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A benefit-cost assessment of new vehicle technologies and fuel economy in the U.S. market

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Abstract

Increasingly stringent fuel economy and emissions regulations alongside efforts to reduce oil dependence have accelerated the global deployment of advanced vehicle technologies. In recent years, original equipment manufacturers (OEMs) and consumers have generally been successful in mutually deploying cleaner vehicle options with little sacrifice in cost, performance or overall utility. Projections regarding the challenges and impacts associated with compliance with mid- and long-term targets in the U.S., however, incur much greater uncertainty. The share of existing new vehicles that is expected to comply with future regulations, for example, falls below 10% by 2020. This article explores advanced technologies that result in reduced fuel consumption and emissions that are commercially available in 2014 Model Year compact and midsize passenger cars. A review of the recent research literature and publicly available cost and technical specification data addressing correlations between incremental cost and fuel economy is presented. This analysis reveals that a 10% improvement in the sales-weighted average fuel economy of passenger cars has been achieved between 2011 and 2014 at costs that are at or below levels anticipated by the regulations by means of reductions in weight, friction, and drag; advancements in internal combustion efficiency; turbocharging combined with engine downsizing; transmission upgrades; and the growth of hybrids. Benefit-cost analyses performed on best-selling models in the selected classifications reveal that consumers thus far are not substantially incentivized to purchase fuel economy. Under baseline conditions, benefit-cost ratios are above a breakeven value of unity for only 6 of 28 models employing improved fuel-economy technologies. Sales-weighted data indicate that the “average” consumer that elected to invest in greater fuel economy spent $1490 to realize a 17.3% improvement in fuel economy, equating to estimated savings of $1070. Thus savings were, on average, insufficient to cover technology costs in the baseline scenario. However, a sensitivity analysis reveals that a majority of new technologies become financially attractive to consumers when average fuel prices exceed $5.60/gallon, or when annual miles travelled exceed 16,400. The article concludes with techno-economic implications of the research on future fuel economy regulations for stakeholders. In general, the additional cost consumers incur in exchange for a given level of fuel economy improvement in the coming years will need to be steadily reduced compared to current levels to ensure that the expected benefits of fuel savings are financially warranted.

Keywords: fuel economy, clean vehicle technologies, alternative vehicles, hybrid vehicles, CAFE, benefit-cost

1. Introduction

A combination of evolutionary and transformational technologies have substantially increased fuel economy levels for light duty vehicles in the U.S., representing a tremendous achievement for consumers, automakers and policymakers alike. With the promulgation of the revised Corporate Average Fuel Economy (CAFE) standards in 2011 for the period 2012-2016 [1], technological innovations bundled into a variety of existing and new vehicle models are increasingly meeting both consumer and regulatory demands. From the 2011 through the 2014 model years, the passenger car fleet has improved from 33.1 to 36.5 miles per gallon (mpg, EPA combined) on a sales weighted basis, outperforming the Federal standard by 8.0% in 2012, 7.8% in 2013, and 7.0% in 2014 [2]. In a similar fashion, sales-weighted CAFE performance for the entire light duty fleet, which includes all cars and light trucks, increased at a rate of 4.3% in 2011, 3.1% in 2012 and 3.0% in 2013 [3].

Leading the U.S. government efforts to shape CAFE, the Department of Transportation's National Highway and Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) aimed to develop a robust policy in hopes of carefully balancing consumer utility and choice against aggressive goals to reduce the national consumption of petroleum fuels and related emissions. Automakers, herein referred to as Original Equipment Manufacturers (or OEMs), have thus far been able to meet and exceed the more stringent requirements by pulling ahead existing fuel-saving technologies and by adjusting business strategies and sales portfolios. A great deal of investigation, consultation, and modeling based upon then current information provided the framework for the rule regulating 2012-2016 model year vehicles. The lead agencies issued the Draft Joint Technical Support Document (TSD) specifically to document relevant technology performance and cost data available prior to rule issuance [4]. Such processes are admittedly uncertain, in part because subject estimates of technology, costs and fleet evolution are based upon projections drawn from 2008 and 2010 model year information [1], yet implementation of the regulations extends more than a decade into the future. Technologies are assumed to penetrate the market based upon a cost-effectiveness algorithm that compares the technology cost to the discounted stream of fuel savings and the value of performance to the consumer [5]. Though the source data detailed technology specificity [6] and delineated assumptions about fuel prices and discount rates, projections of fleet-wide impacts and vehicle sales by technology type were aggregated, making it difficult to explicitly determine the relative performance and cost-effectiveness of fuel savings technologies. Now nearing the mid-term of the first phase of the CAFE regulations for the 2012-2016 model years [1] (a second phase will be implemented between 2017 and 2025 [7]), the timing is appropriate to assess the progress made thus far, the constituent technologies underpinning the improved fuel economy performance, the consumer benefits and costs associated with the trends, as well as some implications for the coming years. This study looks at the empirical record, drawing from vehicle and technology specifications, published selling prices, and established conventions for financial decision-making by consumers and the economy as a whole. To ensure consistency, it uses accepted terms, definitions and concepts while drawing from many of the same literature sources that were used to formalize the standards.

This study seeks to ascertain how closely costs, fuel economy improvements and the recently promulgated regulatory standards align, as well as to quantify the extent to which novel fuel saving technologies are financially attractive to consumers and how their value proposition may evolve in the future. Such an assessment may prove valuable to a wide range of stakeholders, including researchers in transportation and energy, economics and policy as well as consumers and OEMs.

2. Fuel economy overview of the U.S. market: Background and resources

2.1 Current CAFE standards

As noted, Federal fuel economy policies are designed to simultaneously address key challenges and deliver tangible benefits to consumers, the economy, and the country as a whole. Positive aspects of the regulation include: (1) the potential to reduce fuel consumption and preserve consumer choice; (2) the potential to meaningfully reduce emissions and improve air quality; and (3) the promise of a single, consistent national policy for all stakeholders [8]. Sustainably achieving these goals over a period of a decade or more, whether in the United States or elsewhere, requires that regulations be based upon the most current scientific and market-based data available, and appropriately address sources of uncertainty over time. While numerous studies quantify the benefits of fuel economy standards and project the composition of future vehicle fleets in 2035 or 2050 [9-13], researchers have suggested that the market for fuel economy does not function efficiently [14-18], with consumers often undervaluing its benefits. Given the sales-weighted emphasis of most policies, Greene suggested that “policy analysis must be based upon how real world markets actually function,” noting that costs and benefits may vary accordingly [18].

Recent trends indicate that OEM compliance is largely being attained, the policy has thus far been successful, and progress is on track [19]. In fact, and as shown in Figure 1, OEMs began to increase internal CAFE metrics beyond the required level, even before the issuance of the 2012-2016 rule. Specifically, this is illustrated in Figure 1 by the substantial gap between the “Actual fleet” and “Avg Fed Std” fuel economy levels in the year 2010. One reason they have continued to exceed the minimum requirements is that they can generate credits for over-compliance within the current policy, and have the option of carrying them forward or backward, or trading them with other OEMs [7].

A December 2013 EPA report indicates that 28% of MY2013 vehicles meet the 2016 standard [19], which varies slightly among the two regulatory agencies due to the regulation of CAFE vs. CO_2 emissions (34.1 mpg is NHTSA’s CAFE goal for passenger cars, whereas 35.5 mpg is EPA’s “CO_2 equivalent” goal) [1]. It should be noted that the exact regulatory standard is variable within annual limits due to the unknown sales mix and the footprint-specific approach, and also because the authority of NHTSA and EPA requires them to regulate fuel economy and GHG emissions respectively [1, 7, 20]. However, the standards on passenger cars roughly follow a 4.3% increase through 2016, and then a 4 to 5% annual increase beginning in 2017 and extending until 2025. With this steady increase in requirements through 2025, the share of 2014 models that will be able to comply in that terminal year without further modification falls precipitously toward the end of the decade. Only 5% of all light duty MY 2013 vehicles appear to be compliant with the 2025 standards (which include CO_2 equivalent emission targets as well as fuel economy targets) [19]. Aside from today’s hybrids, a portion of those that do are currently low volume, partially or fully-electrified platforms such as plug-in hybrid or electric vehicles which rely on a miles-per-gallon equivalent (mpge) basis to comply [footnote 1].

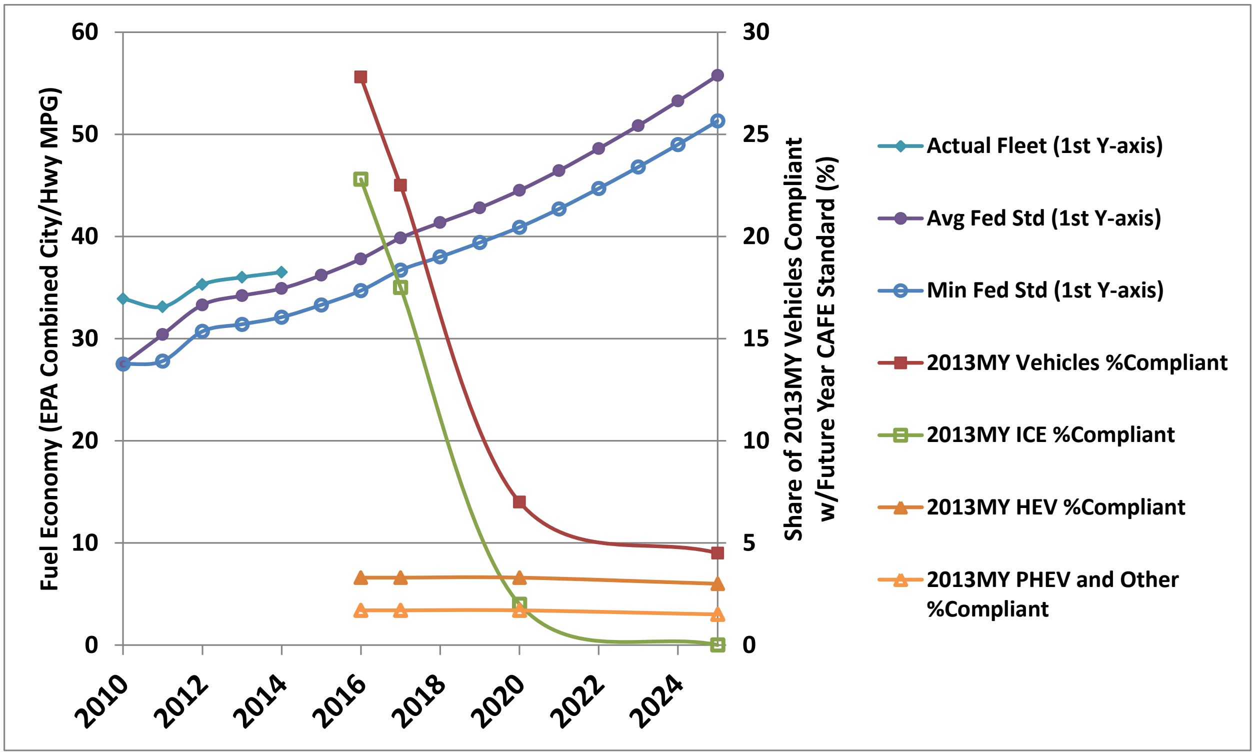


Figure 1. Passenger Car Corporate Average Fuel Economy (CAFE) actual fleet performance vs. Federal standards (left Y-axis); and approximate share of 2013 MY vehicles that are compliant with the Federal standard in future years (right Y-axis). Data sources: [2, 19]

Note: As mentioned, EPA and NHTSA regulations differ slightly. Here, an equivalent CAFE fuel economy standard that estimated an average of the two is shown, labeled “Avg Fed Std.”

Note on Definitions: ICE=internal combustion engine; HEV=hybrid electric vehicles; PHEV=plug-in hybrid electric vehicles; Other=includes electric vehicles (EV) and compressed natural gas (CNG) vehicles.

Thus, two critical, but distinct, near-term challenges facing the industry today are approaches to increase the number of models that comply, and to attract consumers to purchase the ones that do. Regarding the first, the commercial introduction and deployment of an increasingly wide range of advanced technologies will be needed (see Section 3.1). Regarding the second, if the consumer is to benefit financially from stricter standards, costs must be offset by an equal or greater level of benefits to the consumer, and not just to society as a whole (see Section 3.2).

In addition to striving to ensure technological feasibility, conserve energy and reduce emissions, the policy also has a requirement to ensure “economic practicability.” This has implications on the financial capability of the industry, jobs, and consumer demand for fuel economy in addition to other vehicle attributes [7].

This current assessment analyzes critical technologies in today’s marketplace, discusses revealed consumer preference, and explores associated benefits and costs under a range of potential conditions. By taking a consumer perspective and analyzing specific vehicle models and technologies, the study provides insight into current-day economic practicality that has been lacking in previous studies focused on fleet-wide averages [9-13], or based upon past model years [1, 11, 22]. Uncertainty is addressed by means of a straightforward sensitivity analysis on economic and application-dependent parameters. The primary scope of this study is the U.S. passenger car market in 2014, with an emphasis on compact and midsize vehicles. This detailed study is confined to these segments because they are a representative subset of new car sales and, owing to their nature, basic design, and market demands, tend to incorporate a comparatively large number of fuel-saving technologies. This analysis includes 14 of the highest-selling passenger cars in the U.S. market for the period 2012-2014, or about 55% of the entire passenger car market. The data supporting this study are aggregated, and to the greatest practical extent, references to specific makes, models or proprietary technologies are limited so as to avoid any unintended bias toward or against a particular vehicle technology or brand.

2.2 Key fuel economy technologies and their estimated costs

An exhaustive review of all fuel-saving technologies introduced in U.S. cars is well beyond the scope of this paper. However, the literature and market suggest a manageable subset of the most popular and effective solutions that have now become commercially available. A revitalized CAFE standard was formally signaled in 2007, under the Energy Independence and Security Act [23], which originally called for CAFE standards to reach a combined car/truck performance of 35 mpg by 2020. This target was effectively pulled ahead to about 2016 with the final 2012-2016 MY rulemaking [1], as illustrated in Figure 1. For some technologies, long redesign cycles (on the order of 4-8 years) often typical of engines and other transformational technologies, such as hybrid and electric powertrains, are the reality. Other technologies follow a more evolutionary path, can be more readily incorporated into annual or biannual product 'refresh' cycles, and include advanced transmissions, reductions in weight, friction or drag, and valve actuation strategies, for example [6, 22, 24]. These carry generally lower costs, but proportionally lower fuel savings as well. Table 1 provides an overview of several major vehicle technologies that contribute to increased fuel economy. The methods and underlying detail for estimating 2014 MY costs emerging from the authors' study are discussed in Section 3. The table includes data drawn from a comprehensive report on the subject prepared by the National Research Council [22]. In that study, which constituted one of many inputs to the Federal policy, ranges and average values for estimated fuel economy improvements and their associated incremental costs were presented by technology type and vehicle class based upon then-current technology and baseline fleet characteristics. Here, the NRC cost estimates are expressed in 2014 dollars [footnote 2], having been converted from a 2008$ basis via the consumer price index, or CPI [25]. Depending on the context, source and application, "incremental cost" can have multiple meanings. In order to reduce confusion, it is defined here to mean the value which equates to the consumer's retail equivalent price difference between a base technology and an upgraded one. In other words, it is the price difference due solely to the fuel economy technology.

One can get a sense for the recent commercial growth of these selected technologies by comparing their respective market shares among all new light duty vehicles (LDV) in the 2008 model year with the 2013 model year [19]. It is not surprising that the lowest-cost, most "evolutionary" technologies, such as variable valve technologies (VVT) and 6-speed transmissions (AT6), reflect the highest market shares overall (96% and 64%, respectively). However, in terms of growth *rate*, one notes that continuously variable transmissions (CVT) and hybrids (HEV) have nearly doubled, while turbos with downsizing (TRBDS) and gasoline-direct injections (GDI) have increased six-fold and ten-fold, respectively. Quantifying future market penetration, while estimated by previous studies [4, 6, 12, 26], invariably is uncertain, which can be in part illuminated by revealed preferences in current model-year sales, adding to the relevance and timeliness of this study's approach.

Table 1. Overview of selected vehicle technologies that contribute to improved fuel economy, their approximate market share growth, their benefits and costs. [19] and [22].

		Market Share (%LDV**, est.)		**Fuel Econ Benefits** (average % diff)		**Incremental Costs** (est., in $2014)	
	Source:	[19]		[22]	Authors	[22]	Authors
Technology Description	Abbr.	MY2008	MY2013	NRC*** 2011	**MY2014**	NRC 2011	**MY2014**
Weight reduction (2 to 5%)	WT	-	-	2.5	**9.7**	280	**1,233**
Aerodyn. & friction reduct.	AERO	-	-	2.6		133	
Variable Valve Technologies	VVT	58.0	96.0	3.7		279	
Auto Transmission (6 sp)	AT6	19.0	64.0	2.6	**5.6**	510	**817**
Cont. Variable Trans. (CVT)	CVT	7.0	13.0	4.3		266	
Gasoline Direct Injection	GDI	3.1	30.0	3.1	**10.2**	324	**1,301**
Turbocharging & Downsizing	TRBDS	2.5	15.0	5.3		814	
Conversion to Diesel	Diesel	< 1.0	1.0	35.7	**21.8**	3,974	**4,005**
Hybrid	HEV	1.9	3.5	58.1	**58.1**	4,982	**4,098**
Plug In Hybrid*	PHEV	< 1.0	< 1.0	N/A	**91.1**	14,723	**8,849**

*Note 1. NRC study considered a single PHEV with a 40 mile range, although this study includes PHEVs with all electric ranges from 10 to 40 miles. All-electric range is linearly proportional to battery cost and therefore incremental price. Also, NRC did not report on the % fuel economy improvement typical of a PHEV, possibly because it is largely application-dependent and the two modes of energy (electricity and gasoline) make this non-trivial to report on the same basis.
*Note 2. For this study, a Federal subsidy applies to certain PHEV vehicles (>5kWh battery) and has therefore been included [27], whereas the policy had not taken effect when NRC performed its study. CAFE regulations consider mpg and mpge (for certain PHEV) equivalently, and are therefore included accordingly in this study. [1] [7] [footnote 1]
**Note 3: %LDV means % of the light duty vehicle fleet that includes some aspect of the given technology. These numbers are estimates from [19].

***Note 4. The NRC study reported fuel savings in terms of % reductions in fuel consumption. These have been converted to % improvements in fuel economy, though the relationship is inversely proportional. Costs have been converted from 2008$ to 2014$ [22] [25].
***Note 5. Baseline technologies from the NRC study are drawn from 2007 to 2010 era production vehicle data. For the purposes of comparing advanced fuel economy options, baseline technologies are not significantly different in 2014, though it is imperative to be cognizant of the base level of technology against which improvements are compared.

The notional data reflected in Table 1 for both fuel economy improvement and cost represent average values from both the NRC study and the results of the authors' analysis. Regarding technology definitions, in most cases the technology descriptions are self-explanatory. In some cases, a preceding technology is often required in a later evolution, such as is common with gasoline direct injection, downsizing and turbocharging. A second example of bundling is the availability of "fuel economy" packages whereby OEMs may include reductions in weight, friction, rolling resistance and/or aerodynamic drag for some premium charge. Thirdly, in most all new models with advanced fuel economy technologies, such as hybrids, advanced transmissions are being used. Therefore, it may be assumed that the benefits of an automatic transmission with an increased number of speed ratios or a continuously variable transmission (CVT) are normally embodied in such vehicles (even if not so stated). This study combines relevant pairings accordingly as indicated. The relationship between incremental cost and corresponding fuel economy improvement is a complicated, though critical, one with important implications on consumers and regulatory compliance. While each technology is unique, studying them collectively and drawing upon timely market-based data offers unique insights into current fuel economy trends and the comparative value of technology improvements to consumers.

The literature is remarkably consistent in its inclusion of these primary technologies over an extended period of time. For example, a 1994 study names nearly all of the above families of technology options as most impactful, though understandably from a different starting point and cost basis [28]. These are not the only technologies, but are the most prevalent in the selected vehicle classes. Among those excluded are two that are commercially available: stop-start (also known as idle-off) and cylinder-deactivation. Stop-start technology has evolved considerably but has not taken off as quickly in the U.S. due to a perception of limited benefits owing to the simplified 2-cycle EPA fuel economy test, in which the vehicle spends little time idling. In real-world driving, stop-start has proven to reduce fuel consumption substantively, with studies reporting improvements on the order of 4 to 5% under various conditions [22, 29]. Cylinder deactivation is more commonly applied in engines having six or more cylinders, whereas many of the vehicles in the compact and midsize classes feature inline 4-cylinder engines.

2.3 Predicted benefits and costs of compliance from other studies

There is good precedent for utilizing the incremental retail price equivalent (in $) and fuel economy improvements (in percent change) to both assess historical trends and predict future ones. Some studies evaluate pay-back periods or costs and benefits associated with conserving energy using a range of new vehicle technologies [30]. Others develop sophisticated technology-specific analyses to predict technical readiness and future costs using computer simulations or tear-down approaches [31, 32]. A tear-down approach estimates costs and feasibilities associated with the design and manufacture of new products by aggregating constituent components of a larger system in a bottom-up manner. Both the market-based and technology-specific studies help inform future trends. However, given the aggressive rate of required improvements over a more extended period of time, technologies and their costs are changing more quickly than in previous periods of regulatory constraint. One comparative assessment performed by the National Renewable Energy Laboratory (NREL) evaluated technological and market assumptions utilized by EPA in 2009 [4], suggesting that more specific analyses of technology characterization, current usage and expected 2016 usage of selected technologies would be useful [33]. While highlighting technology variances compared to initial EPA assumptions, the NREL study did not include a financial assessment of economic viability. As noted, many high-level policy analyses aggregate vehicle trends on a fleet-wide basis for future extrapolation [9-13]. For many of these, costs and benefits, if investigated, are typically assessed from a *social, economy-wide perspective* [1, 7, 34]. While obviously important in the formulation of public policy, two important factors reinforce the merit of analyzing benefits and costs from a *consumer perspective*. First, determination of economic practicability is ultimately a consumer choice that is revealed in the disaggregated sales data. Second, the first-order cost is incremental technology cost, and the first-order benefit is incremental fuel savings. Secord-order social benefits (such as social cost of carbon, increased consumer surplus, and petroleum market externalities) and second-order costs (such as the rebound effect from additional vehicle miles driven, congestion, and accidents) are generally an order of magnitude lower than first-order effects [1, 7].

To address the loss of resolution due to aggregating, other studies have investigated specific categories of technologies, such as an investigation into hybrid and diesels by Lutsey [35] which suggested that due to uncertainty and rapid evolution in costs and performance, future market shares are pivotal to compliance but complicated to assess. Lutsey acknowledged that cost reductions for hybrids and diesels are critical for mainstream deployment, but did not elaborate on the relative value of these technologies as compared with other fuel-saving technologies or as compared against a break-even condition. A study by Cheah and Heywood integrated a broader range of technologies, but focused more on compliance scenarios and technological readiness, than relative benefits and costs [26]. The Cheah and Heywood study suggests that the 2016 standards are aggressive and may be difficult to attain, even with full emphasis on seeking reduction in fuel consumption. Uncertainty affects 2016 targets differently than longer-term targets. Near-term redesign inflexibility, depreciation of existing capital, and historical reliance on performance over fuel savings could adversely affect consumer compliance by 2016. Conversely, while longer lead times will help facilitate transitions to fuel saving technologies over the course of the coming decade, the uncertainty of exogenous factors will play an increasingly vital role. The authors' present study is therefore a market-based, mid-term assessment of revealed response to

CAFE 2012-2016 and can serve to highlight the comparative value that consumers are actually obtaining from new technologies relative to more conventional ones. Finally, it bears repeating that consumers do not buy fuel economy, or even horsepower; they buy cars. As in every year prior, their preferences are largely revealed in the sales record of the current model year, a year which arguably includes more fuel saving technologies than ever.

3. Benefits and costs of key fuel economy technologies from 2014 MY vehicles

3.1 The vehicles, approach, and analysis

In order to appropriately reflect revealed consumer preferences, many of the best selling cars in the U.S. market for recent years were included in the analysis. A database populated with vehicle sales by model and engine type, specifications, standard options, other options influencing fuel economy, and all associated costs was developed. For the vehicle selling prices, we use Manufacturer's Suggested Retail Prices (MSRPs) [36]. Table 2 indicates the vehicle makes and models that are included in the analysis, along with a few market indicators.

Table 2. Compact and Midsize 2014 MY vehicles included in the analysis [36, 37, 38].

Approx. Rank by sales	**Vehicle Make**	**Vehicle Model**	**Sales** 1000s of units	**MSRP Base Model** in 2014$	**Fuel Economy** **Base Model** mpg	**High mpg Model**** mpg	**EPA Class**
1	Toyota	Camry	450	22,425	28	40	Mid-size
2	Honda	Accord	375	21,955	28	57	Mid-size
3	Nissan	Altima	350	22,300	31	31	Mid-size
4	Toyota	Corolla	350	16,800	31	34	Compact
5	Honda	Civic	335	18,390	31	45	Compact
6	Ford	Fusion	325	22,400	26	51	Mid-size
7	Chevrolet	Cruze	285	18,345	29	33	Compact
8	Ford	Focus	235	16,810	30	31	Compact
9	Hyundai	Elantra	230	17,250	31	32	Compact

10	Hyundai	Sonata	220	21,450	28	38	Large/Mid
11	Toyota	Prius	220	24,200	50	58	Mid-size
12	Chevrolet	Malibu	200	23,165	29	29	Mid-size
13	Nissan	Sentra	190	15,990	30	34	Mid-size
14	VW	Jetta	170	16,895	28	45	Compact
-	Chevrolet	Volt*	23	26,670	63	63	Compact

*Note: The Volt is not among the top-selling passenger cars and lacks an internal-combustion-only version. However, it is included in this analysis because it offers novel fuel-saving technology. Though it is officially classified in a category of its own as an extended-range electric vehicle, it is simply referred to as a PHEV in this analysis. Also, its base MSRP reflects a $7500 discount offered via Federal subsidy because it is a qualifying vehicle [27].
**Note: The "High mpg model" listed corresponds to the vehicle sharing the same chassis as the given base model with the highest EPA combined mpg rating. EVs are not included [see footnote 3].

This grouping of vehicles in Table 2 accounts for nearly 4 million units, or about 55% of new sales (by volume) in the passenger market and 28% of new sales in the entire light duty vehicle fleet (light trucks and SUVs account for nearly 50%). While the top 14 best-selling passenger cars account for more than half of the sales (by unit volume), some 200 additional models account for the remaining portion [39]. For the purpose of estimating fuel economy improvements, officially reported EPA combined city/highway miles per gallon ratings are used [38]. This point is important, because real world fuel economy, often termed "adjusted fuel economy," varies considerably and is generally about 20% lower than official EPA ratings [19, 40]. Though the use of official ratings may give a slightly conservative result (i.e., overstating the benefits attributable to fuel savings), the analysis remains valid because it is most concerned with relative fuel economy improvements over base technologies. Furthermore, Federal CAFE standards also employ the EPA rating basis, facilitating comparisons with other studies and official regulations.

3.1.1 Approach methodology

In this study, costs and fuel economy impacts are compared in two distinct ways. In the first approach, technology changes are compared against a specific base model of the same manufacturer, with the same chassis. This is referred to here as a "model-specific" approach to benefit-cost analysis. In the second approach, a sales-weighted average vehicle is developed for each vehicle class (compact and midsize). Then, by tracking the relative differences as compared to the model-specific base case, it can be determined how a technology compares to a reference vehicle that is representative of consumer preference by class.

Regarding the model-specific approach, the analysis of new technologies against their respective baseline models is insightful because it demonstrates the incremental impact in cost and fuel economy directly associated with a given technology change. The process for extracting this information is not transparent, however, and great attention to detail has therefore been paid in this study to the other variables and attributes of the vehicle model that are unrelated to the fuel economy technology itself (e.g., larger alloy wheels, leather seats, moon roof, navigation, etc.). Thus what is needed is an approach that extracts solely the relevant portion of the price increase that should be allocated specifically to changes in fuel economy. The net price impacts associated with any extraneous attributes included in the inflated MSRP can then be subtracted to establish a net price difference. As discussed, conventional terminology is used for this difference, known as the “incremental retail price equivalent” or IRPE associated exclusively with a given vehicle fuel efficiency technology. This provides the means to populate a chart comparing incremental price changes and fuel economy improvements. Prices are in 2014 dollars, and fuel economy improvements are reported as either absolute Δ mpg (with units of mpg), or as Δ % change (reported in % difference in fuel economy) against a model-specific baseline.

Some vehicle models include upsizing of engine displacement, or turbo-charging at constant displacement, both of which result in increased power, but diminished fuel economy. Others include Compressed Natural Gas (CNG) fuel-capable engine technologies. However, a conscious decision has been made to intentionally leave these technologies out, in order to develop a curve that focuses specifically on technologies that contribute to fuel economy improvements. That said, there is a notable market demand for increased engine power, and even alternative fuel technologies. While the focus of this paper is on fuel economy, certain studies indicate that consumers value an increase in power more than an increase in fuel economy [41]. Certainly the interrelationship between power and fuel economy has unique implications for consumers, OEMs and compliance with future regulations [26].

The model-specific approach is a necessary first step to begin quantifying the revealed market correlation between end-user prices and fuel economy. However, this model-specific aspect which brings clarity to a true “differential cost vs. differential mpg” comparison suffers from the inherent limitation that such findings may not be categorically applied to a broad class of vehicles. In other words, comparing the cost and fuel economy associated with a given upgrade on a given chassis is one thing, but comparing several different models from different OEMs with different standard specifications and features to one another may introduce significant uncertainties in incremental costs and in allocations of utility (such as fuel economy, passenger volume, and power). In addition, a few advanced vehicles have been uniquely designed on exclusive platforms to specifically introduce fuel saving innovations, such as the Toyota Prius and the Chevrolet Volt. A challenge in determining the incremental costs and impacts associated with such vehicles from the model-specific approach is that a “baseline, standard, internal combustion engine (ICE) vehicle only” version is non-existent. To navigate both of these concerns with the model-specific approach, a “classification-average” approach is undertaken in which sales-weighted average criteria for vehicles in the compact and midsize car classifications are established. This is accomplished via current-day investigation into the respective market segments for the selected advanced fuel-efficiency technology vehicles. With just a few minor exceptions (such as the unique hybrid platforms), OEMs of the selected top-selling models generally offer several conventional models, often with multiple engine choices, and one or more models that include improved efficiency technologies available at some premium price.

Even so, the classification-average approach does not fully isolate the cost-fuel economy correlation either, because it remains possible and even likely that aspects of the vehicle’s utility may differ (such as power and passenger compartment volume) from the baseline. For this reason, most of the analysis follows the model-specific approach, whereas the sales-weighted average results are offered merely as a check against this preferred method. Just two exceptions are made to permit the inclusion of data for the Prius and Volt. For these, the sales-weighted average vehicle method is initially employed to establish a baseline, then comparative data is transformed and included into the model-specific analysis [footnote 4]. This is done to capture the effect of such high-profile, commercially available advanced vehicle technologies. PHEVs introduce the need to account for multiple energy sources, and the present study follows EPA guidance to determine relative shares of electricity and gasoline, which varies by OEM model [footnote 5].

3.1.2 Results from the model-specific analysis

The model-specific approach isolates the true incremental price of a new technology specifically allocable to fuel economy, and is performed on a model-by-model basis. By way of example, Table 3 describes the basic process for separating the constituent cost and fuel economy improvement data from an actual model, in this case a hybrid, drawn from the data set. Price variances are accounted for between the new technology model and a baseline vehicle with which it shares an identical chassis.

Table 3. Example of methodology used to determine the model-specific IRPE and % fuel economy improvement. Data sources [36, 38]

Description	Actual MSRP ($)	IRPE for technology alone, model specific case ($)	EPA combined Fuel econ. (mpg)	Fuel econ. change (Δ mpg)	Fuel econ. percent chg (Δ%)
Baseline Vehicle 1	18,390		31	-	-
Unrelated Options	2,550				
Hybrid version Vehicle 1	24,635	**3,695**	45	+14	**+45.2**

This process is continued for each fuel economy technology grouping offered with each model. By using the manufacturer’s suggested retail price (MSRP), it is assumed that technology costs are directly correlated to suggested retail prices. It is reasonable that MSRPs would more closely reflect true costs than heavily discounted prices, for example via year-end or dealer incentives; however, some degree of cost-price uncertainty remains. That said, from a consumer perspective, OEM technology costs are less important than market-based prices, which reflect what the consumer actually pays for a given technology. Collecting incremental price data from multiple OEMs, as is done here, helps reduce potential anomalies. Groupings by technology type are of interest because they provide a means of comparison between different OEMs and with other studies. This allows for decision-makers to assign an order of magnitude to major technology bins as well as assess technology penetration in view of near- and long-term requirements. Figure 2 shows the relative position of major technology categories on a cost vs. fuel economy improvement graph for selected compact cars.

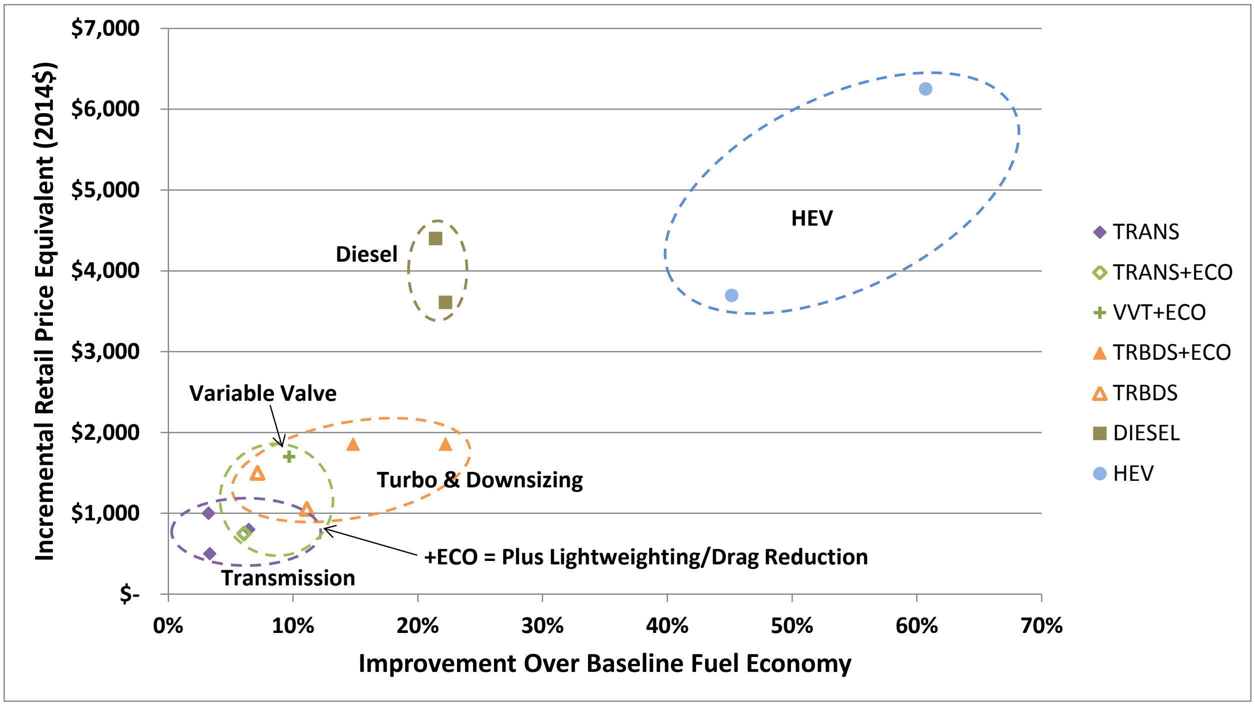


Figure 2. Cost of improved efficiency from 2014MY vehicle technologies, compact class, model-specific basis

The purpose of this figure is to illustrate where the benefits and costs of fuel-saving technologies fall on a spectrum, and that they can roughly be grouped by technology category and relative impact level. A few of the technology categories overlap or are bundled, as shown by data points that include advanced transmissions with 5 or 6 speeds with features marketed in "ECO" packages. These generally include modest weight savings, for example provided by replacing steel wheels with aluminum alloys, or removing a spare tire in exchange for a tire patch kit. Some of the ECO technologies include low rolling-resistance tires, or aerodynamic features such as underbody treatments or spoilers to reduce drag. Generally, transmission technologies and ECO options have costs below $1000 and improvements on the order of 3 to 10%. In the case of most turbo-chargers in the compact and midsize classes, engines are downsized first, and then boosted to recover the power, frequently at a lower fuel consumption level. Turbocharging and downsizing often accompany gasoline direct injection, and therefore often include the impact of all three changes simultaneously. There is variation in different OEM approaches to turbocharging and downsizing, because power is dependent on engine design, which is in turn linked to fuel economy. In most cases, OEMs elect to match or exceed the power level of the normally aspirated version, which does not always result in the same fuel savings. This is a complicated marketing trade off, but one with significant implications on future trends.

The cost of a given improvement in fuel economy over time has been estimated in the literature [22, 42]. Though such estimates cannot be generalized, it is of note that the ranges typical of technologies considered in the authors' study here are consistent with those of other studies. For the compact and mid-size classifications, current technologies in the 0-15% improvement range cost between $50 and $100 per percent improvement in fuel economy. For larger increases, the range can be broader, extending upwards to $200. However, depending on the type of technology used, hybrids appear to come in below $100. It should be noted that at a level of 50 mpg, a 1% increase represents lower volumetric fuel savings (0.000198 gal/mile) than a 1% fuel economy increase on a baseline of 30 mpg (0.00033 gal/mile). For this reason, many researchers prefer to use fuel consumption in lieu of fuel economy when considering broad ranges of improvement, and caution is advised in the use of such rule of thumb indicators. Figure 2 exhibits an interesting bifurcation: there are many relatively low cost technologies that deliver modest gains and another grouping of high cost technologies delivering substantial increases. Though this data set is not comprehensive, the valley between is of note.

3.2 Benefit-cost assessments

In order to generate a baseline benefit-cost analysis, it is more compelling to use the model-specific data since the goal is to estimate the investment and fuel savings on *actual vehicles*. In simplified terms, the model specific approach considers the IRPE as the initial outlay of cost, and the % fuel economy increase as an incremental time-phased benefit (i.e., fuel savings). Table 4 defines the assumed or given values, which along with the existing IRPE and % fuel economy improvement data can establish a baseline benefit-cost curve.

Table 4 Parameters used in the benefit-cost analysis, their baseline values and bases.

Parameter	Baseline Value	Units	Source or Basis
Gasoline Price (initial)	3.50	$/gal	[43]
Diesel Price (initial)	3.87	$/gal	[43]
Annual Mileage	12,000	miles/yr	[44] [45]
Vehicle Service Life	7	years	[46] & author
Residual (Salvage) Value-Default	21.0	%	[47] & author
Residual (Salvage) Value-Hybrid	26.0	%	[47] & author
Residual (Salvage) Value-Diesel	23.0	%	[47] & author
Interest rate (or discount rate)	7.0	%	[1] [7] & author
Inflation rate	2.0	%	[48]
Real interest rate	4.9	%	calculation
Real gas price increase (annual)	1.5	%	[49]
Nominal gasoline price increase (annual)	3.5	%	calculation

Note: When "author" appears in the "source or basis" column next to a given reference citation, that indicates the authors relied upon multiple sources, or applied reasonable judgment to cited norms in selecting the baseline values.

Note: The initial price of U.S. Regular gasoline for the period July 14 through August 4, 2014 is taken to be $3.50 per gallon. The initial price of U.S. on-highway Diesel fuel prices for the same period is taken to be $3.87 per gallon. Per EIA, prices include all taxes [43].

Note: The 12,000 mile annual estimate of vehicle miles traveled is determined by averaging self-reported actual annual mileage for US household vehicles with odometer readings [44, 45].

Note: [46] indicates ownership life of new vehicles was about 6 years in 2011 and is combined with authors' projection of trends to 2014, yielding an average ownership life of new vehicles of about 7 years.

Note: [47] provides residual values by selected technology classes at 5 years from purchase. This was then combined with authors' (exponentially decaying) curve-fitting analysis to project residuals at the end of the 7th year of vehicle ownership.

The impact of the most significant parameters is assessed by virtue of the sensitivity analysis. The residual (or salvage) value is an important aspect of this study, since it is well known that more advanced technologies such as diesels and hybrids retain their value more strongly than vehicles operated exclusively by an internal combustion engine. The residual values indicated in Table 4 represent a best fit exponential function of average residuals by technology type for the subject classes. Since time value of money has not yet been considered, all references to IRPE thus far imply the entire incremental retail price equivalent (i.e., the full price paid for a given technology at the time of purchase). Upon analyzing benefit cost results and for all net present value calculations, attention is now paid to the residual value of the technology assessed, such that a net present value (or NPV) of its salvage value can be deducted from the initial investment, yielding a "net IRPE." For advanced technologies which incur considerable capital cost premiums, residual value may have a significant impact on the final benefit cost result. In this study, a seven-year service life is assumed based upon ownership trends for new vehicles in the U.S. market [46]. That said, since a salvage value is computed at the end of the terminal year, the given service life assumption used in this study has much less effect on the net present value results than annual vehicle miles traveled. In other words, it is vehicle usage, not calendar life that has the greater impact. The baseline assumption for annual usage is 12,000 miles per year, based average new vehicle mileage data for U.S. households drawn from DOT's National Personal Transportation Survey [44]. Using the model specific data, baseline benefits derived from fuel savings over time, and net IRPE costs for the vehicle technologies have been generated. Figure 3 illustrates the benefit-cost results by technology grouping for the baseline case.

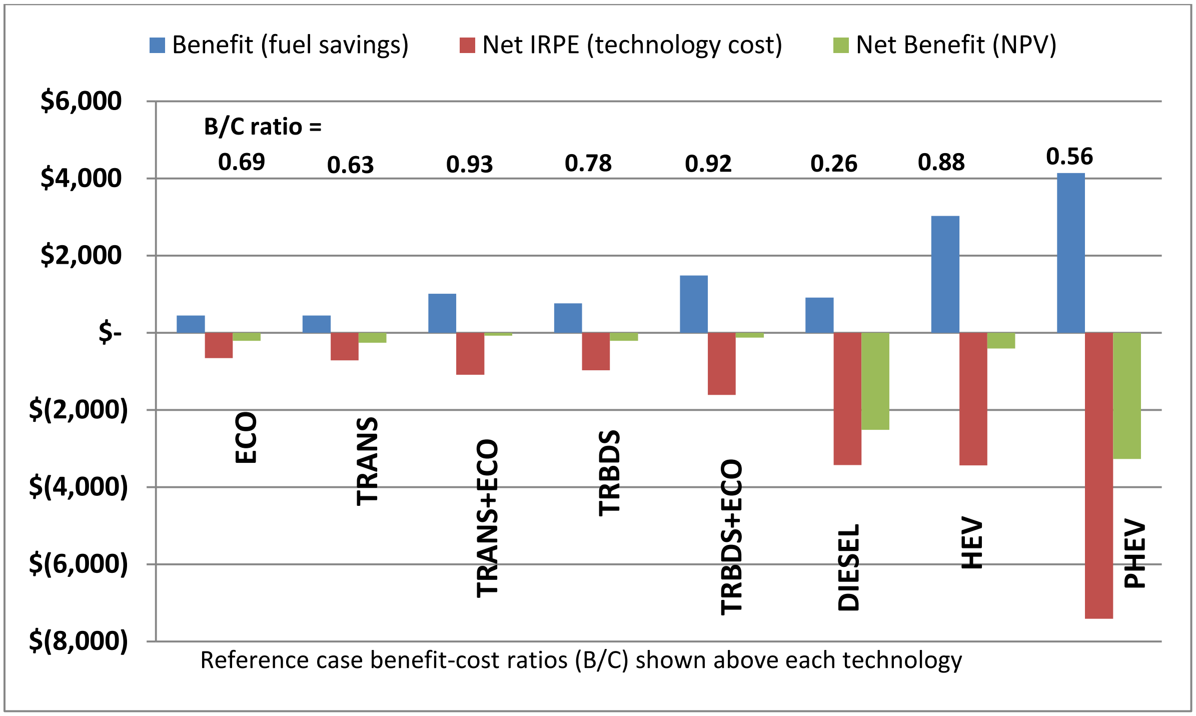


Figure 3. Results of baseline benefit-cost assessment by technology category

By definition, a "Benefit/Cost (B/C) ratio" is the quotient of the net present value of the benefits (or fuel savings) divided by the net incremental retail price equivalent (or net investment costs) of the technology; thus a ratio of 1.0 means that benefits and costs are equal. Benefit-cost ratios for each technology category have been averaged and reported in Figure 3 above each respective grouping. For the baseline condition, an un-weighted average benefit-cost ratio can be obtained by considering each individual observation in the analysis as equal weight. Though perhaps slightly more biased toward what is offered than toward what is actually purchased, this "notional" average ratio of all constituent technologies assessed is 0.73 ($R^2 = 0.88$). This means that under the assumed conditions, these technologies do not, on average, yield economic returns to consumers that buy them instead of base model technologies. Despite these relatively low values, the figure illustrates that substantial fuel savings can be generated at reasonably affordable costs, especially for specific technology groupings such as transmission upgrades, downsized turbos and hybrids. Payback periods and benefit cost ratios obviously have a greater financial impact when a consumer invests in more expensive technologies. Thus, a low B/C ratio may not result in meaningful cash losses by a consumer adopting weight savings, drag reduction, or upgraded transmission technologies; but it would be more imperative to rational consumers that B/C ratios approach or exceed 1.0 for higher cost technologies, such as diesels, hybrids, and PHEVs. Average B/C ratios below one are not meant to imply that specific technologies on specific models do not exceed a breakeven condition (as several do), but rather that consumers of these selected technologies as a whole under the given assumptions do not generally appear to breakeven. Figure 4 displays all of the discrete technology packages on a common plot. For reference, a benefit cost curve equating to a breakeven condition (B/C = 1.0) is shown. This breakeven line was generated by requiring the net IRPE costs to be equal to the benefits of a given model under given assumptions. In other words, we work backward to determine what the costs *have to be* in order to justify their payback in fuel savings over time. The resultant virtual costs are then plotted against the corresponding fuel economy improvements, and linearly regressed to characterize the breakeven condition.

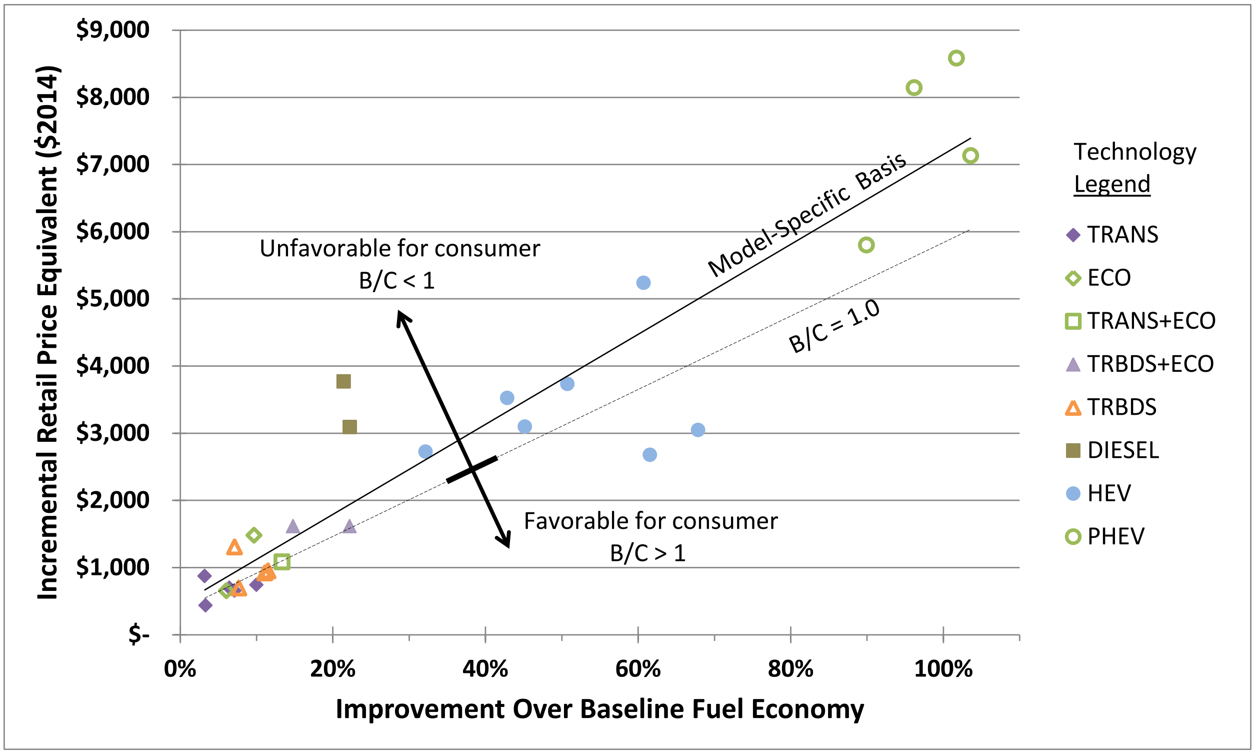


Figure 4. Discretized data points representing compact and midsize car technologies from model-specific basis and best fit regression shown relative to the breakeven line.

As shown in Figure 4, approximately six of the 28 discrete technologies in the study yielded benefit-cost ratios greater than one in the baseline case. Three of these have turbos with downsizing, two are hybrids, and one has a continuously variable transmission. These points appear on the plot below and to the right of the breakeven line in the region that yields a favorable benefit cost ratio for the consumer. Two additional points are extremely close to breakeven (such that the line appears to intersect them), have benefit-cost ratios of 0.94 and 0.93, and include CVT and CVT+ECO, respectively. Conversely, points that are above and to the left will yield an unfavorable result for the consumer under the assumed conditions. A linear regression is performed to characterize the relationship between cost (net IRPE) and fuel economy improvement according to the model specific basis. The relationship is of first order, has an R^2 of 0.88, and can be estimated by the following formula where $IPRE_1$ represents the net incremental retail price equivalent in dollars compared to the model-specific baseline, MPG_X and MPG_{MS} represent the fuel economy of the improved model (X) and the model-specific (MS) baseline respectively, and the argument in parentheses is the percent change in fuel economy relative to the model-specific (MS) baseline.

$$IRPE_1 \approx 67 \cdot \left(\frac{MPG_X - MPG_{MS}}{MPG_{MS}} * 100\right) + 451 \qquad (1)$$

Performing a regression on the aggregated set of technologies has clear limitations, but helps to indicate relative cost effectiveness for both discrete technologies and families of technologies. It serves to demonstrate, for example, that passenger cars with Diesel engines and certain plug-in hybrids deviate significantly from the mean expected trends. It also shows that the initially small gap between the unweighted average trendline and the breakeven line grows larger as a function of fuel economy improvement. The non-zero intercept is of note, and is possibly a function of the model specific approach, where extraneous costs (due to the inclusion of more options as 'standard') are inadvertently linked to "premium" fuel saving technology attributes. When technologies with lower fuel economy improvements (<20%) are evaluated as a separate group, the regression slope decreases with respect to the larger data set and roughly predicts that a \$500 to \$600 incremental cost will buy a 10% increase in fuel economy (from 5% to 15%). However, the non-zero intercept implies some minimum static threshold of cost (up to \$450) may be required on actual vehicles to realize this rate of gain. Downsized turbos provide from 7 to 22% fuel economy improvements for costs ranging from \$700 to \$1600. This seems to offer consumers considerably more value than diesels which increase fuel economy by about 22% at costs between \$3000 and \$4000. Hybrids can deliver about twice this fuel economy improvement (from 35 to 63%) for costs between \$2700 and \$5200.

3.3 Sensitivity Analysis

Uncertainty is inherent in many variables relevant to this analysis, including technology specifications, market pricing, driving modes and behavior, and exogenous macro-economic factors. However, an appropriate sensitivity analysis quantifies the extent to which critical factors influence the results. Included in the sensitivity analysis are discount rate, annual mileage, and fuel price. Table 5 demonstrates the ranges of variables considered, as well as the baseline reference assumptions for each factor.

Table 5. Minimum, baseline, and maximum parameter values used for the sensitivity analysis.

Variable	**Nominal Discount Rate**	**Annual Miles Driven**	**Fuel Price Rate of Change**
Units	%	miles	Rates of change over 7 years
[Source]	[1] [7] [50] & author	[44] [45] & author	[49] [50] & author
Low limit	3	9,000	Decreases at 3% per year
Baseline value	7	12,000	Increases at 1.5% per year
High limit	10	15,000	Increases at 7% per year

Note: For initial fuel prices of fuel, please see Table 4 or source [43].
Note: For fuel price rates of change, annual rates of increase (or decrease) are inferred based upon EIA long-term oil price forecast in 7 years: high case ($165/bbl), reference case ($110/bbl), low case ($75/bbl) [49, 50].
Note: For simplicity and to clarify the independent impacts of the sensitivity variables, only one parameter is set to its low (or high) limit at a time, while the other two are held at their baseline values.
Note: Again, when "author" appears along with a given reference citation, that indicates the authors considered multiple sources and applied reasonable judgment in selecting appropriate ranges for the values of sensitivity parameters.

The literature provides good guidance on parameter values typically used for similar analyses (Table 4), and relevant sources from which the established baseline values and low and high limits are cited (Table 5). This study does not fully consider the impact of differing driving habits or driving modes (such as city vs. highway). Clearly these factors would affect the value proposition, but are highly variable, and would affect "fuel efficient" and "standard" technologies similarly, and are therefore not deemed to be differentiating in this analysis.

Recall that under the baseline conditions, the un-weighted average benefit-cost ratio of all unique models and constituent technologies assessed is about 0.73 with an $R^2 \approx 0.88$. As described in the preceding section, consumers will realize a net economic benefit for anything below or to the right of the breakeven line (B/C=1.0 in Figure 4), and conversely will incur a net economic cost for anything above or to its left. Instead of exploring which specific technologies on this plot have a favorable benefit-cost ratio (which is in itself of interest), this sensitivity analysis is rather aimed at establishing a sense for the likelihood that a consumer will experience a positive net economic benefit from a given technology.

All three sensitivity variables seem to have a similar impact on the results within the stipulated ranges, with annual miles driven being narrowly more significant than fuel price and discount rate. However, if all breakeven benefit-cost ratios are averaged among all technologies, an average B/C of unity is not achieved by any one of the individual sensitivity variables alone, even when calculated at the given limits. In other words, no sensitivity parameter by itself taken to its limit results in a breakeven condition for all technologies. Table 6 illustrates the response of the benefit cost ratio to the sensitivity variables when the others are held at baseline values.

Table 6. Impacts of the sensitivity variables on benefit cost ratio.

	Discount Rate		**Annual Miles Driven**		**Fuel Price Rate of Change**	
	low limit	high limit	low limit	high Limit	low limit	high Limit
	3%	10%	9,000 mi	15,000 mi	-3%/yr	+7%/yr
B/C value	0.896	0.639	0.548	0.914	0.616	0.901

Note: These results assume only one variable is changed (i.e., the heading of the given column) and the other two sensitivity parameters are held at the baseline values (which are: discount rate=7.0%, mileage=12,000, fuel increase = +1.5%).

These observations may be interpreted to mean that economic or personal vehicle use conditions will have to vary *substantially* and *in more than one major* aspect from the assumed baseline for the consumer to realize any net economic savings from the investment in these technologies. To help quantify this, three additional scenarios were performed where sensitivity parameters were allowed to exceed the stipulated min/max criteria in Table 5. When the discount rate falls to 1.1% (a somewhat impractical rate, but meant for illustrative purposes), and the other two parameters are at their baseline values, a B/C of 1.0 is attained. When the annual mileage is 16,400 (a very likely possibility for some consumers), and the other two parameters are at their baseline values, again a B/C of 1.0 is reached. When fuel prices increase at a rate of 9.7% per year (or equivalently, the nominal price of fuel averages about $5.60/gallon over 7 years), and the other two parameters are held at their baseline values, a B/C of 1.0 is reached.

For context, when all parameters from Table 5 are set at their "best case" limits for maximum consumer benefit (i.e., discount rate at 3%, mileage at 15,000 mi/yr, and fuel at +7%/yr), the result is a compelling B/C = 1.39. A combined scenario such as this is extremely unlikely. Conversely, a minimum B/C taken at the opposite limits would approach a highly unfavorable ratio of 0.40. This simplified techno-economic analysis considers only the direct savings in fuel and the incremental capital outlay less residual for the technology upgrade. No consideration is given to either individual or societal follow on benefits of reduced fuel consumption such as reduced fueling time, increased vehicle miles traveled, social cost of carbon, health effects, or energy security implications.

Figure 5 depicts the breakeven conditions graphically. Note that many of the individual technologies are below the breakeven lines for both the high mileage and high fuel price conditions. This is particularly true for the points nearer to the origin, where fuel economy improvements between 5 and 15% have comparatively low investments and compelling cost tradeoffs. It is not surprising that many taxis and fleets in large urban centers, where both fuel and annual miles driven are much higher than average, have been quick to convert vehicles to include downsized turbos, reduced weight options, and hybrids. This figure helps to illustrate why the economic basis for such early adoption is compelling since many key technologies are below the high mileage breakeven line and therefore have B/C ratios greater than 1.0.

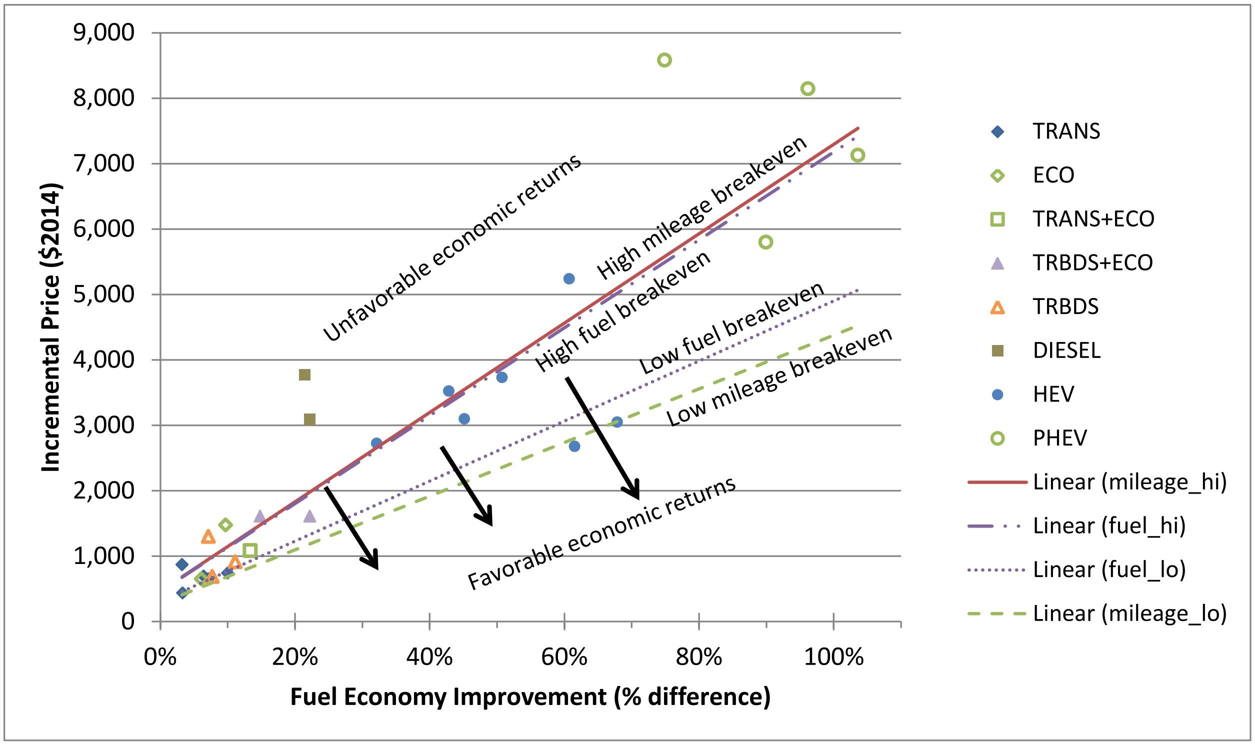


Figure 5. Graphical implications of the sensitivity analysis.

Note: “High mileage breakeven” means mileage=15,000 miles per year, discount rate and fuel price at baseline values. “High fuel breakeven” means fuel price ≈ nom $5.60 avg over 7 years, discount rate and mileage at baseline values. “Low mileage breakeven” means mileage =9,000 miles per year, discount rate and fuel price at baseline values. “Low fuel breakeven” means fuel price ≈ nom $3.20/gal over 7 years discount rate and mileage at baseline values.

It should be noted that even though the low discount rate scenario is not shown in Figure 5, its breakeven line is just slightly below the high fuel breakeven line, meaning that providing other sensitivity parameters are held at their baseline values, a discount rate at 3% has a similar impact on the results as a nominal fuel price of $5.60, as well as an annual mileage in the range of 15,000. It is also of note that transmission upgrades, turbos with downsizing and hybrids are the technologies most significantly impacted by the sensitivity variables. In the high mileage scenario, for example, 3 CVTs, 3 turbos with downsizing and 4 hybrids have B/C ratios of greater than unity.

3.4 Implications of sales-weighting

Though complicated due to OEM options-bundling, the model-specific approach, when IRPE values can be appropriately filtered from the base model, has merit. However, as a final check, it is of interest to consider the average vehicle in a class, by way of understanding whether a new technology is good overall, and not just with regard to its base chassis.

This approach begins with the model-specific IRPE. To this is added (or subtracted) any pricing difference between the MSRP of the base model for the given technology and the MSRP for the sales-weighted average vehicle in that class. This becomes the sales-weighted average IRPE. Likewise, the fuel economy improvement becomes the percentage difference between the fuel economy of the given technology and the sales-weighted average fuel economy in that class (not the model-specific fuel economy). Together the sales-weighted average IRPE and fuel economy improvements are used to characterize the relationship between benefits and costs of new technologies as compared to average vehicles in the appropriate class.

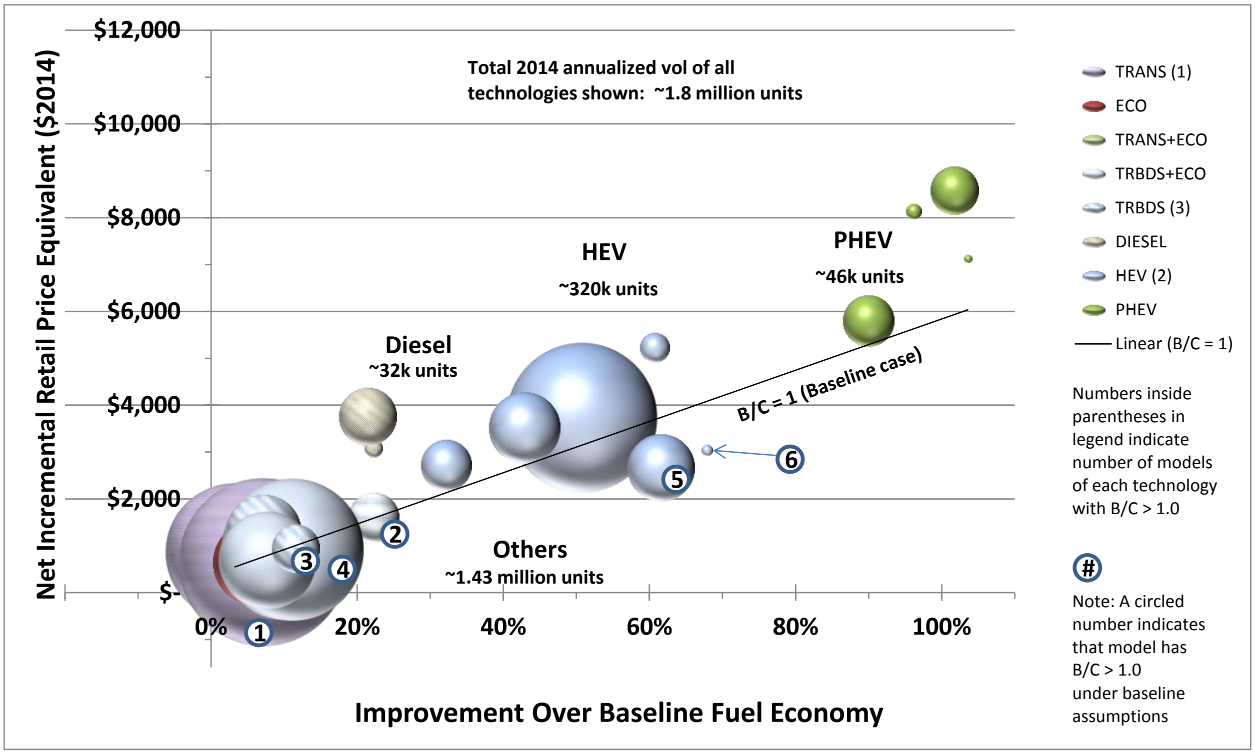
Despite certain obvious differences in MSRP, power and interior volume, the compact and midsize classifications are consistent in their qualitative trends. The average-vehicle basis permits the inclusion of additional Plug-in hybrid electric vehicles (PHEV) and hybrid vehicles for analysis in the model-specific analysis. A linear regression performed on all technologies using the sales-weighted average vehicle approach across both classes fits the data reasonably well ($R^2 = 0.80$) and yields equation 2. Here, $IPRE_2$ represents the net incremental retail price equivalent compared to the sales-weighted average vehicle baseline, MPG_X and MPG_{AV} represent the fuel economy of the improved model (X) and the average vehicle (AV) baseline respectively, and the argument in parentheses is the percent change in fuel economy relative to the average vehicle baseline.

$$IRPE_2 \approx 68 \cdot \left(\frac{MPG_X - MPG_{AV}}{MPG_{AV}} * 100\right) + 142 \tag{2}$$

This relationship essentially only differs from the model-specific case in y-intercept and in certain characteristics near the origin. Weighted class average selling prices are typically between the base MSRP of a given model and the MSRP associated with a fuel economy technology, explaining the price reduction of new technologies relative to an average vehicle basis. This modestly shifts the cost curve downward while keep the slope relatively constant. Serving primarily to corroborate the preferred (model-specific) approach, the sales-weighted average analysis is theoretical, since a consumer cannot actually purchase technologies according to this relationship. However, it may be a useful tool in isolating costs attributable to specific technological changes relative to average vehicle-derived market conditions.

3.5 Implications of revealed consumer preference for fuel-saving technologies

Owing to the multiple interactions between consumers, OEMs, and the regulatory standard, it seems prudent to assess new fuel saving technologies in light of market conditions and the current phase of the regulatory cycle. Figure 6 depicts a sales-weighted bubble chart of the key technologies assessed in this study. Base models are not included, as they comprise more than half of the sales volume, and would further crowd the origin. From this figure, it can be concluded that benefit-cost ratio is not a litmus test for technology acceptability and market penetration. The fact that many high volume technologies have benefit-cost ratios of less than 1.0 (meaning they are above the line in Figure 7) implies that consumers purchase fuel efficiency in spite of the fact that it may not immediately, if ever, return on its investment. An aggregate sales-weighting performed on the entire set of fuel saving technologies reveals that the average consumer paid $1490 for an estimated $1070 savings in fuel, which represented an estimated 17.3% fuel economy improvement as compared to consumers that did not buy fuel saving technologies. As a result, the effective, sales-weighted average benefit-cost ratio for consumers is computed to be 0.72, very close to the un-weighted estimate of 0.73 reported in Section 3.2.



Numbers inside parentheses in legend indicate number of models of each technology with B/C > 1.0

Note: A circled number indicates that model has B/C > 1.0 under baseline assumptions

Figure 6. Costs, fuel economy improvements and sales weighting of key vehicle technologies. Technologies are grouped by categories which share similar shading, and bubble size corresponds to relative sales unit volume for the models employing the subject technologies in 2014 MY vehicles assessed in Table 2. Models with B/C > 1.0 under baseline assumptions are indicated by a circled number.

Several key insights emerge from this analysis of the MY 2014 trends. Based upon recent progress toward improved fuel economy, OEMs are likely to consider several options for compliance. Some are technological, while others are related to business and marketing. OEMs have squeezed additional mpg from existing models via a diversity of measures including refreshed designs, engine tuning, weight trim, aerodynamic tweaks, and friction reduction, among others. Fuel economy gains from such actions have limitations, but are low cost. Advanced transmissions, more aggressive "ECO" countermeasures such as more significant reductions in weight, drag and rolling resistance, and valve actuation technologies are the next set of likely improvements. These have already contributed significantly to the estimated 10% gains in new passenger car fuel economy since 2011. These too will eventually run their course, and be more or less fully integrated into the new vehicle fleet. This is the nature and intent of a continuously improving regulatory standard. That sets the stage for a sustained transition to downsized turbos and diesels, which may ultimately be incorporated into hybrids. The foregoing data indicate that turbos with downsizing deliver nearly twice the value today than diesel engines for small passenger cars. That notwithstanding, diesels may perform better in high mileage cases, or in vehicle applications where the EPA combined fuel economy rating may not be a preferable metric for quantifying the real-world benefits.

Based upon current sales volumes, it is likely that OEMs have adjusted pricing to incentivize purchase of higher efficiency vehicles. This is actually an accounting approach, as there is an implicit cost associated with failure to comply (i.e., a $ fine per mpg below regulatory standard). Even if costs are equal, most OEMs would rather sell volume at reduced or amended pricing than run the risk of paying a fine.

Hybrids are among the most capitally intensive new technologies, but also among the most promising in terms of sizeable leaps in fuel economy. As productivity and learning continue, costs will come down; and benefit-cost propositions will rise for consumers, accelerating their adoption. It is less clear whether PHEVs can be viable in the near term, given the massive subsidization and fuel economy "equivalent" ratings that have been needed thus far to facilitate their early commercial introductions.

Finally, in view of figure 7, consider that each 10% increment can be roughly equated to two years' time (using a 5% yr/yr increase in fuel economy as called for by CAFE 2017-2025). This means that to sustain compliance though 2020, costs will rise to support the aggressive rate of technological improvement.

4. Conclusions:

Eight significant conclusions can be drawn from this research:

- The continued commercialization of fuel efficiency technologies have enabled automakers to comply with CAFE standards, increasing the fuel economy of the passenger car fleet by about 10% since 2011. Vehicle models sold with specific fuel-saving technologies account for approximately 45% of total sales (by unit volume) considered in the present study for the 2014 model year. Key factors underpinning recent improvements include reductions in weight, friction, and drag; advancements in internal combustion efficiency, engine downsizing; transmission upgrades; and the growth of hybrids.
- Data from 2014 Model-Year compact and midsize vehicles provide insight into advanced fuel saving technologies, and their associated costs and benefits. Benefit-cost analysis performed on best-selling models in these classifications reveals a sales-weighted average benefit-cost ratio of 0.72, and as such, consumers thus far are not incentivized to purchase higher fuel economy. Furthermore, under baseline conditions, benefit-cost ratios are above a breakeven value of 1.0 for just 6 of 28 models employing improved fuel economy technologies.
- Aggregated benefits and costs for new fuel saving technologies based upon sales-weighted data indicate that the "average" consumer that elected to invest in greater fuel economy spent \$1490 to realize a 17.3% improvement in fuel economy, equating to estimated savings of \$1070. Thus savings were, on average, insufficient to cover technology costs in the baseline scenario.

- A sensitivity analysis performed on critical parameters reveals that annual miles driven and fuel price are the two most significant parameters influencing a consumer's benefit-cost results. A majority of new technologies become economically attractive to consumers (meaning benefit-cost ratios are greater than 1.0 for the given investment and ownership scenarios) only when annual miles travelled exceed 16,400, or when average fuel prices exceed \$5.60/gallon. For the high mileage scenario, the technologies with the best overall value proposition are turbos with downsizing and regular hybrids (HEV).
- In the near term, fuel economy improvements between 5 and 15% over base models, will continue to be met by increasing transmission speeds from 4 to 5 and 6, and deepening the market penetration of advanced internal combustion technologies including: variable valve architectures, gasoline direct injection, and turbocharging with downsizing. Improvements between 20 and 70% can be achieved by diesels and hybrids. The relationship between costs and fuel economy improvements from these families of technologies can be represented by a linear relationship characterized by a reasonably good fit (R^2=0.88).
- Other vehicle attributes that are related to fuel economy, such as power and torque, have largely been unaccounted for in this study. This is reasonable when vehicles of like size and classification are compared. The exclusion of such parameters has the tendency to overstate the isolated value of fuel economy since reductions in power or other potential loss of utility are not considered.
- Based upon the selected 2014MY vehicles, fuel economy technologies fall into two distinct bins of cost and relative efficiency that are separated by a relatively sizeable gap. Costs up to \$2000 will buy fuel economy improvements up to 20%. Costs between \$3500 and \$10000 are needed to reach improvements that exceed 50%. The large costs associated with large fuel economy

gains present consumers with capital constraints, economic viability issues, and slow their market penetration.

- Regarding alignment of future trends with CAFE predictions by NHTSA or EPA, few advanced technologies in the 2014 MY assessment can demonstrate economic viability at higher fuel economy levels. While technologies having the required efficiency levels are now (and will continue to become) available, current market data indicate that they will be more expensive than predicted by EPA/NHTSA. Even the relatively easy, evolutionary fuel economy gains are often not financially compelling for consumers. This implies OEMs may need to adjust sales with creative pricing strategies, or cross-subsidization. The reality is that the higher fuel economy levels currently envisioned in CAFE are not expected to be economically viable for consumers at currently projected fuel prices.

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FOOTNOTES:

1. Under CAFE regulations, EPA rated mpg and mpge values are considered and reported as equivalent and interchangeable [1] [7]. This implies that the vehicle itself, fully fueled or fully charged (using an energy conversion equal to the full calorific value of 33.7 kWh/gallon gasoline equivalent), is the system boundary. In other words, tailpipe emissions and on-board equivalent energy are the only variables tracked in the policy. For the purposes of fuel economy accounting under the rule, no consideration is therefore given to upstream electricity production, net system efficiency, or lifecycle energy-emissions. When running on all-electric mode, EV and PHEV vehicles get CAFE credit for the inflated mpge values, which is important to note as results are compared. The Department of Energy (DOE) studied U.S. average fossil-fuel electricity generation efficiency in 2000, determining it to be approximately ≈ 0.328 [21] and suggesting a method for calculating a petroleum-equivalency factor (PEF) that would provide an incentive to vehicles that employ electricity. The PEF is equal to 1/0.15, or about 6.7, as is intended to incentivize OEMs to produce and sell electric vehicles, and provide opportunities for significantly boosting CAFE compliance. The factor, however, does not accurately reflect the energy intensities of EV vs. ICE vehicles, nor does the mpge rating.

2. Unless otherwise specified dollar amounts are in 2014 dollars.

3. Fully electric vehicles (or EV's) have not been included in this study. While there are at least 2 EV models in the subject classes, it is complicated to account for the loss of utility through reduced range, as well as to make a fair accounting for the equivalent energy efficiency (see note on mpge). It may also be that due to low volume production, MSRPs are less likely to reflect true costs. PHEV's share some of the same concerns, but have little or no range reduction, and, with qualification, have costs and

weighted equivalent fuel economy ratings that can be compared to the other conventional ICE-only and hybrid vehicles in the study. PHEVs have therefore been included accordingly.

4. In the special case of the Toyota Prius, this vehicle is officially classified by EPA as a mid-size vehicle owing to its passenger (93.7) plus cargo (21.6) volume of (115.3); EPA defines: midsize 110-110, compact 100-109. However, the Prius's power (134 hp) is closer to the average compact (144 hp) than the average midsize (191 hp). Its footprint is 44.22 sq ft, aligning more with compact cars (43-45) than with midsize cars (47-49). Thus in terms of power, footprint and other aspects of utility, the Prius is more similar to a compact car than a midsize. It has therefore been so considered in this analysis, to enable an estimation of its incremental price equivalent and fuel economy % improvement. Thus, for the purposes of this analysis the Prius (at MSRP of 24200 and 50 mpg) is compared against an average compact vehicle (MSRP=19746 and 33.2 mpg).

5. The EPA estimates the share of all-electric driven miles as compared with gasoline driven miles for PHEVs. These estimated shares are model specific and based upon "the vehicle's design and average driving habits." The assumed shares (elec/gasoline) by vehicle are: Fusion Energi (45/55); Volt (66/34); Prius (29/71). The EPA rated all-electric ranges of these vehicles are: Fusion (20); Volt (38); Prius (11). This study uses the EPA assumptions accordingly [38].