck-like designs to crossovers, sport wagons and other larger-size body styles amenable to streamlining, it is reasonable to assume a similar rate of progress across the fleet. Recent studies have shown that even challenging body styles such as pickups can see significant drag reduction (Yang and Khalighi 2005; Monaghan 2008). Over a 30 year horizon, that would enable an average C_D reduction rate on the order of 1.5% per year, more rapid than the 1% per year assumed by

Kasseris & Heywood (2007). That study also assumed the feasibility of a 1.65% per year rate of tire C_R reduction. These assumptions are among those underpinning the future new vehicle efficiency levels on which the scenarios here are based.

Although not reviewed here, additional incremental load reductions can be obtained by improving the efficiency of various vehicle accessories as discussed by the NRC reports, the EPA & NHTSA (2010) TSD, and other detailed technology assessments.

Powertrain Efficiency

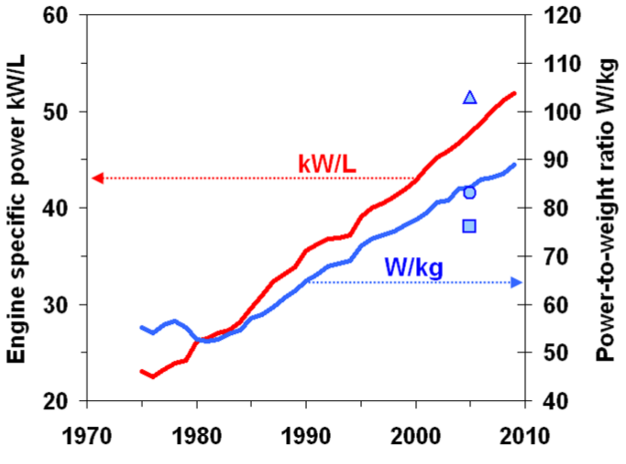
The largest potential for efficiency gain is found in the powertrain, involving the engine-transmission system and including various forms of hybrid drive. The distinctions "diesel" vs. "hybrid" vs. "advanced gasoline" are in many ways artificial for the purposes of a public assessment, even though they represent choices that individual automakers must make privately during product development. The options available are best viewed as a continuum, with different versions of advanced engines, transmissions and hybrid configurations likely to be selected in different ways as automakers decide which combinations of technology are best suited to deliver the right balance of fuel efficiency, performance and cost for a given vehicle in a given segment.

In addition to different types of powertrains, other opportunities for optimizing vehicle system energy efficiency may also emerge. Strategies for energy harvesting (e.g., using thermoelectric or other technologies) can recover additional portions of the substantial low-grade heat now dissipated in vehicles. Such options are not reviewed here, but could offer alternative ways to help reach ambitious efficiency targets.

Engines

The specific power (kW/L) of engines has been steadily increasing as shown here in Figure 6. Those gains have been applied to increases in vehicle power-to-weight ratio (W/kg, equal to kW/tonne), shown on the right axis of the figure, which in turn provide increased acceleration performance. Increases in specific power can instead provide increases in fuel economy if engines are downsized to maximize the allocation of the technological benefit to reducing fuel consumption as opposed to enhancing performance. Ongoing advances in engine technology enable a continuation of specific power gains for the foreseeable future.

Figure 6. Trends in engine specific power and vehicle power-to-weight ratio



Source: Trend lines derived from EPA (2009) for combined U.S. car and light truck fleet. The individual points are power-to-weight ratios for the 2005 reference vehicles analyzed by Kasseris & Heywood (2007): ○ for average performance sedan; □ for pickup truck, and △ for high performance sedan.

Exploiting this progress through engine downsizing is especially valuable for the larger, high-consumption segments of the market, where efficiency gains are well leveraged for reducing fleet average energy intensity. EPA (2009) documents how the specific power of light trucks significantly lags that of cars. Although noise and vibration concerns may limit engine downsizing in smaller vehicles, substantial gains can be had by displacement reductions on the order of one-third that will be possible for V6 and V8 engines (Duleep 2010). Iconic large-displacement engines traditionally featured by some automakers will have diminishing market roles in the future (Wernie 2008). Instead, exploiting a range of engine refinements to enable small engine displacements while maintaining performance is widely seen in the industry as the key near- and mid-term strategy for efficiency gain (Lewin 2008).

One such set of refinements involves the valvetrain. Variable valve control (VVC) refers to a set of approaches for optimally controlling intake and exhaust valves. VVC use has been increasing since its earliest U.S. introduction by Honda two decades ago. Cam phasing and other forms of variable valve timing are already widely used as part of the recent technical efficiency gains that went largely to performance enhancement. All major automakers have now commercialized some form of VVC (Simanaitis 2007 provides an accessible overview). Variable valve lift and other VVC refinements still have a potential for greater use. Among other benefits, valvetrain strategies can reduce throttling losses, enable operation with more efficient engine cycles and generally improve efficiency (Duleep 2010). Valve control can also enable cylinder deactivation. Future possibilities include electromechanical valve actuation, which can lead to throttleless operation and so even greater reductions in frictional losses.

A key technology now seeing greater use is direct injection spark ignition, also known as gasoline direct injection (GDI). In general, GDI offers a higher compression ratio than port-injection and enables efficiency gains due to improved cold start performance; mixture control including charge air cooling, improved scavenging, improved charge stratification; and other benefits including lower emissions and reduced heat loss. Combined with turbo-charging, GDI greatly increases specific power and torque, which is crucial for good responsiveness and real-world performance while reaping the efficiency benefit of significant engine downsizing (Lake et al. 2004). Turbocharged GDI can enable the use of 3-cylinder engines and extend the reach and efficiency benefits of downsizing to smaller vehicle segments (Kirwan et al. 2010).

While efficiency gains in the European market relied on dieselization enabled by historically lenient NOx standards, automakers there have recently been turning to GDI as a way to continue progress on fuel efficiency while meeting tighter emissions constraints (Weernink 2005). GDI provides significant benefits even with stoichiometric operation compatible with established 3-way catalytic controls that achieve near-zero (e.g., PZEV) tailpipe emissions. Lean GDI offers higher fuel efficiency but is still inhibited by tailpipe emissions constraints, although differing GDI modes can enable adequately low emissions with higher efficiency as lean rather than stoichiometric operation is used for an increasing share of operation.

Modern diesel engines with direct injection and turbocharging are common in Europe and seeing some use in the U.S. market, mainly by European manufacturers or in heavy-duty pickups. Diesels' emissions hurdles and higher costs compared to advanced gasoline engines still inhibit more widespread use. Nevertheless, with diesel fuel sulfur levels now much lower (15 ppm) and aftertreatment a very active area of R&D, diesels offer a parallel pathway for efficiency gain well suited to some market segments. Although the scenarios developed below do not rely explicitly on diesels, reductions in aftertreatment cost and other advances may make them competitive within the fundamentals-based technology solution set for a high efficiency fleet.

Even more sophisticated technologies are emerging that further extend the efficiency of internal combustion engines. One such option (also not explicitly assumed for the scenarios here) is homogeneous charge compression ignition (HCCI). This approach achieves uniform combustion throughout a cylinder, avoiding the NOx-forming temperature peaks of a flame front and enables a combination of high efficiency and very low engine-out emissions (Ashley 2001; Sherman 2004). Versions are applicable to either gasoline and diesel fuel, and for diesel in particular hold promise for avoiding NOx problems. Mixed-mode, HCCI-capable engines have been put into production by Nissan and Toyota among others; a barrier has been extending HCCI operation beyond limited load conditions. Whether such very advanced approaches become widely applicable, ongoing gains from engine optimization and friction reduction will extend efficiency improvements well into the future.

Transmissions

Engine efficiency over a given driving cycle is a function of the engine-transmission system (collectively the powertrain), including the choice of the shift schedule that determines which gear is used under what operating conditions. Transmission design and shift optimization balance fuel economy against performance and driving responsiveness. Manual transmissions were once more efficient than automatics because they avoided a torque converter and other internal losses. Now however, with torque converter lockup and other improvements in automatics plus the fact that a well-optimized automatic shift schedule can be more efficient than a typical driver's use of a manual, the distinction is less important than it once was. In addition, steady refinements of materials and lubricants enable ongoing friction reduction throughout the entire driveline.

A transmission with a greater number of gears enables the engine to operate more frequently at efficient points of its map (lower RPM, more open throttle), minimizing pumping losses and other forms of engine friction. The trade-off is performance, and so the design priority placed on efficiency again determines how much benefit can be found. Because shift schedules are now under programmable control, an essentially no-cost gain can be found by choosing a more fuel-efficient shift schedule while sacrificing responsiveness levels likely to be unnoticeable in ordinary driving. This option is demonstrated in a number of vehicles on the market that offer their drivers a choice of shift schedules (e.g., an "eco" vs. performance modes).

The ultimate increase in number of gears leads to the continuously variable transmission (CVT), which enables a smoothly varying range of ratios between engine speed and final drive speed. However, CVTs have higher internal friction than the best fixed-gear automatics and to date have also been load limited, restricting their use to smaller vehicles. Nevertheless, CVTs remain among the options for improving efficiency fleetwide.

The two most significant recent advances in transmission technology are designs based on what is known as the Lepelletier gearset and designs enabling automated direct gearshifts in what is known as the dual-clutch transmission (DCT). The former has enabled a jump to six or more gears at low cost with multiple benefits including higher torque capacity and better acceleration, reduced transmission size and weight as well as higher efficiency. Introduced by transmission supplier ZF Friedrichshafen with BMW a decade ago, Lepelletier-based designs are now in production throughout the industry and likely to become a dominant transmission type in the coming years. The DCT, pioneered in European mass production by Volkswagen and Borg-Warner, uses two clutches and automated controls to select gears using two shafts (for alternating even and odd gears), avoiding the need for a torque converter. Design and control refinements are enabling DCTs to have the smoothness customary to traditional automatics and so provide another competitive option for transmission-based efficiency improvement.

Collectively, these transmission technologies in combination with optimized shift schedules will enable maximum efficiency gains from internal combustion engines, with particular transmission types suited for different applications. The various choices can be broken out with particular levels of efficiency gain, as tabulated by the NRC studies and EPA-NHTSA rulemaking documents, for example. However, the potential benefits are ultimately best viewed more holistically for enabling better optimization for the engine-transmission system, as modeled by Kasseris & Heywood (2007), for example.

Hybrid Drive

Hybridization combines a combustion engine with another type of motor and an energy storage device capable of buffering tractive power. The hybrid electric vehicle (HEV) is being widely commercialized. Other forms of hybrid drive, such as those using hydraulic motors and storage, are being demonstrated for commercial vehicles. The efficiency benefits of hybrid propulsion include enabling the engine to run more often at its most efficient operating points, thereby allowing it to be downsized and be turned off when not needed; recovering braking energy; and providing ample power for electrification of vehicle accessories. A rich literature exists on hybrid technology and so it is not discussed here in depth. Good sources are the overview by German (2004), the analysis by Kromer & Heywood (2007), and the accessible, continually updated information on www.hybridcars.com.

HEVs have captured the popular imagination as a breakthrough enabling much greater gains in vehicle efficiency. From an engineering perspective, however, grid-free (non-plug-in) hybrids are better viewed as a step in the evolution of internal combustion engine vehicles, extending their potential for higher efficiency at higher cost. As shown earlier in Figure 4, the cost-benefit ratio for HEVs largely follows the same increasing marginal cost line as improved conventional technology. Thus, HEVs do not offer higher efficiency gains at lower costs as would be expected of a "game-changing" breakthrough. In short, grid-free hybrids are no more and no less than a valuable advance in the sophisticated and mature field of automotive engineering.

Hybrid vehicles entered the global market with the December 1997 launch of the Toyota Prius in Japan. In the United States, the original Honda Insight hybrid went on sale in early 2000 and the Prius began U.S. sales in July 2000. In 2009, new U.S. hybrid sales tallied to 290,000, or 2.8% of the new U.S. light vehicle market, and global sales approached 600,000 (Hybridcars.com 2010). The United States and Japan are the two largest hybrid markets by far, and the Toyota Prius has been the top selling hybrid nameplate. All major automakers have hybrid programs underway and the number of offerings is rising steadily. Even though hybridization entails an inherent cost increase compared to non-hybrid powertrains, it is now seen as a foundation for automotive technology in the decades ahead. As one industry expert put it, "hybrid technology is the core technology that drives us toward a sustainable future" (Ward 2010).

Although analysts classify hybrids in various ways (series vs. parallel, single vs. two mode, mild vs. full, etc.), the technology is really a spectrum of options. Even a standard alternator can recapture a small amount of braking energy and greater regeneration is possible with start-stop systems, particularly in the more sophisticated form of an integrated starter-generator (ISG). The term hybrid drive is generally reserved for when the electrical machine provides at least some degree of tractive power. Projecting which hybrid configurations will dominate is difficult and not really needed for public policy. The technology will see variations and improvements at all levels, from components such as batteries, motors and controllers to systems integration. The rapid pace of development is all the more reason to rely on engineering fundamentals rather than second guessing the creativity that will unfold during competitively driven product development by automakers and their suppliers.

Thus, even though the fuel efficiency of hybrids is often reported with distinct estimates for different configurations, the potential gains are best viewed along a cost-benefit continuum. Well optimized, fully capable hybrid systems can cut energy intensity by as much as 50% when controlling for performance. However, even start-stop systems that fall short of providing a tractive boost, as well as a variety of single-motor/generator designs, yield benefits that offer cost-effective fuel efficiency solutions. The industry is exploring a range of approaches as seen in recent announcements by General Motors, Hyundai and others. Because much of the potential benefit of hybridization is tied to its ability to optimize engine operation, the efficiency of a hybrid vehicle also depends on the balance of the powertrain system.

Although hybridization can further increase of efficiency of high-output engines such as direct injection turbocharged designs, it can also be very effective with an advanced *low* output engine. That very approach is seen in the Toyota Prius and other vehicles that mate hybrid drive to a naturally aspirated, port-injected Atkinson cycle engine, which uses an extended expansion stroke to extract more work from the charge. That limits torque and therefore limits peak engine power, for which the electric motor-generator components compensate. Kasseris & Heywood (2007) simulate hybrid drive with an advanced, low-friction naturally aspirated engine, which is less costly than the GDI and diesel engines they separately analyze and therefore helps balance the higher costs of electric drive components. Their results by no means represent the limit of the potential efficiency gains for hybridized internal combustion powertrains.

Synthesis of Technology Assessments

Numerous studies have been published that draw by varying degrees on the technical options just summarized. This section starts with an overview, contrasting methods that can be classified as either assuming incremental application of detailed technology specifications or assuming optimal application of capabilities based on engineering fundamentals. The issue of how quickly the necessary technology, particularly extensive use of hybrid drive, might be adopted is addressed by applying logistical functions derived from historical technology adoption rates. These results are then used to construct an ambitious but still evolutionary scenario for the new fleet fuel efficiency horizon through 2035.

INCREMENTAL VS. FUNDAMENTAL ANALYSIS

The technology assessments done to support standards setting are cautious by nature, working from make- and model-level data characterizing a baseline fleet and specifying technology modifications in detail. In contrast, a fundamental approach posits "clean sheet" vehicle designs, which have specified size and performance levels but need not be modified versions of current vehicles, and so is less restrictive of the efficiency potential that can be identified.

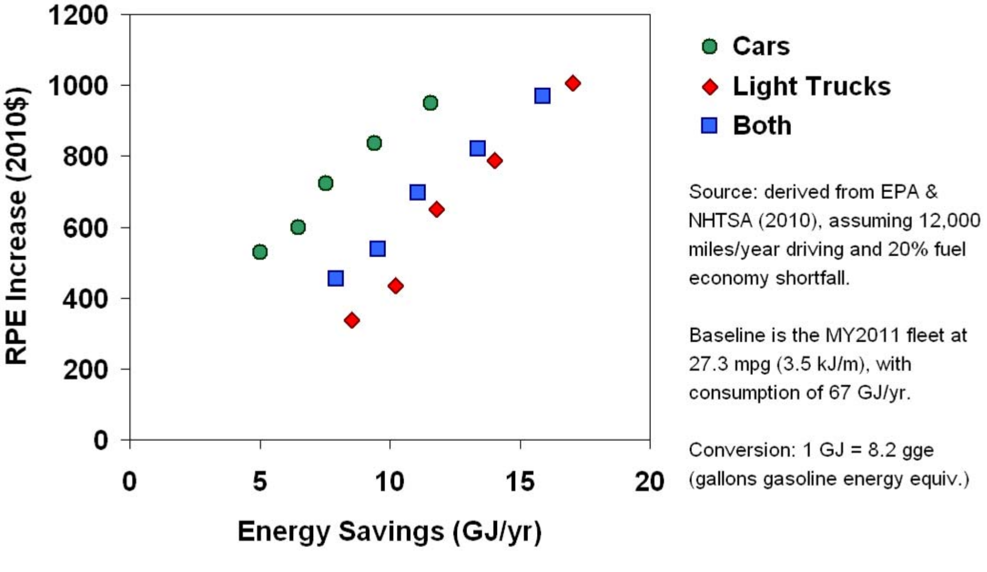
Incremental Approach for Justifying Regulations

An advantage of incremental analysis is its ability to develop detailed cost estimates tied to the use of specified technologies. Working from known vehicle platforms, it enables regulators to identify stepwise changes automakers can make in their products to yield a fleet of higher fuel economy. Identifying a detailed compliance pathway is considered important for justifying standards that impact near-term cycle plans (5-10 years).

A detailed incremental analysis was used for developing the MY2012-16 single national program (EPA & NHTSA 2010 Joint Rule). Its per-vehicle retail price equivalent (RPE) cost estimates are plotted as a function of energy consumption reduction in Figure 7. The rule requires annual increases in fuel economy and cuts in GHG emissions (including air-conditioning related off-cycle and trace gas emissions) leading to a projected 2016 new fleet average of 250 g/mi CO_2-equivalent. The fuel economy part of the proposal aims for 34.1 mpg by 2016, a 25% increase over the projected 2011 level and 38% higher than the 2005 combined fleet average of 24.8 mpg. In consumption terms, the rule implies a 27% reduction relative to the 2005 fleet, which had an average annual fuel use rate of 74 GJ/yr (605 gal/yr of gasoline).

An aggregate incremental approach was used by the NRC fuel economy studies. NRC (2002) reported a midrange estimate of 26% fuel economy gain (21% energy intensity reduction) without significant weight reduction and with cost-effectiveness based on $1.50/gallon gasoline. The NRC (2010) update estimated energy intensity reductions from 29% for non-hybrid gasoline

Figure 7. Costs of energy savings implied by the MY2012-16 Joint Rule



Source: derived from EPA & NHTSA (2010), assuming 12,000 miles/year driving and 20% fuel economy shortfall.

Baseline is the MY2011 fleet at 27.3 mpg (3.5 kJ/m), with consumption of 67 GJ/yr.

Conversion: 1 GJ = 8.2 gge (gallons gasoline energy equiv.)

vehicles to 44% for HEVs as achievable within 15 years. The King Review (2007) drew on incremental assessments for its estimate of a potential 30% energy intensity reduction for the UK light vehicle fleet. Ricardo (2008) simulated incremental powertrain improvements without mass reduction and projected near-term energy intensity reductions of 23%–29% over a set of representative vehicles.

Duleep (2010) also uses an incremental approach, at a high level of aggregation but consistent with the more detailed analyses that his firm has conducted for past agency studies. Relative to a 2005 baseline, such studies support the 32% fuel economy improvement (24% energy intensity reduction) required by the EPA & NHTSA (2010) rule. By 2025, Duleep (2010) estimates a potential 50% fuel economy gain (33% energy intensity reduction) from maximum use of conventional (non-hybrid) technologies.

Fundamental Analysis for Future Horizons

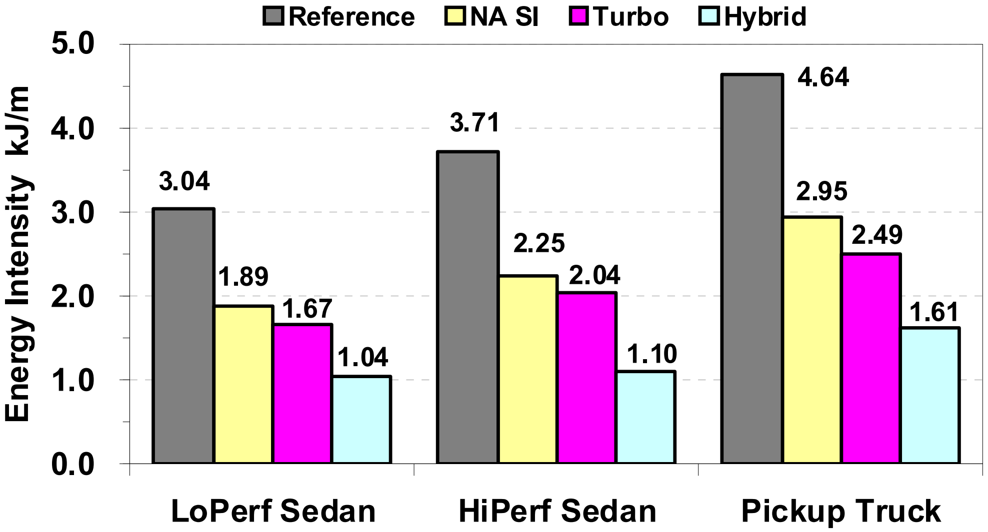
A fundamental approach analyzes future designs of specified characteristics and determines the ability to maximize efficiency based on engineering principles. It identifies technologies usable for future designs but does not detail a technology pathway for modifying today's vehicles to reach future efficiency levels. It can be considered a more theoretical analysis in that regard. Nevertheless, as long as it is based on sound engineering analysis, it yields results to which the fleet can evolve given enough lead time and an ability to execute the necessary design changes. Such a timeframe extends beyond near-term cycle plans and may require automakers to rethink mid- and long-term (10-20 year) product strategies.

Fundamental analyses can be carried out using engineering simulation models (e.g., Kasseris & Heywood 2007) or by using simplified physical models (e.g., EEA 1991, OTA 1995, and one of the approaches used by DeCicco et al. 2001). The opportunities identified by such analyses are based on physical principles related to the tractive and other energy loads that must be met and the efficiency with which the powertrain supplies these loads. By way of historical note, a fundamental approach was used in the "120 Day Study" carried out by DOT & EPA (1974) to support the original CAFE standards, which required a near doubling of passenger car fuel economy within a decade.

With a 2005 baseline and a 2030 time horizon, the Kasseris & Heywood (2007) results average out to a 45% energy intensity reduction from efficient use of conventional technologies and a 67% reduction from a combination of advanced engine technologies and optimized hybrid drive. Their results for gasoline vehicles are summarized in Figure 8, converted to on-road energy intensity in kJ/m. They also analyzed diesel versions of the same vehicles, finding energy intensity reductions somewhat better than turbocharged gasoline engines but short of hybrids. Kasseris & Heywood assumed fixed performance (i.e., Z60 times matching those of the model year 2005 reference vehicles), a 20% reduction in curb weight, and decreases in aerodynamic drag and tire rolling resistance well within the bounds of historical rates of progress.

For averaging their modeled vehicles to represent the overall fleet, weighting factors of 50% low performance, 30% high performance and 20% pickup truck characteristics were assumed. Using the values shown in Figure 8 would imply that an all-hybrid fleet would achieve tripled fuel economy, corresponding to the 67% consumption reduction noted above. As applied here, however, these efficiency projections are combined with adjusted cost projections to develop aggregate cost curves as explained in the next section of the report; the fleet efficiency horizon

Figure 8. Potential gasoline vehicle energy intensity reductions achievable by 2030



Source: Derived from Kasseris & Heywood (2007), using a 55% city and 45% highway (CAFE) cycle weighting adjusted for on-road consumption assuming 20% fuel economy shortfall. Reference vehicles are 2005 models, including a low-performance midsize sedan (currently with a 4-cylinder engine), a high-performance sedan (currently 6-cylinder) and a full-size pickup truck (currently 6-cylinder). Future vehicles all assume a 20% mass-reduced streamlined platform. NA SI = naturally aspirated, possibly direct-injection spark ignition engine; Turbo = turbocharged version thereof; Hybrid = optimized hybrid drive with NA SI engine.

scenario is in turn based on the cost curves. Thus, the future tripled efficiency fleet need not be an all-hybrid fleet, but rather a fleet involving some combination of technology and design changes that realize similar fuel efficiency levels at similar costs.

Those results confirm the potential for large reductions in fuel consumption with internal combustion engine vehicles foreseen by earlier work. For example, the EEA (1991) boundary analysis for 2010 identified a potential to improve fuel economy by a factor of 2.5 (60% energy intensity reduction) using what was then characterized as higher risk technology involving either hybrid drive or small-displacement direct injection diesel engines (but not both). For a 2015 horizon, OTA (1995) projected a potential fuel economy improvement by a factor of 1.9 for advanced conventional (non-hybrid) cars and up to a factor of 2.6 for hybrids, both based on reduced-mass aluminum-intensive body structures. DeCicco et al. (2001) modeled an advanced sport wagon (with capacity and performance similar to a midsize SUV or fullsize minivan) achieving a 55% consumption reduction (factor of 2.2 in fuel economy). This gain was projected without the need for hybrid drive by using a direct-injection gasoline engine with an integrated starter-generator (enabling start-stop) and an automatic, direct shift transmission in a streamlined, 40% reduced mass structure. These older analyses all worked from older baselines having weight and performance levels less than those of recent model years.

Fundamental analyses also guided the Partnership for a New Generation of Vehicles (PNGV). Announced in September 1993, that program had three main goals. One was to improve the competitiveness of U.S. manufacturing; the second was to improve fuel economy and reduce emissions for conventional vehicles; and the third was developing vehicles with a fuel economy three times (3x) that of contemporary midsize cars. The partnership involved the then-Big Three automakers General Motors, Ford and Chrysler. The baseline vehicles were 1994 versions of the

Table 3. PNGV concept car fuel economy and consumption results

FUEL ECONOMY AND CONSUMPTION RATE

Model year 1994 reference cars	mpg	kJ/m	PNGV Concepts	diesel	gasoline-equiv	MPG gain	relative consmp	kJ/m
Chrysler Concorde	26.7	3.55	Chrysler ESX3	72	64.6	2.42	0.41	1.46
Ford Taurus	27.1	3.48	Ford Prodigy	78	69.9	2.58	0.39	1.35
Chevrolet Lumina	26.1	3.63	GM Precept	80	71.7	2.75	0.36	1.32
Average	26.6	3.55	Average	76.5	68.6	2.58	0.39	1.38
			3x Goal		*79.9*	*3.00*	*0.33*	*1.18*

CURB WEIGHT

Reference cars	kg	lb	PNGV concepts	kg	lb	reduct
Chrysler Concorde	1594	3515	Chrysler ESX-3	1021	2251	36%
Ford Taurus	1508	3325	Ford Prodigy	1083	2388	28%
Chevrolet Lumina	1533	3380	GM Precept	1176	2593	23%
Average	1545	3407	Average	1093	2410	29%

Source: PNGV (1994) and NRC (2000).

Chevrolet Lumina, Ford Taurus and Chrysler Concorde, which had a nominal average fuel economy of 26.6 mpg. In energy intensity terms, the 3x goal meant reducing from a baseline 2.84 kJ/m down to 0.95 kJ/m, corresponding to the widely cited target of 80 mpg (nominal). The PNGV (1994) program plan sketched a solution space dependent on three key factors: vehicle mass, powertrain efficiency and degree of regenerative braking. Both regenerative braking and the high powertrain efficiency of either hybridization or all-electric drive were presumed to be necessary for reaching the 3x goal.

Although the program was terminated before reaching its objective of having pre-production prototypes ready in 2004, PNGV concept cars were shown publicly in January 2000 (NRC 2000; Lynn 2004). All of the concepts used diesel hybrid powertrains with lightweight streamlined bodies. Table 3 lists their specifications; the average fuel economy of 76.5 mpg on diesel, or 68.6 mpg gasoline-equivalent, was not triple the baseline, but did demonstrate a factor of 2.6 gain, corresponding to a 61% energy intensity reduction. The concept cars had an average curb weight 29% lower than the baseline, also short of the program's internal 40% mass reduction target.

Although the PNGV concepts did not meet affordability objectives at the time, their technical achievements provide a tangible marker for the efficiency levels projected on the basis of fundamental analysis. Subsequent engineering progress -- including significant evolutionary mass reduction potential, ongoing advances in engines and hybrid drive -- makes a 3x goal more attainable and affordable than it was a decade ago. Such a target is consistent with Kasseris & Heywood (2007), whose projections for what is possible by 2030 average to a 3x fuel economy gain over 2005 reference vehicles, a baseline that reflects many improved features and better performance than the PNGV's 1994 baseline.

In any case, fundamental engineering considerations imply that hybrid drive is a key technology for attaining these efficiency levels. Some may view hybridization as a stepping stone across the divide from internal combustion engines to all-electric vehicles. Regardless of that eventuality, hybrid drive greatly extends the efficiency horizon for vehicles whose prime movers remain internal combustion engines operated on liquid hydrocarbon fuels and which therefore do not require major changes in the energy distribution system. Hybrid utilization is still low, however, and so an important factor is how quickly it might be adopted across the fleet.

RATES OF TECHNOLOGY CHANGE

Automobiles are continually redesigned and technology continually improves, though not always with fuel efficiency as a design priority. Due to constraints of financing, facilities, human resources and supplier capabilities, "it is difficult for automakers to do too much too fast" (CAR 2007, viii). That being said, the questions are whether the 25 year horizon considered here is sufficient for tripling new fleet efficiency and what intermediate levels are possible between now and that long-term target.

For incremental progress toward maximum use of cost-effective near-term technologies, typical lead time estimates are 10-15 years (DeCicco et al. 2001; NRC 2002; CARB 2004a). Such a period is partly based on the time it would take an automaker to systematically redesign all of the vehicles in its fleet (which might include dropping some models and introducing new ones). A quicker time frame is implied by state-of-the-art practices, as driven by competitive pressure and enabled by advances in design and manufacturing that entail round-the-clock global engineering work. Standard product development times are now 2-3 years and typical product cycles are 5-6 years (CAR 2007), suggesting that fleetwide changes can be made in less than a decade.

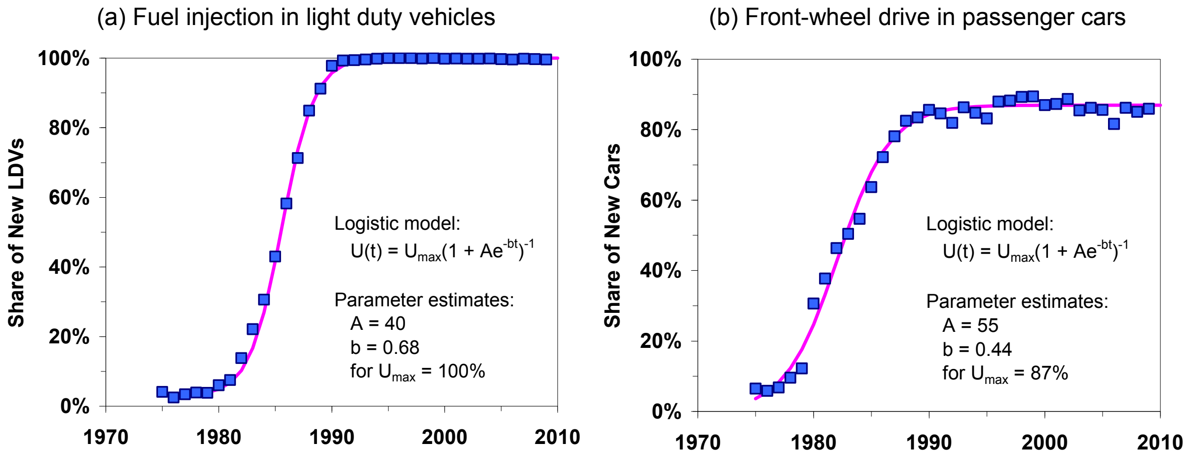
However, major new technologies cannot be advanced from low to high levels of utilization over the course of a single redesign cycle. An empirical basis for rates of technology change can be found in historically observed diffusion of automotive technologies and design changes. Such data are given in EPA's Fuel Economy Trends reports and reveal a wide range for rates of change (EPA 2009). The MIT study notes that "even very cost-effective technologies such as variable valve timing have taken 10-15 years to penetrate half of new vehicles," and that automatic transmissions "having reached half of the market by 1950, required 20 more years to be available in 90% of vehicles" (MIT 2008: 109).

On the other hand, the same EPA database reveals rapid progress for some major changes. Front-wheel-drive was quickly adopted across the passenger car fleet, a major modification that also involved a conversion to unibody construction of the older body-on-frame designs on which most rear-drive vehicles were built. Even more rapid adoption occurred as fuel injection replaced carburetors. Figure 9 shows the utilization rates (U) for these technology changes along with fits to growth curves based on a logistic function:

$$U(t) = U_{max}(1 + Ae^{-bt})^{-1}$$

The function's parameters imply the maximum rate of change (U'_{max}, the slope of the logistic at its inflection point) and the time (t_{90}) needed to reach 90% of maximum utilization (U_{max}). These values are given by $U'_{max} = b/4$, where b is the exponential rate parameter, and $t_{90} = \ln(9A)/b$ (derived from the logistic; see, e.g., Draper & Smith 1981: 508). Using the fits illustrated, t_{90} was 9 years for fuel injection and 14 years for conversion to front-wheel drive, with U'_{max} values of 17%/yr and 11%/yr, respectively. These were very rapid rates of change.

Figure 9. Notable historical rates of change in automotive technology utilization, with fits to logistic functions



(a) Fuel injection in light duty vehicles

(b) Front-wheel drive in passenger cars

Source: author's fits to data from EPA (2009), Table 13. Fuel injection includes all forms (throttle body, port and direct); front-wheel drive includes all-wheel drive variants of front-wheel drive models.

In fact, the rate of adoption for a given technology is tied to the need for the technology. In keeping with a key theme of this paper, the type of technology targeted for progress itself can be considered a matter of design priority. In both cases of rapid adoption shown in Figure 9 there was a strong driver for change. In the early 1980s, automakers faced sudden pressure to improve fuel economy in the wake of the oil crisis and ramp-up of CAFE standards for cars. Some front-wheel drive substitution occurred through redesign of existing models and some occurred competitively, as imported cars displaced domestic models even as the Detroit fleet was modernizing. As shown in Figure 9(b), by 1987 U.S. new cars were 78% front-wheel drive (90% of the plateau value of 87%), up from less than 10% as of 1978. The even more rapid adoption of fuel injection was driven by emissions regulations, which required precise mixture control for 3-way catalysts to operate properly. Fuel injection also offered performance and efficiency benefits, enabling engineers to sidestep the trade-offs encountered when recalibrating carbureted vehicles for lower tailpipe emissions.

Moreover, those changes were not trivial. The conversions to front-wheel drive and unitized body structures had substantial impacts on design and engineering, involving major architectural changes in both vehicle structures and drivelines. It involved new tooling and new supplier relationships, as well as new design, engineering, fabrication and assembly techniques. Although more restricted in the scope of its impact on the whole vehicle, fuel injection was a significant change, involving many new components and the need for computerized engine controls.

Although slower rates of adoption occurred for automatic transmissions and valve train changes, neither technology met needs as compelling as those that drove fuel injection and front-wheel drive. Many consumers continued to prefer manual transmissions (and some, though a declining number, still do), and relative to manuals, automatics once had a fuel economy penalty. Detroit automakers generally eschewed overhead cams and the valvetrain refinements they facilitated, instead continuing to adapt pushrod (over-head valve) engines; moreover, they did not need the benefits of more sophisticated valvetrains until relatively recently.

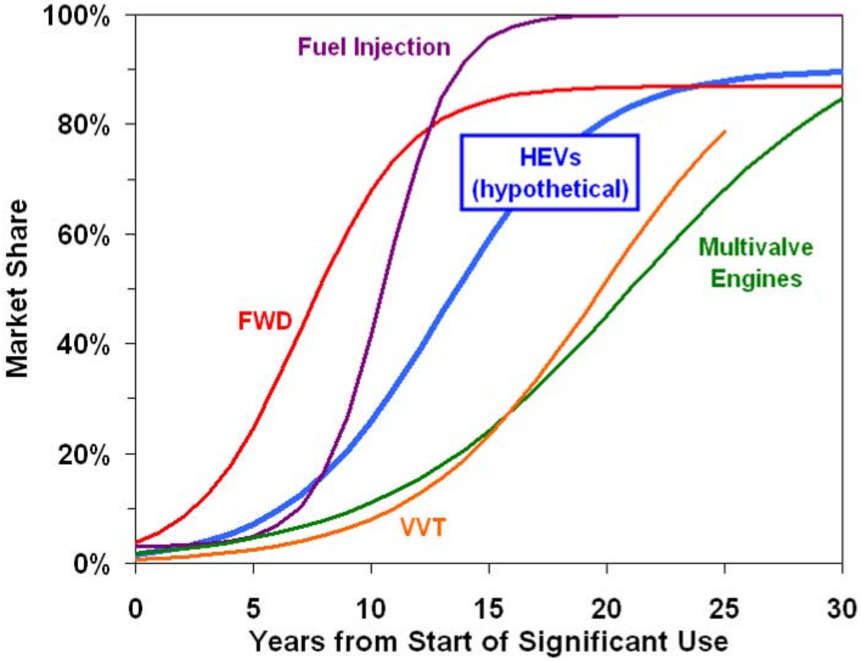
Thus, achievable rates of change depend to a large extent on the pressure to change. Of course, if technology development is shaped in particular directions, progress in other directions may be foregone. It is difficult to predict how cars would have evolved without the fuel economy and emissions control pressures of the early 1980s. Nevertheless, it seems likely that many other comfort, performance and capability amenities would have been seen (or seen sooner) if there had not been the prioritization of fuel economy and emissions control that drove the rapid adoption of front-wheel drive and fuel injection during the 1980s.

The most challenging future change needed is likely to be extensive use of hybrid drive. Hybrid powertrains are used in less than 3% of new light vehicles to date. Nevertheless, given the announced introductions and the spread of hybrid capability from pioneers such as Toyota and Honda to all automakers and major suppliers, the technology could soon enter a phase of rapid adoption, *should the need arise.* That again will depend on the degree of design priority -- as jointly determined by consumers, automakers and policymakers -- placed on achieving much higher fuel efficiency, which is a strength of hybrid drive.

The complexity of the change, in terms of design and engineering needs, is comparable to that of the conversion to front-wheel drive unibody car platforms in parallel to the rise of fuel injection a generation ago. Automakers have successfully managed complex changes in vehicles within relatively short periods of time. However, those past changes did not entail the inherently higher costs seen for some electric drive components. Thus, the rate of hybrid adoption is more likely to be limited by its expense than by the ability to rapidly execute technology change, a situation reflected in the cost estimates incorporated into the scenarios developed below.

If a significant adoption phase starts soon, hybrid utilization eventually plateaus at 90% of the fleet (allowing 10% traditionalist non-hybrid hold-outs), reaches 90% of its plateau in 20 years

Figure 10. Hypothetical market adoption curve for hybrid drive compared to logistic curves based on historical automotive technology adoption rates



(t_{90}=20, i.e., by roughly 2030) and has a logistic parameter similar to that for front-wheel drive (A=55), then the rate parameter given by $\ln(9A)/t_{90}$ is b = 0.31. The maximum rate of increase (the steepest part of the adoption curve) is then 7.6% per year. The resulting hypothetical diffusion curve is shown in Figure 10, with the fits from Figure 9 and some slower technology adoption curves shown for comparison. The conclusion is that an extensive conversion to hybrid drive could happen with adoption rates within the range of those observed historically for other major technology changes.

This discussion is not meant to suggest that hybridization *per se* should follow the trajectory illustrated. A tripled efficiency fleet will undoubtedly see a high utilization of hybrid drive, but the level could be lower than that assumed here if greater progress is seen in any number of other areas including mass reduction, other aspects of load reduction, use of start-stop and new energy harvesting technologies with turbo GDI engines, diesel emissions control and very advanced combustion technologies such as HCCI. As emphasized throughout this report, the intent is not to advocate any particular technological pathway, but rather to identify a solution set for a high-efficiency future fleet while remaining agnostic about the ultimate mix of technologies needed to achieve it, which is best left for the market to determine.

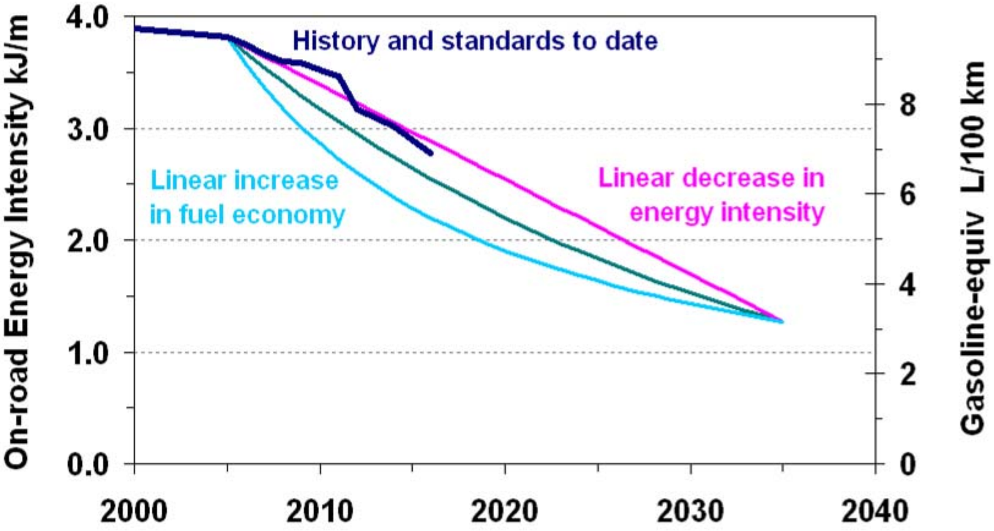
NEW FLEET SCENARIOS

It is common for analysts to posit scenarios based on projected shares of advanced or alternative powertrains. Technologies are distinguished by treating, say, a turbocharged gasoline engine as distinct from a diesel or hybrid powertrain or from a naturally aspirated engine. Automakers themselves need to decide what technologies to use on any given product. But for policy analysis, these "named technology" categories create unnecessary distinctions. This degree of technological specificity results in scenarios called "hybrid" and "diesel" for powertrains, for example, or "steel-based" and "aluminum-intensive" for vehicle bodies, fostering lively debates about hybrids vs. diesels and aluminum vs. steel.

Although perhaps fascinating, such debates cannot be resolved outside the confidential confines of automaker product planning. That is the only context where realistic technology choices can be made, as program directors face the trade-offs due to budget constraints and the numerous parameters that must be considered for defining a successful product. These decisions depend on not only technology readiness and cost, but also its appeal to a product's target customers and how well it leverages a firm's strengths, its brands, and market trends in the particular segments in which products must compete.

Here we avoid such technological specificity and define scenarios strictly based on average fleet energy intensity outcomes, which ultimately depend on performance and size mix as well as on technology. This relegates the role of specific technologies to that of demonstrating feasible levels of efficiency while allowing that other design and technology combinations may also work. It reflects the fact that it is impossible to specify which of today's named technologies will offer the most workable solutions tomorrow, or whether some options that now seem promising will fall by the wayside as new options emerge. An agnostic perspective is also in keeping with fundamental engineering analysis in that many technologies tackle one or more of the same underlying sources of inefficiency.

Figure 11. Scenarios for decline of new fleet energy intensity toward long-term target based on tripled fuel economy



Left axis shows estimated on-road energy intensity adjusted for 20% fuel economy shortfall; right axis is gasoline-equivalent fuel consumption rate in nominal terms (as would be derived from unadjusted lab tests).

The factor of three identified above as attainable through an evolutionary process that exploits known powertrain technologies with moderate degrees of mass reduction and streamlining is adopted as the long-term efficiency horizon for the new U.S. light duty vehicle fleet in 2035. Figure 11 plots trajectories toward that target starting from the 2005 fleet and its on-road average energy intensity of 3.8 kJ/m. The 2035 efficiency horizon is 1.27 kJ/m on-road, corresponding to a nominal (unadjusted) fuel economy of 74 mpg. Also plotted in the figure is the fleet average achieved to date (EPA 2009) and projected through 2016 for the recently promulgated Joint Rule (EPA & NHTSA 2010). Refer back to Figure 1 in the Executive Summary to see this scenario in comparison to the historical data for new fleet energy intensity.

In terms of improvement paths, Figure 11 shows an upper bounding trajectory based on a linear decline in energy intensity (the same as a linear decline in efficiency-related CO_2 emissions rate), representing a slower near-term path toward the long-term target. A lower bounding trajectory is based on a linear increase in fuel economy, which would represent more rapid near-term progress toward the same long-term goal. Here, a middle path is assumed that uses a constant compound rate of change starting in 2005 and ending in 2035. That trajectory entails an average 3.6% per year decline in energy intensity or a 3.7% per year rate of increase in fuel economy.

The implied 5-year targets for 2020-35 are listed in Table 4 along with the 2005 baseline level and projections for 2010 and 2016 based on standards recently promulgated. Estimated on-road fuel economy (adjusted as for average label values) is shown in the row below the nominal levels as used for CAFE compliance. For CO_2 emissions, the first line is a tailpipe-only rate computed using a constant gasoline-equivalent carbon coefficient of 8.887 kg/gal. The last line is a fleet average CO_2-equivalent GHG emissions rate after subtracting 15 g/mi for likely reductions of GHG emissions related to automotive air conditioners; it is less than the potential reductions of 21.2 g/mi identified in EPA & NHTSA (2010 Joint Rule: 25427-28).

Table 4. Light duty fleet average energy intensity and related metrics: reference levels and future targets based on fuel efficiency horizon scenario

New Fleet Average	2005	2010	2016	2020	2025	2030	2035
kJ/m (on road)	3.81	3.52	2.77	2.20	1.83	1.53	1.27
mpg (nominal/CAFE)	24.8	26.9	34.1	43.0	51.6	62.0	74.4
(on-road adjusted)	20	22	27	34	41	50	60
L/100km (nominal)	9.48	8.74	6.90	5.48	4.56	3.80	3.16
g/mi CO_2 (nominal)	358	330	261	207	172	143	119
(with A/C reductions)			250	192	157	128	104

N.B. These projections are for gasoline and diesel vehicles (including non-plug-in hybrids) only.

For the intermediate year of 2025, the implication is a 52% reduction in new fleet average energy intensity, from 3.81 kJ/m in 2005 down to 1.83 kJ/m. The corresponding nominal fuel economy level is 52 mpg in nominal terms (41 mpg on-road), or just over a doubling of the 2005 level.

As one industry-based point of reference, Hyundai recently announced a goal for its overall U.S. car and light truck fleet of "at least 50 mpg by 2025" (Hyundai 2010). Hyundai's fleet is already more efficient than average (its combined fleet of 30.9 mpg was 17% higher than the 26.3 mpg market average in 2008; EPA 2009, Table A-7), so the relative improvement needed is less than average. Therefore, its announcement falls short of corroborating the more ambitious trajectory suggested here. Nevertheless, remarks made by a Hyundai executive capture the spirit of the approach that this report takes in analyzing the efficiency horizon. In an interview following the announcement, Hyundai Motor America president John Krafcik said:

> … at Hyundai, often what we do is set really stretch targets, where at the time we don't necessarily have a specific roadmap, we don't know in detail how to get there. But for this minimum 50 mpg by 2025 we have an awful lot of confidence that we can get there. … It will align the whole company; it will align our engineering teams, our manufacturing and supplier partners; we'll find a way to get it done. And now we'll get into the really hard work, like what are our implementation plans.
>
> -- Krafcik (2010b) interview by *Automotive News*

Mr. Krafcik continued the interview by describing how Hyundai's plans will lean heavily on optimizing non-hybrid internal combustion engine powertrains, which would still account for 75%-80% of Hyundai's mix in 2025. Achieving that degree of efficiency gain without hybridization is consistent with the Kasseris & Heywood (2007) estimates for the capabilities of turbocharged gasoline engines (again, assuming progress on mass reduction and foregoing significant performance gains).

Thus, efficiency levels approaching a doubling of fuel economy do not seem likely to require extensive use of hybrids. However, reaching tripled efficiency for the long-term 2035 horizon will almost certainly require extensive use of hybrid drive. This raises a conundrum automakers might face regarding their long-term powertrain strategies. If the ultimate horizon is on the order of doubled fuel economy, then adoption of hybrid drive can proceed more slowly than illustrated here in Figure 10 for a trajectory that aims for tripled fuel economy. On the other hand, if the long-term target is likely to be much higher, then even though extensive hybridization may not be needed by 2025, investing in it sooner may be important for gaining experience and reducing costs as needed for a more ambitious long-term goal. This issue of path dependence is one that may merit further analysis and discussion.

Cost of Efficiency Improvement

This study adapts previously published cost estimates rather than developing a new cost analysis. Near-term values are derived from recent rulemaking analyses. Long-term values draw mainly on MIT (2008), which analyzed costs for a few representative vehicle types. Those estimates were adjusted downward under an assumption of modest mass reduction at zero net cost as discussed earlier. After discussing interpretation issues, this section describes a methodology for modeling aggregate (fleetwide) costs as quadratic functions that shift rightward (down) over time to reflect cost reductions likely to be achieved through ongoing engineering progress.

Most studies state the cost of modifying vehicles in terms of retail price equivalent (RPE). Those values are calculated by marking up manufacturing cost estimates with multipliers as described by EPA & NHTSA (2010 TSD), for example. RPE estimates should be interpreted carefully, an issue worth some discussion before presenting the cost estimates themselves.

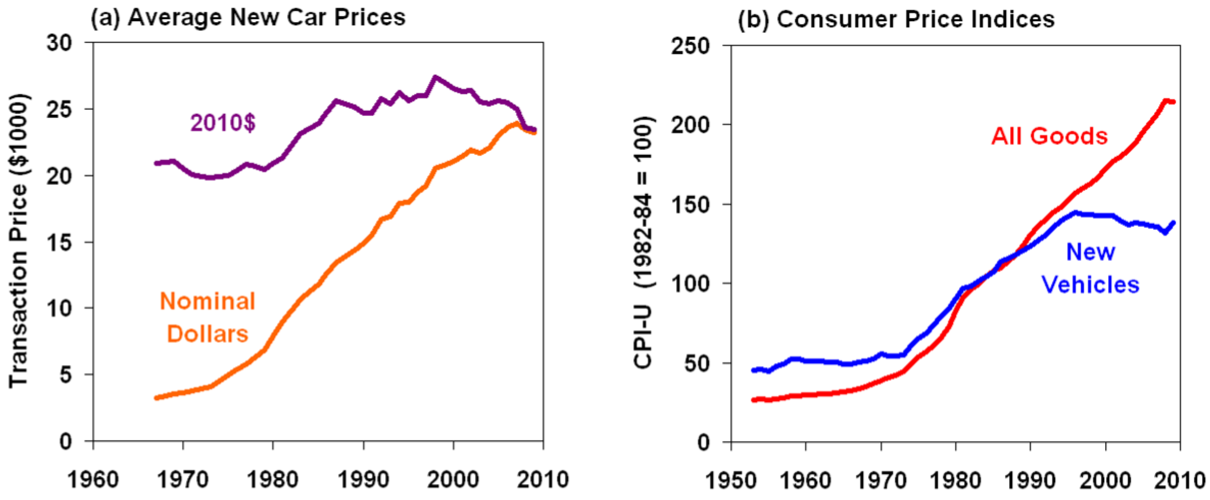
INTERPRETING COST ESTIMATES

It is common to equate RPE with a higher price that consumers will face for new vehicles. For example, the EPA & NHTSA (2010) Joint Rule characterizes its average $950 per vehicle cost as an increase in the consumer price of a 2016 new vehicle. That notion leads in turn to estimates of how long it takes consumers to recoup the price increase through fuel savings. Although this assumption and related cost discounting calculations are a straightforward way to analyze the situation, it is unclear that it well represents the realities of vehicle pricing and sales.

Some assumptions from economic theory suggest that automakers largely pass costs through to consumers. Crandall et al. (1986) found that the costs of safety and emissions standards appeared to be fully passed on after a short lag. However, their analysis covered a period when the car market was sustaining annual real price increases. Considering more recent conditions, several factors make it difficult for automakers to pass costs through to consumers. This seems likely for changes not fully valued by consumers, such as policy-driven fuel economy increases beyond the level that consumers would choose based on fuel prices alone. Also, the auto market has a scale (of total revenue) determined by overall economic conditions, and it is unclear that total vehicle expenditures increase proportionately simply because automakers incur additional costs.

The average price elasticity of new automobile sales is considered to be close to unity (-1); a commonly cited value is -0.87 as estimated by McCarthy (1996). Unit elasticity means that total revenue does not change as prices rise, so that automakers would sell fewer vehicles at a higher price but not gain any revenue. However, the actual market response is complex and not reflected only in sales volume. The impact of a price increase may be partly seen in reduction of content (expenditures by trim level or optional features per unit sold), not just reduction of

Figure 12. Transaction prices and price index for new vehicles in the United States



Source: Ward's (2010) for new car transaction prices; BLS (2010) for price indices.

volume (number of units sold). Either way, automakers may gain little additional revenue by raising prices. Given the industry's high fixed cost structure, a contraction in volume is harmful. For the relatively large cost impacts (upwards of 15% of baseline price) estimated for the long-term efficiency horizons identified here, it seems unlikely that automakers would pass all of the cost on to consumers and suffer the loss of sales volume that it might imply.

The auto market is highly competitive and at least until recently has suffered from chronic overcapacity. Both of these factors also hold prices down. The difficulty automakers have in raising prices, at least over the past 15 years, is apparent in Figure 12. Chart (a) shows average new car transaction prices in both nominal and inflation-adjusted terms. Real prices peaked in 1998 and have been trending downward ever since. These data are for cars only; light truck data are not as readily available and might show less drop-off, but for much of the past two decades the general trend in transaction prices was flat at best even before the current recession. Chart (b) compares the consumer price index for new automobiles with that for all goods and services. New vehicle prices have long lagged general inflation due to productivity gains in manufacturing as well as competition from imports. The recent uptick in the new vehicle index may indicate the start of a pricing recovery, but by how much is yet to be seen. In any case, the cost pass-through question is one that needs further investigation.

To the extent that the ability to raise prices is restricted, financial constraints are more severe. Automakers must develop vehicles on fixed budgets determined by prices actually commanded, the sales volume achieved and the needed return on investment. This economic fundamental of constrained revenues -- scrutinized by financial analysts in both car companies and investment firms from which they raise capital -- disciplines automakers' product planning budgets:

> Every automotive program has an internal business case that is ultimately controlled by vehicle prices and sales volumes; all aspects of a program plan must meet the resulting budget constraint. (CAR 2007: v)

As a result, managing costs means making trade-offs among features in order to stay on budget. Failing to do so (or failing to use realistic assumptions about pricing and sales) results in severe financial risks. Budget constraints affect vehicle attributes and content whether or not they are desired by customers, and so the costs of efficiency improvement are confronted by automakers in that context. Regarding policy requirements:

> Regulations represent things that have to be done—for safety, emissions, and fuel economy—regardless of how they are valued by customers. … In short, product requirements that are not valued by customers force trade-offs in features that would otherwise be designed or included on the basis of customer value. (CAR 2007: 21)

That report goes on to say:

> Some such requirements can be handled at a systems level while fitting within budget constraints. Such a systems-level strategy is the ideal way to address fuel economy, for example. Because it affects nearly every vehicle system, a holistic approach is needed; if this is done well, fuel economy can be handled without incurring additional costs and while staying within budget. (CAR 2007: 21)

These considerations imply that cost estimates for technology change should be interpreted mainly as an indicator of the impact on automakers, only a portion of which gets passed through as an impact on consumer prices. Automakers are likely to have to manage the cost impact by trading off other features to stay within budget and avoid hiking prices to an extent that overly depresses sales. In other words, incremental RPE values can be viewed as measuring the trade-offs that need to be made when improving efficiency rather than improving a product along other dimensions. Much of the cost impact may take the form of foregone spending on other features that otherwise would have been offered.

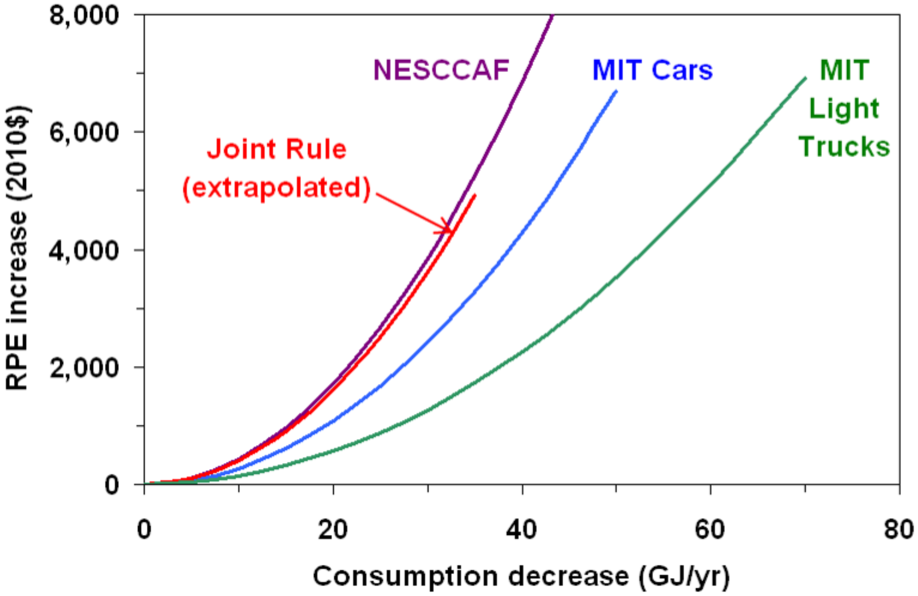
Thus, it is incorrect to simply equate RPE estimates with price increases to be experienced by consumers. A more correct interpretation is that they are retail price equivalent estimates for the opportunity cost of technology changes made within a constrained product development budget. This interpretation suggests that policy-driven energy efficiency gains may be an even better deal for consumers than they are held out to be by presenting the simple payback estimates given by many studies (including some earlier studies by this author). It also means that the challenges are compounded for automakers, who must invest in technology but may be unable to fully recoup those costs in the marketplace.

COST CURVES

To synthesize cost estimates into aggregate values for assessing the efficiency horizon, they can be distilled into curves that enable different results to be readily compared. Such aggregation is well suited for a high-level assessment in light of the uncertainties involved and the fact that the efficiency gains are based on engineering fundamentals rather than detailed technology specifications. Cost curves based on key recent studies are shown in Figure 13, as described below and derived in the Appendix.

It is convenient to use a quadratic form for several reasons, not the least of which is parsimony, i.e., that no more than one or two coefficients are needed. A greater number of parameters is

Figure 13. Average costs of light vehicle energy consumption reduction from quadratic approximations to results of recent studies



Source: derived from EPA & NHTSA (2010) "Joint Rule," MIT (2008) and NESCCAF (2004). The quadratic coefficients are: Joint Rule 4.0, NESCCAF 4.3, MIT cars 2.7 and MIT trucks 1.4 [2010$ per $(\text{GJ/yr})^2$]. For common units, 1 GJ = 8.22 gallons of gasoline equivalent (gge, on-road LHV basis); e.g., 40 GJ/yr ≈ 330 gge/yr.

unlikely to be meaningful in light of the uncertainties in the underlying "data," which are in reality judgment-based estimates of cost. Other advantages are that quadratic total costs imply linear marginal costs, making cost-benefit equations tractable and transparent, and that a quadratic can be seen as a 2^{nd} order approximation to any function near the origin, which is appropriate when calculating costs relative to a baseline (Greene & DeCicco 2000). Finally, inspection of scatter plots suggests as good a fit as is likely to be provided by any function.

In contrast to curves that are quadratic in fuel economy, as used by Greene & DeCicco (2000) and NRC (2002), this analysis represents costs as quadratic in fuel savings (energy intensity reduction). The main reason is that benefits are linear in fuel consumption, as opposed to fuel economy for which successive increments provide a diminishing benefit. The quadratic form itself represents increasing costs, and no particular insight provides a rationale for a quadratic in fuel economy, which would imply costs rising both hyperbolically and quadratically as a function of benefit. For fits within a limited range of incremental improvements, either approach basis is probably suitable. But given this study's objective of characterizing long-term horizons involving large changes in efficiency, a quadratic function of fuel savings seems a more prudent choice. Of course, these curves should not be used to extrapolate beyond the range of technically feasible improvements (otherwise, a quadratic projects a finite cost for reducing consumption to zero, which is not physically possible).

The quadratic approximations to the costs from several studies are shown in Figure 13 based on regressions described in the Appendix. These curves use a single-parameter form, $\Delta C = A(\Delta E)^2$, where ΔC is the projected retail-price equivalent (RPE) cost increase and ΔE is the incremental energy savings. RPE value from the studies were all inflated to 2010$ to facilitate comparison. The resulting quadratic coefficient estimates ($\hat{A}$) are given in the figure caption.

These curves show how a long-term analysis tied to engineering fundamentals paints a more optimistic picture than seen when extrapolating from near-term studies. As shown in Figure 6, the EPA & NHTSA (2010) Joint Rule reflects a relatively limited range of energy use reduction, about 16 GJ/yr relative to a MY2011 baseline consumption of 67 GJ/yr. Quadratic extrapolation to about twice that level of reduction (as illustrated in Figure 13) shows how these near-term estimates are close to those of NESCCAF (2004), which is not surprising since that study was a basis for California's AB 1493 proposal which in turn influenced the Joint Rule.

Notably lower costs are inferred from MIT (2008). That study's 2035 horizon is two decades beyond that of the NESCCAF study and it assumes steady progress over time, allowing greater cost reductions in new technologies as well as ongoing progress in existing technologies. The MIT-based curve for light trucks is lower than that for cars mainly because trucks have a higher base level of consumption, and so proportionally higher savings, while the estimated costs of technology change are not that much higher for light trucks than for cars.

To project costs over the horizon of this study, adjusted quadratic coefficients were derived by assuming that incremental mass reduction does not entail additional cost as it is phased in to a 20% reduction level by 2035. These assumptions plus the lower long-term costs of advanced powertrains imply a steady rightward (falling cost) shift in the curves. The declining costs are modeled by making the quadratic coefficient time dependent:

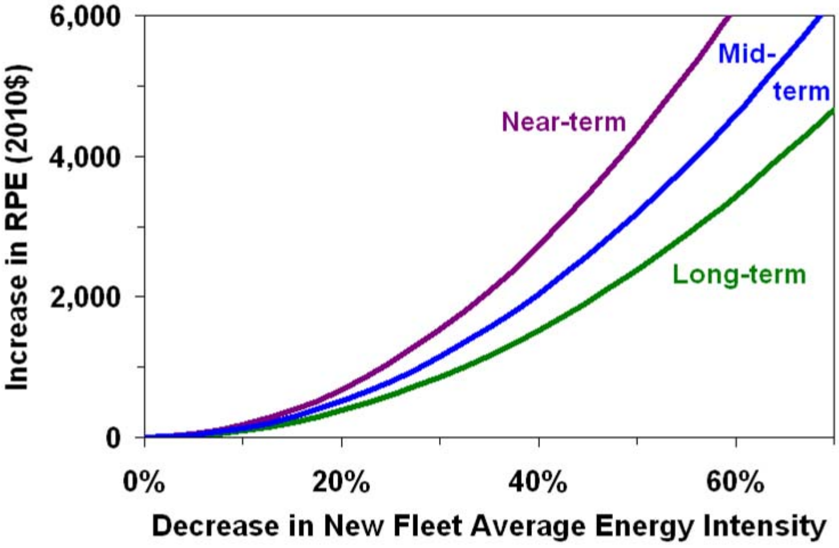
$$A(t) = A_0(1-d)^t$$

where t is number of years from $t_0 = 2015$, A_0 is the coefficient for the near-term curve, and d is an annual rate of decline derived so that A(t) reaches the long-term coefficient by 2035 (see Appendix for details). The rate of decline calculated for the shift projected here is d = 2.9% per year, which corresponds to the cost of achieving a given level of efficiency improvement falling 44% over 20 years. The resulting near-, mid- and long-term cost curves, applicable for 2015, 2025 and 2035 respectively, are plotted in Figure 14.

This substantial reduction of cost over time may seem optimistic relative to other analyses of automotive technology change. A key point is that the efficiency horizon projected here depends only on refinement of technologies already commercialized. It therefore benefits from both competitive and collaborative dynamics within the industry that intently focus on cutting costs to maximize profits. A similar view is seen in Moody's (2008) outlook, which concluded that the costs of complying with the European Union's proposed 130 g/km standards could fall to within €300-€1000 per car, notably lower than EU agency estimates of €1300 per car and industry (ACEA) estimates of €3650 per car.

As described in the Appendix, the coefficient of a quadratic cost curve specified as a function of percent decrease in fuel consumption can be related to the "halving cost," or cost of a 50% reduction in vehicle energy intensity. That is the form illustrated in Figure 14. For the mid-term (2025) time frame, an average RPE cost of about $3,200 per vehicle is implied for cutting the rate of fuel consumption in half (i.e., doubling fuel economy) relative to the 2005 baseline. By

Figure 14. Cost curves for horizons of automotive efficiency improvement



Quadratic cost curves for $\Delta C = 4hx^2$ where x is percent decrease in fleet average energy intensity from the 2005 level of 3.81 kJ/m (corresponding to 24.8 mpg CAFE or 9.5 L/100km) and the coefficients (h) are "halving costs." These h values are ~$4,300 near-term (2015), ~$3,200 mid-term (2025) and ~$2,400 long-term (2035). The corresponding coefficients for quadratics given in terms of consumption reduction (similar to those in Figure 13) are 3.15 near-term, 2.35 mid-term and 1.76 long-term [2010$ per $(GJ/yr)^2$].

2035 the halving cost falls to an average of $2,400 per vehicle. The coefficients in terms of consumption reduction (GJ/yr) are also listed in the figure caption.

Besides technology cost, the other costs to consider are those of externalities (congestion, accidents and noise) associated with the additional driving (rebound effect) induced by higher vehicle efficiency. The parameters for representing those driving-related costs are also discussed in the Appendix.

NET PRESENT VALUE RESULTS

This report does not attempt to analyze benefits and costs using economic welfare theory. Although it tallies changes in driving-related externalities tied to higher vehicle efficiency, its cost-benefit results are limited to an accounting analysis that estimates the net present value of fuel efficiency gains based largely on the difference between fuel savings and technology costs. Whether or not or to what extent consumers value the fuel savings, the avoided monetary costs of fuel are real and dominate such a calculation.

As discussed earlier, it is not clear that consumers will see significantly higher vehicle prices. Moreover, from a policy perspective, the reason to pursue higher auto efficiency is not to save consumers money *per se*, but rather to address GHG emissions and the costs of oil imports. Issues surrounding benefits to consumers and how to characterize them have been broadly debated, as discussed in the EPA & NHTSA (2010) rule and supporting studies. At the crux of the issue -- one of longtime disagreement between proponents of government intervention and industries regulated by such intervention -- is a question about the extent to which consumers make socially optimal decisions given the right price signals. In this case, the question is whether

Table 5. Cost and benefit results for fuel efficiency horizon scenario

Per-vehicle Averages for the New Light Duty Fleet	Base & Current year		Projections by Model Year			
	2005	2010	2020	2025	2030	2035
Energy intensity reduction	0%	8%	42%	52%	60%	67%
Fuel economy (unadjusted mpg)	24.8	26.9	43.0	51.6	62.0	74.4
CO_2 (unadjusted tailpipe g/mi)	358	330	207	172	143	119
with A/C reductions (g/mi)			192	157	128	104
Lifetime Values (on-road)						
Energy Consumption (gge)	6,803	6,298	4,037	3,393	2,851	2,396
Energy Savings (gge)		590	3,264	4,039	4,696	5,254
CO_2 reduction (metric tons)		5	29	36	42	47
Discounted Lifetime Costs						
Total benefit (avoided cost, $)			6,113	7,566	8,798	9,842
Rebound externalities ($)			489	657	829	1,005
Net benefit (avoided cost, $)			5,625	6,908	7,968	8,838
Technology costs ($ RPE)			2,635	3,436	3,960	4,229
Net Present Value (2010$)			2,990	3,472	4,008	4,608

Assumptions: $2.88/gal (2010$) for lifetime average shadow price of fuel; total lifetime driving of 166,000 miles, 7% discount rate; 10% rebound effect; 20% fuel economy shortfall; energy given as gallons of gasoline equivalent (gge) based on LHV of 115.4 kBtu/gal; unadjusted (tailpipe) CO_2 is test-cycle end-use only based on 8,887 g/gal; the second CO_2 line is CO_2-equivalent GHG emissions after subtracting 15 g/mi for likely A/C-related reductions; technology costs are RPE values based on the curves shown in Figure 14.

consumer choices based on the price of fuel yield market outcomes with the "right" amount of fuel economy in light of societal concerns about transportation energy use. Windows into other sides of this debate are given by Crandall et al. (1986) and Kleit & Lutter (2004).

The narrowly framed results given here are derived by applying the cost functions shown in Figure 14 to the new fleet energy intensity trajectory shown in Figure 11. The resulting cost estimates are given in Table 5. Costs are compared to benefits based on the present discounted value of fuel consumption avoided over the lifetime of the fleet. These values can be computed using a present value function and assumed lifetime, as done by NRC (2002), or calculated from vehicle travel and survival statistics as given by NHTSA (2006). This analysis uses the present value method, with base case results assuming a 7% discount rate, a 4.5% per year drop-off in surviving miles as vehicles age and a 14 year vehicle lifetime (similar to NRC 2002). The resulting discounted lifetime travel value (denoted D_L) is 108,000 miles. Due to discounting, this distance is 65% of the average U.S. light duty vehicle total lifetime operation of 166,000 miles given by NHTSA (2006).

To evaluate the societal benefits, a shadow price (P_E) for vehicle energy consumption is used. It depends on three factors: the expected pre-tax price of fuel, assumed to be $2.50/gal (based roughly on $80/bbl crude oil); the social cost of carbon, assumed to be $22/ton$CO_2$ or $0.20/gal (from the EPA & NHTSA 2010 Joint Rule); and the economic benefits of reduced oil imports, assumed to be $0.18/gal (also from the Joint Rule). These numbers are in 2010$, inflated from their respective sources. P_E then amounts to \$2.88/gal gasoline energy equivalent (\$23.62/GJ). Note that 87% of this shadow price is based on the pre-tax price of fuel.

Table 5 summarizes the costs and benefits for the trajectory given in Figure 11 and Table 4. The net present value increases through time because benefits grow in proportion to declining vehicle energy intensity while the relative cost of a given level of energy intensity declines. These results are also shown in Figure 2 of the Executive Summary.

The efficiency horizon identified here has monetary benefits that exceed monetary costs by a large margin. By the 2025 model year, for example, the trajectory leads to a 52% reduction in new fleet average energy intensity from the 2005 level, roughly equivalent to doubling fuel economy (a nominal average of about 52 mpg) and halving CO_2 emissions rate (to an average of 172 g/mi, tailpipe only). This report does not analyze the added incremental costs of improved automotive air conditioning systems, which are assumed to reduce CO_2-equivalent GHG emissions by an additional 15 g/mi as noted in Tables 4 and 5. Those costs are relatively small, amounting to less than \$75 per vehicle (EPA & NHTSA 2010 RIA, Chapter 2). For the efficiency improvements analyzed here using the mid-term cost curve in Figure 15, the projected 2025 RPE technology cost is roughly \$3,400 per vehicle (rounded 2010\$). That is a substantial cost, equivalent to 16% of a 2005 baseline light vehicle price of \$21,000 or 12% of recent new vehicle transaction prices averaging \$28,000.

Nevertheless, the lifetime avoided costs from such a halving of energy intensity are even more substantial, amounting to \$6,900 per vehicle after netting out driving-related externalities. The result is a strongly positive net present value of \$3,500 per new vehicle in 2025. For the tripled efficiency horizon in 2035, the RPE technology cost is \$4,200 per vehicle and the net present value reaches \$4,600. Recall that most of the benefit is based on fuel cost savings, which account for 87% of the total avoided cost with the shadow price assumptions used here.

Automakers Invest, Consumers Save

A distributional and timing disparity exists between the upfront costs that automakers bear, and can probably only partly pass on, and the benefits that accrue to consumers over the lifetime of the improved vehicles. The problem is a classic one in public policy including automobile regulation. What is notable in this case is that the costs of an efficiency horizon such as that projected here are much larger than those of recent regulations, such as the 2010 Joint Rule's estimate of \$950 (RPE) for average per-vehicle costs by model year 2016.

Looking back historically, the auto market has absorbed large costs for emissions and safety requirements. The Bureau of Labor Statistics estimated the price difference between a 2005 new car with and without safety and emissions equipment at \$5,100 relative to a comparable vehicle from the pre-regulatory era (Ward's 2008: 69, adjusted to 2010\$). A difference between the situation for conventional pollution control and safety and that for fuel economy is that the former policies did not yield large direct consumer savings but rather reductions in external costs, which indirectly save money through avoided mortality, morbidity and monetary costs associated with those impacts (although some tailpipe pollution controls had small ancillary fuel savings benefits). In the case of fuel efficiency, automakers are asked to make an investment (or at least invest differently) on behalf of society while direct financial benefits accrue to consumers in addition to the benefits that accrue to society.

Thus, an issue these results raise is the extent to which the high incremental technology costs projected here deviate from a historical trend regarding the automobile market's ability to absorb the costs of regulatory requirements. To the extent that costs exceed the trend, a further question becomes one of what measures are available for mitigating the impact on automakers so that society can obtain the benefits that high levels of vehicle efficiency would provide.

Sensitivity Analysis

The results in Table 5 depend on assumptions that can be varied to yield different cost and benefit values. The set of sensitivity cases described below is summarized in Table 6, where each case represents changing a single assumption (the combined effects of changing more than one parameter at a time are not shown). The values are tabulated as calculated by the spreadsheet model used for the analysis, but in the following narrative are rounded to the nearest $100 under a presumption of no more than two digits of significance.

The first sensitivity case lowers the discount rate from 7% to 3%. This change raises the 2025 net present value (NPV) from $3,500 to $5,200 and raises the 2035 NPV from $4,600 to $6,800. In the Joint Rule, a 3% rate was used for the main analysis while 7% was used as a sensitivity case. A higher discount rate is considered appropriate for policies that alter private use of capital, an assumption in line with the present study's view that automakers have a poor ability to recoup technology costs (see discussion in EPA & NHTSA 2010 Joint Rule: 25596).

The rebound effect also influences the net benefits. Lowering the assumed rebound elasticity from 10% to 5% raises the net present value from $3,500 to $4,100 in 2025 and from $4,600 to $5,400 in 2035. A lower rebound effect becomes more appropriate as time goes on, at least if the fuel price level does not rise greatly. The higher net benefits calculated using a lower rebound assumption may better reflect the value of the long-term efficiency horizon in 2035.

As discussed in the section on mass reduction, an argument can be made that evolutionary mass reduction can be achieved with net cost savings. Assuming that the 20% mass reduction used as the basis of the efficiency horizon identified here can be achieved with a 2% cost savings, as suggested by Lotus (2010), would lower the costs as seen in the quadratic curves (Figure 14). Phasing such a reduction in by 2035 would result in the cost curve coefficient declining by 3.4% per year instead of 2.9% per year as in the base case. It would decrease the 2025 coefficient from 2.35 to 2.24 and decrease the 2035 coefficient from 1.76 to 1.59 [2010$ per $(\mathrm{GJ/yr})^2$]. Projected technology costs would fall from $3,400 to $3,300 in 2025 and from $4,200 to $3,800 in 2035.

Conversely, one can use less optimistic assumptions regarding cost reduction. If costs fall at only half the rate assumed in the base scenario -- i.e., the quadratic coefficient decreases by 1.4% per year rather than 2.9% per year -- then the costs of achieving the efficiency horizon would rise accordingly. Such an assumption yields the values for the last sensitivity case in Table 6, with technology costs of $4,000 in 2025 and $5,700 in 2035, and NPV falling to $3,000 in 2025 and $3,200 in 2035.

The underlying price assumed for fuel, largely determined by the world oil price, dominates any results. A conservative fixed-price assumption of $2.50/gal (roughly corresponding to $80/bbl crude oil) was used. The benefits calculation can be easily scaled by a different fixed price and it is also straightforward to run the calculations with other fuel price projections. Such analyses are

Table 6. Sensitivity analysis results

retail price equivalent (RPE) in 2010$	Technology costs		Net present value	
	2025	2035	2025	2035
Base case	3,436	4,229	3,472	4,608
Lower discount rate to 3%	(unchanged)		5,186	6,802
Lower rebound effect to 5%	(unchanged)		4,098	5,436
Mass reduction at 2% cost savings	3,269	3,828	3,639	5,010
Half the rate of cost reduction	3,981	5,677	2,927	3,161

Base case results are from Table 5 and sensitivity cases are as described in the text.

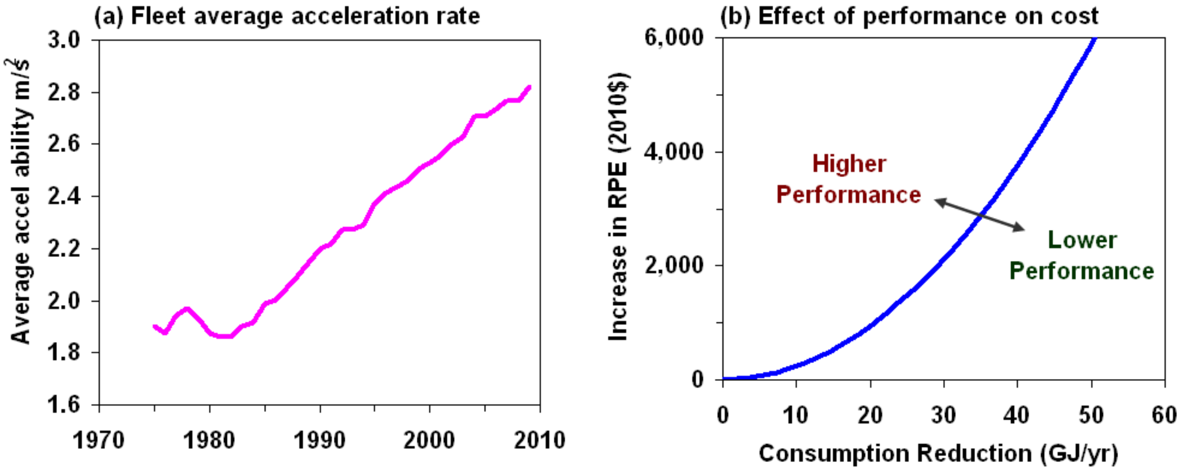
routine and their implications are obvious, and so creating fuel price scenarios is left as an exercise for others.

Another important factor, which this study is not able to fully analyze quantitatively, is the sensitivity to power performance, e.g., as expressed by zero-to-sixty (Z60) time. The cost curves used here all assume fixed fleet average performance. If performance rises, the cost of achieving a given level of efficiency improvement will also rise, resulting in a leftward (higher cost) shift of the cost curves. Calculating the degree of shift for a given change in acceleration ability requires estimation of three relationships: (1) that between fuel consumption and acceleration; (2) that between acceleration (or its correlate, power-to-weight ratio) and engine displacement; (3) and that between engine displacement and cost.

The first relationship is reasonably well known (see, e.g., Cheah et al. 2008; MacKenzie 2009), with correlations that take the form of $z = pf^{-q}$ where z is Z60 time, f is fuel consumption rate, and p and q are empirically determined coefficients. The former (p) relates to the technology level of the fleet and so changes through time, e.g., reflecting a decrease in fuel consumption rate at fixed performance as technology improves. The latter (q) reflects the underlying trade-off and appears fairly stable (which is consistent with the PSFI relationship shown in Figure 5). A recent estimate for q is 0.865 (MacKenzie 2009: 43). Inverting the preceding equation and expressing fuel consumption as a function of average actual acceleration (e.g., m/s^2) yields an equation of the form $f = ka^{(1/q)}$ where k depends on p and unit conversions. Using the above cited value yields $1/q = 1.16$, which is slightly greater than one and so indicates a strong, slightly superlinear sensitivity of fuel consumption to acceleration performance.

The estimated light duty fleet average Z60 in 2005 was 9.9 seconds (EPA 2009, Table 2), which is the constant performance level on which the efficiency horizon projection is based. That implies an average acceleration rate of 2.7 m/s^2 (a value that could be expressed dimensionlessly as $0.27g$ relative to the gravitational acceleration $g = 9.8\ m/s^2$). As shown here in Figure 15(a), the historical trend has been fairly linear since acceleration ability bottomed out in 1982. Note that these EPA estimates are based on a fixed correlation of Z60 time to power-to-weight ratio, and so do not reflect other forms of progress that can further enhance acceleration ability, such as improvements in aerodynamics, tires, driveline friction, vehicle body structures and suspensions.

Figure 15. Light duty fleet average acceleration performance and effect on the cost of achieving a given level of consumption reduction



Source: (a) derived from EPA (2009), Table 2; (b) qualitative illustration using mid-term curve from Figure 14.

In any case, a fit to the 1982-2009 data in Figure 15(a) implies an average increase of 0.036 m/s^2 per year ($r^2 = 0.995$).

Extrapolating this trend to 2035 yields a fleet average acceleration of 3.8 m/s^2 and corresponding Z60 time of 7.1 seconds. Such a number is not implausible given that today's high performance cars readily exceed that level of capability. Applying the sensitivity factor of 1.16 noted above to the resulting 40% gain in acceleration performance yields a 47% increase in average energy intensity, or a 32% loss in fuel economy, for the future fleet. Thus, such a performance gain would reduce the horizon from one of tripled fuel economy down to roughly doubled fuel economy by 2035. The implied rate of increase in new fleet average efficiency would fall from 3.7% per year to 2.4% per year, for 2025 fleet of roughly 40 mpg instead of 52 mpg. Note that this is an approximate calculation based on simply scaling by a sensitivity factor and so is subject to verification through direct modeling of a higher performance fleet. Nevertheless, it is broadly in line with the trade-offs modeled by Cheah et al. (2008), which examined efficiency levels less ambitious than those projected here.

The other two relationships needed to tie changes in performance assumptions to changes in cost can also be examined empirically, with some existing work on which to draw, but doing so was not possible within the scope of this study. Note that the cost impact of engine downsizing may be at least partly quantized in that little savings may accrue when changing displacement with a fixed number of cylinders, but a significant savings can result when decreasing the number of cylinders. For example, NESCCAF (2004) reports savings of $550 for replacing a 6-cylinder engine with a 5-cylinder and $700 for replacing a 6 with a 4.

Evaluating the impact of such changes (cost positive or negative depending on whether engines are upsized or downsized) would be a rather involved effort that requires analyzing the projected engine mix in the fleet and assessing how various changes in displacement would affect cylinder counts. In any case, a qualitative view is illustrated in Figure 15(b).

Conclusions

Important perspective is provided by viewing technology in the context of other factors that influence vehicle design. A review of the past several decades' automotive trends shows how technological progress was harnessed largely to objectives other than improving fuel efficiency. This trade-off spotlights the challenge of directing future progress toward measurable reductions in energy intensity as opposed to increasing the technical energy efficiency with which other vehicle amenities are provided. Therefore, auto efficiency should be seen as a matter of design priority -- that is, an outcome of a process that emphasizes multiple objectives, only one of which may be fuel efficiency -- rather than mainly as a matter of technology change.

Overall fleet efficiency also depends on high-level choices of what to prioritize in the multilevel, competitive process that determines not only technology use in individual models but also the product strategy of a company and the directions of the industry as a whole. Sensitivity analysis of fleetwide performance indicates that the fuel efficiency level attainable using a given set of technologies varies greatly depending on how the technological capabilities are used. Thus, this report distinguishes what are termed compatible strategies for efficiency improvement -- those that emphasize features that avoid conflict with a need to reduce energy intensity -- from the purely technical strategies commonly considered.

The technological opportunities are substantial and were reviewed here with reference to the existing automotive technology literature. Synthesizing such results yields a projection of the fuel efficiency levels feasible if technology applications are fully prioritized for reducing vehicle energy intensity. Because the goal was to identify an efficiency horizon, the analysis draws on studies using a fundamental engineering approach rather than specifying detailed technology pathways. Nevertheless, extensive use of hybrid drive appears necessary for realizing high levels of fleetwide fuel efficiency.

The rate at which technologies might be adopted was examined by reviewing historical adoption rates as represented by logistic curves. Cost estimates were distilled into quadratic cost curves, which present an aggregate view of likely impacts and are convenient for modeling reductions in cost expected through engineering progress. These estimates were used to construct a scenario of energy intensity reduction for the light duty fleet as it could evolve between now and 2035. Even though costs rise, they are greatly exceeded by fuel savings over the lifetime of the fleet, resulting in a positive net present value that rises over time. Nevertheless, automakers bear any technology costs upfront; the extent to which they are passed on to consumers is unclear.

In summary, tripling new fleet fuel efficiency is an ambitious but defensible horizon for 2035. Reaching it will entail rising costs that are best seen as opportunity costs for features that might otherwise appear in cars if high fuel efficiency levels are not sought. Achieving this horizon at the costs projected means foregoing further gains in average acceleration performance, a marked departure from past trends. If instead performance rises in line with its historical trend, the 2035 horizon drops from tripled down to roughly doubled fuel efficiency. Nevertheless, improving the fleet toward such a horizon through evolutionary change remains less costly than "revolutionary" alternatives requiring extensive new infrastructure. In short, attaining or even approaching the fuel efficiency horizon projected here will yield substantial benefits for reducing oil consumption and limiting GHG emissions from the transportation sector. ■

Appendix:
Cost Curve Derivations

A quadratic form is useful for approximating technology cost as a function of vehicle energy intensity decrease. It represents costs as a function of the benefits delivered, which are proportional to avoided fuel consumption. Figure A-1 compares estimates from some of the studies reviewed here (MIT 2008, NESCCAF 2004, and EPA 2004) along with the quadratic fits used for the summary curves that were shown in Figure 13.

Although different studies analyze different reference vehicles, all use relatively recent base years (2002-2006). Those years, which were prior to the recent changes induced by high fuel prices and strengthened CAFE standards, saw little change in average efficiency-related characteristics of the fleet. Given this study's long-term horizon, the baseline differences are small compared to the magnitude of changes projected.

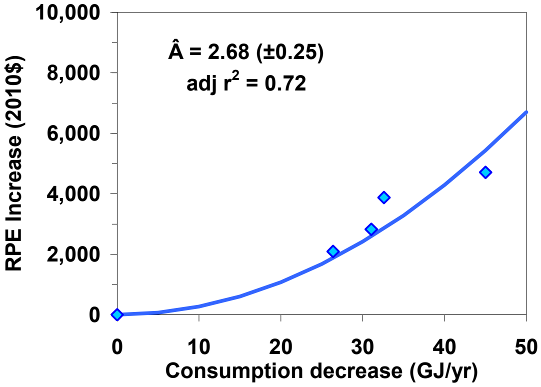
As seen in Figure A-1, total incremental cost (given as retail price equivalent, RPE) is plotted against a decrease in energy consumption calculated assuming 12,000 miles of annual driving and a 20% fuel economy shortfall for all vehicles. Estimates from the studies were fit to the function:

$$TC_T = A \cdot Q^2 \qquad \text{(A1)}$$

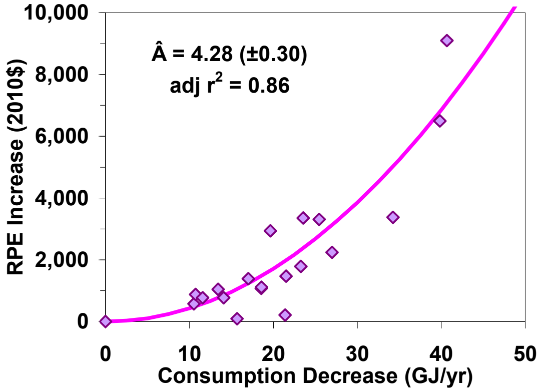
where TC_T is the total cost of technology improvement and Q is the quantity of energy savings on an annualized basis (GJ/yr). The resulting coefficient estimates $\hat{A}$ are shown with each graph, with the units of $\hat{A}$ being 2010\$ per $(\text{GJ/yr})^2$.

Figure A-1. Cost increase (retail price equivalent) vs. consumption decrease for selected studies

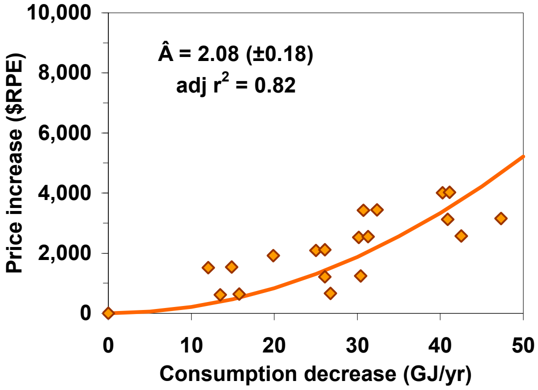
(a) MIT estimates for midsize sedan



(b) NESCCAF estimates for midsize sedan



(c) EPA ATD estimates for large SUV

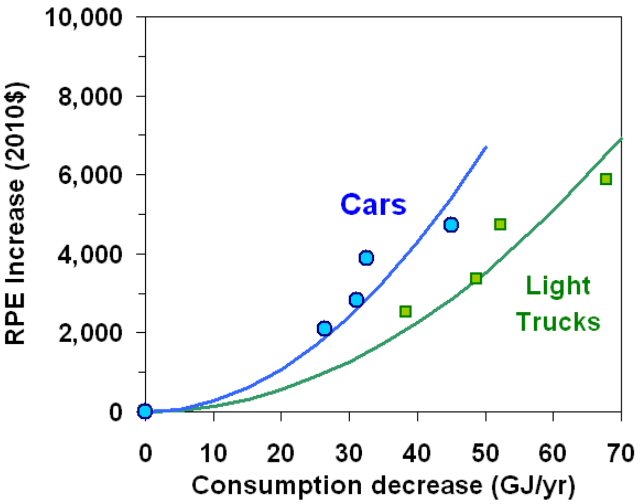


The NESCCAF fit yields a quadratic coefficient (A) of 4.28, somewhat larger than the estimate of 4.02 implied by the cost of reaching the light duty fleet average CAFE level in 2016 projected by the EPA & NHTSA (2010) Joint Rule. As was shown in Figure 13, those two curves are very close in any case. The latter coefficient, $A_0 = 4.02$ [2010\$ / $(GJ/yr)^2$], is chosen for defining a near-term technology cost curve.

Shown for comparison are results from the EPA (2004) Advanced Technology Division (ATD) study, which provides an optimistic bounding analysis. The estimates plotted in Figure A-1(c) are for a large SUV using various configurations of hydraulic hybrid drive with advanced gasoline or diesel engines. That study estimated costs of hydraulic hybrids as markedly lower than those of electric hybrids, and the hardware is suited to larger vehicles (demonstrations to date have been in SUVs or delivery trucks). Not shown here are the EPA ATD estimates for a midsize sedan, which are somewhat more costly per unit energy savings because a sedan's baseline consumption is lower than an SUV's and some technology configurations for sedans cost a bit more than those for SUVs.

Figure A-2 plots MIT's estimates for cars and light trucks. The truck values again appear less costly because the relative energy saving is significantly higher than that for cars while the technology cost is only a bit higher. The resulting quadratic coefficient ($\hat{A}$) estimate for light trucks is 1.41 (±0.09) compared to an estimate of 2.68 (±0.25) for cars [2010\$ per $(GJ/yr)^2$]. A composite LDV cost curve can be derived from a weighted average of these two curves, with a 60% car share implying a coefficient of 2.17. The resulting composite curve is not plotted here but this coefficient is used as an input for deriving the adjusted long-term cost curve as described below.

Figure A-2. Cost estimates and quadratic fits for cars and light trucks based on MIT (2008)



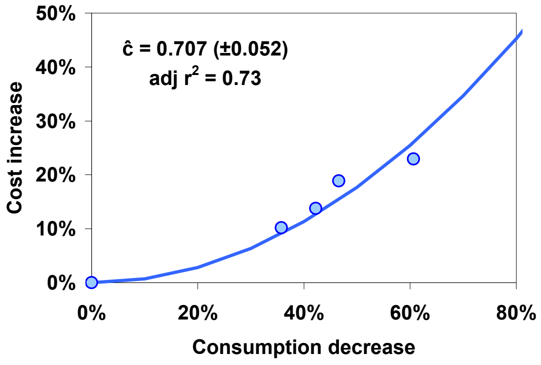
Note that the 60% share used for cars is not intended to reflect a legal car-truck distinction, but rather an assumption that 60% of the future fleet will have characteristics that are more car-like than truck-like in terms of functional requirements. The market has already more than moved in that direction, with truck-based vehicles dropping from 31% in 2007 to 23% through the first half of 2010, and is very unlikely to shift back to the higher fractions of truck-based products seen at the peak of the SUV boom (Snyder 2010). EPA & NHTSA already assume cost to a 67%-33% car-truck split for the fleet mix going forward. However, a higher car weighting for the composite curve would not reflect the fact that much of the baseline fleet falls under a light truck classification and so has a greater potential for lower cost consumption reduction.

These plots also enable discussion of the general shape of the cost curve in light of the scatter involved. Some of the cost estimates might just as well be fit by a straight line, or perhaps a two-parameter quadratic with a dominant linear term. In particular, points from EPA & NHTSA

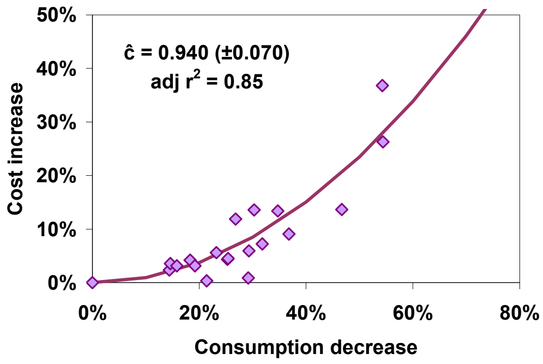
(2010) shown earlier in Figure 6 appear more linear than quadratic for the limited range of reductions assessed for near-term policy. A linear relationship is not surprising for near-term estimates because what drives such an analysis is largely greater utilization of a static set of technologies that are modeled with costs that are either constant or slightly declining. This situation is unlike that for a long-term assessment, which involves tapping more expensive technologies as less costly options are exhausted.

Figure A-3. Normalized plots of cost increase vs. consumption decrease

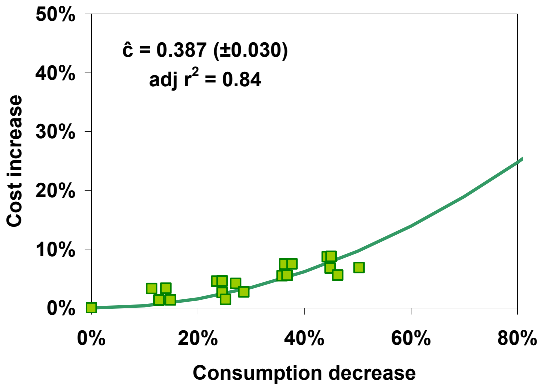
(a) MIT (2008), relative to a 2005 midsize sedan



(b) NESCCAF (2004), relative to a 2002 midsize sedan



(c) EPA (2004), relative to a 2002 large SUV



The NESCCAF (2004) estimates, which incorporate both nearer- and longer-term technologies, show a more quadratic trend as seen in Figure A-1(b). The EPA (2004) ATD estimates could readily be represented as linear as could the MIT (2008) estimates. The latter have just a few points in any case; although not shown here, a linear fit to the MIT estimates yields an adjusted r^2 of 0.73, compared to 0.72 for the quadratic.

It is difficult to be conclusive given the scatter involved. This analysis adopts a quadratic for the reasons noted in the main text, particularly the desire to represent increasing marginal costs as seems appropriate for a fundamentals-based long-term efficiency horizon.

For comparing studies, it is useful to normalize one or both of the cost and fuel savings variables, expressing them in percentage terms relative to a base vehicle or base fleet (Santini et al. 2002). Curves normalized in both cost and fuel consumption enable comparisons in dimensionless form, obtained by fitting:

$$\Delta C/C_0 = c(\Delta E/E_0)^2 \qquad \text{(A2)}$$

Here C_0 and E_0 are the base cost (RPE) and energy consumption (GJ/yr) of the reference vehicle used in a given study. The relationships to the parameters of Equation (A1) are given by $\Delta C = TC_T$ and $\Delta E = Q$. Figure A-3 shows normalized cost and savings values and their respective curve fits.

Recall that although its units are RPE, TC_T should not be viewed as an actual price increase likely to be experienced by consumers, but rather as a retail equivalent estimate for the impact of the technology changes on automakers' product development budgets. As discussed in the main text, automakers probably cannot fully pass costs on to consumers; rather, the cost impact is likely to be reflected as foregone spending on other features that might have been offered instead of higher fuel economy. Thus, the percent cost increases shown in Figure A-3 should be interpreted as measuring such opportunity costs relative to the retail price of the reference vehicle.

The normalized coefficient ($\hat{c}$) is readily adaptable for calculating the relative cost of halving vehicle energy intensity (doubling fuel economy). In this case, $\Delta E/E_0 = ½$ and the percent change in cost is given by $\hat{c}(½)^2 = \hat{c}/4$. Relative halving costs on the order of, say, 18% as suggested for a 50% decrease in consumption along the MIT-based curve, clearly have a large impact on an automaker's product development budget, and if passed through to consumers, would represent a major impact on retail price as well. The projected "halving cost" ($h = \hat{c}/4$) is an intuitive way to present the quadratic coefficients, as illustrated in Figure 14.

Cutting vehicle energy intensity by two-thirds (a 67% reduction) is an extrapolation beyond the range of cost estimates from most studies. However, it is not much beyond MIT's results for a hybrid-electric vehicle, estimated as achieving a 61% reduction in fuel consumption rate. In normalized quadratic terms, the cost of such a tripling of fuel economy can be extrapolated as $\hat{c}(⅔)^2 = 0.444\hat{c}$. For the MIT passenger car curve, this implies a relative RPE impact of 31%. As for any application of this curve, such estimates are for a long-term time horizon of 2035.

Another thing to note when interpreting these estimates is that the RPE normalization was done relative to vehicles from non-luxury segments. That is, it estimates impacts based on reference vehicles from high-volume segments that do not command premium prices. Thus, these normalized estimates should not be applied relative to the price of a vehicle carrying a price premium that reflects many features, or even intangibles related to brand status, that would not see proportional cost increases for technology to improve fuel efficiency.

Adjusting the Cost of Weight Reduction

As noted in the main text, mass reduction up to if not beyond the 20% level assumed in the MIT (2008) analysis is within the range achievable by ongoing evolutionary refinements in materials and technique. This analysis therefore assumes that fleet average mass reductions incur no additional cost at the incrementally increasing levels entailed in the efficiency horizon identified here. Although the Lotus (2010) study estimates the potential for a 21% mass reduction at 2% cost savings even for a relatively near-term (2017) program, reviewers raised concerns about the ability to achieve that degree of optimization in all vehicles. That more optimistic view is treated here as a sensitivity case that results in lower cost estimates for 2020-2035. The cost curves derived above were adjusted to reflect these assumptions as explained below.

Adjusting the near-term cost curve involves subtracting the costs of mass reduction used in the recent Joint Rule. EPA & NHTSA (2010 TSD: 3-79) applied an average mass reduction cost of \$1.48 per pound (2007\$, which inflates to \$1.55/lb 2010\$, or \$3.42/kg). They assumed varying amounts of mass reduction ranging 3.5%–8.5% for various segments of the fleet (with some vehicles seeing no reduction). Applying the average of this range (6%) to the average 2005 light duty vehicle curb weight of 3800 lbs yields \$350. Assuming further that this cost applies to about half of the fleet suggests a downward adjustment of \$175. This value is subtracted at the average level of the 2016 CAFE rule to lower the near-term cost curve at this point. Recomputing the near-term quadratic coefficient (A_0) accordingly yields a value of 3.15, compared to the value of 4.02 derived earlier; units are 2010\$/(GJ/yr)^2.

The long-term (2035) curve is adjusted by subtracting costs from the composite curve derived from MIT (2008). That study assumed a constant cost per unit of mass reduction for new vehicles in 2035, which they project to be 20% lighter than the 2005 reference vehicle (assuming 100% emphasis on reducing fuel consumption). They assume that a 14% mass reduction through materials substitution costs \$3/kg and that the rest of the reduction to the 20% level is obtained from secondary weight savings at no cost. The resulting estimates are \$700 per car and \$900 per light truck (2007\$; MIT 2008: 36-37), which average to \$816 assuming a 60%-40% car-truck split and inflating to 2010\$. This cost is subtracted from the MIT-based composite curve at the point of 60% normalized reduction in energy intensity. The resulting adjusted quadratic coefficient of 1.76 [2010\$ per (GJ/yr)^2] defines the long-term (2035) cost curve shown in Figure 14. For years between now and 2035, with intermediate levels of mass reduction also assumed at zero net cost, cost curves are defined by the shift function described below.

A sensitivity case examining the likelihood of even lower mass reduction costs is based on the Lotus (2010) study's "low development program" estimate of 21% mass reduction with a 2% cost savings. Based on detailed component- and vehicle subsystem-level analyses, the study argues that such savings can result from a synergistic, whole-vehicle strategy for cutting mass. Lotus (2010) based its cost savings estimate on the non-powertrain portion of a base vehicle, which accounts for 77% of vehicle cost. Using the MIT (2008) base vehicle costs, which average to \$21,100 (inflated to 2010\$) and taking (2%)(77%) implies an average savings of \$325. This value is combined with the \$816 calculated above for a total downward adjustment of \$1,141. Subtracting this value from the MIT-based composite curve at the 60% consumption reduction point yields a quadratic coefficient of 1.59 [2010\$ per (GJ/yr)^2], which is used for the lower cost sensitivity case given in Table 6.

Cost Curve Shifts Through Time

The drop in costs as projected in the curves derived above can be viewed as a rightward shift in the cost ("supply") curve for energy conservation through vehicle efficiency improvement. To interpolate cost curves for intervening years, a shift through time can be modeled by making the quadratic coefficient (A) a function of time (t):

$$A(t) = A_0(1-d)^t \qquad \text{(A3)}$$

where d represents a rate of decline in cost. If t_0 is 2015, a rightward shift over the 20 year period until 2035 can be represented by starting with $A_0 = 3.15$, as derived above by adjusting costs from the EPA & NHTSA (2010) Joint Rule, and ending with $A_{20} = 1.76$, as derived above by adjusting costs from the MIT (2008) study. The resulting decline in the quadratic cost coefficient is d = 2.9% per year. This shift function is used to derive the mid-term curve (for a 2025 time frame) shown in Figure 14. A greater rate of shift is implied by the lower-cost mass reduction sensitivity case, which implies a decline (d) of 3.4% per year in the quadratic coefficient. In this case, which can be seen as reflecting greater productivity gains in supplying technologies for vehicle efficiency, the cost of achieving a given fleet average energy intensity reduction drops by 50% between 2015 and 2035, compared to a 44% drop in the base case.

Costs of Percentage Changes in Fleet Average Energy Intensity

It is useful to parametize the cost function using percent reduction of annual energy consumption relative to the base year (2005), a variable that is also useful for calculating the other costs and benefits that are proportional to the change in vehicle energy use. Therefore, let x represent the percent reduction in energy intensity relative to the base fleet:

$$x = \Delta E/E_0 = Q/E_0 \tag{A4}$$

where E_0 is the consumption level (GJ/yr) of the base year fleet. The time-varying total cost of technology from Equations A1 and A3 is then given by:

$$TC_T = A(t)\cdot Q^2 = A(t)E_0^2x^2 \tag{A5}$$

The other costs to be considered are the externalities associated with additional driving induced by the rebound effect. Small and Van Dender (2007) found that the rebound effect for U.S. conditions is small (about 10%) and likely declining as time goes on; it is denoted here by δ and a fixed value of 10% is assumed. The total shadow price (P_D) of these externalities (congestion, accidents and noise) is assumed to be $0.08 per mile, a car-truck average from EPA & NHTSA (2010) inflated to 2010$. Their total cost is then given by

$$TC_D = P_DD_L(1-x)^{-\delta} \tag{A6}$$

where D_L is the discounted lifetime travel distance of the average vehicle as discussed in the main text. These functions were used to calculate the values in Table 5.

The total cost (TC) is the sum of the technology cost plus the external costs of induced driving. It can be given in terms of percent reduction in energy intensity (x) by year (t) as:

$$TC(x,t) = TC_T + TC_D = A(t)E_0^2x^2 + P_DD_L(1-x)^{-\delta} \tag{A7}$$

The marginal cost is then:

$$MC(x,t) = 2A(t)E_0^2x - \delta P_DD_L(1-x)^{-\delta-1} \tag{A8}$$

Although a formal cost-benefit analysis is not attempted here, this equation could be used to derive so-called "cost-efficient" levels of energy intensity reduction by equating the marginal benefit to the marginal cost (MB = MC). MB is essentially a linear function of intensity reduction and so can also be parametized by x. MB is dominated by the fuel price projection, which can vary as a function of time (t) but of course remains highly uncertain.

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