# How Much Do Consumers Value Fuel Economy and Performance? Evidence from Technology Adoption

Benjamin Leard* University of Tennessee

Joshua Linn University of Maryland and Resources for the Future

Yichen Christy Zhou Clemson University

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## Abstract

During historical periods in which US fuel economy standards were unchanging, automakers increased performance but not fuel economy, contrasting with recent periods of tightening standards and rising fuel economy. This paper evaluates the welfare consequences of automakers forgoing performance increases to raise fuel economy as standards have tightened since 2012. Using a unique data set and a novel approach to account for fuel economy and performance endogeneity, we find undervaluation of fuel cost savings and high valuation of performance. Welfare costs of forgone performance approximately equal expected fuel savings benefits, suggesting approximately zero net private consumer benefit from tightened standards.

Key words: passenger vehicles, fuel economy standards, technology adoption, consumer welfare

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*Benjamin Leard (leard@rff.org) is an assistant professor at the university of Tennessee. Joshua Linn (linn@rff.org) is an associate professor at the University of Maryland and a senior fellow at Resources for the Future. Christy Zhou (yichen2@clemson.edu) is an assistant professor at Clemson University. We thank Jim Sallee, Ashley Vissing, Hendrik Wolff, and seminar participants at the University of Maryland, Carnegie Mellon University, American University, Resources for the Future, EPA NCEE, and participants at the IIOC (Boston), AERE (Pittsburgh), Transportation, Economics, Energy, and the Environment (TE3) Conference at Michigan, APPAM (Chicago), SRA (Washington), TRB (Washington), and AEA/ASSA (Philadelphia) for valuable comments. We thank Kevin Roth for sharing vehicle scrappage data. We are grateful to the Sloan Foundation for supporting the research.

# 1 Introduction

Motivated by climate and energy security concerns, the US Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) impose standards for passenger vehicle greenhouse gas emissions and fuel economy. The agencies project that the current standards will roughly double new vehicle fuel economy between 2011 and 2025, substantially reducing fuel consumption and greenhouse gas emissions.

In their benefit-cost analysis, EPA and NHTSA conclude that the standards create climate and energy security benefits (EPA 2012; EPA et al. 2016). In addition to these social benefits, the agencies argue that the standards create private welfare benefits because there is a market failure for fuel economy, which is often referred to as the *energy efficiency gap*: vehicle manufacturers and consumers fail to adopt technologies and increase fuel economy even when the value of the fuel savings exceeds the adoption costs. An extensive literature (e.g., NRC 2015) concludes that a gap exists by identifying numerous specific fuel-saving technologies, the value of whose fuel savings exceeds the adoption costs. The agencies argue that the standards increase consumer welfare by stimulating the adoption of fuel-saving technologies and correcting distortions from the market failure. In fact, the value of the fuel savings to consumers accounts for about 70 percent of the estimated benefits of the standards.[1]

The energy efficiency gap literature has focused on situations where *ex ante* utility from a product, which is utility at the time of purchase, is less than realized utility from the product, which is utility over the lifetime of the product. In the context of passenger vehicles, the literature has focused on whether new vehicle consumers undervalue fuel savings, meaning that when they purchase the vehicle they are willing to pay less for fuel savings than the present discounted value of realized savings over the vehicle's lifetime (or equivalently, *ex ante*

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[1] Fuel or carbon taxes are more efficient than fuel economy or emissions standards at reducing energy security or climate market failures (e.g., Jacobsen 2013). However, fuel or carbon taxes do not directly address the market failure associated with the energy efficiency gap (Jaffe and Stavins 1994). If the gap is large enough, standards could be more efficient than fuel and carbon taxes (Fischer 2010; Parry et al. 2007).

utility is less than realized utility). Undervaluation would be consistent with the energy efficiency gap, which implies that manufacturers have insufficient incentive to adopt fuel-saving technology. Earlier studies yielded a wide range of results, from approximately zero valuation to substantial overvaluation (see literature reviews by Helfand and Wolverton 2009 and Greene 2010), but recent studies by Busse et al. (2013) and Allcott and Wozny (2014) have found full or nearly full valuation, implying that there is not an energy efficiency gap and that standards are unlikely to increase private consumer welfare.

When analyzing efficiency standards for passenger vehicles as well as other energy-consuming durable goods such as light bulbs and appliances, economists and policy makers have focused on the energy efficiency gap under the presumption that if there is a gap, tighter efficiency standards would raise private consumer welfare. We argue that this inference is incorrect because it ignores the effects of tighter standards on other vehicle characteristics such as horsepower, which arises from the technological trade-off between fuel economy and other vehicle characteristics.[2] Klier and Linn (2016) and Reynaert (2015) conclude that tighter standards cause manufacturers to trade off performance for fuel economy, causing performance to increase less than if standards had not tightened.

Because tightening passenger vehicle fuel economy standards affect fuel economy and performance, the welfare effects of tighter standards depend on consumer willingness to pay (WTP) for the fuel economy and performance changes caused by tighter standards.[3] Although the literature has estimated the effects of fuel economy standards on performance, the WTP for the performance change is not well understood in the current literature; in particular, for reasons we explain below, previous estimates of WTP for performance are likely to suffer from omitted variables bias. And although recent articles such as Busse et al.

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[2] A similar consideration would pertain for other goods, such as the trade-off between thermal insulation and storage space for refrigerators, or the trade-off between efficiency and color for light bulbs.

[3] Standards may affect weight or footprint (Whitefoot and Skerlos 2012; Klier and Linn 2016). We focus on performance because there is a technological relationship between fuel economy and performance. Estimating willingness to pay for weight would require a different identification strategy from the one we employ.

(2013) and Allcott and Wozny (2014) address the omitted variables problem when estimating WTP for fuel cost savings, they do not estimate WTP for performance.

Moreover, the welfare effects of recently tightened standards depend partly on consumer responses to the resulting fuel economy improvements. Busse et al. (2013) and Allcott and Wozny (2014) estimate WTP for fuel economy using gasoline price variation from the late 1990s and early 2000s to identify WTP, when standards and fuel economy were not changing. However, emissions or fuel economy standards cause fuel economy to increase over time without directly affecting fuel prices (Whitefoot et al. 2013; Reynaert 2015).[4] If consumers have rational expectations, full information about future gasoline prices and fuel economy, and expect changes in fuel economy and gasoline prices to be equally persistent, consumers would respond by the same amount to changes in fuel prices and fuel economy. In that case, researchers would estimate the same WTP for fuel cost savings whether they use variation in gasoline prices or fuel economy. However, if these assumptions do not hold, estimated WTP would differ across the two sources of variation. For example, if gasoline price changes are more salient than fuel economy changes (Gillingham 2012 and Li et al. 2014), WTP from fuel economy changes would be smaller than WTP from gasoline price changes. Uncertainty about fuel prices and fuel economy could also cause the two estimates to differ from one another (Metcalf and Hassett 1993; Dixit and Pindyck 1994). Because fuel economy standards affect fuel economy and not fuel prices, WTP for fuel economy changes is appropriate for evaluating policy changes.

We address the limitations of the previous literature by implementing a new strategy to estimate consumer WTP for changes in performance and fuel economy. We find that consumers undervalue fuel economy improvements in the 2010s, meaning that their *ex ante* utility is less than their realized utility. This result contrasts with studies using gasoline price variation in 1990s and 2000s. Notwithstanding the undervaluation, once we account

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[4] In the short run, vehicle manufacturers can respond to fuel price changes and economic conditions by altering vehicle price. In the medium run, manufacturers can adjust vehicle attributes such as fuel economy and performance. In the long run, manufacturers can introduce or discontinue vehicles.

for changes in performance, we find that recently tightened standards have had approximately zero net effect on private consumer welfare. These results highlight the importance of obtaining consistent WTP estimates as well as accounting for the effects of standards on product attributes other than energy consumption.

Next, we describe the paper in more detail. Knittel (2011) and Klier and Linn (2012) argue that manufacturers can respond to tighter standards by trading off performance for fuel economy. Manufacturers can use fuel-saving technology to increase fuel economy or performance (such as towing capacity), for example, by retuning the engine so that the new vehicle has the same fuel economy and greater performance than the original vehicle (Klier and Linn 2012; Whitefoot et al. 2013; Zhou 2016).[5] As we show in Section 2, during periods when fuel economy standards were not changing, manufacturers used fuel-saving technology to increase performance while maintaining fuel economy, improving vehicle efficiency by about 2 percent per year (Knittel 2011). During periods when the standards tightened, manufacturers chose to trade off performance for fuel economy.

Tighter standards have two effects on vehicle attributes. First, tighter standards increase the incentive to adopt fuel-saving technology, raising the rate at which manufacturers add technology (Klier and Linn 2016). This effect raises vehicle fuel economy and production costs, which may increase vehicle prices. Second, tighter standards cause manufacturers to trade off performance for fuel economy holding fixed the set of fuel-saving technologies installed on the vehicle. Manufacturers may also reduce the relative prices of vehicles with high fuel economy to increase their market shares. With the exceptions of Klier and Linn (2012) and Whitefoot et al. (2013), previous welfare analysis of vehicle standards treat performance as exogenous (e.g., Jacobsen (2013)), and thus do not directly capture technological trade-offs between fuel economy and performance.

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[5] For example, between 1980 and 2014, Honda adopted many fuel-saving technologies to double the Civic's horsepower without changing its fuel economy. Certain technologies, such as turbochargers, improve performance and reduce fuel economy, whereas other technologies increase fuel economy without affecting performance. When adopting fuel-saving technologies, manufacturers can combine these technologies and retune the engine to achieve the desired combination of fuel economy and performance increases.

Given these manufacturer responses, in Section 3.1 we explain that contrary to the literature, undervaluation does not necessarily imply that marginally tightening standards raises private consumer welfare. We consider a manufacturer who maximizes profits by choosing fuel economy and performance subject to a technological tradeoff between the two attributes. In an unregulated equilibrium, undervaluation causes the manufacturer to choose a level of fuel economy that is less than the optimum from the perspective of the consumer's realized utility. Given this internality, a regulator can mandate a minimum level of fuel economy above the equilibrium. The regulation has two opposing effects on consumer utility: it raises consumer utility by causing fuel economy to exceed the unregulated equilibrium fuel economy, but reduces consumer utility by lowering performance. If the regulator has perfect information about consumer preferences for fuel economy and performance, the regulator can choose the fuel economy requirement that maximizes utility accounting for fuel economy and performance changes. However, if the regulator has imperfect information about consumer preferences, the regulator may choose a level of fuel economy that is too high from the perspective of the consumer's realized utility. This situation is more likely to occur the lower is the undervaluation and the higher is the preference for performance.

Thus, the central questions regarding the private welfare effects of standards are whether consumers undervalue fuel economy and the relative WTP for performance and fuel economy. Most studies either have not estimated WTP for performance or have assumed that performance is uncorrelated with unobserved attributes.[6] Because vehicle manufacturers simultaneously choose fuel economy, performance, and other attributes, fuel economy and performance are likely to be correlated with unobserved attributes (Klier and Linn 2012). Most earlier studies (e.g., Berry et al. 1995) that estimate WTP for performance assume that performance is exogenous, but a few recent papers, such as Whitefoot et al. (2013), instrument for performance. These recent studies primarily rely on

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[6] Recent papers that focus on consumer valuation of fuel economy, including Busse et al. (2013), Allcott and Wozny (2014), and Sallee et al. (2016), do not attempt to estimate WTP for performance.

variation from the vehicle's fuel type or drive type (e.g., 4-wheel-drive). However, because consumers directly value fuel type and drive type, and not just their effects on fuel economy and performance, the instruments are likely to be correlated with unobserved vehicle attributes. For example, automakers may provide better (unobserved) technology packages for 4-wheel-drive vehicles than for 2-wheel-drive vehicles, causing inconsistent estimates.

We use a unique data set and a novel empirical strategy to account for the endogeneity of both fuel economy and performance. Our data include 535,124 observations of new vehicles purchased or leased between the fourth quarter of 2009 and the third quarter of 2014. For each vehicle, we observe a transaction price, household demographics, and a vehicle identification number (VIN), which we use to assign extensive vehicle characteristics such as fuel economy, horsepower, torque, and weight. To compare our results with the recent literature, we build upon the framework of Busse et al. (2013) and estimate average WTP for fuel economy and performance across all consumers in the market. The WTP is computed from the estimated equilibrium effects of fuel economy and performance on vehicle prices and sales. We adopt two strategies to account for the endogeneity of fuel economy and performance. First, we include vehicle model-variant fixed effects, defining a model-variant at a highly disaggregated level. The fixed effects control for cross-sectional correlations among fuel economy, performance, and unobserved vehicle attributes such as technology packages and safety features. Second, we use instrumental variables (IVs) constructed from EPA microdata on fuel-saving technology adoption. The instruments are indicators for the adoption of specific technologies in individual model-variants, and they are strong predictors of fuel economy and performance. The WTP is identified by within-vehicle variation over time in fuel economy and performance predicted by technology adoption. We report evidence supporting the underlying exclusion restrictions, by showing that the instrumented fuel economy and performance are uncorrelated with observed demographics and proxies for (unobserved) vehicle quality.[7]

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[7] Klier and Linn (2016) report rough welfare estimates of the forgone performance, but the underlying WTP estimates are subject to the shortcomings noted in the text. This paper improves on our previous

We find that consumers undervalue fuel savings arising from higher fuel economy. The preferred estimates imply that consumers use a real discount rate of 12 percent to discount future fuel cost savings, compared to reported real market interest rates of 1.3 percent in our sample. The fact that the implicit discount rate exceeds the market rates suggests that consumers undervalue the fuel savings. An equivalent interpretation is that if we use market rates to discount future fuel cost savings, consumers pay 54 cents for $1 of discounted future fuel cost savings. In contrast, Busse et al. (2013) find full valuation and Allcott and Wozny (2014) estimate that consumers pay 76 cents for $1 of discounted fuel savings. We obtain similar undervaluation as in our baseline using our data and the methodology in Busse et al. (2013), suggesting that differences in sample period, rather than methodology, explain the discrepancies. The similarity also provides indirect support for the IV strategy, because the methodology in Busse et al. (2013) does not rest on the validity of the technology instruments. The lower WTP for the most recent period is consistent with Leard, Linn, and McConnell (forthcoming), who show that new vehicle purchases responded differently in the late 1990s and early 2000s (when fuel prices were low or rising) than in the late 2000s and early 2010s (when fuel prices were high and volatile, and when fuel economy was increasing).

Consumers are willing to pay $94 for a 1 percent performance increase arising from fuel-saving technology adoption. This corresponds to a WTP of $1,100 for a 1-second reduction in the time needed to accelerate from rest to 60 miles per hour (0-to-60 time), which lies in the middle of the range of estimates in the literature (e.g., Whitefoot and Skerlos 2012; Greene et al. 2016). Comparing the ordinary least squares (OLS) and IV estimates, we conclude that failing to account for the endogeneity of fuel economy and performance would understate consumer valuation of fuel economy and performance.

The WTP estimates have three implications. First, combining our WTP estimates with estimates of the technological trade-offs between fuel economy and performance (Knittel

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attempts to address endogeneity of fuel economy and performance (Klier and Linn 2012; Zhou 2016), by using actual transaction prices rather than manufacturer suggested retail prices, and by relaxing assumptions on consumer demand and the exogeneity of power train attributes. Copeland (2014) demonstrates the importance of using transaction prices rather than retail prices.

2011; Klier and Linn 2016) suggests that consumers are willing to pay about three times as much for a performance increase as for a comparable fuel economy increase. This result is consistent with the observation that during the 1990s and early 2000s, when vehicle standards were not tightening, manufacturers adopted the fuel-saving technologies to increase performance rather than fuel economy. This result raises the possibility that even though consumers undervalue fuel savings, they may not benefit from tighter standards.

Second, after accounting for the welfare costs of lower performance, recently tightened standards have had approximately zero net effect on private consumer welfare. We consider a hypothetical tightening of the standards by 1 percent during our sample period. Using technology cost estimates from Leard et al. (2016) (which are based on EPA 2012), and estimated trade-offs between fuel economy and performance, we find that tighter standards reduce consumer welfare by 0.4 percent of the the average price per vehicle sold. This implication contrasts with the conclusion that one would obtain by considering only the estimated undervaluation and ignores performance changes. In that case, one would estimate that tighter standards raise consumer welfare by 0.6 percent of the average price per vehicle. These results imply that failing to account for the forgone performance in a benefit-cost analysis would understate the agencies' estimated costs by about $4.6 billion per year.

The third implication regards the effect of fuel economy or greenhouse gas standards on consumer demand for new vehicles. A particularly contentious aspect of the existing standards is whether they reduce aggregate consumer demand for new vehicles, which the marketing literature refers to as consumer acceptance of new vehicles. This possibility is a manifestation of vintage differentiated regulation (Gruenspecht 1982; Stavins 2005)—that is, the fact that the regulations apply to new vehicles but not existing vehicles. This form of regulation raises the cost of purchasing a new vehicle compared with the cost of purchasing a second-hand vehicle, reducing aggregate new vehicle demand. Lower demand reduces manufacturer profits, and by delaying the replacement of older with newer vehicles, lower demand also reduces the overall fuel and greenhouse gas savings of the standards (Jacobsen and van Benthem 2015). We find that tightening standards by 1 percent reduces WTP for new vehicles by $236, or 0.8 percent of the average price per vehicle.[8]

The results illustrate the importance of estimating WTP for performance. Our results contrast with other recent estimates, in that we find strong evidence of undervaluation. Yet, once we include the welfare costs of lower performance, we find that tighter standards have had approximately no net effect on private consumer welfare, which contrasts with the conclusion that one would obtain by ignoring the welfare costs of lower performance.

# 2 Data and Summary Statistics

## 2.1 Data

We assembled the main data set from several sources, the most important of which includes household survey data collected by MaritzCX. Based on vehicle registration information, MaritzCX contacts households that recently obtained new vehicles. The survey is administered online or by mail, with a 9 percent response rate. Our data include households that obtained new vehicles between October 2009 and September 2014. The final sample includes 535,124 observations, which represents about 1 percent of all new vehicles obtained during the five-year period.

The survey includes questions about the new vehicle and household demographics. For each transaction, we use the transaction price net of state taxes and without adjusting for any trade-in credit. As in many other recent vehicle market analyses (e.g., Busse et al. 2013; Copeland 2014), we use the transaction price provided by the survey respondent, rather than the manufacturer suggested retail price (MSRP), to reflect the outcome of any price negotiation or unobserved incentives for the vehicle. The transaction price includes cash incentives that car dealers offer to consumers in response to supply or demand shocks such as fuel price variation (Langer and Miller 2013).[9] To the extent that transaction prices

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[8] This result is consistent with Dou and Linn (2018), who find tighter standards reduce new vehicle sales.

[9] We observe substantial differences between the MSRP and transaction price. Respondents typically complete the survey a month after obtaining a new vehicle. Given the short recall time and the high price associated with a new vehicle purchase relative to other durable purchases, there is little risk of recall bias and these data are likely to accurately represent actual transaction prices. In contrast, some recent studies

are measured with error, because we use price as a dependent variable, the measurement error affects only the variance of our estimates but not their consistency (Hausman 2001). Household demographic characteristics include state of residence, household size and income, and the respondent's age, years of schooling, gender, marital status, and other characteristics.

The MaritzCX data include a vehicle identification number (VIN) for each observation. We use the VIN to define a unique model-variant for each vehicle, which is the combination of a vehicle's manufacturer, make, model name, trim/series, fuel type, drive type, displacement, and number of cylinders. For example, a unique model-variant is the Toyota Lexus HS250H Premium, with front-wheel drive and a gasoline-powered engine that has four cylinders and 2.4-liter displacement. Our definition of a model-variant is similar to the definition of a unique vehicle used in recent studies (e.g., Allcott and Wozny 2014). Note that two versions of the same model-variant can have different body types, which we also observe in the data. The final sample contains 2,166 unique model-variants and about 250 observations per model-variant (Table 1). The VIN allows us to obtain an extensive set of vehicle attributes from Chrome Automotive such as vehicle weight, horsepower, and torque.

We use the ratio of horsepower to weight as a proxy for passenger car performance, and the ratio of torque to weight for light truck performance. This definition follows previous studies that estimate vehicle demand, such as Berry et al. (1995). Car consumers typically have stronger preference for acceleration, which is closely related to the ratio of horsepower to weight, whereas light-truck consumers often have stronger preference for towing ability than acceleration (Knittel 2011). We note that several aspects of vehicle performance may affect consumer purchasing decisions, such as the time needed to accelerate from rest to 60 miles per hour, or the time needed to accelerate from 20 to 50 miles per hour (which is more relevant in certain situations such as merging onto a highway). In practice, these performance measures are highly correlated with one another. For example, the ratio of

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have used transaction prices reported by marketing companies such as J.D. Power. Unfortunately, based on personal correspondence, J.D. Power data are not currently available for purchase by academic researchers.

horsepower to weight accurately predicts 0-60 time (Greene et al. 2016; Linn 2016). The results are similar if we use the ratio of horsepower to weight for all vehicles.

We obtain fuel economy ratings and fuel-saving technology data from EPA. The technology data include indicators for variable valve lift and timing, a turbocharger, a supercharger, gasoline direct injection, cylinder deactivation, continuously variable transmission, and other advanced transmissions. NRC (2015) concludes that each of these technologies raises fuel economy or performance as well as production costs, holding fixed all other attributes. For example, cylinder deactivation, which effectively shuts off a subset of engine cylinders when the vehicle operates under a light load, raises fuel economy by as much as 5 percent, and raises production costs by \$118 to \$133 per vehicle. Because EPA data do not recognize differences in fuel economy across body types within a model-variant, fuel economy and fuel-saving technologies vary across model-variants.[10]

To correct for the non-random sampling of the MaritzCX survey, we obtained from Information Handling Service Market (IHS) quarterly new vehicles registration by model year, model-variant, and body type for all vehicles in the U.S. The weighted sample matches the distribution of new vehicle buyers from other data sources. Lastly, from the Energy Information Administration (EIA), we collect monthly gasoline and diesel prices by Petroleum Administration for Defense District (PADD), for each of four districts (Midwest, Gulf Coast, Mountain, and West Coast), and three subdistricts on the East Coast.[11]

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[10] Our definition of the model-variant preserves 99 percent of the EPA estimated fuel economy variation across new vehicles. We do not include fuel-saving technologies that were widely adopted at the beginning of the sample, such as variable valve timing, or technologies that consumers value directly (either negatively or positively), such as stop-start ignition. The EPA data include more detail on transmissions than Chrome. We average the technology variables across transmission type (automatic or manual), and for most observations in the final data set the technology variables are either zero or one, implying that the aggregation sacrifices little variation. Below we refer to the technology variables as indicator variables for convenience.

[11] Flex-fuel vehicles can use fuel that has a high ethanol content, but in practice few owners of flex-fuel vehicles use gasoline with ethanol content greater than 10 percent (Anderson and Sallee 2011). When constructing the fuel cost variables described in the next section, we use gasoline prices for gasoline powered vehicles and flex-fuel vehicles, and diesel fuel prices for diesel fuel powered vehicles.

## 2.2 Summary statistics

This subsection discusses vehicle attributes and consumer demographics. Panel A of Table 1 shows the distributions of vehicle characteristics. There is substantial variation in fuel economy and performance, and average fuel economy is about 23.9 mpg.

Figures B.1 and B.2 illustrate time series variation in vehicle attributes. The fuel economy standards for light trucks tightened throughout the period, and the standards for cars began tightening in model-year 2012. Figure B.1 shows that fuel economy increases after 2011. Horsepower, torque, and weight fluctuate over the same period.[12] Table 2 further shows changes in vehicle fuel economy and horsepower since 1996.[13] Fuel economy standards began increasing in 2005 for light trucks and in 2012 for cars. Fuel economy increased quickly and horsepower increased slowly during periods when standards tightened. This evidence motivates our analysis of the effects of tightening standards on private consumer welfare, accounting for changes in fuel economy as well as performance.

Figure 1 shows the market shares of fuel-saving technologies that we use as IVs. In most cases the market shares increase over time, such as gasoline direct injection. Most decreases in this figure arise from year-to-year changes in vehicle market shares rather than instances of manufacturers removing technologies from particular vehicles. Klier and Linn (2016) and Klier et al. (2017) suggest that tightening fuel economy standards as well as market factors such as fuel prices explain the technology adoption.[14]

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[12] Tightening fuel economy standards and rising gasoline prices likely explain the decreases in horsepower, torque, and weight. Between 2011 and 2012, standards increased by about 2 miles per gallon, and gasoline prices increased by about $1 per gallon. Estimates in Leard, Linn, and McConnell (forthcoming) imply that the increase in gasoline prices reduced average horsepower and weight by about 2 percent.

[13] Data from Leard, Linn, and McConnell (forthcoming).

[14] Figure B.2 further reports variation in engine and transmission attributes. Engine size, as measured by the number of cylinders or displacement, decreases over the sample period. Market shares of the three drive types are fairly stable. The market share of diesel fuel vehicles increases between model years 2010 and 2014 (the Volkswagen emissions scandal occurred after the end of the sample). The market shares of hybrids and flex-fuel vehicles decrease at the end of the sample. The latter may reflect the elimination of the flex-fuel vehicle credits that manufacturers could use to demonstrate compliance with the fuel economy standards (Anderson and Sallee 2011).

Figures B.3 and B.4 illustrate monthly variation in fuel prices and vehicle prices.[15] Panel A of Figure B.3 shows that the sample includes periods of rising fuel prices (2009 through mid-2011) and volatile or declining fuel prices (mid-2011 through 2014).[16]

Turning to consumer attributes, Table 1 reports consumer demographics. Figure B.5 further shows that typical household income of vehicle buyers in our sample is higher than the typical US household income, which reflects the fact that higher-income households are more likely than lower-income households to obtain new vehicles.[17] Table B.1 reports information on the form of payment. About two-thirds of consumers finance their purchases, with an average nominal loan rate of 3.34 percent for about 5 years. About one quarter of consumers purchase their vehicles entirely via cash, and the remainder lease their vehicles.

# 3 Empirical Strategy

## 3.1 The link between fuel economy undervaluation and welfare

In this section, we provide a conceptual model to show that tightening fuel economy standards can reduce realized private welfare even if consumers undervalue fuel economy prior to purchasing the vehicle. A single-product manufacturer sells a vehicle and maximizes profits by choosing the vehicle's price, fuel economy, and performance. There is a trade-off between fuel economy and performance: $mpg = f(perf)$, where $mpg$ is the fuel economy and $perf$ is performance. The trade-off is analogous to moving along a long-run production possibilities frontier $f_1$ illustrated in Figure 2. As the manufacturer moves along the frontier, the cost of producing the vehicle does not change. An increase in the level of technology causes the frontier to shift away from the origin.

Consumers can choose among vehicles in the market. A consumer's utility from buying a vehicle depends on its price, fuel economy, performance, and an idiosyncratic taste shock. We distinguish *ex ante* consumer utility from realized utility. *Ex ante* utility (which is sometimes

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[15] Figures B.3 and B.4 indicate regular seasonal variation. Fuel prices tend to be higher in the summer than in other quarters. Vehicle prices tend to increase over the year before decreasing at the end of the year.

[16] Panel B shows that regional prices are positively correlated with one another, and that prices in the West Coast and Midwest tend to be higher than in other regions.

[17] The income distribution in our data is fairly close to the income distribution of new vehicle buyers as reported in the 2009 wave of the NHTS, which is a nationally representative survey.

referred to as decision utility) is the utility the consumer expects to receive from purchasing the vehicle. Figure 2 shows the *ex ante* indifference curve $u_A^e$ of a representative consumer. As shown in Klier and Linn (2012), the indifference curve is tangent to the frontier $f_1$ at the point $A$, which represents the manufacturer's equilibrium choices of fuel economy and performance. Realized utility (which is sometimes referred to as experience utility) differs from *ex ante* utility and is depicted by indifference curve $u_A^r$ in Figure 2. Realized utility may differ from *ex ante* utility because actual fuel costs differ from expected fuel costs or for other reasons. The curve $u_A^r$ passes through point $A$ but it is flatter than the *ex ante* indifference curve, consistent with undervaluing fuel cost savings (i.e., the consumer's realized preference for fuel economy is higher than their *ex ante* preference).

Suppose that a regulator recognizes that consumers undervalue fuel economy and introduces a minimum fuel economy requirement for the manufacturer, such that the fuel economy cannot be lower than this requirement. If the regulator chooses a requirement of $\overline{mpg}^*$, the manufacturer chooses performance and fuel economy at point B. Because realized utility is tangent to the frontier at this point, the fuel economy requirement maximizes the consumer's realized welfare. (We assume that the marginal utility of income equals one, so that a change in utility corresponds to a change in welfare.)

The regulator can choose the requirement that maximizes realized consumer welfare if it knows the consumer's realized indifference curve. However, the regulator may think that consumers have a stronger realized preference for fuel economy relative to performance than they actually do and choose a fuel economy requirement greater than $\overline{mpg}^*$. Consider a standard $\overline{mpg}^C$ that causes manufacturer to locate along the frontier at point $C$. Realized indifference curve passing through point $C$ lies below realized indifference curve through point $A$, indicating that the fuel economy requirement $\overline{mpg}^C$ reduces realized consumer welfare. In fact, any fuel economy requirement above the horizontal dashed line through $A'$ decreases realized consumer welfare compared to point $A$. Thus, Figure 2 illustrates tightening standards may not increase realized private consumer welfare even if consumers undervalue fuel economy. Appendix Section A.1 presents a formal version of this model.

The same conclusion applies if we expand the model to include the possibility that the manufacturer can adopt fuel-saving technology to shift the frontier away from the origin in the medium to the long run. We define the frontier as $mpg = f(perf, T)$, where $T$ is the level of technology. Suppose a standard $\overline{mpg}^D$ is already in place and the manufacturer produces at point $D$. If the regulator sets the same standards as in Figure 2, $\overline{mpg}^C$, the manufacturer can add fuel-saving technology that causes the frontier to shift from $f_1$ to $f_2$ as shown in Figure 3. The resulting equilibrium is at point $E$. The figure shows that realized utility at point $E$ is less than realized utility at point $D$, meaning that the tighter fuel economy requirement reduces realized consumer welfare. Because technology adoption may affect realized consumer welfare, we account for such technology adoption in the welfare calculations in Section 5.[18]

## 3.2 Empirical framework

To estimate consumer valuation for fuel economy and performance, we build upon the approach taken by Busse et al. (2013) and estimate separate reduced-form price and quantity regressions. In this subsection, we derive the price and quantity regression equations from an equilibrium model of the new vehicle market.

We return to the case considered in the previous subsection, in which a manufacturer chooses the price, fuel economy, and performance of vehicle $j$ at time $t$. The WTP of consumer $i$ for vehicle $j$ depends on the vehicle's fuel costs $fc_{ijt}$, performance $perf_{jt}$, and demographics $Z_{ijt}$. Fuel costs vary across consumers because consumers in different regions may face different fuel prices, whereas performance is common across consumers. One can construct the demand curve by ranking consumers in order of decreasing WTP for the vehicle.

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[18] In two additional scenarios, a tighter standard can reduce consumer welfare. First, manufacturers may mis-optimize and fail to choose the profit-maximizing levels of fuel economy and performance. Second, there may be a kinked technology frontier caused by constraints on technology adoption that pertain in the medium run (i.e., in-between major vehicle and engine redesigns that occur every 5-10 years). Contact authors for additional theories and figures.

In equilibrium, the price of vehicle $j$ at time $t$ equals the WTP of marginal consumer $i$ who is indifferent between obtaining and not obtaining the vehicle. Equilibrium sales of the vehicle are determined by the intersection of the marginal revenue from selling the vehicle and the marginal cost of producing the vehicle. Consequently, equilibrium sales depend on fuel costs and performance. The price-WTP equilibrium relationship is expressed as

$$p_{ijt} = WTP_{ijt}\left(fc_{ijt},\, perf_{jt},\; q_{jt}\left(fc_{ijt},\, perf_{jt}\right) \mid Z_{ijt}\right) \tag{1}$$

Willingness to pay $WTP_{ijt}(\cdot)$ is specific to consumer $i$ month-year $t$ and model-variant $j$. Partially differentiating equation (1) with respect to fuel costs and performance yields

$$\frac{\partial WTP_{ijt}}{\partial fc_{ijt}} = \frac{\partial p_{ijt}}{\partial fc_{ijt}} - \frac{\partial WTP_{ijt}}{\partial q_{jt}} \frac{\partial q_{jt}}{\partial fc_{ijt}}$$

$$\frac{\partial WTP_{ijt}}{\partial perf_{jt}} = \frac{\partial p_{ijt}}{\partial perf_{jt}} - \frac{\partial WTP_{ijt}}{\partial q_{jt}} \frac{\partial q_{jt}}{\partial perf_{jt}}$$

Figure 4 provides the intuition for the two terms in both expressions. For convenience, we conceive of a Bertrand model with differentiated products. Given the initial demand curve $D_1$ and marginal cost curve $MC_1$, the manufacturer chooses the price such that at the resulting quantity, $Q_1$, the marginal revenue curve (the downward sloping dashed line) intersects $MC_1$. The figure illustrates a hypothetical situation in which the manufacturer adopts fuel-saving technology and increases the vehicle's fuel economy. The higher fuel economy reduces fuel costs, causing the demand curve to shift to $D_2$. The technology adoption increases marginal costs to $MC_2$, which results in the equilibrium price $P_2$ and quantity $Q_2$. The first term in both expressions is the change in equilibrium price, corresponding to $l_1$ in the diagram. The second term is the effect of moving along the new demand curve, i.e. $l_2$ in the diagram. The change in WTP equals the sum $l_1 + l_2$.

We assume a log-log functional form for the relationships among *equilibrium* sales, fuel costs, and performance. We show in Appendix Section A.2 that this assumption does not amount to assuming a log-log relationship between consumer demand, fuel costs, and performance. In fact, the equilibrium relation can be approximated as log-log even when the demand is a linear or nonlinear function of fuel costs and performance. Specifically,

$$\frac{\partial \ln p_{ijt}}{\partial \ln fc_{ijt}} = \alpha_f, \quad \frac{\partial \ln p_{ijt}}{\partial \ln perf_{jt}} = \alpha_p, \quad \frac{\partial \ln q_{jt}}{\partial \ln fc_{ijt}} = \beta_f, \quad \frac{\partial \ln q_{jt}}{\partial \ln perf_{jt}} = \beta_p$$

Finally, we assume a constant price elasticity of demand $\mu$ for all model-variants which implies that $\frac{\partial WTP}{\partial q_{jt}} \frac{q_{jt}}{p_{ijt}} = \frac{1}{\mu}$. We express the marginal WTP for fuel costs and performance in terms of observed variables, as well as parameters that we can estimate:

$$\frac{\partial WTP_{ijt}}{\partial fc_{jt}} = \alpha_f \cdot \frac{p_{ijt}}{fc_{ijt}} - \frac{\beta_f}{\mu} \cdot \frac{p_{ijt}}{q_{jt}} \frac{q_{jt}}{fc_{ijt}} \tag{2}$$

$$\frac{\partial WTP_{ijt}}{\partial perf_{jt}} = \alpha_p \cdot \frac{p_{ijt}}{perf_{jt}} - \frac{\beta_p}{\mu} \cdot \frac{p_{ijt}}{q_{jt}} \frac{q_{jt}}{perf_{jt}} \tag{3}$$

Parameters $\{\alpha_f,\ \alpha_p,\ \beta_f,\ \beta_p\}$ are to be estimated. For $\mu$, we use a range of elasticities estimated from the vehicle demand literature. The empirical objectives are to estimate elasticities of equilibrium prices to fuel costs and performance $\{\alpha_f,\ \alpha_p\}$, and elasticities of equilibrium quantities to fuel costs and performance $\{\beta_f,\ \beta_p\}$. We then use equations (2)–(3) to compute the marginal WTP for fuel costs and performance. This procedure is different from the conventional estimation of hedonic price functions because it accounts for both price and sales elasticities with respect to vehicle attributes to identify WTP. In contrast, hedonic price functions are identified from the equilibrium relationship between price and non-price attributes. As Busse et al. (2013) note, an alternative approach would be to estimate the demand curve directly, which would require assumptions on the structure of the demand at the outset. In contrast, the reduced-form approach requires only an assumption on the demand elasticity, which is made after the estimation. An advantage of our approach is that it facilitates accounting for the endogeneity of fuel economy and performance. Later we show that the main conclusions are insensitive to the assumed demand elasticity.

## 3.3 Price regression

This subsection describes the estimation of the equilibrium relationship between a vehicle's transaction price, $p_{ijt}$, and its attributes, where the subscript indicates that household $i$ obtained new passenger vehicle $j$ in month $t$. As we showed in the previous subsection, equilibrium price is a function of fuel costs, performance, and other vehicle attributes (but not production costs):

$$\ln p_{ijt} = \alpha_f \ln fc_{ijt} + \alpha_p \ln perf_{jt} + X_{ijt}\delta + \varepsilon_{ijt} \tag{4}$$

where $fc_{ijt}$ is fuel costs; $perf_{jt}$ is performance; $X_{ijt}$ is a vector of variables described next. The performance variable is the horsepower-to-weight ratio for cars and the torque-to-weight ratio for light trucks. The vector $X_{ijt}$ includes month fixed effects interacted with PADD region and fuel type to account for aggregate and regional supply and demand shocks, seasonality in fuel or vehicle prices, as well as time-varying shocks to demand for used vehicles; state fixed effects; an indicator if the vehicle has flex-fuel capability; fixed effects of the number of transmission speeds, as well as the interactions of these variables with an indicator for a light truck; and controls for fuel economy regulatory stringency.[19] At the end of the subsection, we explain the motivation for controlling for transmission speeds and flex-fuel capability.

The controls for fuel economy regulatory stringency incorporate two sources of variation. First, under the current standards, a vehicle's fuel economy requirement depends on its size; manufacturers selling smaller vehicles must attain a higher overall level of fuel economy. Second, at the outset of the sample period, manufacturers varied in the difference between the level of fuel economy required by the standards and the level of fuel economy their vehicles actually attained (Jacobsen 2013). Stringency is measured as in Klier and Linn (2016), by computing the difference between the fleet level fuel economy a manufacturer must attain to meet the standards in model-year 2016 and the manufacturer's average fuel economy at the beginning of the sample. The stringency variable is interacted with model-year fixed effects to allow for the possibility that regulatory pressure varies over time.

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[19] Because the equation includes region-month fixed effects, the fuel cost and performance coefficients are identified by variation relative to the means in the corresponding region and month. The fixed effects control for the mean fuel costs and performance across vehicles in the market, as well as the mean fuel costs and performance across the entire on-road vehicle fleet. For this reason, we interpret the coefficients and the resulting WTP estimates in relative terms. For example, the WTP for performance is the WTP for increasing performance marginally above the mean performance, rather than the WTP for the absolute level of performance. One should be careful about extrapolating the WTP estimates to contexts in which the mean fuel costs and performance differ substantially from the levels observed in the sample.

We separate fuel costs and performance from the other attributes because estimating separate consumer valuation of fuel costs and performance is the main focus of the paper. The fuel cost variable is equal to the price of fuel in the month and the PADD region in which the vehicle is obtained, divided by the vehicle's fuel economy. Under the assumption that the current fuel price equals the expected real fuel price, which is consistent with Anderson et al. (2013), the ratio of the fuel price to fuel economy is proportional to the present discounted value of fuel costs over the lifetime of the vehicle (Busse et al. 2013). The interactions of month fixed effects with PADD region and fuel type absorb the direct effect of fuel prices on fuel costs, because of which the coefficient $\alpha_f$ is identified by fuel economy variation.

Because the price, fuel costs, and performance variables enter equation (4) in logs, the coefficients represent elasticities. We expect the fuel cost coefficient to be negative because higher fuel costs raise the total cost of the vehicle over its lifetime, and we expect the performance coefficient to be positive. We interpret these estimates as the effect of fuel economy or performance on the average transaction price across all vehicles in the market.[20] As the previous subsection shows, the interpretation of the coefficients does not depend on the underlying demand or competitive structure of the market.

Note that we do not interpret the fuel cost and performance coefficients as being proportional to parameters in a consumer's utility function. The log-log functional form is not derived from an underlying utility function. Rather, we use the log-log functional form to approximate equilibrium relationships among vehicle prices and attributes; see equation (1). Likewise, Busse et al. (2013) use a functional form that approximates an equilibrium relationship rather than deriving the functional form from a utility function.

Although equation (4) yields a straightforward economic interpretation of the coefficients, the main identification concern is that the vehicle characteristics may be correlated with omitted vehicle or household characteristics. For example, vehicles with high performance may include more comfortable seating or better entertainment devices

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[20] We have estimated versions of equation (4) that allow the fuel cost and performance coefficients to vary across vehicles, such as by car or light truck. In many cases the differences are imprecisely estimated.

than vehicles with lower performance. Although our data include an extensive set of characteristics, and more than the vehicle demand literature has typically used, we do not observe all vehicle characteristics that consumers value. For example, we observe seating material (cloth versus leather), but overall seating comfort depends on other factors, such as lower back support, which our data do not include. OLS estimates of equation (4) would be biased and inconsistent if we fail to include all vehicle attributes that consumers value.

For expositional purposes we use the term *quality* to refer to the combined effect of all unobserved vehicle characteristics on the equilibrium price. The term includes seating comfort, entertainment devices, and anything else about the vehicle that consumers value but that is not included in equation (4). Quality also depends on consumer perceptions of the unobserved attributes. Obtaining consistent estimates of WTP for fuel costs or performance therefore amounts to controlling for quality.

One approach to control for time-invariant quality is to include model-variant fixed effects.[21] But within-model-variant changes in fuel economy or performance may still be correlated with changes in quality. For example, when a manufacturer redesigns a model-variant and alters its fuel economy or performance, it may change other vehicle quality attributes at the same time; the fixed effects do not control for such changes. Moreover, the fixed effects do not control for changes in consumer perceptions over time.

To address potential omitted variables bias, we add vehicle model-variant fixed effects to equation (4), instrument for fuel costs and performance, and estimate:

$$\ln p_{ijt} = \alpha_f \ln fc_{ijt} + \alpha_p \ln perf_{jt} + X_{ijt}\delta + \eta_j + \varepsilon_{ijt} \tag{5}$$

where $\eta_j$ denotes a fixed effect for vehicle model-variant $j$. There is no fuel economy variation within a model-variant and model year. The fixed effects absorb the vehicle's fuel type and

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[21] Instead, we could include interactions of model-variant fixed effects and model year, and identify the fuel cost coefficient by cross-sectional and time series variation in fuel prices. The benefit is that the fuel cost coefficient is identified from perceptible differences in fuel costs among different vehicle types. However, it is not possible to identify the performance coefficient because the model-variant by model year interactions would be perfectly colinear with performance. Moreover, the fuel cost coefficient would be identified by fuel price variation rather than fuel economy variation. As we argued in the introduction, the consumer response to fuel economy is directly relevant to standards that affect fuel economy and not fuel prices, and consumers may respond differently to the two sources of variation in fuel costs.

whether the power train is a hybrid, but they do not absorb the number of transmission speeds or whether the vehicle is flex-fuel capable. Consequently, we include those attributes in $X_{ijt}$. The instruments are seven indicators for the fuel-saving technologies shown in Figure 1: variable valve lift and timing, turbocharger, supercharger, gasoline direct injection, cylinder deactivation, continuously variable transmission, and other advanced transmissions. EPA (2014) and NRC (2015) identify these technologies as improving the efficiency of the engine or transmission. We further interact these instruments with an indicator for a light truck to allow the technologies to have different effects across cars and light trucks (NRC 2015). Because of the model-variant fixed effects, the first stage is identified by variation within a model-variant in fuel economy, performance, and technologies. The fact that fuel costs and performance enter equation (5) in logs is consistent with engineering assessments of the technologies that indicate that they affect fuel economy proportionately. The fuel cost and performance coefficients are identified by variation in those attributes induced by the adoption of the fuel-saving technologies; note that the estimates do not include the effects of substituting lighter for heavier construction materials.

The IV strategy is valid if the instruments predict fuel economy and performance and are uncorrelated with the error term. Failing to satisfy the first condition would raise concerns about weak instruments bias. The results reported in the next section indicate a strong correlation among the instruments, fuel economy, and performance, minimizing such concerns. Moreover, the results in the next section indicate that the values of fuel costs and performance predicted in the first stage are sufficiently uncorrelated with one another that we can identify the coefficients on fuel costs and performance in the second stage.

The second condition is supported both by theoretical arguments presented in this section and by empirical evidence that we present in the next section. First, we choose technology variables that consumers do not value per se as opposed to the fuel economy or performance increase that they enable. If consumers valued the technologies, IVs would be correlated with the error term. For this reason, we exclude technologies for which there are widespread reports of consumer dissatisfaction.[22] This feature of the IVs represents an improvement over other studies, such as Whitefoot et al. (2013), which have used power train characteristics as instruments because consumers likely value those characteristics directly, yielding inconsistent WTP estimates.

Also, the tightening fuel economy and emissions standards combined with staggered redesigns, reduces the likelihood that the technology variables are correlated with quality.[23] During the period of analysis, fuel economy standards tightened by about 4 to 5 percent per year after a long period in which they were unchanged. As Klier and Linn (2016) show, the tighter standards doubled the rate at which technologies were adopted, causing adoption to be more widespread across vehicles in the market than previously observed. Vehicles are typically redesigned in 4- to 6-year cycles, and manufacturers stagger the redesigns across vehicles and do not adopt technologies simultaneously on all of their vehicles. When standards tightened, given time and resource constraints for redesigning vehicles, a manufacturer is less likely to change vehicle quality in response to a demand shock than during prior periods in which standards were not tightening. Therefore, the source of technology variation is distinct from typical decisions about whether to install technology, when manufacturers may be more likely to redesign the vehicle to adopt technology as well as improve quality. Moreover, controlling for the standards addresses the possibility that the standards affect quality. These considerations also reduce concerns that household demographics, which equation (5) does not include, may be correlated with

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[22] The Atkinson cycle gasoline-powered engine that Mitsubishi installed in some of its vehicles received negative consumer reviews because it harmed performance. There have been a few negative reports related to consumer perceptions of continuously variable transmission and cylinder deactivation. We prefer to include them because these technologies have been widely adopted (see Figure 1), and because the negative reports are scarce. In the robustness analysis we show that our estimates are similar if we omit these variables as IVs or drop observations that include these technologies. We address similar issues related to turbochargers.

[23] Because of the region by month interactions, fuel prices do not help identify the first stage coefficients. The second-stage coefficients are identical if we replace fuel costs with fuel economy in the first and second stages. Appendix Table B.2 shows the key variables have variation within and across generations.

quality.[24] The fact that the standards drove fuel-saving technology adoption during the sample period reduces the likelihood that omitted demographics are correlated with quality.

Third, manufacturers sometimes adopt fuel-saving technology in luxury vehicles before adopting it in other vehicles (such as a Lexus sedan prior to a Toyota sedan). This behavior would cause technology adoption to be correlated with unobserved quality at a specific time. The model-variant fixed effects address time-invariant correlations between quality and technology adoption to control for situations in which a vehicle has a fuel-saving technology throughout the sample, whereas another vehicle does not have the technology.

The main remaining concern is that manufacturers simultaneously change quality and adopt technology. We have argued that this is less likely to be the case during our sample than during historical periods of technology adoption. Appendix Section C shows that the results are robust to adding several proxies for quality to equation (5). Finally, and perhaps most importantly, although quality is most likely to vary across redesigns than within redesigns, our results are robust to controlling for redesigns, in which case the coefficients are identified by technology, fuel cost, and performance variation within redesigns, which may be more likely to be uncorrelated with quality than variation across redesigns.

## 3.4 Quantity regression

The quantity regression is similar to the price regression. We use the log of quarterly registrations as the dependent variable and estimate the equation at the model-variant level:

$$\ln q_{jt} = \beta_f \ln fc_{ijt} + \beta_p \ln perf_{jt} + X_{ijt}\gamma + \xi_j + \nu_{ijt} \tag{6}$$

The independent variables are the same as in equation (5). We use model-variant fixed effects and the same instruments to account for the endogeneity of fuel economy and performance. Note that model-variant fixed effects $\xi_j$ are defined by trim, fuel type, drive type, and body type, to match the aggregation of the registration data.

Similar to equation (5), fuel cost coefficient is identified by variation in fuel economy rather than fuel prices. This strategy implies that the coefficients are identified by the

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[24] For example, high-income households may have higher WTP for seating comfort. In the robustness analysis, we show that the instruments are uncorrelated with demographics.

same underlying consumer preferences and manufacturer supply responses. Consequently, we interpret the coefficients in both equations as the average equilibrium effects across vehicles in the market. In contrast, if we were using different estimation samples or empirical strategies for the two equations, one might be concerned that the coefficients represent averages across different sets of vehicles, in which case it would not be appropriate to combine the results to infer WTP for fuel economy and performance.

An important difference between interpreting the price and quantity regressions is that for the quantity regressions the signs of the fuel cost and performance coefficients are ambiguous. On the one hand, an increase in fuel economy (or performance) causes the demand curve to shift away from the origin, increasing equilibrium quantity (see Figure 4). This effect would cause a negative fuel cost coefficient and a positive performance coefficient. On the other hand, adopting technologies would increase marginal costs, which reduces equilibrium quantity and pushes the coefficients in the opposite direction as the demand curve shift.

# 4 Estimation Results

## 4.1 Willingness to pay for fuel cost savings and performance

Table 3 reports the main coefficient estimates. In column 1 we show the OLS estimates of equation (4) and the corresponding quantity regression. Column 2 includes model-variant fixed effects as in equation (5) and (6), and in column 3 we report our preferred IV estimates. The price regression is weighted using the number of registrations for each model-variant. The quantity regression is not weighted. Table B.3 reports the first stage estimates.[25]

Because the transaction price, sales, fuel costs, and performance are in logs, we interpret the fuel cost and performance coefficients as elasticities. Panel A of Table 3 reports the estimates of the price regression. Comparing columns 1 and 2 shows that the model-variant fixed effects increase the magnitude of the fuel cost coefficient. The OLS estimate of the fuel cost coefficient is -0.156 in column 2, and the IV estimate is -0.354 in

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[25] Some of the first stage coefficients have unexpected signs, likely due to the high correlation among the IVs. Below we confirm the overall positive relation among technology adoption, fuel economy, and performance. Our instruments are jointly significant and they pass the weak identification test (see Appendix Table B.3).

column 3, both of which are negative and statistically significant at the one percent level. The larger magnitude of the IV estimate suggests that time-varying quality is positively correlated with fuel costs (and negatively correlated with fuel economy), which biases the OLS estimate toward zero. The OLS estimate of the performance coefficient in column 2 is negative. In contrast, the IV estimate of the performance coefficient is 0.203, which is positive and significant at the one percent level, suggesting that consumers are willing to pay for better performance. Comparing the OLS and IV estimates of the performance coefficient in columns 2 and 3 suggests that unobserved quality is negatively correlated with performance. Thus, failing to account for the endogeneity of fuel costs and performance yields inconsistent estimates.

Panel B of Table 3 reports the estimated coefficients from the quantity regression. In column 3 the IV coefficient on fuel costs is -0.338 and the coefficient on performance is 0.371, both of which are statistically significant at the one percent level.

The baseline estimates in column 3 suggest that a 1 percent fuel economy increase (which reduces fuel costs by 1 percent) raises the equilibrium transaction price and quantity by about 0.3 percent. A 1 percent performance increase raises the transaction price by 0.2 percent and raises the quantity by 0.4 percent. To convert these estimates to WTP, we first compute the marginal equilibrium price effect ($l_1$ in Figure 4) using the price regression coefficients. Then we adjust for the quantity change ($l_2$ in Figure 4) using the the quantity regression coefficients and the assumed own-price elasticity of demand of -3, which lies in the middle of the range considered in Busse et al. (2013).[26]

Panel C report that consumers are willing to pay about $133 for a 1 percent fuel economy increase and about $94 for a one percent performance increase. We report 95 percent confidence intervals using the delta method.[27] Appendix Table D.1 reports

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[26] Because the dependent variables are logs of price and quantity, to account for Jensen's inequality and predict the levels of prices and quantities we would need to account for fact that the error term is log-normally distributed. However, because we are interested in changes in prices and quantities caused by attribute changes, the correction term cancels in these calculations, yielding consistent WTP estimates.

[27] We compute the confidence intervals of WTP assuming zero covariance between the price regression coefficient and the quantity regression coefficient.

estimates of $l_1$ and $l_2$; $l_1$ explains 76 percent of the WTP for fuel economy and 62 percent of the WTP for performance. Using the estimated relationship between the ratio of horsepower to weight and 0-to-60 time from Greene et al. (2016), the performance coefficient estimate implies that consumers are willing to pay about $1,100 for a 1-second decrease in 0-to-60 time, which is similar to many estimates in the literature.[28]

We briefly describe robustness checks in Appendix C. The main threat to identification is the potential correlation between unobserved quality and the IVs. Our estimates are similar if we control for vehicle attributes that are likely to be correlated with quality, such as a sunroof, if we include consumers' self-reported satisfaction with the vehicle, and if we control for household demographics. Also, consumers could have either positive or negative value of certain technologies. For example, some manufacturers advertise the presence of a turbocharger and include a reference to a turbocharger in the vehicle's nameplate. The results are robust to dropping these instruments or a vehicle if its nameplate includes these technologies. We find no evidence that macroeconomic conditions affect the results.

## 4.2 Do consumers undervalue fuel cost savings?

We use two measures of consumer valuation to interpret the magnitude of the WTP for fuel economy. The first measure is the valuation ratio, the amount the marginal consumer is willing to pay for a 1 percent fuel economy increase over the present discounted value of the associated fuel cost savings. If the ratio equals one, the consumer fully values the fuel economy improvement; a value less than one implies undervaluation and a value greater than one implies overvaluation.

We consider the same 1 percent increase in fuel economy as in the previous section. For a vehicle purchased in year $y$ by consumer $i$, the present discounted value of future fuel costs is $PDV_{ifc} = \sum_{\tau=y}^{y+T} \frac{\pi_\tau V_{i\tau} f_\tau}{m(1+r)^\tau}$, where $T$ is the lifetime of the vehicle, $\pi_\tau$ is the probability that the

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[28] In theory, households expecting to drive their vehicles intensively should have higher WTP for fuel economy than other households. We test this hypothesis using survey information about the household's expected annual miles traveled for the new vehicle. We compute the average mileage by household income group and vehicle type (car or light truck). We add to the baseline specification the interaction of this variable with log fuel costs (see Table B.5). The magnitude of the interaction coefficient implies relatively little variation across households. The estimated WTP for performance is similar to the baseline.

vehicle is not retired before year $\tau$ (hereafter the survival probability rate), $V_{i\tau}$ is the number of miles the vehicle is driven in year $\tau$, $f_\tau$ is the real fuel price in year $\tau$, $m$ is the vehicle's fuel economy, and $r$ is the real discount rate.[29] See Appendix Sections A.3 and A.4 for details. The real discount rate $r$ is computed using the observed annual percentage rate (APR) from the MaritzCX survey adjusted by the inflation rate during the sample. For consumers who lease or finance their purchases, the rate represents the opportunity cost of the lease or loan payments. For consumers paying by cash, the rate represents the opportunity cost of investing the cash in other financial instruments (Allcott and Wozny 2014). In our sample, the average borrowing rate is about 3.3 percent and the average inflation rate is 2.0 percent, implying a 1.3 percent real borrowing rate.[30] Given the evidence reported in Anderson et al. (2013), we assume that real fuel prices follow a random walk, in which case the current price equals the expected real future price. We note that Allcott and Wozny (2014) and Sallee et al. (2016) directly estimate the valuation ratio, whereas we estimate the WTP and calculate the valuation ratio subsequently; inferences for consumer undervaluation do not depend on the approach. We choose this approach because it facilitates computation of multiple measures of consumer valuation that we can compare with the broader literature.

Table 4 reports the valuation ratio results. The baseline calculation of the fuel cost savings is \$249.[31] Combining fuel cost savings with the WTP in Table 3 Panel C, \$133, we compute a valuation ratio of 54 percent. This value means that the marginal consumer

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[29] Using income from the MaritzCX survey, annual income growth rates from the Consumer Population Survey, and VMT from the NHTS, we project future $V_{i\tau}$ for households from different income groups.

[30] The observed APR is similar to the mean APR reported in the 2013 wave of the Survey of Consumer Finance (SCF), which equals 3.36. For households paying cash and not taking out an auto loan, we could impute their discount rate using other market rates, such as the real rate of return of stocks or bonds. We prefer to use the APR because households that paid for their vehicle with cash could have taken out an auto loan that would have had a similar APR to the average APR we observe. The decision not to take out a loan reveals that the APR is an upper bound to the opportunity cost of funds for these households. That is, if the opportunity cost of funds were higher than the APR, we would observe these households taking out auto loans and purchasing higher-yield investments. Moreover, according to the SCF, 22 percent of new vehicle owners have credit card debt. Because just one-fifth of new vehicle consumers have credit card debt, the credit card APR is substantially higher than the relevant borrowing rate for a typical new vehicle consumer. Appendix Table A.1 evaluates the sensitivity of the APR assumption, including assuming a higher APR that accounts for the small fraction of new vehicle owners who report having credit card debt in the SCF.

[31] These savings are a weighted average of the present value of fuel cost savings for a one percent increase in fuel economy, where the weights are identical to those used in the price regressions.

pays 54 cents for $1 of present discounted fuel cost savings, implying undervaluation. This valuation ratio has a 95-percent confidence interval from 51 percent to 56 percent, which is significantly different from the 76 percent reported in Allcott and Wozny (2014) and is significantly different from the 100 percent reported in Sallee et al. (2016). As we noted in the introduction, the broader literature has yielded a wide range of valuation ratios, from close to zero to much greater than 1. Computing the valuation ratio requires a number of assumptions. In Appendix D we shows our results are robust to alternative assumed elasticities, interest rate, and calculation methods.

We report a second valuation measure, which is the implicit discount rate that implies a valuation ratio equal to one. In other words, if a consumer uses the implicit discount rate to discount future fuel cost savings, the consumer would be willing to pay $133 for a 1 percent fuel economy increase. An implicit discount rate equal to market borrowing rates would imply full valuation of fuel economy increases; a discount rate higher than market rates would imply undervaluation; and a discount rate below market rates would imply overvaluation. Table 4 reports the baseline estimated implicit discount rate of 12 percent. This is much higher than the average reported real borrowing rate in our data, which is 1.3 percent, implying undervaluation of fuel economy improvements.

We briefly discuss the possible reasons why we find evidence of undervaluation, whereas Busse et al. (2013) imply full valuation. One possibility is that they identify consumer valuation from fuel price variation. The consumer may response to fuel price induced changes in fuel costs differs from the response to fuel economy induced changes in fuel costs. Also, it is possible that the variation in fuel costs we use is based on relatively small year-to-year changes in fuel economy within the same model-variant, while the variation in fuel costs induced by fuel price changes is defined by potentially large fuel cost differences among model-variants. It could be that consumers fully value fuel cost savings achieved from substituting among model-variants but undervalue fuel cost savings gained from marginal fuel economy gains for the same model-variant. However, in Appendix D we show that these possibilities appear not to explain the differing results, as we obtain similar estimates of undervaluation using the Busse et al. (2013) methodology. We also show that this difference does not arise from differing assumptions on vehicle miles traveled and survival probability, macroeconomic conditions such as the 2008 recession, and functional form.

# 5 Implications

## 5.1 Consumer valuation of fuel economy and performance

We argued in Section 3 that if the regulator chooses a level of fuel economy above the optimum, undervaluation does not imply that fuel economy standards make consumers better off. This situation is more likely to occur the higher is the WTP for performance relative to fuel economy. In this subsection we compare the magnitudes of the WTP for fuel economy and an equivalent change in performance and we show that the WTP for performance exceeds WTP for an equivalent change in fuel economy.

Historically, during periods of time in which the stringency of fuel economy standards was not changing, manufacturers have adopted fuel-saving technology and retuned engines to improve performance while maintaining fuel economy. Between 1990 and 2005 the standards did not change, and the market-wide average fuel economy was unchanged while the ratio of horsepower to weight increased by 33 percent (Klier and Linn 2012). We showed in Table 2 that when light truck standards began to tighten in 2005, the rate of horsepower improvements slowed while fuel economy began increasing. For cars, standards began to tighten in 2011, and we observe the same shift from horsepower to fuel economy improvements. Klier and Linn (2016) show that the tightening standards caused a shift to improving fuel economy and a shift away from improving other vehicle attributes. These patterns suggest that consumers value performance more than fuel economy.

To assess whether our WTP estimates are consistent with these patterns, we combine the estimates with the estimated technological trade-off between fuel economy and performance from the literature. Suppose a manufacturer uses the fuel-saving technology that would raise fuel economy by 1 percent, and increases performance rather than fuel economy. Knittel (2011) and Klier and Linn (2016) estimate technical trade-offs among fuel economy, horsepower, and other attributes. These estimates imply that, holding weight and marginal costs constant, rather than increasing fuel economy by 1 percent the manufacturer could increase performance by 3 to 6 percent (depending on market segment). Our WTP estimates suggest that consumers would pay $394 for the performance increase, far exceeding the value of the fuel economy increase at $133. Consumers would value vehicles more if automakers use fuel-saving technology to raise performance rather than fuel economy, consistent with historical patterns of manufacturer attribute choices. The results suggest that the ratio of the marginal WTP for performance, relative to the marginal WTP for fuel economy, is about 0.7, which exceeds the technological trade-offs between the two attributes, which ranges from 0.17 to 0.33. This evidence suggests that when fuel economy standards are unchanging over time, manufacturers use fuel-saving technology to increase performance as much as possible.

Above, we noted the possibility that pre-existing regulatory distortions could cause the ratio of WTP to exceed the trade-off. In that case, the difference between WTP for performance and fuel economy would be proportional to the marginal cost of the standards. Anderson and Sallee (2011) and Leard and McConnell (2017) imply that the standards do not fully explain our findings, because their estimated marginal cost of the standards is too small to explain our estimated WTP for performance. However, we note that (e.g., Jacobsen 2013) estimates substantially larger marginal costs, and we leave for future research the question of why the ratio of WTP exceeds the trade-off.

## 5.2 How do tighter standards affect private consumer welfare?

In this subsection, we show that tighter standards have approximately zero net effect on private consumer welfare, notwithstanding the estimated undervaluation. The cost of adopting technology and increasing performance is less than WTP for fuel economy improvements. These results mean that undervaluation does not necessarily imply that standards make consumers better off.

We make assumptions on three sets of parameter values based on the recent literature. The first is the demand elasticity and second is technology adoption cost estimates from Leard et al. (2016). Based on technology cost estimates in EPA (2012), Leard et al. (2016) estimate that increasing fuel economy by 1 percent raises vehicle costs by \$90.[32] Given the technological trade-off from the previous subsection, the cost estimate implies that increasing performance by 1 percent raises vehicle costs by \$23. According to Table 3, consumers are willing to pay \$94 for the 1 percent performance increase, which exceeds the technology cost. We return to this point in the conclusion.

Third, we obtain the technological trade-off from Klier and Linn (2016). Their estimates imply that, in response to a 1 percent fuel economy tightening, manufacturers adopted technology that increased vehicle efficiency and fuel economy by 0.12 percentage points more than they would have if the standards had not been tightened (the technology adoption corresponds to an outward shift of the frontier from $f_1$ to $f_2$ in Figure 3). Manufacturers trade off performance for fuel economy to attain the remaining 0.88 percentage points (moving along $f_2$ from point $D'$to point $E$ in Figure 3).

Therefore, the total cost of the 1 percent fuel economy increase includes the cost of adopting the fuel-saving technology, as well as the welfare cost of the lower performance (i.e., relative to the counterfactual in which performance increases due to fuel-saving technology adoption). Leard et al. (2016) estimate that increasing fuel economy by 0.12 percent, while holding other attributes constant, raises costs by \$11 per vehicle. Using the WTP for performance, the welfare cost of reducing performance to increase fuel economy by 0.88 percent is \$347. Compare these costs with the present discounted value of fuel savings at \$247, the tighter standards reduce private consumer welfare by \$109 per vehicle, or 0.4 percent of the average transaction price in the sample.[33]

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[32] Implicit in our analysis is the assumption that manufacturers comply with tighter fuel economy standards by adopting technology. In practice, they may also reduce the relative prices of vehicles with low fuel economy (Goldberg 1998), which would reduce the cost relative to our estimate. However, Klier and Linn (2012) suggest that this effect would be small in magnitude.

[33] Using the 95 percent confidence intervals from Klier and Linn (2016), the changes of private consumer welfare ranges from -0.3 to -0.5 percent.

We make two observations about this result. The first is that the estimate is different from the estimate one would obtain by ignoring the costs of forgone performance. In their benefit-cost analysis of the standards EPA and NHTSA assume that tighter standards do not cause manufacturers to trade off performance for fuel economy. Instead, to meet the 1 percent fuel economy increase required in this example, manufactures adopt sufficient fuel-saving technology to increase fuel economy by 1 percent which implies an increase in vehicle costs by $90 per vehicle. Accounting for the value of the fuel savings, tightening standards by 1 percent would increase private consumer welfare by $158 per vehicle, or about 0.6 percent of the average transaction price. These results imply that the regulatory agencies substantially underestimated costs of the standards, in particular by a factor of 4 in our sample period. Maintaining their assumptions of annual sales of 16 million vehicles during the 2012–2016 period of tightening standards, these calculations suggest that if the agencies had included forgone performance improvements in their analysis, they would have estimated the costs of the standards to be $4.6 billion (39 percent) higher than the estimates they reported.

Second, the consumer welfare effects depend on the effect of the standards on the rate of technology adoption and on several other estimated parameters. The more that standards increase this rate, the less manufacturers trade off performance for fuel economy, causing the standards to have less of a negative effect on consumer welfare. Our estimate of -$109 per vehicle is based on the estimated effect of standards on technology adoption from the post-2010 time period. Estimates from Klier and Linn (2016) for earlier periods indicate larger technology adoption effects of tighter standards. Those estimates imply that tightening standards by 1 percent changes consumer welfare by -$25 per vehicle, or 0.1 percent of average transaction price. Efficiency improvements would have to account for at least half of the fuel economy improvement for tighter standards to increase private consumer welfare. These calculations imply negative consumer welfare effects and indicate some of the uncertainty around the point estimate of -$109.

In Appendix E we show our welfare conclusions are robust even if we substantially over-estimate the WTP for performance, or if we allow manufacturers to use weight reduction rather than fuel saving technologies. These conclusions are subject to several caveats. The technology cost estimates are based on interpolations described in Leard et al. (2016). The reduction in consumer welfare refers to the private welfare of new vehicle consumers; it does not include the social benefits arising from improved energy security and climate. Moreover, this conclusion does not account for potential induced innovation or vehicle entry and exit caused by tighter standards, market failures associated with insufficient market incentives for innovation (e.g., Fischer 2010; Porter and van der Linde 1995), market failures associated with imperfect competition such as the possible underprovision of fuel economy, and interactions between the new and used vehicle markets (Jacobsen and van Benthem 2015). Finally, the conclusion does not account for transitional dynamics. Klier and Linn (2016) find that tighter standards increase the rate of technology adoption, implying that standards may trade off higher fuel economy in the near term for lower performance in the long run. Accounting for these effects would require a dynamic analysis of new vehicle standards, which remains for future research.

## 5.3 Tighter standards and consumer acceptance

A contentious issue regarding the fuel economy and greenhouse gas emissions standards is whether the standards reduce overall consumer demand for new vehicles. If the standards reduce demand, tighter standards could cause some consumers to forgo obtaining a new vehicle and instead obtain a used vehicle or continue using their existing vehicles longer than they would have. Lower demand would reduce the total number of new vehicles that manufacturers sell and their profits. In addition, lower demand would decrease the rate at which lower-emitting new vehicles replace higher-emitting existing vehicles, reducing equilibrium social welfare benefits of the standards.

We estimate the effects of tighter standards on consumer demand for a typical new vehicle—i.e., the change in consumer surplus for the new vehicle—accounting for changes in vehicle prices, fuel economy, and performance. In this analysis, we use the WTP for fuel economy (that is, from an *ex ante* perspective) to value the fuel economy increase, rather than the discounted value of the fuel cost savings. This change is appropriate because consumers choose vehicles based on WTP rather than the discounted value of fuel savings. This measure is relevant to the effects of standards on consumer acceptance of new vehicles and aggregate vehicle demand.

Our estimates suggest that tighter standards reduce consumer demand in the short run. Specifically, tightening standards by 1 percent in our sample increases WTP by $133. The same tightening of the standards raises vehicle prices by $11 and reduces WTP for performance by $347. Overall, consumer WTP for new vehicles, net of vehicle price, fuel economy, and performance changes, decreases by $227 per vehicle, or 0.8 percent of the average transaction price. The result carries the same caveats as in the previous subsection. We leave for future work quantifying the welfare implications of this effect of fuel economy standards on total sales.

# 6 Conclusion

If an energy efficiency gap exists for passenger vehicles, new vehicle fuel economy or greenhouse gas emissions standards could increase private welfare of new vehicle consumers and producers. NHTSA and EPA have argued that a gap exists and conclude that the benefits of the fuel savings from existing standards exceed the costs of achieving the 2012-2016 standards; these benefits account for about 70 percent of the total estimated benefits.

To draw welfare implications for standards, the literature has focused on whether consumers undervalue fuel economy. However, we argue that the literature has focused narrowly on consumer valuation of fuel economy and has not considered the welfare costs of forgone performance increases.[34] Manufacturers can use those fuel-saving technologies to increase either fuel economy or performance. If manufacturers use those fuel-saving

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[34] Goldberg (1998) and Jacobsen (2013) account for welfare changes from foregone performance caused by consumer substitution in response to tighter standards, but they model performance as exogenous they do not analyze explicitly the technological trade-offs between fuel economy and performance.

technologies to increase performance if standards do not tighten, and if tighter standards cause manufacturers to use those technologies to increase fuel economy instead of performance, manufacturers forgo the opportunity to increase performance. The forgone performance reduces consumer welfare, opposing the positive consumer welfare effect of fuel savings caused by standards. Under certain conditions tighter standards could reduce private consumer welfare even in the presence of undervaluation.

We use a unique data set and novel identification strategy to estimate consumer valuation of fuel economy and performance. Consumers are willing to pay about 54 cents for $1 of discounted future fuel savings. This estimate is smaller than Busse et al. (2013) and Allcott and Wozny (2014), which likely reflects differences in sample period rather than methodology. The performance estimates imply that consumers pay about $94 for a 1 percent performance increase, which corresponds to $1,100 for a 1-second reduction in 0-to-60 time.

The estimated undervaluation of fuel economy would seem to suggest that tighter standards increase private consumer welfare. However, the estimated consumer valuation of performance is sufficiently large that the entire welfare cost of increasing fuel economy approximately equals the value of the fuel savings. This conclusion is subject to the caveats we discuss in Section 5.2, and we note that standards may increase social welfare after accounting for the energy security and climate benefits.

Our WTP estimates suggest two puzzles. First, the estimated WTP for a 1 percent performance increase ($94) exceeds the cost of adopting fuel-saving technology and increasing performance ($23), suggesting that manufacturers should adopt fuel-saving technology more quickly than they do. Such a performance gap does not have the same policy implications as an energy efficiency gap, because there are not any obvious external costs if there is too little performance from a consumer's perspective. The literature has emphasized consumer mis-optimization in explaining the energy efficiency gap, but mis-optimization for performance could occur on the manufacturer side as well. In this case, our estimates would imply that engineers over-estimate the costs by a factor of four and that tighter standards could increase welfare if they induce manufacturers to add fuel-saving technologies that simultaneously increase fuel economy and performance. On the other hand, hidden costs of technology adoption could explain a performance gap, just as hidden costs could explain the energy efficiency gap, where hidden costs could include disutility that consumers experience.

The second puzzle is that the WTP for performance implies that manufacturers would avoid trading off performance for fuel economy because consumers value the performance so highly. Yet, the patterns in Table 2 as well as estimates in Klier and Linn (2016) suggest that manufacturers do make this trade-off when facing tighter standards. Future research can investigate whether hidden costs, consumer preference heterogeneity, or other factors explain these apparent puzzles.

Although fuel economy standards may not increase consumer welfare, other policies could improve consumer welfare by targeting the cause of the undervaluation. If the lack of information about fuel cost savings causes the consumer to undervalue savings, improving information could increase consumer welfare. Future research could attempt to determine the cause of undervaluation and identify appropriate policies to correct market failures.

The results have implications for the effects of fuel economy and emissions standards on demand for new vehicles. Our estimates imply that tightening standards by 1 percent reduces consumer valuation by 0.8 percent per vehicle, although we suggest that these results should not be extrapolated far out of sample because they are based on marginal WTP. Future work could incorporate these effects in a comprehensive welfare analysis of the standards.

More broadly, similar considerations pertain to trade-offs with other vehicle attributes (such as weight) and to energy efficiency standards for products in which there are technological relationships between energy efficiency and other product attributes that consumers value (Houde and Spurlock 2015). For example, the U.S. Department of Energy imposes efficiency standards on refrigerators. Manufacturers have a variety of options for improving refrigerator energy efficiency, including adding insulation. Given size constraints on refrigerators, adding insulation implies reducing storage space. Whether these trade-offs imply large welfare effects is an open question for future research.

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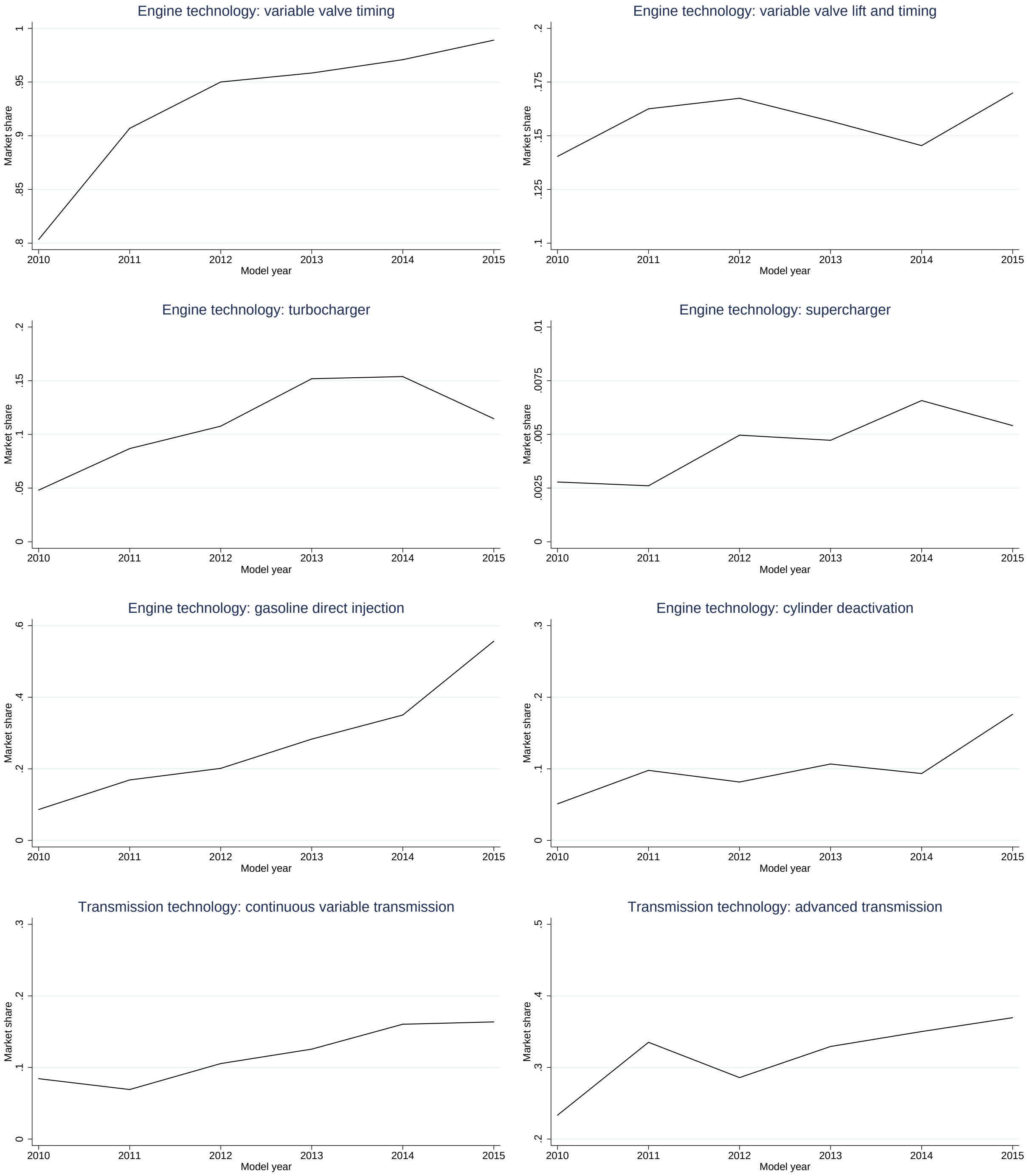
# Figures

Figure 1: **Market Penetration of Selected Fuel-Saving Technologies, 2010–2014**


Engine technology: variable valve timing

Engine technology: variable valve lift and timing

Engine technology: turbocharger

Engine technology: supercharger

Engine technology: gasoline direct injection

Engine technology: cylinder deactivation

Transmission technology: continuous variable transmission

Transmission technology: advanced transmission

*Notes*: The figure reports the the registration-weighted market shares of the engine and transmission variables used to construct the IVs.

Figure 2: **Effects of Fuel Economy Standard on Fuel Economy and Performance**

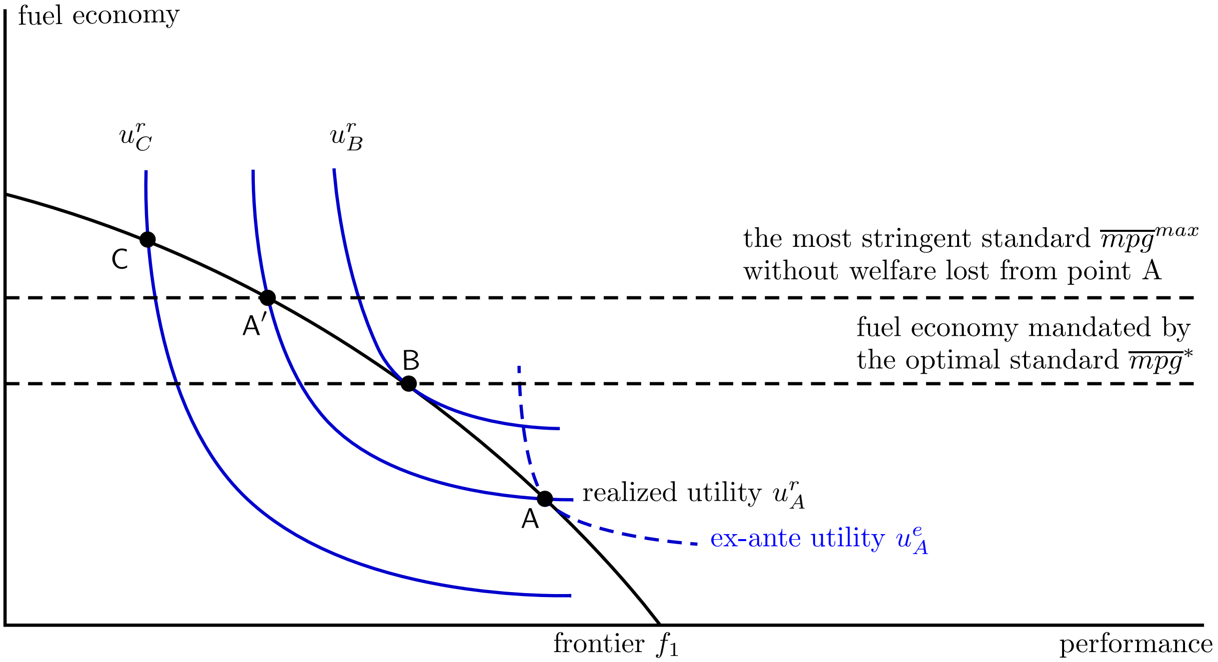


Figure 3: **An Overshot Fuel Economy Standard from an Existing Standard and Allowing Fuel Economy Frontier to Shift**

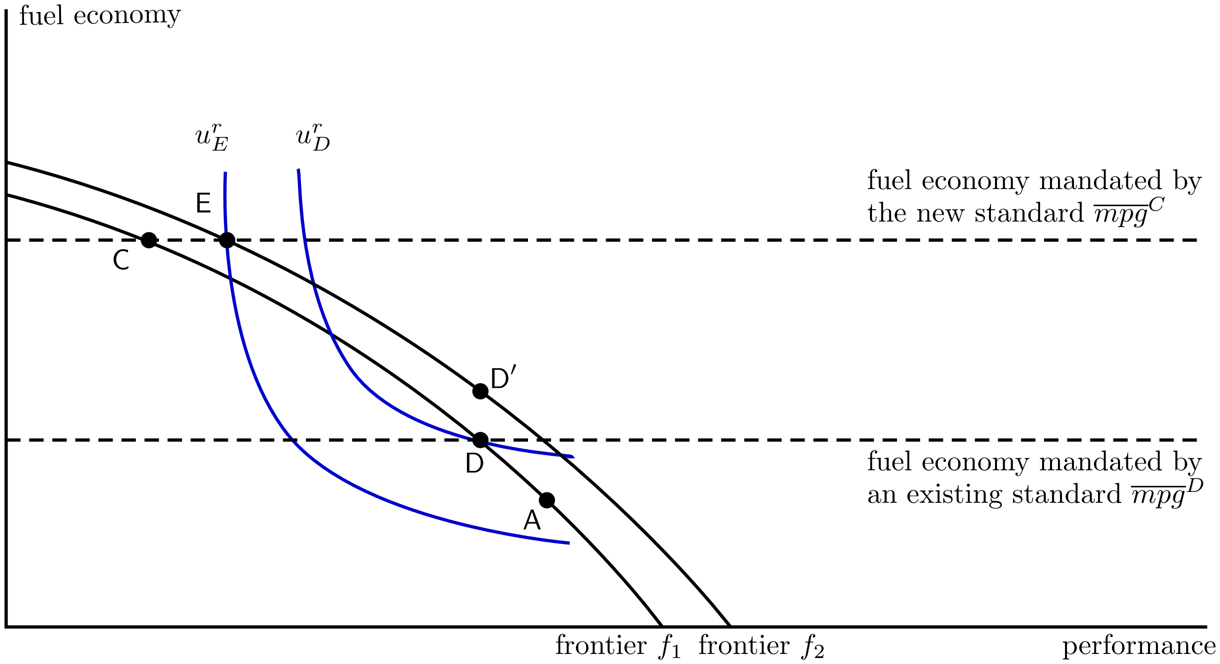
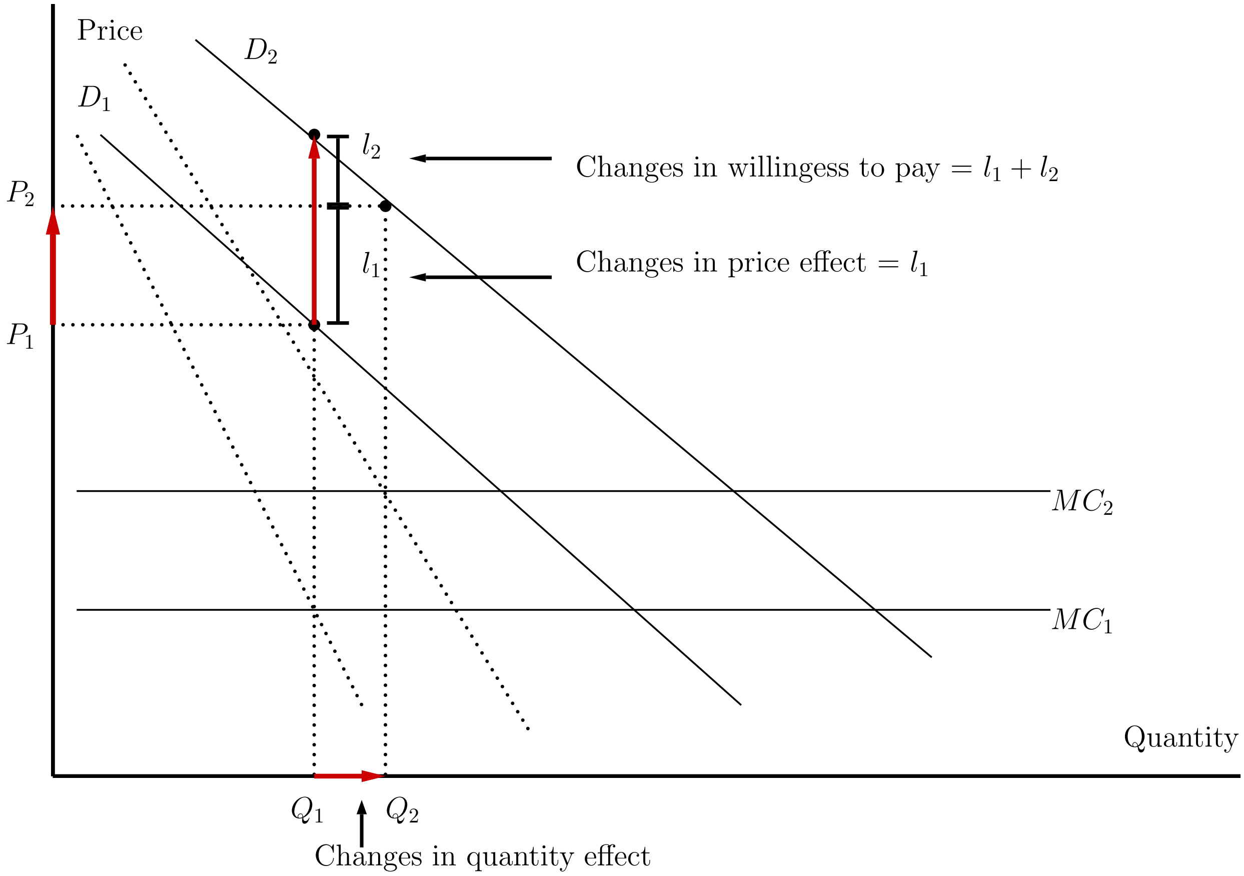


Figure 4: **Effects of Fuel Economy Increase on Equilibrium Prices and Quantities**



# Tables

Table 1: **Summary Statistics**

| | Mean | Std. dev. | Min. | Max. |
|---|---|---|---|---|
| **Panel A. Price and vehicle characteristics** | | | | |
| Transaction price (2010 USD) | 28,693 | 11,402 | 5,998 | 191,622 |
| Fuel economy (miles/gallon) | 23.9 | 6.6 | 12 | 50 |
| Horsepower (hp) | 226 | 78 | 70 | 662 |
| Torque (newton meter, nm) | 306 | 113 | 92 | 856 |
| Weight (pounds, lb) | 4,055 | 1,264 | 1,808 | 8,200 |
| Engine displacement (liters) | 3.0 | 1.2 | 1 | 8.4 |
| Hybrid | 0.05 | 0.21 | 0 | 1 |
| Flex fuel | 0.11 | 0.32 | 0 | 1 |
| All-wheel/4-wheel-drive | 0.37 | 0.48 | 0 | 1 |
| **Panel B. Demographics of respondent** | | | | |
| Household size | 2.5 | 1.2 | 1 | 6 |
| Age (years) | 52.6 | 15.4 | 15 | 99 |
| Male | 0.61 | 0.49 | 0 | 1 |
| Urban | 0.55 | 0.50 | 0 | 1 |
| Number of unique vehicle models | | | | 450 |
| Number of unique vehicle trims | | | | 1,351 |
| Number of unique vehicle model-variants | | | | 2,166 |
| Number of observations | | | | 535,130 |

*Notes*: Panel A reports the registration-weighted average, standard deviation, minimum, and maximum of the variables indicated in the row headings. Engine displacement is the volume of the engine cylinders, in liters. Hybrid and flex fuel are indicator variables for whether the vehicle has a hybrid power train or is capable of using E85 fuel. All-wheel/4-wheel-drive is an indicator for whether the vehicle has all-wheel- or 4-wheel-drive. A model has a unique company name, manufacturer name, vehicle series name, and vehicle "nameplate" description. A trim is a unique model and a unique trim name. A model-variant is a trim with a unique combination of drive train specification (front-wheel-drive, rear-wheel-drive, or all/4-wheel-drive), fuel type (gasoline, diesel fuel, or other), displacement, and number of cylinders.

Table 2: **Annual Percent Growth of Vehicle Attributes by Time Period**

| | Cars | | | Light trucks | | |
|---|---|---|---|---|---|---|
| | Fuel economy | Horsepower | Weight | Fuel economy | Horsepower | Weight |
| 1996–2000 | -0.6 | 1.9 | 0.6 | 0.2 | 4.0 | 1.3 |
| 2001–2004 | 0.4 | 1.8 | 0.7 | -0.6 | 4.7 | 3.2 |
| 2005–2011 | 0.2 | 1.2 | 0.4 | 1.0 | 1.0 | -0.3 |
| 2012–2015 | 2.1 | 0.2 | 1.2 | 2.5 | 0.7 | -0.9 |

*Notes*: The table reports annual percent growth rates for cars and light trucks by time period. The data are from Leard, Linn, and McConnell (forthcoming).

Table 3: **Willingness to Pay for Fuel Cost Savings and Performance**

|  | (1) | (2) | (3) |
|---|---|---|---|
| Estimated by | OLS | OLS | IV |
| **Panel A. Dependent variable is log transaction price** |  |  |  |
| Log fuel cost (dollars/mile) | -0.113*** | -0.156*** | -0.354*** |
|  | (0.018) | (0.020) | (0.075) |
| Log performance (hp/lb or nm/lb) | 0.068*** | -0.230*** | 0.203*** |
|  | (0.014) | (0.020) | (0.074) |
| Model-variant fixed effect |  | Yes | Yes |
| Number of observations | 457,525 | 535,124 | 535,124 |
| RMSE | 0.13 | 0.13 | 0.13 |
| **Panel B. Dependent variable is log new registrations** |  |  |  |
| Log fuel cost (dollars/mile) | -1.651*** | -0.636*** | -0.338*** |
|  | (0.119) | (0.045) | (0.116) |
| Log performance (hp/lb or nm/lb) | -0.578*** | -0.030 | 0.371*** |
|  | (0.061) | (0.028) | (0.083) |
| Model-variant fixed effect |  | Yes | Yes |
| Number of observations | 457,525 | 535,124 | 535,124 |
| RMSE | 0.6 | 0.39 | 0.39 |
| **Panel C. Willingness to pay (2010 USD)** |  |  |  |
| For 1 percent increases in |  |  |  |
| • fuel economy | 190.9 | 105.6 | 133.4 |
|  |  |  | [128.8, 139.1] |
| • performance | -109.8 | -5.7 | 93.6 |
|  |  |  | [87.4, 99.5] |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Robust standard errors in round parentheses, clustered by vehicle model-by-state. 95% confidence interval in square brackets. Performance is the ratio of horsepower to weight for cars and torque to weight for trucks. All specifications include fixed effects for number of transmission speeds and a dummy variable for flex fuel capability, as well as the interactions of these variables with a dummy variable for light trucks. All specifications include fixed effects for state, model year, and PADD region-month-fuel type, a lease dummy and a CAFE stringency variable interacted with model-year fixed effects. In all price regressions, observations are weighted by the number of registrations, and all quantity regressions are not weighted. Column 1 includes trim fixed effects, displacement, weight, length, width, height, fuel tank volume, maximum number of passengers, wheelbase, the number of cylinders, fixed effects for drive type and fuel type. Column 1 in Panel B also includes body type fixed effects. For columns 2 and 3, price regressions include model-variant fixed effects as defined in the Maritz data and Panel B includes model-variant fixed effects as defined in the IHS data. Columns 1 and 2 are estimated by OLS and column 3 by IV. In column 3, log fuel costs and performance are instrumented using indicator variables for the fuel-saving technologies from Figure 1, as well as the interactions of the indicator variables with a light truck indicator variable. First-stage results for price regressions are in Table D.5, and quantity regressions are in Table D.6. Panel C reports the change in WTP caused by a one percent increase in fuel economy or performance, assuming an own-price elasticity of demand equal to -3.

Table 4: **Valuation Ratios and Implicit Discount Rates**

|  |  |  |
|---|---|---|
| **Panel A. Valuation ratio (percentage)** |  |  |
| Demand elasticity = -3, real discount rate = real reported APR 1.3 percent | 53.6 | [51.7, 55.9] |
| **Panel B. Implicit discount rate (percentage)** |  |  |
| Demand elasticity = -3 | 12.25 |  |

*Notes*: 95% confidence interval in square brackets. Panel A reports the valuation ratio, which is the ratio of the estimated WTP for a 1 percent fuel economy increase to the present discounted value of future fuel cost savings. Panel B reports the implicit discount rate, which is the discount rate that results in a valuation ratio of one. Both the valuation ratio and implicit discount rate are reported in percentages. See text for details on calculations and parameter assumptions.

# Appendix for Online Publication

## A.1 Analytical Model of Welfare

This section presents a formal model to complement the graphical analysis in Section 3.1. In this section, we present a simple model to show that a fuel economy standard can lower welfare even when consumers undervalue fuel cost savings.

Consider a setting with a representative manufacturer choosing performance and fuel economy and subject to a technological tradeoff between the two attributes. The function $f(\cdot)$ describes the technological tradeoff between fuel economy and performance, also known as the fuel economy frontier. The tradeoff function $f(\cdot)$ satisfies typical properties of a production possibilities frontier, including being continuous and strictly concave down in the entire positive fuel economy-performance quadrant, as is the case for the curve $f_1$ in Figure 2.

The manufacturer maximizes profits by equating the slope of the technological tradeoff and the slope of a representative consumer indifference curve, as in Figure 2. This decision is equivalent to a representative consumer choosing performance $perf$ and fuel economy $mpg$ to maximize *ex ante* utility, which is denoted as $u^e(\cdot)$. The combination of $(perf, mpg)$ is feasible for the consumer to choose if it lies along the technological frontier $mpg = f(perf, T)$ as defined in section 3.1. For simplicity in this section we hold technology fixed in a given year, and $mpg = f(perf)$. The consumer's utility maximization problem is

$$\max_{perf,mpg} u^e\left(perf, mpg\right), \text{ subject to } mpg = f(perf)$$

We assume that the derivative of $u^e(\cdot)$ with respect to income is equal to one, so that maximized *ex ante* utility equals *ex ante* welfare. We denote $(perf^e, mpg^e)$ as *ex ante* optimal choice of performance and fuel economy. In Figure 2, point A represents the optimal *ex ante* bundle, and the indifference curve $u^r_A$ tangents with the frontier $f_1$ at point $A$. We can simplify *ex ante* optimization problem by substituting the tradeoff equation into the objective function:

$$\max_{perf} u^e\left(perf, f(perf)\right)$$

Define $u^r(\cdot)$ as realized utility, also known as *ex post* utility or experienced utility. Realized utility exceeds *ex ante* utility if the consumer undervalues fuel cost savings. We denote realized equilibrium welfare without fuel economy regulated as $u^r_A \equiv u^r(perf^e, mpg^e) = u^r(perf_A, mpg_A)$.

Similar to *ex ante* utility, we assume that the indifference curves of realized *ex post* utility function $u^r(\cdot)$ are continuous and and strictly concave up in the entire positive fuel economy-performance quadrant. A regulator seeking to maximize *ex post* utility has the problem

$$\max_{perf,mpg} u^r\left(perf, mpg\right), \text{ subject to } mpg = f(perf)$$

Denote the optimal realized *ex post* choice by $(perf^*, mpg^*)$. In Figure 2, point $B$ represents the optimal *ex ante* bundle and the indifference curve $u^r_B$ tangents with the frontier $f_1$ at point $B$, $u^r_B \equiv u^r(perf^*, mpg^*)$.

When the consumer undervalues fuel cost savings, the consumer chooses performance greater than the (realized) optimal level and fuel economy lower than the (realized) optimal level, i.e., $perf_A > perf_B$ and $mpg_A < mpg_B$. Realized utility at point $A$ is lower than the optimal realized utility at point $B$, i.e., $u^r_B > u^r_A$. Therefore, a fuel economy standard requiring fuel economy at $mpg_B$maximizes realized welfare. We denote this standard as the optimal standard $\overline{mpg}^*$ in Figure 2. Under this standard, the manufacturer chooses fuel economy $\overline{mpg}^*$ and the consumer chooses point $B$.

We next show that the standard can be set at a point that lowers realized welfare compared to the unregulated equilibrium. At point $A$, realized *ex post* welfare is $u^r_A$. This is identical to realized welfare at point $A'$ in Figure 2, which lies on the same indifference curve as point $A$ and locates on the frontier $f_1$.

$$u^r\left(perf_A, mpg_A\right) = u^r\left(perf_{A'}, mpg_{A'}\right)$$

Denote the fuel economy at point $A'$ as $\overline{mpg}^{max}$. This is the most stringent fuel economy that can be in place without lowering realized welfare from point $A$. To examine the effect of an overly stringent standard, we consider how welfare changes if a standard with a fuel economy requirement higher than $\overline{mpg}^{max}$ is in place, which represents a non-marginal increase in fuel economy. Analyzing this outcome is equivalent to considering the effect of lowering performance (and increasing fuel economy) from point $A'$.[35] The change in welfare $du^r/dperf$ when performance is marginally lower is:

$$\left.\frac{du^r(perf, mpg)}{dperf}\right|_{A'} = \underbrace{\left.\frac{\partial u^r\left(perf, mpg\right)}{\partial perf}\right|_{A'}}_{\substack{(-)\\ \text{welfare loss}\\ \text{from lowering}\\ \text{performance}}} + \underbrace{\left.\frac{\partial u^r\left(perf, mpg\right)}{\partial mpg}\cdot\frac{\partial f(perf)}{\partial perf}\right|_{A'}}_{\substack{(+)\\ \text{weflare gain}\\ \text{from increasing}\\ \text{fuel economy}}} \tag{1}$$

When performance is mandated to be lower than $perf_{A'}$, the first term in this expression represents the welfare loss from sacrificing performance, and the second term represents the welfare gain from increasing fuel economy. The sign of the overall effect depends on which of the two effects dominates. To examine the sign of expression (1), we note that realized indifference curve is steeper than the frontier $f_1$, which is the slope of the tradeoff function $f(\cdot)$:

$$-\left.\frac{dmpg}{dperf}\right|_{A',\ u^r(perf,mpg)=u^r_A} < -\left.\frac{dmpg}{dperf}\right|_{A',\ mpg=f(perf)} < 0$$

We apply the implicit function theorem on the left hand side

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[35] Although we derive analytical expressions for the effects of marginal changes in the attributes, we derive the effects at levels of the attributes that represent non-marginal required increases in fuel economy. Therefore, the signs of the marginal changes that we derive apply to non-marginal changes.

$$\left.\frac{\frac{\partial u^r(perf,mpg)}{\partial perf}}{\frac{\partial u^r(perf,mpg)}{\partial mpg}}\right|_{A'} < -\left.\frac{\partial f(perf)}{\partial perf}\right|_{A'}$$

Isolating terms on one side of the inequality and suppressing the subscript (point $A'$) yields

$$\frac{\partial u^r\left(perf,mpg\right)}{\partial perf} + \frac{\partial u^r\left(perf,mpg\right)}{\partial mpg}\cdot\frac{\partial f(perf)}{\partial perf} > 0. \tag{2}$$

This inequality implies that expression (1) is negative, i.e., $\left.\frac{du^r(perf,mpg)}{dperf}\right|_{A'} < 0$. Note that inequality (2) represents the changes in realized welfare when performance increases, suggesting the above inequality would flip as performance is mandated to decrease as in expression (1) . Therefore, at point $A'$, welfare would decrease if the fuel economy standard is tightened. The welfare gain from increasing fuel economy beyond point $A'$ does not make up for the welfare loss from reducing performance. For example, consider point $C$, which lies above point $A'$. If a standard is imposed at $\overline{mpg}^C$, realized indifference curve going through point $C$ is lower than realized indifference curve through point $A$, and the standard reduces welfare.

Note that we analyze the above model from the consumer's perspective for consistency with Figure 2. Our conclusion is the same if we set up an optimization problem from the perspective of a manufacturer choosing attributes and taking consumer demand as given because of the dual nature of the stylized problem.

In summary, we find that a sufficiently stringent fuel economy standard can reduce welfare even when consumers undervalue fuel cost savings. In Figure 2, this includes any standard exceeding $\overline{mpg}^{max}$.

## A.2 Deriving the Log-Log Equilibrium Functional Form

In this section we show that the assumed log-log relationships among vehicle price, sales, fuel costs, and performance approximate the relationships in perfect and imperfect competitions regardless of the functional form of the demand curve.

**1. Perfect competition and free entry.** Consider the pricing decision of a manufacturer operating under perfect competition. The manufacturer maximizes profits by equating the price of vehicle $j$ in year $t$ and the marginal costs of production: $p_{jt} = c_{jt}$. The complete pass-through of marginal cost changes to price changes is consistent with assumptions made by EPA and NHTSA in their analyses of fuel economy and GHG standards (EPA 2012). The economics and engineering literatures suggest a log-log relationship between vehicle technology costs and fuel costs, and between technology costs and performance (Knittel 2011; NRC 2015)

$$\ln c_{jt} = \alpha_f \ln fc_{jt} + \alpha_p \ln perf_{jt} \tag{3}$$

The parameters $\alpha_f$ and $\alpha_p$ represent the percentage change in vehicle costs stemming from a one percent change in vehicle fuel costs or performance. The above profit maximization condition and the log-log cost structure in equation (3) imply a log-log equilibrium relationship of vehicle prices and fuel costs, and a log-log equilibrium relationship of price and performance:

$$\ln p_{jt} = \alpha_f \ln fc_{jt} + \alpha_p \ln perf_{jt}$$

If consumer utility is linear in fuel costs, economic theory suggests that demand is linear in fuel costs. In this setting, even when quantity demanded is a linear function of fuel costs, the equilibrium price-fuel cost relationship is log-log.

**2. Imperfect competition in the short run**. Next, we consider manufacturers competing in a model of Bertrand competition. To simplify the exposition, we consider a single-product manufacturer choosing price (i.e., in the short run): $\max_{p_{jt}} \left[(p_{jt} - c_{jt})\, q_{jt}\right]$, where $q_{jt}$ denotes vehicle $j$ sales in time $t$.[36] The first-order condition for price is

$$p_{jt} = c_{jt} - \frac{q_{jt}}{\frac{\partial q_{jt}}{\partial p_{jt}}} \tag{4}$$

The second term on the right-hand side is the standard markup that is related to the price elasticity of demand. Differentiating the first-order condition (4) with respect to fuel costs and performance yields

$$\begin{cases} \frac{\partial p_{jt}}{\partial fc_{jt}} & = \frac{\partial c_{jt}}{\partial fc_{jt}} - \frac{\frac{\partial q_{jt}}{\partial fc_{jt}}}{\frac{\partial q_{jt}}{\partial p_{jt}}} = \frac{\partial c_{jt}}{\partial fc_{jt}} - MWTP_{fc} \\ \frac{\partial p_{jt}}{\partial perf_{jt}} & = \frac{\partial c_{jt}}{\partial perf_{jt}} - \frac{\frac{\partial q_{jt}}{\partial perf_{jt}}}{\frac{\partial q_{jt}}{\partial p_{jt}}} = \frac{\partial c_{jt}}{\partial perf_{jt}} - MWTP_{perf} \end{cases}$$

$MWTP_{fc}$ and $MWTP_{perf}$ denote marginal willingness to pay (MWTP) for fuel costs and performance. Most existing studies have assumed that utility is linear in fuel costs, performance, and price (e.g., Berry et al. (1995)). In this case, MWTP terms are constant for all values of fuel costs and performance, and $\frac{\partial p_{jt}}{\partial fc_{jt}}$ and $\frac{\partial p_{jt}}{\partial perf_{jt}}$ depend on how fuel costs and performance affect costs, i.e., $\frac{\partial c_{jt}}{\partial fc_{jt}}$ and $\frac{\partial c_{jt}}{\partial perf_{jt}}$. Even if MWTP is constant, the derivatives of price with respect to fuel costs and performance are not constant as long as the marginal cost terms are non-constant.[37] Combining the log-log cost assumption with the above expression yields

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[36] The manufacturer profit maximization problem can also include a fuel economy or GHG constraint. To simplify the exposition, we omit this constraint and consider any costs imposed by these constraints to enter through the vehicle cost term, $c_{jt}$.

[37] The relationships between price, fuel costs, and performance can become more linear as the marginal cost terms become smaller relative to the magnitudes of MWTP. On the other hand, the constant MWTP terms are derived from simplistic linear demand assumptions. Relaxing these assumptions can make these terms non-constant.

$$\begin{cases} \frac{\partial \ln p_{jt}}{\partial \ln fc_{jt}} & = \frac{\partial \ln c_{jt}}{\partial \ln fc_{jt}} \cdot \frac{c_{jt}}{p_{jt}} - \frac{fc_{jt}}{p_{jt}} \cdot \frac{\frac{\partial q_{jt}}{\partial fc_{jt}}}{\frac{\partial q_{jt}}{\partial p_{jt}}} = \frac{\partial \ln c_{jt}}{\partial \ln fc_{jt}} \cdot \frac{c_{jt}}{p_{jt}} - \frac{\frac{\partial q_{jt}}{\partial \ln fc_{jt}}}{\frac{\partial q_{jt}}{\partial \ln p_{jt}}} \\ & = \delta_f \cdot \left(1 + \frac{1}{\varepsilon}\right) - \ln MWTP_{\ln fc} \\ \frac{\partial \ln p_{jt}}{\partial \ln perf_{jt}} & = \delta_{perf} \cdot \left(1 + \frac{1}{\varepsilon}\right) - \ln MWTP_{\ln perf} \end{cases}$$

The terms $\ln MWTP_{\ln fc}$ and $\ln MWTP_{\ln perf}$ represents the log of the marginal WTP for fuel cost and performance. Therefore, the equilibrium relationship between price and fuel cost (and between price and performance) is log-log under the assumption of a single-product firm facing linear demand in the short run.

**3. Imperfect competition in the medium run**. Next, we consider the case in which manufacturers choose price, fuel economy, and performance. We refer to the situation as the medium run, because manufactures typically choose fuel economy and performance less frequently than they choose price. This is the setting relevant to our estimation models, in which fuel economy and performance are chosen endogenously and may be correlated with unobserved quality. The profit maximization problem is

$$\max_{p_{jt}, fc_{jt}, perf_{jt}} \left[p_{jt}\left(fc_{jt}, perf_{jt}\right) - c_{jt}\left(fc_{jt}, perf_{jt}\right)\right] q_{jt}\left(p_{jt}, fc_{jt}, perf_{jt}\right) \tag{5}$$

The first-order condition with respect to price is the same as above, $q_{jt} + (p_{jt} - c_{jt})\frac{\partial q_{jt}}{\partial p_{jt}}$. Differentiating the first-order condition with respect to fuel costs and performance yields

$$\begin{cases} \frac{\partial p_{jt}}{\partial fc_{jt}} & = \frac{\partial c_{jt}}{\partial fc_{jt}} - \frac{1}{\frac{\partial q_{jt}}{\partial p_{jt}}} \left\{ \frac{\partial q_{jt}}{\partial fc_{jt}} + (p - c)\frac{\partial^2 q_{jt}}{\partial p_{jt} \partial fc_{jt}} \right\} \\ \frac{\partial p_{jt}}{\partial perf_{jt}} & = \frac{\partial c_{jt}}{\partial perf_{jt}} - \frac{1}{\frac{\partial q_{jt}}{\partial p_{jt}}} \left\{ \frac{\partial q_{jt}}{\partial perf_{jt}} + (p - c)\frac{\partial^2 q_{jt}}{\partial p_{jt} \partial perf_{jt}} \right\} \end{cases}$$

Similar to the case above, the second term includes the MWTP for fuel costs and performance. In this case, MWTP also includes the indirect effect of fuel costs on demand via price, which is a second-order effect. When utility is linear in price, fuel costs, and performance, the second-order term disappears. More generally, as long as the second order term is small compared to the other terms, the log-log functional form approximates the equilibrium relationships among prices, fuel costs, and performance. In summary, under perfect or imperfect competition, we can approximate the relationships among price, fuel costs, and performance using a log-log functional form. This approximation does not imply that the log of quantity demanded depends on the log of fuel costs.

## A.3 Vehicle Miles Traveled Schedules

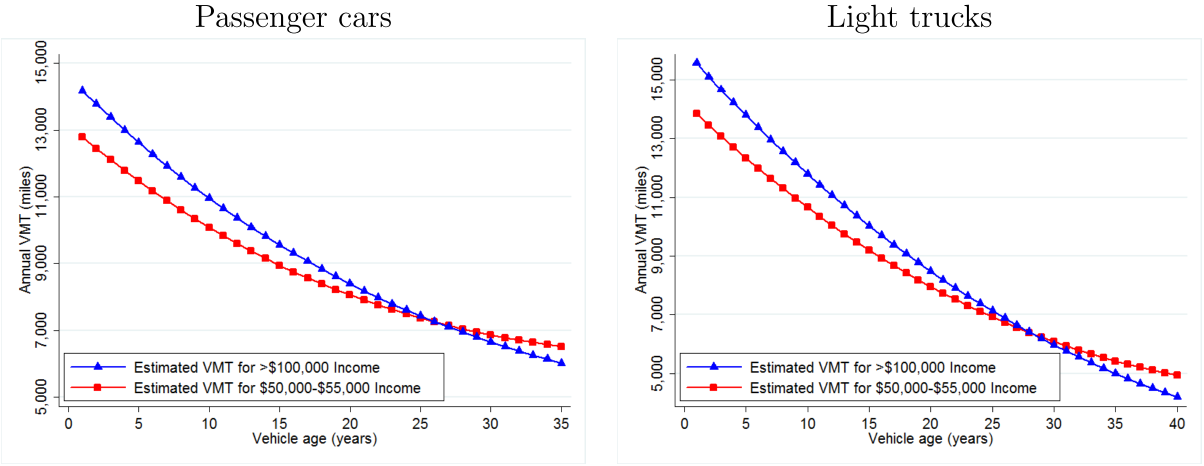
We estimate lifetime fuel costs from annual vehicle miles traveled (VMT) data by model year, income group, and vehicle class (cars or light trucks) from the 2009 National Household Travel Survey (NHTS) by building on the models presented in Lu (2006). We use the 2009 National Household Travel Survey (NHTS) to estimate VMT schedules. The publicly available data include vehicle and household information for 309,163 vehicles held by 150,147 surveyed households. We estimate the relationships among VMT, vehicle age, and household income. We follow Lu (2006) in specifying a cubic relationship between VMT and vehicle age, where vehicle age is measured in years. We take a semi parametric approach in specifying the relationship between VMT and household income. We create 13 bins of household income, which correspond to bins present in both the NHTS and MaritzCX survey data, and we aggregate bins where necessary to make the bins consistent between the surveys. We convert income bins from the NHTS to 2014$ for consistency with the MaritzCX data, which are measured in 2014$.

We estimate a separate intercept for each income group by regressing VMT on a fixed effect for each group. We also interact these fixed effects with a linear vehicle age variable to capture differences in VMT across income groups for different vehicle vintages. The interaction effects model the possibility that household driving intensity over the lifetime of a vehicle varies by income. Following Lu (2006), we estimate separate VMT models for cars and light trucks. We aggregate vehicle/household level observations to vehicle age by household income bin averages, yielding 869 and 785 observations for the car and light truck specifications. The estimates for both models appear in Appendix Table B.6.

The estimates are plausible and most are statistically significant. For both vehicle classes, VMT increases with household income. The vehicle age/household income interaction terms are mostly negative and significant and are decreasing in household income. This implies that the marginal reduction in VMT from a vehicle aging by one year is larger for high-income households than for low-income households. This pattern is consistent with multi-vehicle high-income households driving new vehicles intensively by substituting miles away from their older vehicles to their newer vehicles. Conversely, low-income households tend to keep vehicles longer and drive them more when they are older. This relationship is apparent by plotting VMT schedules as a function of vehicle age for high- and low-income groups. Appendix Figure A.1 illustrates the schedules effect for cars and light trucks.

To account for the effect of fuel prices on VMT, we adjust the estimated VMT schedules by the change in national average fuel prices between the period of the 2009 NHTS (March 2008 to April 2009) and each year of the MaritzCX sample. The adjustment uses an elasticity of VMT to fuel prices of -0.1.

Figure A.1: **Estimated Vehicle Miles Traveled by Vehicle Age and Household Income**


Passenger cars

Light trucks

## A.4 Vehicle Survival Schedules

Using proprietary data from R. L. Polk on annual scrappage rates from 2003-2014, we estimate a survival rate as a function of vehicle class and age following Lu (2006). We assume that vehicles have maximum lifespans of 35 years for cars and 40 years for light trucks.

We update the vehicle survival schedules in Lu (2006) using R. L. Polk data on vehicle registrations from 2002 to 2014. The R.L. Polk data are disaggregated by vehicle class (car and light truck), vehicle age, and year, where registrations are recorded for each vehicle age up to age 14. We drop observations with age 1 to account for the fact that some vehicles are obtained in future model years (for example, a vehicle produced in 2004 that is first obtained in 2006), which would imply survival rates above 1. We estimate the following model:

$$age_{it} = \gamma_0 + \gamma_1 \ln(-\ln(1 - rate_{it}))$$

The variable is the survival rate of vehicles of age $i$ in year $t$ and equals the number of registered vehicles of age $i$ in year $t$ divided by the number of registered vehicles of age $i$ in year $t$. Inverting the above equation yields a model that is comparable to the coefficient estimates in Lu (2006):

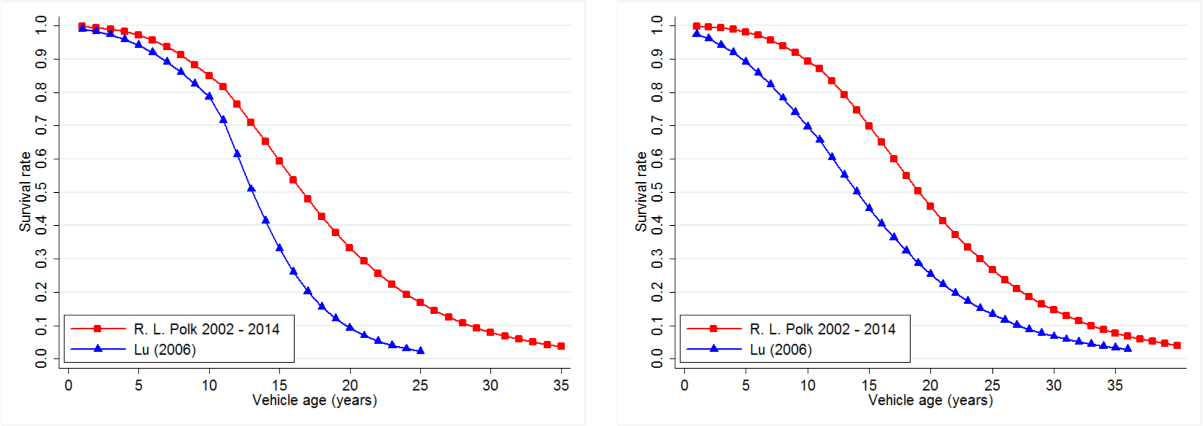
$$rate_{it} = 1 - \exp(-\exp(-\gamma_0/\gamma_1 + age_{it}/\gamma_1))$$

Defining $A = -\gamma_0/\gamma_1$ and $B = 1/\gamma_1$, Appendix Table B.7 presents estimates comparable to Lu (2006).

Appendix Figure A.2 plots the survival schedules for cars and light trucks. The figure illustrates that cars and light trucks survive longer than they did historically. This is consistent with Lu (2006), who documents longer survival schedules than earlier time periods. The figures also highlight the importance of using more recent data for estimating vehicle survival schedules, as the newer data suggest greater VMT–and hence greater expected fuel costs–over vehicle lifetimes.

Figure A.2: **Vehicle Survivability Schedule**

Passenger cars　　Light trucks



## A.5 Alternative Discount Rates

In the main calculations, we use reported APRs of new vehicle loans from the MaritzCX data to compute discount rates. In this section, we consider alternative discount rates based on data from the survey of Consumer Finances (SCF).

The SCF is a nationally representative survey that is conducted approximately once every three years. During our sample period, two waves of the SCF were completed, in 2010 and 2013.

We obtained data from the 2013 wave to compute discount rates based on various forms of credit reported in the SCF. In the 2013 sample, the total sample of new vehicle buyers and leasers is 5,622. We identify new vehicle buyers in the survey using self-reported vehicle model year and purchase or lease year.

The SCF reports four alternative measures of interest rates: new vehicle loan APR, education loan APR, mortgage interest rate for real estate loans, and credit card APR. Each household can report rates for multiple loans of each credit type.

We compute the maximum rate by household and loan type. For example, households can report information for up to four owned vehicles and two leased vehicles. The maximum new vehicle APR is the highest APR among all new vehicles purchased or leased in 2012 or 2013. The education APR maximum rate includes education loans that are not in deferment at the time of the survey. The credit card APR maximum rate is assigned for households that stated that they had a positive credit card balance after their most recent payment was made. Households that paid their credit card balances in full during their most recent payment are not assigned a credit card APR maximum rate. We report cross-household average maximum rates of each loan type in Table A.1. We also compute a maximum rate across all loans held for each household. The right-most column in the table reports the cross-household average.

Table A.1: **Maximum APRs and Interest Rates of Loans Held by New Vehicle Buyers and Leasers in the 2013 Survey of Consumer Finances**

| Statistic | New Vehicle APR | Education APR | Mortgage Interest Rate | Credit Card APR | Maximum Rate Across All Loan Types |
|---|---|---|---|---|---|
| Unweighted Average | 2.19 | 5.51 | 4.15 | 14.77 | 5.79 |
| Weighted Average | 3.36 | 5.86 | 4.39 | 14.83 | 7.78 |
| Sample Size of Sampled Households with Loan Type | 4,060 | 590 | 2,831 | 1,252 | 5,010 |
| Percentage of All New Vehicle Buyers and Leasers | 72 | 10 | 50 | 22 | 89 |

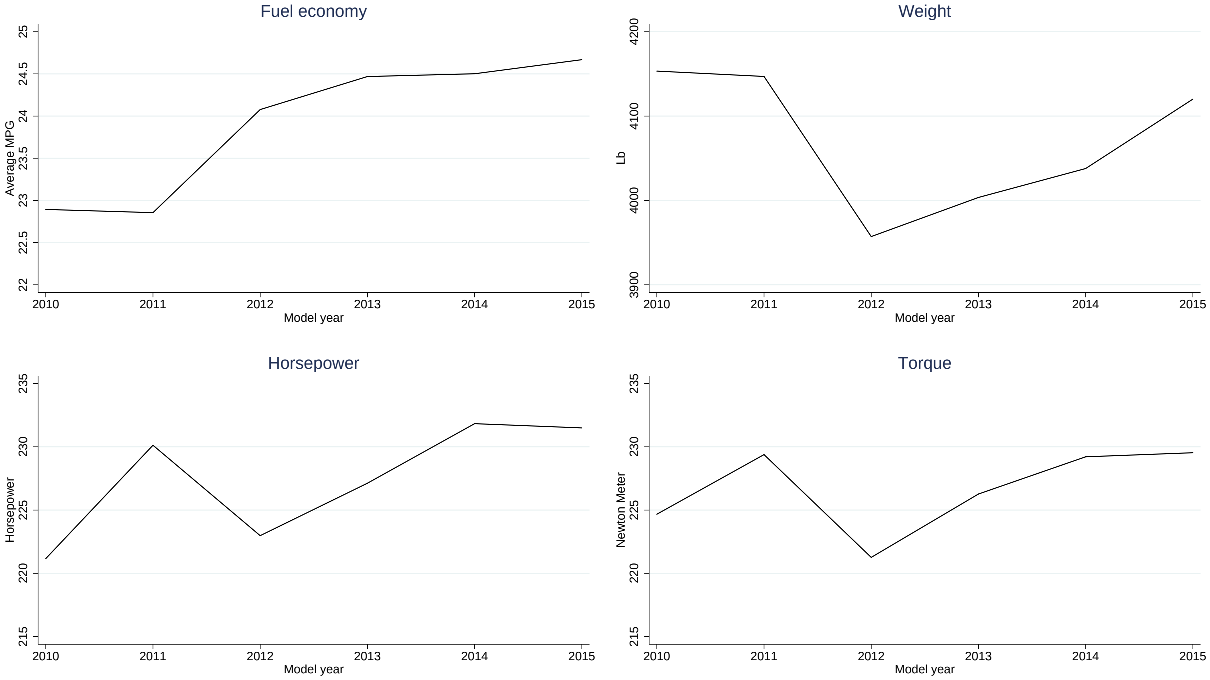
*Notes*: We compute discount rates from the Survey of Consumer Finances (SCF). Each column shows the loan type indicated in the column heading. For each household, we compute the maximum loan rate for each loan type. The first two rows report the means across households of the maximum loan rate by loan type. We also compute the household's maximum loan rate across all loan types. The right-hand column reports the cross-household average of the household's maximum loan rate across all loan types.

Credit card APR rates are higher than the rates from other loans. New vehicle APRs generally have the lowest rate. The maximum rate across loan types, which can be interpreted as the highest opportunity cost of funds for each household, is between 5.79 percent and 7.78 percent, depending on sample weighting. This range is well below the average credit card APR but is above the average new vehicle APR. This is because only 22 percent of the sample has credit card debt, and education and mortgage interest rates are generally higher than new vehicle APRs. Table D.2 reports valuation ratios using discount rates up to 12 percent to show how the range of interest rates affects estimated WTP for fuel cost savings.

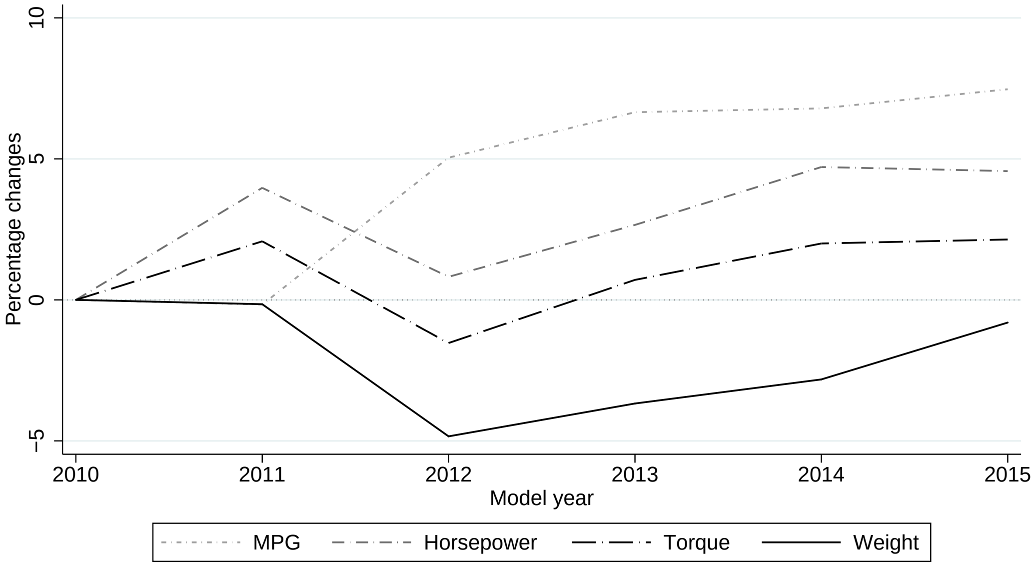
# B Additional Figures, Summary Statistics, First-stage Results, and Robustness Results

Figure B.1: **Fuel Economy, Weight, Horsepower, and Torque by Model Year, 2010–2014**

Panel A. Registration-weighted averages

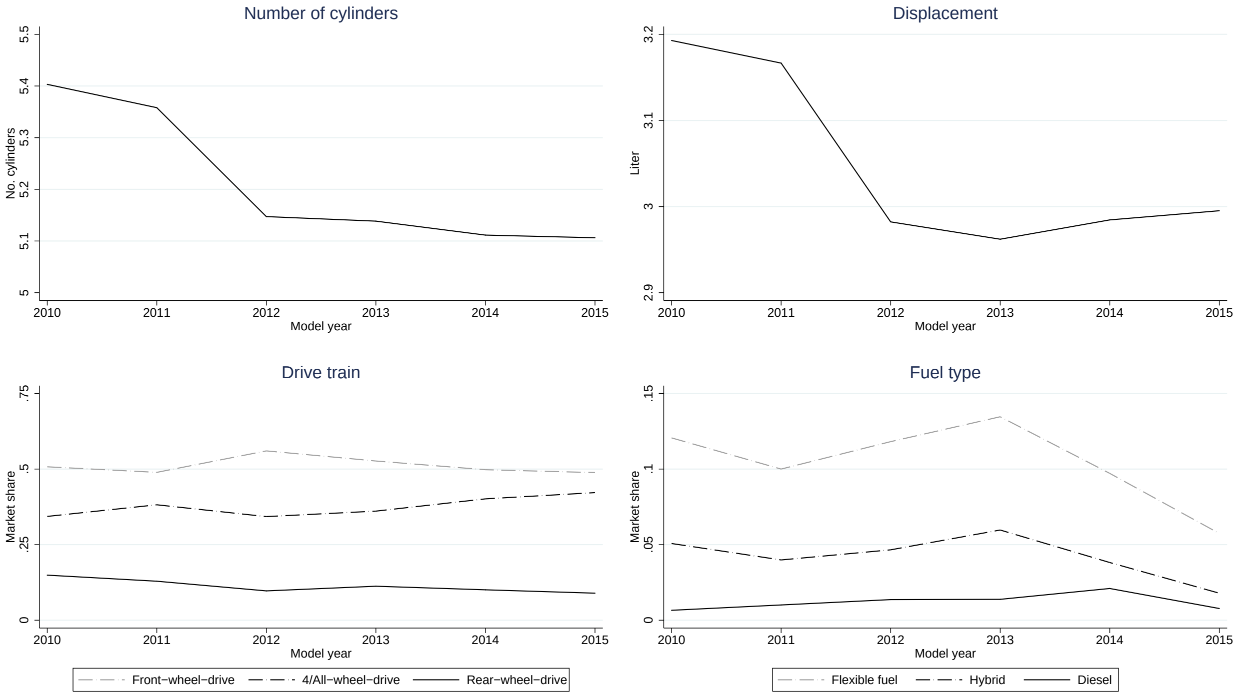


Panel B. Percentage changes



*Notes*: Panel A reports registration-weighted average fuel economy, weight (in pounds, lb), horsepower, and torque (newton meters, nm) by model year. Panel B reports percent changes in these variables since the 2010 model year.

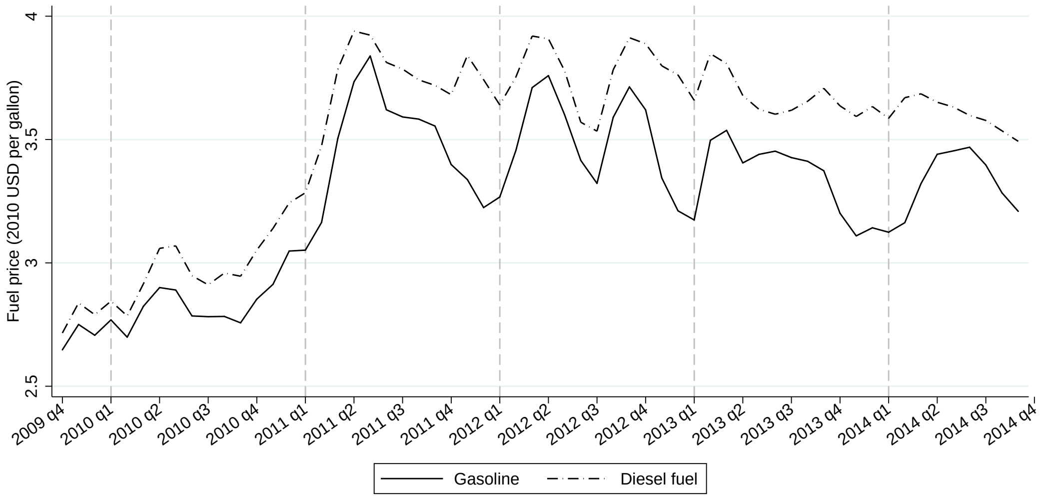
Figure B.2: **Engine and Transmission Variables by Model Year, 2010–2014**



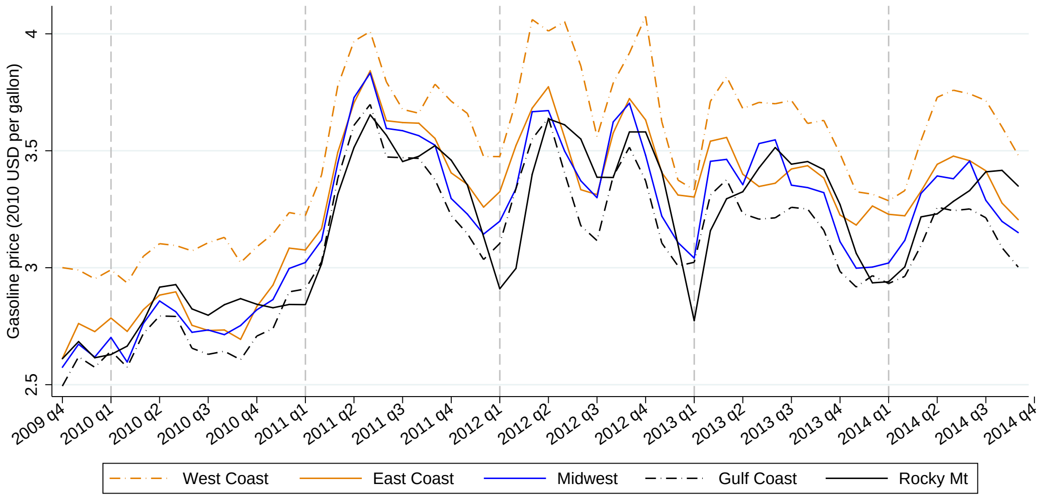
*Notes*: The figure shows registration-weighted number of cylinders and engine displacement, as well as the market shares of drive train type and fuel type.

Figure B.3: **Monthly Fuel Prices, 2009–2014**

Panel A. National average monthly gasoline and diesel fuel prices

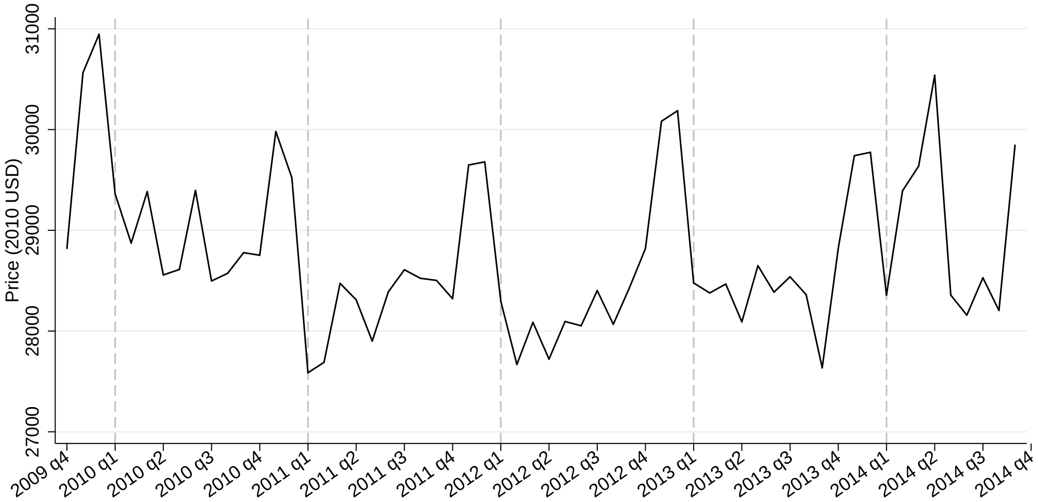


Panel B. Regional average monthly gasoline prices



*Notes*: Panel A shows monthly average national gasoline and diesel fuel prices. Panel B shows monthly gasoline prices by petroleum administration for defense district. Dashed vertical lines indicate the beginning of calendar years.

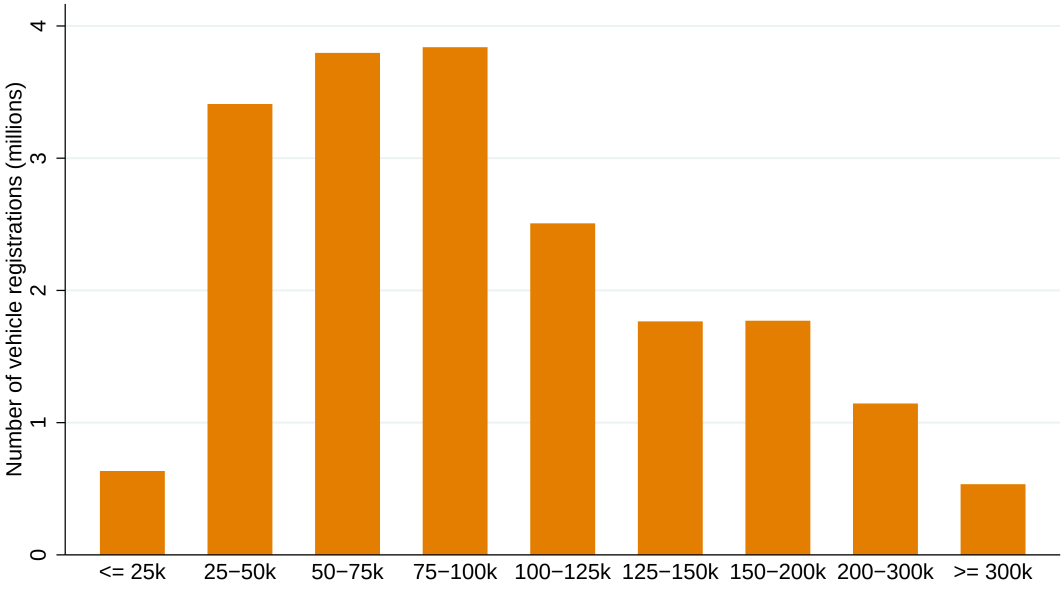
Figure B.4: **Vehicle Transaction Prices, 2009–2014**



*Notes*: The figure shows the monthly registration-weighted average transaction prices, with dashed vertical lines indicating the beginning of calendar years.

Figure B.5: **Distributions of Income and Education**

Panel A. Household income



Panel B. Education

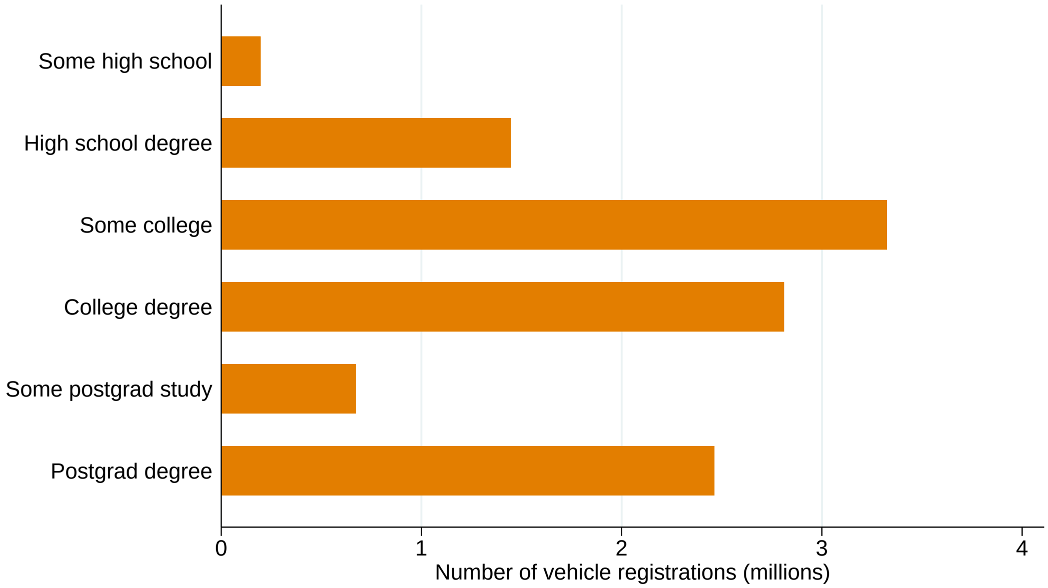


Table B.1: **Summary Statistics on Financing and Purchase Terms, 2009–2014**

| Payment method | Share of vehicles (%) | Annual percentage rate (%) | Length (months) | Monthly payment (USD) | Down payment (USD) |
|---|---|---|---|---|---|
| **Panel A. Purchased** | | | | | |
| 1. Financed | 63.7 | 3.34 | 59.6 | 471 | 2,884 |
| 2. Cash | 23.6 | NA | NA | NA | NA |
| **Panel B. Leased** | 12.7 | NA | 37.0 | 423 | 9,417 |

*Notes*: Annual percentage rate, length of the loan or lease, and payment information are weighted by registrations.

Table B.2: **Variation in Key Attributes Within and Across Model Generations**

Panel A. Model-Variant

| | (1) Across Model Generation Years | | (2) Within Model Generation Years | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Fuel Economy Increase (Percentage) | 0.77 | 3.1 | 0.26 | 2.0 |
| Performance Increase (Percentage) | 0.19 | 3.4 | 0.05 | 4.0 |

Panel B. Trim

| | (1) Across Model Generation Years | | (2) Within Model Generation Years | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Fuel Economy Increase (Percentage) | 1.60 | 4.7 | 0.51 | 3.4 |
| Performance Increase (Percentage) | 0.63 | 6.1 | 0.22 | 5.7 |

Table B.3: **First-Stage Coefficient Estimates from Baseline Price Specification**

| Dependent variable | Log fuel cost | | Log performance | |
|---|---|---|---|---|
| Supercharger | 0.013** | (0.006) | 0.156*** | (0.003) |
| Turbocharger | -0.006** | (0.003) | 0.086*** | (0.027) |
| Gasoline direct injection | -0.055*** | (0.007) | 0.070*** | (0.004) |
| Var. valve lift and timing | 0.023*** | (0.005) | 0.001 | (0.002) |
| Cylinder deactivation | 0.033*** | (0.006) | 0.006*** | (0.002) |
| Cont. variable transmission | -0.126*** | (0.004) | -0.035*** | (0.006) |
| Advanced transmission | -0.024*** | (0.004) | -0.011*** | (0.004) |
| Supercharger × truck | -0.002 | (0.007) | -0.177*** | (0.019) |
| Turbocharger× truck | -0.029*** | (0.007) | 0.110*** | (0.031) |
| Gasoline direct inject. × truck | 0.056*** | (0.009) | -0.042*** | (0.005) |
| Var. valve lift and timing × truck | -0.088*** | (0.006) | 0.021*** | (0.004) |
| Cylinder deactivation × truck | -0.015** | (0.006) | -0.014*** | (0.002) |
| Cont. variable transmission × truck | 0.026*** | (0.007) | 0.047*** | (0.006) |
| Advanced transmission × truck | -0.019*** | (0.005) | 0.002 | (0.005) |
| | | | | |
| Num. of observations | 535,124 | | 535,124 | |
| First-stage Weak Id F test: Stock-Wright F(13, 18272) | 224.9 | | 202.3 | |
| First-stage Weak ID F test: Anderson-Rubin Robust F(14,18272) | - | | 17.2 | |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Robust standard errors in parentheses, clustered by vehicle model and state. The table reports the first stage coefficient estimates for the baseline specification from column 3 of Table 3, Panel A. The bottom row reports the F-statistic on the test that the instruments are jointly equal to zero.

Table B.4: **First Stage Coefficient Estimates from Baseline Quantity Specification**

| Dependent variable | Log fuel cost | | Log performance | |
|---|---|---|---|---|
| Supercharger | 0.053*** | (0.014) | 0.270*** | (0.021) |
| Turbocharger | -0.081*** | (0.006) | -0.033*** | (0.012) |
| Gasoline direct injection | 0.016*** | (0.005) | 0.103*** | (0.009) |
| Var. valve lift and timing | -0.033*** | (0.008) | 0.006 | (0.009) |
| Cylinder deactivation | 0.109*** | (0.007) | 0.216*** | (0.011) |
| Cont. variable transmission | -0.096*** | (0.009) | -0.056*** | (0.011) |
| Advanced transmission | 0.007* | (0.004) | -0.014 | (0.008) |
| Supercharger × truck | -0.066*** | (0.021) | -0.098*** | (0.023) |
| Turbocharger × truck | -0.020* | (0.010) | 0.149*** | (0.015) |
| Gasoline direct inject. × truck | -0.004 | (0.008) | -0.093*** | (0.012) |
| Var. valve lift and timing × truck | 0.040*** | (0.010) | 0.014 | (0.012) |
| Cylinder deactivation × truck | -0.076*** | (0.008) | -0.102*** | (0.014) |
| Cont. variable transmission × truck | 0.071*** | (0.015) | 0.024* | (0.013) |
| Advanced transmission × truck | -0.008*** | (0.001) | 0.005*** | (0.001) |
| | | | | |
| Num. of observations | 535,124 | | 535,124 | |
| F-stat (1st stg excl var.) | 112.1 | | 150.1 | |

* $p<0.10$ ** $p<0.05$ *** $p<0.01$.

*Notes*: Robust standard errors in parentheses, clustered by vehicle model and state. The table reports the first stage coefficient estimates for the baseline specification from column 3 of Table 3, Panel B. The bottom row reports the F statistic on the test that the instruments are jointly equal to zero.

Table B.5: **Baseline WTP by Expected Vehicle Miles Traveled (VMT)**

| | (1)<br>Baseline | (2) |
|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | |
| Log fuel cost | -0.354*** | 2.894*** |
| | (0.075) | (0.785) |
| Expected VMT (in 1 million miles) | | -35.329*** |
| | | (8.564) |
| Log fuel cost × expected VMT | | -17.508*** |
| | | (4.251) |
| Log performance | 0.203*** | 0.176*** |
| | (0.074) | (0.050) |
| | | |
| Number of observations | 535,124 | 450,635 |
| RMSE | 0.13 | 0.14 |
| F-stat (fuel cost) | 185.5 | 185.5 |
| F-stat (fuel cost by VMT) | | 188.6 |
| F-stat (performance) | 243.4 | 243.4 |
| **Panel B. Dependent variable is log new registrations** | | |
| Log fuel cost | -0.338*** | -13.131*** |
| | (0.116) | (3.695) |
| Expected VMT (in 1 million miles) | | 133.401*** |
| | | (38.981) |
| Log fuel cost × expected VMT | | 67.245*** |
| | | (19.642) |
| Log performance | 0.371*** | 0.498*** |
| | (0.083) | (0.086) |
| | | |
| Number of observations | 535,124 | 450,635 |
| RMSE | 0.39 | 0.43 |
| F-stat (fuel cost) | 112.1 | 112.1 |
| F-stat (fuel cost by VMT) | | |
| F-stat (performance) | 150.1 | 150.1 |
| **Panel C. Willingness to pay (2010 USD)** | | |
| For 1 percent increases in | | |
| • fuel economy | 133.4 | |
| at average VMT at 0.19 million miles | | 156.3 |
| with one s.d. of VMT at 0.01 million miles | | [141.3, 172.0] |
| • performance | 93.6 | 97.9 |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline in Table 3. In column 2, we include expected lifetime VMT as an exogenous variable and its interaction with fuel costs as an endogenous variable. The lifetime VMT depends on household income group and broad market segment (car or truck). We construct it from survival data and annual VMT data as described in Section A.3.

## Table B.6: **Estimates for Predicting Vehicle Miles Traveled**

| Dep. var.: vehicle miles traveled | (1) | | (2) | |
|---|---|---|---|---|
| Variables | Cars | | Light truck | |
| Vehicle age | -298.5*** | (16.87) | -341.0*** | (21.61) |
| Vehicle age squared | 6.493*** | (0.582) | 5.013*** | (0.839) |
| Vehicle age cubed | -0.0391*** | (0.00698) | -0.0152 | (0.0110) |
| Household income \$20,000-\$25,000 | -206.2 | (258.2) | -538.1* | (322.5) |
| Household income \$25,000-\$30,000 | 810.5*** | (252.5) | -258.2 | (319.3) |
| Household income \$30,000-\$35,000 | 557.0** | (232.4) | 37.95 | (284.9) |
| Household income \$35,000-\$40,000 | 1,607*** | (262.1) | 710.3** | (328.7) |
| Household income \$40,000-\$45,000 | 1,099*** | (225.5) | 953.9*** | (277.1) |
| Household income \$45,000-\$50,000 | 2,132*** | (257.6) | 1,651*** | (327.5) |
| Household income \$50,000-\$55,000 | 2,096*** | (227.5) | 1,331*** | (276.1) |
| Household income \$55,000-\$65,000 | 2,608*** | (207.6) | 1,883*** | (261.6) |
| Household income \$65,000-\$75,000 | 2,878*** | (216.3) | 1,988*** | (262.4) |
| Household income \$75,000-\$85,000 | 3,061*** | (213.3) | 2,311*** | (262.8) |
| Household income \$85,000-\$100,000 | 3,647*** | (201.8) | 2,828*** | (249.5) |
| Household income >\$100,000 | 3,526*** | (182.8) | 3,098*** | (231.3) |
| Vehicle age x household income \$20,000-\$25,000 | 21.99 | (19.35) | 27.94 | (22.45) |
| Vehicle age x household income \$25,000-\$30,000 | -45.81** | (18.53) | 7.359 | (21.73) |
| Vehicle age x household income \$30,000-\$35,000 | -12.81 | (17.57) | -13.43 | (19.01) |
| Vehicle age x household income \$35,000-\$40,000 | -50.82** | (20.03) | -21.02 | (24.13) |
| Vehicle age x household income \$40,000-\$45,000 | -25.37 | (16.73) | -52.54*** | (19.57) |
| Vehicle age x household income \$45,000-\$50,000 | -80.87*** | (20.01) | -65.82*** | (25.24) |
| Vehicle age x household income \$50,000-\$55,000 | -71.09*** | (17.42) | -68.50*** | (17.42) |
| Vehicle age x household income \$55,000-\$65,000 | -86.40*** | (15.27) | -82.73*** | (19.13) |
| Vehicle age x household income \$65,000-\$75,000 | -88.93*** | (16.78) | -88.46*** | (19.75) |
| Vehicle age x household income \$75,000-\$85,000 | -94.87*** | (16.25) | -91.95*** | (20.13) |
| Vehicle age x household income \$85,000-\$100,000 | -119.1*** | (15.16) | -111.6*** | (18.92) |
| Vehicle age x household income >\$100,000 | -125.9*** | (13.64) | -131.2*** | (16.74) |
| Constant | 11,069*** | (177.7) | 12,937*** | (228.6) |
| | | | | |
| Observations | 869 | | 785 | |
| R-squared | 0.893 | | 0.905 | |

* p<0.10 ** p<0.05 *** p<0.01

## Table B.7: **Estimates for Survival Rate**

| | (1) | | (2) | |
|---|---|---|---|---|
| | Cars | | Light truck | |
| | Age $\leq 10$ | Age $> 10$ | Age $\leq 10$ | Age $> 10$ |
| $A = -\gamma_0/\gamma_1$ | 1.90 | 2.28 | 1.96 | 2.21 |
| $B = 1/\gamma_1$ | -0.13 | -0.16 | -0.12 | -0.14 |

# C Addressing potential sources of bias

As discussed in Section 3, the IV strategy would yield inconsistent estimates if time-varying vehicle quality is correlated with the technology instruments, after controlling for average quality of each vehicle model-variant. This appendix provides evidence supporting the validity of the IV estimates.

If the instruments are correlated with quality, we would expect that the fuel economy and performance estimates would change if we add variables that are likely to be correlated with quality. We address this possibility in two ways, first by including variables that may directly measure vehicle quality, and second by including variables that may be indirectly correlated with quality. We begin by collecting variables from Chrome that are typically not included in vehicle demand models, and which may therefore reflect quality that is unobserved in these other studies. Specifically, in column 2 of Appendix Table C.1 we add controls that vary within model-variants and across model years, including the number of passengers, cubic feet of passenger volume, cubic feet of cargo volume, and a dummy for a moonroof or a sunroof. They are not reported for some of the observations in our data, which reduces the sample size. The coefficient estimates in the price equation remain similar to the baseline specification (which is reported in column 1 for convenience), while the fuel cost coefficient in the quantity equation increases in magnitude. As a result, the implied willingness to pay for fuel economy is higher (as shown in Panel C of Appendix Table C.1), suggesting a valuation ratio of 0.77. Although this ratio is higher than in the baseline, the conclusion holds that consumers undervalue fuel economy. Moreover, the welfare conclusions in Section 5 are the same if we use these estimates rather than the baseline.

As an alternative measure of quality, we include consumer experience ratings reported in the MaritzCX survey. Respondents report ratings on a scale of 1 to 5 for a number of vehicle attributes, such as the vehicle's appearance and the quality of the sound system. We include 10 of these attributes as covariates in column 3. Although these measures are subjective, they are likely to be correlated with the consumer's perceived quality, and hence the transaction price. Identification rests on the assumption that the instrumented fuel economy and performance are uncorrelated with these quality measures, which is confirmed in column 3.

Recall that manufacturers typically make major redesigns of individual vehicles every 5-7 years; each redesign results in a new "generation" of the model. During a redesign, manufacturers are more likely to make major changes to the vehicle that could affect quality, compared to changes that are typically made between redesigns. This market regularity suggests that quality variation across generations may be more strongly correlated with the instruments than quality variation within generations. If this is the case, interacting model-variant fixed effects with model generation fixed effects would cause WTP estimates to differ from the baseline. Columns 4 and 5 show that this is not the case. In column 4, we interact model-variant fixed effects with model generation fixed effects, and in column 5, we interact model-variant fixed effects with an indicator that equals one if the model year represents a new generation.[38] In each of these specifications, the implied valuations for fuel economy and performance (shown in Panel C) are similar to those found in the baseline model.

Next we turn to indirect proxies for quality in Appendix Table C.2. Suppose that vehicles have (unobserved) automated safety features, such as blind spot detection. If manufacturers add automated safety features at the same time as adopting fuel-saving technology, quality would be correlated with the instruments. However, in this case quality would also be correlated with income and household size, as one expects households that have higher income or that include children to have higher WTP for automated safety features. Based on this reasoning, we add to the baseline IV specification of equations (5) and (6) six demographic controls: respondent's age, household size, male indicator, urban indicator, fixed effects for the respondent's education group (12 groups), and fixed effects for 23 household income groups. Note that the sample is smaller than the baseline because of missing demographics data. This specification controls for unobserved features correlated with demographics. Column 1 of Appendix Table C.2 repeats the baseline estimates for convenience, and column 2 reports the coefficient estimates when including these controls. The estimates are similar to the baseline. We estimate equations (5) and (6) with additional demographic controls in column 3, including the number of wage earners, number of children, an indicator equal to one if the respondent's spouse is employed, fixed effects for the respondent's race (6 categories), and fixed effects for the respondent's occupation (20 categories). The additional demographics further reduce the sample size, but the coefficient estimates are similar to the baseline.[39]

A vehicle's quality may also vary by location and time. Returning to the safety example, residents of the Northeast may have higher WTP for safety features because of the poor weather conditions in that region. The state fixed effects control for the average probability that the vehicles contain these features, but preferences or costs of the features may vary over time. If preference or cost changes are correlated with technology adoption, the IV estimates would be inconsistent. In column 4 we include additional time fixed effects by interacting state fixed effects with model-year fixed effects, and interacting state fixed effects with month-of-year fixed effects. In Appendix Table C.4 we further include fixed effects of region by month by year by fuel type with vehicle segment or body type. The coefficient estimates are similar to the baseline.

Above, we noted that there have been a few negative reports of consumer experiences with continuously variable transmissions and cylinder deactivation, particularly when these technologies first entered the market. If consumers value (either negatively or positively) these technologies for reasons other than their effects on fuel economy and performance, the IV estimates would be

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[38] We collected model generation years from Klier et al. (2017). These data are available upon request.

[39] The recession and post-recession recovery could affect the composition of households that participate in the new vehicle market. The fact that the WTP estimates are robust to controlling for demographics suggests that such selection does not bias our estimates. Appendix Table C.5 provides further evidence that the post-recession recovery does not affect the results.

inconsistent because the instruments would be correlated with quality. Column 5 of Appendix Table C.2 shows that omitting these variables as instruments does not affect the point estimates.

A concern related to the negative reports is that some consumers may value the technologies directly. For example, a household may value having a turbocharger, independently of the changes in horsepower enabled by the technology. A household's reported ratings of the vehicle's technical innovation, engine performance, power, and transmission are likely to be correlated with its perception of the technologies that affect performance, such as a turbocharger. Appendix Table C.3 shows that the results are robust to controlling for these ratings. The results are also robust to dropping observations that include a turbocharger, which may be more visible to consumers than the other technology instruments because manufacturers sometimes advertise the presence of a turbocharger to consumers. Thus, the results in Appendix Tables C.2 and C.3 reduce concerns that consumer valuation of the IVs, independent of their effects on fuel economy and performance, cause the IV estimates to be inconsistent.

If households face borrowing constraints, changes in financial market conditions could affect borrowing costs and the composition of households that choose to purchase a new vehicle. If WTP varies across households and the variation is correlated with borrowing costs, the WTP estimates could be inconsistent. However, column 6 of Appendix Table C.2 shows that controlling for financing arrangement and payment type does not affect the results, reducing this concern. Likewise, column 7 shows that the results are similar if we omit observations from 2009, when borrowing rates were relatively high following the economic recession. Results are similar although noisier if we omit 2010 as well, which covers the beginning of the post-recession recovery (not reported). Appendix Table C.5 shows that the results are similar to the baseline if we add further time interactions to control for macroeconomic conditions. These results suggest that macroeconomic conditions do not affect our WTP estimates.

As a final validation of the IV strategy, we report the reduced-form relationship between transaction prices and the fuel-saving technology instruments. Because the technologies can increase both fuel economy and performance, we expect a positive and monotonic relationship between a vehicle's price and the number of technologies it contains. In contrast, although we expect a positive correlation between the number of technologies and quality, the relationship between the number of technologies and quality is not necessarily monotonic. Therefore, if quality is correlated with the instruments, we may observe a non monotonic relationship between the number of fuel-saving technologies in a vehicle and its transaction price. We compute the number of technologies for each vehicle in the sample (we top-code the count at five because few observations contain more than five technologies). We regress the log of the transaction price on the same independent variables as in the baseline specification of equation (5), as well as fixed effects for the number of fuel-saving technologies. The top panel of Appendix Figure C.1 plots the coefficients and 95 percent confidence intervals. The figure illustrates a positive and monotonic relationship between the transaction price and the technology count.

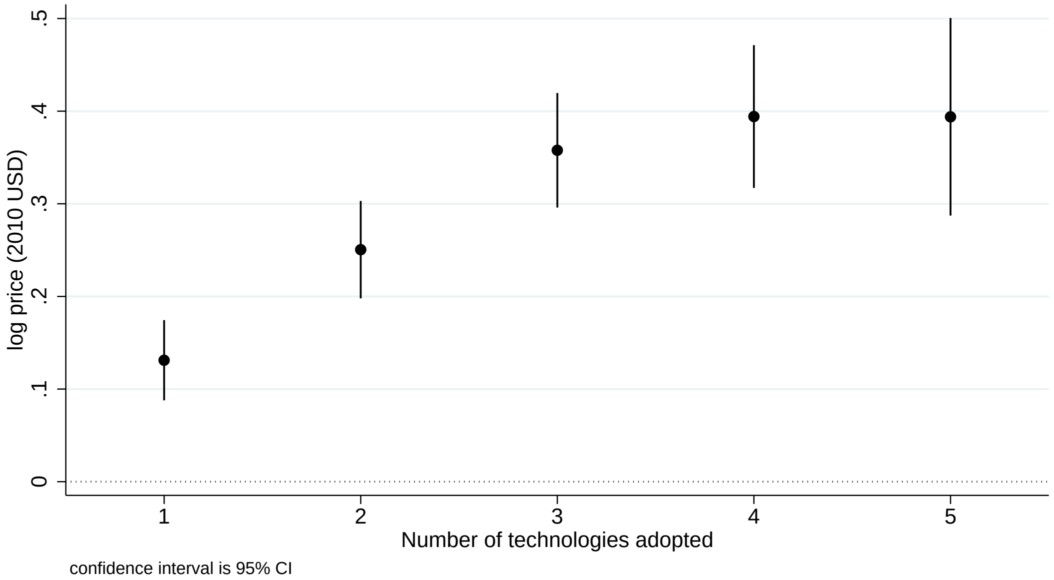
We estimate a second reduced-form regression of the transaction price on indicator variables for each technology. If the instruments are valid, each technology should increase the transaction price. However, if quality is positively correlated with some instruments and negatively correlated with others, we could observe negative correlations among transaction price and the latter technologies. The bottom panel of Appendix Figure C.1 reports the estimated coefficients and confidence intervals. All coefficients are positive and most are statistically significant at the 5 percent level. Overall, both sets of reduced-form regressions support the IV strategy.

Finally, we consider two potential sources of bias related to the performance variable. First, in the baseline we use different measures of performance for cars and light trucks, under the assumption that car consumers value acceleration time (proportional to horsepower) and truck consumers value towing capacity (proportional to torque). Many truck consumers may value acceleration time at least as much as towing capacity. However, Appendix Table C.6 shows that the results are similar to the baseline if we use acceleration rather than towing capacity for light trucks, which likely reflects the high correlation between horsepower and torque.

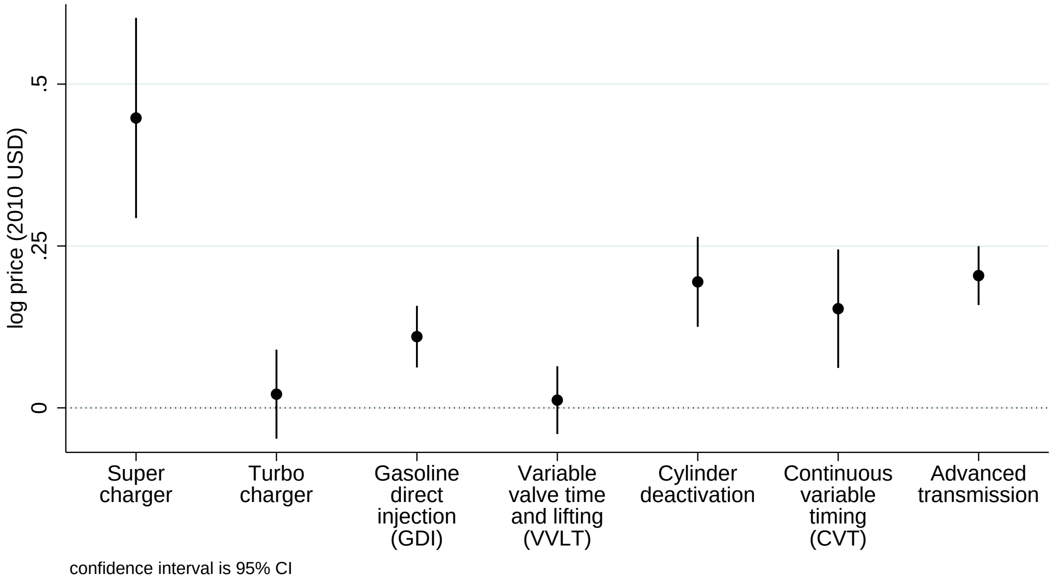
Second, a household's actual enjoyment of a vehicle's performance may differ from the household's expected enjoyment. For example, a household may expect to enjoy a high-performance vehicle more than it actually does. In that case, we would expect that controlling for the household's self-reported *ex post* enjoyment of the vehicle's performance would affect the estimated WTP for performance. In fact, Appendix Table C.7 shows that adding these controls does not affect the WTP estimates.

Figure C.1: **Reduced-Form Relationships: Prices and Fuel-Saving Technologies**

Panel A. Number of fuel-saving technologies



Panel B. Individual fuel-saving technologies



*Notes*: Panel A reports the coefficients on fixed effects for the number of fuel-saving technologies from a regression of log transaction price on the count fixed effects and the other independent variables from column 3 of Table 3. The number of technologies is top-coded at five because fewer than 1 percent of observations have more than five technologies. Panel B reports results from a similar regression, except that the count fixed effects are replaced by fixed effects for each technology. The vertical lines indicate 95 percent confidence intervals.

Table C.1: **Directly Control for Vehicle Quality**

| | (1) Baseline | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | | | | |
| Log fuel cost | -0.354*** | -0.385*** | -0.312*** | -0.172*** | -0.297*** |
| | (0.075) | (0.078) | (0.054) | (0.055) | (0.056) |
| Log performance | 0.203*** | 0.280*** | 0.205*** | 0.335*** | 0.255*** |
| | (0.074) | (0.041) | (0.048) | (0.039) | (0.045) |
| Control for vehicle quality | | Quality attributes | Consumer experience ratings | Model-variant FE interacted with model generation FE | Model-variant FE interacted with generation change dummy |
| Number of observations | 535,124 | 410,770 | 454,660 | 535,124 | 535,124 |
| RMSE | 0.13 | 0.13 | 0.13 | 0.39 | 0.13 |
| F-stat (fuel cost) | 185.5 | 163.5 | 174.6 | 110.0 | 163.1 |
| F-stat (performance) | 243.4 | 102.1 | 216.0 | 206.3 | 272.0 |
| **Panel B. Dependent variable is log new registrations** | | | | | |
| Log fuel cost | -0.338*** | -0.860*** | -0.319*** | -0.722*** | -0.258** |
| | (0.116) | (0.149) | (0.115) | (0.154) | (0.117) |
| Log performance | 0.371*** | 0.353*** | 0.320*** | 0.298*** | 0.362*** |
| | (0.083) | (0.099) | (0.084) | (0.074) | (0.078) |
| Control for vehicle quality | | Quality attributes | Consumer experience ratings | Model-variant FE interacted with model generation FE | Model-variant FE interacted with generation change dummy |
| Number of observations | 535,124 | 410,770 | 454,660 | 535,124 | 535,124 |
| RMSE | 0.39 | 0.40 | 0.39 | 0.39 | 0.39 |
| F-stat (fuel cost) | 112.1 | 104.5 | 110.8 | 110.0 | 118.4 |
| F-stat (performance) | 150.1 | 229.4 | 141.9 | 206.3 | 210.4 |
| **Panel C. Willingness to pay (2010 USD)** | | | | | |
| For 1 percent increases in | | | | | |
| • fuel economy | 133.4 | 192.5 | 119.7 | 118.2 | 109.6 |
| • performance | 93.6 | 113.8 | 89.2 | 124.3 | 107.5 |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline in Table 3. Column 2 includes additional characteristics from the Chrome dataset to capture vehicle quality: number of passengers, passenger volume (cubic ft), cargo volume (cubic ft), and "moonroof" or "sunroof" dummy variables. Column 3 adds controls of consumers' experience rating in the MaritzCX survey on a scale of 1 to 5: overall appearance; usefulness for carrying passengers; performance of entertainment system; exterior styling and workmanship; overall front room; interior material including seating and interior styling; quietness inside the vehicle; well equipped to prevent theft and vandalism; and exterior workmanship and attention to detail. In column 4, we further interact model-variant fixed effects with model generation fixed effects. In column 5, we further interact model-variant fixed effects with an indicator if the model is a new generation in the observed model year.

Table C.2: **Include Proxies for Vehicle Quality and Other Sources of Bias**

| | (1)<br>Baseline | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | | | | | | |
| Log fuel cost | -0.354*** | -0.351*** | -0.352*** | -0.356*** | -0.387*** | -0.333*** | -0.336*** |
| | (0.075) | (0.055) | (0.056) | (0.054) | (0.083) | (0.055) | (0.054) |
| Log performance | 0.203*** | 0.221*** | 0.228*** | 0.207*** | 0.200*** | 0.215*** | 0.210*** |
| | (0.074) | (0.048) | (0.050) | (0.046) | (0.050) | (0.045) | (0.047) |
| Control for vehicle quality | | Demographic | Demographic | Richer time controls | Drop CVT, deactivation | | |
| Finance control | | | | | | Yes | |
| Drop 2009 | | | | | | | Yes |
| Num. of obs. | 535,124 | 497,867 | 450,515 | 535,124 | 535,124 | 515,994 | 507,461 |
| RMSE | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| F-stat (fuel cost) | 185.5 | 182.3 | 181.0 | 186.3 | 68.4 | 187.9 | 182.8 |
| F-stat (perform.) | 243.4 | 239.9 | 233.4 | 247.2 | 290.8 | 229.6 | 229.7 |
| **Panel B. Dependent variable is log new registrations** | | | | | | | |
| Log fuel cost | -0.338*** | -0.348*** | -0.334*** | -0.325*** | -0.055 | -0.339*** | -0.363*** |
| | (0.116) | (0.116) | (0.118) | (0.037) | (0.142) | (0.116) | (0.102) |
| Log performance | 0.371*** | 0.363*** | 0.345*** | 0.356*** | 0.505*** | 0.371*** | 0.184** |
| | (0.083) | (0.084) | (0.083) | (0.022) | (0.136) | (0.083) | (0.075) |
| Control for vehicle quality | | Demographic | Demographic | Richer time controls | Drop CVT, cylinder deactivation | | |
| Finance control | | | | | | Yes | |
| Drop 2009 | | | | | | | Yes |
| Num. of obs. | 535,124 | 497,867 | 450,515 | 535,124 | 535,124 | 515,994 | 507,461 |
| RMSE | 0.39 | 0.40 | 0.40 | 0.39 | 0.40 | 0.39 | 0.38 |
| F-stat (fuel cost) | 112.1 | 111.2 | 109.2 | 112.5 | 77.9 | 112.9 | 112.3 |
| F-stat (perform.) | 150.1 | 147.6 | 143.0 | 149.5 | 127.3 | 149.8 | 138.2 |
| **Panel C. Willingness to pay (2010 USD)** | | | | | | | |
| For 1 percent increases in | | | | | | | |
| • fuel economy | 133.4 | 133.7 | 132.6 | 132.9 | 116.0 | 127.7 | 130.8 |
| • performance | 93.6 | 97.2 | 98.1 | 93.2 | 105.4 | 96.9 | 77.6 |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline in Table 3. Column 2 adds to column 1 six demographic controls: respondent's age, household size, indicator for male, urbanization indicator, 12 respondent education group fixed effects, and 23 household income group fixed effects. Column 3 adds to column 2 five additional demographic controls: number of wage earners, number of children, indicator equaling one if the respondent's spouse is employed, six respondent race fixed effects, and 20 respondent occupation fixed effects. Column 4 includes state by model-year fixed effects and state by month-of-year fixed effects. In column 5, we drop continuously variable transmission, cylinder deactivation, and their interactions with truck as instruments. In column 6, we include fixed effects for financing source (arrange own financing, finance via dealership, or do not finance) and fixed effects for payment type (automaker's loan/lease, bank loan/lease, friend/relative, cash, credit union loan, another finance company loan/lease, or other). In column 7, we drop observations if a transaction took place in 2009.

## Table C.3: **Accounting for Potentially Visible IVs**

| | (1) | (2) | (3) |
|---|---|---|---|
| | Baseline | | |
| **Panel A. Dependent variable is log transaction price** | | | |
| Log fuel cost | -0.354*** | -0.328*** | -0.355*** |
| | (0.075) | (0.064) | (0.055) |
| Log performance | 0.203*** | 0.188*** | 0.208*** |
| | (0.074) | (0.050) | (0.047) |
| Feature rating (technical innovation) | | 0.007*** | |
| | | (0.001) | |
| Feature rating (engine performance) | | -0.003** | |
| | | (0.001) | |
| Feature rating (power) | | 0.000 | |
| | | (0.001) | |
| Feature rating (transmission) | | 0.003*** | |
| | | (0.001) | |
| Drop if "turbocharger" is part of nameplate | | | Yes |
| Drop if a vehicle has turbocharger | | | |
| Num. of obs. | 535,124 | 313,879 | 517,420 |
| RMSE | 0.13 | 0.13 | 0.40 |
| **Panel B. Dependent variable is log new registrations** | | | |
| Log fuel cost | -0.338*** | -0.323*** | -0.337*** |
| | (0.116) | (0.122) | (0.122) |
| Log performance | 0.371*** | 0.380*** | 0.423*** |
| | (0.083) | (0.087) | (0.090) |
| Feature rating (technical innovation) | | 0.008*** | |
| | | (0.001) | |
| Feature rating (engine performance) | | 0.000 | |
| | | (0.002) | |
| Feature rating (power) | | -0.012*** | |
| | | (0.002) | |
| Feature rating (transmission) | | 0.001 | |
| | | (0.001) | |
| Drop if "turbocharger" is part of nameplate | | | Yes |
| Drop if a vehicle has turbocharger | | | |
| Num. of obs. | 535,124 | 313,879 | 517,420 |
| RMSE | 0.39 | 0.39 | 0.40 |
| **Panel C. Willingness to pay (2010 USD)** | | | |
| For 1 percent increases in | | | |
| • fuel economy | 133.4 | 124.7 | 133.7 |
| • performance | 93.6 | 72.5 | 80.8 |
| * p<0.10 ** p<0.05 *** p<0.01 | | | |

*Notes*: Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline. Column 2 adds ratings of the indicated vehicle attributes, which are measured on a scale of 1 to 5. Column 3 omits observations that include "turbocharger" or a related term in the nameplate.

Table C.4: **Additional Time Fixed Effects**

| | (1) (Baseline) | (2) | (3) |
|---|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | | |
| Log fuel cost | -0.354*** | -0.442*** | -0.455*** |
| | (0.075) | (0.055) | (0.064) |
| Log performance | 0.203*** | 0.118** | 0.167*** |
| | (0.074) | (0.047) | (0.045) |
| Region by month by fuel type interacted with | | truck | body type |
| Num. of obs. | 535,124 | 535,124 | 534,457 |
| RMSE | 0.13 | 0.13 | 0.13 |
| **Panel B. Dependent variable is log new registrations** | | | |
| Log fuel cost | -0.338*** | -0.376*** | -0.267** |
| | (0.116) | (0.116) | (0.113) |
| Log performance | 0.371*** | 0.379*** | 0.306*** |
| | (0.083) | (0.082) | (0.075) |
| Region by month by fuel type interacted with | | truck | body type |
| Num. of obs. | 535,124 | 535,124 | 534,457 |
| RMSE | 0.39 | 0.39 | 0.38 |
| **Panel C. Willingness to pay (2010 USD)** | | | |
| For 1 percent increases in | | | |
| • fuel economy | 133.4 | 162.5 | 155.8 |
| • performance | 93.6 | 72.3 | 58.4 |
| **Panel D. Welfare implications (2010 USD)** | | | |
| Welfare benefit: | | | |
| Fuel cost savings | 249 | 249 | 249 |
| Welfare cost | | | |
| Tech adoption | 11 | 11 | 11 |
| Performance tradeoff | 413 | 319 | 258 |
| Total | -175 | -81 | -20 |
| Compare to vehicle price | -6% | -3% | -0.7% |
| * p<0.10 ** p<0.05 *** p<0.01 | | | |

*Notes:* Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline in Table 3. Columns 2 and 3 include interactions of truck or body type fixed effects with interactions of region, month, and fuel type.

## Table C.5: **Control for the Great Recession and Other Unobservables**

| | (1) Baseline | (2) Tab B.12(7) | (3) Tab B.12(4) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | | | | | |
| Log fuel cost | -0.354*** | -0.336*** | -0.356*** | -0.357*** | -0.348*** | -0.351*** |
| | (0.075) | (0.054) | (0.054) | (0.054) | (0.054) | (0.054) |
| Log performance | 0.203*** | 0.210*** | 0.207*** | 0.206*** | 0.243*** | 0.239*** |
| | (0.074) | (0.047) | (0.046) | (0.046) | (0.048) | (0.048) |
| Time Frame | | Drop 2009 | | | | |
| Additional interactions$m^2$ | | | State fixed effects by linear year and month trend | Column 3 with linear and quadratic trends | Income, hh size, gender, married, race, urban, occupation by linear year and month trend | Column 5 with linear and quadratic trends |
| Num. of obs. | 535,124 | 507,461 | 535,124 | 535,124 | 479,446 | 479,446 |
| RMSE | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| **Panel B. Dependent variable is log new registrations** | | | | | | |
| Log fuel cost | -0.338*** | -0.363*** | -0.325*** | -0.338*** | -0.332*** | -0.335*** |
| | (0.116) | (0.102) | (0.037) | (0.115) | (0.117) | (0.116) |
| Log performance | 0.371*** | 0.184** | 0.356*** | 0.367*** | 0.359*** | 0.349*** |
| | (0.083) | (0.075) | (0.022) | (0.083) | (0.083) | (0.082) |
| Time Frame | | Drop 2009 | | | | |
| Additional interactions | | | State fixed effects by linear year and month trend | Column 3 with linear and quadratic trends | Income, hh size, gender, married, race, urban, occupation by linear year and month trend | Column 5 with linear and quadratic trends |
| Num. of obs. | 535,124 | 507,461 | 535,124 | 535,124 | 479,446 | 479,446 |
| RMSE | 0.39 | 0.38 | 0.39 | 0.39 | 0.39 | 0.39 |

* $p<0.10$ ** $p<0.05$ *** $p<0.01$

Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline in Table 3. Column 2 drops observations from 2009. Columns 3 through 6 add the interactions indicated in the table.

## Table C.6: **Alternative Measure of Performance**

| Dependent variable: log price or quantity | (1) Baseline | (2) |
|---|---|---|
| **Panel A. Price regression estimates** | | |
| Log fuel cost | -0.354*** | -0.334*** |
| | (0.075) | (0.111) |
| Log performance (hp/lb, or nm/lb) | 0.203*** | |
| | (0.074) | |
| Log performance (hp/lb) | | 0.217* |
| | | (0.123) |
| Number of observations | 535,124 | 535,130 |
| RMSE | 0.13 | 0.13 |
| F-stat (fuel cost) | 185.5 | 19.1 |
| F-stat (performance) | 243.4 | 98.0 |
| **Panel B. Quantity regression estimates** | | |
| Log fuel cost | -0.338*** | -0.580*** |
| | (0.116) | (0.038) |
| Log performance (hp/lb, or nm/lb) | 0.371*** | |
| | (0.083) | |
| Log performance (hp/lb) | | 0.589*** |
| | | (0.026) |
| Number of observations | 535,124 | 535,130 |
| RMSE | 0.39 | 0.40 |
| F-stat (fuel cost) | 112.1 | 1540.2 |
| F-stat (performance) | 150.1 | 2047.9 |
| * $p<0.10$ ** $p<0.05$ *** $p<0.01$. | | |

*Notes*: Standard errors in parentheses, clustered by trim. Column 1 repeats the baseline. Column 2 use horsepower-to-weight ratio for all vehicles.

Table C.7: **Controlling for Rated Experience of Performance**

| | (1) Baseline | (2) |
|---|---|---|
| **Panel A. Dependent variable is log transaction price** | | |
| Log fuel cost | -0.354*** | -0.336*** |
| | (0.075) | (0.054) |
| Log performance | 0.203*** | 0.195*** |
| | (0.074) | (0.048) |
| Control for experience ratings of performance | | Yes |
| Num. of obs. | 535,124 | 457,474 |
| RMSE | 0.13 | 0.13 |
| **Panel B. Dependent variable is log new registrations** | | |
| Log fuel cost | -0.338*** | -0.341*** |
| | (0.116) | (0.114) |
| Log performance | 0.371*** | 0.328*** |
| | (0.083) | (0.085) |
| Control for experience ratings of performance | | Yes |
| Num. of obs. | 535,124 | 457,474 |
| RMSE | 0.39 | 0.39 |
| **Panel C. Willingness to pay (2010 USD)** | | |
| For 1 percent increases in | | |
| • fuel economy | 133.4 | 124.7 |
| • performance | 93.6 | 72.5 |
| * p<0.10 ** p<0.05 *** p<0.01 | | |

*Notes*: Robust standard errors in parentheses, clustered by vehicle model by state. Column 1 repeats the baseline. In column 2, we control for 9 ratings (from 1 to 5) on driving performance, engine power and acceleration, sound of engine/exhaust during driving, engine runs smoothly while idling, transmission responsiveness and smoothness, ride smoothness on good roads at highway speed, ride smoothness over bumps and potholes, maneuverability in city traffic and tight spaces, and feeling in control while driving around curves on highways.

Table C.8: **Welfare Implications under Alternative Assumptions of Demand Elasticities**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Assumed elasticity | -2 | -3 (baseline) | -4 | -5 |
| Panel A: Previous literature | | | | |
| Fuel cost savings | \$249 | \$249 | \$249 | \$249 |
| Consumer Valuation (based on WTP for fuel cost) | \$150 | \$133 | \$125 | \$121 |
| Welfare benefit | \$99 | \$116 | \$124 | \$128 |
| Panel B: This paper | | | | |
| Welfare benefit: | | | | |
| Fuel cost savings | \$249 | \$249 | \$249 | \$249 |
| Welfare cost: | | | | |
| Tech adoption cost | \$11 | \$11 | \$11 | \$11 |
| Performance trade-off (based on WTP for performance) | \$413 | \$347 | \$314 | \$294 |
| Total cost | \$424 | \$358 | \$325 | \$305 |
| Welfare net benefit | -\$175 | -\$109 | -\$76 | -\$56 |
| Compared to average price | (6%) | (4%) | (3%) | (2%) |

*Notes*: Panel A shows the welfare calculations performed in the standard analysis, which does not include forgone performance. Panel B shows the results when we include the forgone performance.

Table C.9: **Welfare Implications with Heterogeneous Elasticities Correlated with Performance WTP**

| | (1) | (2) |
|---|---|---|
| | (baseline) | heterogeneous elasticity |
| Assumed elasticity | -3 for all vehicles | -4 if log perf. < 33rd percentile<br>-3 if log perf. from 33rd to 67th percentile<br>-2 if log perf. > 67th percentile |
| Panel A: Willingness to pay (2010 USD) | | |
| For 1 percent increases in | | |
| • fuel economy | \$133.4 | \$135.3 |
| • performance | \$93.6 | \$75.0 |
| Panel B: Welfare Implications | | |
| Welfare benefit: | | |
| Fuel cost savings | \$249 | \$249 |
| Welfare cost: | | |
| Tech adoption cost | \$11 | \$11 |
| Performance tradeoff (based on WTP for performance) | \$347 | \$278 |
| Total cost | \$358 | \$289 |
| Welfare net benefit | -\$109 | -\$40 |
| Compared to average price | (4%) | (1.5%) |

*Notes*: Panel A shows the WTP calculations under the assumed own-price elasticity of demand indicated in the column heading. Panel B shows the corresponding welfare calculations.

# D WTP and Fuel Savings under Alternative Assumptions

In section 4.2 we show undervaluation using our baseline assumptions. In this section, we describe alternative methods of calculating WTP and fuel savings and our results are robust to alternative assumptions.

Our WTP estimates depend on the slope of the demand curve. We assume the demand elasticity is -3 in our baseline. Table D.1 show that the ranges of WTP for fuel saving and performance if the demand elasticity is equal to -2, -4, or -5. In Table Table D.2 Panel A.1 and Panel B.1, we show that the undervaluation is robust to demand elasticities.

Table D.2 Panel A.2 also reports results using alternative real discount rates that have been used in the literature, of 5, 7, 10, and 12 percent. To put these alternative higher discount rates in context, a 7 percent real discount rate is about the national average interest rate for a 24-month personal loan, and 12 percent is close to the credit card real interest rate in our sample period.[40] A potential argument for using the credit card rate as the discount rate is that a substantial share of US households have credit card debt, and for these households the credit card rate would represent the marginal cost of borrowing. However, new vehicle buyers have higher income than typical households, and are less likely to have credit card debt than are typical households. In our sample, about 75 percent of survey respondents report having perfect credit with no late payments. It would be inappropriate to use credit card rates as the discount rate for a typical househld because the credit card rate does not represent the marginal cost of borrowing. Thus, the conclusion about undervaluation is robust to using discount rates that are appropriate for our sample.

Moreover, we find undervaluation if, instead of assuming that fuel prices follow a random walk, we use projected fuel prices from the Energy Information Administration's Annual Energy Outlook. We report results Table D.2 Panel A.3. In Thus, we consistently find undervaluation when we vary the survival probability, miles traveled, demand elasticity, discount rate, and fuel price projection.

Lastly, we explore factors that may drive the difference of our results and Busse et al. (2013). One possibility is that we use different assumptions of vehicle use. Busse et al. (2013) evaluate the extent of consumer undervaluation using the same methodology from Lu (2006), but using older data than we use. Our assumptions are described in Table D.3 and we describe how we compute these numbers in Appendix A. If we use data in Busse et al. (2013) instead of ours, the present discounted value of fuel cost savings declines from \$249 to \$184. Using their data we obtain a valuation ratio of 73 percent, showing that the undervaluation is robust to the choice of data. Table D.2 Panel A.4 and B.2 shows that the conclusion of fuel saving undervaluation is robust using methodologies in Busse et al. (2013).

Our replication of their methodology using our data suggests otherwise.[41] Table D.4 shows that whereas Busse et al. (2013) report discount rates of -4.0 to 9.8 percent, using our data and their

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[40] Data from the federal reserve: https://www.federalreserve.gov/releases/g19/current/.

[41] Tables D.5 and D.6 report the estimation results.

methodology we estimate higher discount rates of 2.1 to 25 percent (see Table D.2). Thus, we find consistent evidence of consumer undervaluation regardless of the estimation strategy or parameter assumptions. Moreover, differences between our functional form and theirs do not explain the differing results. This exercise implies that the different time period between our sample and theirs explains the differing results, perhaps because WTP depends on fuel prices (which were higher during our sample), on macroeconomic conditions (our sample includes the recovery from the 2008 to 2009 recession), or on other factors that differed between the two sample periods.[42]

Table D.1: **Composition of Willingness to Pay for Fuel Cost Savings and Performance**

| Willingness to pay (2010 USD) for 1 percent increases in | Fuel economy (1) | Performance (2) |
|---|---|---|
| **Panel A. WTP (Baseline)** | | |
| • price effect $l_1$ | 101.3 | 58.3 |
| | [98.8, 104.4] | [56.2, 60.4] |
| • quantity effect $l_2$, assuming elasticity = -3 | 32.3 | 35.5 |
| | [30.0, 34.7] | [33.1, 38.0] |
| • overall equilibrium effect, assuming elasticity = -3 | 133.4 | 93.6 |
| | [128.8, 139.1] | [89.3, 99.5] |
| **Panel B. Average alternative elasticity** | | |
| • overall equilibrium effect, assuming elasticity = -2 | 149.5 | 111.3 |
| | [143.6, 156,2] | [105.6, 117.1] |
| • overall equilibrium effect, assuming elasticity = -4 | 125.4 | 84.7 |
| | [121.2, 130.3] | [80.8, 88.7] |
| • overall equilibrium effect, assuming elasticity = -5 | 120.5 | 79.4 |
| | [116.6, 125.0] | [75.9, 83.0] |

*Notes*: For equilibrium price effect $l_1$ and additional price from quantity effect $l_2$, we report 95% confidence interval of $l_1$ and $l_2$ in square parentheses using delta method. For the overall WTP, we report the 95% confidence interval assuming zero covariance between the price regression coefficient and the quantity regression coefficient.

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[42] Another commonly used measure of consumer valuation of fuel economy is the payback period. Following the definition that EPA and NHTSA use, we compute the number of years from the time of purchase so that the discounted stream of fuel savings equals the estimated WTP for a 1 percent fuel economy increase. Under our baseline assumption, the payback period for a 1 percent fuel economy increase is 7 years.

Table D.2: **Alternative Assumptions for Computing Valuation Ratios and Implicit Discount Rates**

| | Estimate | Confidence Interval |
|---|---|---|
| **Panel A. Valuation ratio (percentage)** | | |
| **A.1 Alternative demand elasticity** | | |
| A.1.1 Real discount rate = 1.3 percent, demand elasticity = -2 | 60.0 | [54.0, 62.7] |
| A.1.2 Real discount rate = 1.3 percent, demand elasticity = -3 **(base)** | 53.6 | [51.7, 55.9] |
| A.1.3 Real discount rate = 1.3 percent, demand elasticity = -4 | 50.3 | [48.7, 52.3] |
| A.1.4 Real discount rate = 1.3 percent, demand elasticity = -5 | 48.4 | [46.8, 50.2] |
| **A.2 Alternative real discount rate** | | |
| A.2.1 Real discount rate = 1.3 percent, demand elasticity = -3 **(base)** | 53.6 | [51.7, 55.9] |
| A.2.2 Real discount rate = 5 percent, demand elasticity = -3 | 69.1 | [66.7, 72.1] |
| A.2.3 Real discount rate = 7 percent, demand elasticity = -3 | 77.7 | [75.0, 81.0] |
| A.2.4 Real discount rate = 10 percent, demand elasticity = -3 | 90.4 | [87.3, 94.3] |
| A.2.4 Real discount rate = 12 percent, demand elasticity = -3 | 98.9 | [95.5, 103.1] |
| **A.3 Alternative future gasoline price assumptions** | | |
| A.3.1 Gasoline price follows random walk **(base)** | 53.6 | [51.7, 55.9] |
| A.3.1 Gasoline price follow EIA AEO projection | 57.2 | [55.3, 59.6] |
| **A.4 Alternative assumptions on VMT and scrappage** | | |
| A.4.1 Our assumption described in Section A.3-A.4 **(base)** | 53.6 | [51.7, 55.9] |
| A.4.2 Assumptions in as in Busse et al. (2013) | 73.0 | [70.5, 76.1] |
| **Panel B. Implicit discount rate (percentage)** | | |
| **B.1 Alternative demand elasticity** | | |
| B.1 Real discount rate = 1.3 percent, demand elasticity = 2 | 9.72 | |
| B.2 Real discount rate = 1.3 percent, demand elasticity = 3 **(base)** | 12.25 | |
| B.3 Real discount rate = 1.3 percent, demand elasticity = 4 | 13.79 | |
| B.4 Real discount rate = 1.3 percent, demand elasticity = 5 | 14.83 | |
| **B.2 Alternative assumptions on VMT and scrappage** | | |
| B.2.1 Our assumption described in Section A.3-A.4 **(base)** | 12.25 | |
| B.2.2 Assumptions in as in Busse et al. (2013) | 7.30 | |

*Notes*: The table reports valuation ratios in Panel A and implicit discount rates in Panel B, in percentages. The calculations use the same assumptions as in Table 4, except as indicated in the column and row headings.

Table D.3: **Assumptions for Implicit Discount Rate Calculations**

| | Our assumptions | | | | Assumptions of Busse et al. (2013) | | | |
|---|---|---|---|---|---|---|---|---|
| Vehicle age (years) | VMT cars | VMT trucks | Survival rate cars | Survival rate trucks | VMT cars | VMT trucks | Survival rate cars | Survival rate trucks |
| 1 | 13,379 | 14,821 | 0.9972 | 0.9982 | 14,231 | 16,085 | 0.9900 | 0.9741 |
| 2 | 12,963 | 14,334 | 0.9944 | 0.9964 | 13,961 | 15,782 | 0.9831 | 0.9603 |
| 3 | 12,563 | 13,864 | 0.9897 | 0.9933 | 13,669 | 15,442 | 0.9731 | 0.9420 |
| 4 | 12,179 | 13,409 | 0.9823 | 0.9885 | 13,357 | 15,069 | 0.9593 | 0.9190 |
| 5 | 11,810 | 12,969 | 0.9714 | 0.9813 | 13,028 | 14,667 | 0.9413 | 0.8913 |
| 6 | 11,456 | 12,545 | 0.9564 | 0.9711 | 12,683 | 14,239 | 0.9188 | 0.8590 |
| 7 | 11,117 | 12,136 | 0.9367 | 0.9574 | 12,325 | 13,790 | 0.8918 | 0.8226 |
| 8 | 10,792 | 11,742 | 0.9122 | 0.9399 | 11,956 | 13,323 | 0.8604 | 0.7827 |
| 9 | 10,482 | 11,363 | 0.8828 | 0.9184 | 11,578 | 12,844 | 0.8252 | 0.7401 |
| 10 | 10,185 | 10,997 | 0.8488 | 0.8927 | 11,193 | 12,356 | 0.7866 | 0.6956 |
| 11 | 9,902 | 10,646 | 0.8168 | 0.8724 | 10,804 | 11,863 | 0.7170 | 0.6501 |
| 12 | 9,633 | 10,309 | 0.7650 | 0.8345 | 10,413 | 11,369 | 0.6125 | 0.6040 |
| 13 | 9,376 | 9,,985 | 0.7093 | 0.7922 | 10,022 | 10,879 | 0.5094 | 0.5517 |
| 14 | 9,131 | 9675 | 0.6515 | 0.7466 | 9,633 | 10,396 | 0.4142 | 0.5009 |
| 15 | 8,900 | 9,377 | 0.5932 | 0.6986 | 9,249 | 9,924 | 0.3308 | 0.4522 |
| 16 | 8,680 | 9,093 | 0.5357 | 0.6493 | 8,871 | 9,468 | 0.2604 | 0.4062 |
| 17 | 8,471 | 8,821 | 0.4804 | 0.5996 | 8,502 | 9,032 | 0.2028 | 0.3633 |
| 18 | 8,274 | 8,,561 | 0.4280 | 0.5505 | 8,144 | 8,619 | 0.1565 | 0.3236 |
| 19 | 8,088 | 8314 | 0.3791 | 0.5027 | 7,799 | 8,234 | 0.1200 | 0.2873 |
| 20 | 7,913 | 8,078 | 0.3341 | 0.4568 | 7,469 | 7,881 | 0.0916 | 0.2542 |
| 21 | 7,748 | 7,854 | 0.2931 | 0.4133 | 7,157 | 7,565 | 0.0696 | 0.2244 |
| 22 | 7,593 | 7,642 | 0.2562 | 0.3724 | 6,866 | 7,288 | 0.0527 | 0.1975 |
| 23 | 7,448 | 7,440 | 0.2231 | 0.3343 | 6,596 | 7,055 | 0.0399 | 0.1735 |
| 24 | 7,312 | 7,250 | 0.1938 | 0.2992 | 6,350 | 6,871 | 0.0301 | 0.1522 |
| 25 | 7,186 | 7,070 | 0.1679 | 0.2670 | 6,131 | 6,739 | 0.0227 | 0.1332 |
| 26 | 7,068 | 6,,900 | 0.1451 | 0.2377 | | 6,663 | | 0.1165 |
| 27 | 6,959 | 6,740 | 0.1252 | 0.2111 | | 6,648 | | 0.1017 |
| 28 | 6,857 | 6,591 | 0.1079 | 0.1871 | | 6,648 | | 0.0887 |
| 29 | 6,764 | 6,451 | 0.0928 | 0.1655 | | 6,648 | | 0.0773 |
| 30 | 6,678 | 6,320 | 0.0797 | 0.1462 | | 6,648 | | 0.0673 |
| 31 | 6,600 | 6,199 | 0.0684 | 0.1290 | | 6,648 | | 0.0586 |
| 32 | 6,528 | 6,086 | 0.0587 | 0.1137 | | 6,648 | | 0.0509 |
| 33 | 6,463 | 5,982 | 0.0503 | 0.1001 | | 6,648 | | 0.0443 |
| 34 | 6,404 | 5,887 | 0.0431 | 0.0880 | | 6,648 | | 0.0385 |
| 35 | 6,352 | 5,800 | 0.0369 | 0.0773 | | 6,648 | | 0.0334 |
| 36 | | 5,720 | | 0.0679 | | 6,648 | | 0.0290 |
| 37 | | 5,648 | | 0.0596 | | | | |
| 38 | | 5,584 | | 0.0522 | | | | |
| 39 | | 5,527 | | 0.0458 | | | | |
| 40 | | 5,477 | | 0.0401 | | | | |

*Notes*: The table reports the estimated vehicle miles traveled (VMT) and survival probability for cars and light trucks by vehicle age. Our estimates are from the 2009 wave of the National Household Travel Survey following the methodology of Lu (2006). The four columns on the right of the table show the assumptions from Busse et al. (2013).

Table D.4: **Implicit Discount Rates Using Busse et al. (2013) Methodology**

| Assumed demand elasticity | Implicit discount rate | |
|---|---|---|
| | Results reported in Busse et al. (2013) | Our results using Busse et al. (2013) methodology |
| -2 | -4.0 | 2.1 |
| -3 | 1.0 | 9.8 |
| -4 | 5.5 | 17.6 |
| -5 | 9.8 | 25.3 |

*Notes*: The implicit discount rate is computed by comparing vehicles in the fourth fuel economy quartile (highest fuel economy) with vehicles in the first fuel economy quartile (lowest fuel economy) assuming the own-price demand elasticities indicated in each row. Busse et al. (2013) results are repeated from their Table 9 column "NHTSA VMT and NHTSA PSR" and rows "Q1 versus Q4". To produce our results using their methodology, we estimate a price regression in Table D.5 (column 4) and quantity regression in Table D.6. We convert our estimates to implicit discount rates using the spreadsheet provided by Busse et al. (2013).

Table D.5: **Price Regression Using Busse et al. (2013) Methodology**

| Dependent variable: price | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Gas prices × MPG quartile 1 (least efficient) | -142.052*** | -149.354*** | -104.193*** | -112.484*** |
| | (25.341) | (25.611) | (23.813) | (24.062) |
| Gas prices × MPG quartile 2 | -22.614* | -25.443** | -20.104* | -24.213** |
| | (11.584) | (11.171) | (11.102) | (10.967) |
| Gas prices × MPG quartile 3 | -40.029** | -40.828** | -37.303** | -38.539** |
| | (15.435) | (17.662) | (16.854) | (18.531) |
| Gas prices × MPG quartile 4 (most efficient) | 25.754 | 31.412* | 6.596 | 12.342 |
| | (16.824) | (18.694) | (18.303) | (20.767) |
| | | | | |
| State FE | Yes | Yes | | |
| Model-year FE | Yes | Yes | | |
| Month-of-year FE | Yes | Yes | | |
| State × year FE | | | Yes | Yes |
| State × month-of-year FE | | | Yes | Yes |
| Include demographics | | Yes | | Yes |
| Number of observations | 535,130 | 457,324 | 535,130 | 457,324 |
| R-squared | 0.90 | 0.90 | 0.90 | 0.90 |
| Differences in WTP of Q1 versus Q4 | $167 | $180 | $110 | $135 |

* p<0.10 ** p<0.05 *** p<0.01

*Notes*: Standard errors in parentheses, clustered by trim. The specifications are similar to Busse et al. (2013). The dependent variable is the transaction price, and the reported independent variables are interactions of the fuel price with fixed effects for the vehicle's fuel economy quartile. Observations are weighted by registrations, and regressions include model-variant fixed effects as well as the fixed effects indicated at the bottom of the table.

Table D.6: **Quantity Regressions Using Busse et al. (2013) Methodology**

| Dependent variable: quantity | Coef. | SE | Average new cars registered per month per state (100) | Percentage change |
|---|---|---|---|---|
| Gas prices × MPG quartile 1 (least efficient) | -6.353*** | (1.928) | 87.99 | 17.41 |
| Gas prices × MPG quartile 2 | -3.479* | (2.057) | 96.62 | 20.47 |
| Gas prices × MPG quartile 3 | 8.848*** | (2.489) | 109.73 | 24.27 |
| Gas prices × MPG quartile 4 (most efficient) | 25.442*** | (5.668) | 122.57 | 30.84 |
| Number of observations | 12,182 | | | |
| R-squared | 0.87 | | | |
| * p<0.10 ** p<0.05 *** p<0.01 | | | | |

*Notes*: Standard errors in parentheses, robust to heteroskedasticity. The regression follows the Busse et al. (2013) methodology reported in their Tables 6 and 7. The dependent variable is the registrations by fuel economy quartile, state, and month. The regression reported in this table includes interactions of state fixed effects and transaction year fixed effects, interactions of state fixed effects and month of year fixed effects, and fuel economy quartile fixed effects. Observations are weighted by registrations.

# E Consumer Welfare Implications under Alternative Assumptions

In Section 5.2 we show the net zero welfare effect of tightening fuel economy standard on consumer. In this section we present welfare calculation under alternative assumptions.

The conclusion that consumers do not benefit from higher fuel economy holds even if we have substantially over-estimated WTP for performance. If WTP for performance were 42 percent smaller than the baseline estimate (which lies well outside the 95 percent confidence interval), or if the performance-fuel economy trade-off were 42 percent less steep, the private consumer welfare change would equal zero. The conclusion is robust to alternative assumptions of demand elasticities (see Appendix Tables C.8 and C.9).

The conclusions also hold if we allow for the possibility that manufactures use weight reduction technologies rather than fuel-saving technologies. The main calculations reported above include the implicit assumption that adoption of fuel-saving technology does not affect weight or horsepower. This assumption is consistent with the technology model in EPA (2012), from which our technology cost estimates were derived. However, the welfare effects would be different from those we estimate if manufacturers use weight-reduction technologies, because reducing weight would increase performance. We can derive an upper bound to how much the main estimate of -$109 would change if we allow for the possibility that manufactures reduce weight rather than adopting fuel-saving power train technologies. We suppose that rather than using power train technologies to raise fuel economy, manufacturers instead reduce weight to achieve the 0.12 percent fuel economy increase. According to the trade-off between weight and fuel economy estimated in Klier and Linn (2016), this would amount to reducing weight by 0.4 percent. Performance would increase by an equivalent 0.4 percent, for which consumers would be willing to pay $37 according to our baseline estimate. This increase partially offsets the forgone performance from trading off fuel economy and performance, causing an overall welfare loss of $72 rather than $109.[43] Thus, we conclude that tighter standards are unlikely to substantially improve consumer welfare, and our central estimate is that tighter standards have approximately zero effect.

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[43] We consider the change of $37 to be an upper bound to the magnitude of the change because we use the same technology cost assumptions. According to EPA (2012), the cost of reducing weight is likely to be higher than the cost of adding fuel-saving power train technologies.