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TRANSPORTATION (D CHEN, SECTION EDITOR)

Implications of Behavioral Economics for the Costs and Benefits of Fuel Economy Standards

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Abstract

Purpose of Review This review focuses on recent developments in the application of behavioral economics to the evaluation of energy efficiency and greenhouse gas regulations. Transportation is the largest source of CO_2 emissions from energy use in the US economy and a major and growing source worldwide. Regulating the efficiency of motor vehicles has been a core component of energy policy in the USA, the EU, China, Japan, Canada, and many other nations. Recent findings concerning consumers' actual decision-making about energy efficiency indicate that the premises of the rational economic model are not appropriate for evaluating energy-efficiency standards.

Recent Findings Progress in behavioral psychology and economics has shown that loss aversion, the principle that faced with a risky choice human beings tend to weigh potential losses about twice as heavily as gains, is strongly affected by framing. Simple, risky choices in which there is a status quo option generally provoke loss-averse responses. Recent analyses show that the choice to buy or not buy energy-efficiency technologies induces loss aversion and can result in systematic underinvestment in energy efficiency. Empirical investigation of consumers' fuel economy decision-making contradicts the rational economic model and is consistent with loss aversion. However, recent economic evaluations of fuel economy and greenhouse gas regulations are explicitly or implicitly premised on rational economic behavior.

Summary Insights developed by behavioral psychologists and behavioral economists about the decision-making of real consumers provide a coherent explanation that fundamentally alters the way fuel economy regulations should be evaluated. If consumers are assumed to make decisions according to the rational economic model and markets are reasonably efficient, regulations cannot produce large private fuel savings. The behavioral economic model explains not only why such savings do exist but why consumers strongly support fuel economy regulations. The private savings from fuel economy regulations can be large relative to the social benefits of fuel economy and greenhouse gas regulations.

Keywords Fuel economy standards · Loss aversion · Energy-efficiency gap · Greenhouse gas regulations · Behavioral economics · Cost/benefit analysis

> "The single most important area of action is efficiency improvement in all sectors."
>
> *Global Energy Assessment: Toward a Sustainable Future*, [1], p., 23.

This article is part of the Topical Collection on *Transportation*

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Introduction

The Global Energy Assessment concluded that improving energy efficiency was the cornerstone strategy for achieving sustainability goals for the global energy system (1, p. xii).[1] As the largest source of CO_2 emissions from energy

[1] The sustainability goals are stabilizing global climate change, enhancing energy security and resiliency, eliminating air pollution, and achieving universal access to modern energy services.

use in the US economy (2, Ch. 7) and a major and growing source worldwide, transportation must substantially increase its energy efficiency. Regulating motor vehicle efficiency has been a core component of energy policy in the USA, the EU, China, Japan, Canada, and many other nations.

Improvements in the fuel economy of US passenger cars and light trucks since 1975 have greatly reduced energy use by light-duty vehicles [2] p. 7-9. Prior to 1975, fuel use and vehicle travel increased together. After 1975, increased fuel economy due to the CAFE standards, continuing technological progress, and volatile gasoline prices disconnected their trajectories saving a total of two trillion gallons of gasoline (Fig. 1).[2]

The US Corporate Average Fuel Economy (CAFE) standards, adopted in 1975 and first enforced in 1978, have been in effect for over 40 years. This durable policy has consistently enjoyed strong public approval across the political spectrum, with typically 70–80% public support [5, 6] (Table 9.2). Yet, economic analyses almost always condemn fuel economy standards as inefficient and inferior to taxing fossil fuels or carbon [7–15]. Why are fuel economy and greenhouse gas regulations so popular with the public and unpopular with economists? The answer can be found in the insights about the decision-making of real (as opposed to theoretical) consumers developed over the past few decades by behavioral psychologists and behavioral economists.

From the behavioral perspective, energy-efficiency regulations can not only contribute to achieving sustainability goals but can also provide private benefits to consumers. As a consequence, energy efficiency can be increased beyond the level justified by social benefits alone. On the other hand, if the rational economic consumer perspective is correct, the unregulated market solution already maximizes private benefits and the only net benefits of regulation are the social benefits. The rulemaking establishing light-duty vehicle CAFE and GHG standards for 2017–2025 illustrates the importance of this point [16]. It concluded that private benefits in the form of net savings on fuel comprised more than 75% of the gross benefits of the standards (Table 1). Indeed, it was the excess of fuel savings over costs that made the standards decidedly cost-effective. This could only happen if consumers substantially undervalue fuel economy relative to its discounted present value [12]. The costs and benefits of past and present fuel economy standards depend to a large degree on whether the market systematically undervalues fuel economy technologies relative to the expected present value of their fuel savings.

Analyses of the technological potential to increase fuel economy indicate that there has consistently been substantial potential to cost-effectively improve light-duty vehicle fuel economy. Over the past 40 years, numerous studies, including four analyses by committees of the US National Academies [6, 17–19], found that technologies existed that could substantially and cost-effectively increase passenger car and light truck fuel economy, but that were not being widely adopted in new vehicles. The tendency of markets to neglect apparently cost-effective energy-efficiency technologies is known as the “energy-efficiency gap” and has been observed in energy using durable goods from light bulbs to refrigerators to motor vehicles. Various explanations for the gap have been proposed, ranging from flawed analysis of the costs of energy efficiency, to opportunity costs to various aspects of less than economically rational behavior [20, 21]. Among the systematic differences from the rational economic model one, loss aversion appears to exert an especially strong influence on consumers’ decisions to buy or not buy energy-efficient technologies and appears to be primarily responsible for the general undervaluing of energy-efficient technologies [22–24]. Loss aversion is especially interesting because whether or not consumers are loss-averse depends greatly on how choices are framed.

Over the past four decades, behavioral economics has established that real consumers behave in ways that systematically differ from the rational economic agent model [25–28]. Prospect theory (PT), one of the most thoroughly studied and best established of those decision-making biases, describes how individuals make risky choices. According to PT, faced with a risky choice, human beings typically weigh potential losses about twice as heavily as potential gains. The simple option to pay more upfront for technologies claimed to provide uncertain future fuel savings or to decline to do so is just such a risky choice. Future fuel savings are uncertain because although every new vehicle has a rated fuel economy, the actual fuel economy an individual will obtain differs substantially depending on factors such as traffic conditions, driving style, trip lengths, and weather. The unpredictability of future fuel prices, the other key determinant of future fuel savings, adds to the uncertainty.

Behavioral research has established that the framing of risky choices, the context in which they are presented, influences whether or not decision-makers will be loss-averse [29, 30]. The option to buy or not to buy a technology that improves fuel economy frames “not buy” as the “do nothing” or “status quo” option. Such choices are ideally framed to induce a loss-averse response. On the contrary, complex choices in which many alternatives with many different attributes must be simultaneously considered are not framed to induce loss aversion. The decision to buy one of many different makes and models of new vehicles, buy one of many different used vehicles or buy no vehicle, is not framed to induce loss aversion. Changes in consumers’ vehicle choices induced by changes in the price of gasoline are also not ideally framed to induce loss aversion, although they may still differ from the rational economic model.

[2] Figure 1 does not include the “rebound effect,” which is the tendency for vehicle travel to increase when fuel economy improves; however, the 2 trillion gallon estimate does [2].

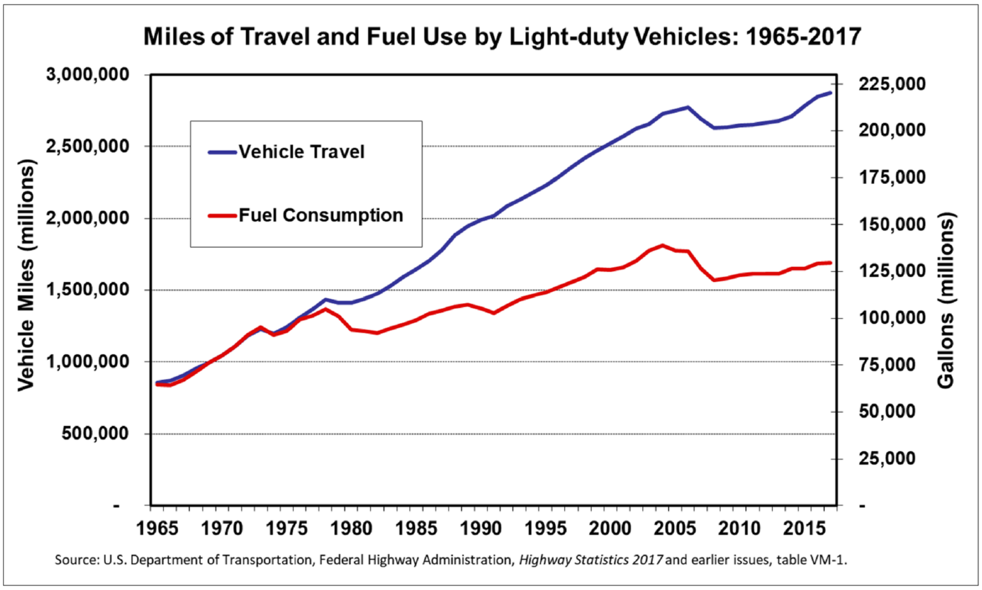

Fig. 1 Miles of travel and fuel use by US light-duty vehicles: 1965–2017 [3].

This paper explains and illustrates the central role of loss aversion in consumers' decisions about fuel economy technologies and the implications for fuel economy standards. The focus on loss aversion is not intended to imply that other differences between reality and the rational economic model are unimportant. Incomplete information, rational inattention, lack of self-control, satisficing, and other heuristics used by real consumers making complex decisions undoubtedly affect fuel economy decisions to some degree [21]. Loss aversion is emphasized because the direction of its impact is clear, and it appears to be at the heart of the matter. "Prospect Theory and Consumers' Decisions when Faced with Uncertainty" presents insights from behavioral economics that are relevant to consumers' decisions about fuel economy. "How Do Humans Make Fuel Economy Decisions?" reviews recent empirical evidence, including the availability of unused cost-effective technology, econometric estimates of consumers' willingness to pay (WTP) for increased fuel economy or reduction in fuel costs per mile, and survey responses to questions framed to induce loss aversion. "Expected Utility Theory with Loss Aversion" adds loss aversion to the rational economic model of expected utility theory to create a mathematical model of fuel economy decisions including loss aversion. "Simulating Market Solutions for EUT and LA" uses the model to illustrate how markets made up of loss-averse consumers ("Humans") respond differently to fuel price and technological changes than markets comprised of economically rational consumers ("econs").

Table 1 Estimated 2017–2025 model year lifetime discounted costs and benefits of 2017–2025 light-duty vehicle fuel economy and greenhouse gas emissions standards (Billions of 2010 dollars)

Lifetime present value at 3% real discount rate	
Costs	$150
Fuel savings	$475
Other benefits	$126
Net benefits	$451
Lifetime present value at 7% real discount rate	
Costs	$144
Fuel savings	$364
Other benefits	$106
Net benefits	$326

[15], (Table 1)

Prospect Theory and Consumers' Decisions When Faced with Uncertainty

> To a psychologist, it is self-evident that people are neither fully rational nor completely selfish, and that their tastes are anything but stable. Our two disciplines seemed to be studying different species, which the behavioral economist Richard Thaler later dubbed Econs and Humans [27], p., 269[3]

The rational economic model makes the following assumptions about consumers' decision-making.

- Consumers' preferences are complete, transitive, and unaffected by the framing of choices.

[3] Daniel Kahneman was awarded the Nobel Prize in Economics in 2002 for his work in behavioral economics including Cumulative Prospect Theory and loss aversion. His book cited here, *Thinking Fast and Slow*, won the National Academies' Best Book Award for 2012 [31]. Richard Thaler won the 2017 Nobel Prize in Economics for his work in behavioral economics.

- Consumers have full knowledge of the options available and possess and use all the skills necessary to make optimal decisions.
- Every consumer always chooses the option that maximizes his or her utility.

Generally, economists do not claim that these assumptions are literally and always true, yet they are the assumptions economists typically make when analyzing the costs and benefits of fuel economy standards.

Psychologists have found that human beings have two different modes of processing information and making decisions: an automatic system, also known as System 1, and an effortful, deliberative System 2. Kahneman describes the two systems as follows.

- "*System 1* operates automatically and quickly, with little or no effort and no sense of voluntary control.
- *System 2* allocates attention to effortful mental activities that demand it, including complex computations." [27], p., 22

Kahneman further explains:

> I describe System 1 as effortlessly originating impressions and feelings that are the main source of the explicit beliefs and deliberative choices of System 2. [27], p., 22 When all goes smoothly, which is most of the time, System 2 adopts the suggestions of System 1 with little or no modification. You generally believe your impressions and act on your desires, and that is fine, usually. [27], p., 25

System 1 is loss-averse [27], p., 281. Because system 1 is loss-averse, consumers faced with a risky choice will be loss-averse unless they make a deliberate, conscious effort to engage system 2. The existence of loss aversion in consumers' decision-making has been repeatedly verified in controlled experiments [26]. It has been detected in neuroimaging of brain activity in dopaminergic regions and their targets [32].

The psychological principles of judgment and choice under uncertainty were combined into a coherent theory of choice under uncertainty by Kahneman and Tversky [33] known as cumulative prospect theory (CPT). CPT has since been extensively studied and refined by psychologists and behavioral economists (25, literature review; 29, recent survey and critique). CPT posits that decision-making under risk is affected by four systematic differences from the rational economic model:

1. Reference dependence, the tendency to evaluate outcomes relative to a reference point, often the *status quo*
2. Loss aversion, weighing losses relative to the reference point approximately twice as heavily as potential gains [33][4]
3. Overweighting low probability events and underweighting more likely outcomes
4. The tendency to be risk-averse when one is winning but risk-seeking when attempting to recover from a loss

Häckel et al. [23] applied CPT to decisions about investments in energy efficiency, and quantified the relative impacts of the four factors via sensitivity analysis. Their results demonstrated that of the four components of CPT, loss aversion and reference dependence have by far the greatest impacts on consumers' energy-efficiency choices.[5]

Heutel [22] conducted a choice experiment in an online survey to determine the effect of loss aversion on consumers' choices of energy-efficiency options, including efficient lighting, programmable thermostats, and energy audits.

> Empirically, I find evidence that prospect theory explains people's investments (or lack thereof) in energy efficiency [22], p., 5

In addition, Heutel [22] found that the private benefits (the energy savings) from correcting the "market failure" of loss aversion exceeded the value of the reduced external costs from excessive energy use, echoing the results of the EPA's 2012 rulemaking (see Table 1 above).

> Simulation results suggest that the behavioral market failure from loss aversion can be quite large relative to the market failure from the externality. [22], p., 6

Heutel [22], p., 26 concluded that both his empirical and theoretical results pointed to the importance of incorporating CPT into energy policy evaluation and design.

When a manufacturer offers consumers the option to buy or not buy a fuel economy technology, it is offering a risky choice. The upfront cost is known (often after some haggling) but the fuel savings over the life of the vehicle are inherently uncertain. Not only do the benefits come in the future over a period of 15 years or so, but they depend directly on future fuel prices and real-world efficiency gains, both of which are substantially uncertain from the consumer's point of view.

[4] Weighing losses twice as much as gains is a typical or average loss-averse response. Kahneman [27] cites a range of 1.5 to 2.5, but there is even greater variation among individuals.

[5] "Third, by implementing the modular elements of CPT, we can conclude that loss aversion is the major driver of the EE gap. Our results indicate that other elements of CPT, such as probability weighting, have a rather negligible influence. As an exception, however, we find the determination of the reference-point to be very important. Depending on how the EE investment is framed, or perceived by the decision-maker, the EE gap might vanish or be amplified." [23]

Fuel economy labels provide information based on fixed driving cycles and fuel prices but for any individual, large uncertainty remains.[6] An analysis of 75,000 self-reported fuel economy estimates from individual drivers found that even after correcting for the government's test cycle, fuel economy rating, reported driving style, vehicle class, engine type and size, transmission, and other factors, a two-standard deviation confidence interval for reported fuel economy was + 49 to − 33% of the predicted value [35•]. Uncertainty about future gasoline costs, measured by the ratio of standard deviation to the mean, was ± 29% based on annual, constant dollar prices for the period 1965–2017. The variation in prices over the next 10 years discounted at 7% per year for the period 1965–2008 is almost as great: the ratio of standard deviation to mean is 22%.[7] The price of oil, the predominant determinant of the price of gasoline, has been shown to be indistinguishable from a random walk [36]; additional effort would be unlikely to reduce uncertainty about future fuel prices.[8] Likewise, there is presently no feasible method by which consumers can accurately predict the fuel economy they will obtain in their own driving [35•, 38]. Future fuel savings are uncertain.

Integral to the concept of loss aversion is context dependence, the fact that loss aversion is induced by the framing of choices [29, 39]. Framing not only determines whether consumers will undervalue fuel savings in the context of a risky choice, it also explains why consumers should not be expected to undervalue future fuel savings in other contexts. Since the development of CPT, researchers have continued to investigate which contexts are and are not framed to induce a loss-averse decision. Novemsky and Kahneman [29] were among the first to identify situations in which loss aversion would and would not apply.

> Although early work finds loss aversion to be ubiquitous, applying to many types of goods and risks, it is important to note that there are limits to loss aversion [29], p., 127
>
> The results from the current studies suggest that loss aversion is highly sensitive to the context in which the decision is made. People exhibit loss aversion in certain situations, but not in others [30], p., 216
>
> Risky buyers are in a similar situation to that of buyers, except that they face a risky decision rather than a riskless one. Because risky buyers are gambling their money, we expect loss aversion for that money. [28, p., 121]

Subsequent research has further clarified the types of risky choices that do and do not induce loss aversion [30, 40]. Researchers have found that individuals are more likely to decline a gamble when it is framed as the alternative to doing nothing, i.e., the status quo, highlighting the role of reference dependence [30]. Loss aversion is more likely when the risky choice in question is not frequently encountered; repeated experience with a specific risky choice tends to reduce loss aversion through learning [41], p., 372. Factors strongly conducive to loss aversion are the perception of the choice as an action (accepting the bet) versus inaction (status quo), and gambles that involve higher versus lower stakes [33], p., 279.

> The results highlight two conditions that seem to trigger absolute loss aversion: the presentation of the risky options as an alternative to the status quo, and the use of high nominal pay-off magnitudes. [30, p., 215]

These findings produce a more precise description of the context of consumers' purchases in which loss aversion should be expected.

- Consumer purchases involving risky choices
- The presentation of the choice as a simple buy (accept the risky choice) or not-buy (decline and keep the status quo)
- The pay-offs (both gains and losses) are relatively large numbers (e.g., \$100s or \$1000s)
- Choices that are made infrequently with little or no feedback to the decision maker

The choice to buy or not buy a fuel economy technology or a bundle of fuel economy technologies in a new vehicle fits all four criteria well. Uncertainty about real-world fuel economy, future fuel prices and other factors make the decision substantially risky. The offer to buy or not buy a novel fuel economy technology is a simple risky choice that frames the do-not-buy option as the status quo. Engine options (e.g., diesel, hybrid, turbo-charging and downsizing) or transmissions (e.g., automatic vs. continuously variable transmission) or substantial material substitution (aluminum for steel auto-bodies) are likely to be priced in the hundreds to thousands of dollars at the retail level. Finally, new car purchases are infrequent; the average length of time a US household holds onto a given vehicle is estimated to be 6.6 years [42, 43]. Obtaining meaningful feedback about such fuel economy decisions requires effort because fuel economy naturally varies with such factors as traffic conditions, trip lengths, speed, and temperature, and the counterfactual case is typically not observed. Although

[6] Sallee [34] simulated annual fuel costs based on 100,000 random drawings from actual distributions of annual miles, discount rates and the gasoline price forecasts of individual consumers. The estimates varied widely in relation to label values even though uncertainty about actual on-road fuel economy was not included. "This means that even if a fuel economy label explained the lifetime fuel costs accurately for the median driver, that estimate will be too high or too low by \$6200, or 50%, on average." [34], p., 789

[7] The measure of variability is insensitive to the discount rate assumed. The analysis is based on annual prices of regular grade gasoline from the EIA October 26, 2018 Monthly Energy Review Table 9.4, converted to 2017 dollars using the FRED GDP price deflator.

[8] Hamilton [36] demonstrated that world oil prices are indistinguishable from a random walk, and nearly all the variability in US gasoline prices over time can be explained by changes in world oil prices [37].

households could conceivably quantitatively evaluate fuel economy technology decisions, even infrequently, the research available on the subject indicates that they do not do so [44•]. Instead, system 1 decision-making predominates.

The importance of framing in risky choices implies that consumers are not likely to make all fuel economy decisions in the same way, and that not all fuel economy choices will induce loss aversion. The four framing criteria imply that the following three types of fuel economy choices will be made differently, and only the first will consistently trigger loss aversion.

1. The choice to purchase or not purchase a fuel economy technology matches on all four points and is expected to induce loss aversion.
2. The choice, motivated by changes in fuel prices, among makes, models, and model years with many different attributes, of which fuel economy is only one, is much less well framed to induce loss aversion because it involves comparisons of vehicles on many attributes rather than a simple buy vs. do-not-buy choice.
3. The choice to buy or not to buy a particular new vehicle when fuel economy regulations are gradually increasing the fuel economy of all new vehicles is a complex choice involving numerous vehicles and attributes, one that is not normally chiefly motivated by fuel economy, and there is no well-defined status quo option. Loss aversion about fuel economy should not be expected.

Behavioral economics predicts that the market for fuel economy will undervalue future fuel savings relative to discounted expected savings when consumers choose between buying or not buying fuel economy technologies. As a consequence, manufacturers will have difficulty selling fuel economy technologies, and technologies that could cost-effectively improve fuel economy will go unused or will be applied to another purpose, such as acceleration performance.

How Do Humans Make Fuel Economy Decisions?

> We found no household that analyzed their fuel costs in a systematic way in their automobile or gasoline purchases. (43, p. 1213)

Only one published, peer-reviewed study has objectively documented the actual fuel economy decision-making processes of real households. Two anthropologists, Turrentine and Kurani (T&K) [44•], conducted extended interviews of 57 California households for approximately 2 h each concerning their history of vehicle ownership and purchases. Six households were recruited by random sampling in each of ten lifestyle categories. The interviews began by listening to the household members talk about past vehicle purchases and their reasons for their vehicle choices. Next, they asked about the most recent vehicle purchase in greater detail. The third step was to ask the households to design the next vehicle they imagined themselves buying, referring to a table of attributes one of which was fuel economy. In the fourth phase, the researchers revealed their interest in fuel economy for the first time and asked questions about willingness to pay for a 50% increase in the fuel economy of their imagined next purchase, and introduced concepts such as payback periods.

The results were definitive. Half of the households were unwilling or unable to offer a willingness to pay for the 50% increase in fuel economy. Only two individuals offered what the interviewers judged to be answers arrived at through a process that could be described as economically rational. This result is especially surprising because three of the ten groups were comprised of (1) college or graduate students nearing graduation, (2) computer hardware or software engineers, and (3) professionals in the financial services sector.[9] T&K's findings not only demonstrate that households do not think in terms of the rational economic model, but they also cast doubt on the notion that individuals might be able to arrive at the right answer through intuition or use of other sources of information.

> One effect of this lack of knowledge and information is that when consumers buy a vehicle, they do not have the basic building blocks of knowledge assumed by the model of economically rational decision making, and they make large errors estimating gasoline costs and savings over time. (43•, p. 1213)
> It is clear that few households understand the financial calculations that lie behind questions about "an investment in fuel economy" and payback periods, and that even those few do not apply such knowledge to their household vehicle purchase and use. (43, p. 1220)
> In short, the consumers we spoke to do not think about fuel economy in the same way as experts, nor in the way experts assume consumers do. (43, p. 1221)

The 57 real consumers in T&K's study unanimously relied on system 1 and not system 2 when making decisions about fuel economy.

In a more recent survey, Leard [46] found that three out of four respondents claimed to have made no calculations about fuel costs when deciding on their most recent vehicle purchase. Twenty-four percent indicated they had not considered fuel

[9] This result is consistent with Dharshing and Hille [45] who found that numeracy and energy literacy were not statistically significantly related to the energy efficiency choices of Swiss households but impulsivity and risk aversion were.

costs at all, 52% said they had thought some about fuel costs but made no calculations, and the remaining 24% chose the option: "I made some calculations to compare fuel costs". Although this implies greater attention than T&K found in their interviews, the phrase "some calculations" could mean many things.

According to NRC [6], automobile manufacturers also believe that consumers' willingness to pay for fuel economy technologies is only a fraction of the discounted, expected fuel savings over the life of the vehicle. US automakers have been selling mass-produced vehicles to consumers for more than a century.[10]

> During its information-gathering process, the committee found that auto manufacturers perceive that typical consumers would pay upfront for only one to four years of fuel savings, a fraction of the lifetime-discounted present value. [6, p., 315]

Requiring a short payback period is the same as requiring that the payoff (the fuel savings) far exceeds the potential loss (the upfront cost). Payback periods as short as 1 to 4 years correspond to weighing potential losses at least twice as much as potential gains.

Survey data reported in Greene [24] and Greene et al. [47] provide consistent evidence supporting manufacturers' perceptions. Participants in four 1000-household random sample surveys (2004, 2011, 2012, 2013) conducted by ORC International, Inc. were asked to consider the next vehicle they planned to purchase or lease. They were then asked how much they would be willing to pay for a more fuel-efficient engine, just as good in all respects as the one they were considering except that it would save them $400 per year on fuel. In the 2004, 2011, and 2012 surveys, respondents were randomly assigned either to the previous question (A) or were told that the engine would cost $1200 and were asked how much it would have to save them in fuel each year before they would be willing to buy it (question B). The 2012 survey used a different engine cost ($1900) and annual savings ($600). In the 2013 survey, only question A was asked with an engine cost of $1500. Individual answers varied widely, but the mean calculated payback periods from the four surveys ranged from 2.6 to 3.5 years [47].

Engineering analyses have repeatedly identified substantial potential to cost-effectively increase fuel economy. The four National Research Council (NRC) Committees convened to evaluate the potential of technologies to increase light-duty vehicle fuel economy, and the CAFE standards found substantial potential to increase fuel economy at costs well below the expected present value of future fuel savings [6, 17–19].[11] The NRC committees' findings, plus estimates for 1975 and 1980 based on a peer-reviewed literature review [48•], are summarized by the fuel economy cost curves in Fig. 2. Each curve is defined relative to typical vehicles of a recent model year at the time the studies were conducted. Every curve indicates substantial potential to increase fuel economy at costs much smaller than the present value of expected fuel savings. For example, a vehicle traveling 10,000 miles per year would save 100 gal per year for a fuel economy increase from 20 to 25 miles per gallon. At $2.50 per gallon, the discounted lifetime value of fuel savings to the consumer would be about $2250.[12] Fuel savings of this magnitude would justify substantial increases in both passenger car and light truck fuel economy in every year in which the potential to increase fuel economy was assessed (Fig. 2).

Inferences about consumers' willingness to pay for fuel economy from econometric studies (usually explicitly or implicitly assuming rational economic behavior) have produced widely varying and inconsistent results. Evidence from the econometric literature was reviewed by Greene [49], Helfand and Wolverton (50•), USEPA [50] and Greene et al. [51].[13] All found a wide range of estimates with no consensus that consumers either undervalued or overvalued fuel economy relative to its expected value. Greene et al. [51] carried out a meta-analysis of 95 estimates of the marginal WTP for a $0.01/mile reduction in a vehicle's fuel cost derived from 52 US studies covering the period 1995 to 2015 and found that the mean of estimates based on stated preference surveys supported full valuation of future fuel savings while the mean of estimates based on revealed preference survey data and market sales data supported undervaluing by approximately 40 to 50%.

> Unfortunately, the meta-analysis seems to offer support for a wide range of conclusions about WTP for fuel cost reduction, depending on one's beliefs about the reliability of inferences from different kinds of data and the necessity of using estimation methods that account for endogeneity of vehicle prices. [51, p., 272]

Five recent studies have also reached contradictory conclusions about WTP for fuel economy improvements. Allcott and Wozny [53] found that inferences about WTP for future fuel savings depended strongly on assumptions about how consumers anticipate future fuel prices. If expectations were based on oil future prices, they estimated that consumers were willing to pay for about 76% of expected lifetime, discounted fuel savings. But if prices were assumed to follow a random

[10] The Ford Model T was introduced in 1908.

[11] The fifth committee's work is still in progress and no findings have been issued.

[12] Assumes a 6% annual discount rate and a 13-year vehicle lifetime.

[13] The four studies are not independent. Helfand and Wolverton [52] make extensive use of Greene [49], and Greene et al. [51] is based on estimates presented in EPA [50].

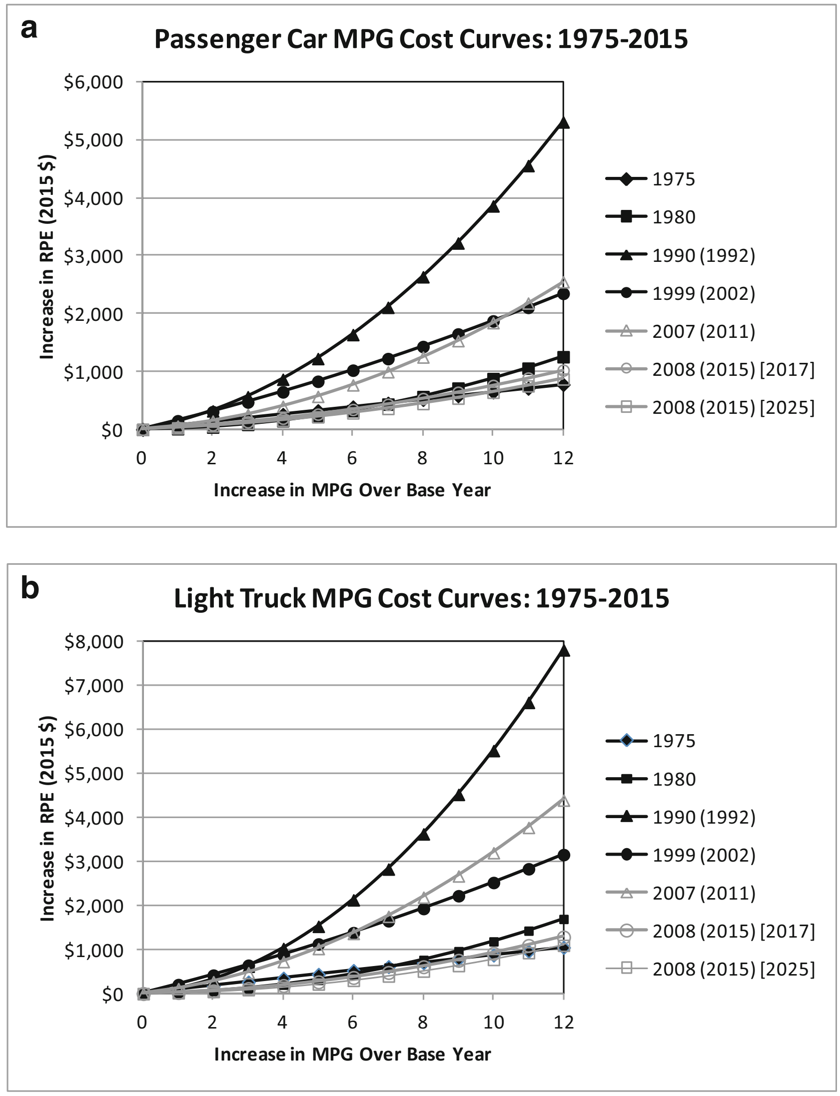

Fig. 2 **a** Passenger car fuel economy cost curves. 1975–2025 [4]. RPE retail price equivalent is the estimated cost to the consumer. Curves are identified by the base model year vehicle, the year of the NRC report is shown in round brackets (), and for the 2008 study the year in which the cost curve is estimated to apply is shown in square brackets []. **b** Light truck fuel economy cost curves 1975–2025 [4]. RPE retail price equivalent is the estimated cost to the consumer. Curves are identified by the base model year vehicle, the year of the NRC report is shown in round brackets (), and for the 2008 study the year in which the cost curve is estimated to apply is shown in square brackets []

walk or matched expectations based on actual consumer surveys [54], consumers would pay for only 55% or 51%, respectively, similar to requiring a simple payback of about 4 years for a vehicle with an expected lifetime of 15 years.

Using data on wholesale transactions, Sallee et al. [55] found that buyers of used cars with odometer readings of 10,000 to 100,000 miles valued remaining fuel savings at approximately their discounted present value but that buyers of vehicles with 100,000 to 150,000 miles on their odometers were willing to pay for only about 30% of the present value of remaining fuel savings. US passenger cars and light trucks reach 100,000 miles after about 7 years, and approximately half of the light-duty vehicles on US roads are more than 7 years old [56]. Busse et al. [57] estimated the effects of changes in the price of gasoline on new and used vehicle prices and concluded that there was little evidence in either the new or used car markets that consumers dramatically undervalued changes in expected future fuel costs. Bento et al. [58] found evidence of undervaluing, indicating consumers value a $1 decrease in operating cost at between $0.22 and $0.96. Leard et al. [59] analyzed survey data for over 500,000 new car buyers and concluded that consumers would pay $0.54 for a $1 increase in present value fuel savings, almost identical to Allcott and Wozny's [53] results assuming fuel price expectations consistent with a random walk or static expectations. In a study of how consumer inattention to fuel costs in their vehicle purchase decisions correlated with stated preferences about willingness to pay for fuel economy, Leard [46] estimated that the average respondent would pay only $0.45 to reduce present value lifetime fuel costs by one dollar.

All these studies analyzed consumers' choices among different types of vehicles as a consequence of changes in the price of gasoline. These are complex choices among vehicles with many differing attributes, not simple choices to accept or reject risky bets. There is no clear status quo option. Because the framing of the choices is complex, loss aversion is less likely to come into play, although other departures from rational economic decision-making are still relevant, and estimates may also have been affected by data source, model formulation, or choice of statistical method [51].

The choice among an array of makes and models of new vehicles differs from the choice to buy or not buy a fuel economy technology in another important way. New vehicles of a given model year are likely to embody similar levels of technology. Given similar levels of technology, differences in fuel economy among vehicles will be chiefly due to differences in mass and engine power [60, 61].[14] Consumers' intuition about vehicle size and fuel economy may reduce their uncertainty about fuel economy when choosing among vehicles of different sizes because, holding technology constant, size, mass, engine power, and fuel economy are strongly correlated. A 10% reduction in the mass of a vehicle combined with an equivalent reduction in engine horsepower reduces fuel economy by about 6.7%, on average [60]. Associating fuel economy with vehicle and engine size may reduce consumers' uncertainty about fuel economy differences when choosing among vehicles of substantially different sizes.

Other deviations from the rational economic model are likely to be present in consumers' choices among vehicles. Decision-making biases caused by bounded rationality and imperfect information, the potential lack of salience of fuel economy differences between similar vehicles, rational attention [34], and lack of self-control probably all apply to some degree. Researchers have also demonstrated that consumers have an "mpg illusion": they tend to value changes in miles per gallon (mpg) equally regardless of the initial mpg [62]. Thus, a five mpg increase from 10 to 15 mpg may count as much as a 5-mpg increase from 25 to 30 mpg, even though the difference in fuel consumption per mile is five times greater for the improvement from 10 to 15 mpg. Although the analysis below focuses on loss aversion, other differences from the rational economic model are also at work with potentially important consequences.

Expected Utility Theory with Loss Aversion

> The failure of EU (expected utility, ed.) theory as both a descriptive and predictive model stems from an inadequate recognition of various psychological principles of judgment and choice. [63]

In this section, mathematical models of consumers' decision-making under expected utility theory (EUT), the extension of the rational economic model to include uncertainty, and loss aversion (LA) are presented. In the following section, their implications for consumers' fuel economy choices are illustrated via simulation analysis and compared. Katsikopoulos [64] refers to CPT as an "idealistic" model of bounded rationality because it models a deviation from the neoclassical economic model of unbounded rationality. From this perspective, it is reasonable to augment the EUT model by modifying the representation of utility to incorporate loss aversion. However, adding loss aversion to the EUT model makes it substantially more complex.[15] If the overwhelming majority of real consumers do not explicitly make expected utility calculations, it would be absurd to claim that they make more complex loss-averse expected utility computations [63]. Instead, both mathematical models should be considered idealized (and incomplete) descriptions of actual consumers' decision-making.

EUT asserts that the subjective value, U, associated with a risky choice is equal to the statistical expectation of the potential outcomes of the gamble.[16] Faced with a risky decision with i = 1 to $n > 1$ possible outcomes, x_i, having values, $U(y,x_i)$ where y_0 is an initial level of wealth, each with probability $p(x_i)$, a risk-neutral decision-maker will determine the value of the decision by the sum of the probability weighted outcomes (Eq. 1):

$$U(y,x) = \sum_{i=1}^{n} p(x_i) v(y_0 + x_i) \tag{1}$$

According to EUT, risk-neutral decision-makers' willingness to pay for future fuel savings is equal to their discounted expected value over the life of a vehicle.[17] Assuming a constant discount rate, r, the present value of future savings, S, can be calculated by integrating the rate of fuel savings per time, t, multiplied by the discounting function, over the life expectancy, L, of the vehicle. The rate of fuel savings depends on the difference in fuel use per mile multiplied by miles driven, m_t, and the price of gasoline, p_t. The difference in fuel use per mile is equal to the difference of the inverses of the reference miles per gallon, mpg_0, and the increased miles per gallon $mpg_0 + \Delta$, adjusted for the shortfall between test and real-world mpg, $k \approx 0.8$. Both p_t and $1/k$ are assumed to be independent random variables with means $\boldsymbol{p}$ and $1/\boldsymbol{k}$, so that Eq. 2 gives the expected value of S:

$$S = \int_{t=0}^{L} m_t \boldsymbol{p}_t \left(\frac{1}{\boldsymbol{k} mpg_0} - \frac{1}{\boldsymbol{k}(mpg_0 + \Delta)} \right) e^{-rt} dt \tag{2}$$

The net value of the decision is the savings from increased fuel economy minus the upfront cost, $C(\Delta)$.

[14] A vehicle's mass determines the physical work that must be done to accelerate it and to overcome the friction of rolling resistance. Mass is also correlated with size and frontal area, a key determinant of aerodynamic resistance. Finally, apart from a vehicle's mass, for vehicles with stoichiometric engines, engine size determines how much fuel is consumed per engine revolution.

[15] The mathematical representation of loss aversion used is taken from Bernartzi and Thaler [65] and was intended to describe consumers' behavior in the case of simple win or lose bets. Uncertainties about future fuel savings are far more complex. How best to describe consumers' decision-making in the face of more complex uncertainties would seem to be an important subject for future research.

[16] EUT can include risk aversion. However, risk aversion is different from loss aversion and cannot explain the magnitude of undervaluing implied by loss aversion [66].

[17] A common definition of willingness to pay is the maximum amount of money a consumer will give up to obtain a good or avoid a bad [67].

Of course, fuel savings are uncertain. Every vehicle has an official mpg rating that comes with a warning:

> Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. (https://www.fueleconomy.gov/feg/Find.do?action=bt1)

Consumers understand this uncertainty. A random sample of 1000 US households were asked what mpg they would expect to attain for a vehicle rated at 25 mpg, as well as the best and worst mpg they would expect to get with that vehicle. The average expected mpg was 22.9 and the average range from worst to best was 8 mpg [47]. There is also evidence that the deviations from rated fuel economy for vehicles in the same household are only weakly correlated [68], indicating that the shortfall a consumer experiences with one vehicle is not necessarily a good predictor of the shortfall that will be experienced with another.[18] As noted above, the future price of gasoline (P_t) is also uncertain because it is primarily determined by the price of petroleum. Other parameters of Eq. 2 are also uncertain to some degree, including miles traveled (m_t), vehicle life (L), and future discount rates (r).

Manufacturers' and consumers' statements about how quickly fuel savings must repay any additional cost are not consistent with risk-neutral EUT. The payback period implied by Eq. 2, assuming that miles traveled decrease exponentially with vehicle age, $m_t = m_0 e^{-\rho t}$, that consumers expect future gasoline prices to be the same as the current price and that fuel economy is approximately constant over the life of a vehicle [4], is given by Eq. 3:

$$Y = \int_{t=0}^{L} e^{-(\rho+r)t} dt = \frac{1}{(\rho+r)}\left[1-e^{-(\rho+r)L}\right] \qquad (3)$$

Plausible discount rates range from 3 to 10% [69], rates of decline in vehicle use range from 2 to 4%, [70] and expected vehicle lifetimes from 13 to 17 years depending on the type of vehicle [56, 71]. Given these parameters, a consumer requiring payback in 2, 3, or 4 years would be undervaluing future fuel savings by 67 to 83%, 52 to 74%, or 34 to 65% of expected lifetime savings, respectively. Yet these are the payback periods car makers and consumers themselves say they require for fuel economy technology. Such short payback periods are consistent with loss aversion, however.

Loss aversion can be added to the present value function of the EUT model. Let $C(\Delta) = b_1\Delta + b_2\Delta^2$ be a quadratic cost function of the change in test mpg with intercept = 0, M be discounted lifetime vehicle miles, and $kS(mpg, \Delta, P)$ be the fuel savings per mile obtained by increasing test cycle fuel economy from mpg to $mpg + \Delta$. P and k are assumed to have independent probability distributions $f(k)$ and $g(P)$.[19] If the consumer perceives the fuel economy choice as a risky bet, the loss-averse utility function, V, would be used to estimate the value of the risky choice:

$$\begin{aligned} V^{-}(x) &= \int_{S^*}^{\infty} -\lambda\left[-\left(PMS(mpg,k,\Delta)-b_1\Delta-b_2\Delta^2\right)\right]^{\beta} f(k)g(P)dS, \text{ if } S < 0 \\ V^{+}(x) &= \int_{0}^{S^*}\left[PMS(mpg,k,\Delta)-b_1\Delta-b_2\Delta^2\right]^{\alpha} f(k)g(P)dS, \text{ if } S \geq 0 \end{aligned} \qquad (4)$$

The functional form of the loss aversion function is from Bernartzi and Thaler [65], which specifies parameter values of $\lambda = 2.25$ and $\alpha = \beta = 0.8$. The loss-averse value function is discontinuous at values of S^* where fuel savings exactly equal cost. Finding the optimum value of Eq. 4 is not a calculation a typical consumer would or could make. The loss-averse weighting function of CPT is intended to be an approximate mathematical description of typical behavior rather than the actual algorithm used by decision-makers.

Simulating Market Solutions for EUT and LA

Solutions to the EUT and LA models can be computed by Monte Carlo simulation, given a fuel economy cost function, parameters for the fuel savings equation and probability distributions for the random variables. The key assumptions are discussed below followed by results for the value of mpg improvements over average 2008 model year and then 2017 model year passenger cars. The cost estimates are from NRC [6]. The average passenger car test cycle mpg (as opposed to on-road mpg) for model year 2008 was 30.5 [72]. The NRC's high-cost function for increased mpg beyond 30.5 is illustrated by the solid gray line in Fig. 3.[20] Given the mean values of the parameters in Table 2, the economically rational consumer's total willingness to pay for increased fuel economy is illustrated by the dashed gray line in Fig. 3.[21] The solid black line with dots shows the difference between the two, the net value of increased fuel economy according to expected utility theory.

Net value reaches a maximum between 13 and 14 mpg.[22] From a private perspective, it appears that an increase to about 43.9 test cycle mpg would be optimal based on EUT. The

[18] A large part of this may be due to different vehicles having different drivers making different kinds of trips.

[19] The assumption of independence is a convenient simplification. There is some evidence that the on-road shortfall responds to the price of gasoline [24].

[20] The NRC's high cost function was chosen because it better illustrates situations in which loss-averse consumers would decline fuel economy improvements.

[21] A car buyer's willingness to pay (WTP) for increased fuel economy is calculated based on estimated on-road as opposed to test cycle fuel economy, annual miles driven and the rate at which miles decrease over time, expected vehicle life, expected price of gasoline, and the discount rate for future fuel savings.

[22] Taking external costs of fuel consumption into account, the socially optimal mpg would be higher than the privately optimal mpg. On the other hand, the private optimum would include fuel taxes in the price of fuel while the social optimum would not.

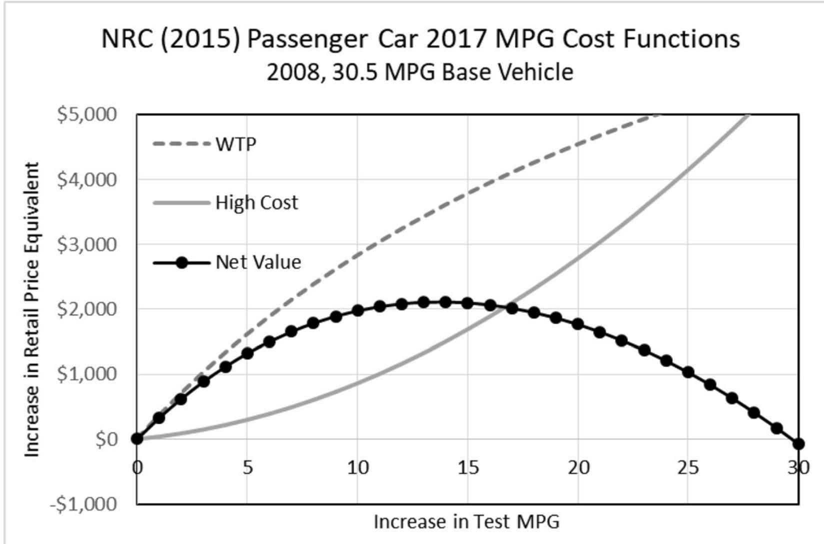

Fig. 3 Expected utility analysis of the value of increased fuel economy for a model year 2008 passenger car using the NRC [6] high cost estimates

actual average test cycle fuel economy of model year 2017 passenger cars was 37.9. The net value function is relatively flat near the optimal value, varying less than $170 dollars between 10 and 18. Observing that the cost of obtaining useful fuel cost information might exceed its expected value, Sallee [34] noted that inattention to fuel economy differences this small could be rational.

Expected values of the loss-averse value function were calculated by Monte Carlo simulation using the @Risk™ software and the parameter values and probability distributions shown in Table 2. Ten thousand iterations were performed for each increase in mpg.

For the 2008 base 30.5 mpg passenger car, the optimal value of the loss-averse value function implies almost the same optimal increase in mpg (i.e., 13) as the EUT value function (Fig. 4). The "net value" curve in Fig. 4 was not produced by simulation. It was calculated using the expected values of the random variables. Net value produced by the simulation runs, "simulated NV", is represented by the "+" symbols. The simulated NV does not include loss aversion and is almost identical to the net value calculated using the mean parameter values. As net value increases from 0 to 13 mpg, the probability of loss decreases because the relative uncertainties about real-world fuel economy, fuel prices, and other factors do not increase with the increase in test mpg. Given the data and parameters shown in Table 2, and starting with a 30.5 test cycle mpg passenger car, even a loss-averse consumer would prefer 43.5 test cycle mpg. However, trade-offs with other attributes, such as acceleration, will be affected by the reduced value of fuel economy under LA. The uncertainty of future fuel savings makes fuel economy less attractive to the loss-averse consumer relative to acceleration performance or vehicle size, because the latter are tangible and directly observable prior to purchase. Nonetheless, the positive value of mpg increases to even the loss-averse consumer may help explain why manufacturers agreed to the fuel economy improvements proposed in the 2017–2025 rule [16].

Table 2 Parameters of the consumer's willingness to pay for increased fuel economy

Variable	Distribution	Mean	Min	Max
Annual discount rate	Triangular	6.0%	3.0%	9.0%
Annual decrease in miles	Triangular	2.7%	2.0%	3.4%
Total annual discount rate	Sum of 2 triangular	8.7%	5.0%	12.4%
Expected vehicle life (yrs.)	Triangular	13	5	21
Annual vehicle miles of travel	Triangular	13,912	11,850	16,025
Price of gasoline (2017$/gal.)	Triangular	$2.50	$1.25	$3.75
Real-world/test mpg ratio	Triangular	.772	.637	.907
Base-to-Increased mpg	Correlation coefficient	0.2		

Sources: FRED https://fred.stlouisfed.org/categories/33058, [3] https://nhts.ornl.gov/, USDOT/NHTSA "SAFE" [73, 74] Fig. 8–23, USEPA [72] Table 10.2

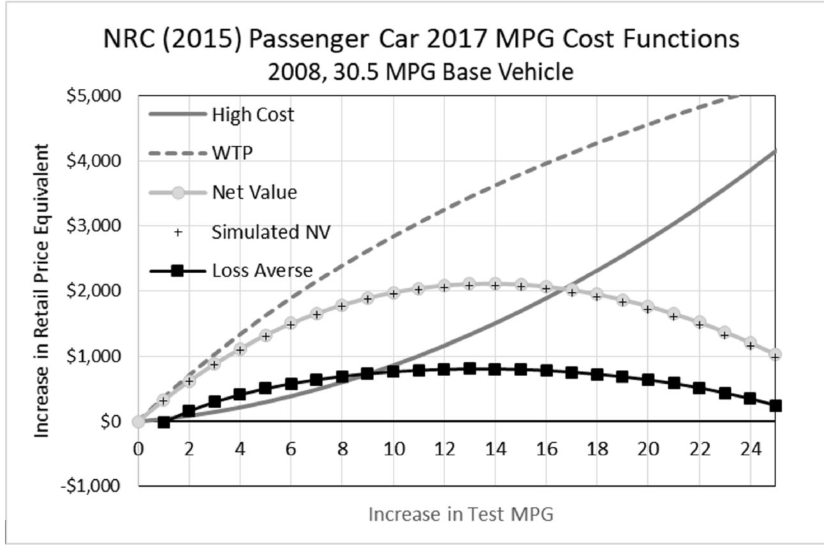

Fig. 4 Loss-averse and expected utility analyses of fuel economy improvements to a typical 2008 model year, 30.5 mpg passenger car

Things looked different in 2017, however, when the average test cycle mpg of a new passenger car was 37.9 (7.4 mpg higher than 2008). From the higher mpg level of 37.9, each additional 1 mpg increase provides less net value at a higher cost. The additional increases to 43.9 test cycle mpg that appeared optimal to the LA consumer from the perspective of a 30.5-mpg car in 2008 now appear unattractive (Fig. 5). This result may partly explain why the same manufacturers who in 2012 concurred with the 2025 CAFE standards sought to change them in 2017. Of course, the decline in gasoline prices from \$3.50 in 2012 to \$2.00 in 2017 was also a major factor (Figs. 5 and 6 assume a mean price of \$2.50/gal).

To the loss-averse decision-maker, all the bets on fuel economy improvements have negative value in 2017. The loss-averse value function still has the same optimum as the EUT net value, a 6–7-mpg increase, but the value of that risky bet is negative, indicating that the typical loss-averse consumer in 2017 would decline the option to pay for a 6-mpg increase. Even for the rational economic consumer of EUT, the net value of fuel economy increases up to 10 mpg do not amount to more than \$405 and the value function is once again very flat near the optimum suggesting that fuel economy improvements over a wide range may not be salient to consumers.

By far the most important uncertainty affecting the loss-averse value function is uncertainty about the actual on-road fuel economy of vehicles. This is illustrated in Fig. 6 by a tornado chart showing the effect of the variability of each factor on the mean net value of an increase in fuel economy from 37.9 to 43.9 test cycle mpg. The effect

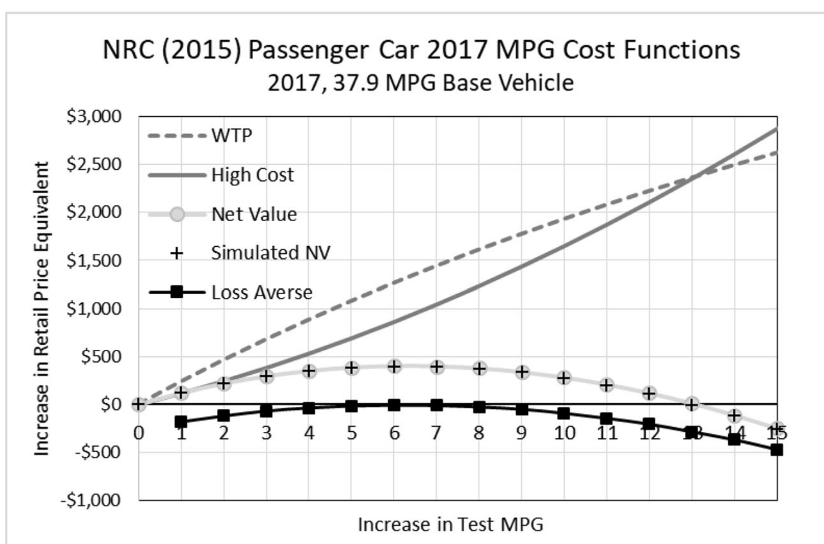

Fig. 5 Loss-averse and expected utility analyses of fuel economy improvements to a typical 2017 model year, 37.9 mpg passenger car

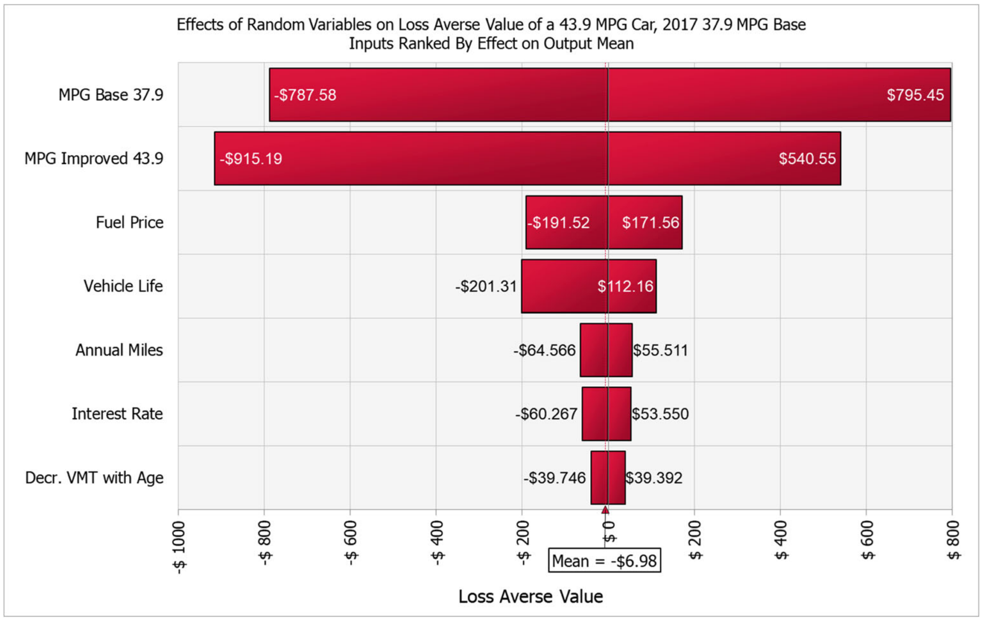

Fig. 6 Tornado chart of effects of random variables on the loss-averse value of an increase in mpg from 37.9 to 43.9, inputs ranked by effect on the mean value

of uncertainty about both the base and improved vehicles' fuel economies is approximately four times as large as the effect of uncertainty about future fuel prices. The Monte Carlo simulation takes into account that the on-road shortfalls of the base and increased fuel economy vehicles are weakly correlated, with a correlation coefficient of 0.2. Uncertainty about vehicle lifetime has about one fifth as great an impact as uncertainty about on-road mpg, followed by uncertainty about actual vehicle use with an order of magnitude smaller influence than mpg.

Conclusion

How consumers value technologies that improve fuel economy matters a great deal. Loss aversion and other differences between the decision-making of "humans" and econs have important implications for public policy toward energy efficiency and greenhouse gas emissions [75]. Energy savings available because of loss aversion and other differences from the rational economic model of consumer behavior can exceed the external benefits of reduced energy use (21; 15, Tables 7.3–4, 7.3–5, 7.3–6 and 7.3–7). The EPA's rulemaking for 2017 to 2025 model year light-duty vehicles claims fuel savings to consumers that would not exist in a market comprised of economically rational consumers and competitive car makers. Yet such savings can exist in a market comprised of humans and can justify greater GHG reductions than could be justified by external costs alone.

The framing of consumers' fuel economy decisions matters and appears to explain why even loss-averse

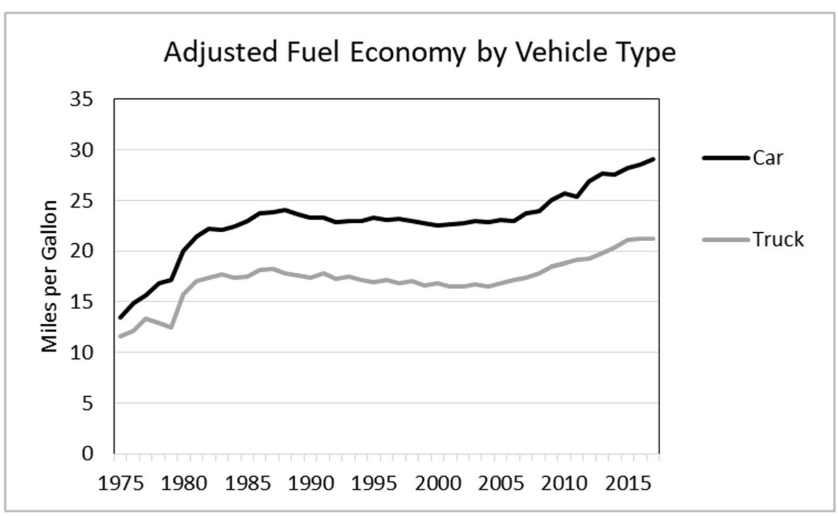

Fig. 7 Adjusted fuel economy by vehicle type, 1975–2017. (71, Tables 3.4.1 and 3.4.2)

consumers support fuel economy regulation. In the absence of regulation, the decision to buy or not buy a fuel economy technology appears to be a risky bet that loss-averse consumers are likely to decline. On the other hand, when the fuel economies of all new vehicles are gradually increasing because of regulatory standards, consumers' vehicle choices are not framed to induce loss aversion. First, there is no longer a simple risky choice to buy or not buy a fuel economy technology because manufacturers will have applied fuel economy technologies to all vehicles.[23] As a result, fuel economy will be but one of many different attributes of new and used vehicles. Second, fuel economy regulations require gradual improvements year after year (Fig. 7). Such gradual and continued improvement gives consumers time to become aware of the general improvement in fuel economy and learn about its value in actual driving, thereby reducing uncertainty.[24]

Because the framing of choices under regulatory standards is not conducive to loss aversion, car buyers are likely to approximately fully value the fuel savings they obtain with the higher mpg vehicles required by fuel economy standards. This also appears to explain why fuel economy standards have been so popular with the public. That popularity has made CAFE standards a durable policy that has remained in effect, with modifications, for over 40 years. In any case, as consumers driving the new vehicles save on fuel, a dollar saved on fuel will be worth the same as any other dollar. The perceived utility at the time a fuel economy decision is made may vary by the context, but the experienced utility from increased income due to lower fuel costs should not be affected by the initial context of the choice of vehicle [76, 77].

When consumers undervalue future fuel savings from vehicle technologies, taxing fuel to internalize external costs, such as GHG emissions, will not produce the optimal level of fuel economy [78]. Taxes on inefficiency and/or subsidies for efficiency are also required.[25] However, the same result could also be accomplished by the shadow price on inefficiency induced by regulations that required the optimal level of efficiency. Because of this, a tax on carbon, for example, should not be viewed as a replacement for fuel economy standards but rather as a complementary policy.

[23] The automotive market is very competitive even if it is not perfectly competitive. Even assuming oligopolistic supply and Bertrand competition, the shadow price of a binding fuel economy or greenhouse gas emission constraint will induce the adoption of fuel economy improving technologies across all vehicles, except for vehicles that have already adopted all technologies justified by the shadow price.

[24] Surveys indicate that US consumers consistently and overwhelmingly approved of fuel economy standards. Typically, 70 to 80% of respondents favored fuel economy standards and raising the standards (5, Table 9.2; 4).

[25] Feebates that tax-inefficient vehicles and subsidize efficient vehicles at a fixed rate per gallon per mile are an example of such taxes [79, 80].

Policies to achieve a sustainable global energy system should be evaluated based on consumers' actual behavior rather than the unrealistic behavior of economically rational agents. Insights from behavioral psychology and behavioral economics enable a more realistic representation of consumer behavior and help explain why well-formulated fuel economy standards can be cost-effective, durable because of their popularity with the public, and justify greater efficiency improvements than would be justified by reducing externalities alone.

Compliance with Ethical Standards

Conflict of Interest David L. Greene declares that he has no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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