

White Paper 2:17

The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the U.S.: A Retrospective and Prospective Analysis

David L. Greene

Senior Fellow

Howard H. Baker Jr. Center for Public Policy

Jilleah G. Welch

Research Associate

Howard H. Baker Jr. Center for Public Policy

March 2017

Baker Center Board

Cynthia Baker
Media Consultant, Washington, DC

Sam M. Browder
Retired, Harriman Oil

Patrick Butler
CEO, Assoc. Public Television Stations
Washington, DC

Sarah Keeton Campbell
Attorney, Special Assistant to the Solicitor General
and the Attorney General, Nashville, TN

Jimmy G. Cheek
Chancellor, The University of Tennessee, Knoxville

AB Culvahouse Jr.
Attorney, O'Melveny & Myers, LLP
Washington, DC

The Honorable Albert Gore Jr.
Former Vice President of The United States
Former United States Senator
Nashville, TN

Thomas Griscom
Communications Consultant
Former Editor, *Chattanooga Times Free Press*
Chattanooga, TN

James Haslam II
Chairman and Founder, Pilot Corporation
The University of Tennessee Board of Trustees

Joseph E. Johnson
Former President, University of Tennessee

Fred Marcum
Former Senior Advisor to Senator Baker
Huntsville, TN

Amb. George Cranwell Montgomery
Former Ambassador to the Sultanate of Oman

Regina Murray, Knoxville, TN

Lee Riedinger
Vice Chancellor, The University of Tennessee, Knoxville

Don C. Stansberry Jr.
The University of Tennessee Board of Trustees
Huntsville, TN

The Honorable Don Sundquist
Former Governor of Tennessee
Townsend, TN

Baker Center Staff

Matt Murray, PhD
Director

Nissa Dahlin-Brown, EdD
Associate Director

Charles Sims, PhD
Faculty Fellow

Krista Wiegand, PhD
Faculty Fellow

Jilleah Welch, PhD
Research Associate

Jay Cooley
Business Manager

Elizabeth Woody
Office Manager

Kristin England
Information Specialist

William Park, PhD
Director of Undergraduate Programs
Professor, Agricultural and Resource
Economics

About the Baker Center

The Howard H. Baker Jr. Center for Public Policy is an education and research center that serves the University of Tennessee, Knoxville, and the public. The Baker Center is a nonpartisan institute devoted to education and public policy scholarship focused on energy and the environment, global security, and leadership and governance.

Howard H. Baker Jr. Center for Public Policy
1640 Cumberland Avenue
Knoxville, TN 37996-3340

Additional publications available at
<http://bakercenter.utk.edu/publications/>

Disclaimer

Findings and opinions conveyed herein are those of the authors only and do not necessarily represent an official position of the Howard H. Baker Jr. Center for Public Policy or the University of Tennessee.

The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the U.S.: A Retrospective and Prospective Analysis

David L. Greene, Senior Fellow
Howard H. Baker Jr. Center for Public Policy

Jilleah G. Welch, Research Associate
Howard H. Baker Jr. Center for Public Policy

Acknowledgement

The authors thank the Energy Foundation and the National Transportation Research Center of Oak Ridge National Laboratory for their financial support. We are grateful for comments and suggestions from Gloria Helfand, Mark Cooper, Zhenhong Lin, Scott Holladay, and Charles Sims.

Disclaimer

The views expressed in this report, however, are those of the authors and do not necessarily reflect the views of the Energy Foundation, Oak Ridge National Laboratory, the University of Tennessee or the colleagues who gave of their time and expertise to review our report. All errors are our own.

Contents

Executive Summary	5
1. Introduction	14
2. The Fuel Economy of New and Used Vehicles	16
3. Decomposition Analysis	20
3.1 Methodology	20
3.2 Data	21
3.3 Key Assumptions	24
3.4 Descriptive Statistics and Trends	25
3.5 Decomposition Analysis Results	30
4. Econometric Analysis of Used Vehicle Prices	37
4.1 Methodology	37
4.2 Theoretical Model	41
4.4 Data	47
4.5 Econometric Analysis Results	47
5. Alternative Approaches: The Cost of Fuel Economy and Net Impacts by Income Quintile	56
5.1 Approximation Using Ratio of Cost of Fuel Economy Improvements to Increase in Vehicle Prices	57
5.1.1 Price Impacts of Fuel Economy Improvements, 1975-2014	57
5.1.2 Effect on Used Vehicle Prices and Expenditures on Vehicles	62
5.2 User Cost of Capital Method Using Cost Curves for Fuel Economy Improvements	66
5.2.1 Fuel Economy Cost Functions	67
5.2.2 User Cost of Capital Results	73
6. Estimated Impacts of Future Fuel Economy Improvements	76
6.1 Vehicle Stock Turnover, Miles Traveled and Fuel Consumption	77
6.2 Sharing	79
6.3 Net Impacts on Income	83
6.4 Results	85
7. Conclusions	89
References	92

Executive Summary

Lower income households tend to spend more on motor fuel than on vehicles while households in the highest income quintile tend to spend more on vehicles (Figure E-1) (NRC, 2015; CFA, 2012). This observation suggests that the regulatory standards that require increased fuel economy but at the cost of higher vehicle prices might affect the distribution of disposable income in the United States. This study analyzes the effects of historical increases in fuel economy on households' expenditures on fuel and vehicles over the past four decades and quantifies the impacts by income quintile. Distributional impacts are also estimated for future fuel economy improvements which are expected to increase through 2025 given fuel economy standards currently in place. We do not estimate the effects of fuel economy improvements on producer and consumer surplus. Rather we estimate the impacts of fuel economy improvements on disposable income: the difference between decreased expenditures on fuel and increased expenditures on motor vehicles.

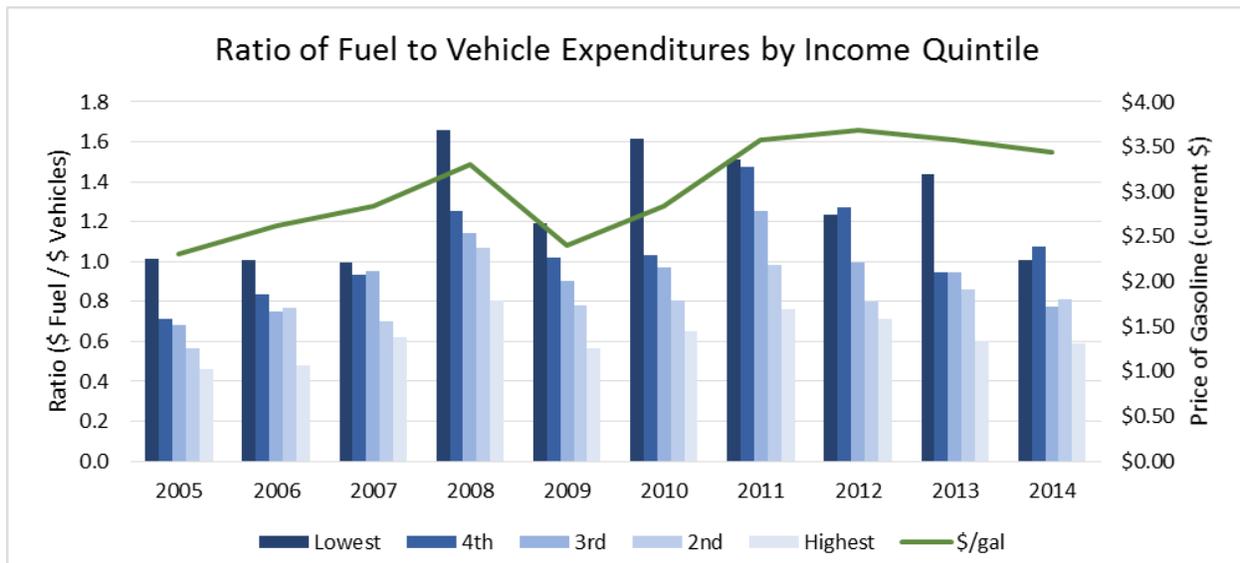


Figure E-1. Ratio of Fuel to Vehicle Expenditures by Income Quintile (CES, 2005-14, table 1101).

Detailed analysis of the Consumer Expenditure Surveys from 1980 to 2014 indicates that fuel economy improvements have produced greater benefits relative to income for the lower quintiles of the income distribution. The impact of increased fuel economy on the distribution of income has apparently been progressive. Households in the lower 80% of the U.S. income distribution received annual net savings on vehicles and fuel estimated at 0.5% to 2.0% of their

average annual income over the 1980-2014 period. The net effect is relatively smaller for the highest income quintile, with our estimates indicating a range of 0.0% to 0.3%. Net benefits relative to income uniformly increase with decreasing income. In terms of total net savings, the greatest net benefits accrued to the three middle income quintiles. Estimation of the impacts of future improvements from 2015 to 2040 produces very similar results. The highest income quintile averages net savings of 0.5% of income annually while the lowest income quintile annual savings average just over 2% of income.

The study relies on data from all Consumer Expenditures Surveys (CES) from 1980 to 2014. The CES is the authoritative source of information on expenditures by U.S. households and provides a nearly continuous record of expenditures on fuel and vehicles, as well as household incomes from 1980 to 2014. Data on new vehicle fuel economy was obtained from the U.S. Environmental Protection Agency (EPA, 2015), and the effect of vehicle age on fuel economy was analyzed using the U.S. Energy Information Administration's Residential Transportation Energy Consumption Surveys (RTECS) (EIA, 2016).

We first quantify the effects of fuel economy and vehicle price changes, holding other factors constant, by means of decomposition analysis. Over the 1980 to 2014 period, fuel economy improvements reduced household's expenditures on fuel by 25% to 30%, given the actual patterns of fuel prices and vehicle use (Figure E-2).¹ The higher income groups experience the benefits of fuel economy earliest because they tend to buy more new vehicles. Over time, the effects equalized because new vehicle fuel economy essentially stopped increasing in 1985 and remained nearly level for more than a decade. The effect of the shift in sales from passenger cars to light trucks can also be seen in Figure E-2. After 1995, the benefits of increased fuel economy are slightly reduced, once again the higher income groups lead the way. Finally, recent improvements in new vehicle fuel economy are again causing rates of fuel consumption to decrease.

¹ Divisia decomposition does not adjust for phenomena like the "rebound effect", the tendency for households to drive more when fuel cost per mile decreases. Assuming households choose to increase vehicle use because it increases their welfare, the rebound effect would be an additional benefit to households not accounted for in our analysis.

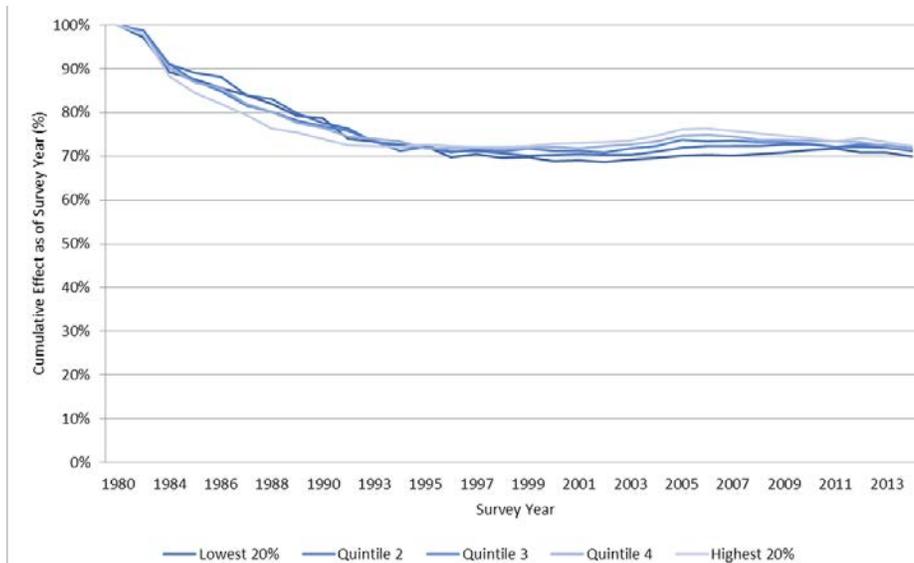


Figure E-2. Effect of Fuel Economy Improvement on Fuel Expenditures by Income Quintile

Expenditures on vehicles reflect the prices of new and used vehicles, choices of new versus used vehicles, choice of type of vehicle and accessories, and the decision to buy or not buy a vehicle. Expenditures per vehicle have varied much more over time than fuel economy partly because of the effect of economic conditions but also due to sampling variability (Figure E-3). The effects of gasoline prices and the Great Recession are evident in the decline in per vehicle expenditures after 2005. With the beginning of the recovery after 2010, expenditures per vehicle returned to approximately the same level as 1980.

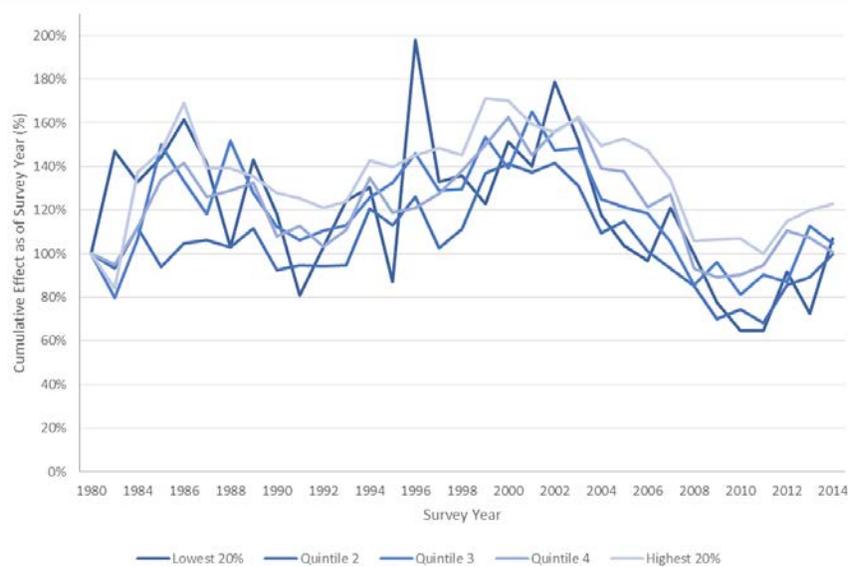


Figure E-3. Average Expenditure per Owned Vehicle: Vehicle Expenditures by Income Quintile

As a percent of income, savings on fuel are greatest for lower income households. The total effect of fuel economy improvements since 1980 on household expenditures in calendar year 2014 reduced fuel expenditures by over \$500 for households in the lowest income quintile, and by \$1,500 for households in the highest income quintile (Table E-1).² The savings amounted to 4.3% of annual income for the lowest income quintile but only 0.9% for the highest quintile.

Table E-1. Impact of Fuel Economy, Gas Prices, and Vehicle Miles Traveled Relative to 1980 Values on 2014 Fuel Expenditures

Income Quintile	Fuel Economy		Gas Prices		VMT	
	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income
Lowest 20%	(509)	-4.3%	(29)	-0.2%	556	4.7%
Quintile 2	(734)	-2.7%	(45)	-0.2%	716	2.6%
Quintile 3	(990)	-2.1%	(61)	-0.1%	954	2.1%
Quintile 4	(1,211)	-1.6%	(73)	-0.1%	1,094	1.5%
Highest 20%	(1,499)	-0.9%	(95)	-0.1%	1,535	0.9%

Although the decomposition analysis does not consider the “rebound effect”, the tendency for vehicle miles to increase with decreasing fuel cost per mile, its effect on fuel expenditures was undoubtedly small. A 10-20% rebound effect implies an increase of 3-6% in miles traveled for the 30% reduction in fuel use per mile. The total increase in household vehicle miles traveled (VMT) from 1980 to 2014 was 65%, meaning that the increase in expenditures due to the rebound effect was about 4.6% to 9.2% of the observed increase in expenditures due to VMT growth.

The cumulative impact of expenditures per vehicle owned and numbers of vehicles owned in 2014 is shown in Table E-2. Increases in expenditures per vehicle raised vehicle expenditures by less than 1% in 2014 across the income quintiles. Although both new and used vehicle prices increased from 1980 to 2014 and expenditures per vehicle were generally higher in the intervening years, by 2014 annual expenditures per vehicle owned in constant dollars had returned to the 1980 level. By 2014, expenditures per vehicle had just begun to recover from the effects of the Great Recession. Most of the increase in expenditures was due to increased vehicle ownership, with the largest increases for the lower quintiles.

² 2015 dollars are used throughout this report, and the Consumer Price Index (CPI-U) was used for all conversions.

Table E-2. Impact of Average Cost per Vehicle and Number of Vehicles Relative to 1980 Values on 2014 Vehicle Expenditures

Income Quintile	Average Cost per Vehicle		Number of Vehicles	
	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income
Lowest 20%	74	0.6%	493	4.2%
Quintile 2	(9)	0.0%	870	3.2%
Quintile 3	141	0.3%	1,250	2.7%
Quintile 4	24	0.0%	1,299	1.7%
Highest 20%	1,300	0.8%	2,580	1.6%

Unfortunately, there is no definitive estimate of the impact of fuel economy improvements on vehicle prices since 1975. Fuel economy improvements could not possibly be responsible for all of the observed price increase. Numerous factors beyond fuel economy added to the cost of vehicles over the 1975 to 2014 period. These include technological and design innovations (e.g., power accessories, electronics, cruise control, navigation systems, etc.), increased vehicle weight and engine power, safety features (e.g., air bags, antilock brakes, etc.), increased market shares of luxury and near-luxury vehicles, and emissions controls. All contributed to raising the average price paid for a new car or light truck. On the other hand, fuel economy improvements undoubtedly caused some increase in vehicle prices.

An approximate estimate of the impact of fuel economy improvements on retail prices was derived from a literature review of early studies (Greene and DeCicco, 2000) and four National Research Council reviews of the Corporate Average Fuel Economy (CAFE) standards (NRC, 1992; 2002; 2010; 2015). Based on these sources, we provide two additional alternatives to measuring the actual cost of fuel economy improvements to consumers. First, we adopt a simple approximation using an estimate for the ratio of costs of improving fuel economy to the total increase in the price of a new vehicle over the same period. Second, we use the estimated cost functions from the aforementioned literature and a user cost of capital method to estimate the distributional impacts of historical fuel economy improvements.

For the approximation, we adopted \$150 to \$250 per test cycle MPG as a reasonable range of uncertainty for the average impact of fuel economy improvements on new vehicle prices from 1975 to 2014. The average test cycle fuel economy for light-duty vehicles (passenger

cars and light trucks combined) increased from 15.3 MPG in 1975 to 30.7 MPG in 2014 (EPA, 2015). This implies a price increase due to fuel economy improvement of \$2,310 to \$3,850, which includes the estimated cost of the 7.2 MPG increase in fuel economy from 1975 to 1980: \$1,080 to \$1,800. The CES data indicate that the prices households paid for new light-duty vehicles increased by \$7,340 between 1980 and 2014. Dividing the estimated price increases due to fuel economy improvements (\$2,310 to \$3,850) by the estimated 1980-2014 price increase plus the 1975 to 1980 increase due to fuel economy improvements (\$8,420 to \$9,140) implies that fuel economy improvements accounted for approximately 27% to 42% of the increase in vehicle prices between 1975 and 2014. This estimate is likely to overstate fuel economy's share in the cost increase. First, we do not attempt to include the effects of technological advances and learning by doing on the cost of improving fuel economy over the 34 year period. Second, we include the increase in vehicle prices from 1975-1980 due to only fuel economy but no fuel savings from that time period.

A key question is whether used vehicle prices are predominantly determined by depreciation of new vehicle costs or whether the present value of benefits of improved fuel economy from one model year to the next are capitalized to some degree in the prices of used vehicles. If the latter is the case, the benefits to lower income households could be reduced because their expenditures favor used versus new vehicles. This question was investigated by means of a statistical analysis of the CES data on prices paid for different model years of used passenger cars and light trucks and their expected fuel savings relative to the average fuel economy of all light-duty vehicles in use in a calendar year. The data supported both hypotheses to some degree. One model implied that none of the expected fuel savings of a model year cohort would be reflected in its market price but that the price would reflect only the depreciated initial purchase price and macroeconomic factors. The other implied that approximately 20% of the expected remaining fuel savings (compared with other vehicles on the road) would be capitalized in the price of a used vehicle. Note that the depreciated price of a used vehicles already includes the depreciated initial cost of fuel economy improvements.

The estimated net impacts on consumer expenditures take into account the high and low estimates of the cost of fuel economy, no or partial capitalization of future fuel savings in used vehicle prices and the share of each income quintiles' expenditures on used versus new vehicles over the 1980 to 2014 period. The estimated cumulative effects of fuel economy improvements on vehicle and fuel expenditures are shown for each income quintile in Table E-3. Both fuel savings and increased vehicle costs due to fuel economy improvements increase with increasing income. In terms of dollars, net savings are greatest for the three middle income quintiles. In terms of annual net savings as a percent of income, benefits are greatest for the lowest income quintile, whose annual net savings averaged 1.5% to 2% of average annual income over the 35 year period. Savings relative to income decrease steadily with increasing income. The highest income quintile may have no net savings up to a savings of about 0.3% of average annual income.

Table E-3. Worst to Best Case Estimates for Total Impacts on Fuel and Vehicle Expenditures, 1980-2014

Income Quintile	Fuel Economy	Average Cost per Vehicle		Annual Net Cost or (Savings) as Percent of Average Household Income
	Accumulation of Cost or (Savings) per Household	Accumulation of Cost or (Savings) per House	Net Cost or (Savings)	
Lowest 20%	(10,591)	4,007 - 2,139	(6,583) - (8,451)	(1.56%) - (2.00%)
Quintile 2	(15,329)	2,472 - 938	(12,857) - (14,391)	(1.52%) - (1.71%)
Quintile 3	(20,820)	9,640 - 5,430	(11,180) - (15,390)	(0.81%) - (1.12%)
Quintile 4	(25,560)	14,826 - 8,736	(10,734) - (16,825)	(0.50%) - (0.78%)
Highest 20%	(31,652)	30,180 - 18,816	(1,471) - (12,835)	(0.04%) - (0.31%)

In this report, which is a follow-up to our previously published Baker Center report on the distributional impacts of fuel economy improvements³, we add a more direct approach to estimating the actual cost of fuel economy improvements. Estimates for the price of fuel economy improvements from four National Research Council reviews (NRC, 1992; 2002; 2010; 2015) and Green and DeCicco (2000) are used to develop the cost of fuel economy improvements for new vehicles by model year. These estimated prices of fuel economy improvements are assigned to an inventory of owned vehicles over the 1980 to 2014 time period

³ The first published Baker Center report, The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the United States, can be found here: <http://bakercenter.utk.edu/the-impact-of-increased-fuel-economy-for-light-duty-vehicles-on-the-distribution-of-income-in-the-united-states/>

using supplementary data from the Consumer Expenditure Surveys. Prices of fuel economy improvements are depreciated using the aforementioned econometric analysis of used vehicle prices and based on vehicle age. A user cost of capital method is then used to calculate the cost of fuel economy improvements by income quintile (a more complete description of the method can be found in Section 5.2, below). Consumers' savings in fuel expenditures are from the decomposition of fuel expenditures as described above. Results are shown in Table E-4. Using the user cost of capital method, savings in fuel expenditures and the total cost of fuel economy improvements both increase as income increases. Relative to income, the lowest income quintile still benefits the most from fuel economy benefits. We consider the user cost of capital method to be our preferred method as it provides a more direct measure of the actual cost of fuel economy standards. Yet, results from all analyses indicate that net savings relative to income are progressive and all income quintiles have benefited from fuel economy improvements in terms of their expenditures on fuel and vehicles.

Table E-4. Total Impacts on Fuel and Vehicle Expenditures Using Cost of Capital Method, 1980-2014

Income Quintile	Accumulation of (Savings) per Household in Fuel Expenditures	Accumulation of Fuel Economy Improvement Costs per Household	Net (Savings)	Annual Net Cost or (Savings) as Percent of Average Household Income
Lowest 20%	(10,591)	1,910	(8,680)	(2.06%)
Quintile 2	(15,329)	3,099	(12,230)	(1.45%)
Quintile 3	(20,820)	4,501	(16,318)	(1.18%)
Quintile 4	(25,560)	6,011	(19,550)	(0.91%)
Highest 20%	(31,652)	8,492	(23,159)	(0.56%)

The fuel savings estimates are believed to be accurate because household fuel expenditures come directly from the CES and the fuel economy estimates are taken from EPA new vehicle data adjusted for age effects using all of the EIA's RTECS surveys. The vehicle cost estimates rely on cost estimates taken predominantly from National Research Council studies which reflect a greater degree of uncertainty. The question of how fuel economy affects used vehicle prices introduces additional uncertainty. In developing the vehicle cost estimates, we have attempted to err on the side of overestimating the impacts of fuel economy improvements on vehicle prices. In light of this, the conclusion that the impacts of fuel economy improvements

have had a progressive impact on the distribution of income is robust in the opinion of the authors. Furthermore, at least the lowest four income quintiles and very likely all income quintiles have realized net savings from fuel economy increases over the past 35 years.

Fuel economy standards currently in place are expected to increase new passenger car and light truck fuel economy on the government’s fuel economy tests from 31 MPG in 2015 (EPA, 2015, Table 4.4) to 45 MPG in 2025 (EPA et al., 2016, Table 12.9). In addition, new vehicle fuel economy improved from 24 MPG in 2004 to 31 MPG in 2014 (EPA, 2015, Table 9.1), and these improvements have yet to have their full impact on the stock of vehicles in use. We use the NRC (2015) estimates of the cost of fuel economy improvements, together with the Energy Information Administration’s projections of future vehicles sales, use and fuel economy to estimate the future impacts of fuel economy improvements. Once again, it appears that future fuel economy improvements will benefit all income groups and that the impacts will be progressive. The highest income quintile is projected to average a savings of 0.5% of their income annually, increasing uniformly to 2.2% of income saved annually for the lowest income quintile (Figure E-4).

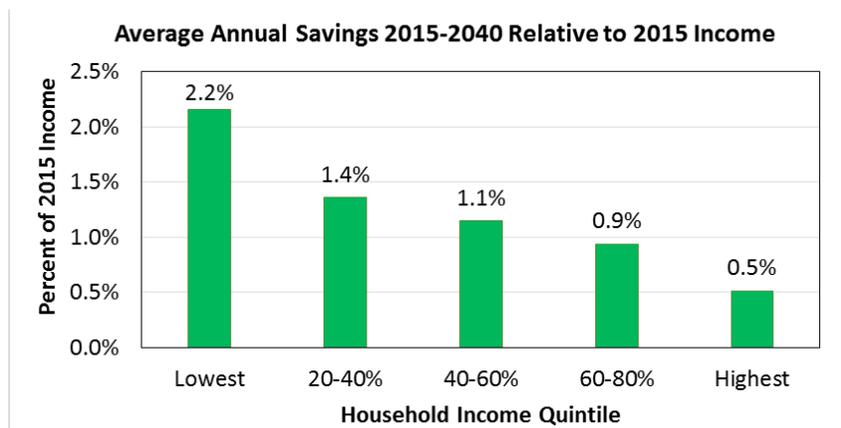


Figure E-4. Average Annual Savings 2015-2040 by Income Quintile Relative to 2015 Income.

Sensitivity analysis indicates that the findings that all income groups will experience net savings and that net savings increase with decreasing income is robust to a number of key assumptions.

1. Introduction

Driven by regulatory standards and intermittently by volatile oil prices, the fuel economy of new light-duty vehicles (passenger cars and light trucks) sold in the U.S. increased by 45% from 1975 to 1980 and another 30% from 1980 to 2014 (EPA, 2015). The Corporate Average Fuel Economy (CAFE) standards required manufacturers to increase the fuel economy of *new* passenger cars and light trucks gradually, by model year, beginning in 1978. These changes provided fuel savings to consumers but also increased the cost of new vehicles. Income quintiles differ greatly in the degree to which they purchase new and used vehicles. The impacts of the fuel economy improvements on income groups are therefore dependent not only on the initial cost of improved fuel economy but on how fuel economy and its cost change as vehicles age. This depends on how the prices and fuel economy of model year vehicle cohorts change as the vehicles age and are passed from higher to lower income groups.

In this study we investigate the impacts of fuel economy on income quintiles using data from Consumer Expenditures Surveys (CES) from 1980 to 2014. Decomposition analyses of household expenditures on vehicles and fuel quantify the factors causing changes for each income group over the past quarter century. Although the CES data allow us to separate the benefit of increased fuel economy from changes in fuel prices and vehicle use, the data do not permit us to separate the costs of fuel economy improvement from all the other reasons for changes in vehicle prices. We address this problem in a few ways. First, we attempt to determine whether the prices of used vehicles are determined by the depreciated prices of new vehicles or if model years with higher than average fuel economy command rent based on expected fuel savings over the vehicles' remaining lifetimes. We then draw on estimates of the costs of fuel economy improvements to new vehicles in the published literature. We then estimate a plausible range for the portion of the increases in vehicle expenditures that could be attributed to increased fuel economy. Applying those percentages to the observed change in household expenditures on vehicles due to changes in expenditures per vehicle, we estimate the

costs of fuel economy improvements to buyers of new and used vehicles and the net savings or cost of fuel economy improvements by income quintile.

Second, and in an extension to the original Baker Center report, we use fuel economy cost estimates, an inventory of owned vehicles according to the CES, and a cost of capital method to produce an alternative estimate of the cost of fuel economy to households in each income quintile. The fuel economy cost estimates are primarily from the National Research Council (2015, 2010, 2002, and 1992) and include estimates from Greene and DeCicco's (2000) literature review. The method is described in detail in Section 5.2.1. Using the NRC (2015) fuel economy cost curves we then estimate the impacts of future fuel economy improvements by income group over the 2015 to 2040 period.

In the analysis we aggregate vehicles across makes, models and classes and distinguish them by model year and between passenger cars and light trucks. These distinctions match those of the fuel economy standards. Our focus is on the impacts of fuel economy improvements rather than on market responses to fuel price changes. In fact, fuel prices in constant dollars were almost exactly the same in 2014 as in 1980, having gone through an extended period of low prices in the intervening years.

In the sections that follow, we first consider how the miles per gallon (MPG) of cars and light trucks may change as they age and are sold from one group of consumers to another. This information is important because all of the CES identify household vehicles by model year and vehicle type, and make and model detail is generally not available. The model year MPG estimate together with gasoline prices and the CES household expenditures are then used to carry out decomposition analyses of expenditures on vehicles and fuels over the 1980-2014 period. The individual effects of changes in fuel prices, vehicle miles of travel (VMT) and fuel economy are quantified, as are the effects of vehicle ownership and vehicle prices. Unfortunately, neither the CES data nor any other source separates changes in vehicle prices into fuel economy related and other components. This problem is analyzed in two steps. Via an econometric analysis of CES used car price data we attempt to determine whether the price of fuel economy

improvements to used car buyers is comprised solely of the depreciated cost to new car buyers or whether it also includes economic rent for more fuel efficient model years reflecting some fraction of the expected fuel savings over the remaining life of the vehicle. Relying mainly on analyses by the National Research Council, we then estimate the fraction of new car price increases from 1980 to 2014 that was likely due to fuel economy improvements. Finally, we combine the results of all the analyses to estimate the net impacts of fuel economy improvements on household expenditures by income quintile.

2. The Fuel Economy of New and Used Vehicles

Because lower income quintiles predominantly purchase used vehicles, the benefits of increased fuel economy to them depend on:

1. How an individual vehicle's fuel economy changes as it ages.
2. How the mix of vehicles changes as the cohort ages.

The physics of vehicle energy use suggest that a vehicle's fuel economy should change very little over its lifetime, assuming an unchanged duty cycle. The principal determinants of a vehicle's energy use are its mass, aerodynamics, rolling resistance, the size of its engine and the efficiency with which the engine converts the energy in fuel into useful work. Unless a vehicle is in need of major repair (e.g. a malfunctioning oxygen sensor or spark plugs, both of which noticeably affect drivability) none of these factors should change much over the life of a vehicle. Empirical studies indicate that fuel economy either does not deteriorate with vehicle age (Murrell, 1980; Greene et al., 2015) or deteriorates very slightly, on the order of 1 MPG per 14 years (Lin and Greene, 2011).

The Residential Transportation Energy Consumption Surveys (RTECS) conducted by the U.S. Energy Information Administration between 1979 and 2001, provide estimates of average household vehicle fuel economy by model year (EIA, 2016). In the early years of RTECS, households reported fuel purchases and odometer readings for each vehicle in fuel purchase diaries. In 1988, RTECS discontinued the gasoline purchase diaries and substituted imputed MPG estimates calculated by matching EPA fuel economy numbers to the make, model and

year of each vehicle and adjusting for household location and usage patterns. The RTECS and EPA data are plotted by model year in Figure 1 and by age in Figure 2. Figure 1 shows that the RTECS data correspond well with the EPA adjusted MPG numbers, and that both generally follow the pattern prescribed by the CAFE standards. Figure 2 shows that the EPA estimates are generally a bit higher than the RTECS estimates and suggests that the difference may increase with vehicle age. This trend is likely due to differences in usage patterns rather than changes in the vehicle itself. Vehicles tend to be used less as they age (NHTSA, 2006). Fewer miles per year correlates with shorter trips which are inherently less energy efficient. Provided that this pattern remains reasonably consistent over time, it will not affect inferences about how the fuel economy of model year cohorts changes as they age.

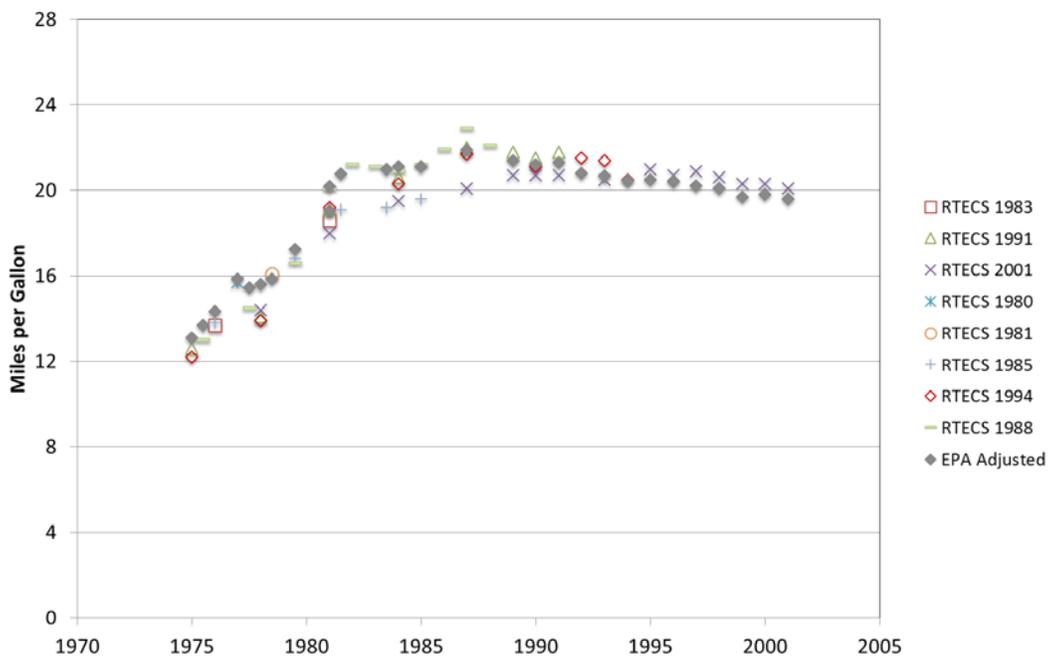


Figure 1. Fuel Economy by Model Year: RTECS and EPA Adjusted.

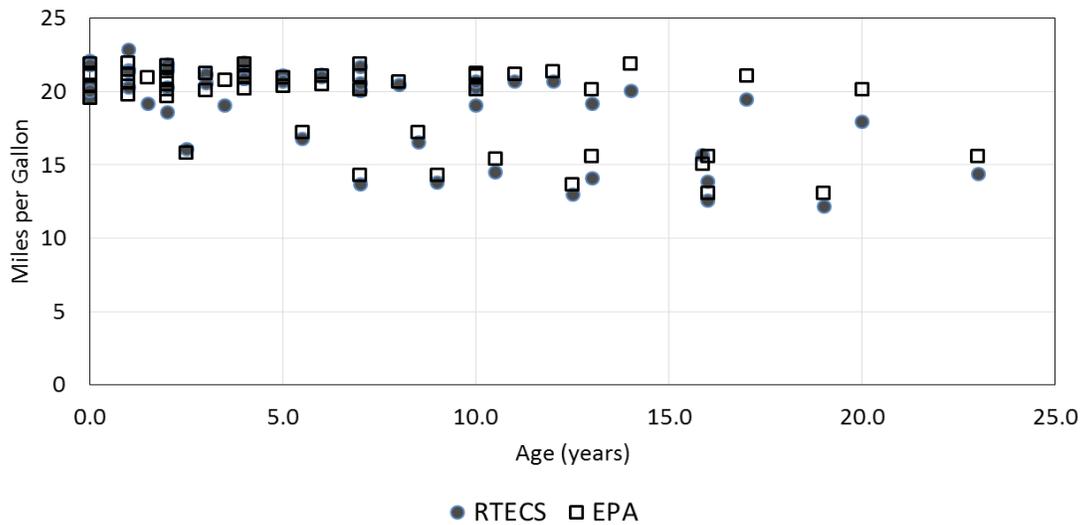


Figure 2. Fuel Economy by Vehicle Age: RTECS and EPA Adjusted.

We regressed the RTECS model year fuel economy estimates for light-duty vehicles from published tables (EIA, 2016) on vehicle age (in years) and EPA adjusted fuel economy estimates by model year (EPA, 2015). We tested for differences between the two survey methods by introducing an indicator variable for surveys conducted prior to 1988 and by interacting the indicator with vehicle age. Results of the three regression analyses are summarized in Table 1. Age is statistically significant at the 0.05 level in all models. The correlation with EPA MPG is close to 1.0 but indicates that, holding age constant, the EPA adjusted MPG numbers may overstate RTECS MPG estimates for vehicles with MPGs above 25 in the case of Model 1 and about 28 in the case of Model 2. Model 2 indicates that the intercept for vehicles surveyed using the diary method is about 1.14, while that for vehicles using the imputation method is 1.86. The effect of age is to decrease MPG by about 0.9 MPG per ten years in Model 1 and 0.7 MPG in Model 2. The result for Model 2 is almost identical to that of Lin and Greene (2011) who found a 1 MPG decrease after 14 years. Model 3 tests the interaction between age and pre-1988 data and finds that it is not statistically significant, indicating that the effect of age does not differ between the two methods used by the EIA to calculate MPG (gasoline purchase diary versus imputation). Thus, it does appear that the MPG of a vehicle cohort decreases gradually with vehicle age, at a rate somewhat less than 1 MPG per 10 years.

Table 1. Estimated effect of model year cohort age on fuel economy.

Variable	Model 1		Model 2		Model 3	
	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Intercept	1.0172	0.254	1.862	0.027	1.7992	0.035
Age	-0.0869	<0.001	-0.0683	<0.001	-0.0876	0.021
EPA MPG	0.9602	<<0.001	0.9335	<<0.001	0.9401	<<0.001
Pre-1988			-0.721	<0.001	-0.8342	0.004
Pre*Age					0.0252	0.552

If the mix of vehicles differs across income groups, the effect on average fuel economy appears to be minimal. Figure 3 compares the distributions of vehicles by EPA adjusted fuel economy across income groups. The data are from the 2009 National Household Travel Survey (NHTS, 2016). Prior to the survey, the fuel economy of new passenger cars and light trucks was almost constant for two decades (Figure 4). The percent of vehicle holdings in each MPG bin varies little across the five income groups.

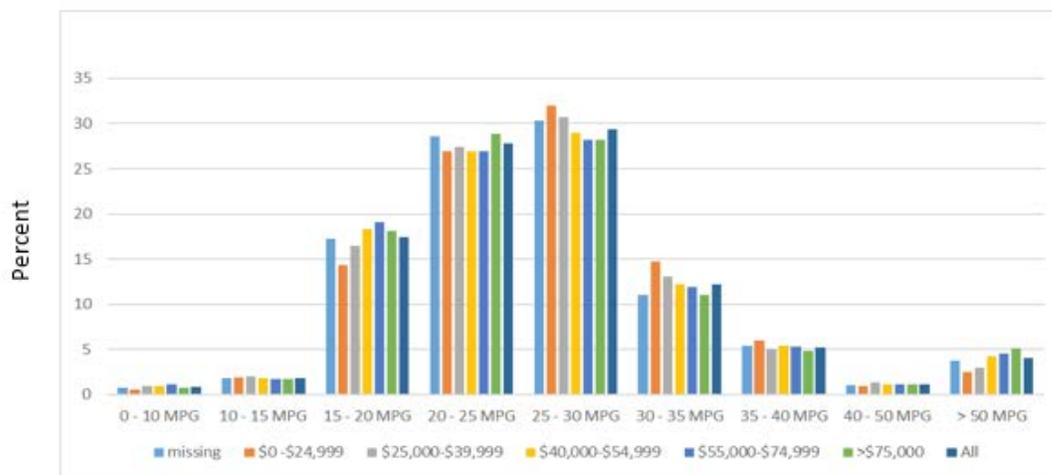


Figure 3. Distribution of Vehicles by MPG Across Income Groups.

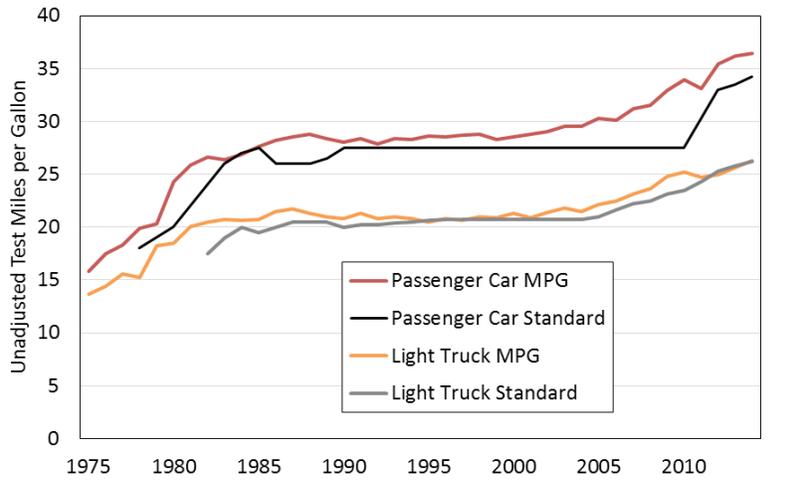


Figure 4. Car and Light Truck Fuel Economy and Standards (Davis et al., 2015; EPA, 2015).

3. Decomposition Analysis

3.1 Methodology

Decomposition methods can be used to measure the relative contributions of each component of fuel and vehicle expenditures while holding other factors constant. We use the Log-Mean Divisia Index Method I (LMDI I) (Ang and Liu, 2001; Ang, 2005). The main advantages of the LMDI I decomposition method are that it is consistent in aggregation and yields a perfect decomposition in that it eliminates residual terms. Additionally, the LMDI I method is appropriate given the multiplicative nature of the factors that determine fuel and vehicle expenditures. It is a rigorous yet not a computationally intensive method.

For fuel expenditures, there are the following two index decomposition analysis (IDA) identities.

$$F_{t,q} = \sum_{i=1}^2 P_t * G_{t,q,i} = \sum_{i=1}^2 P_t * M_{t,q,i} * \frac{1}{MPG_{t,q,i}} \quad (1)$$

Sectors are the subpopulations of urban and rural residents, and $F_{t,q}$ are fuel expenditures in survey year t for income quintile q . Annual national gasoline prices are represented by P_t , total gallons of fuel consumed is $G_{t,q,i}$, and $M_{t,q,i}$ is total miles driven. The inverse of miles per gallon ($MPG_{t,q,i}$) is $\frac{G_{t,q,i}}{M_{t,q,i}}$, and represents the average fuel consumption per mile of households'

owned vehicles. Similarly, the IDA for vehicle expenditures is the following.

$$V_{t,q} = \sum_{i=1}^2 E_{t,q,i} * N_{t,q,i} \quad (2)$$

Vehicle expenditures for survey year t and income quintile q are represented by $V_{t,q}$. Average cost per vehicle is $E_{t,q,i}$ and the number of vehicles is represented by $N_{t,q,i}$.

Therefore, as shown in Ang and Liu (2001), the ratio of fuel and vehicle expenditures in year T to a base year 0 is as follows:

$$\frac{F_T}{F_0} = D_G * D_P = D_P * D_M * D_{1/MPG} \quad (3)$$

$$\frac{V_T}{V_0} = D_E * D_N \quad (4)$$

where, the effect of the k^{th} factor on the ratio of expenditures is represented by D_k , which is calculated using the following formula:

$$D_{x_k} = \exp \left(\sum_{i=1}^2 \frac{L(F_i^T, F_i^0)}{L(F^T, F^0)} \ln \left(\frac{X_{k,i}^T}{X_{k,i}^0} \right) \right) \quad (5)$$

where, the logarithmic mean is defined as $L(X, Y) = (X - Y) / (\ln X - \ln Y)$.

3.2 Data

Data for the analyses come from the Consumer Expenditure Survey (CES), which is an interview survey conducted quarterly by the U.S. Bureau of Labor Statistics.⁴ The survey is regularly used to update the Consumer Price Index, but it is also widely used in research as it contains a plethora of microdata including detailed information on households' expenditures, income, and characteristics. Households or consumer units⁵ are interviewed for up to five consecutive quarters. Earnings and income information are collected in the second and fifth

⁴ CES data was obtained from the Bureau of Labor Statistics website (<http://www.bls.gov/cex/pumdhome.htm>) for years 1996 to 2014. For years prior to 1996, data was obtained from the Inter-university Consortium for Political and Social Research (ICPSR) (<https://www.icpsr.umich.edu/icpsrweb/ICPSR/series/20>).

⁵ The CES technically surveys consumer units, but the terms consumer unit and household are used interchangeable in this report. Consumer units are all members of a household that are related legally or through blood or marriage, persons living alone, persons who are financially independent but who are living with others, or persons living together who make joint decisions about expenditures.

interview, and for the second through fifth interview, the CES contains households' monthly expenditures for the three months prior to the interview.^{6,7} Quarterly surveys have been conducted on an annual basis since 1980, and we utilize surveys from 1980 to 2014 with some notable exceptions. Survey years 1982 and 1983 are excluded from the decomposition analysis because they exclude the rural population. Additionally, these years along with survey year 1992 do not have supplementary data on households' owned vehicles, so these years are excluded from the analysis on fuel expenditures.⁸ For both fuel and vehicle purchases, we analyze the data by income quintile. We restrict the sample to complete income reporters,⁹ and income quintiles are calculated by survey year using households' before tax income from the fifth interview or the most recently available interview. All dollar values in this report are converted to 2015 dollars using the Consumer Price Index, and all expenditures are aggregated by survey year, income quintile, and by urban or rural residents using population weights. Below we further describe the data and how it was compiled for both the fuel and vehicle decomposition analysis.

For the decomposition of fuel expenditures, fuel expenditures includes spending on gasoline, diesel fuel, and gasoline on out-of-town trips. Monthly fuel expenditures are divided by monthly national gasoline prices from the U.S. Energy Information Administration¹⁰ (EIA) to estimate households' gallons of gasoline consumed. These data are then mapped to quarterly vehicle ownership data. The CES has a supplementary survey on households' owned vehicles that collects an inventory of all vehicles owned, vehicle model years, and vehicle type (i.e., car or light-duty truck). Adjusted fuel economy estimates for new vehicles from the U.S. Environmental Protection Agency (EPA) are mapped to vehicles based on vehicle vintage and

⁶ For example, if a consumer is interviewed in February of 2010, the CES reports monthly expenditures in January 2010, December 2009, and November 2009.

⁷ As indicated in annual users' documentation for CES data, business expenditures are excluded.

⁸ The decomposition analysis measures the impact of factors on the ratio of expenditures from one time period to the next, so excluding these survey years does not affect the analysis.

⁹ From 1980 to 2014, there are 290, 238 households (unweighted), and roughly 89% are considered complete income reporters which generally means that the major sources of income were reported.

¹⁰ Monthly gasoline prices (all grades, U.S. city average retail prices) are from the U.S. Energy Information Administration, February 2016 Monthly Energy Review, Table 9.4 which was obtained from the following website (<https://www.eia.gov/petroleum/data.cfm#prices>).

vehicle type.^{11,12} The CES classifies owned vehicles by either an automobile or a truck, minivan, van, or SUV (i.e., light-duty truck); therefore, car and light-duty truck fuel economy estimates are mapped to these two groups of vehicles, respectively. For households that are missing vehicle data in one quarter, the average of the households' non-missing MPGs are used. If a household is missing vehicle data altogether and thus MPG, the average MPG of households within the same survey year, quintile, and urban versus rural setting is used.¹³ Quarterly miles are then calculated by multiplying the harmonic mean of MPG for a household times gallons of gasoline consumed. Lastly, fuel expenditures, gasoline consumption, and miles driven are aggregated by survey year, quintile, and urban versus rural areas, and the average fuel economy for households' owned vehicles is calculated using aggregated miles and gallons.

Vehicle expenditures include new and used vehicle purchases, leases, rentals, and out-of-town rentals. There are a couple reasons why these vehicle expenditures are examined together. First, changes in data collection make it difficult to consistently break out vehicle leases over the time period studied.¹⁴ Additionally, the sample sizes for the rural populations within income quintiles are relatively small. Moreover, households do not frequently purchase vehicles. Therefore, to prevent data composition from impacting results, we use vehicle purchases, leases, and rentals together. The number of vehicles includes owned vehicles by a household which includes automobiles, trucks, minivans, vans, SUVs, motorcycles, boats, etc. as well as an estimate of the number of leased vehicles. Monthly vehicle lease amounts are available beginning in 1991 and are comparably consistent over time. To estimate the number

¹¹ EPA adjusted fuel economy estimates for car and trucks were obtained from the EPA, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015 Trends Report, December 2015, Table 9.1, page 121. For cars with models years prior to 1975, fuel economy is from the EPA, Passenger Car Fuel Economy: EPA and Road Report, EPA 460/3-80-010, September 1980, Page 19, Fuel Economy Scenarios and New-Car Fleet Fuel Economy Trends. For trucks with model years prior to 1975, MPG was estimated by using trends in MPG from both the EPA and the Federal Highway Administration (FHWA).

¹² In earlier surveys years prior to 1995, a few older vehicle years are grouped together (e.g., 1970-1974) or are censored at 1969 or earlier. For these years, the average of vehicle MPGs were used, and for vehicle vintages censored at 1969, fuel economy in 1969 is used.

¹³ About 21% of quarterly observations are missing vehicle model year and thus assigned MPG. For about 4% of these, we are able to use the average MPG for the household from other interview quarters. For 17%, we use the average MPG for households within the same survey year, quintile, and urban or rural setting.

¹⁴ Prior to 1991, car and truck leases and rentals were grouped together under the same expenditure code. After 1991, car and truck leases and rentals were assigned separate expenditure codes.

of leased cars or the user cost of capital for a vehicle, lease and rental expenditures are divided by the average vehicle lease amount. This measure for the number of vehicles may overstate the number of cars and light-duty trucks owned by a household because other vehicles in addition to cars and trucks are included, but due to data limitations, this is the best available measure of vehicle stock for our purposes in the CES.¹⁵ Then, similar to the data on fuel expenditures, vehicle expenditures and the number of vehicles is aggregated for households within the same survey year, income quintile, and urban versus rural settings.

3.3 Key Assumptions

There are a few key assumptions in our decomposition analysis that are worth discussing in more detail. First, as previously mentioned, earlier work has found that MPG either does not deteriorate or slightly deteriorates over a vehicle's lifetime (Lin and Greene, 2011; Greene et al., 2015; Murrell, 1980). We perform a supplementary analysis using EIA's Residential Transportation Energy Consumption Survey (RTECS)¹⁶ and National Household Travel Survey (NHTS) data to examine this issue. We found through auxiliary regressions that MPG generally decreases by about .1 MPG per year for vehicles, and this is relatively similar to the aforementioned existing literature.¹⁷ Therefore, we adjust vehicles' fuel economy according to their age, although the results are only slightly affected by not making this adjustment.

Secondly, expenditures are aggregated using population weights, and the decomposition analysis is at the national level. Therefore, we use EIA national gasoline prices (all grades, U.S. city average). Historical prices at the city or regional level are only available beginning in 2000 and 1994, respectively. Additionally, it would be difficult to map regional prices to CES respondents based on region or state. We do not believe this is problematic though given that

¹⁵ Alternatively, the CES does include a count of automobiles, but this measure would exclude trucks, SUVs, minivans, and vans. Also, the supplementary survey on households' owned vehicles could be used to estimate the number of cars and light-duty vehicles owned by households, but this data is unfortunately missing for a non-trivial amount of households.

¹⁶ RTECS data was obtained from the U.S. Energy Information Administration. Retrieved on 5/25/2016 from <http://www.eia.gov/consumption/archive/rtecs/contents.html>

¹⁷ Using RTECS surveys from years 1980, 1981, 1983, 1985, 1988, 1991, and 1994 and NHTS from 2001, reported or calculated respondents' MPG is regressed on the EPA adjusted MPG (based on model year) and age by model year, and estimates generally indicate that a vehicle's MPG decreases by about 1 MPG over ten years.

major trends in gasoline prices are captured by national gasoline prices, and it is not clear that using city or regional prices would improve the accuracy of the decomposition.

Lastly, the CES data indicates the model year of vehicles purchased or owned, and with the exception of very few survey years, make and model are not available. Analyzing fuel economy improvements by car versus light-duty truck and model year is consistent with how CAFE standards are set and regulated by the EPA and NHTSA. Previously, auto manufacturers had to meet CAFE standards based on target standards for cars and light-duty trucks. For model years 2012-2016 and forward, fuel economy targets are based on a vehicle's footprint, so smaller vehicles must achieve a higher MPG compared to larger vehicles. In both instances, vehicle manufacturers can meet standards based on the average for their fleet rather than specific models meeting a given year's standard. There are also multiple opportunities for vehicle manufacturers to receive credits. In general though, CAFE and greenhouse gas standards are formulated and set for cars and light-duty trucks by model year versus for specific vehicle makes and models. Thus, in evaluating the impacts of fuel economy, the data is analyzed in a similar fashion.

3.4 Descriptive Statistics and Trends

Figures 5 through 12 show the trends from 1980 to 2014 by income quintile for aggregate fuel and vehicle expenditures and the factors that affect them. Expenditures per household follow the same trends as total expenditures by quintile because each quintile is comprised of the same number of households. As can be seen in Figure 5, fuel expenditures increase with increasing income, and the amount of increase is similar across all income quintiles. Fuel expenditures closely follow the trend in gasoline prices as they decrease in the early eighties and generally increase after 2002 with the exception of falling expenditures and gas prices following the financial crisis in 2008. Fuel economy for new cars and light-duty trucks also changed over this time period. EPA adjusted fuel economy estimates for new vehicles increased to 23 MPG and 17.5 MPG in 1985 for cars and light-duty trucks, respectively. Thereafter, fuel economy estimates were generally stable until around 2004 and then ultimately increased to 27.9 and 20.4 in 2014 for cars and light-duty trucks, respectively. EPA adjusted fuel economy estimates

for *new* vehicles and the average fuel economy of households' *owned* vehicles are shown in Figure 6 by income quintile. There is a lag effect as the stock of households' vehicles includes both new and used vehicles of various vintages. Also, the highest income households have a higher average MPG, and there is a lag effect for lower income households. This demonstrates how vehicles trickle down through income groups. Higher income households buy more new vehicles, so MPG increases for these consumers first. The dips in MPG that begin in the mid-nineties are likely attributable to the growth in sport utility vehicles (SUVs).

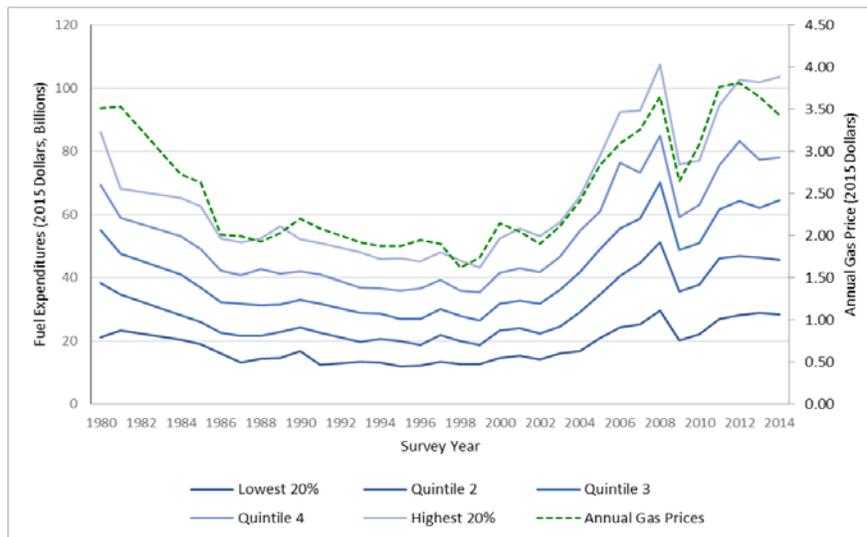


Figure 5. Fuel Expenditures by Income Quintile and Annual Gasoline Prices

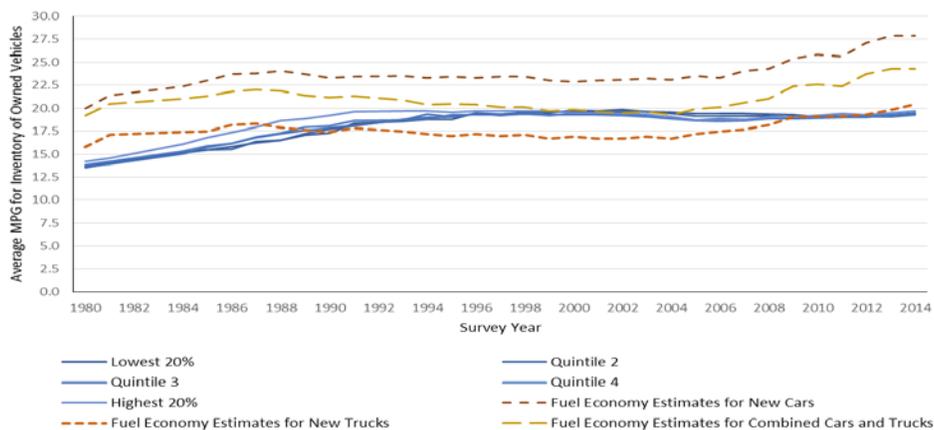


Figure 6. Average Fuel Economy of Households' Owned Vehicles by Income Quintile and EPA Adjusted Fuel Economy Estimates for New Cars and Light-duty Trucks

Vehicle miles traveled (VMT) is another factor that affects fuel expenditures. Increasing the fuel economy of motor vehicles reduces their operating cost, and that leads to an increase in vehicle travel known as the rebound effect (Gillingham et al., 2013; Greening et al., 2000). Typically, a ten percent increase in miles per gallon will induce a 1-2 percent increase in miles traveled (Small & van Dender, 2007; Greene et al., 1999). Divisia decomposition does not make adjustments for the rebound effect, and the effect of fuel economy is conditional on the vehicle miles actually traveled, not what they would have been had fuel economy remained constant. Figure 7 shows vehicle miles traveled by income quintile since 1980. Vehicle miles traveled is estimated by multiplying the quarterly harmonic mean of MPG for a household's inventory of vehicles by fuel expenditures and the inverse of gasoline prices. There is generally an upward trend in vehicle miles traveled for all income groups. Vehicle miles traveled are higher for each consecutive income quintile, and vehicle miles traveled for the highest income quintile is consistently three to four times as much as the lowest income quintile. Yet, as shown below in Figure 12, lower income households own fewer vehicles, so VMT per vehicle is actually higher for lower income households. The trends presented here demonstrate how factors such as gasoline prices, fuel economy, and vehicle miles traveled are factors of fuel expenditures. The decomposition analysis will further demonstrate and quantify how these factors relatively affect fuel expenditures.

Turning to vehicle expenditures, Figure 8 shows vehicle expenditures over time broken out by new vehicle purchases, used vehicle purchases, and vehicle leases and rentals. As vehicles are a durable good, consumers seem to be more likely to purchase cars when gas prices are falling and delay purchasing cars when gas prices are high. It is also evident how vehicle leases have substantially grown over time, but it should be noted that it is somewhat difficult to directly compare vehicle purchases to vehicle leases here. Vehicle leases and rentals are the aggregate of households' monthly lease payments or rental expenditures while new and used vehicle purchases are the aggregate of the purchase price of vehicles regardless of whether a consumer finances a vehicle with an auto loan or not.

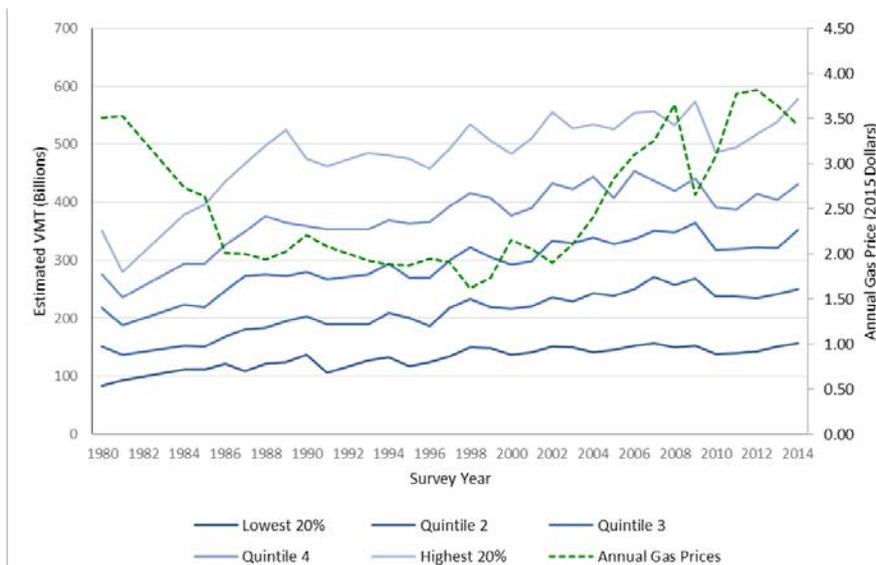


Figure 7. Estimated Vehicle Miles Traveled by Income Quintile

New and used vehicle purchases are shown in Figures 9 and 10, respectively. There appears to be some noise in these data, but it is clear that higher income households spend more on new vehicles than lower income households. Since 1980, the highest income quintile’s new vehicle expenditures are on average eleven times as much as the lowest income quintile. Yet, the highest income quintile’s expenditures on used vehicles is only about four times as much, on average, as the lowest income quintile. Figure 11 demonstrates how the highest income quintile contributes the most to the growth in the number of vehicle leases. Lastly, Figure 12 demonstrates the number of vehicles owned including the estimated number of leased vehicles by income quintile. Households’ number of vehicles is relatively stable but increases both over time and by income quintile since 1980.

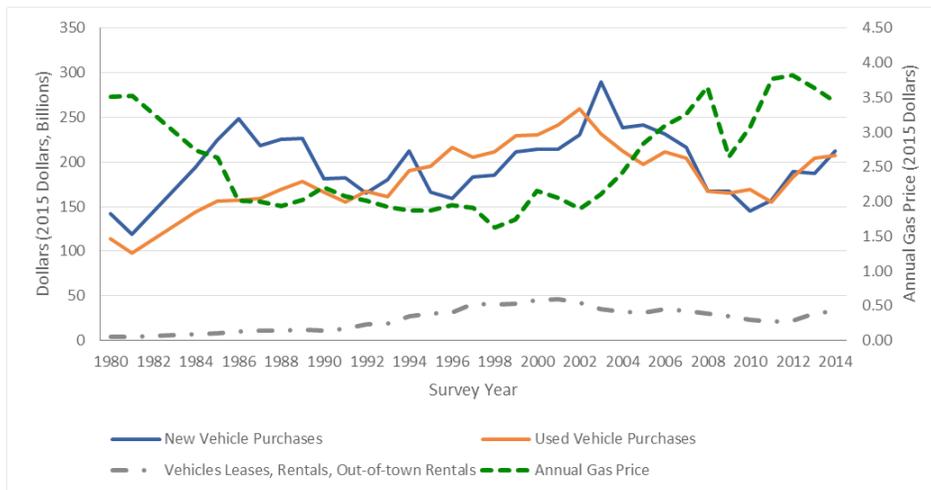


Figure 8. Total Vehicle Expenditures for All Income Quintiles

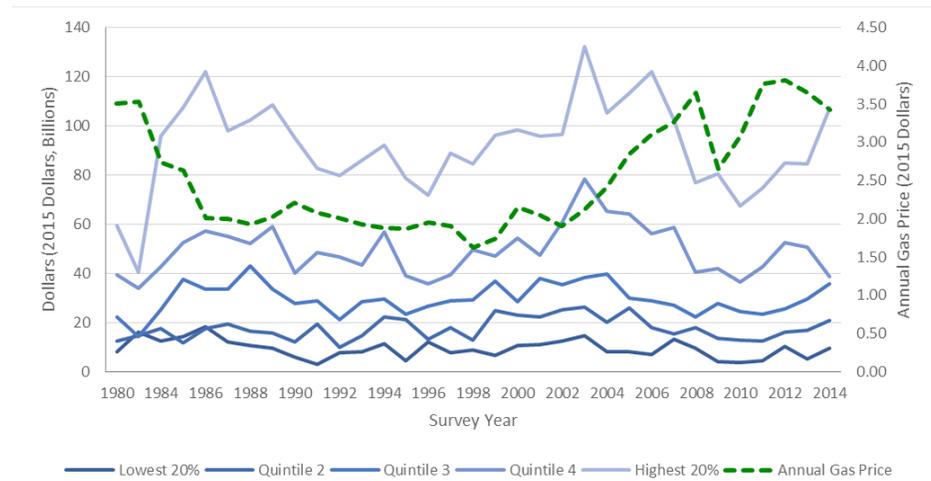


Figure 9. New Vehicle Purchases by Income Quintile

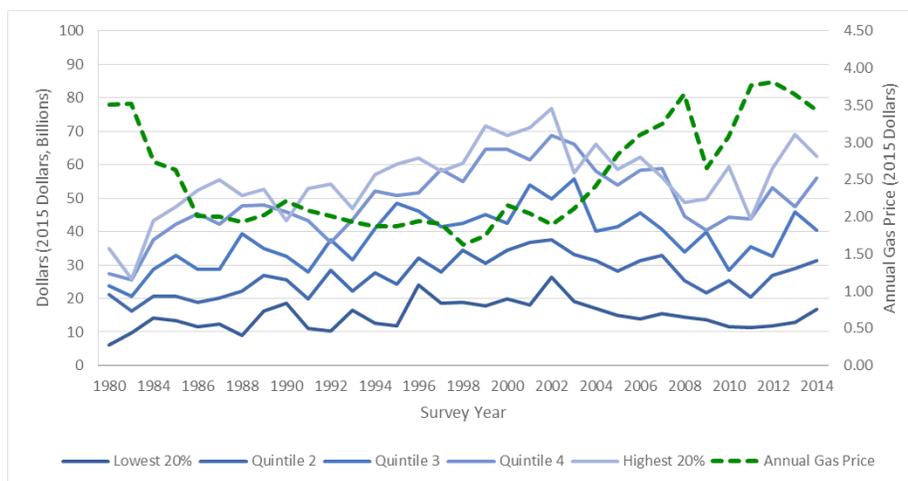


Figure 10. Used Vehicle Purchases by Income Quintile

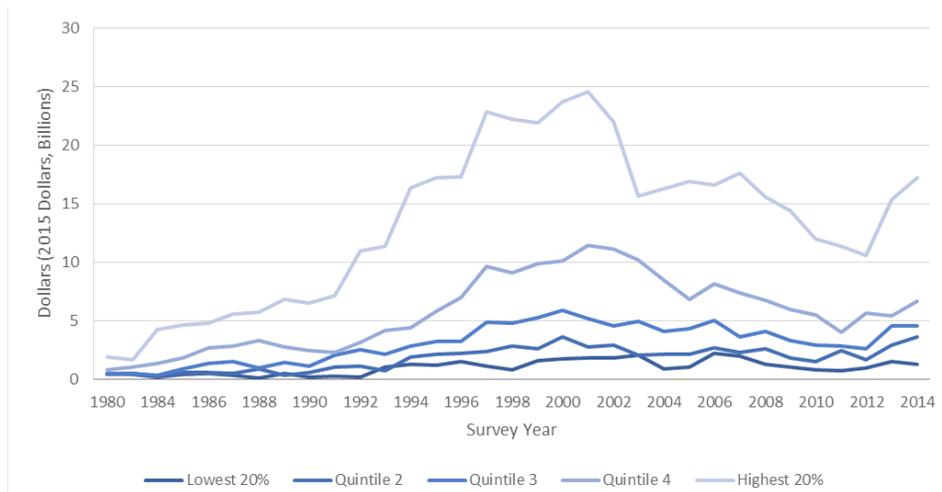


Figure 11. Aggregate of Monthly Vehicle Leases and Rental Expenditures by Income Quintile

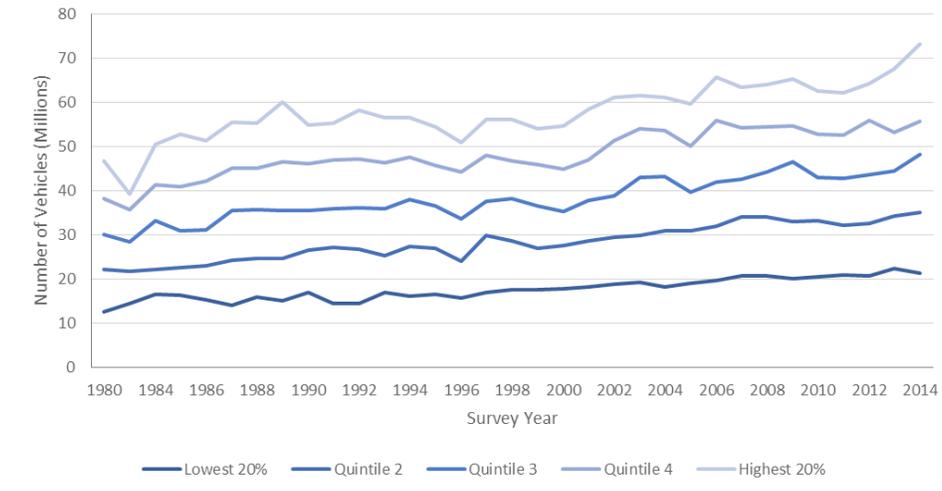


Figure 12. Vehicle Stock by Income Quintile

3.5 Decomposition Analysis Results

For the decomposition analysis, Equation 5 is used to find the effect of each factor on the ratio of expenditures from one survey year to the following survey year within an income quintile. The cumulative effects as of a given survey year of gasoline prices, vehicle miles traveled, and the inverse of MPG for each income quintile are shown in Figures 13 through 15, respectively. These figures show the cumulative effect of each factor from 1980 to a given year on expenditures in that year. We call this effect in each year the cumulative factor effect to distinguish it from estimates of the cumulative changes in expenditures over the entire time period.

The effect of gasoline prices on fuel expenditures is shown in Figure 13. Given that gasoline prices are national prices, the effect is identical across income groups. The cumulative effect of gasoline prices on fuel expenditures in 2014 compared to 1980 is almost zero, but this is due to the trend in gasoline prices over this time period. In 2015 dollars, national gas prices in 1980 were around \$3.51, and while prices dropped as low as \$1.62 in 1998, gas prices increased back to \$3.43 in 2014. Therefore, the gasoline prices decreased the ratio of fuel expenditures by as much as 54% in 1997 since gas prices had generally been falling to that point, but the ratio of fuel expenditures grew by about the same amount when gas prices were rising thereafter. Thus, the effect of gas prices on fuel expenditures significantly decreases and then increases, but from the beginning to the end of the time period studied, the effect is minimal. The effect of vehicle miles traveled can be seen in Figure 14. Vehicle miles traveled consistently increases fuel expenditures over this time, by roughly sixty percent for most income groups with the exception of the lowest income quintile. Vehicle miles traveled has a greater effect for these consumers, but this departure appears to occur in the early 1980's and persists over time.

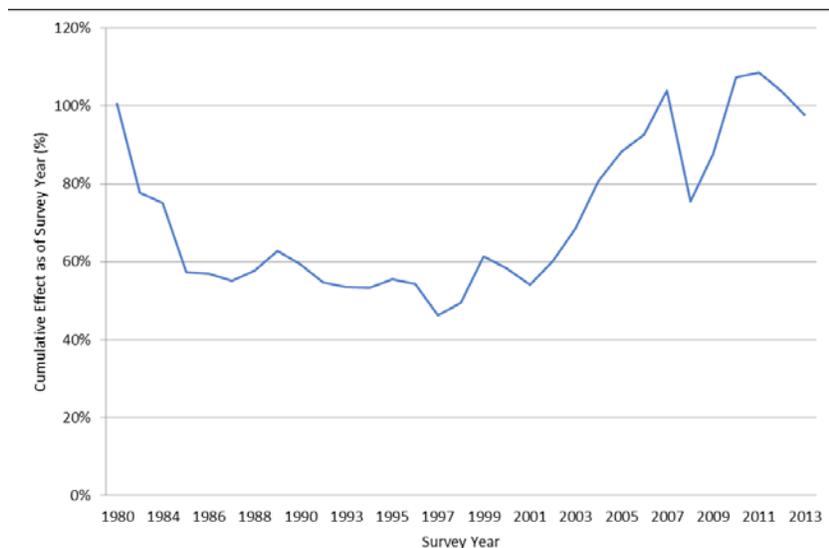


Figure 13. Gasoline Price Component: Fuel Expenditures for all Income Quintiles

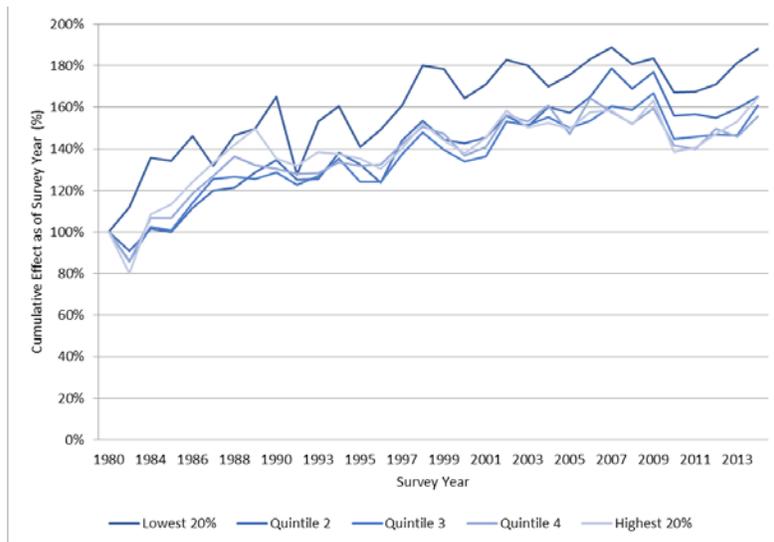


Figure 14. Miles Component: Fuel Expenditures by Income Quintile

Lastly, Figure 15 demonstrates the effect of fuel economy on fuel expenditures. The ratio of fuel expenditures decreases by about thirty percent for all income groups due to increased fuel economy from 1980 to 2014. The highest income groups' fuel expenditures decrease first as they buy more new vehicles with higher fuel economy. Lower income households buy more used vehicles, so while, increased fuel economy decreases their fuel expenditures, it takes longer for this effect to take place. For the highest income quintile, the rise in fuel expenditures due to fuel economy, starting in the second half of the nineties, is likely due to growth in the light truck market, and again, there is a lag effect for lower income households.

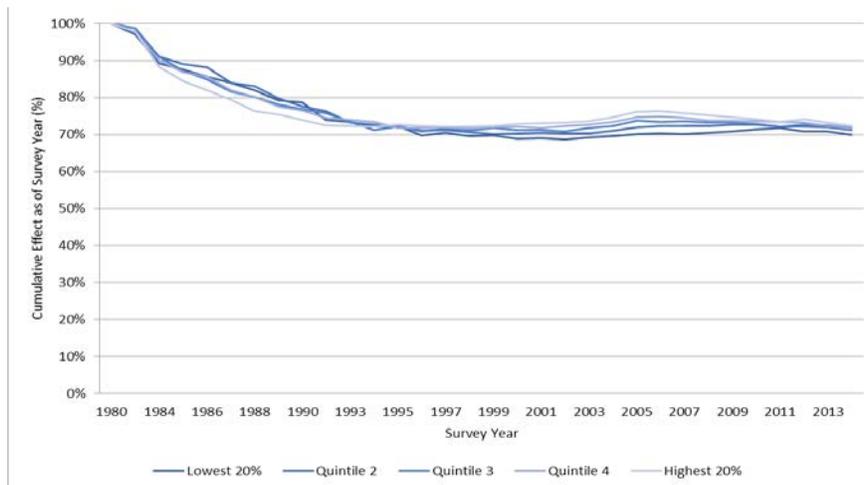


Figure 15. MPG Component: Fuel Expenditures by Income Quintile

Turning to the second decomposition analysis which examines vehicle expenditures, Figure 16 and 17 show the cumulative factor effect of the average expenditure per owned vehicle and vehicle ownership on vehicle expenditures, respectively. The average cost per vehicle is an aggregate measure of vehicle costs and includes vehicle purchases, leases, and rentals. Moreover, embedded in these values are not only the advancements and technology needed to increase fuel economy but also other vehicle attributes that have changed over time (e.g. luxury and convenience features, performance, safety equipment, emissions controls, and more recently, automated driving systems). The average expenditure per vehicle increases and decreases over the time period studied and generally follows macroeconomic business cycle trends and gas prices which affect total vehicle expenditures likewise. While there is some noise in the data, Figure 16 illustrates how average expenditures per vehicle consistently have a larger impact on total vehicle expenditures for the highest income quintile. Notice that while vehicle purchase prices increase over the time period studied, expenditures per owned vehicle return to approximately the same level as in 1980 after the Great Recession. Increased vehicle life expectancy as well as households holding onto vehicles longer explain this phenomenon. The cumulative factor effect of vehicle ownership, shown in Figure 17, exhibits an upward trend over time, but is relatively stable. The effect of the number of vehicles on total vehicle expenditures is greatest for the lowest income quintile, but again, this departure seems to occur at the beginning of the sample period and persists versus changing over the time period studied.

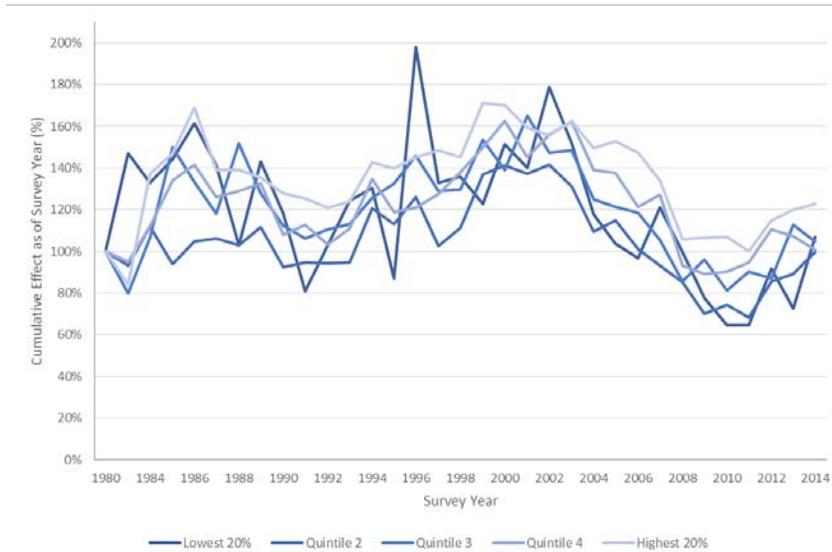


Figure 16. Average Expenditure per Owned Vehicle: Vehicle Expenditures by Income Quintile

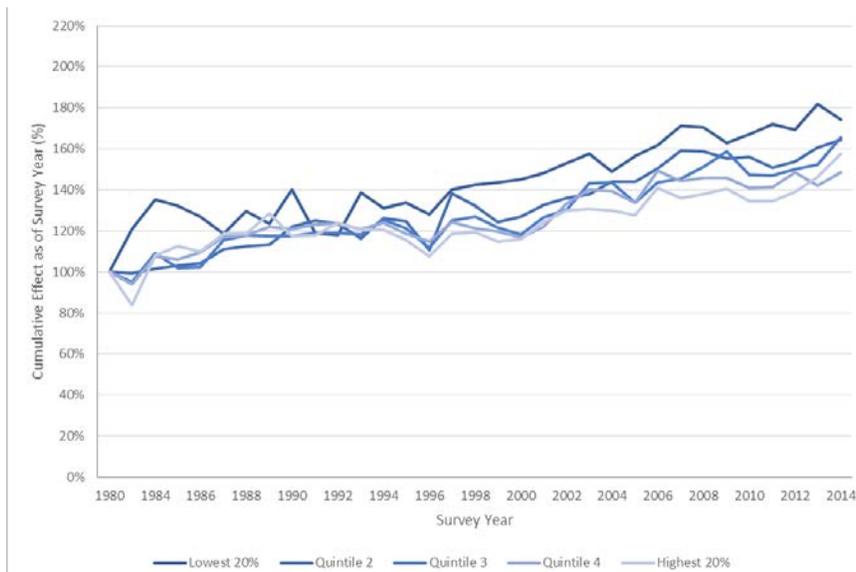


Figure 17. Number of Owned Vehicles Component: Vehicle Expenditures by Income Quintile

To better understand how these cumulative factor effects on fuel expenditures translate to consumers, Table 2 illustrates the 2014 costs or savings (i.e., in parentheses) per household due to fuel economy, gas prices, and vehicle miles traveled. Using the cumulative factor effects, we calculate counterfactual expenditures or for example, what fuel expenditures would have been in absence of rising fuel economy. We then find the difference between these counterfactual expenditures and actual expenditures for each income quintile and survey year. This allows us to look at the change in expenditures per household. Households

in all income quintiles save money in terms of fuel expenditures due to increased fuel economy, but the highest income quintile saves the most. In 2014, the average savings per household for the highest income quintile is about \$1,500 while households in the lowest income quintile save about \$509. Although, in terms of a percentage of income, lower income households save the most (4.3% of their income), and higher income households save the least (0.9% of their income). Gas prices over the sample period greatly decrease and then increase and affect fuel expenditures accordingly, but given that 1980 and 2014 gas prices are relatively similar in constant dollars, fuel expenditures do not greatly change for any of the income groups. Vehicle miles traveled results in an increased cost in fuel expenditures for all income groups, and this cost per household increases by income quintile. It is worth noting that although the decomposition analysis does not consider the rebound effect, its effect on fuel expenditures was undoubtedly small. A 10-20% rebound effect implies an increase of 3-6% in miles traveled for the 30% reduction in fuel use per mile. The total increase in household VMT from 1980 to 2014 was about 65%, meaning that the increase in expenditures due to the rebound effect was about 4.6% to 9.2% of the observed increase in expenditures due to VMT growth.

Table 2. Impact of Fuel Economy, Gas Prices, and Vehicle Miles Traveled Relative to 1980 Values on 2014 Fuel Expenditures

Income Quintile	Fuel Economy		Gas Prices		VMT	
	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income
Lowest 20%	(509)	-4.3%	(29)	-0.2%	556	4.7%
Quintile 2	(734)	-2.7%	(45)	-0.2%	716	2.6%
Quintile 3	(990)	-2.1%	(61)	-0.1%	954	2.1%
Quintile 4	(1,211)	-1.6%	(73)	-0.1%	1,094	1.5%
Highest 20%	(1,499)	-0.9%	(95)	-0.1%	1,535	0.9%

Table 3 shows similar results for vehicle expenditures. Households in the highest income quintile incur the largest expense in 2014 due to the average expenditure per vehicle. Yet, this cost in terms of percentage of income is somewhat comparable and less than one percent across all income groups. Across all income quintiles, increased vehicle ownership also contributes to increased vehicle expenditures, and this cost increases by income quintile.

Table 3. Impact of Average Expenditure per Vehicle and Number of Vehicles Relative to 1980 Values on 2014 Vehicle Expenditures

Income Quintile	Average Cost per Vehicle		Number of Vehicles	
	Cost or (Savings) per Household	% of Income	Cost or (Savings) per Household	% of Income
Lowest 20%	74	0.6%	493	4.2%
Quintile 2	(9)	0.0%	870	3.2%
Quintile 3	141	0.3%	1,250	2.7%
Quintile 4	24	0.0%	1,299	1.7%
Highest 20%	1,300	0.8%	2,580	1.6%

Finally, to summarize our decomposition analysis, we sum all costs or savings in fuel and vehicle expenditures due to each of the factors to find the cumulative impacts from 1980 to 2014. Table 4 illustrates the total impact of fuel economy and the average expenditure per vehicle on households' expenditures over the 1980 to 2014 period. Savings in fuel expenditures per household increase by income quintile, and over the three and half decades studied, savings amount to roughly \$10,600 per household for the lowest income quintile and \$31,700 per household for the highest income quintile. Increased vehicle expenditures due to the average expenditure per vehicle also increase by income quintile, with the lowest and highest income quintiles incurring a total cost of about \$7,800 and \$68,700 per household, respectively. On net, households in the lowest income quintile save about \$2,800, which on an annual basis, equates to about 0.66% of average household's income. Households in the highest income quintile incur a total cost of about \$37,000, which represents on an annual basis, about 0.9% of average households' income. It is important to note that the increases in vehicle expenditures in Table 4 reflect changes in vehicle prices due to all changes in vehicle attributes in addition to the costs associated with increasing fuel economy. Therefore, these estimates serve as more of an utmost upper bound for the effect of fuel economy on households' expenditures. This analysis demonstrates though that households in the lowest income quintile benefit the most from increased fuel economy compared to households in the highest income quintile when examining vehicle prices as a whole. Furthermore, while the highest income group incurs a net cost when using vehicle prices as a whole, the cost is still a relatively small percentage of their income. In the econometric analysis that follows, we examine how much of the present discounted value

of fuel savings is captured in used vehicle prices. In Section 5, we discuss estimates of how much of total vehicle price changes are actually due to integrating fuel economy advancements and technology into vehicles. We then combine these analyses and findings to formulate an estimate of the cost of fuel economy improvements over the time period studied. This allows us to refine the summary of how fuel economy improvements affect households' expenditures by income quintile, although it still serves as a conservative approximation. In this extension to our original report, we provide an additional, more direct approach for estimating the cost of fuel economy improvements. We use cost function estimates for fuel economy improvements chiefly from studies by the National Research Council (NRC), supplemented with estimates for years prior to 1990 from a literature review by Greene and DeCicco (2000). All curves have been converted to 2015 dollars and represent estimates of the retail price car buyers would pay for fuel economy technologies added to new vehicles. The estimates provide a more direct measure of the actual cost to implement fuel economy improvements. Using cost functions, an inventory of owned vehicles from the CES, and a user cost of capital method, we create new estimates of the impact of fuel economy improvements on households' expenditures (see Section 5.2). Finally, we compare results from using all three methodologies for estimating the cost of fuel economy improvements (see Table 10).

Table 4. Total Impacts of Factors on Fuel and Vehicle Expenditures, 1980-2014

Income Quintile	Fuel Economy	Average Cost per Vehicle		Annual Net Cost or (Savings) as Percent of Average Household Income
	Accumulation of Cost or (Savings) per Household	Accumulation of Cost or (Savings) per House	Net Cost or (Savings)	
Lowest 20%	(10,591)	7,808	(2,783)	-0.66%
Quintile 2	(15,329)	3,423	(11,906)	-1.41%
Quintile 3	(20,820)	19,817	(1,003)	-0.07%
Quintile 4	(25,560)	31,882	6,322	0.29%
Highest 20%	(31,652)	68,672	37,021	0.90%

4. Econometric Analysis of Used Vehicle Prices

4.1 Methodology

The market prices of used vehicles reflect the depreciated value of the vehicles when they were new. However, for model years with improved fuel economy, used car prices may

also include economic rent reflecting future fuel savings relative to other vehicles on the road. If the new vehicle market is sufficiently competitive, the price of fuel economy improvements to new cars would be approximately equal to the long-run average cost of their production.¹⁸ The question is then what used car buyers would pay for vehicles with increased fuel economy. If new and used cars were perfect substitutes, used car buyers would pay no more than the long-run average cost of new vehicle fuel economy, adjusted for depreciation of the used vehicle. But because the supply of used vehicles is inelastic and new and used vehicles are not perfect substitutes, the effect of fuel economy improvements on the prices of used vehicles is not obvious. Sellers of high fuel economy used vehicles might be able to obtain economic rent for model years with above average fuel economy since their availability is limited. The economic rent would be proportional to their advantage in fuel consumption per mile, the expected future price of fuel and the expected remaining vehicle miles of travel.

Three recent studies analyzed the effects of changes in gasoline prices on new and used car prices of different fuel economies. Allcott and Wozny (2014), Sallee et al. (2015) estimated the effect of vehicle fuel economy and fuel price fluctuations on the prices of used vehicles at the make, model, engine, and transmission level. They found that 51%, 55% or 76% of expected fuel savings were capitalized in the prices of used vehicles, depending on how consumers formed their expectations about future fuel prices. The highest percentage (76%) based expectations on oil futures markets while the estimate of 51% was based on actual consumers' beliefs about future fuel prices, as recorded in the Michigan Survey of Consumers (Anderson et al., 2011). The estimate of 55% assumed that the best predictor of future gasoline price was the current price. Sallee et al. (2015) found that the fraction of expected future fuel costs reflected in wholesale used vehicle prices depended on a vehicle's cumulative mileage. They found that for vehicles with fewer than 100,000 miles, 100% of future fuel costs were reflected in vehicle prices, but for vehicles with 100,000 to 150,000 miles on their odometers only 30% was. This result is important because U.S. light-duty vehicles reach 100,000 miles after about 7 years and

¹⁸ This would be the case if the new vehicle market were perfectly competitive, monopolistically competitive, or oligopolistic if manufacturers arrived at a Cournot equilibrium.

approximately half of the vehicles in use are more than 7 years old (NHTSA, 2006). Busse et al. (2013) estimated the short-run effect of gasoline prices on vehicles in four fuel economy quartiles and estimated implicit discount rates for future fuel savings. The rates vary from 20.9% to -6.8% with 80% probability intervals of -0.9% to 9.0% for new cars and 2.8% to 16.9% for used cars, depending on which quartiles are compared and how future vehicle use was estimated. Because the primary determinants of a vehicle's fuel economy are its mass and engine size, the quartiles generally differ greatly with respect to vehicle and engine sizes. Thus, Busse et al. (2013), like the other two studies, are predominantly estimating the effect of gasoline price on the equilibrium prices of vehicles of different sizes. Vehicles of different classes are less substitutable than vehicle cohorts of adjacent model years. In addition, estimates based on consumers' short-run responses to gasoline price changes may be exaggerated. Behavioral economists maintain that consumers initially respond to a price change relative to a reference point, such as the previous price level. In the case of a sudden change in gasoline price the initial response is likely to be much larger than adjustments consumers make after becoming accustomed to the higher price (Ariely, 2009, p. 49).

The major difference between the econometric analysis below and the three studies described above is that we compare model year cohorts of passenger cars and light trucks rather than individual vehicles. Model year cohorts include a full range of vehicle types and differ chiefly by age and accumulated mileage. They should therefore be much closer substitutes than individual make, model, engine, transmission and trim configurations which can be as different as a four-passenger economy subcompact and a large luxury SUV or pick-up truck. Most importantly, changes in average fuel economy between model years are predominantly due to technology and engineering changes to vehicles rather than vehicle and engine size (EPA, 2015). Paying more for a vehicle that appears to be similar but claims better fuel economy may be seen as a risky bet, triggering loss averse decision making (e.g., Greene, 2011, 2013). Finally, fuel economy differences between adjacent model year cohorts are small, on the order of 1 MPG (Figure 4) and may not be salient to car buyers (Sallee, 2014). Consequently, the

degree to which the prices of used vehicles are determined by depreciation of new vehicle prices (and macroeconomic fluctuations) or by economic rent derived from the value of superior fuel economy is an empirical question that depends on consumer behavior, the competitiveness of vehicle markets and the substitutability of new vehicles and used vehicles of different model years.

The original Corporate Average Fuel Economy standards required manufacturers to improve the sales-weighted harmonic mean fuel economy of their vehicles incrementally, by model year. The CAFE standards were enacted in December, 1975 and first took effect in model year 1978 (NRC, 2015). Different and separate standards were set for passenger cars and light trucks. Figure 4 compares the unadjusted, EPA-test fuel economy numbers used to certify compliance with the standards for passenger cars and light trucks. The changes from one model year to the next are gradual: from 1975 to 1985, EPA-test passenger car MPG increased at an average rate of 1.1 MPG/year and adjusted MPG increased by 0.9 MPG/year. The corresponding rates for light trucks were 0.7 MPG/year and 0.6 MPG/year. On-road fuel economy has averaged about 15-20% lower than the test cycle estimates (Greene et al., 2015).

In general, manufacturers met the standards by adding content to their vehicles in the form of fuel economy enhancing technologies (EPA, 2015), rather than by pricing vehicles to induce customers to buy smaller and less powerful vehicles (Greene, 1991). Since 1975, the sales-weighted interior volume of passenger cars has remained essentially constant. Acceleration performance (indicated by the ratio of horsepower to weight) held approximately constant through the early 1980s but has since increased by about 70% (Figure 18). These trends were affected very little by large fluctuations in the price of gasoline. Changes occur gradually, year by year following vehicle redesign cycles. As a general rule, manufacturers make major changes to vehicles every five to seven years and minor changes every two to three years (NRC, 2015). As a consequence, most vehicles in adjacent model years have very similar designs and fuel economy numbers.

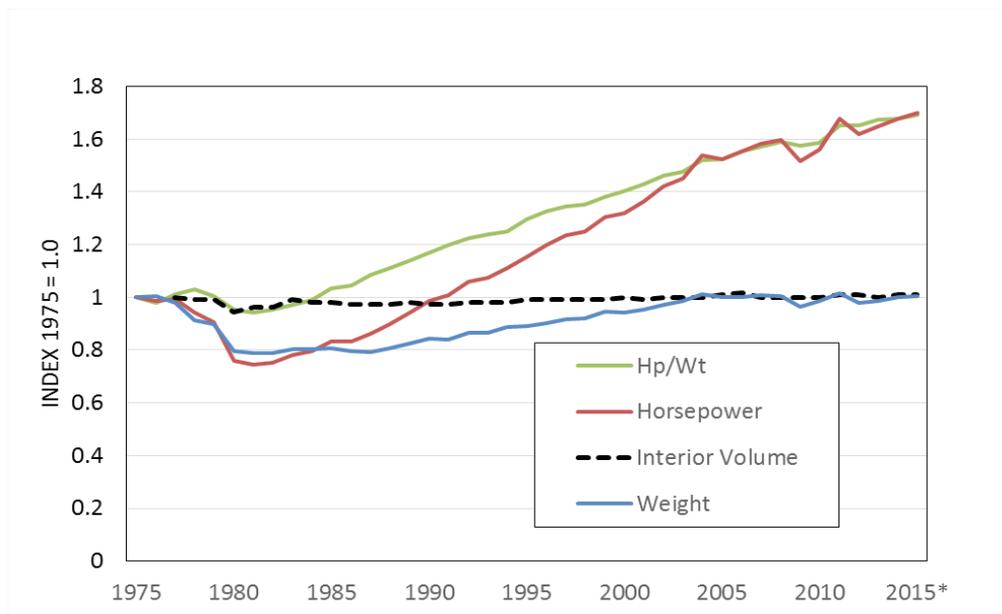


Figure 18. Selected Attributes of Passenger Cars: 1975-2015 (EPA, 2015).

4.2 Theoretical Model

If the market for new cars is monopolistically competitive, or if manufacturers achieve a Cournot equilibrium competing with one another, new cars will tend to sell at their long-run average cost of production. In addition, new car supply for a model year (as opposed to a particular make and model) is highly elastic under most circumstances, even in the short run. Used car supply, on the other hand, is highly inelastic, and some have assumed it to be fixed for analytical purposes (e.g., Allcott and Wozny, 2015; Sallee et al., 2015). Given elastic supply of new vehicles at long-run average cost and inelastic supply of used vehicles, how increasing fuel economy will affect the prices of used vehicles will depend on the substitutability of used vehicles of different model years and how consumers value fuel economy.

To illustrate how mandated fuel economy increases may affect used car prices, we adopt Allcott and Wozny's (2014) model of vehicle prices. Allcott and Wozny applied their model to thousands of makes, models and model years of vehicles, while we consider only model years and passenger cars and light trucks. The average consumer's utility of owning and using a vehicle of age a over its remaining life in year t is represented by Ω_{at} (the distinction between

cars and light trucks is omitted in the model derivation for simplicity). The remaining (expected) cost of fuel for the same vehicle is F_{at} . For a vehicle with an expected lifetime of L years, F_{at} equals the sum over the remaining $L-a$ years of life of annual miles of travel, $M(t)$ times the price of fuel, p_f , divided by miles per gallon, MPG . Let Y be the consumer's income, P_{at} be the price of an a -year-old vehicle in year t , let β be the marginal utility of a dollar and ϕ be a parameter that translates a discounted present value of expected fuel costs into a price equivalent. The consumer's indirect utility, U_{at} , of an a -year-old vehicle in year t is given by Equation 6.

$$U_{at} = \beta(Y - P_{at} - \phi F_{at}) + \Omega_{at} \quad (6)$$

Allcott and Wozny (2014) include a random utility component, ε_{at} , with an extreme value distribution, from which it follows that the market shares of different model years will be a multinomial logit function of their indirect utilities. Because we do not use the logit form in our statistical analysis we omit ε_{at} . They also assume that the supply of used vehicles in any given year is perfectly inelastic. While this appears to be a reasonable approximation, the supply of used vehicles in any given year depends on the sales of new vehicles in previous years, which are sensitive to macroeconomic factors. The econometric analysis must allow changes in the supply of used vehicles from one year to the next to affect the prices of used vehicles.

As a vehicle is used, the utility of owning and operating it decreases. Assume that the loss of utility from one year to the next is a result of using up its total lifetime miles and can be represented by exponential depreciation, e^{-ba} . Thus, the utility at age a is $\Omega_0 e^{-ba}$ and the remaining fuel costs are $F_0 e^{-ba}$. If the differences in price between a new and used vehicle exactly compensate for the loss of indirect utility as the vehicle ages, then the price of an a -year-old vehicle is given by Equation 7.

$$\begin{aligned} \beta(y - P_0 - \phi F_0) + \Omega_0 &= \beta(y - P_{at} - \phi F_0 e^{-ba}) + \Omega_0 e^{-ba} \\ P_a &= P_0 + \phi F_0 (1 - e^{-ba}) + \frac{1}{\beta} \Omega_0 (e^{-ba} - 1) \end{aligned} \quad (7)$$

Equation 7 states that the price of a used vehicle depreciates exponentially from its value when new as its utility is consumed through usage, but also increases as the remaining fuel costs

diminish. Because fuel costs make up 10% to 20% of the total costs of owning and operating a vehicle, and because the monetary cost must be less than or equal to its utility, the net effect is an exponential depreciation of vehicle prices as vehicle age. In real markets other factors influence used vehicle prices, as well. Technological progress will accelerate price depreciation, and it is generally understood that the value of a new vehicle will instantly depreciate by about 10% as soon as it is driven away from the dealership (e.g., Edmonds, 2016). Because motor vehicles are durable goods, their prices are also strongly affected by macroeconomic shocks.

As a vehicle approaches the end of its useful life its price approaches zero (in reality even a very old vehicle will have a scrappage value). Setting $a = \infty$ and $P_\infty = 0$ gives Equation 8.

$$P_\infty = P_0 + \varphi F_0 - \frac{1}{\beta} \Omega_0 = 0 \quad (8)$$

Rearranging terms in Equation 7 to isolate those that include the exponential, and substituting Equation 8 in Equation 7 produces the result that the net usage value of a vehicle (in dollars) depreciates exponentially with age.

$$P_\alpha = \left(\frac{\Omega_0}{\beta} - \varphi F_0 \right) e^{-ba} \quad (9)$$

Because the price of a new car depreciates by approximately 10 percent the moment it leaves the dealership (e.g., Edmonds, 2016) there is an abnormally high rate of depreciation between years 0 and 1. This 0-year depreciation is not due to the consumption of the vehicle's utility but rather due to the unique property of newness that is lost once anyone takes ownership. Equation 9 which accounts for only the consumption of utility implies that $P_1 = P_0 e^{-b}$. In the econometric analysis below the special depreciation of a new vehicle is eliminated by expressing P_a a function of the price of a 1-year-old vehicle.

The net value of a used car of a given age (the term in parentheses in Equation 9) will not be constant over time. Fluctuations in the price of fuel change operating costs and changes in macroeconomic factors like unemployment and household income can change the expected utility of owning a vehicle. In addition to demand shocks, fluctuations in new vehicle sales

cause supply shocks that also affect the prices of used vehicles. In the econometric analysis that follows, year-specific indicator variables, d_t , allow the net value of a vehicle to change yearly in response to supply and demand shocks.

If one model year, a^* , has better fuel economy than the others, $F_0 \cdot f$ with $f > 0$, (but is otherwise identical) its price could be greater than it would have been without the fuel savings, f .

$$P_{a^*} = \left(\frac{\Omega_0}{\beta} - \varphi F_0 \right) e^{-ba^*} + \varphi f e^{-ba^*} \quad (10)$$

Equation 10 provides the equation for used vehicle prices by age and model year that we estimate below. Note that if fuel economy increases and then stabilizes, as it did after 1985 (Figure 4), all f_a would approach zero because all model years would have the same fuel economy.¹⁹

Like Allcott and Wozny (2014), we define the discounted remaining lifetime miles of a vehicle of age $a = t - y$ (y = model year) as a function of its probability of surviving to age a , $Prob(a)$, its annual miles, $M(a)$, a discount rate, r , and its maximum lifetime, L (Equation 11).

$$D_a = \sum_{x=a}^L \frac{Prob(x)}{Prob(a)} \frac{M(x)}{(1+r)^{x-a}} \quad (11)$$

NHTSA (2006) tables provide the average miles traveled by U.S. passenger cars and light trucks of different ages, as well as the probability that a new vehicle will survive to each age level. $Prob(x) / Prob(a)$ is the probability that a vehicle that has survived to be a years old will survive to be $x > a$ years old, while $M(x)$ is the observed miles traveled by vehicles that are x years old, and r is a discount rate.

Regression models are used to test the effects of price depreciation versus expected fuel savings on the prices of model year cohorts of passenger cars and light trucks. Following Equation 10, vehicle prices depreciate exponentially as vehicles age.²⁰ Equation 12 substitutes

¹⁹ If the depreciation of fuel economy with age is due to conditions of use, this would be strictly true since any vehicle would have the same fuel economy if used in the same way.

²⁰ According to Edmunds.com (2016), on average, a new car loses 11% of its value the moment it is driven away from a dealership and depreciates 15%-25% per year for its first five years. Sallee et al. (2015) find a better association between cumulative mileage and price than between age and price. Since the CES does not, in general, include odometer readings for household vehicles we use age as a surrogate for cumulative usage. In reality, depreciation is a function of both cumulative mileage and age.

a calendar year specific constant, γ_t , for the price of a one year old vehicle. This allows the level of the exponential depreciation curve to change from one year to another due to secular changes in the supply and demand for used vehicles. Equation 12 also assumes a constant rate of depreciation with vehicle age, in years.

$$P(a,t) = \left(\sum_{t=1980}^{2014} d_t \gamma_t \right) e^{ba} + \varphi \left(\frac{1}{MPG_a} - \frac{1}{mpg_t} \right) D_a p_t \quad (12)$$

The assumption of constant depreciation rates with age is questionable. To relax this assumption we add a possible second order effect of age on depreciation that allows depreciation rates to change with age in a systematic way.

$$b_1 a + b_2 a^2 \quad (13)$$

It is also likely that the depreciation rates of passenger cars differ from those of light trucks. There is clear evidence that survival rates and usage rates differ for the two vehicle types (NHTSA, 2006). To account for this, we multiply by $(1 + jA_0)$, where $j = 1$ if the vehicle type is light truck and zero otherwise, times the summation of constant terms in Equation 12. We also add similar terms to the age constants to allow depreciation rates to differ for the two vehicle types. Finally, there is evidence that the expected lifetime of light-duty vehicles has been increasing model year by model year (NHTSA, 2006; Davis et al., 2015 tables 3.12 & 3.13). To reduce correlation among the right-hand side variables and since it is likely that the rate of improvement in vehicle longevity has slowed over time, we include the natural logarithm of model year minus 1960, $\ln(y - 1960)$, in the depreciation equation. By interacting this term with one minus a coefficient times a dummy variable for light trucks, we test whether the longevity trend has differed for the two vehicle types.

$$P(j,a,t) = (1 + jA_0) \left(\sum_{t=1980}^{2014} \gamma_t a_t \right) e^{(1+jb_3)b_1 a + (1+jb_4)b_2 a^2 + b_5 \ln(y-1960)} + \varphi \left(\frac{1}{MPG_{jat}} - \frac{1}{mpg_t} \right) D_{j,a} p_t \quad (14)$$

The more complex depreciation patterns allowed by Equation 14 turned out to be statistically significant and improved the distribution of residuals, as well. The term allowing

different effects of the log trend variable for cars and light trucks was not statistically significant and so both vehicle types are assumed to be affected equally by the trend of improved longevity.

If the prices of model year cohorts are partly determined by rents reflecting the expected remaining fuel costs, ϕ should be statistically significant. The potential rent for a given model year is obtained by subtracting the estimated average gallons per mile ($1/mpg_t$) of all passenger cars and light trucks in the CES sample from the model year and vehicle type gallons per mile ($1/MPG_{jat}$), and multiplying by the price of gasoline and expected remaining usage by year, discounted to present value. Because the fuel savings term is defined to be negative when a cohort's MPG is above average and positive when below, $0 < \phi < 1$ is expected. During a period of increasing fuel economy, Equation 14 allows more efficient model years to obtain economic rent as a consequence of their superior fuel economy. However, if the fuel economy of new vehicles were to stabilize and remain constant for an extended period, all model years would eventually have the same fuel economy and no model year could command a premium due to superior fuel economy.

To summarize, the constant terms γ_t of the exponential depreciation function are intended to measure the effects of year-to-year changes in used vehicle supply and demand on used vehicle prices, but they will also reflect sampling variability in the CES. The exponential depreciation terms are intended to measure the loss of value with cumulative usage and age, technological and design obsolescence, changes in depreciation rates over time to the extent the squared age term can reflect them, and differences in these factors between passenger cars and light trucks.

The probability that a passenger car will survive to be greater than 20 years old is less than 10% (NHTSA, 2006). The same study indicates that light trucks have a 12% probability of surviving to be older than 25 years. Beyond those ages the CES sample sizes become small and some vehicles are held as collectors' items, leading to some instances of increasing price with age. For these reasons the samples were truncated beyond 20 years for cars and 25 years for trucks. In addition, model years for passenger cars older than 15 years with weighted

average prices greater than \$10,000 were deleted as outliers. This left 408 usable observations for cars and 463 observations for light trucks. Both models were estimated using the Stata™ nl (nonlinear) procedure with the “robust” variance-covariance matrix estimation option, and using the number of CES sample observations for each model year as weights. The expected value of future fuel savings is estimated with three alternative discount rates: 3%, 6% and 10%.

4.4 Data

Like the decomposition analysis, the econometric analysis primarily uses data from the CES. For each survey year, the purchase prices of used cars and light-duty trucks (trucks, minivans, vans, and SUVs) are separately aggregated by model year. For each model year within a survey year, an average vehicle price is calculated as well as the age of the vehicle. For the discounted present value of fuel savings, EPA adjusted MPG is modified based on vehicle age²¹, and an average fuel economy for households’ vehicles within a survey year (i.e., an MPG estimate for vehicles on the road) is calculated by using estimated weighted total miles and gallons, which are developed from the CES analogous to the decomposition analysis.²² Lastly, EIA annual national gasoline prices and NHTSA vehicle survivability and travel mileage schedules (NHTSA, 2006) are used to predict fuel savings.

4.5 Econometric Analysis Results

Equation 14 was estimated using the Stata™ nonlinear regression procedure with and without the log trend variable. In both cases, three sets of regressions were estimated using different values of expected fuel savings based on real annual discount rates of 3%, 6% and 10%. In all cases the robust error correction procedure was used. Each observation (calendar year, model year, vehicle type) was weighted by the number of vehicles it represents in the CES

²¹ Given auxiliary regressions as discussed in Section 3.3, MPG is adjusted based on age so that MPG decreases by .1 MPG per year.

²² Similar to the decomposition analysis, monthly fuel expenditures from the CES are divided by monthly national gasoline prices from the EIA to estimate households’ gallons of gasoline consumed. Then, adjusted fuel standards from the EPA are mapped to households’ owned vehicles data using model year and vehicle type (i.e., car or light-duty truck), and after adjusting for vehicle age, a harmonic mean of MPG is calculated for each household. This average MPG in turn is used to calculate households’ vehicle miles traveled.

survey. Zero year old vehicles were not included in the regression due to the instantaneous depreciation that occurs when the first owner takes possession. Some vehicles with a calculated age of one may also have been new when sold and so 1-year-old vehicles have been excluded, as well.

In the regressions that did not include the log trend variable the ϕ coefficient was never statistically significant. The signs were negative as expected but the values ranged from -0.04 to -0.05 with p-values of 0.37 to 0.40.²³ R^2 values of 0.9995 were achieved by all of the models. This extremely high R^2 value is partly due to the fact that the nonlinear model includes no constant term. Adding an arbitrary constant reduces the calculated R^2 to about 0.94. Collinearity among the right-hand side variables was tested by regressing the three variables against the other right-hand side variables. For the fuel savings variable, R^2 values ranged from 0.71 to 0.72.

The results of a regression including the log trend term and calculating fuel savings using a 6% discount rate are shown in Table 5. The calendar year intercepts are labeled γ_1 - γ_{32} . The light truck dummy variable for intercepts is A_0 . The regression using a 6% discount rate produced an estimated ϕ of -0.2. At 3% the estimated ϕ was -0.19 while the 10% rate resulted in an estimate ϕ of -0.25. The model also achieved an adjusted R^2 of 0.9995. However, including a constant term reduced the R^2 to 0.94 and also made the coefficient of ϕ statistically insignificant with a p-value of 0.49. Both the AIC and BIC measures are very slightly better for the regressions that include the log trend term (but no constant) compared to those that do not. For example, for the 6% discount rate, the AIC of the model including log trend is 15,051, while that of the model excluding it and removing insignificant variables is 15,068. The corresponding BIC numbers are 15,237 versus 15,240.

Correlation of the right-hand side variables is a concern. A regression of the other right-hand side variables (including the log trend) on expected fuel savings, produced an unadjusted R^2 of 0.80. However, there is also strong collinearity among the other right-hand side variables.

²³ The same models were estimated using the full discounted, expected remaining lifetime fuel costs (calculating D using model year and age gallons per mile without subtracting the average gallons per mile in that year), which is similar to the formulation of Allcott and Wozny (2014). The estimated ϕ coefficients ranged from -0.05 to -0.07 with p-values ranging from 0.07 to 0.10.

A regression of the log trend variable on the remaining right-hand side variables (excluding fuel savings) resulted in an R^2 of 0.9992. The correlation, however, is almost entirely between the log trend variable and the calendar year intercept terms. Regressing the log trend on age, age^2 and the vehicle type indicator produces an R^2 of 0.16. The fact that the terms appearing in the exponential function are not highly correlated with each other should ameliorate the problem. Still, the strong correlations of the calendar year intercepts with other right-hand side variables implies that the results of the log trend regression should not be considered definitive. As noted above, if the log trend variable is omitted, the coefficient on expected fuel savings, ϕ , is statistically insignificant at all three interest rates.

Table 5. Estimated coefficients of vehicle price model with 6% discount rate.

Coefficient	Estimate	Robust Std. Err.	t	P> t	95% Conf.	Interval
A_0	0.08645	0.0397	2.18	0.030	0.0085	0.1645
γ_1	87751	41355	2.12	0.034	6577	168925
γ_2	92804	45053	2.06	0.040	4372	181235
γ_3	128810	69210	1.86	0.063	-7037	264657
γ_4	128673	66932	1.92	0.055	-2703	260049
γ_5	139788	74092	1.89	0.060	-5642	285218
γ_6	141736	76720	1.85	0.065	-8852	292323
γ_7	151800	82410	1.84	0.066	-9958	313557
γ_8	153988	84841	1.82	0.070	-12540	320516
γ_9	155567	86706	1.79	0.073	-14622	325755
γ_{10}	151394	85564	1.77	0.077	-16553	319341
γ_{11}	168763	97545	1.73	0.084	-22701	360227
γ_{12}	191968	112202	1.71	0.087	-28265	412201
γ_{13}	203637	120153	1.69	0.090	-32203	439476
γ_{14}	223951	133212	1.68	0.093	-37521	485424
γ_{15}	233611	140268	1.67	0.096	-41712	508934
γ_{16}	245842	148915	1.65	0.099	-46453	538137
γ_{17}	263694	161033	1.64	0.102	-52386	579773
γ_{18}	268908	165526	1.62	0.105	-55991	593806
γ_{19}	273928	169818	1.61	0.107	-59395	607251
γ_{20}	283701	177121	1.6	0.110	-63958	631360
γ_{21}	261759	164718	1.59	0.112	-61554	585073
γ_{22}	261656	165758	1.58	0.115	-63698	587010
γ_{23}	264564	168539	1.57	0.117	-66249	595376
γ_{24}	263254	168981	1.56	0.120	-68427	594935
γ_{25}	270387	174996	1.55	0.123	-73100	613875
γ_{26}	266594	173044	1.54	0.124	-73061	606249
γ_{27}	272789	177939	1.53	0.126	-76474	622053

γ_{28}	290081	192204	1.51	0.132	-87183	667346
γ_{29}	302566	201266	1.5	0.133	-92484	697616
γ_{30}	312376	208671	1.5	0.135	-97210	721961
γ_{31}	321861	215671	1.49	0.136	-101465	745187
γ_{32}	325214	219482	1.48	0.139	-105592	756019
b1	-0.2432	0.0105	-23.21	0.000	-0.2638	-0.2226
b3	-0.1867	0.0396	-4.72	0.000	-0.2644	-0.109
b2	0.0059	0.0005	11.43	0.000	0.0048	0.0069
b4	-0.3418	0.087	-3.93	0.000	-0.5126	-0.1709
b5	-0.5834	0.1663	-3.51	0.000	-0.9097	-0.257
phi	-0.2144	0.0607	-3.53	0.000	-0.3335	-0.0952
<hr/>						
Number of observations	=	868				
R-squared	=	0.9996				
Adj R-squared	=	0.9995				
Root MSE	=	1379.057				
Res. dev.	=	15306.04				

Calculating the expected remaining fuel savings using different discount rates had a small effect on the other coefficients in the model. Model coefficients other than the calendar year intercept estimates are shown in Table 6.

Table 6. Effect of alternative discount rates on coefficient estimates.

Variable	3% Discount	6% Discount	10% Discount
A_0 Intercept Light Truck Adjustment	0.8827	0.08645	0.08412
b_1 Age	-0.2427	-0.2432	-0.2438
b_3 Light Truck Adjustment	-0.1855	-0.1867	-1.881
b_2 Age ²	0.0058	0.0059	0.0059
b_4 Age ² Light Truck Adjustment	-0.3402	-0.3418	-0.3436
b_5 Ln(model Year Trend)	-0.5788	-0.5834	-0.5873
Phi Expected Fuel Cost Difference	-0.1859	-0.2144	-0.2512

One plus the coefficient A_0 is multiplied by all the year-specific constants ($\gamma_1 - \gamma_{32}$) to represent the constants for light trucks versus passenger cars. It implies that, all else equal, the price of a light truck will be about 9% higher than that of a passenger car of the same age. The constants γ_1 through γ_{32} represent the price of a hypothetical 0-year-old *used* vehicle multiplied by the logarithmic model year trend adjustment. Dividing by the trend adjustment recovers the estimated prices. The intercepts of the models estimated on vehicles 2 years of age, adjusted to recover vehicle prices, are compared with the average of the prices of 2- to 4-year-old vehicles

in the CES data set in Figure 19. The price trends of the model and CES data are very similar. The CES prices were averaged over all vehicles 2 to 4 years old to increase the number of observations per calendar year. They should be expected to be lower than 2-year-old prices since they include prices of 3 and 4-year-old vehicles.

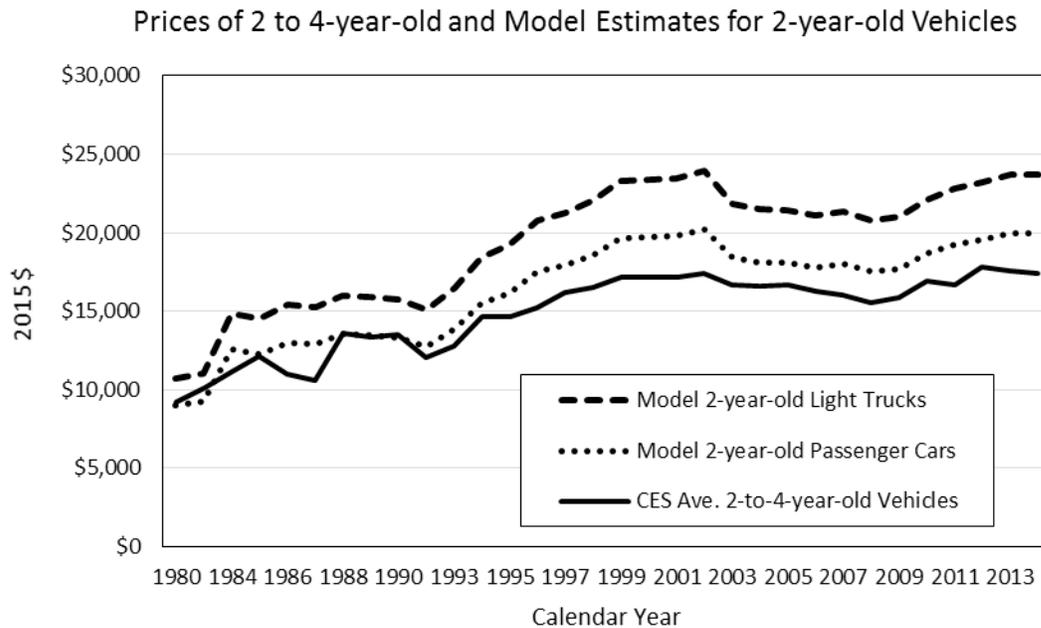


Figure 19. Average of 2-to-4-year-old Vehicle Prices Compared to Model Intercepts for Light Trucks

The coefficient of age in the exponential depreciation function is b_1 . One plus the coefficient b_3 adjusts this coefficient to reflect a lower depreciation rate for light trucks versus cars. The rate of depreciation is also affected by age^2 the coefficient of which is b^2 , which is adjusted for light trucks by multiplying by $(1 + b_4)$. The effect of age^2 is to slow the rate of depreciation as vehicles age. The effect of increased longevity of both types of vehicles is represented by the coefficient of the log model year trend, b_5 . The combined effects of all five coefficients are illustrated in Figure 20. Although the 32 curves are difficult to untangle, it is evident that the curves shift upward over time at a decreasing rate, becoming very compressed as 2014 is approached.

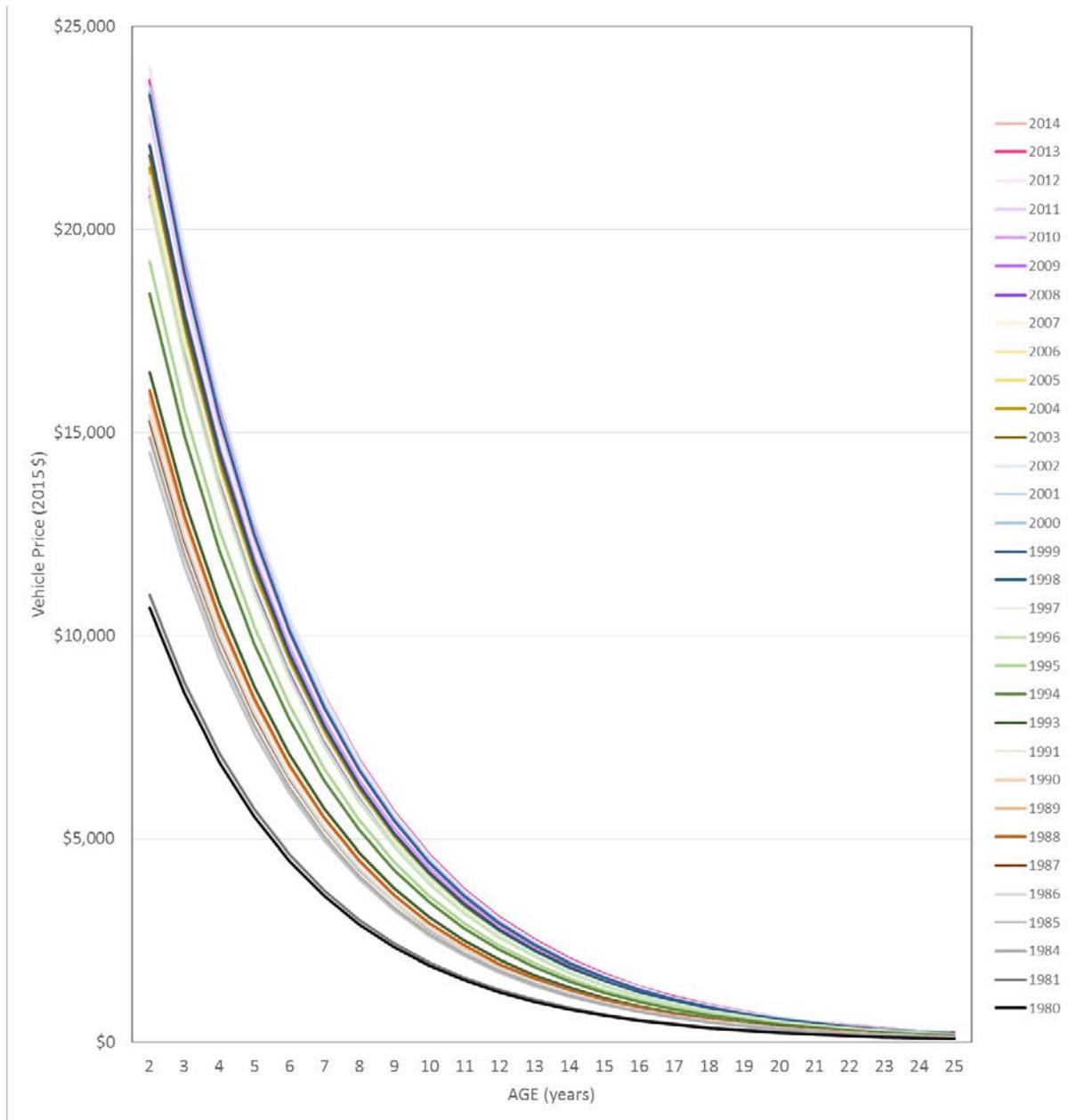


Figure 20. Light Truck Price Depreciation Curves by Calendar Year

The model implies that vehicle prices depreciate at a somewhat faster rate than the decrease in expected remaining lifetime miles. The price depreciation function implies that a vehicle sold today would lose about 56% its value by the time it was four years old but 64% by the time it was five years old.²⁴ The expected remaining lifetime miles functions used in this

²⁴ Edmunds.com similarly estimates that a vehicle will lose 51% of its initial value by the end of its fourth year (<http://www.edmunds.com/car-buying/how-fast-does-my-new-car-lose-value-infographic.html> accessed on 7/1/2016).

study (NHTSA, 2006) imply that after four years a passenger car or light truck has 51% of its 0-year-old expected lifetime miles remaining. After ten years, a passenger car would have 28% of its expected lifetime miles remaining while a light truck would have 35% remaining. On the other hand, the ten-year old vehicles' prices would be only 13% of their price when new.

A kernel density plot comparing the distribution of residuals from the non-linear regression with a normal distribution indicates some moderate skewness towards large positive residuals (Figure 21). All the residuals plots shown below include only vehicles aged 2 years or more.

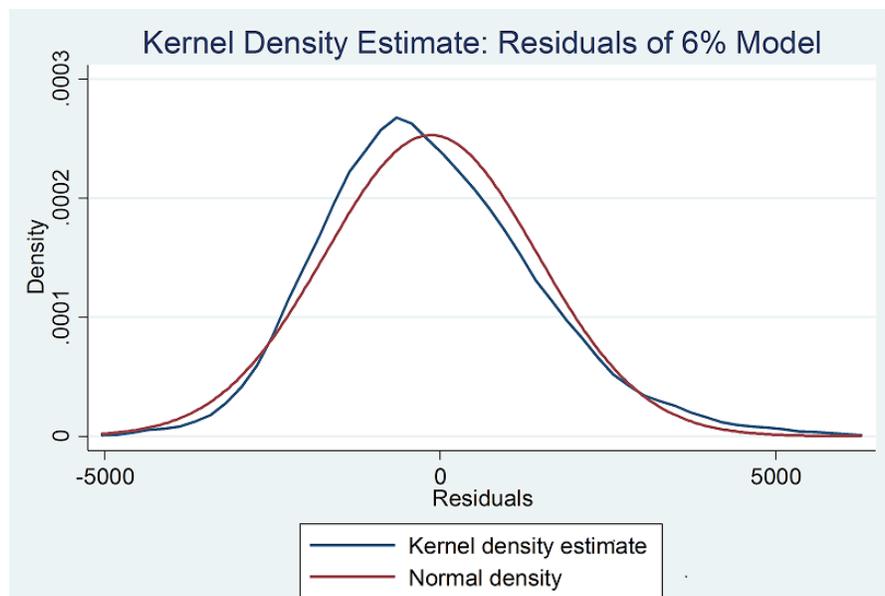


Figure 21. Kernel Density Estimate of Residuals from 6% Model.

Residuals from the 6% regression plotted versus vehicle age show a some tendency for certain years to be less well centered around zero than others (Figure 22). This is particularly evident for 2-year-old vehicles. The deviations are not large, however, and some variability is expected.

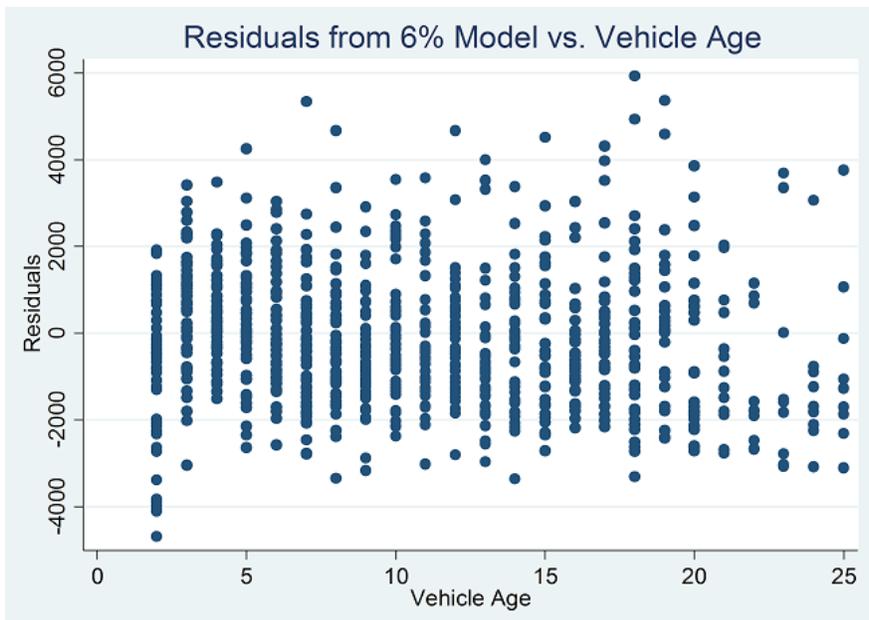


Figure 22. Residuals from 6% Model versus Vehicle Age.

Graphing residuals versus survey year shows some tendency for variance to increase from the earlier to the later survey years (Figure 23). This most likely reflects the increasing number of observations over time. The robust variance estimator of Stata™ was used to correct estimated standard errors for heteroscedasticity.

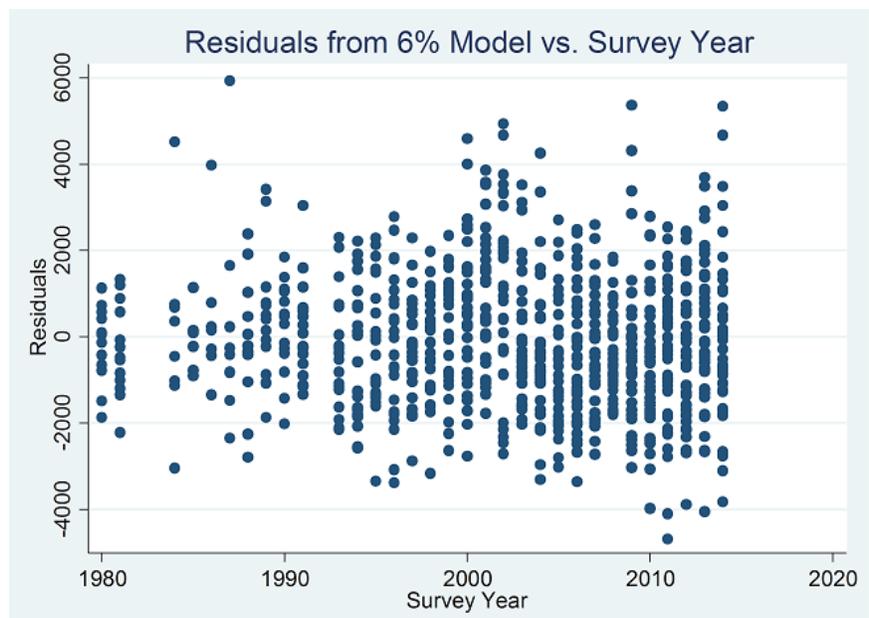


Figure 23. Residuals from 6% Model Versus Survey Year.

The full set of equations (3 discount rates, with and without the log model year trend variable) were re-estimated using the Allcott-Wozny measure of expected future fuel costs. This measure is identical to our expected fuel cost difference measure except that the average fuel economy of all vehicles is not subtracted from the model year and vehicle type fuel economy. When the log trend variable was included, the Allcott-Wozny measure was statistically significant at the 0.003 level or better. However, the estimated coefficients were smaller in size, ranging from -0.120 to -0.177. If the log model year trend term was omitted, the Allcott-Wozny measure was not statistically significant at the 0.05 level but the signs remained negative. Once again, adding an arbitrary constant term to the model made the measure of remaining fuel costs statistically insignificant, with a p-value of 0.85.

Taken together, the regression results indicate that if model year cohort fuel savings affect the prices of used vehicles at all, the effect is small, on the order of 20% of the discounted, expected remaining lifetime fuel savings. There is a strong likelihood that the apparent statistical significance of the remaining fuel savings variable in the model including a log trend is an artifact caused by overfitting.

Twenty percent is less than Allcott and Wozny (2014), Sallee et al. (2015) and Busse et al. (2013) found in their analyses discussed above. There are good reasons to expect our estimates of ϕ to be less than those of the studies cited above. In our model, the depreciated cost of improved fuel economy of a model year cohort when it was new is included in the price of the used vehicle. Our model (see, Equation 10) implies that quality improvements to new vehicles will be reflected in the depreciated prices of used vehicles. When calculating used car price indices, the BLS similarly assumes that quality improvements to new automobiles depreciate at the same rate as the vehicle itself (BLS, 2016). Thus, used car buyers will already be paying something extra for a cohort with better than average fuel economy. Our ϕ measures how much more than that used car buyers pay.

Finally, our analysis of the prices of model year cohorts of passenger cars and light trucks is highly aggregated. Allcott and Wozny (2014), like Sallee et al. (2015) analyzed consumers'

choices among vehicles at a very detailed level (make, model, model year, trim, engine, transmission). Their data include much larger MPG differences between small cars, large trucks, hybrids and high performance vehicles. Not only are these differences more salient they are also much less uncertain. The mass, engine size and aerodynamic differences between a large truck and a small car, for example, are evident and their relationship to fuel economy is intuitive. Differences between different model years of the same make and model are much less so. Loss aversion implies that consumers will pay less for an uncertain fuel economy benefit than for a certain one (e.g., Greene, 2011).

5. Alternative Approaches: The Cost of Fuel Economy and Net Impacts by Income Quintile

In the decomposition analysis, we determined how fuel economy affected fuel expenditures and how the average cost per vehicle affected vehicle expenditures. However, as previously mentioned, the vehicle prices in the decomposition analysis included all attributes of a car because the CES data do not enable us to estimate the price paid for fuel economy improvements alone. Here, we address this issue by providing two alternative approaches to estimating the cost of fuel economy improvements for consumers.

First, we use a simple approximation. We estimate a range for the total costs of improving passenger car or light truck MPG over the 1975 to 2014 period. We then calculate the ratio of the costs of improving fuel economy to the total increase in the price of a new vehicle over the same period. We multiply the total cumulative constant dollar increases in vehicle expenditures due to changes in expenditures per vehicle for each income quintile by the high and low estimates of the fraction of new vehicle costs due to fuel economy improvements. We further describe this methodology and corresponding impacts in Section 5.1.

Second, in this updated report we provide a more direct and arguably more accurate measure of fuel economy improvement costs compared to the estimates produced using the aforementioned methodologies. Cost estimates for fuel economy improvements are primarily from the National Research Council (2015, 2010, 2002, 1992). These estimates along with an

inventory of owned vehicles from the CES are used to calculate the user cost of capital, which is summed across survey years to find the total cost of fuel economy improvements by income quintile. Further details and estimated impacts using this methodology are presented in Section 5.2.

5.1 Approximation Using Ratio of Cost of Fuel Economy Improvements to Increase in Vehicle Prices

For the approximation to work reasonably well, the change in constant dollar expenditures per vehicle implied by the CES should be similar to the change in the inflation-adjusted quality changes in light-duty vehicles. Each year, the Bureau of Labor Statistics reports the change in new passenger car and light truck prices due to quality improvements, q_t , and inflation, I_t . Quality improvements include safety and emissions control equipment, other changes in engines, transmissions, optional equipment and other vehicle attributes including fuel economy. In the case of the CES price changes, changes in the mix of vehicle types sold are also included. The price of model year t vehicles, P_t , can be decomposed into last year's price, inflation and quality improvement. The inflation adjusted new vehicle price in year t is last year's price plus the quality changes.

$$P_t^* = P_{t-1} + I_t + q_t \left(\frac{P_{t-1} + q_t}{P_{t-1} + I_t + q_t} \right) = P_{t-1} + q_t \quad (15)$$

The sum of the BLS' quality adjustments for passenger cars from 1975 to 2014, in 2015 dollars, is \$7,980. The sum from 1980 to 2014 is \$7,348. Unfortunately, the BLS quality adjustment estimates for light trucks go back only to 1995. The increase in light truck prices due to quality changes for the 1995 to 2014 period was \$6,364. For comparison, the total increase in expenditures per new light-duty vehicle (light trucks and passenger cars) implied by the CES for the 1980 to 2014 period is \$7,340.

5.1.1 Price Impacts of Fuel Economy Improvements, 1975-2014

There is no definitive estimate of the impact of fuel economy improvements on vehicle prices over the period covered by the 1980 to 2014 CES. Instead, we compare a range of

estimates of vehicle price impacts of fuel economy improvements to the observed increase in prices paid for new light-duty vehicles as reported in the CES. We then use the ratio of the possible fuel economy impact to the overall price increase to estimate the share of increased vehicle costs that could be attributed to increased fuel economy. This produces a very rough approximation. Numerous factors beyond fuel economy added to the cost of vehicles over the 1975 to 2014 period. These include many technological and design innovations (e.g., power accessories, electronics, cruise control, navigation systems, etc.), increased vehicle weight and power, safety features (e.g., air bags, antilock brakes, etc.), and emissions controls. All contributed to raising the average price paid for a new car or light truck. However, even a rough approximation is a substantial improvement over assigning either all or none of the price increase to fuel economy.

The CES data indicate an increase of \$3,087 in the average price of a new car from 1980 to 1985 (Figure 24). Between 1985 and 2004, when the standards were relatively constant²⁵, the average price of a new light-duty vehicle increased by \$6,062. The standards began to be increased for light trucks in 2005 and for passenger cars in 2011. During that period the average price decreased by \$1,809. Obviously many factors other than fuel economy affected the average price of a new light-duty vehicle over this time period. Recessions and higher gasoline prices not only depressed vehicle sales but induced consumers to purchase less expensive makes and models. For example, the impact of the Great Recession is evident in Figure 24.

Early assessments of the cost of increasing automobile fuel economy were reviewed by Greene and DeCicco (2000). Estimates of the cost of improving fuel economy that predate the enactment of the CAFE standards in 1975 were made by government agencies. The US DOT estimated that the standards would increase new car prices in 1985 by just under \$300 (2015 dollars, \$54 in 1973 dollars) for an average cost of only \$25 per MPG. On the other hand,

²⁵ The fuel economy standards for passenger cars and light trucks varied little after 1985 until 2005. Passenger cars standards were decreased by 1.5 MPG for 1986-88 but restored to 27.5 MPG in 1990, where they remained through 2010. Starting in 2011, passenger car standards were increased gradually to 34.2 in 2014. From 20 MPG in 1984, the light truck standards were decreased to 19.5 MPG in 1985, increased to 20.0 in 1986, varied between 20.0 and 20.6 MPG until 1995, were set at 20.7 in 1996 and remained at that value through 2004. The light truck standards were gradually increased starting in 2005 and reached 26.2 by 2014. (Davis et al., 2015, tables 4.20 & 4.21).

a study for the Congressional Budget Office estimated that increasing the fuel economy of a subcompact car from 20 to 24 MPG would raise its price by about \$300 but that an increase

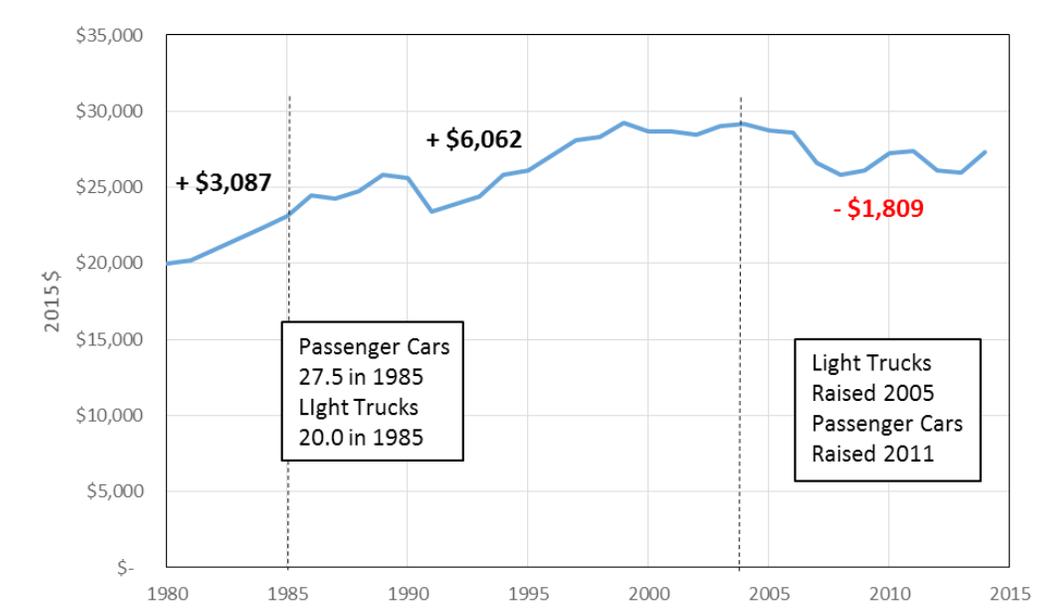


Figure 24. Average Price Paid for a New Light-duty Vehicle

to 27.5 MPG would increase the car's price by \$2,600 (2015 dollars), almost \$350 per MPG. Seven sources estimated the long-run average cost of increasing passenger car fuel economy from 19.9 MPG, the EPA test cycle average in 1978, to 27.5 MPG, the level required by the CAFE standards in 1985. Discarding the highest estimate (which concluded 27.5 was not feasible) and lowest estimate (which found that costs would decrease) leaves a range (in 1975 dollars) of \$275 estimated by the U.S. Department of Transportation to \$550, estimated by Ford Motor Company. Converted to 2015 dollars using the CPI-U gives a range of \$1,210 (or about \$160/MPG) to \$2,425 (\$295/MPG).

Four reports of the National Research Council published between 1991 and 2015 have provided estimates of the costs of increasing fuel economy. The 1992 report provides high and low estimates of the impact on price of increasing passenger car fuel economy from 27.5 to 32.5 MPG that range from \$435 to \$1,160 (2015 dollars) or about \$87 to \$232 per MPG. Cost estimates for light-duty trucks were somewhat higher. The estimated price impact of increasing a minivan's fuel economy from 23 to 27 MPG ranged from \$400 to \$1,650, or about \$100/

MPG to \$400/mpg. NRC (2002) provides low-cost/high MPG, Average, and High-cost/low MPG estimates for four classes of passenger cars and six types of light trucks. The optimistic estimates for passenger cars averaged \$117 (2015 dollars) per MPG and \$174 per MPG for light trucks (NRC, 2002, table 4-2). The means of the average estimates are \$156/MPG for cars and \$257/MPG for light trucks and the pessimistic estimates average \$213/MPG for cars and \$282 for light trucks. NRC (2010, pp. 145-149) estimated retail price increases for percent reductions in fuel consumption. Converting to \$/MPG, the costs for a midsize or large passenger car average \$182/MPG for a 41% increase in test cycle fuel economy. For SUVs with unibody construction, the cost per MPG averages \$206 for 41% increase in MPG. For small trucks the average cost per MPG is \$242 for a 37% increase and the corresponding estimate for large trucks is \$473 for a 39% increase in MPG. The most recent NRC (2015) report estimated the direct manufacturing cost (not price increase) of increasing the MPG of a midsize passenger car from 30.9 to 56-57 MPG at \$2,318 to \$2,747.²⁶ Assuming a markup of 1.5 from cost to retail price, this corresponds to a price impact of approximately \$130 to \$165 per MPG. For other vehicle types only individual technology cost and MPG impact estimates were provided. From these it is clear that costs for light trucks are higher than for the midsize passenger car.

These historical cost numbers may be compared with the latest estimates of the future costs of fuel economy improvements by the EPA and NHTSA. According to the agencies, the cost of increasing the fuel economy of all new light-duty vehicles from 38.3 to 46.3 MPG over the period 2022 to 2025 would increase the retail price of a typical vehicle by \$894 to \$1,245, or an average of \$112 to \$156 per MPG (EPA, 2016).

A plausibility check on the costs of fuel economy improvements to passenger cars from 1975 to 2014 can be inferred from the BLS estimates of retail price increases due to quality improvements to passenger cars (Wards, 2016). The BLS estimates price impacts for three categories of quality improvements: safety, emissions and “other”. Although safety and emissions requirements can affect fuel economy, changes designed for the purpose of improving

²⁶ These estimates represent technology and manufacturing costs in 2017.

fuel economy are included with many other types of changes in the “other” category (Foster, 2016). Assuming that all “other” price increases in the 29 years in which EPA test fuel economy increased should be attributed to fuel economy, fuel economy improvements from 1975 to 2014 increased passenger car retail prices by at most \$2,879. Dividing by the total increase in fuel economy from 15.8 to 35.6 (i.e., 19.8 MPG) gives an average retail price increase per MPG of \$145. If “other” price increases are counted only for the 22 years in which test MPG exceeded the previously highest MPG level the total impact on new car retail price was \$2,241 or an average of \$113 per MPG. Because the “other” category, in general, includes all other quality changes not for purposes of safety or emissions control these estimates should be interpreted as upper bound estimates.

There is clearly a relatively high degree of uncertainty about the costs of increasing fuel economy. All else equal, costs should increase with increasing MPG levels because the most cost-effective options would be adopted first. The average costs presented above were obtained by dividing the total cost of a large fuel economy improvement by the total change in MPG. Costs for smaller improvements would be lower while the marginal cost at higher levels would be higher. Over time costs typically decrease due to technological change and learning by doing. For example, NRC (2015) indicates about a 15% reduction in the total cost of fuel economy improvements from 2017 to 2025 due to learning by doing. Thus, historical cost estimates may overstate actual costs in subsequent years.

Given the estimates presented above, a range of \$150 to \$250 per MPG (2015 dollars) appears to be a reasonable range for the average retail price impacts of light-duty fuel economy improvements from 1975 to 2014, not taking into consideration technological change nor learning by doing. The average EPA-test fuel economy of passenger cars and light trucks, combined, in 1975 was 15.3 MPG and increased to 22.5 in 1980 and to 30.7 by 2014. Assuming average retail price increases of \$150 and \$250 per MPG gives a range of price increase of \$1,080 to \$1,800 for the 7.2 MPG increase from 1975 to 1980 and \$2,310 to \$3,850 for the 15.4 MPG increase from 1975 to 2014 (EPA, 2015, table 9.1). From 1980 to 2014, the average price

of a new light duty vehicle in the CES increased by a total of \$7,340. Adding the cost of only the fuel economy improvement from 1975 to 1980 gives lower bounds of \$8,420 to \$9,140 for the total increase in vehicle prices from 1975 to 1980. Dividing the respective fuel economy price impact by these total cost estimates gives a range of 27% to 42% for the fuel economy cost share. This range is likely to overstate the cost share of fuel economy improvements between 1980 and 2014 because we have omitted vehicle price increases between 1975 and 1980 due to changes other than fuel economy from the denominator and because the most recent price impacts have not yet fully affected used car buyers. In addition, we have not attempted to include the effects of technological change and learning by doing on costs over time. On the other hand, household expenditures per vehicle can decrease if households purchase vehicles less frequently or purchase less expensive vehicles. Assigning to fuel economy 27% to 42% of the total change in expenditures due to increased expenditures per vehicle is a rough approximation but it is preferable to assigning all or none of the observed increase in expenditures per vehicle to fuel economy.

5.1.2 Effect on Used Vehicle Prices and Expenditures on Vehicles

The CES data indicate that average new vehicle prices increased \$9,149 from 1980 to 2004, then decreased by \$1,809 by 2014 for a net increase of \$7,340 over the entire period (Figure 24). The average price of all vehicles, new and used, followed a similar trend (Figure 25). Macro-economic shocks toward the end of the time period (i.e., increased gasoline prices, the Great Recession) depressed both new and used vehicle prices after 2005 but prices began to recover in the last few years.

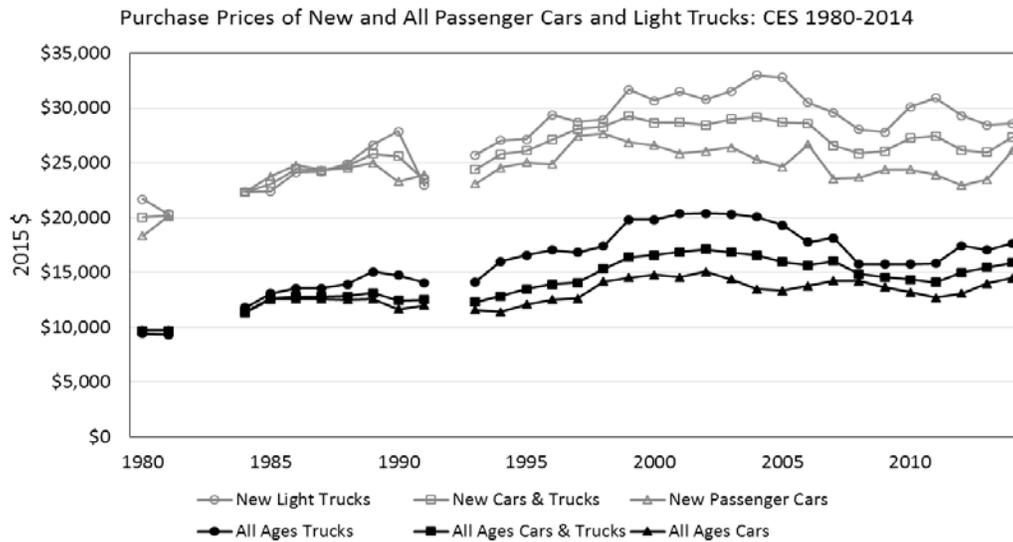


Figure 25. Purchase Prices of New and All Passenger Cars and Light Trucks: CES 1980-2014.

The cumulative additional expenditures on vehicles per household due to increased expenditures per vehicle are shown in Figure 26. There is a gap from 1981-1984 due to missing CES data as explained in Section 3. The average annual increase (2015 \$) in household vehicle expenditures ranges from \$101 for quintile 2 to \$2,020 for the highest income group, quintile 5. The fact that the cumulative effect of expenditures per vehicle is greater for the lowest quintile than for the second lowest is due to the large increase in expenditures per vehicle for the lowest quintile between the 1980 and 1981 CES. The effect then persists through the future years. We have discussed this seeming anomaly with the BLS but have not been able to determine whether this is a real change or an artifact. From 27% to 42% of the cumulative changes shown in Figure 26 are estimated to be due to fuel economy improvements.

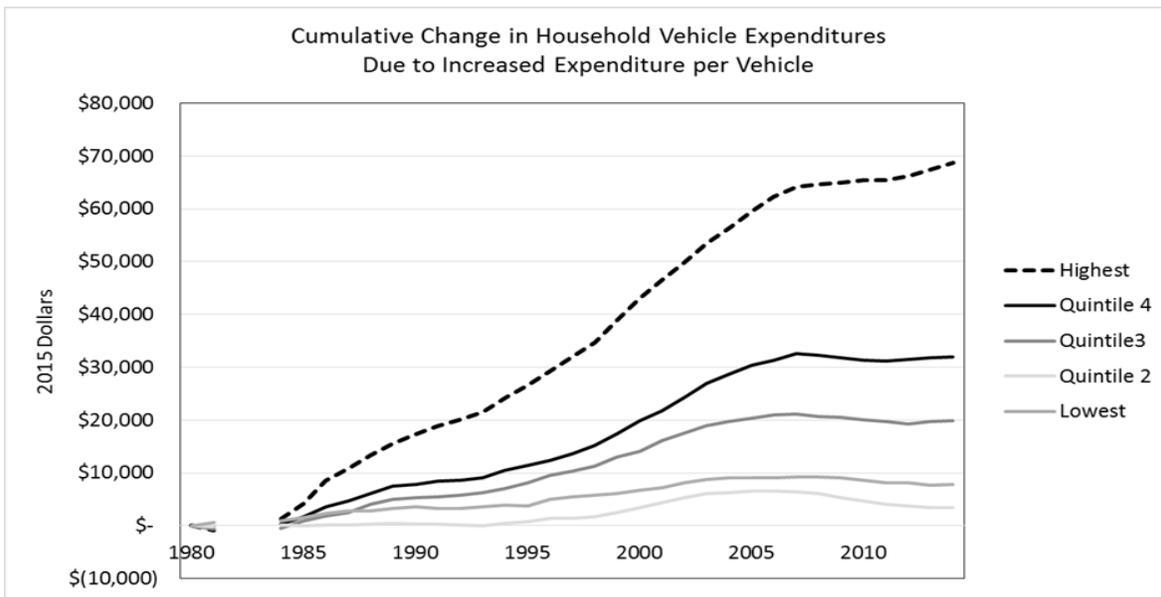


Figure 26. Cumulative Change in Household Vehicle Expenditures Due to Changes in Expenditures per Vehicle Owned.

Four alternative estimates of increased expenditures due to fuel economy improvement were calculated using: 1) the high (42%) and low (27%) fuel economy cost shares, 2) assuming 20% and 0% of remaining fuel savings would be capitalized in the price of a used vehicle. Assuming that none of the remaining fuel savings of a used vehicle is reflected in its price, the estimated total cost of fuel economy improvements over the 1980-2014 period is just the cumulative increase in expenditures multiplied by either 0.27 or 0.42. If the price of a used vehicle includes 20% of the remaining fuel savings, it is not sufficient to multiply by 27% or 42% to capture the full price of increased fuel economy.²⁷ By multiplying the increase in expenditures by 27% or 42% we capture only part of the 20% of remaining fuel savings. When the total increase in expenditures is multiplied by 0.27/0.42, 73%/58% of the fuel savings capitalized in the cost of the vehicle is missed. To correct for this, we add $0.73 \times 0.2 = 0.146$ or $0.58 \times 0.2 = 0.116$ of the estimated cumulative fuel savings to 0.27 or 0.42 times the cumulative increase in vehicle expenditures. The capitalization of expected remaining fuel savings is

²⁷ In fact, fuel economy rent on a used vehicle is a transfer payment from the buyer to the seller. This likely induces transfer payments among income groups. In the calculations described, we count the cost to the buyer but not the benefit to the seller. Our accounting is therefore incomplete and will tend to overestimate the cost of increased fuel economy.

assumed to apply only to used vehicle sales since new vehicle vintages are assumed to sell at long-run average cost. Therefore, we adjust the amount added back for each income quintile by the share of vehicle expenditures on used vehicles.²⁸ The advantage of this method is that it is straightforward and based on actual household expenditures on vehicles over the 1980-2014 period. It assumes that if used vehicle prices were depressed or inflated by demand shocks, the price paid by used vehicle purchasers for fuel economy would be proportionately decreased or increased. Using the ending year fuel economy improvement rather than the average improvement over all years is likely to overstate fuel economy's cost share. When it is assumed that 20% of remaining fuel savings are capitalized in the price of a used vehicle, the recovery of residual fuel savings when a household sells a used vehicle should be credited against the amount paid when the vehicles was purchased. However, CES households do not report the revenue received from sales of their vehicles and we have omitted such potential transfers among households. Finally, as noted above, we take no account of the likelihood that learning-by-doing and technological advances have reduced the cost of fuel economy improvements over time.

All income quintiles are estimated to have benefited from the fuel economy improvements (Table 7). Net savings in dollars are greatest for the three middle income quintiles, which are estimated to have saved from \$10,000 to \$17,000 (2015 dollars) per household between 1980 and 2014. Relative to income, the lowest two income quintiles benefited the most, saving from 1.5% to 2.0% of average annual household income over the period. The highest income quintile had the greatest fuel savings but also spent much more on vehicles, more than twice as much as the second highest income quintile. As a consequence their estimated net savings range from 0.0% to 0.3% of average annual income. Relative to income, the estimated impact of fuel economy improvements over the 1980-2014 period has been strictly progressive, increasing uniformly with decreasing income.

²⁸ In the previous report, the missing portion of fuel savings capitalized was deducted from the savings in fuel expenditures due to fuel economy. Since these fuel savings are capitalized in the price of vehicles, we instead add this missing portion to vehicle costs per household due to the average cost per vehicle. Table 7, which shows the worst to best case estimates by income quintile, has been changed accordingly. However, the net savings and thus savings as a percent of average household income are not affected as the missing portion is now in third column rather than the second column of Table 7.

Table 7. Worst to Best Case Estimates for Total Impacts on Fuel and Vehicle Expenditures, 1980-2014

Income Quintile	Fuel Economy	Average Cost per Vehicle		Annual Net Cost or (Savings) as Percent of Average Household Income
	Accumulation of Cost or (Savings) per Household	Accumulation of Cost or (Savings) per House	Net Cost or (Savings)	
Lowest 20%	(10,591)	4,007 - 2,139	(6,583) - (8,451)	(1.56%) - (2.00%)
Quintile 2	(15,329)	2,472 - 938	(12,857) - (14,391)	(1.52%) - (1.71%)
Quintile 3	(20,820)	9,640 - 5,430	(11,180) - (15,390)	(0.81%) - (1.12%)
Quintile 4	(25,560)	14,826 - 8,736	(10,734) - (16,825)	(0.50%) - (0.78%)
Highest 20%	(31,652)	30,180 - 18,816	(1,471) - (12,835)	(0.04%) - (0.31%)

5.2 User Cost of Capital Method Using Cost Curves for Fuel Economy Improvements

For the user cost of capital method, supplementary data on vehicles by model year from the CES is combined with data on household characteristics to create an inventory of the number of owned vehicles by vehicle type (i.e., car versus light truck), survey year, quintile, and model year. The implicit expenditures on fuel economy for households' owned vehicles is then calculated by a user cost of capital method. Essentially, the annual cost of fuel economy is assumed to be the cost of fuel economy at the beginning of the year minus the discounted cost of fuel economy at the end of the year. In other words, the user cost of capital for vehicle type j , model year v , in survey year t (and thus age $a = t - v$) is the difference in the price from the beginning of the year to the end of the year, assuming a 6% discount rate (r). That is:

$$C_{j,v,t,a} = P_{j,v,t,a} - \frac{P_{j,v,t+1,a+1}}{(1+r)^2} \quad (16)$$

The cost of fuel economy, $P_{j,v,t,a}$, for a specific model year is the depreciated cost of fuel economy based on the vehicle's age. Initial fuel economy cost estimates for new vehicles were taken primarily from four assessments by the National Research Council (2015, 2010, 2002, 1992). Cost estimates for years prior to 1990 were obtained from a literature review by Greene and DeCicco (2000). Below we provide further detail explaining how we use these cost functions to estimate historical costs of fuel economy improvements by model year and future costs of fuel economy improvements. The cost estimates for fuel economy improvements to new vehicles are depreciated using the depreciation model that was used in Section 4 based on

the econometric analysis of used vehicle prices (see Equation 14). In a sensitivity analysis, we examine whether results are affected by omitting the log trend term and future fuel savings from the model. When Equation 14 was estimated in the econometric analysis, future fuel savings were insignificant when the log trend term was omitted. In addition to assessing the sensitivity of the results to different depreciation models, we also assess whether results are sensitive to using a 3%, 6%, or 10% discount rate in calculating future fuel savings.

The total cost of fuel economy improvements is found by multiplying the number of vehicles ($N_{j,v,t,q}$) of type j , model year v , in survey year t , and quintile q by the user cost of capital ($C_{j,v,t,a}$) for a vehicle of type j and model year v in survey year t . Summing these costs across all vintages (or vehicles of all ages) and years examined generates an estimate of the total cost of fuel economy improvements for each income quintile over the 1980 to 2014 time period (see Equation 17).

$$K_q = \sum_{t=1980}^{2014} \sum_{\forall v} N_{j,v,t,q} * C_{j,v,t,a} \quad (17)$$

5.2.1 Fuel Economy Cost Functions

The NRC studies cited previously estimate the potential to improve fuel economy and the cost of doing so by applying technologies and design changes to a base year vehicle. The most logical way to use the NRC estimates appears to be to interpret them as snapshots taken at different points in time. Each assessment re-establishes costs and potential relative to a set of base year, reference vehicles. For the 1992 study the base year is 1990, while for the 2002, 2015 and 2011 studies the respective base years are 1999, 2007 and 2008. Although the NRC (2015) cost functions are intended to reflect costs in 2017 and 2025, they apply technologies to a base 2008 vehicle (NRC, 2015, p. 263 fn.). The 2011 NRC study uses 2007 vehicles as its base vehicles. For years between NRC studies, costs are based on a time-weighted average of the NRC cost curves that bracket the year in question, as explained below. From 2009 to 2016 the cost functions reflect a linear combination of the 2011 and 2015 NRC cost curves. Thus, although the publication of a new NRC cost curve resets the zero point of fuel economy

improvement, cost curves change yearly, trending from the previous study's estimates toward those of the succeeding study.

The NRC vehicle sets are comprised of vehicle classes (e.g., subcompact, crossover SUV, full-size pickup, etc.) that change from one study to the next. Fuel economy cost estimates in NRC (2015), for example, are differentiated by engine size. We aggregate the classes to two, passenger cars and light trucks, by sales-weighted averaging of the fuel economy potential and cost estimates.

DeCicco and Greene (2000) found that the costs of increasing MPG over a base level were accurately described by a quadratic function of the change in MPG from a base value. Zero intercepts were assumed since the cost of no improvement in MPG is \$0. Let Δ be the change in MPG from the base year, A and B be coefficients to be estimated and $C(\Delta)$ the retail price equivalent cost.

$$C(\Delta) = A\Delta + B\Delta^2 \quad (18)$$

Before estimating the two cost curve coefficients by ordinary least squares (OLS), technologies were ranked by cost effectiveness (\$/MPG) from lowest cost to highest cost. In a few cases, the ranking implied a sequence of implementation of technologies that was illogical from an engineering perspective, for example, a higher pressure turbocharging with engine downsizing before a more moderate increase in turbocharging with downsizing. In such cases we combined the technologies into a single package to be implemented together.²⁹ With this adjustment, the quadratic functional forms were also found to fit the cost estimates of the NRC studies very well. Figures 27-29 illustrate the fit of quadratic cost functions to NRC (2015) cost estimates for vehicles with inline 4-cylinder, V-6 and V-8 engines. Engine type sales-weighted averages of these functions were used to create passenger car and light truck cost functions. The data and cost functions shown in Figures 27-29 are in 2010 dollars. The A and B coefficients were multiplied by 1.0845 (the ratio of the 2015 to 2010 GDP deflators) to convert to 2015 dollars. All costs in the model are 2015 dollars.

²⁹ Manufacturers might implement technologies differently than this method implies, in order to reduce risk, for example. Such instances are infrequent, however, and the impact of our method on the overall cost estimates is very small.

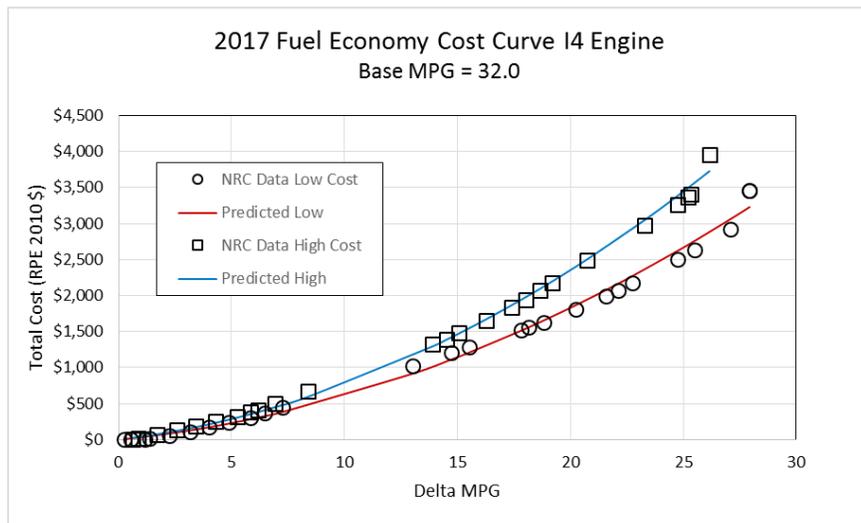


Figure 27. 2017 Fuel Economy Cost Curve for Vehicles with Inline 4-Cylinder Engines

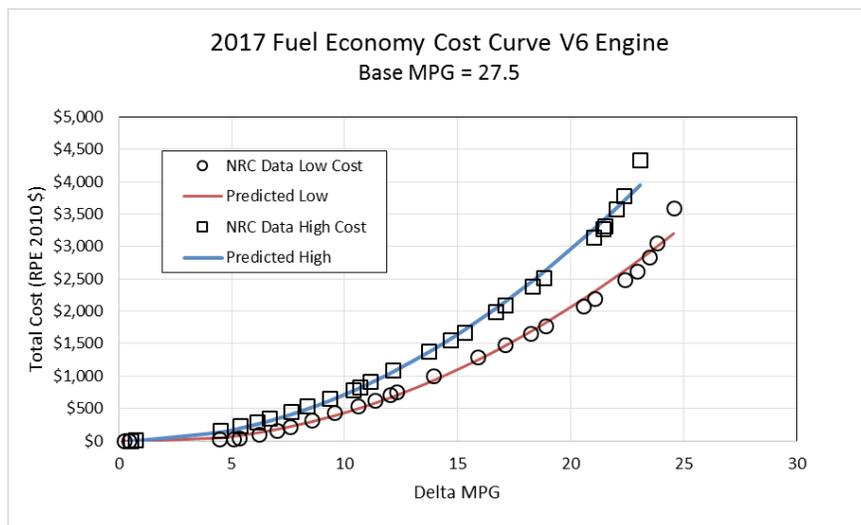


Figure 28. 2017 Fuel Economy Cost Curves for Vehicles with V-6 Engines

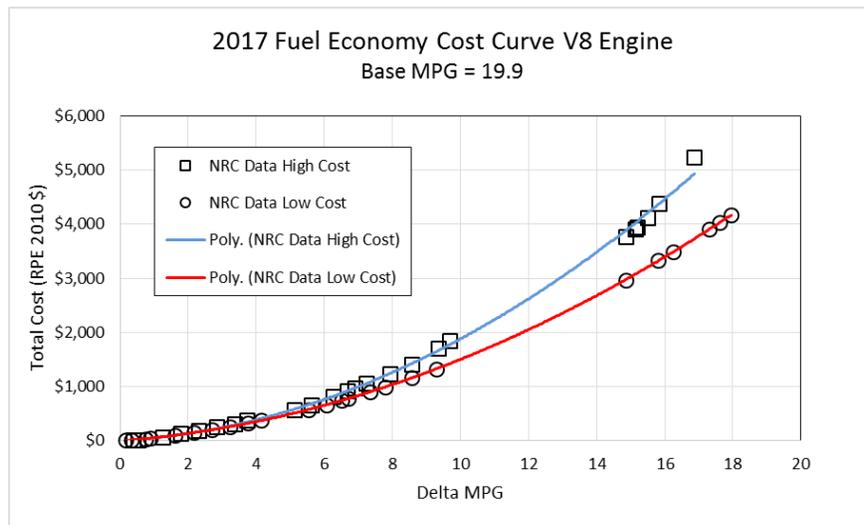


Figure 29. 2017 Fuel Economy Cost Curves for Vehicles with V-8 Engines

The averages of the NRC studies’ High and Low cost curves were used as the reference cost curves in this study. The reference cost functions are shown in Figures 30 and 31, respectively. The 1990 NRC report produced the highest cost estimates, illustrated by the gray line in Figures 30 and 31. The High cost estimates of the 1992 NRC study are exceptionally high relative to the other NRC studies and that pulls up the average costs. In the sensitivity analyses we test the effect of removing the 1990 High cost curve and using the 1990 Low cost curve. The earliest cost estimates and the most recent are the most similar. One might expect the earliest cost estimates to be the lowest because the first efforts to improve fuel economy would take advantage of the lowest cost options available. The most recent estimates, on the other hand, are the most rigorous. The methods used to estimate fuel economy improvement potential and cost have been greatly improved over the past forty years. The NRC 2015 study relied extensively on evidence developed by means of full vehicle simulation modeling and detailed tear-down studies. Such rigorous assessment tools were not available to the NRC 2002 and earlier studies. The fact that the NRC 2015 estimates are both the most rigorous and among the lowest cost is almost certainly a reflection of the progress of automotive technology.

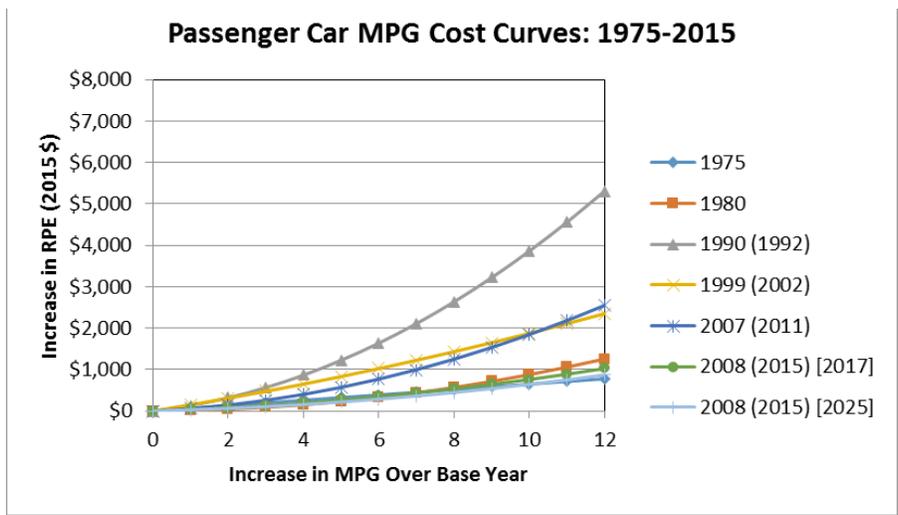


Figure 30. Passenger Car MPG Cost Curves: 1975-2015.

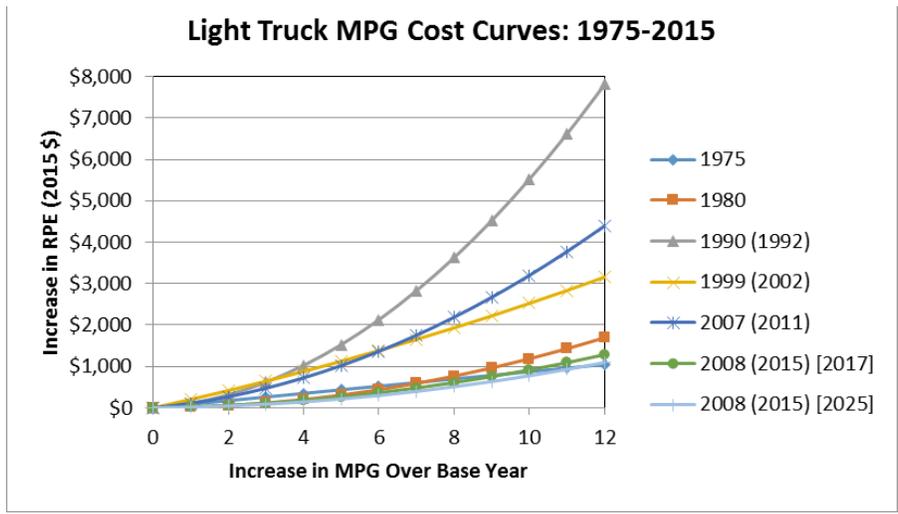


Figure 31. Light Truck MPG Cost Curves: 1975-2015.

Differences between adjacent NRC cost and fuel economy potential estimates may be due to a variety of factors, including technological change, the quality and quantity of information available to the NRC committees as well as their judgments about the risks and consumer acceptance of fuel economy technologies. In this study, the differences are assumed to reflect changes in technology. Rather than assuming that technology changed suddenly just before the base year of each NRC study, we assume linear technological change between study years. This is accomplished by taking a weighted average of the quadratic curve coefficients. Let A_1 and B_1

be the initial quadratic curve coefficients at time t_1 , and A_2 and B_2 the coefficients at $t_2 > t_1$. The coefficients for year t , $t_1 < t < t_2$, are the following.

$$A_t = \left(\frac{t_2-t}{t_2-t_1}\right)A_1 + \left(\frac{t-t_1}{t_2-t_1}\right)A_2 ; B_t = \left(\frac{t_2-t}{t_2-t_1}\right)B_1 + \left(\frac{t-t_1}{t_2-t_1}\right)B_2 \quad (19)$$

This formulation is consistent with the premise that technology changes gradually over time in a linear fashion, but that each NRC assessment reflects a new generation of vehicle designs which takes advantage of the technology available in the base year.

Learning by doing is an important source of cost reduction in the automotive industry. With respect to learning by doing for mature technologies, the NRC (2015, p. 251) observes that,

“It is common practice in the automotive industry for OEMs to negotiate contracts with suppliers that stipulate annual cost reductions in the range of 1 percent to 3 percent, depending on the technology.”

We incorporate learning by doing by reducing previous costs of fuel economy improvement by 2% per year before adding the current year’s costs. The effects of a range of learning rates from 0% to 3% are tested by sensitivity analysis. Unlike previous NRC analyses, the 2015 study estimated costs for future years, namely 2017 and 2025. In the 2017 cost curve, learning by doing was incorporated for certain advanced technologies, with base years of 2012, 2015 (NRC, 2015, p. 266). Learning for those technologies was also incorporated in the 2025 curve, as well as a small number of other technologies which had a base year of 2017. Because learning by doing for several important technologies is already incorporated in the 2017 and 2025 cost functions, it is not applied to costs of improving fuel economy incurred from 2017 to 2025. After 2025 a reduced rate of learning by doing of 1% per year is applied to all costs. The lower rate was chosen to produce more conservative estimates of costs beyond 2025.

The resulting estimates of the incremental costs of fuel economy improvements by model year are shown in Figure 32. Costs rise through 1988 for passenger cars and 1987 for light trucks, after which the fuel economy of both types of vehicles gradually declines and remains nearly constant until about 2005. Costs are expected to increase steadily in future years

as passenger car fuel economy increases from about 38 MPG to 55 MPG and light truck fuel economy grows from 27 MPG to 39 MPG.

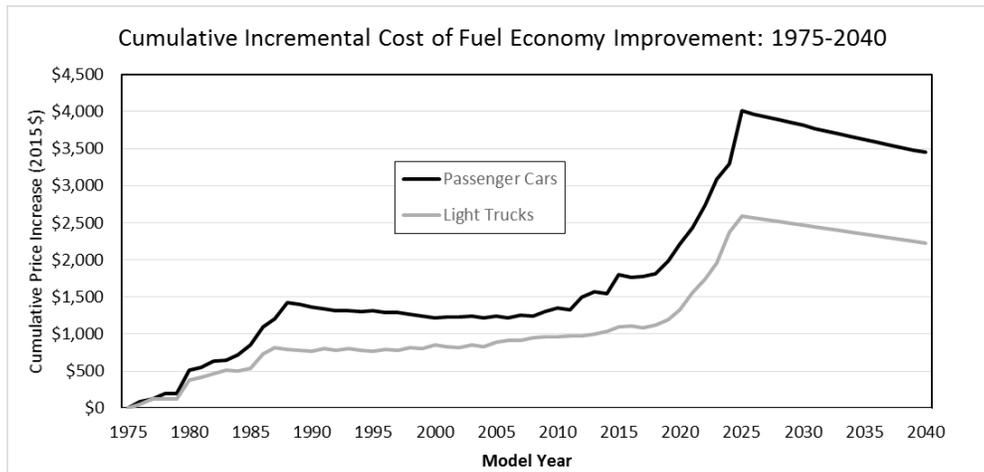


Figure 32. Estimated Cumulative Incremental Cost of Fuel Economy Improvement: 1975-2040.

In general, the NRC-based cost estimates are higher than those developed by the EPA, NHTSA and California ARB. For example, the EPA (2017, p. 20) predicts an increase in vehicle costs of \$875 on average for all new light-duty vehicles for the 2022 to 2025 model years. Using the same car and truck shares, the cost curves based on NRC estimates indicate an average RPE increase of \$1,151. Use of the NRC cost estimates in this study is not meant to imply that the authors consider the Agencies' estimates too optimistic. In the authors' judgment the Agencies estimates are highly credible and supported by sound analysis, as are those of the NRC.

5.2.2 User Cost of Capital Results

Results for estimating total impacts on fuel and vehicle expenditures by income quintile are shown in Table 8. The savings per household in fuel expenditures are results from the decomposition analysis of fuel expenditures and are identical to those presented in Table 4. Total estimated costs of fuel economy improvements are calculated via the user cost of capital method and using Equation 17. Fuel economy improvement cost calculations represent not only increases in vehicle prices due to fuel economy improvements but also a portion (~21%) of future fuel savings that are captured in vehicle prices (see Equation 14). These baseline results assume a 6% discount rate in calculating future fuel savings, a 2% per year reduction in costs of

fuel economy improvements due to learning by doing, and include the high cost curve in 1990. Below we discuss the sensitivity of the results to these various assumptions and demonstrate the robustness of the results.

Again, all income quintiles are estimated to have benefited from the fuel economy improvements. Savings in fuel expenditures and the total cost of fuel economy improvements, both increase as income increases. However, savings are over five times as much as costs for the lowest income quintile while savings are about three and half times as much as costs for the highest income quintile. Net savings from 1980 to 2014 increase as income increases and are about \$8,680 per household for the lowest income quintile and \$23,000 for the highest income quintile. The lowest income quintile saves the most relative to income, 2.06% of average annual household income over the time period examined. Relative to income, the estimated impact of fuel economy improvements over the 1980 to 2014 time period has been strictly progressive, which is consistent with our previous results utilizing different methods for estimating the cost of fuel economy improvements.

Table 8. Total Impacts on Fuel and Vehicle Expenditures Using Cost of Capital Method, 1980-2014

Income Quintile	Accumulation of (Savings) per Household in Fuel Expenditures	Accumulation of Fuel Economy Improvement Costs per Household	Net (Savings)	Annual Net Cost or (Savings) as Percent of Average Household Income
Lowest 20%	(10,591)	1,910	(8,680)	(2.06%)
Quintile 2	(15,329)	3,099	(12,230)	(1.45%)
Quintile 3	(20,820)	4,501	(16,318)	(1.18%)
Quintile 4	(25,560)	6,011	(19,550)	(0.91%)
Highest 20%	(31,652)	8,492	(23,159)	(0.56%)

Table 9 demonstrates the robustness of results using the user cost of capital method. Column I list baseline results which are equivalent to those presented in Table 8. Column II through VI show results by changing one assumption at a time. Column II and III use a discount rate of 3% and 10% for calculating future fuel savings. The high 1990 cost curve is omitted from cost curve interpolations and calculations in Column IV. Column V lists results when future fuel savings as well as the log trend term is excluded from the depreciation function. Finally Column VI presents results when there are no reductions in the cost of fuel economy improvements

to account for learning by doing. Changing the discount rate only results in slight changes in savings. Likewise, while omitting the 1990 high cost curve lowers the cost of fuel economy improvements, costs only decrease by a small amount and changes in savings relative to income are small. When future fuel savings are not assumed to be incorporated into vehicle prices, costs decrease but not by enough to drive significant changes in savings or savings relative to income. Lastly, not accounting for learning by doing also does not greatly change the results. Together, Table 9 demonstrates that the results seem to be robust to several of the assumptions used in the cost of capital method. In all cases, results indicate that all income quintiles benefit from fuel economy improvements. Net savings increase as income increases, and relative to income, savings are consistently progressive and increase with decreasing income.

Table 9. Sensitivity of Results: Annual Net Cost or (Savings) as Percent of Average Household Income, 1980-2014

	(I)	(II)	(III)	(IV)	(V)	(VI)
Income Quintile	Baseline Results: User Cost of Capital Method	Future Fuel Savings Calculated Using 3% Discount Rate	Future Fuel Savings Calculated Using 10% Discount Rate	High 1990 Cost Curve Omitted from Cost Curve Calculations	Future Fuel Savins and Log Trend Term Omitted from Depreciation Function	Assuming No Reductions in Costs due to Learning by Doing
Lowest 20%	(2.06%)	(2.03%)	(2.08%)	(2.13%)	(2.22%)	(1.98%)
Quintile 2	(1.45%)	(1.43%)	(1.47%)	(1.51%)	(1.58%)	(1.39%)
Quintile 3	(1.18%)	(1.16%)	(1.20%)	(1.24%)	(1.29%)	(1.12%)
Quintile 4	(0.91%)	(0.89%)	(0.92%)	(0.96%)	(1.00%)	(0.86%)
Highest 20%	(0.56%)	(0.55%)	(0.58%)	(0.60%)	(0.64%)	(0.53%)

Finally, Table 10 lists total impacts by income quintile for the three different methods used to calculate the cost of fuel economy improvements. Results in Column I are those using the decomposition method for both fuel and total vehicle expenditures and are the same as those presented in Table 4. On net, savings relative to income are progressive yet smaller as costs include changes in total vehicle prices due to all changes in vehicle attributes in addition to costs directly related to fuel economy improvements. In Column II, we reduce total vehicle expenditures and aim to isolate the cost of fuel economy improvements by approximating the ratio of fuel economy costs to total increases in vehicle prices. We also incorporate findings from our econometric analysis of used vehicle prices and consider including a portion of future

fuel savings that may be captured in vehicle prices. While we do rely on the literature to produce estimates, the estimated percentages serve as a rough approximation and are presented as ranges, similar to their presentation in Table 7. This method is preferable to allocating all or none of the increase in total vehicle expenditures to fuel economy improvements. Lastly, Column III lists results using the user cost of capital method and are identical to those presented in Table 8. This method is the preferred method because it relies on a more direct measure of actual fuel economy costs which should result in more accurate estimates of the cost of fuel economy improvements over the time period examined. These analyses indicate that the impact of historical increases in fuel economy have been progressive as savings relative to income increase with decreasing income, and that all income groups have benefited from fuel economy improvements.

Table 10. Results by Method: Annual Net Cost or (Savings) as Percent of Average Household Income, 1980-2014

Income Quintile	(I)	(II)	(III)
	Decomposition of Fuel and Total Vehicle Expenditures	Worst to Best Case Estimates: Using the Ratio of Fuel Economy Improvement Costs to Increases in Vehicle Prices	Fuel Economy Improvement Costs Calculated via User Cost of Capital Method
Lowest 20%	(0.66%)	(1.56%) - (2.00%)	(2.06%)
Quintile 2	(1.41%)	(1.52%) - (1.71%)	(1.45%)
Quintile 3	(0.07%)	(0.81%) - (1.12%)	(1.18%)
Quintile 4	0.29%	(0.50%) - (0.78%)	(0.91%)
Highest 20%	0.90%	(0.04%) - (0.31%)	(0.56%)

6. Estimated Impacts of Future Fuel Economy Improvements

In this section, we estimate the impacts of *future* fuel economy improvements on household income by quintile. Fuel economy standards currently in place are expected to increase new passenger car and light truck fuel economy on the 2-cycle tests from 31 MPG in 2015 (EPA, 2015, Table 4.4) to 45 MPG in 2025 (EPA et al., 2016, Table 12.9). In addition, new vehicle fuel economy improved from 24 MPG in 2004 to 31 MPG in 2014 (EPA, 2015, Table 9.1), and these improvements have yet to have their full impact on the stock of vehicles in use. The future impacts of increases in fuel economy depend on many factors of which the most important are the amount of fuel economy improvement, the consequent increases in new vehicle

prices and the price of gasoline. In Section 5.2.1, we discussed fuel economy cost functions and the costs of future fuel economy improvements. We use these cost functions in addition to the model described below to estimate future impacts of fuel economy improvements on the distribution of income in the U.S. We construct a model to estimate:

1. the evolution of the stocks of passenger cars and light trucks by model year and income quintile,
2. vehicle miles of travel by passenger cars and light trucks by model year and income quintile,
3. fuel use based on miles traveled and fuel economy by model year and income quintile, and
4. expenditures on fuel by calendar year and income quintile.

Projections of future sales of passenger cars and light trucks, their fuel economies and the price of gasoline were obtained from the Energy Information Administration’s (EIA) Annual Energy Outlook (AEO) 2017. The EIA projections include estimated in-use fuel economy as well as estimated EPA fuel economy test numbers, separately for new cars and light trucks. The projected fuel economy numbers reflect the MPG improvements required by current fuel economy and greenhouse gas (GHG) emission standards through 2025.

The following sections describe, 1) how passenger cars and light trucks of different ages were apportioned among the five income quintiles, 2) the vehicle stock evolution, use and fuel use model, and 3) the resulting estimates of effects on incomes by quintile and sensitivity analysis of those impacts.

6.1 Vehicle Stock Turnover, Miles Traveled and Fuel Consumption

Fuel use (G) is calculated by multiplying the number of vehicles (N) by miles traveled per vehicle (M) and dividing by fuel economy (E). Each factor is tracked by two vehicle types (j), passenger cars and light trucks, and by model year (y) for each calendar year. Calendar year minus model year equals the age of a vehicle ($t - y = a$). Fuel expenditures are equal to fuel use multiplied by the price of gasoline (p).

$$p_t G_{jatq} = p_t \frac{N_{jatq} M_{jat}}{E_{jat}} \quad (20)$$

Fuel economy is always adjusted for vehicle age. A vehicle's miles per gallon is assumed to decrease by 0.1 MPG per year as the vehicle ages. Expenditures by income quintile are estimated by sharing the number of vehicles by type and age among the income quintiles according to historical patterns of vehicle ownership. The method is explained in the following section.

The initial 2014 distribution of passenger cars and light trucks by ages 0 through 25+ years was obtained from the Consumer Expenditures Survey. Projections of new passenger car and light truck sales were taken from the 2017 Annual Energy Outlook (AEO) Reference Case Projection of the Energy Information Administration (EIA, 2017). All projections, including new vehicle fuel economies, gasoline prices, and GDP were obtained from the 2017 AEO. Survival rates (S_{ja}) for vehicles of different ages are from NHTSA (2006). The number of vehicles of a given age and type surviving from one year to the next is a constant fraction of the previous year's vehicle inventory.

$$N_{ja+1t+1} = S_{ja} N_{jat} \quad (21)$$

The AEO's light-duty vehicle sales projections include business and government fleet purchases, as well as household vehicle purchases. The AEO sales projections are reduced by 10% to approximately remove business and government fleet purchases.

Likewise, miles traveled per vehicle as a function of age are from NHTSA (2006). The model predicts 2,348 billion vehicle miles of household travel in 2015. This compares well with the National Household Travel Survey of 2009, which estimated 2,351 billion miles of household vehicles travel (117,181 households x 20,060 miles per household). The model's 2,348 billion miles of household vehicle travel are 86% of the AEO 2017's total miles of travel by all light duty vehicles. Future miles traveled per vehicle are adjusted to take into account the rebound effect and, potentially, the effect of economic growth. The elasticity of vehicle use with respect to fuel cost per mile (p_f/E_{jat}) is assumed to be -0.15, a value generally consistent with the recent literature (e.g. Hymel and Small and 2015; Greene, 2007), although alternative values are tested

via sensitivity analysis. An elasticity of vehicle use with respect to GDP can be chosen so that the growth rate of vehicle travel predicted by the model matches that of the AEO Reference Case Projection. However, a GDP elasticity of 0.00 closely matched the model's predicted growth of light-duty vehicle travel (0.45%/year) to the AEO 2017 Reference Case rate of 0.44%/year. The model's estimated household fuel use for 2015 is 113.0 billion gallons, 87% of the AEO 2017's estimated total light-duty vehicle fuel use for that year.³⁰

6.2 Sharing

Fuel use and fuel expenditures are allocated to income groups by sharing the stock of vehicles among the income groups by vehicle type and age. Vehicles of a given age and type are assumed to have the same survival probabilities, be driven the same number of miles each year and have the average efficiency of their model year. Allocating vehicles to quintiles requires estimating the quintiles' patterns of ownership by vehicle type and age. A statistical model of an income quintile's propensity to own vehicles by type and age was estimated using the 1980-2014 CES data. For each year the estimated ownership of passenger cars and light trucks of each age from 0-25 years was converted to shares of each age group owned by each of the five quintiles. Thus, the sum of shares across quintiles equals 1.0 for each age and vehicle type category. An index of propensity to own (V) is defined by Equation 22 as a function of a (0,1) quintile indicator variable, d_q , vehicle age, a_{jatq} , a logarithmic trend variable taking on the value of $\ln(1)$ in year 1980, and other variables, x_{jt} , such as the average price of a vehicle of type j in year t . A_q , $B1_q$, $B2_q$, $B3_q$, $K1_q$, and $K2_q$, are quintile-specific coefficients to be estimated. Coefficients for only four quintiles are estimated.

$$V_{jatq} = \sum_{q=1}^4 d_q \left(A_q + B1_q a_{jatq} + B2_q a_{jatq}^2 + B3_q a_{jatq}^3 + K1_q \ln(t-1979) + K2_q x_{jt} \right) \quad (22)$$

The propensity of quintile q to own vehicles of type j and age a , σ_{jaq} , is a multinomial logit function of V .

³⁰ The AEO 2017 reports fuel use in quadrillion Btu. The EIA uses the higher heating value for gasoline of 125,000 but this must be adjusted downward by approximately 3% to account for the blending of 10% ethanol in nearly all U.S. gasoline.

$$\sigma_{jaq} = \frac{e^{V_{jaq}}}{\sum_{r=1}^5 e^{V_{jar}}} \quad (23)$$

Each quintile has its own set of coefficients (A , $B1$, $B2$, $B3$, $K1$ and $K2$) except for quintile 5 whose coefficients are all set to zero to insure that the sum of shares across quintiles equals 1.

Estimation results for the passenger car and light truck equations are shown in Tables 11 and 12, respectively. In general, the linear age and cubic age³ variables are statistically significant while most of the squared age² variables are not but are kept to complete the cubic polynomial. The pattern of coefficient values indicates that the propensity to own older vehicles increases with decreasing income. All but two of the log trend terms are statistically significant. Linear trends terms were tested but both the AIC and BIC criteria indicated that the log trend form provided a better fit. The constant terms indicate that vehicle ownership generally increases with increasing income. The model fits the data reasonably well, given that the CES vehicle ownership data are often sparse at this level of detail.

Table 11. OLS Regression Results for Passenger Car Quintile Shares Model

Variable	Coefficient	Estimate	Std. Err.	t	P> t	95% Conf.	Interval
age 1	B1 ₁	0.116	0.015	7.63	0.000	0.086	0.146
age 2	B1 ₂	0.094	0.014	6.56	0.000	0.066	0.122
age 3	B1 ₃	0.058	0.013	4.39	0.000	0.032	0.083
age 4	B1 ₄	0.041	0.011	3.91	0.000	0.021	0.062
age 12	B2 ₁	0.003	0.002	2.02	0.044	0.000	0.007
age 22	B2 ₂	0.002	0.002	1.11	0.269	-0.001	0.005
age 32	B2 ₃	0.002	0.002	1.28	0.202	-0.001	0.005
age 42	B2 ₄	0.001	0.001	0.44	0.657	-0.002	0.003
age 13	B3 ₁	0.000	0.000	-3.73	0.000	0.00	0.000
age 23	B3 ₂	0.000	0.000	-2.46	0.014	0.000	0.000
age 33	B3 ₃	0.000	0.000	-2.11	0.035	0.000	0.000
age 43	B3 ₄	0.000	0.000	-1.27	0.205	0.000	0.000
ltrnd1	K1 ₁	0.052	0.022	2.33	0.020	0.008	0.095
ltrnd2	K1 ₂	0.074	0.020	3.71	0.000	0.035	0.113
ltrnd3	K1 ₃	0.051	0.015	3.34	0.001	0.021	0.080
ltrnd4	K1 ₄	0.022	0.012	1.83	0.068	-0.002	0.045
qt1	A ₁	-2.141	0.073	-29.37	0.000	-2.284	-1.998
qt2	A ₂	-1.511	0.065	-23.15	0.000	-1.639	-1.383

qt3	A ₃	-0.969	0.048	-20.13	0.000	-1.063	-0.874
qt4	A ₄	-0.540	0.037	-14.75	0.000	-0.612	-0.468

Number of observations = 2,645

R-squared = 0.8523

Root MSE = .22471

Table 12. OLS Regression Results for Light Truck Quintile Shares Model

Variable	Coefficient	Estimate	Std. Err.	t	P> t	95% Conf.	Interval
age 1	B1 ₁	0.091	0.019	4.80	0.000	0.054	0.128
age 2	B1 ₂	0.131	0.015	8.59	0.000	0.101	0.160
age 3	B1 ₃	0.090	0.012	7.28	0.000	0.066	0.114
age 4	B1 ₄	0.061	0.011	5.65	0.000	0.040	0.083
age 12	B2 ₁	0.008	0.002	3.88	0.000	0.004	0.012
age 22	B2 ₂	0.003	0.002	1.78	0.075	0.000	0.006
age 32	B2 ₃	0.003	0.001	2.00	0.046	0.000	0.005
age 42	B2 ₄	0.001	0.001	0.83	0.406	-0.001	0.003
age 13	B3 ₁	0.000	0.000	-5.36	0.000	0.000	0.000
age 23	B3 ₂	0.000	0.000	-4.21	0.000	0.000	0.000
age 33	B3 ₃	0.000	0.000	-3.96	0.000	0.000	0.000
age 43	B3 ₄	0.000	0.000	-2.19	0.028	0.000	0.000
ltrnd1	K1 ₁	-0.111	0.028	-3.91	0.000	-0.167	-0.055
ltrnd2	K1 ₂	-0.041	0.025	-1.68	0.094	-0.090	0.007
ltrnd3	K1 ₃	-0.081	0.018	-4.62	0.000	-0.115	-0.047
ltrnd4	K1 ₄	-0.067	0.016	-4.11	0.000	-0.099	-0.035
qt1	A ₁	-2.070	0.104	-20.00	0.000	-2.273	-1.867
qt2	A ₂	-1.730	0.084	-20.65	0.000	-1.894	-1.566
qt3	A ₃	-0.880	0.057	-15.49	0.000	-0.991	-0.768
qt4	A ₄	-0.336	0.055	-6.12	0.000	-0.443	-0.228

Number of observations = 2,645

R-squared = 0.8905

Root MSE = .25603

Ownership of vehicles by type, age and quintile is calculated by multiplying the appropriate quintile share by the corresponding stock of vehicles.

$$N_{jatq} = N_{jat} \sigma_{jaq} \quad (24)$$

Although the log trend variable is statistically significant, by 2015 its effect on shares is very small. Because its impact on future shares is small and because its usefulness in predicting future trends is dubious, we set the shares at the 2015 levels for all future years. The impact of the log trend variable on predicted quintile shares is illustrated in Figures 33 and 34. Figure 33 shows 2025 light truck ownership using 2015 shares while Figure 34 uses predicted 2025

shares including the extrapolated 2025 log trend effect. Light truck shares are shown because the difference between the smallest and largest log trend coefficients is greater for light trucks than for passenger cars.

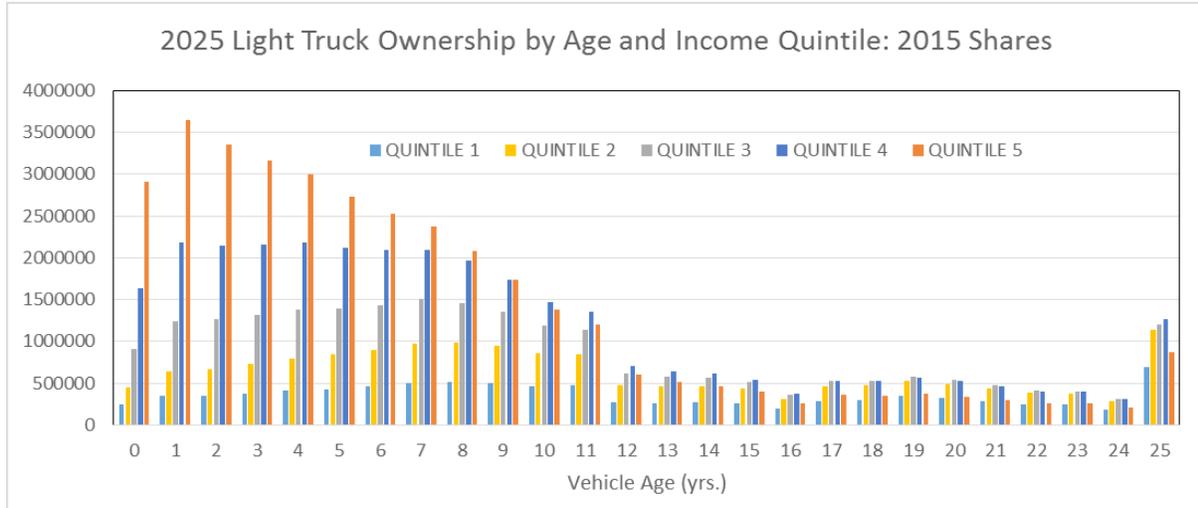


Figure 33. 2025 Light Truck Ownership by Age and Income Quintile: 2015 Shares

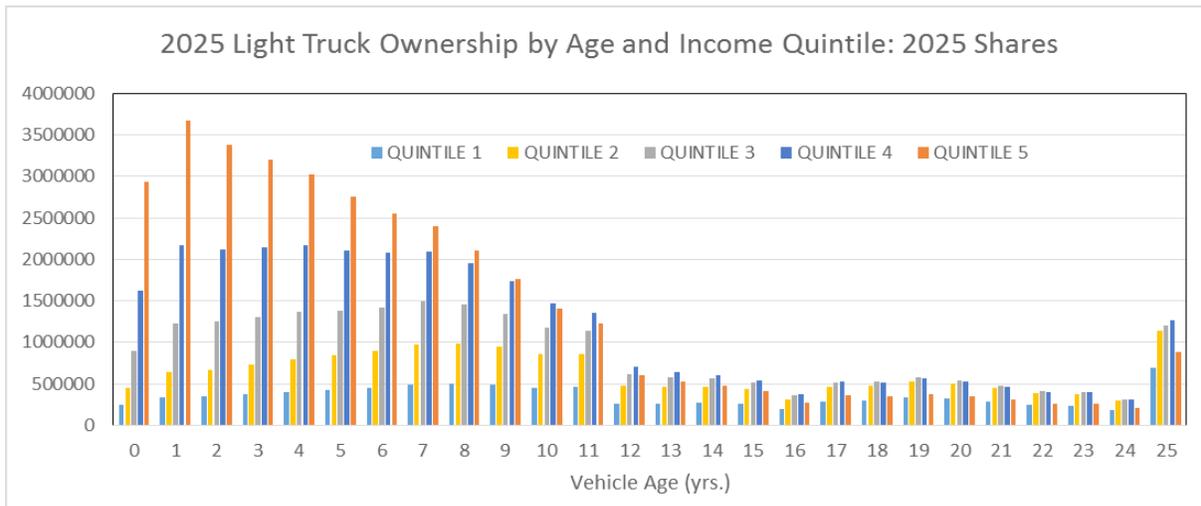


Figure 34. 2025 Light Truck Ownership by Age and Income Quintile: 2025 Shares.

Next the net changes in vehicle ownership by vehicle type, age and quintile are calculated. These changes are used to estimate income transfers among quintiles due to the buying and selling of used vehicles. When prices of used vehicles are calculated using the used car price model that includes economic rent for more efficient vehicles in addition to the depreciated cost of increased fuel economy, there can be net income transfers among quintiles.

The net change from year t to $t+1$ in the stock of vehicles of type j and age a held by income quintile q , $n_{ja+1t+1q}$, is the difference between actual holdings and the number of vehicles one year younger that are expected to survive from the previous year (Equation 25).

$$n_{ja+1t+1q} = N_{ja+1t+1q} - N_{jatq} S_{ja} \quad (25)$$

A net gain (loss) is interpreted to mean that the quintile purchased (sold) more of the respective vehicles than it sold (purchased). Net changes are calculated only for vehicles that have become two years old or older in the current year. The net income transfer for that age and type of vehicle is calculated by multiplying $n_{ja+1t+1q}$ by the estimated economic rent for vehicles of type j , and model year $t+1 - (a+1)$ in year $t+1$. A quintile's total income transfer is the sum over vehicle types and ages.

6.3 Net Impacts on Income

The net impact of fuel economy improvements on income consists of three components:

1. Fuel savings (or costs)
2. Annualized capital cost
3. Transfer payments as a consequence of price premiums for more efficient used vehicles.

Fuel savings (costs) are calculated as the difference between the reference estimate of total expenditures on fuel, X_{tq} , and what expenditures would have been, Z_{tq} , had fuel economy not changed since 1989, the model year of the oldest vehicles represented in the model. Reference total expenditures by quintile q in year t are the sum of expenditures shown in Equation (20) over vehicle types and ages.

$$X_{tq} = \sum_{j=1}^2 \sum_{a=0}^{25} p_t G_{jatq} \quad (26)$$

Expenditures on fuel without fuel economy improvements since 1989, Z_{tq} , are calculated using model year 1989 fuel economies for passenger cars and light trucks, adjusted for age. Because a fuel economy rebound effect is included in the vehicle stock and use model, expenditure without fuel economy improvements must be adjusted to remove the rebound effect. In Equation 27, E_t is the total vehicle stock fuel economy, E_{1989} is what the total stock

fuel economy would have been had fuel economy not improved since 1989 and β is the rebound elasticity, whose default value is -0.15 (Hymel and Small, 2015; Greene, 2012; Hymel, Small and Van Dender, 2010; Small and Van Dender, 2007)³¹.

$$Z_{tq} = \left(\frac{E_t}{E_{1989}} \right)^\beta \sum_{j=1}^2 \sum_{a=0}^{25} \frac{N_{jatq} M_{jat}}{E_{ja1989}} \quad (27)$$

The capital cost of fuel economy improvement is converted to an annual cost of capital for comparability with annual fuel expenditures and annual transfers. The first step is to calculate the increase in new vehicle prices since 1989 due to fuel economy improvements over the 1989 level, c_{jt} , by subtracting the 1989 cost increase due to fuel economy improvements, decreased by the rate of learning by doing, λ , from the current level of cost increase, C_{jt} .

$$c_{jt} = C_{jt} - C_{j1989} (1 - \lambda)^{t-1989} \quad (28)$$

The annual cost of capital, k , is the (depreciated) cost of a vehicle's fuel economy improvement at its current age minus the cost one year later discounted to present value. The cost of capital for quintile q in year t is the sum over vehicle types and ages of the cost of capital multiplied by the number of vehicles owned by the quintile.

$$c_{tq} = \sum_{j=1}^2 \sum_{a=0}^{25} k_{jat} N_{jatq} = \sum_{j=1}^2 \sum_{a=0}^{25} N_{jatq} \left(c_{jat} - \frac{c_{ja+1t+1}}{(1+r)} \right) \quad (29)$$

Econometric analysis of used car prices paid by CES participants found some support for reflecting economic rent equivalent to about 20% of the remaining discounted present value of a particular vehicle type and model year's fuel savings, relative to the average vehicle on the road in that year. Rent, R_{jat} , is calculated as the product of the price of fuel, p_t , the difference in fuel consumption per mile ($1/E$) and expected remaining miles of travel, discounted at 6% per year, m_{jat} .

³¹ Recent studies based on national or state-level VMT data indicate a declining rebound effect over time and that the rebound effect of falling gasoline prices (analogous to increasing fuel economy) is much less than -0.1.

$$R_{jat} = p_t m_{jat} \left(\frac{1}{E_{jat}} - \frac{1}{E_t} \right) \quad (30)$$

Discounted, expected remaining miles are calculated from the NHTSA (2006) survival probabilities and annual miles data, as the sum from $a = 1$ to 25 years in the case of passenger cars and 36 years in the case of light trucks, of the product of annual miles by a vehicle of type j and age a , the probability of surviving to age a conditional on having survived to age $a-1$, $P(j|a)$, discounted at r per year.

$$m_{ja} = \sum_{a=1}^{25 \text{ or } 36} P(j|a) \frac{M_{ja}}{(1+r)^{j+0.5}} \quad (31)$$

The net rent transfer, T_{qt} , for income group q is the sum over vehicle types and ages of the product of the rent per vehicle, R_{jat} and the net change in vehicle holdings, n_{jatq} .

$$T_{tq} = \sum_{j=1}^2 \sum_{a=2}^{25} R_{jat} n_{jatq} \quad (32)$$

The total net annual income impact is the sum of fuel savings (cost), annualized capital cost (savings) and the net rent transfer.

$$I_{tq} = (X_{tq} - Z_{tq}) + T_{tq} - c_{tq} \quad (33)$$

6.4 Results

Total fuel savings are estimated to far outweigh incremental vehicle costs. By 2025, total annual fuel savings are estimated to be \$92 billion, while households' annual capital cost is estimated to be \$25 billion (shown as negative values in Figure 35). By 2040, most vehicles on the road have reached the 2025 fuel economy levels and estimated annual fuel savings have increased to over \$170 billion. Annual capital costs are estimated to stabilize at about \$33 billion. After 2040, savings continue to grow with increasing vehicle travel while costs are held in check by per vehicle cost reductions due to learning by doing.

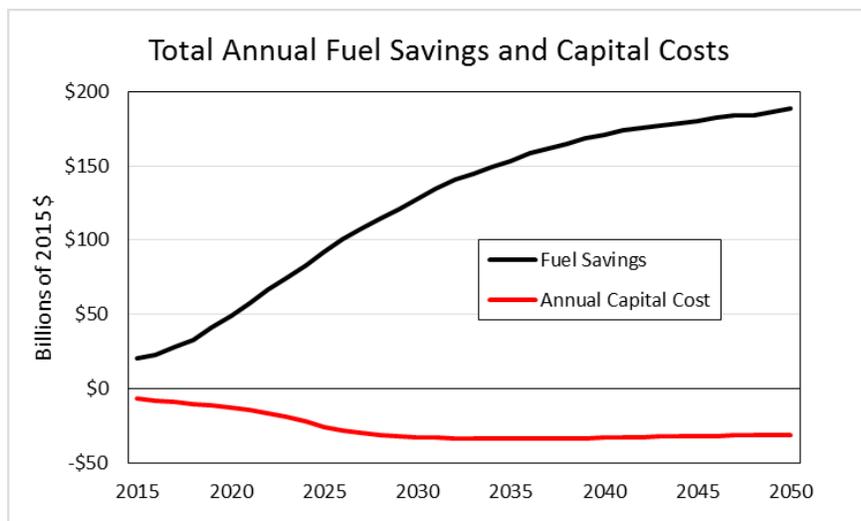


Figure 35. Total Annual Household Fuel Savings and Annualized Capital Costs.

Estimated net savings (annual fuel savings minus annual capital costs) accumulate rapidly after 2020, reaching \$415 billion undiscounted by 2025 and \$344 billion discounted to present value (in 2015) at 3% per year (Figure 36). By 2040 undiscounted cumulative net savings reach \$2 trillion, while discounted savings are estimated to be \$1.3 trillion.

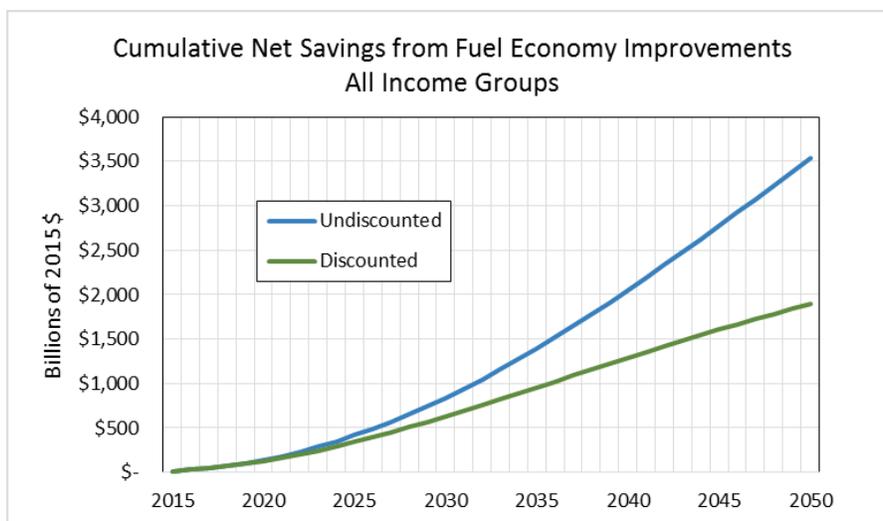


Figure 36. Cumulative Total Net Savings from Fuel Economy Improvements.

All income quintiles are estimated to receive substantial savings from the fuel economy improvements between 1989 and 2025. Fuel savings and costs are estimated increase over time for all income quintiles as fuel economy levels increase but savings increase more rapidly (Table 13). In 2015 fuel savings are approximately three times as large as annual capital costs and by

2040 estimated fuel savings are five times as large as estimated annual capital costs. Estimated net transfer payments among quintiles are small relative to fuel savings and capital costs, and always sum to zero over the quintiles. Estimated fuel savings and total net savings increase with increasing income due to increasing vehicle ownership and use. In 2025, the highest income quintile saves five times as much on fuel as the lowest income quintile and spends seven times as much on vehicle purchases. By 2040, as even the older vehicles approach the 2025 fuel economy levels for new vehicles, the highest income quintile saves a little less than four times as much on fuel as the lowest and spends less than six times as much on vehicles. In 2025, net savings accruing to the highest income quintile are 70% greater than those of the middle income quintile, but 50% greater in 2040.

Table 13. Summary of Savings and (Costs) by Income Quintile (Billions of 2015 \$)

	2015	2025	2040	Total thru 2050
A. Fuel Savings				
Quintile 1	\$1.56	\$6.49	\$14.13	\$357
Quintile 2	\$2.74	\$11.77	\$24.70	\$629
Quintile 3	\$3.91	\$17.38	\$34.00	\$881
Quintile 4	\$5.33	\$24.26	\$44.39	\$1,170
Quintile 5	\$7.14	\$32.44	\$53.99	\$1,461
Subtotal	\$20.68	\$92.34	\$171.21	\$4,497
B. Annual Capital Cost				
Quintile 1	(\$0.45)	(\$1.43)	(\$2.12)	(\$59)
Quintile 2	(\$0.82)	(\$3.31)	(\$4.62)	(\$131)
Quintile 3	(\$1.25)	(\$4.27)	(\$5.84)	(\$168)
Quintile 4	(\$1.78)	(\$6.25)	(\$8.19)	(\$238)
Quintile 5	(\$2.24)	(\$10.02)	(\$12.00)	(\$357)
Subtotal	(\$6.55)	(\$25.28)	(\$32.77)	(\$953)
C. Net Transfers				
Quintile 1	(\$0.01)	\$0.01	\$0.03	\$0.52
Quintile 2	(\$0.05)	(\$0.02)	(\$0.03)	(\$0.91)
Quintile 3	(\$0.05)	(\$0.02)	(\$0.05)	(\$1.28)
Quintile 4	\$0.01	\$0.02	(\$0.03)	(\$0.07)
Quintile 5	\$0.10	\$0.00	\$0.08	\$1.74
Subtotal	\$0.00	\$0.00	\$0.00	\$0.00
D. TOTAL				
Quintile 1	\$1.11	\$5.07	\$12.04	\$298
Quintile 2	\$1.86	\$8.45	\$20.05	\$497
Quintile 3	\$2.61	\$13.09	\$28.11	\$712
Quintile 4	\$3.56	\$18.04	\$36.17	\$932
Quintile 5	\$4.99	\$22.42	\$42.07	\$1,105
Net Total Impact	\$14.13	\$67.06	\$138.45	\$3,544

Net savings have a progressive effect on income (Figure 37). Average annual savings from 2015 to 2040 relative to each quintile’s 2015 income range from 2.2% for the lowest income quintile down to 0.5% for the highest. As a percent of 2015 income net savings increase consistently with decreasing income.

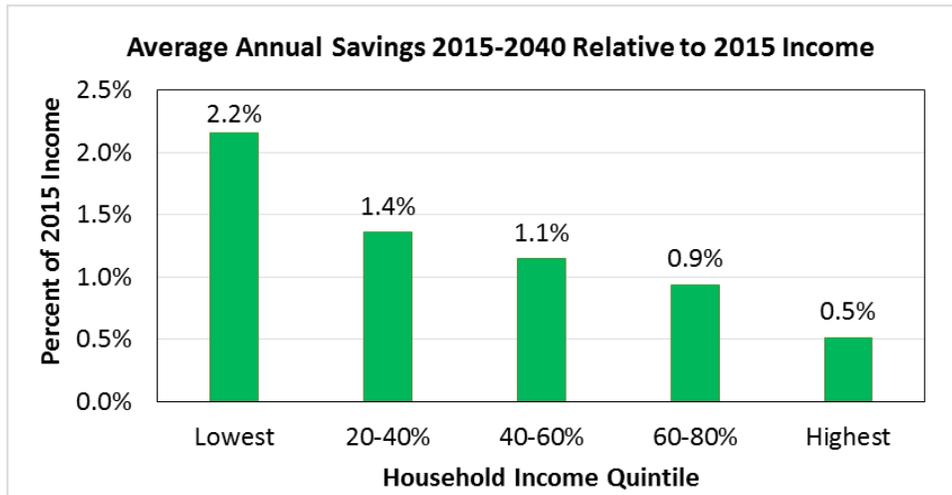


Figure 37. Average Annual Savings 2015-2040 by Income Quintile Relative to 2015 Income.

To test the sensitivity of the projected impacts we ran 10,000 Monte Carlo simulations of the model varying four key parameters:

1. Weighting the NRC’s “High” versus “Low” fuel economy cost curves by θ and $1-\theta$, $0 \leq \theta \leq 1$.
2. Rates of learning by doing.
3. Rebound effect (elasticity of vehicle use with respect to fuel cost per mile)
4. Discount rate (a determinant of the user cost of capital)

Triangular distributions were assumed for each parameter with the ranges and most likely values shown in Table 14.

Table 14. Ranges of Parameter Values (Triangular Distributions) for Sensitivity Analysis

Parameter	Lower Bound	Most Likely Value	Upper Bound
High vs. Low Cost	100% Low	Average of High & Low	100% High
Learning by Doing	1%/year	2%/year	3%/year
LBD after 2025	0%/year	1%/year	2%/year
Rebound Elasticity	-0.05	-0.15	-0.25
Discount Rate	3%/year	6%/year	9%/year

The combined effect of varying these key parameters was relatively modest changes in

the estimates of net savings relative to consumer income. The minimum and maximum values and the 5th and 95th percentiles of the simulation results are shown for each income quintile in Table 15. Even the maximum and minimum results of the simulations indicate positive net savings for all income groups and a progressive effect of the fuel economy improvements on household income. Of the parameters varied the rebound elasticity had the greatest impact on net savings. This reflects the fact that we estimate only dollar savings and dollar costs and not effects on consumer and producer surplus. Additional travel induced by the rebound effect reduces dollar fuel savings but also has value to households. We do not include the value of additional travel enabled by lower fuel costs in our estimates. The weighting of the high and low fuel economy cost curves had the second largest impact, followed by the assumed rates of learning by doing and the discount rate. Nevertheless, as the results in Table 15 indicate, varying all of these factors did not alter the findings that future fuel economy improvements will benefit all income groups and that, relative to income the greatest benefits will accrue to the lower income groups.

Table 15. Results of Sensitivity Analysis of Income Impacts of Fuel Economy Improvements to 2040

Income Quintile	Minimum	5th Percentile	95th Percentile	Maximum
Lowest	+1.7%	+2.0%	+2.3%	+2.5%
20%-40%	+1.0%	+1.3%	+1.5%	+1.6%
40%-60%	+0.9%	+1.1%	+1.2%	+1.3%
60%-80%	+0.7%	+0.9%	+1.0%	+1.1%
Highest	+0.4%	+0.5%	+0.6%	+0.6%

7. Conclusions

Because lower income households typically spend more on motor fuel than on vehicles, NRC (2015) and CFA (2012) deduced that fuel economy improvements should benefit them more than upper income households. A detailed analysis of data from all Consumer Expenditure Surveys from 1980 to 2014 supports the conclusion that all income groups received substantial fuel savings and that the greatest *net* benefits relative to income have accrued to the lower income quintiles. According to our best estimates, the lowest income quintile’s annual net savings averaged between 1.5% and 2.0% of their average annual income over the period. In

terms of total benefits, the net savings generally increase with increasing income.

Between 1980 and 2014, fuel economy improvements that closely followed the Corporate Average Fuel Economy standards reduced average fuel consumption per mile by 25% to 30%. The improvement would have been greater had we been able to include CES data going back to 1975. In addition to the CES data, the findings of our study depend on the premise that the fuel economy of a model year cohort of vehicles changes little as the cohort ages. Analysis of the Energy Information Administration's Residential Transportation Energy Consumption Surveys confirmed the findings of other published studies, i.e., that the fuel economy of a model year cohort decreases very slowly with age if at all: 0.1 MPG per year or less. Evidence from the National Household Travel Survey on the fuel economy of vehicles owned by different income groups also supports this key premise.

Fuel savings due to fuel economy improvements can be estimated with a high degree of confidence due to the reliability of the key data sources: 1. Household expenditures (CES), 2. Model year fuel economy (EPA), 3. Gasoline prices (EIA).

The impact of fuel economy improvements on the prices paid for new and used vehicles is less well known. Published studies of the cost of increasing new vehicle fuel economy provide a relatively wide range of estimates. There is no source of actual expenditures on the fuel economy content of vehicles over time. This study presents two different estimates, both relying primarily on estimates by four committees of the National Research Council (1991; 2002; 2010; 2015). Chiefly based on these studies, the first method assumes that fuel economy improvements from 1975 to 2014 raised the prices of new vehicles by an average of \$150 to \$250 per MPG. This range implies that fuel economy may have accounted for 27% to 42% of the increase in constant dollar new vehicle prices from 1980 to 2014. In the authors' opinion these estimates are more likely to be high than low. The second method uses direct estimates of the costs of fuel economy improvements derived from the four NRC studies and a review of the literature on fuel economy cost estimates published in 2000.

The impact of fuel economy on households' expenditures on vehicles also depends on

how model years with higher fuel economy are priced in the used car market. The CES data provides prices paid for both new and used cars and light trucks and the ages of the vehicles from 1980 to 2014. An econometric analysis of the CES data indicated some support for two alternative hypotheses:

1. The price of fuel economy improvements in used vehicles reflects only the depreciated purchase price of vehicles when they were new and,
2. The price of fuel economy improvements in used vehicles additionally includes approximately 20% of the present value of any fuel savings advantage relative to other vehicles on the road, discounted over the expected remaining life of the vehicle.

Both possibilities are included in the range of estimated net effects of fuel economy improvements. In estimating the effects on income quintiles, each quintiles' expenditures on used versus new vehicles is taken into account. The net income transfers are small, however, relative to fuel savings and the costs of improved fuel economy.

Regardless of the method use, the same patterns of net savings were found:

- 1) All income quintiles received net savings as a result of fuel economy improvements,
- 2) As a percent of income, savings were progressive, increasing with decreasing income, and
- 3) In total dollars, net savings increased with increasing income.

We estimate that the impacts of future fuel economy improvements on household income will be similar to the historical impacts. All income groups are estimated to receive net savings. Net savings are estimated to be progressive and similar percentages of household income as the historical impacts. The lowest income group is expected to save about 2% of annual income, decreasing gradually with increasing income to about 0.5% of annual income for the highest income quintile. The conclusion that fuel economy improvements benefit all income groups and have a progressive effect on household income appears to be robust.

References

Allcott, H. and N. Wozny, 2014. “Gasoline Prices, Fuel Economy, and the Energy Paradox”, *The Review of Economics and Statistics*, vo. 96, no. 5, pp. 779-795.

Anderson, S.T., R. Kellogg and J.M. Sallee, 2013. What Do Consumers Believe about Future Gasoline Prices?, *Journal of Environmental Economics and Management*, 66, 383-403.

Ang, B.W. and F.L. Liu. (2001). A New Energy Decomposition Method: Perfect in Decomposition and Consistent in Aggregation. *Energy*, 26, 537-548.

Ang, B.W. (2005). The LMDI Approach to Decomposition Analysis: A Practical Guide. *Energy Policy*, 33, 867-871.

Bureau of Labor Statistics (BLS), 2016. “How BLS Measures Price Change for Used Cars and Trucks in the Consumer Price Index” accessed at <http://www.bls.gov/cpi/cpifacuv.htm> on 6/29/2016.

Busse, M.R., C.R. Knittel and F. Zettelmeyer, 2013. Are Consumers Myopic? Evidence from New and Used Car Purchases, *American Economic Review*, 103, 220-256.

Consumer Federation of America (CFA) et al., 2012. “Proposed Rule 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: Comments of Consumer Groups”, Docket Nos. EPA-HQ-OAR-2010-0799; FRL-9495-2 and NHTSA–2010–0131, February 13.

Davis, S.C., 2015. *Transportation Energy Data Book: Ed. 34*, ORNL-6991, Oak Ridge National Laboratory, Oak Ridge, TN, table 10.12, accessed at <http://cta.ornl.gov/data/index.shtml> on 7/8/2016.

Edmunds.com, 2016. “Depreciation Infographic: How Fast Does My New Car Lose Value?” accessed at <http://www.edmunds.com/car-buying/how-fast-does-my-new-car-lose-value-infographic.html> on 6/29/2016.

Energy Information Administration (EIA), 2016. “Transportation Energy Consumption Surveys”, Historical Data Tables, accessed on 5/25/2016 at <http://www.eia.gov/consumption/archive/rtecs/contents.html> , U.S. Department of Energy, Washington, DC.

Environmental Protection Agency (EPA), 2016. Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025 Executive Summary, EPA-420-D-16-901, Office of Transportation and Air Quality, accessed at <https://www3.epa.gov/otaq/climate/documents/mte/420d16901.pdf> on 9/9/2016.

Environmental Protection Agency (EPA), 2015. *Light-Duty Automotive Technology, Carbon*

Dioxide Emissions, and Fuel Economy Trends: 1975 – 2015, accessed at <https://www3.epa.gov/otaq/fetrends-complete.htm> , Office of Transportation and Air Quality, Ann Arbor, Michigan.

Federal Register (FR), 2012. *2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule*, vol. 77, no. 199, Environmental Protection Agency and Department of Transportation, Washington, DC, October 15.

Foster, T., 2016. Personal communication August 31, 2016. Mr. Foster is author of “Report on Quality Changes for 2016 Model Vehicles”, Bureau of Labor Statistics, U.S. Department of Labor, <http://www.bls.gov/web/ppi/ppimotveh.htm>.

Gillingham, Kenneth, Matthew Kotchen, David Rapson, and Gernot Wagner. (2013). The Rebound Effect is Overplayed. *Nature*, 493, 475-476.

Greene, D.L., 1991. “The Cost of Short-Run Pricing Strategies to Increase Corporate Average Fuel Economy,” *Economic Inquiry*, vol. XXIX, no. 1, pp. 101–114.

Greene, D.L., 2011. “Uncertainty, Loss Aversion and Markets for Energy Efficiency”, *Energy Economics*, vol. 33, pp. 608-616, 2011.

Greene, D.L. and J. DeCicco, 2000. “Engineering-Economic Analyses of Automobile Fuel Economy Potential in the United States”, *Annual Review of Energy and Environment*, vol. 25, pp. 477-535.

Greene, D.L., and D.H. Evans and J. Hiestand, 2013. “Survey evidence on the willingness of U.S. consumers to pay for automotive fuel economy”, *Energy Policy*, vol. 61, pp. 1539-1550, 2013.

Greene, D.L, A. Khattak, J. Liu, J.L. Hopson, X. Wang and R. Goeltz, 2015. *How do Motorists’ Own Fuel Economy Estimates Compare with Official Government Ratings? A Statistical Analysis*, Baker Report 4:15, Howard H. Baker, Jr. Center for Public Policy, The University of Tennessee, Knoxville, September 30, 2015. Available at <http://bakercenter.utk.edu/2015/10/01/baker-fellow-greene-investigates-gap-between-motorists-fuel-economy-estimates-and-government-ratings/> .

Greene, David L., James R. Kahn, and Robert C. Gibson. (1999). Fuel Economy Rebound Effect for U.S. Household Vehicles.” *The Energy Journal*, 20(3), 1-31.

Greening, Lorna A., David L. Greene, and Carmen Difiglio. (2000). Energy Efficiency and Consumption-the Rebound Effect-a Survey. *Energy Policy*, 28 (6-7), 389-401.

Lin, Z. and D.L. Greene, 2011. *Predicting Individual On-road Fuel Economy Using Simple Consumer and Vehicle Attributes*, SAE Technical Paper Series No. 11SDP-0014, Society of Automotive Engineers, Warrendale, PA.

Murrell, J.D., 1980. *Passenger Car Fuel Economy: EPA and Road*, A report to Congress, U.S. Environmental Protection Agency, Ann Arbor, Michigan, January.

NADA, 2012. “Volatility in Used Vehicle Depreciation: Historical Trends & Future Outlook”, nada.com/b2b, accessed on 6/29/2016.

National Highway Traffic Safety Administration (NHTSA)’s National Center for Statistics and Analysis, U.S. Department of Transportation (2006). *Vehicle Survivability and Travel Mileage Schedules*, Technical Report DOT HS 809 952, January, Tables 7 and 8.

National Research Council (NRC), 2015. *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*, Report of the Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Research Council, Washington, D.C. Available at http://www.nap.edu/download.php?record_id=21744 .

National Research Council (NRC), 2010. *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, Report of the Committee on the assessment of Technologies for Improving Light-duty Vehicle Fuel Economy, National Academies Press, Washington, D.C..

National Research Council (NRC), 2002. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, Report of the Committee, National Research Council, National Academy Press, Washington, 2002.

National Research Council (NRC), 1992. *Automotive Fuel Economy: How Far Can We Go?* Report of the Committee on Automobile and Light Truck Fuel Economy, National Research Council, National Academy Press, Washington, DC.

Sallee, J.M., S.E. West and W. Fan, 2015. “Do Consumers Recognize the Value of Fuel Economy? Evidence from Used Car Prices and Gasoline Price Fluctuations”, NBER Working Paper 21441, July 2015, accessed at <http://www.nber.org/papers/w21441> on July 8, 2016, National Bureau of Economic Research, Cambridge, MA.

Sallee, J.M., 2014. “Rational Inattention and Energy Efficiency”, *Journal of Law and Economics*, vol. 57, no. 3, pp. 781-820.

Small, Kenneth A., and Kurt van Dender. (2007). Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect. *Energy Journal*, 28(1), 25-51.