Title

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Publication Date

2009-07-13

Peer reviewed

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July 13, 2009

Abstract

New car fleet fuel economy, weight and engine power have changed drastically since 1980. These changes represent both movements along and shifts in the "fuel economy/weight/engine power production possibilities frontier". This paper estimates the technological progress that has occurred since 1980 and the trade-offs that manufacturers and consumers face when choosing between fuel economy, weight and engine power characteristics. The results suggest that if weight, horsepower and torque were held at their 1980 levels, fuel economy for both passenger cars and light trucks *could have* increased by nearly 50 percent from 1980 to 2006; this is in stark contrast to the 15 percent by which fuel economy actually increased. I also find that once technological progress is considered, meeting the CAFE standards adopted in 2007 will require halting the observed increases in weight and engine power characteristics, but little more; in contrast, the standards recently announced by the new administration, while certainly attainable, require non-trivial "downsizing". I also investigate the relative efficiencies of manufacturers. I find that US manufacturers tend to be above the median in terms of their passenger vehicle fuel efficiency conditional on weight and engine power, and are among the top for light duty trucks; Honda is the most efficient manufacturer for both passenger cars, while Volvo is the most efficient manufacturer of light duty trucks. However, I also find that over time, US manufacturers' relative efficiency in both passenger cars and light trucks has degraded. These results may provide insight into their current financial troubles.

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*This paper has benefitted from conversations with Severin Borenstein, K.G. Duleep, David Greene, Jonathan Hughes, Mark Jacobsen, Doug Miller, David Rapson, Ken Small, Anson Soderbery, Dan Sperling, Frank Wolak and Catherine Wolfram, as well as seminar participants at UC Davis and the UC Energy Institute. Omid Rouhani and Anson Soderbery provided excellent research assistance. Financial support from the California Air Resource Board and the Institute of Transportation Studies is gratefully acknowledged. I am grateful to K.G. Duleep for providing me with data. *Affiliations:* Department of Economics and Institute of Transportation Studies, University of California, Davis; University of California Energy Institute; and NBER, *email:* crknittel@ucdavis.edu.

1 Introduction

Within the US, the transportation sector accounts for over 30 percent of greenhouse gas emissions. Despite this, the US has done little over the past 25 years to incentivize increases in passenger automobile fuel economy. Corporate Average Fuel Economy (CAFE) Standards for passenger cars have not increased since 1990. For light trucks and SUVs, they have grown by only 10 percent since 1990.[1] While CAFE standards increased substantially for passenger vehicles from 1978 to 1990 (from 18 MPG to 27.5 MPG), consumers shifted to SUVs—treated as light duty trucks under CAFE. Because of this shift, the resulting sales-weighted CAFE standard has changed little over since 1983.

In contrast to Europe, US policy-makers have also been reluctant to incentivize carbon reductions through either gasoline or carbon taxes. The lack of tax policies combined with lower oil prices led to a 30 percent *reduction* in real gasoline prices from 1980 to 2004. While rapid increases in gas prices appear to have led to a shift to fuel economy from 2006 to 2007, gasoline prices did not include the externality costs of climate change and other externalities.[2]

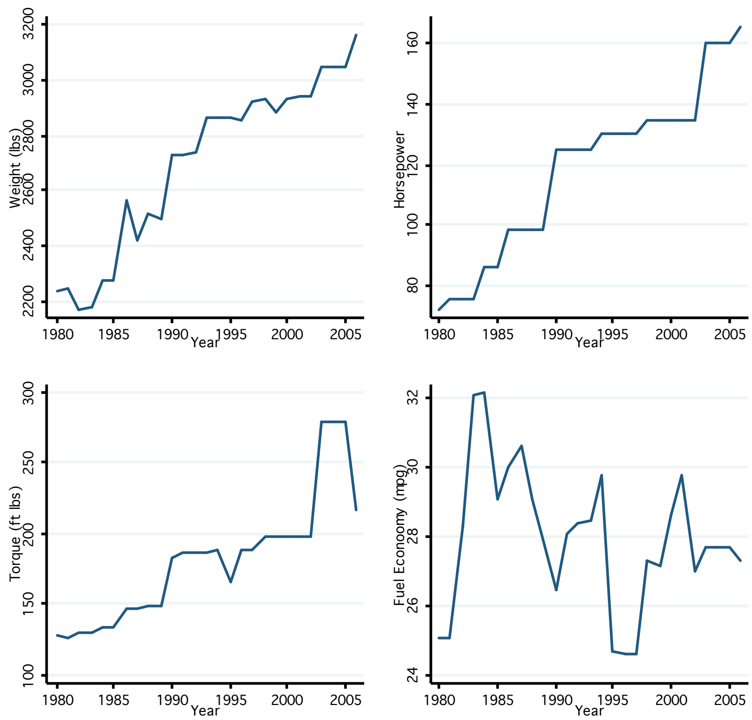
The lack of either pricing mechanisms or standards has meant US fleet fuel economy has been stagnant despite apparent technological advances. From 1980 to 2004 the average fuel economy of the US new passenger automobile fleet increased by less than 6.5 percent. During this time, the average horsepower of new passenger cars increased by 80 percent, while the average curb weight increased by 12 percent. Changes in light duty trucks have been even more pronounced. Average horsepower increased by 99 percent and average weight increased by 26 percent from 1984 to 2004. The change *within* passenger cars and light trucks hides much of the story. In 1980 light trucks sales were roughly 20 percent of total passenger vehicles sales; in 2004, they were over 51 percent. Figure 1 highlights much of the within-vehicle class changes that have occurred over this time through the lens of a single model. The figure plots weight, horsepower, torque and fuel economy for Honda Accord over time.[3] The attributes of a Honda Accord have changed significantly over the past

[1] Much of this increase occurred during a time when consumers where shifting to more fuel efficient vehicles because of market forces. CAFE standards for light trucks were 20 MPG in 1990, 20.7 MPG from 1996 to 2004, and are currently 22.2 MPG. Therefore, over 68 percent of the increase occurred after 2004.

[2] See Busse, Knittel and Zettelmeyer (2009) for a detailed study of how gas prices affected fuel economy. These changes are also evident in the aggregate data, new car fleet fuel economy increased rapidly from 2004 to 2007, increasing by roughly 10 percent, a period where gasoline prices increased by over 70 percent.

[3] I chose the Accord because it is one of the few model name's that is present in every year. The figure uses the average values of these variables across all Accord models that are offered. It looks similar if I use the min, max or median.

Figure 1: Changes in the Honda Accord Attributes over Time



26 years. Weight has increased by over 50 percent, while horsepower has nearly tripled! After an initial increase in fuel economy, during the run up in CAFE standards and high gasoline prices of the early 1980s, fuel economy decreased as gas prices also fell. The period of relatively constant fuel economy and increases in both weight and power illustrate that *potential* fuel economy gains have given way to more weight and power.

These changes in vehicle characteristics are driven by consumer preferences and shifts in the "weight/power/fuel economy production possibilities frontier"—the trade-off between fuel economy, engine power and weight. The different 2009 Honda Accord four door sedans offered in the US and UK serve as a frame of reference. Two engines are offered in the US, a 2.4 liter 4-cylinder and a 3.5 liter V-6. The 2.4 liter has a maximum horsepower of 177 hp, while the 3.5 liter has a maximum horsepower of 271 hp. In the UK where gas prices are substantially higher, three engines are offered: a smaller 2.0 liter gasoline 4-cylinder, a 2.4 liter gasoline 4-cylinder, and a 2.2 liter diesel 4-cylinder. The gasoline engines are rated at 154 hp and 170 hp, respectively.[4] The

[4]The 2.4 liter in the UK achieves higher horsepower through a higher compression ratio.

diesel engine is rated at 148 hp. The two countries use different fuel economy "test cycles", so the fuel economy ratings are not directly comparable, but for completeness the US models achieve a combined fuel economy of 24 MPG and 22 MPG for the 2.2 liter and the 3.5 liter models with automatic transmissions, respectively. The UK models with automatic transmissions achieve 31 MPG (2.0 liter gasoline engine), 27 MPG (2.4 liter gasoline engine) and 37 MPG (2.2 liter diesel engine).[5] The variation in engines offered across the two countries suggests that manufacturers are able to move along some sort of production possibilities frontier and where they choose to be on this frontier is driven by either consumer preferences or the regulatory environment.

A large literature focuses on estimating consumer preferences for fuel economy and power characteristics measured as either horsepower, torque or acceleration.[6] The goal of this paper is to better understand the technological trade-offs that manufacturers and consumers face when choosing between fuel economy, weight and engine power characteristics, as well as how this production possibilities frontier (PPF) has changed over time. The results serve as a guide as to how the market may respond to increases in CAFE standards or a carbon tax, as well as how far regulatory standards can push fleet fuel economy.

Using detailed model-level data from 1980 to 2006, the results suggest that if weight, horsepower and torque were held at their 1980 levels, fuel economy for both passenger cars and light trucks *could have* increased by nearly 50 percent from 1980 to 2006; this is in stark contrast to the 15 percent by which fuel economy actually increased. Technological progress was fastest during the early 1980s, a period where CAFE standards were rapidly increasing and gasoline prices were high. This is consistent with the results of Newell, Jaffe, and Stavins (1999) and Popp (2002) which find that the rate of energy efficiency innovation depends on both energy prices (Newell, Jaffe, and Stavins and Popp) and regulatory standards (Newel, Jaffe, and Stavins).

The trade-off between weight and fuel economy suggests that, for passenger cars, fuel economy increases by over 4 percent for every 10 percent reduction in weight. On average, fuel economy increases by 2.6 percent for every 10 percent reduction in horsepower. The effect of torque is less precisely estimated. For light duty trucks, weight reductions of 10 percent are associated with increases in fuel economy of 3.5 percent, a 10 percent increase in torque is correlated with a 3

[5] This converts imperial gallons to US gallon equivalents.

[6] For example, see such seminal papers as Goldberg (1995) and Berry, Levinsohn, and Pakes (1995). Typically, the influence of gasoline prices is not the focus of these papers. Two exceptions are Klier and Linn (2008) and Sawhill (2008).

percent increase in fuel economy, while the association with horsepower is not precisely estimated.

The results shed light on how difficult it will be to meet the CAFE standards passed by the Bush Administration and those recently proposed by the Obama Administration. The Bush CAFE standards call for an economy-wide average fuel efficiency of 35 MPG by 2020; the Obama standards call for an average fuel economy of 35.5 MPG by 2016. I calculate different methods for complying with the two standards by taking into account (a) technological progress, (b) the trade-off between fuel economy and weight and engine power characteristics and (c) the passenger car to light truck ratio. I find that meeting the Bush standards will not require large behavioral changes, but will require halting the rate of growth in engine power and weight. In particular, if we continue with the average rate of technological progress, the standard can be met by reducing the increase in weight and engine power that has occurred since 1980 by less than 50 percent.[7] Alternatively, shifting the car to truck ratio back to levels observed in the 1990s will suffice. The results also suggest that reducing weight and engine power characteristics to their 1980 levels along with rates of technological progress that were typical during the increases in CAFE standards in the early 1980s, fleet fuel economy could reach over 50 MPG by 2020.

Meeting the Obama standards will require "downsizing" of fleet attributes; although the standards are certainly attainable. With average rates of technological progress, new vehicle fleet fuel economy can reach 35.5 MPG by shifting the car/truck mix to their 1980 levels while at the same time reducing the weight and power characteristic gains since 1980 by 25 percent. Alternatively, the car/truck mix can remain constant, but weight and power reduced to their 1980 levels. A mixture of these two extremes is also possible. With rapid technological progress along with aggressive shifts in the car/truck mix and downsizing, fleet fuel economy can reach nearly 46 MPG by 2016.

The empirical model also yields firm-specific estimates of "efficiency", defined as the relative ability of a given manufacturer to extract fuel economy from a vehicles with a given level of weight, horsepower, torque and a variety of other characteristics. For passenger cars, the top four firms are Honda, Toyota, GMC and Nissan, respectively. Honda's fuel economy is nearly 7 percent greater than a comparable Ford passenger car; 13 percent greater than a comparable Hyundai. Across the entire sample, US manufacturers tend to be above the median. Korean manufacturers fair the worst, among "non-exotic" manufacturers; and German manufacturers tend to lie below US man-

[7] If we infer causality for the above trade-offs, this can be met by either altering the makeup of existing vehicles or shifting which vehicles are purchased. If the above trade-offs are viewed as simply correlations, then this represents shifting which vehicles, among those vehicles that are already offered, are purchased.

ufacturers. Interestingly, relative efficiency changes significantly for light duty trucks. While Ford lags behind Honda, Nissan and Toyota in relative fuel economy for passenger cars and GMC behind Honda and Toyota, they outperform Nissan and Toyota in light truck fuel economy. Over time, however, the relative position of US firms in both passenger cars and light trucks has diminished. The drop in US productivity may provide insight into their current financial troubles.

The remainder of the paper is organized as follows. Section 2 discusses the theoretical and empirical models. Section 3 discusses the data. Section 4 provides graphical evidence of both trade-offs and technological progress. In Section 5, I discuss the empirical results, including estimated trade-offs, technological progress and compliance strategies for the new CAFE standards. Section 6 estimates alternative models and investigates robustness. In Section 7, I provide evidence that the results are not driven by either within-year or cross-year changes in how much manufacturers spend on engine technology. Section 8 investigates heterogeneity across manufacturers. Finally, Section 9 concludes the paper.

2 Theoretical and Empirical Models

The goal of the empirical work is to estimate the technical relationship between vehicle weight, engine power and fuel economy—which I refer to as a production possibilities frontier (PPF)—and how this PPF shifts out over time. I begin by discussing an estimation strategy when vehicles are completely described by four characteristics: weight, horsepower, torque and fuel economy. I then discuss how relaxing these assumptions may introduce bias and provide empirical support that this bias is small in Section 6.

Let the production possibilities frontier at time t be represented by $a(t)T(w_{it}, hp_{it}, tq_{it}, mpg_{it})$, where w_{it} is the vehicle's weight, hp_{it} its horsepower, tq_{it} its torque and mpg_{it} its fuel economy. Given $a(t)T(w_{it}, hp_{it}, tq_{it}, mpg_{it})$ the function that relates fuel economy of a vehicle on the PPF to the other characteristics is given as follows:

$$mpg^*_{it} = \max_{mpg_{it}} : (mpg_{imt}, w_{imt}, hp_{imt}, tq_{imt}) \in a(t)T(w_{it}, hp_{it}, tq_{it}, mpg_{it}) \tag{1}$$

The maximum fuel economy that a vehicle can achieve, given its weight, horsepower and torque can be represented as:

$$mpg^*_{it} = a(t)f(w_{it}, hp_{it}, tq_{it}) \tag{2}$$

I focus on this relationship and how it has shifted over time.

2.1 Additional Factors

The discussion above assumes the PPF is a function of only fuel economy, horsepower, torque and weight. In practice, a number of factors may influence the PPF. Perhaps, the most notable is the cost devoted to technologies that influence the PPF. A firm can shift out the PPF, within a year or over time, by using more expensive technologies. Omitting expenditures on technology from the empirical model may lead to two sources of bias. First, if the goal is to estimate how the PPF has changed over time, *holding how much is devoted to technologies that influence the PPF fixed*, then the estimated shifts out in the PPF will be biased. The direction of the bias is unknown. If firms have increased the amount spent on these technologies over time, then the shifts will reflect the sum of technological progress and this increase. In contrast, if firms have reduced expenditures on technology over time, the shifts will understate technological progress. The second source of bias may come from within year variation in the cost devoted to technologies if this variation is correlated with one of the characteristics. This would bias the estimates of the engineering relationship between fuel economy and engine power or weight. Here, I briefly discuss why these biases are small and provide detailed evidence in Section 7.

I provide two sources of evidence that suggest the shifts in the PPF will understate technological progress. The first relies on existing literature, while the second, discussed in detail in Section 7, shows that the results are robust to controlling for proxies for expenditures on technology. A number of papers have used hedonic pricing models to show that price indexes for automobiles have fallen over time; although the recent analyses have focused on vehicles outside of the US. For example, Matas and Raymond (2008) find that Spanish real automobile prices fell from 1981 to 2005 by 40 percent. Requena-Silvente and Walker (2008) and Dalen and Bodie (2004) find similar results for the UK and Netherlands, respectively. If the amount spent on technologies that shift the PPF out within a year is positively correlated with the real price of automobiles, then these studies would suggest that the estimated technological progress is biased downward.

Furthermore, I also note that for much of the analysis assuming shifts in the PPF reflect only technological progress is not required. Specifically, I use the estimates to answer two related questions. One, how would fuel economy today compare to fuel economy in 1980 if we have held size and power constant? And two, how would new fleet fuel economy look in the future if we were to reduce vehicle attributes and continue to progress at rates observed in the data? Insofar as the observed progression captures both shifts in the PPF due to technological progress and increases in how much firms are devoting to technology, the results should be interpreted in this light. That is, statements regarding how fleet fuel economy in 2006 would change if we had kept vehicle characteristics the same, and projections of fleet fuel economy in the future, can still be accurately made if we continue with the observed changes in both the PPF and technology expenditures. The second concern is that the variation in fuel economy/engine power/weight technology expenditures on technology is correlated with attributes. The robustness analysis in Section 7 suggests that this is not the case.

Besides the cost devoted to technologies that influence the PPF, other factors also alter the relationship between fuel economy, engine power and weight. For example, vehicles with manual transmissions are able to achieve higher fuel economy than automatic transmissions, conditional on weight and engine power. Turbochargers also increase fuel efficiency. Insofar as my data allow, I control for a number of these factors, labelled as X_{it}; I discuss these variables below.

2.2 Sources of the Shifts

Shifts in the PPF represent not only increases in engine technology, but other advances such as advances in transmissions, aerodynamics, rolling resistance, etc. Since the early 1980s, a number of fuel economy/power technologies have become prevalent in vehicles. On the engine side, large efficiency gains have been captured through fuel injection, as opposed to carburetors. In contrast to an engine in the 1980s, the typical engine today has the camshaft—the apparatus that lifts the valves as it rotates—above the engine head. This eliminates friction causing pushrods and rockers. In addition, the majority of engines today have multiple camshafts, allowing for multiple valves per cylinder are now possible (more than two); many also have variable valve timing technologies. Multiple valves allow for the smoother flow of both the fuel/air mixture and exhaust in and out of the cylinder, while variable valve timing allows for the timing of the valve lift to adjust to driving conditions.[8] Turbochargers or superchargers also increase the efficiency of an engine by using a turbine, spun by either the engine's exhaust (turbocharger) or the rotation of the engine's

[8]Chon and Heywood (2000) find that multiple valves increase fuel efficiency two to five percent above two-valve designs, while variables valve timing increases fuel efficiency by roughly two to three percent.

crankshaft (supercharger), to force air into the engine.[9] Most recently, cylinder deactivation and hybrid technology are now beginning to be utilized. Hybrid technologies use both an gasoline engine and electric motor (with a battery) to propel the vehicle. Whne there is sufficient stored electricity, the car runs solely on the electric motor. During times when the vehicle is coasting, the electric motor runs in reverse, thereby recharging the battery. Cylinder deactivation deactivates a set of cylinders during times when power is not needed.

Transmissions have also become more efficient through by utilizing more speeds, variable transmissions and torque converter lock-up. Increasing the number of speeds allows the engine to operate at more efficient speeds. Variable speed transmissions have a continuous number of speeds allowing the engine's RPMs to keep relatively constant. Torque converter lockups reduce the efficiency losses by fixing the torque converter to the drivetrain at highway speeds. Front wheel drive increases fuel efficiency by having the engine closer to the wheels receiving power. Finally, advanced materials, tire improvements and advances in aerodynamics and lubricants have also lead to technological improvements.

The penetration of a number of these technologies since 1975 is plotted in Figures 2 and 3.[10] Figure 2 focuses on engine-related technologies, while Figure 3 focuses on other parts of the drivetrain. Figure 2 illustrates that compared to the typical vehicle built in 1980, a vehicle today is likely to be fuel injected, have more than two valves per cylinder and have variable valve timing. While turbochargers and superchargers have not penetrated the market nearly as much as these other technologies, their use has also increased. Finally, hybrid technologies have also increased in recent years. The diffusion of non-engine drivetrain technologies has also been rapid. Front wheel drive, torque converter lock-ups (for vehicles with an automatic transmission) and transmissions with at least four gears became commonplace in the early 1980s and essentially standard by 1990. By 2006, we also find that nearly 70 percent of vehicles had a transmission with at least five speeds; continuous transmissions have also entered the market.

A number of technologies are also "waiting in the wings". These include advances in hybrid technology, plug in hybrids, camless engines, further reductions in engine friction, higher voltage electrical systems and improved air conditioning.[11]

[9] Ecker, Gill, and Schwaderlapp (2000) finds that supercharging diesel engines can yield fuel efficiency improvements as large as 10 percent when combined with variable valve timing.

[10] Data from all variables, other than transmission speeds is taken from http://www.epa.gov/otaq/fetrends.htm. Data for transmission speeds are taken from the model-level data used in this paper.

[11] For a discussion of the cost of these potential technologies and their impact on fuel economy see, for example,

2.3 Empirical Specification

I model $a(t)$ non-parametrically in the sense that shifts in the PPF, relative to the base year, can take any value in a given year. Functional form assumptions are made regarding $f(.)$. Technological progress is modeled as "input" neutral in the sense that it is multiplicative to the function relating fuel economy and power and weight. I begin the analysis by focusing on two functional forms: Cobb-Douglas and translog. Section 6 relaxes both of these assumptions. A mean zero error term, ϵ_{it}, captures additional characteristics of the vehicle that are assumed to be uncorrelated with the other right hand side variables

Under the Cobb-Douglas and translog assumptions, fuel economy is modeled, respectively, as:

$$\ln mpg^*_{it} = T_t + \beta_1 \ln w_{it} + \beta_2 \ln hp_{it} + \beta_3 \ln tq_{it} + \beta_j X_{it} + \epsilon_{it} \tag{3}$$

and,

$$\begin{aligned} \ln mpg^*_{it} = T_t + \beta_1 \ln w_{it} + \beta_2 \ln hp_{it} + \beta_3 \ln tq_{it} + \gamma_1 (\ln w_{it})^2 + \gamma_2 (\ln hp_{it})^2 + \gamma_3 (\ln tq_{it})^2 \\ + \delta_1 \ln w_{it} \ln hp_{it} + \delta_2 \ln w_{it} \ln tq_{it} + \delta_3 \ln hp_{it} \ln t_{it} + \beta_j X_{it} + \epsilon_{it} \end{aligned} \tag{4}$$

3 Data

I use model-level data on nearly all vehicles sold within the United States and subject to CAFE standards. Therefore, the analysis omits vehicles that have a curb weight in excess of 8500 pounds which are exempt from CAFE regulation; the results should be interpreted in this light, reflecting the progress and trade-offs associated with vehicles with curb weights below 8500 pounds. Fuel economy data come from NHTSA and are supplemented with data from Automobile News and manufacturer websites. The data report a weighted average of city and freeway fuel economy, weight, maximum horsepower and maximum torque.[12] The weight measures for cars and trucks differ. For passengers cars, the data report the curb weight—the weight of the vehicle unloaded. For

Greene and Duleep (1993), DeCicco and Ross (1996) and DeCicco, An, and Ross (2001).

[12]Horsepower and torque are closely related. In fact, at a given RPM, horsepower=torque*RPM/5250. Because the maximum values used in the analysis occur at different RPM levels, there is still information in each. The results are robust to including only one of the two measures.

light duty trucks the weight measure is the weight, including the vehicle's own, in which the vehicle is rated to carry. In addition, data are available on fuel type, aspiration type (e.g., turbocharger), transmission type, and engine size.[13]

Whether to include these additional covariates depends on the question of interest. If one was interested in understanding how much more efficient a normally aspirated, gasoline passenger car with an automatic transmission, conditional on its weight, horsepower and torque, is today compared to in 1980, we would want to include not only weight, horsepower, torque, but also all of the additional variables. If instead one was interested in knowing how much more efficient is a vehicle today, compared to in 1980, allowing for changes in engine size, aspiration-rates, fuel types, etc., then the additional variables should be omitted. That is, if a portion of technological advances is coming from advances in turbo equipment, fuel shifting or the ability to extract more power from smaller engines, we would not want to include the other covariates, thereby allowing the year effects to absorb these advances. It seems fairly clear that one would not want to condition on engine size; the other variables are not so clear. However, while we would want to omit those variables that represent endogenous technological responses by manufacturers, we do want to control for characteristics that move where we on the PPF that are chosen by consumers. In what follows, I present results both including all of the variables and results when I include only transmission and fuel type. They are broadly consistent with each other, but as expected omitting the other variables tend to imply slightly larger technological advances.

In addition to these variables, I impute a vehicle's 0-60 acceleration time using the following equation from the EPA's *Light-Duty Automotive Technology and Fuel Trends: 1975 to 2007*:

$$t = F(HP/WT)^{-f} \tag{5}$$

I use the EPA's values for F and f: 0.892 and 0.805 for automatic transmissions and 0.967 and 0.775 for manual transmissions. Given the flexibility of the empirical models, I never use acceleration in the econometric analysis, but it is a useful variable to compare across time.[14]

Finally, a number of the empirical models will include manufacturer fixed effects. Given the

[13]Fuel economy is measured as a weighted average of city fuel economy (45 percent) and highway fuel economy (55 percent).

[14]Because the analysis uses the natural log of each variable, acceleration is implicitly controlled for.

variety of ownership changes over the sample, I take steps to construct a stable definition of manufacturers. For example, I keep Mercedes and Chrysler separate throughout the sample.

I take a few steps to uncover errors in the data. Specifically, I exclude all vehicles that have missing observations and observations with torque exceeding 2000 ft lbs[15], observations with fuel economy below 5 MPG and observation with fuel economy above 70MPG (except for the Honda Insight). An observation therefore becomes a vehicle that is offered.

4 Summary Statistics and Graphical Evidence

Before estimating econometric models of the PPF, I provide summary statistics and graphical analyses of both the trade-offs and shifts in the PPF.

Table 1 reports the summary statistics for vehicles across the entire sample and separately for 1980 and 2006. It is important to note that these statistics represent what cars were available; they differ from the new vehicle fleet summary statistics since the fleet summary statistics are sales obviously weighted. The average fuel economy for passenger cars is just under 28 MPG for the entire sample. The least fuel efficient vehicle has a fuel economy of 8.7 mpg (the 1990 Lamborghini Countach), while the most fuel efficient vehicle is the 2000 Honda Insight at 76.4 MPG. The average fuel economy of automobiles offered was over 27 MPG in 2006, while it was under 23 MPG in 1980. This represents an increase of roughly 18.5 percent.

The average car has a curb weight of over 3000 pounds. Weight has increased by nearly 14 percent over the sample; remarkably, horsepower has more than doubled over this time, while torque has increased by over 45 percent. All of these gains have occurred with smaller engines. Fewer diesel engines are offered now, compared to in 1980, while the percentage of turbocharged and supercharged vehicles has increased. A similar number of manual transmissions are offered in the two periods. Acceleration has increased by nearly 40 percent over this time period. These changes are similar to changes in the new passenger car fleet from 1980 to 2004 (thus, sales weighted). For the fleet, fuel economy increased by 19.8 percent; weight increased by 13 percent; horsepower increased by 80 percent; diesel penetration went from 4.2 percent to 0.3 percent, due in large part to increasing limits on particulate matter emissions; the percent of cars with either a turbocharger or

[15]This omits 5.1 percent of the sample, 97 percent of these are due to missing data. From looking at the data, it appears as though the RPM level at the maximum torque level and torque are reversed for some of these observations. As a frame of reference, the 2006 Dodge Viper has a maximum torque of 712 ft lbs; the Lamborghini Diablo has 620 ft lbs of torque.

supercharger increased from 1.0 percent to 5.9 percent; and the percentage of manual transmission went from 30 percent to 20 percent.

Among vehicles that are offered, the increases in fuel economy for light duty trucks have surpassed passenger vehicles, an increase of over 35 percent. Weight gains have been similar to passenger vehicles. Horsepower has increased by 70 percent, torque by 15 percent. Acceleration has not increased as much, but has increased by over 25 percent. Fleet data are available for light duty trucks for fuel economy from 1980 to 2004 and for other attributes from 1984 to 2004. For the actual fleet, over these time periods, fuel economy increased by 15.7 percent, weight increased by 26 percent, horsepower increased by 99 percent, diesel penetration went from 2.8 percent to 2.5 percent, the percent of cars with either a turbocharger increased from 0.4 percent to 1.5 percent and the percentage of manual transmission went from 41.8 percent to 7.0 percent.

The simple summary statistics hide a lot of the changes that have taken place. Figures 4 through 6 plot the probability distributions for fuel economy, horsepower and acceleration for both passenger cars and light duty trucks in 1980 and 2006, respectively. For fuel economy, the distribution for passenger cars has not only shifted out, but has become more symmetric. That is while the mode has increased, a larger fraction of offered cars are below this mode than in 1980. The same is also true for light duty trucks, but the distribution remains left skewed. Horsepower today has a much larger right tail than in 1980. Finally, acceleration has shown much larger advances in passenger cars compared to light duty trucks reflecting the smaller weight gains in passenger cars compared to trucks.

Next, I present graphical evidence of the trade-offs that exist between fuel economy and other automobile attributes and the technological progress that took place from 1980 to 2006. Figure 7 plots fuel economy against weight separately for 1980 and 2006 for passenger cars. For visual ease, I truncate fuel economy above 50 MPG. A lowess smoothed non-parametric line is also fitted through the data. The figure suggests that a 3000 pound passenger car gets roughly 10 more MPG in 2006, compared to 1980. These increases are roughly constant over the weight distributions. At the mean fuel economy in 1980, this reflects a 45 percent increase. Similarly, Figure 8 suggests that a passenger car with 200 horsepower gets roughly 10 more MPG in 2006 than in 1980; as with weight the shift in the "isoquant" is fairly parallel. Finally, Figure 9 plots fuel economy torque for passenger cars. While the shift is not as large, it also appears parallel, roughly 8 miles per gallon for a given level of torque.

To confirm that similar trade-offs exist for light duty trucks, Figures 10 through 12 repeat the exercise for light duty trucks. Two things are worth noting. First, while the shifts remain substantial, they do not appear to be as large. Second, the shift is not as constant across the attributes when compared with passenger cars. These figures motivate the econometric model which allows for non-parallel shifts by including higher order variables of the characteristics.

5 Econometric Results

Tables 2 and 3 report the fuel economy production possibilities frontier estimates for passenger cars; Tables 4 and 5 report the results for light trucks. For brevity, I omit the standard errors associated with the year effects; all of which are statistically significant at the 1 percent level.[16] The models vary the amount of control variables and fixed effects. Before discussing the specific results, I describe each model. Models 1 through 3 assume a Cobb-Douglas functional form in weight and engine power characteristics, and vary the set of other covariates. Model 1 includes a full set of technology indicator variables—e.g., manual transmission, diesel fuel, turbocharger and supercharger. Model 2 adds fixed manufacturer effects to Model 1. Model 3 omits the turbocharger and supercharger indicator variables. Again, the rationale is that if some of the technological progress is coming from better turbocharger or supercharger technologies leading to their greater use, then we want this to be included in the technology fixed effects. Models 4 through 6 repeat these variations assuming a translog functional form. Reported standard errors are clustered at the manufacturer level.

5.1 Trade-Offs

To understand the trade-offs between fuel economy and other vehicle characteristics I focus on Model 3, which includes the Cobb-Douglas terms, fixed manufacturer effects and indicator variables for whether the vehicle has a manual transmission or uses diesel fuel.[17]As the standard errors for Models 4 thru 6 indicate, the translog functional form over-parameterizes the production possibilities frontier. While the flexibility is useful to understand robustness, it makes elasticity calculations noisy.

[16]Figures 14 and 17 include 95 percent confidence intervals for Model 3 for passenger cars and light trucks, respectively

[17]As Tables 2 and 3 indicate Model 3 explains a large portion of the variation in log fuel economy. If we decompose this into within-year fit, the average within-year R-square for passenger cars is 0.71, for light trucks it is 0.59.

The Cobb-Douglas results imply that, *ceteris paribus*, a ten percent decrease in weight is associated with a 4.26 percent increase in fuel economy. Large efficiency gains are also correlated with lowering horsepower; all else equal, a ten percent decrease in horsepower is associated with a 2.57 percent increase in fuel economy. The relationship between fuel economy and torque is small and not precisely estimated; a ten percent increase in torque is correlated with a 0.77 percent increase in fuel economy. Interpreting changes in fuel economy for a change in only one of these variables is difficult, since they are strongly correlated and jointly determined.[18] For the compliance strategy calculations below, I use the empirical distribution of sales-weighted data to capture these correlations.

The trade-offs are similar for light duty trucks. The key difference is that torque replaces horsepower as the most significant engine power characteristic. Increases in weight of 10 percent are associated with reduction in fuel economy of 3.55 percent, slightly smaller than with passenger cars. On average, fuel economy decreases by 3.13 percent when torque increases by 10 percent; the effect of horsepower is not precisely estimated. Notice that the sum of the horsepower and torque coefficients—the most correlated of the three variables—is larger with light duty trucks than with passenger vehicles, 0.376 compared to 0.308, implying larger fuel economy gains from reducing engine power characteristics for light duty trucks. In contrast, larger increases in fuel economy are associated with weight reductions for passenger vehicles.

Finally, the coefficients associated with manual transmissions and diesel engines suggest fuel economy savings for these two attributes. Their sign and magnitudes are consistent with non-econometric engineering estimates. The gains from a manual transmission are between 3 and 5 percent for passenger cars and 4.5 percent for light duty trucks. These are consistent with matched vehicles estimates. However, it also appears to be the case that the efficiency gains from manual transmissions have fallen over time as automatic transmission technology has increased; this increase would be reflected in the technology fixed effects.

The increase in fuel efficiency from diesel technology is between 19 and 23 percent and 24 to 27 percent for passenger cars and light duty trucks, respectively. These gains reflect both the increase in thermal efficiency of diesel engines—the ability to convert the BTUs in the fuel to useful energy,

[18]For passenger cars, the pair-wise correlations are 0.71 for weight and horsepower, 0.82 for weight and torque and 0.91 for horsepower and torque. For light trucks, they are 0.53 for weight and horsepower, 0.67 for weight and torque and 0.80 for horsepower and torque.

rather than heat—and the fact that diesel fuel has a greater energy content.[19] The key difference in the two technologies is that diesel engines replace a spark plug with much higher compression ratios—the ratio of the cylinder volume when the piston is at its lowest point to when it is at its highest point.[20] With higher compression ratios the heat from the compressed air combined with the more combustible diesel fuel is sufficient to ignite the air/fuel mixture. The higher compression rates lead to efficiency gains.

While estimates of the theoretical gains in thermal efficiency vary, as do the engineering estimates of the gains in practice, Isuzu estimates that the thermal efficiency of gasoline vehicles is between 25 and 30 percent, while the thermal efficiency of diesel engines is between 35 and 42 percent.[21] These estimates suggest a minimum efficiency gain of 17 percent and a maximum gain of 68 percent. At their average levels, the efficiency gain is 40 percent. Accounting for the higher energy content would imply efficiency gains near the low end of this range. The larger increases in fuel efficiency for light duty trucks is consistent with anecdotal evidence that the gains from diesel technology are largest for larger, more powerful, engines.[22]

5.2 Technological Progress

The technological progress estimates are very similar across models. For passenger cars, the Cobb-Douglas models yield slightly higher estimates of progress and the models are robust to including manufacturer fixed effects or the turbocharger and supercharger indicator variables. Tables 3 and 5 report the coefficients for passengers cars and light duty trucks, respectively. I focus on summarizing the estimates graphically. Figure 13 plots the estimated technological progress for passenger cars across all models. All of the models imply that, conditional on weight and power characteristics, fuel economy is over 45 percent greater in 2006, compared to 1980. The results are also tightly estimated. Figure 14 plots the estimates and 95 percent confidence interval for Model 3; the other models yield similar confidence intervals. The rate of progress was greatest early in the sample—a time when gasoline prices were high and CAFE standards were rapidly increasing. To see this,

[19]The higher energy content also translates to a proportional increase in greenhouse gas emissions. The EPA reports that a gallon of gasoline has 124,000 BTUs, while a gallon of diesel has 139,000 BTUs. http://www.eia.doe.gov/kids/energyfacts/.

[20]Another difference is that the fuel is injected later in a diesel engine, while in a gasoline engine the air/fuel mixture is sucked in as the piston drops after the previous cycle.

[21]www.isuzu.co.jp/world/technology/clean/

[22]A likely reason diesel engines become more prevalent, the larger the vehicle (e.g., heavy-duty diesel trucks, trains, ships, etc.).

Figure 15 plots the annual rate of technological progress from Model 3 and percentage change in passenger car CAFE standards.

The results are also robust across models when considering light duty trucks; by the end of the sample, the estimates across passenger cars and light duty trucks are similar. Figure 16 plots the estimated technological progress for light trucks. All of the models imply that, conditional on weight and power characteristics, fuel economy is over 42.8 percent greater in 2006, compared to 1980. As with passenger cars, the rate of progress was greatest early in the sample (Figure 19); however unlike passenger cars, technological progress has not been monotonic for light trucks, leading to a flatter curve during the 1990s and a more rapid rate of progress later in the sample.[23]

The correlation between technical progress and high gasoline prices and the adoption of CAFE standards is consistent with a small literature that finds regulatory standards and energy prices affects innovation. Newell, Jaffe, and Stavins (1999) find a similar result using product level data for room and central air conditioners. Specifically, they find that electricity prices affect technological progress for both central and room air conditioners, and room air conditioner efficiency standards also increased technological progress. In contrast, they do not find an effect of natural gas prices on gas water heater efficiency. Popp (2002) finds similar results using patent counts related to energy efficiency and energy prices. Popp uses patent counts from 11 classifications related to either energy supply or energy demand from 1970 to 1994. He finds a positive relationship between patents counts and energy prices (measured as dollars per BTU, across all sectors).

5.3 CAFE Standard Compliance Strategies

The Bush Administration recently adopted new CAFE standards that will increase fleet fuel economy to 35 MPG by 2020. The Obama Administration has more recently announced tougher CAFE standards that call for a 35.5 MPG average by 2016. Using the results I calculate how fleet fuel

[23]These estimates are somewhat larger compared to two related papers in the engineering literature. Lutsey and Sperling (2005) who yearly fleet average observations to decompose annual fuel economy changes from 1975 to 2004 by regressing fleet average fuel economy on estimates of engine and drivetrain efficiency, aerodynamic drag and rolling resistance, fleet average weight and fleet average acceleration. Using their estimates they calculate that fuel economy would have been 12 percent higher from 1987 to 2004 if weight, size and acceleration were held constant; my results imply a gain of roughly 22 percent. Given that they use proxies for engine efficiency, drag and rolling resistance, the coefficients from the their regression may be biased downward because of attenuation bias. This would in turn lead to smaller potential efficiency gains. Chon and Heywood (2000) analyze only engine technological progress and find that from 1984 to 1999 "brake mean effective pressure"—the average pressure applied to the piston during an engine's power stroke—grew at an average rate of 1.5 percent per year. Because the fixed year effects capture improvements throughout the vehicle, it is not surprising that the progress in one component of this, the engine, is smaller than the aggregate.

economy changes in 2020 and 2016 with respect to (a) changes in technological progress, (b) the trade-offs between fuel economy, weight and power, and (c) changes in the passenger car/light duty truck mix to change.[24]

I assume three levels of technological progress: none, a rate of progress equal to the average annual rate estimated and a rate equal to the 75th percentile. I use data on changes in *fleet* characteristics to construct sensible movements along the fuel economy and weight/power level curve. Data on weight and horsepower are available from 1980 to 2004 for passenger cars and from 1984 to 2004 for light duty trucks. Using these data I measure the average yearly increase for these variables and extrapolate to 1980 to 2006. Because horsepower and torque are so correlated, I use the ratio of the increase in torque and the increase in horsepower in my data and assume the same ratio exists for the sales weighted increase in torque. For example, for passenger cars the implied increase for horsepower from 1980 to 2006 is 89 percent. Among cars that are offered, it is 123 percent, while the increase in torque is 46 percent. To construct the assumed increase in sales-weighted torque, I use (46/123)*89 percent. The resulting assumptions for passenger cars is an increase in weight of 14.1 percent from 1980 to 2006, 89.3 percent for horsepower and 33.5 percent for torque. For light trucks, the assumed increases are 35.4 percent, 144.9 percent and 31.8 percent for weight, horsepower and torque, respectively. I also analyze how fuel efficiency would evolve if engine power and weight continued to grow at their average rates over this time period.

Using the assumptions regarding the increases in vehicle attributes from 1980 to 2006, I can vary how close fleet characteristics are to their 1980 levels. To construct reasonable changes in the car/truck mix, I report results from the mix in 2006, 43.4 percent cars, and incrementally increase this to 80 percent passenger cars—the level in 1980.

Table 6 summarizes new vehicle fleet fuel economy in 2020 across changes in these three dimensions; the table reports results using the trade-off estimates from Model 3. Shading reflects meeting the 2020 standards. The first set of rows assume zero technological progress over the 14

[24] I abstract away from two changes to how the new CAFE standards will be implemented. The new standards will be "footprint" based. That is, it creates car specific standards based on footprints and the compliance will be met such that a firm's weighted sum of the difference between the car-specific standard and the actual level must be positive. While many details are yet to be determined, presumably the shape of the footprint function will be adjusted such that fleet fuel economy will reach the reported levels of 35 and 35.5 MPG, respectively. A second change that makes the compliance strategies more relevant is that trading will be allowed. Therefore, the constraint will act as an industry-wide constraint and the fuel economy across all manufacturers is the relevant number of interest. Second, the Obama standards will be implemented through the Clean Air Act and will account for greenhouse gas emissions that are also emitted through such sources as the vehicle's air conditioning system. In talking with industry sources, air conditioner improvements may lead to greenhouse gas emission reduction of roughly three percent.

years from 2006 to 2020. The columns allow engine power and weight to continue to grow at their average rates (third column), stay at their current levels (fourth column) and move progressively closer to their 1980 levels (columns five through seven). The zero growth, zero reduction and zero mix shift reports the average new fleet fuel economy in 2006 across passenger cars and light duty trucks—25.8 MPG. The first row implies that if we were to continue with the same car/truck mix, we could increase fuel economy to over 33 MPG by reducing size and power to their 1980 levels. Shifting to just over 60 percent passenger cars, from the 43.4 mix in 2006, while also reverting to 1980 power and weight achieves the new CAFE standards. In contrast, if we continued with the same car/truck mix and the same rate of growth in engine power and weight, fuel economy would fall to 18.1 MPG in 2020.

Once we allow for technological progress, the 2020 standards appear easy to meet provided we do not continue along the same growth path for engine power and weight. I present two sets of results. The first assumes that the average rate of technological progress for cars and trucks holds from 2006 to 2020 (1.76 and 1.78 percent for cars and trucks, respectively). The second assumes that firms progress at a rate equal to the 75th percentile over the data (2.24 percent and 2.38 percent, respectively). Using the average rate of progress and keeping vehicle size and power attributes constant, we can meet the standard by shifting to 65 percent cars. Alternatively, we can move 25 percent towards the size and power of 1980 vehicles. If we progress at a rate equal to the 75th percentile over 1980 to 2006, we meet the standard without shifting of size/power attributes or the car/truck mix. Rapid technological progress combined with shifts to cars and "downsizing" results in an average fuel economy of over 51 MPG.

Table 7 reports new vehicle fleet fuel economy in 2016. The panel with zero technological progress does not change. Unlike the weaker Bush standards, the Obama standards will require moderate "downsizing" of vehicle characteristics—either shifts to more passenger cars or reducing weight and engine power characteristics near their 1980 levels. With average technological progress for cars and trucks and no shifting of the car/truck mix, we can only meet the standards with weight and engine power levels equal to their 1980 levels; changing only the car/truck mix does not achieve the standard. More rapid technological progress makes the standards easier to achieve, but still requires changes in fleet characteristics, either through the car/truck mix or weight and engine size.

There are a number of reasons to prefer the upper levels of technological progress. Recall progress was most rapid during the run up of CAFE standards in the early 1980s, a time when real gas prices were roughly equal to those of today. For passenger cars, CAFE standards tightened from their inception in 1978 to 1985; they went from 18 mpg to 27.5. CAFE standards actually decreased to 26 mpg from 1986 to 1988. During this period of increasing CAFE standards, the average estimated progress for passenger cars is 3.07 percent. This is well above the 75th percentile. For light truck CAFE standards, the initial increase in the standard stopped in 1987. During this time, the estimated rate of progress is 2.12 percent per year, roughly equal to the 75th percentile. Using these rates of progress leads to two additional compliance strategies for the newest CAFE standards, compared to the average rate of progress, while the standards adopted under the Bush Administration met by simply stopping the observed increases in engine power and weight.

6 Alternative Estimators

The previous models implicitly assume that the "trade-off" coefficients remain constant over time. One concern is that this masks aspects of technological progress that change these trade-offs. Because the above trade-off coefficients will represent the average trade-offs across all years in the data (appropriately weighted), if the trade-offs in later years are not as large, technological progress may be biased downwards.[25] I relax this assumption in two ways and discuss the results at the end of the section.

6.1 Oaxaca/Blinder-Type Decomposition

Blinder (1973) and Oaxaca (1973) note that the estimates of the effect of a dummy variable, race in their case and year in my case, in a model where the remaining coefficients are assumed to be constant, will also capture changes in the coefficients associated with the other right hand side variables if the mean of these variables differ across the two samples. They also note that the estimated effect from turning on or off the indicator variable depends on which set of coefficients you "hold constant". In many cases, there is no obvious group of coefficients to hold fixed; in my case since we are interested in asking what the fuel economy of current vehicles would be if they were produced using the technology available in 1980, a natural choice is to use the coefficients

[25] If the mean weight, horsepower, etc. are the same in both time periods, then the year effects will correctly represent the average increase in fuel economy. However, if the trade-offs become less severe and the average of these characteristics in the later years is larger than in the earlier years, then they year effects will underestimate the true increase. As discussed above, the characteristics have indeed increased over time.

from the beginning of the sample to estimate the fuel economy of a given vehicle in 2006 using the technology in 1980.

To implement this, I estimate Models 3 and 6 using data from only first three years of the sample.[26] Using these coefficients, I fit fuel economy for the remaining observations and calculate the difference between actual fuel economy and the fitted value.[27] The difference measures technological progress using the estimated trade-offs in the first three years of the sample, therefore it accounts for relaxation of these trade-offs.

6.2 Matching Estimator

As a second robustness check, I estimate a propensity score matching model. Matching models are often used to estimate a treatment effect when there is selection on observables. By comparing an observation in the "treatment group" with one in the "control" group which has a very similar *ex ante* probability of being in the treatment group, as measured by the propensity score, the estimate will be consistent in the presence of selection on observables.

To reframe technological progress within standard uses of matching estimators, to estimate technological progress from 1980 to 2006, we are interested in how the fuel economy of a vehicle built in 2006 would change if the characteristics of the vehicle, in terms of weight, engine power, etc., did not change, but the vehicle used the technology available in 1980. We can define the "treatment", $W_i = 1$, as using 2006's technology; $W_i = 0$ implies using 1980's technology. If we define the log of fuel economy for vehicle, i, as y_i, we want to estimate:

$$\triangle y_i = y_i(W_i = 1) - y_i(W_i = 0) \tag{6}$$

We can then summarize the sample *average treatment effect* as:

$$\overline{\triangle y_i} = SATE = \frac{1}{N} \sum y_i(W_i = 1) - y_i(W_i = 0) \tag{7}$$

[26]There is a power/bias trade-off. Using only the first year will minimize any bias, but yields noisier coefficients on some of the translog coefficients. While the results are robust to using only the first year, I include the first three years for more precision. The estimated technological progress for 1981 and 1982 therefore becomes the year effects associated with these years. The results are robust to moving this cut-off around.

[27]If we were interested in the heterogeneity of this estimate across all vehicles in a given year, X, a better measure may be the fitted values of these vehicles from a regression using the data from X. Since I only report the mean across all vehicles doing this would yield the same measure.

More important is the *average treatment effect for the treated* which measures how much more fuel efficient the average vehicle in 2006 is compared to if these same vehicles were produced using technology from 1980:

$$\overline{\triangle y_i|W_i = 1} = SATT = \frac{1}{N_1} \sum_{i|W_i=1} y_i(W_i = 1) - y_i(W_i = 0) \tag{8}$$

where N_1 is the 2006 sample.

Of course, we cannot view the actual counterfactual as we never see a 2006 Honda Accord being made with 1980 technology. The matching estimate uses "similar" vehicles in 1980 to compare to the 2006 vehicle as a way to impute the fuel economy of the 2006 Honda Accord using 1980 technology. If we had only fuel economy and, say, weight, this would be a simple estimator. We would choose the m closest cars, in terms of weight, to the 2006 Honda Accord and calculate the average difference in fuel economy across the 2006 Honda Accord and the "control group". Multiple attributes requires reducing these to a single index using some norm; the propensity score does this.

Given a set of vehicles made in two years, say 1980 and 2006, the propensity score is defined as the probability a given vehicle is produced in 2006, conditional on a set of attributes, $Pr(W_i = 1|X_i)$. I estimate the propensity score by estimating a probit model where the dependent variable is one if the vehicles is built in 2006 and zero if built in 1980. Using this, for a given vehicle in 2006 the "control group" is the average fuel economy of the closest four vehicles as measured by the fitted probability from the probit, i.e., the four closest matches to the 2006 vehicle.

To estimate the propensity score Hirano, Imbens, and Ridder (2003) suggests being as flexible as possible; I include the set of translog variables from Model 6 as conditioning variables and use the nearest four vehicles as matches. Abadie and Imbens (2002) show that unless matches are perfect, the estimates will be biased. I adopt their bias-correction procedure that uses the relationship between the estimated treatment effect and the propensity score to adjust comparisons that do not match perfectly. I use the Cobb-Douglas set of co-variates for the bias correction.[28] I also correct the standard errors to account for heteroskedasticity.

[28] Abadie and Imbens (2002) also use a smaller set of covariates for the bias correction term. I have found that using the translog set yields unrealistically large estimates of progress.

6.3 Results from Alternative Estimators

Columns 8 and 9 of Tables 3 and 5 report the technological progress estimates from these two alternative estimators for passenger cars and light trucks, respectively. Both the Oaxaca/Blinder-type (OB) and matching model estimates largely agree with the more parametric models. Three of the four models yield larger estimates of than the previous models. For passenger cars, the OB estimates imply technological advances between 42.7 and 61.8 percent by 2006; these estimates bookend the previous results. For light duty trucks, both OB estimates are larger than the previous models. The matching models tend to yield noisier estimates, but are still consistent with the previous models. For passenger cars, progress is estimated to be 47.6 percent by 2006 for passenger cars and 68.2 percent for light duty trucks.

Combined these results suggest that using the parametric models yields conservative estimates for the technological progress.

7 Robustness to Vehicle-Specific Technology Expenditures

I estimate three additional models that shed light on whether the technological progress and trade-off estimates above are biased due to movements in vehicle-specific technology expenditures either within a year or over time. The first model includes vehicle-specific relative prices *within a given year* on the right hand side. Tables 8 and 9 report the trade-off and technological progress estimates for passenger cars, respectively, while Tables 10 and 11 report the trade-off and technological progress estimates for light duty trucks, respectively.

If the degree of technology adoption is correlated with the other right hand side variables, we would expect the trade-off estimates to changes once price was included on the right hand side, since vehicles prices re likely positively correlated with technology adoption.[29] This does is not the case. For the Cobb-Douglas specification, the trade-off estimates are extremely similar across both passenger cars and light duty trucks. For passenger cars, the largest change is less than 0.03 (the coefficient associated with horsepower), while the largest change for trucks is less than 0.01 (the coefficient associated with weight). The translog specification is more difficult to interpret since the right hand side variables are so correlated, so I focus on the estimates of technological progress.

[29] I use the model's MSRP. For 381 of the 27,185 observations price is not available.

The estimates of technological progress also change little when we account for relative prices. For the Cobb-Douglas model, the estimated technological gains by 2006 are 44.8 percent, compared to 47.4 percent when the relative price is omitted for passenger cars, and 45.9 percent compared to 46.3 percent when price is omitted for light duty trucks. For the translog model, once relative prices are included, the gains by 2006 change from 45.7 percent to 41.0 percent for passenger cars and from 43.4 percent to 42.0 percent for light trucks.

In both the Cobb-Douglas and translog models, relative prices are negatively correlated with fuel economy and the effect is small. The Cobb-Douglas model suggests that a doubling of price is correlated with a 2.7 percent reduction in fuel economy for passenger cars and a 1.8 percent reduction for light trucks; this effect is significant at the 5 percent level for cars, but is statistically insignificant for trucks. The translog model suggests that a doubling of price is correlated with a 5.3 percent reduction in fuel economy for passenger cars and a 3.4 percent reduction for light trucks; this effect is significant at the 1 percent level for cars, but again is statistically insignificant for trucks.

The second model includes the log of the real price on the right hand side. If shifts in the PPF capture increases in how much manufacturers are spending on technology over time, we would expect that including the real price would reduce the technological progress estimates. Given the inclusion of fixed year effects, the within year trade-off estimates are identical to those when we include relative prices, so I only discuss the technological progress estimates. For the Cobb-Douglas model, the estimated technological gains by 2006 is 46.4 percent, compared to 47.4 percent when the real price is omitted for passenger cars. For light trucks it is 47.0 percent compared to 46.4 percent when price is omitted. For the translog model, the coefficient for passenger cars changes from 45.8 percent (base model) to 44.0 percent and increases from 43.4 percent to 43.9 percent for light trucks.

The final model is similar in nature and compares the relative fuel economy of base and "luxury" brands offered by the same manufacturer. That is, I compare the relative efficiency of Acura v. Honda, Ford v. Lincoln, GMC v. Cadillac, Infiniti v. Nissan and Toyota v. Lexus. For passenger cars, the luxury brand is correlated with lower fuel economy and once again the coefficient is small. For light trucks the coefficient is also small and the correlation is not statistically significant. Interestingly, despite the fact that this model uses only five manufacturers, the estimated trade-offs change very little. Again focusing on the Cobb-Douglas results, the largest change for passenger cars is less than 0.02 (weight). The coefficients change slightly more for light trucks, but the changes remain below 0.08. The estimated efficiency gains are also similar. For passenger cars, the degree of technological progress by 2006 changes from 47.4 to 45.9 percent and from 45.8 to 43.9 percent for the Cobb-Douglas and translog models, respectively. For light trucks, the estimates change from 46.4 to 45.8 percent and from 43.4 to 42.6 percent for the Cobb-Douglas and translog models, respectively

All three of these extensions to the base models suggest that prices have a small negative correlation with fuel economy and that the estimated technological progress is largely unaffected. This supports the view that the the shifts in the PPF represent technological progress. The small and often statistically insignificant association between price and fuel economy, conditional on weight and engine power and the small change in the trade-off estimates also suggests that the bias in the trade-off estimates is likely to be small.

8 Manufacturer Heterogeneity

In this section, I investigate whether there is firm heterogeneity in terms of their ability to generate fuel economy from a vehicle of a certain engine power level and weight. Using a particular firm as the "baseline", the manufacturer fixed effects measure how much more or less fuel economy another manufacturer is able to achieve, conditional on a particular level of engine power and weight.[30]

The estimates for passenger cars are plotted in Figure 20 ranked from lowest to highest. I omit the eleven least efficient firms from the graph, which are the "exotic" manufacturers, as well as Yugo. (Omitting these firms from the regressions does not change the results.) To see whether the rank of firms has changed over time, I estimate separate coefficients for the first half of the sample, the entire sample and the second half. US manufacturers perform reasonably well. GMC is among the top in terms of extracting fuel efficiency from a given weight, HP and torque. Chrysler and Ford—the firm set to the "numeraire"—outperform a number of other firms, including many of the German and Korean manufacturers.

These results also inform us as to how the relative positions of firms change over time. While the rankings are fairly stable from the first to the second half of the sample, the results suggest that Honda has increased its relative efficiency a large amount. Using the first half of the data,

[30]The fixed effects will also capture manufacturer heterogeneity in technology use. However, I note that the order remains largely unchanged when I include either relative or real prices on the right hand side.

Hondas achieve 3.1 percent greater fuel economy compared to Ford. This increases to 9.3 percent in the second half. The drop in Ford's efficiency relative to Honda is not unique. The vast majority of firms improve their position relative to Ford. Of the 25 manufacturers for which their is a fixed effect estimate in both time periods, 85 percent increase relative to Ford; 80 percent of non-exotic firms increase their relative efficiency. This pattern also holds for GMC and Chrysler. Eighty percent of the firms increase their position relative to GMC; 64 percent of non-exotics. Eighty-one percent of manufacturers increase their relative position compared to Chrysler; 76 percent among non-exotics. These results may provide some insight into the financial conditions of US firms.

Next I compare firm-level efficiency across passenger cars and light duty trucks in Figure 21, ranked by the light truck fixed effect. The estimates are ranked by the firms' light truck efficiency; the rankings change considerably. Honda, Toyota and Nissan rank higher than US manufacturers for passenger cars (Nissan and GMC are effectively equal), but the three Japanese manufacturers trail GMC when building light duty trucks, while only Honda surpasses Ford. At a first glance, these results suggest that the decision of US manufacturers to focus on light truck sales may have been a good one. However, a further cut of the data suggests that this is not the case. Figure 22 plots the estimated fixed effects from estimating Model 3 using the first and second halves of the data. While across the entire sample, GMC and Ford are among the best in terms of fuel efficiency, over time their relative positions have diminished. Firms such as Audi, Toyota, Honda and Subaru have made large gains relative to US manufacturers. Across all manufacturers, 86 percent of the firms increase their relative position compared to Ford; all of the firms increased their position relative to GMC, while 43 percent did so relative to Chrysler.

9 Conclusions

This paper estimates the trade-offs that consumers and manufacturers face when choosing between fuel economy, vehicle size and vehicle power, as well as the technological advances that have occurred over these dimensions from 1980 to 2006. The results imply that if we were to have kept vehicle size and power at their 1980 levels, fuel economy would have been nearly 50 percent higher in 2006.

The results also generate a variety of potential compliance strategies for the new CAFE standards adopted by both the Bush and Obama administrations. The findings suggest that the Bush CAFE standards would have done little to push manufacturers and consumers to smaller, less powerful cars, or away from SUVs and back into passenger cars. In contrast the Obama standards will require shifts to smaller, less powerful cars and fewer SUVs.

The empirical model generates estimates of manufacturers' relative ability to obtain fuel economy conditional on weight and engine power. Somewhat surprisingly, I find that US manufacturers fair well compared to other manufacturers in the production of passenger cars. While Honda, Toyota and Nissan perform well, GMC outperforms Nissan, while Ford outperforms most non-Japanese manufacturers. In addition, when considering light trucks, GMC outperforms all three Japanese manufacturers, while Ford trails only Honda. However, the results also suggest that the US advantage subsides during the second half of the sample. This suggests that one driver of their recent financial troubles may be losing ground to their competitors when it comes to fuel economy, weight and engine power.

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Appendix

1 Tables

Passenger Cars						
Variable	**Mean**	**Std. Dev.**	**Min**	**Max**	**Mean in 1980**	**Mean in 2006**
Fuel Economy	27.90	6.43	8.70	76.40	22.89	27.11
Curb Weight	3019.45	593.70	1450.00	6200.00	3041.64	3455.04
HP	157.14	76.97	48.00	660.00	110.63	247.02
Torque	238.71	105.16	69.40	1001.00	226.29	329.67
Acceleration	10.56	2.52	3.03	20.75	13.14	8.08
Liters	2.77	1.15	1.00	8.30	3.41	3.22
Diesel	0.03	0.18	0	1	0.07	0.01
Manual	0.38	0.49	0	1	0.35	0.35
Supercharged	0.01	0.11	0	1	0.00	0.05
Turbocharged	0.11	0.31	0	1	0.03	0.15
Sample Size	14337				507	572
Light Trucks						
Fuel Economy	20.76	4.65	9.90	45.10	16.81	22.80
Curb Weight	3835.90	915.72	0.00	6700.00	3877.33	4427.68
HP	160.37	53.76	48.00	500.00	138.59	236.52
Torque	296.01	90.95	76.60	750.00	304.48	351.21
Acceleration	12.13	2.34	4.89	28.19	13.16	9.65
Liters	4.06	1.33	1.20	8.30	4.72	3.95
Diesel	0.05	0.21	0	1	0.02	0.00
Manual	0.33	0.47	0	1	0.42	0.17
Supercharged	0.00	0.05	0	1	0.00	0.01
Turbocharged	0.01	0.11	0	1	0.00	0.03
Sample Size	12805				669	470

Table 1: Summary Statistics

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ln(Weight)	-0.401**	-0.390**	-0.426**	0.435	0.193	-0.038
	(0.047)	(0.032)	(0.030)	(1.250)	(1.270)	(1.256)
ln(HP)	-0.315**	-0.257**	-0.251**	-3.032**	-3.596**	-3.433**
	(0.047)	(0.040)	(0.044)	(0.868)	(0.733)	(0.806)
ln(Torque)	-0.030	-0.077*	-0.057	0.277	0.524	0.495
	(0.038)	(0.033)	(0.037)	(0.764)	(0.622)	(0.714)
$\ln(\text{Weight})^2$				-0.213+	-0.173	-0.162
				(0.114)	(0.114)	(0.117)
$\ln(\text{HP})^2$				-0.219*	-0.140*	-0.191**
				(0.103)	(0.055)	(0.061)
$\ln(\text{Torque})^2$				-0.053	0.001	-0.044
				(0.123)	(0.065)	(0.067)
ln(Weight)*ln(HP)				0.543**	0.564**	0.550**
				(0.149)	(0.137)	(0.154)
ln(Weight)*ln(Torque)				-0.030	-0.104	-0.088
				(0.106)	(0.126)	(0.142)
ln(HP)*ln(Torque)				0.105	0.042	0.127*
				(0.195)	(0.061)	(0.059)
Manual	0.034**	0.045**	0.047**	0.038**	0.048**	0.049**
	(0.006)	(0.005)	(0.005)	(0.006)	(0.005)	(0.005)
Diesel	0.194**	0.211**	0.228**	0.262**	0.254**	0.277**
	(0.019)	(0.020)	(0.026)	(0.019)	(0.025)	(0.033)
Turbocharged	0.026*	0.050**		0.016*	0.051**	
	(0.010)	(0.010)		(0.007)	(0.009)	
Supercharged	0.061**	0.037**		0.060**	0.040*	
	(0.019)	(0.013)		(0.020)	(0.016)	
Year Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer Fixed Effe	No	Yes	Yes	No	Yes	Yes
Observations	14423	14423	14423	14423	14423	14423
R-squared	0.834	0.878	0.848	0.845	0.888	0.854

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 2: Trade-Off Estimates for Passenger Cars

Year	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	OB - Cobb-Douglas	OB - Translog	Matching Model
1981	5.4%	5.4%	5.4%	5.2%	5.1%	5.1%	5.3%	5.2%	4.1%
1982	9.2%	9.1%	9.3%	8.8%	8.7%	8.8%	9.0%	8.9%	8.1%
1983	13.1%	12.7%	12.9%	12.4%	12.1%	12.1%	12.5%	12.5%	12.4%
1984	15.6%	15.1%	15.4%	14.5%	14.3%	14.5%	14.5%	14.6%	14.1%
1985	18.1%	17.4%	17.8%	16.7%	16.4%	16.7%	16.7%	17.0%	17.9%
1986	20.8%	20.3%	20.7%	19.1%	19.1%	19.3%	19.1%	20.0%	20.7%
1987	21.6%	21.1%	21.5%	19.8%	20.0%	20.2%	19.5%	20.7%	21.8%
1988	24.0%	23.1%	23.4%	22.2%	22.1%	22.2%	21.8%	23.4%	24.3%
1989	24.7%	23.8%	24.2%	22.7%	22.7%	22.8%	22.3%	24.2%	24.3%
1990	26.3%	25.2%	25.4%	24.4%	24.1%	24.1%	23.6%	26.9%	25.8%
1991	27.4%	26.2%	26.4%	25.4%	25.1%	25.1%	24.3%	28.2%	26.5%
1992	28.6%	27.4%	27.5%	26.4%	26.2%	26.1%	25.3%	29.6%	27.7%
1993	31.5%	30.2%	30.2%	29.4%	28.8%	28.5%	28.5%	33.2%	30.8%
1994	33.4%	31.9%	31.8%	31.2%	30.5%	30.2%	30.1%	36.2%	32.1%
1995	36.3%	34.8%	34.7%	33.9%	33.2%	32.9%	32.9%	39.3%	34.9%
1996	37.4%	35.6%	35.4%	34.9%	34.2%	33.7%	33.4%	40.1%	34.7%
1997	38.2%	36.7%	36.6%	35.8%	35.3%	35.0%	34.4%	41.6%	35.9%
1998	39.4%	38.2%	38.2%	37.1%	36.8%	36.6%	35.5%	43.9%	36.8%
1999	38.9%	38.2%	38.2%	36.5%	37.0%	36.7%	34.7%	43.8%	36.9%
2000	39.7%	39.4%	39.2%	37.3%	38.2%	37.9%	35.5%	44.7%	37.8%
2001	40.8%	40.3%	40.4%	38.5%	39.2%	39.0%	36.5%	46.9%	39.1%
2002	42.3%	41.9%	41.9%	39.9%	40.7%	40.5%	37.7%	49.5%	40.7%
2003	44.0%	43.2%	43.2%	41.8%	42.1%	42.0%	39.2%	52.4%	42.2%
2004	44.8%	43.8%	43.9%	42.7%	42.5%	42.6%	39.8%	54.3%	43.4%
2005	45.8%	45.0%	45.2%	44.0%	43.8%	43.9%	40.4%	57.7%	44.9%
2006	48.5%	47.4%	47.3%	46.3%	45.7%	45.7%	42.7%	61.8%	47.6%

Table 3: Technological Progress Estimates for Passenger Cars

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ln(Weight)	-0.362**	-0.355**	-0.355**	0.092	1.228	1.180
	(0.052)	(0.040)	(0.043)	(1.706)	(1.289)	(1.346)
ln(HP)	-0.040	-0.063	-0.063	-1.699*	-1.973**	-1.954**
	(0.043)	(0.042)	(0.042)	(0.743)	(0.545)	(0.557)
ln(Torque)	-0.283**	-0.313**	-0.313**	-0.377	-0.433	-0.441
	(0.048)	(0.056)	(0.054)	(1.116)	(0.858)	(0.853)
$\ln(\text{Weight})^2$				-0.188+	-0.236**	-0.232**
				(0.101)	(0.067)	(0.072)
$\ln(\text{HP})^2$				0.017	0.064	0.061
				(0.169)	(0.156)	(0.155)
$\ln(\text{Torque})^2$				-0.408**	-0.386*	-0.382*
				(0.120)	(0.138)	(0.137)
ln(Weight)*ln(HP)				0.035	0.002	0.004
				(0.115)	(0.093)	(0.093)
ln(Weight)*ln(Torque)				0.436**	0.404**	0.400**
				(0.149)	(0.113)	(0.112)
ln(HP)*ln(Torque)				0.215	0.224	0.224
				(0.305)	(0.286)	(0.284)
Manual	0.045**	0.044**	0.044**	0.044**	0.042**	0.042**
	(0.011)	(0.008)	(0.008)	(0.012)	(0.008)	(0.008)
Diesel	0.269**	0.245**	0.246**	0.279**	0.252**	0.255**
	(0.022)	(0.019)	(0.024)	(0.020)	(0.016)	(0.019)
Turbocharged	0.003	0.004		0.015	0.026	
	(0.051)	(0.058)		(0.041)	(0.048)	
Supercharged	-0.054	-0.020		-0.062	-0.028	
	(0.053)	(0.055)		(0.046)	(0.044)	
Year Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer Fixed Effects?	No	Yes	Yes	No	Yes	Yes
Observations	12572	12572	12572	12572	12572	12572
R-squared	0.760	0.791	0.746	0.772	0.802	0.760

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 4: Trade-Off Estimates for Light Duty Trucks

Year	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	OB - Cobb-Douglas	OB - Translog	Matching Model
1981	6.9%	6.7%	6.7%	6.6%	6.3%	6.3%	6.6%	5.2%	4.3%
1982	10.1%	9.7%	9.7%	9.7%	9.3%	9.3%	9.3%	7.5%	5.8%
1983	12.8%	11.7%	11.7%	12.6%	11.3%	11.3%	12.0%	10.2%	10.1%
1984	12.7%	11.1%	11.1%	12.8%	11.0%	11.1%	12.5%	10.5%	12.1%
1985	13.4%	11.9%	11.9%	12.8%	11.4%	11.4%	13.0%	11.0%	13.3%
1986	15.5%	14.3%	14.3%	14.8%	13.8%	13.8%	15.2%	12.9%	15.6%
1987	15.7%	14.8%	14.8%	15.2%	14.5%	14.5%	15.7%	13.8%	17.8%
1988	18.5%	17.8%	17.8%	18.3%	17.7%	17.7%	19.2%	18.4%	23.7%
1989	18.6%	18.3%	18.3%	18.2%	18.1%	18.1%	19.4%	18.0%	20.9%
1990	19.8%	19.6%	19.6%	19.6%	19.5%	19.6%	20.9%	19.6%	24.3%
1991	19.7%	19.8%	19.8%	19.5%	19.7%	19.7%	21.0%	20.1%	24.4%
1992	23.0%	22.9%	22.9%	22.5%	22.5%	22.5%	24.8%	23.7%	30.2%
1993	22.8%	22.9%	22.9%	22.3%	22.5%	22.5%	24.5%	23.4%	30.1%
1994	25.4%	25.3%	25.3%	25.0%	24.9%	25.0%	27.6%	26.7%	34.1%
1995	25.3%	25.6%	25.6%	24.9%	25.2%	25.2%	27.9%	27.3%	33.3%
1996	25.7%	25.9%	25.9%	27.4%	27.3%	27.4%	28.5%	34.4%	39.7%
1997	29.5%	30.3%	30.3%	30.9%	31.5%	31.5%	33.0%	37.0%	48.8%
1998	28.8%	29.1%	29.1%	28.7%	28.9%	28.9%	31.7%	33.1%	42.1%
1999	30.8%	31.9%	31.9%	31.1%	31.9%	31.9%	34.2%	36.0%	49.7%
2000	33.2%	34.5%	34.5%	32.1%	33.2%	33.2%	36.7%	37.9%	47.1%
2001	30.1%	31.3%	31.3%	29.2%	30.0%	30.0%	33.8%	35.8%	48.4%
2002	31.0%	32.2%	32.2%	29.8%	30.6%	30.6%	34.9%	37.4%	51.2%
2003	33.2%	33.8%	33.8%	31.9%	32.0%	32.0%	37.2%	40.6%	58.4%
2004	37.4%	38.4%	38.4%	35.5%	35.8%	35.9%	41.9%	46.6%	68.7%
2005	42.5%	43.5%	43.5%	40.3%	40.4%	40.5%	47.3%	52.9%	80.3%
2006	45.1%	46.3%	46.3%	42.8%	43.2%	43.3%	50.1%	55.1%	68.2%

Table 5: Technological Progress Estimates for Light Duty Trucks

		Change in Weight and Engine Power					
Technological Advance	**Car/Truck Mix**	**Continued Growth**	**0% Reduction**	**25% Move to 1980 Levels**	**50% Move to 1980 Levels**	**75% Move to 1980 Levels**	**1980 Levels**
No Advance	No Shift in Mix	18.1	25.8	27.6	29.4	31.3	33.1
No Advance	Cars 50%	18.7	26.3	28.2	30.0	31.9	33.7
No Advance	Cars 60%	19.6	27.1	29.0	30.9	32.8	34.7
No Advance	Cars 70%	20.5	27.8	29.8	31.7	33.7	35.7
No Advance	Cars 80%	21.4	28.6	30.6	32.6	34.6	36.6
Average Advance	No Shift in Mix	21.6	33.0	35.3	37.6	40.0	42.3
Average Advance	Cars 50%	22.3	33.6	36.0	38.4	40.7	43.1
Average Advance	Cars 60%	23.4	34.6	37.0	39.5	41.9	44.3
Average Advance	Cars 70%	24.4	35.5	38.0	40.5	43.1	45.6
Average Advance	Cars 80%	25.4	36.5	39.1	41.6	44.2	46.8
75 Percentile Advance	No Shift in Mix	25.8	35.6	38.1	40.6	43.1	45.6
75 Percentile Advance	Cars 50%	26.6	36.2	38.8	41.3	43.9	46.4
75 Percentile Advance	Cars 60%	27.8	37.2	39.8	42.4	45.0	47.7
75 Percentile Advance	Cars 70%	29.1	38.1	40.8	43.5	46.2	48.9
75 Percentile Advance	Cars 80%	30.3	39.1	41.9	44.6	47.4	50.1

Table 6: Fuel Economy Counterfactuals in 2020 (Bush Standards)

		Change in Weight and Engine Power					
Technological Advance	**Car/Truck Mix**	**Continued Growth**	**0% Reduction**	**25% Move to 1980 Levels**	**50% Move to 1980 Levels**	**75% Move to 1980 Levels**	**1980 Levels**
No Advance	No Shift in Mix	20.6	25.8	27.6	29.4	31.3	33.1
No Advance	Cars 50%	21.1	26.3	28.2	30.0	31.9	33.7
No Advance	Cars 60%	22.0	27.1	29.0	30.9	32.8	34.7
No Advance	Cars 70%	22.8	27.8	29.8	31.7	33.7	35.7
No Advance	Cars 80%	23.6	28.6	30.6	32.6	34.6	36.6
Average Advance	No Shift in Mix	24.5	30.8	32.9	35.1	37.3	39.4
Average Advance	Cars 50%	25.2	31.3	33.6	35.8	38.0	40.2
Average Advance	Cars 60%	26.2	32.2	34.5	36.8	39.1	41.3
Average Advance	Cars 70%	27.2	33.1	35.5	37.8	40.1	42.5
Average Advance	Cars 80%	28.2	34.0	36.4	38.8	41.2	43.6
75 Percentile Advance	No Shift in Mix	25.9	32.4	34.7	37.0	39.3	41.6
75 Percentile Advance	Cars 50%	26.5	33.0	35.4	37.7	40.0	42.4
75 Percentile Advance	Cars 60%	27.6	34.0	36.3	38.7	41.1	43.5
75 Percentile Advance	Cars 70%	28.6	34.9	37.3	39.8	42.2	44.7
75 Percentile Advance	Cars 80%	29.6	35.8	38.3	40.8	43.3	45.8

Table 7: Fuel Economy Counterfactuals in 2016 (Obama Standards)

	Cobb-Douglas Model				Translog Model			
	Base	**Relative Prices**	**Real Prices**	**Luxury**	**Base**	**Relative Prices**	**Real Prices**	**Luxury**
ln(Weight)	-0.428**	-0.426**	-0.426**	-0.409**	-0.459	-2.740*	-2.740*	-3.743**
	(0.028)	(0.030)	(0.030)	(0.012)	(1.252)	(1.338)	(1.338)	(0.662)
ln(HP)	-0.256**	-0.228**	-0.228**	-0.255**	-3.352**	-3.074**	-3.074**	-2.094**
	(0.044)	(0.041)	(0.041)	(0.008)	(0.802)	(0.652)	(0.652)	(0.289)
ln(Torque)	-0.052	-0.052	-0.052	-0.062**	0.736	1.308+	1.308+	1.614**
	(0.038)	(0.038)	(0.038)	(0.009)	(0.778)	(0.747)	(0.747)	(0.403)
$\ln(\text{Weight})^2$					-0.199**	-0.190**	-0.190**	-0.096**
					(0.059)	(0.057)	(0.057)	(0.024)
$\ln(\text{HP})^2$					-0.117	0.085	0.085	0.277**
					(0.123)	(0.135)	(0.135)	(0.059)
$\ln(\text{Torque})^2$					-0.042	-0.061	-0.061	0.156**
					(0.068)	(0.072)	(0.072)	(0.037)
ln(Weight)*ln(HP)					0.535**	0.450**	0.450**	0.308**
					(0.150)	(0.115)	(0.115)	(0.051)
ln(Weight)*ln(Torque)					-0.132	-0.221	-0.221	-0.464**
					(0.154)	(0.154)	(0.154)	(0.074)
ln(HP)*ln(Torque)					0.146*	0.213**	0.213**	0.062
					(0.060)	(0.069)	(0.069)	(0.051)
Manual	0.044**	0.043**	0.043**	0.043**	0.046**	0.045**	0.045**	0.043**
	(0.005)	(0.005)	(0.005)	(0.002)	(0.005)	(0.005)	(0.005)	(0.002)
Diesel	0.227**	0.235**	0.235**	0.195**	0.275**	0.275**	0.275**	0.212**
	(0.025)	(0.029)	(0.029)	(0.006)	(0.033)	(0.033)	(0.033)	(0.007)
Relative Price		-0.027*				-0.053**		
		(0.012)				(0.009)		
Real Price			-0.027*				-0.053**	
			(0.012)				(0.009)	
Luxury				-0.013**				-0.028**
				(0.004)				(0.004)
Year Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15061	14879	14879	7057	15061	14879	14879	7057
R-squared	0.869	0.869	0.869	0.872	0.879	0.879	0.879	0.882

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 8: Trade-Off Estimates for Passenger Cars Controlling for Proxies of Technology Expenditures

	Cobb-Douglas Model				Translog Model			
	Base	**Relative Prices**	**Real Prices**	**Luxury**	**Base**	**Relative Prices**	**Real Prices**	**Luxury**
1981	0.054**	0.055**	0.056**	0.043**	0.051**	0.053**	0.054**	0.041**
	(0.010)	(0.009)	(0.009)	(0.007)	(0.009)	(0.009)	(0.009)	(0.006)
1982	0.093**	0.095**	0.096**	0.074**	0.087**	0.091**	0.094**	0.071**
	(0.013)	(0.012)	(0.013)	(0.006)	(0.012)	(0.011)	(0.011)	(0.006)
1983	0.129**	0.132**	0.133**	0.114**	0.121**	0.126**	0.129**	0.106**
	(0.014)	(0.014)	(0.015)	(0.006)	(0.012)	(0.012)	(0.012)	(0.006)
1984	0.155**	0.156**	0.158**	0.145**	0.145**	0.149**	0.154**	0.140**
	(0.012)	(0.012)	(0.012)	(0.006)	(0.009)	(0.009)	(0.009)	(0.006)
1985	0.179**	0.178**	0.182**	0.166**	0.167**	0.169**	0.175**	0.161**
	(0.011)	(0.010)	(0.011)	(0.006)	(0.009)	(0.009)	(0.009)	(0.006)
1986	0.207**	0.206**	0.210**	0.198**	0.193**	0.195**	0.202**	0.190**
	(0.010)	(0.009)	(0.009)	(0.006)	(0.009)	(0.009)	(0.009)	(0.006)
1987	0.215**	0.212**	0.218**	0.215**	0.202**	0.200**	0.211**	0.208**
	(0.011)	(0.011)	(0.011)	(0.006)	(0.012)	(0.013)	(0.012)	(0.006)
1988	0.235**	0.230**	0.237**	0.236**	0.222**	0.217**	0.230**	0.231**
	(0.013)	(0.014)	(0.012)	(0.007)	(0.015)	(0.016)	(0.014)	(0.006)
1989	0.243**	0.236**	0.244**	0.241**	0.228**	0.222**	0.235**	0.233**
	(0.011)	(0.012)	(0.011)	(0.007)	(0.012)	(0.013)	(0.012)	(0.007)
1990	0.255**	0.248**	0.255**	0.253**	0.242**	0.233**	0.247**	0.244**
	(0.012)	(0.012)	(0.011)	(0.007)	(0.012)	(0.013)	(0.012)	(0.007)
1991	0.265**	0.256**	0.264**	0.258**	0.251**	0.240**	0.255**	0.249**
	(0.012)	(0.011)	(0.011)	(0.007)	(0.011)	(0.011)	(0.011)	(0.007)
1992	0.276**	0.266**	0.274**	0.273**	0.261**	0.247**	0.264**	0.264**
	(0.015)	(0.014)	(0.014)	(0.007)	(0.014)	(0.014)	(0.014)	(0.007)
1993	0.303**	0.292**	0.301**	0.296**	0.287**	0.271**	0.288**	0.283**
	(0.016)	(0.015)	(0.015)	(0.007)	(0.015)	(0.015)	(0.014)	(0.007)
1994	0.319**	0.308**	0.318**	0.316**	0.303**	0.285**	0.304**	0.305**
	(0.017)	(0.018)	(0.016)	(0.007)	(0.016)	(0.017)	(0.016)	(0.007)
1995	0.349**	0.335**	0.346**	0.337**	0.330**	0.309**	0.330**	0.324**
	(0.017)	(0.016)	(0.015)	(0.007)	(0.015)	(0.016)	(0.015)	(0.007)
1996	0.355**	0.342**	0.351**	0.346**	0.337**	0.319**	0.336**	0.335**
	(0.015)	(0.015)	(0.014)	(0.007)	(0.014)	(0.015)	(0.014)	(0.007)
1997	0.367**	0.352**	0.362**	0.349**	0.350**	0.329**	0.346**	0.339**
	(0.017)	(0.016)	(0.015)	(0.007)	(0.015)	(0.015)	(0.014)	(0.007)
1998	0.384**	0.369**	0.378**	0.367**	0.368**	0.344**	0.362**	0.356**
	(0.018)	(0.017)	(0.016)	(0.008)	(0.016)	(0.016)	(0.015)	(0.008)
1999	0.382**	0.362**	0.377**	0.360**	0.367**	0.336**	0.364**	0.350**
	(0.018)	(0.017)	(0.016)	(0.008)	(0.017)	(0.017)	(0.015)	(0.008)
2000	0.393**	0.372**	0.386**	0.378**	0.379**	0.346**	0.373**	0.370**
	(0.019)	(0.018)	(0.017)	(0.008)	(0.018)	(0.019)	(0.017)	(0.008)
2001	0.404**	0.386**	0.398**	0.389**	0.390**	0.360**	0.384**	0.382**
	(0.020)	(0.021)	(0.019)	(0.008)	(0.019)	(0.021)	(0.019)	(0.008)
2002	0.419**	0.396**	0.411**	0.406**	0.405**	0.368**	0.396**	0.398**
	(0.022)	(0.022)	(0.020)	(0.008)	(0.021)	(0.022)	(0.020)	(0.008)
2003	0.433**	0.412**	0.424**	0.424**	0.420**	0.384**	0.407**	0.414**
	(0.024)	(0.024)	(0.023)	(0.008)	(0.023)	(0.025)	(0.023)	(0.008)
2004	0.440**	0.419**	0.432**	0.442**	0.426**	0.388**	0.413**	0.429**
	(0.022)	(0.023)	(0.022)	(0.008)	(0.021)	(0.023)	(0.021)	(0.008)
2005	0.452**	0.431**	0.445**	0.449**	0.440**	0.400**	0.427**	0.436**
	(0.022)	(0.022)	(0.021)	(0.008)	(0.021)	(0.022)	(0.021)	(0.008)
2006	0.474**	0.448**	0.464**	0.459**	0.458**	0.410**	0.440**	0.439**
	(0.024)	(0.023)	(0.022)	(0.008)	(0.023)	(0.023)	(0.022)	(0.008)
Year FEs?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer FEs?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15061	14879	14879	7057	15061	14879	14879	7057
R-squared	0.869	0.869	0.869	0.872	0.879	0.879	0.879	0.882

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 9: Technological Progress Estimates for Passenger Cars Controlling for Proxies of Technology Expenditures

	Cobb-Douglas Model				Translog Model			
	Base	**Relative Prices**	**Real Prices**	**Luxury**	**Base**	**Relative Prices**	**Real Prices**	**Luxury**
ln(Weight)	-0.356**	-0.345**	-0.345**	-0.339**	1.302	1.170	1.170	3.213**
	(0.043)	(0.051)	(0.051)	(0.009)	(1.329)	(1.240)	(1.240)	(0.462)
ln(HP)	-0.063	-0.063	-0.063	-0.130**	-1.890**	-2.061**	-2.061**	-2.085**
	(0.042)	(0.044)	(0.044)	(0.012)	(0.570)	(0.604)	(0.604)	(0.311)
ln(Torque)	-0.313**	-0.315**	-0.315**	-0.234**	-0.473	-0.257	-0.257	-0.369
	(0.054)	(0.053)	(0.053)	(0.010)	(0.863)	(0.853)	(0.853)	(0.326)
$\ln(\text{Weight})^2$					0.064	0.069	0.069	0.166**
					(0.156)	(0.162)	(0.162)	(0.030)
$\ln(\text{HP})^2$					-0.238**	-0.224**	-0.224**	-0.323**
					(0.070)	(0.065)	(0.065)	(0.032)
$\ln(\text{Torque})^2$					-0.381*	-0.392**	-0.392**	-0.312**
					(0.137)	(0.136)	(0.136)	(0.025)
ln(Weight)*ln(HP)					-0.006	0.000	0.000	-0.058
					(0.094)	(0.092)	(0.092)	(0.049)
ln(Weight)*ln(Torque)					0.406**	0.384**	0.384**	0.361**
					(0.114)	(0.121)	(0.121)	(0.049)
ln(HP)*ln(Torque)					0.220	0.234	0.234	0.134**
					(0.285)	(0.295)	(0.295)	(0.045)
Manual	0.044**	0.043**	0.043**	0.037**	0.043**	0.041**	0.041**	0.034**
	(0.008)	(0.009)	(0.009)	(0.003)	(0.008)	(0.009)	(0.009)	(0.003)
Diesel	0.246**	0.247**	0.247**	0.214**	0.255**	0.259**	0.259**	0.225**
	(0.024)	(0.022)	(0.022)	(0.005)	(0.019)	(0.018)	(0.018)	(0.006)
Relative Price		-0.018				-0.034		
		(0.023)				(0.021)		
Real Price			-0.018				-0.034	
			(0.023)				(0.021)	
Luxury				0.030**				0.009
				(0.009)				(0.009)
Year Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer Fixed Effects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12565	12386	12386	8213	12565	12386	12386	8213
R-squared	0.791	0.795	0.795	0.748	0.802	0.806	0.806	0.762

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 10: Trade-Off Estimates for Light Duty Trucks Controlling for Proxies of Technology Expenditures

	Cobb-Douglas Model				Translog Model			
	Base	**Relative Prices**	**Real Prices**	**Luxury**	**Base**	**Relative Prices**	**Real Prices**	**Luxury**
1981	0.067**	0.067**	0.068**	0.054**	0.063**	0.064**	0.065**	0.048**
	(0.011)	(0.010)	(0.010)	(0.007)	(0.011)	(0.010)	(0.010)	(0.007)
1982	0.097**	0.097**	0.098**	0.078**	0.093**	0.093**	0.095**	0.074**
	(0.017)	(0.017)	(0.018)	(0.007)	(0.015)	(0.015)	(0.015)	(0.007)
1983	0.117**	0.117**	0.118**	0.110**	0.113**	0.114**	0.116**	0.104**
	(0.016)	(0.017)	(0.018)	(0.006)	(0.016)	(0.016)	(0.017)	(0.006)
1984	0.111**	0.110**	0.112**	0.092**	0.110**	0.109**	0.113**	0.088**
	(0.018)	(0.018)	(0.018)	(0.007)	(0.017)	(0.017)	(0.017)	(0.007)
1985	0.118**	0.118**	0.120**	0.115**	0.113**	0.113**	0.117**	0.106**
	(0.009)	(0.008)	(0.008)	(0.008)	(0.011)	(0.010)	(0.009)	(0.008)
1986	0.143**	0.143**	0.145**	0.142**	0.137**	0.138**	0.143**	0.134**
	(0.010)	(0.009)	(0.009)	(0.007)	(0.012)	(0.011)	(0.010)	(0.007)
1987	0.148**	0.148**	0.152**	0.142**	0.144**	0.145**	0.152**	0.136**
	(0.012)	(0.011)	(0.011)	(0.007)	(0.012)	(0.011)	(0.009)	(0.007)
1988	0.178**	0.177**	0.182**	0.171**	0.177**	0.175**	0.184**	0.167**
	(0.011)	(0.011)	(0.011)	(0.008)	(0.011)	(0.010)	(0.008)	(0.007)
1989	0.183**	0.181**	0.186**	0.179**	0.181**	0.178**	0.187**	0.176**
	(0.010)	(0.010)	(0.010)	(0.008)	(0.008)	(0.009)	(0.007)	(0.008)
1990	0.195**	0.194**	0.199**	0.180**	0.195**	0.193**	0.202**	0.178**
	(0.016)	(0.017)	(0.013)	(0.008)	(0.018)	(0.018)	(0.014)	(0.008)
1991	0.198**	0.196**	0.201**	0.201**	0.197**	0.192**	0.202**	0.200**
	(0.008)	(0.010)	(0.008)	(0.008)	(0.010)	(0.011)	(0.009)	(0.008)
1992	0.229**	0.226**	0.232**	0.219**	0.225**	0.219**	0.230**	0.219**
	(0.014)	(0.016)	(0.011)	(0.008)	(0.013)	(0.015)	(0.010)	(0.008)
1993	0.230**	0.227**	0.233**	0.211**	0.226**	0.220**	0.231**	0.210**
	(0.023)	(0.025)	(0.019)	(0.008)	(0.022)	(0.024)	(0.019)	(0.008)
1994	0.253**	0.250**	0.257**	0.233**	0.251**	0.244**	0.257**	0.233**
	(0.023)	(0.025)	(0.019)	(0.008)	(0.020)	(0.022)	(0.016)	(0.008)
1995	0.256**	0.253**	0.260**	0.235**	0.252**	0.245**	0.259**	0.235**
	(0.026)	(0.030)	(0.022)	(0.008)	(0.024)	(0.027)	(0.020)	(0.008)
1996	0.258**	0.257**	0.263**	0.242**	0.274**	0.269**	0.281**	0.263**
	(0.025)	(0.028)	(0.022)	(0.008)	(0.016)	(0.018)	(0.014)	(0.008)
1997	0.303**	0.300**	0.306**	0.289**	0.315**	0.308**	0.319**	0.306**
	(0.018)	(0.022)	(0.016)	(0.011)	(0.013)	(0.014)	(0.012)	(0.010)
1998	0.291**	0.291**	0.297**	0.278**	0.289**	0.285**	0.296**	0.279**
	(0.022)	(0.025)	(0.018)	(0.010)	(0.020)	(0.021)	(0.015)	(0.009)
1999	0.319**	0.309**	0.319**	0.295**	0.319**	0.304**	0.323**	0.292**
	(0.026)	(0.031)	(0.021)	(0.009)	(0.028)	(0.031)	(0.021)	(0.009)
2000	0.346**	0.341**	0.351**	0.323**	0.332**	0.322**	0.339**	0.308**
	(0.024)	(0.029)	(0.019)	(0.009)	(0.024)	(0.029)	(0.019)	(0.009)
2001	0.313**	0.311**	0.319**	0.302**	0.300**	0.292**	0.307**	0.285**
	(0.022)	(0.028)	(0.019)	(0.009)	(0.022)	(0.027)	(0.019)	(0.009)
2002	0.322**	0.318**	0.327**	0.309**	0.306**	0.295**	0.314**	0.289**
	(0.022)	(0.028)	(0.018)	(0.009)	(0.023)	(0.028)	(0.018)	(0.009)
2003	0.338**	0.334**	0.342**	0.318**	0.320**	0.309**	0.324**	0.298**
	(0.032)	(0.038)	(0.029)	(0.009)	(0.032)	(0.036)	(0.028)	(0.009)
2004	0.384**	0.359**	0.367**	0.371**	0.359**	0.327**	0.343**	0.342**
	(0.030)	(0.035)	(0.025)	(0.009)	(0.031)	(0.036)	(0.027)	(0.009)
2005	0.436**	0.432**	0.442**	0.436**	0.406**	0.395**	0.412**	0.400**
	(0.023)	(0.028)	(0.019)	(0.009)	(0.022)	(0.026)	(0.017)	(0.009)
2006	0.464**	0.459**	0.470**	0.458**	0.434**	0.420**	0.439**	0.426**
	(0.027)	(0.035)	(0.024)	(0.009)	(0.024)	(0.030)	(0.020)	(0.009)
Year FEs?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer FEs?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12565	12386	12386	8213	12565	12386	12386	8213
R-squared	0.791	0.795	0.795	0.748	0.802	0.806	0.806	0.762

Notes: ** denotes significance at the one percent level, * at the five percent level, and + at the 10 percent level.
Standard errors are clustered at the manufacturer level.

Table 11: Technological Progress Estimates for Light Duty Trucks Controlling for Proxies of Technology Expenditures

2 Figures

Figure 2: Penetration of Engine-Related Technologies that would Shift the Production Possibilities Frontier

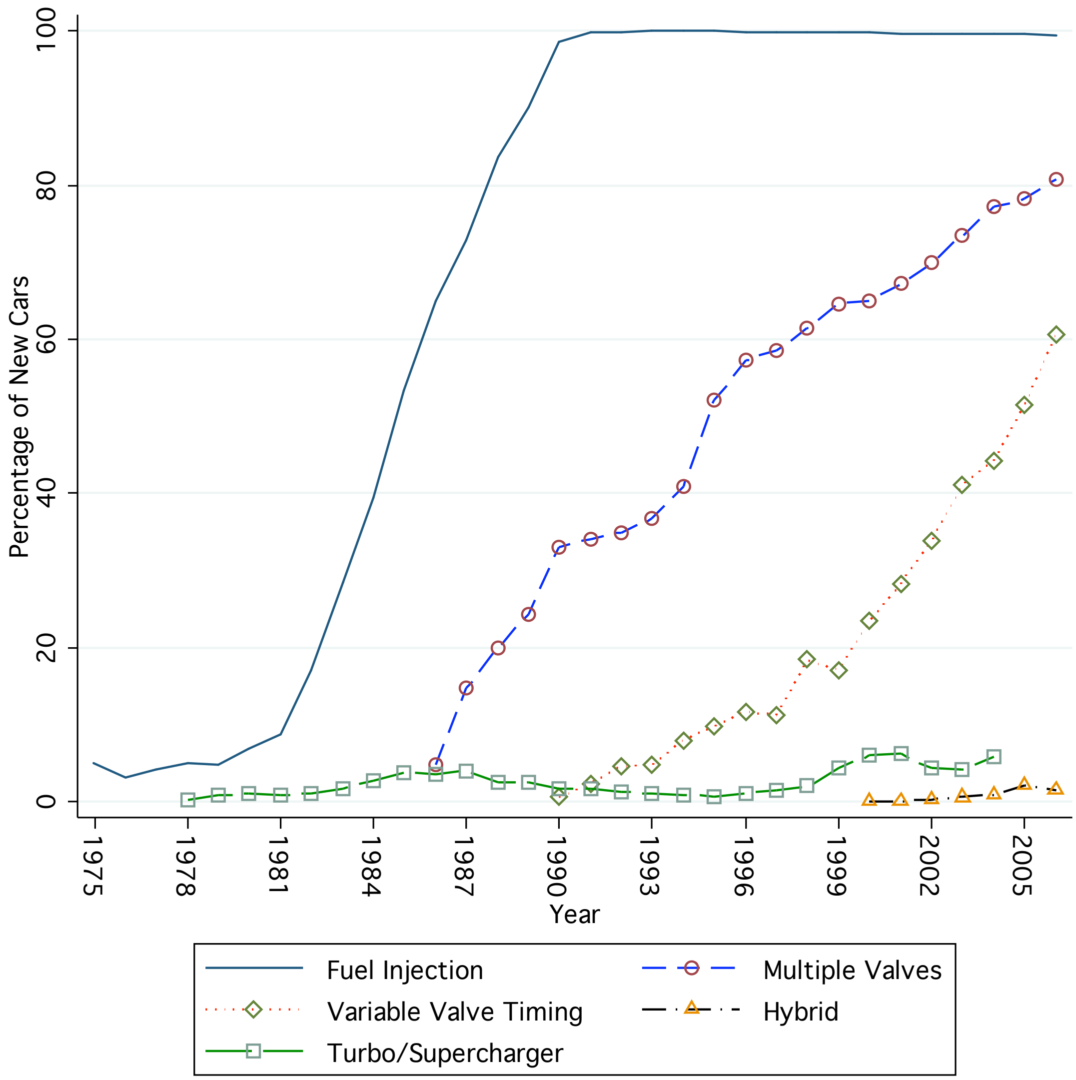

Figure 3: Penetration of non-Engine-Related Technologies that would Shift the Production Possibilities Frontier

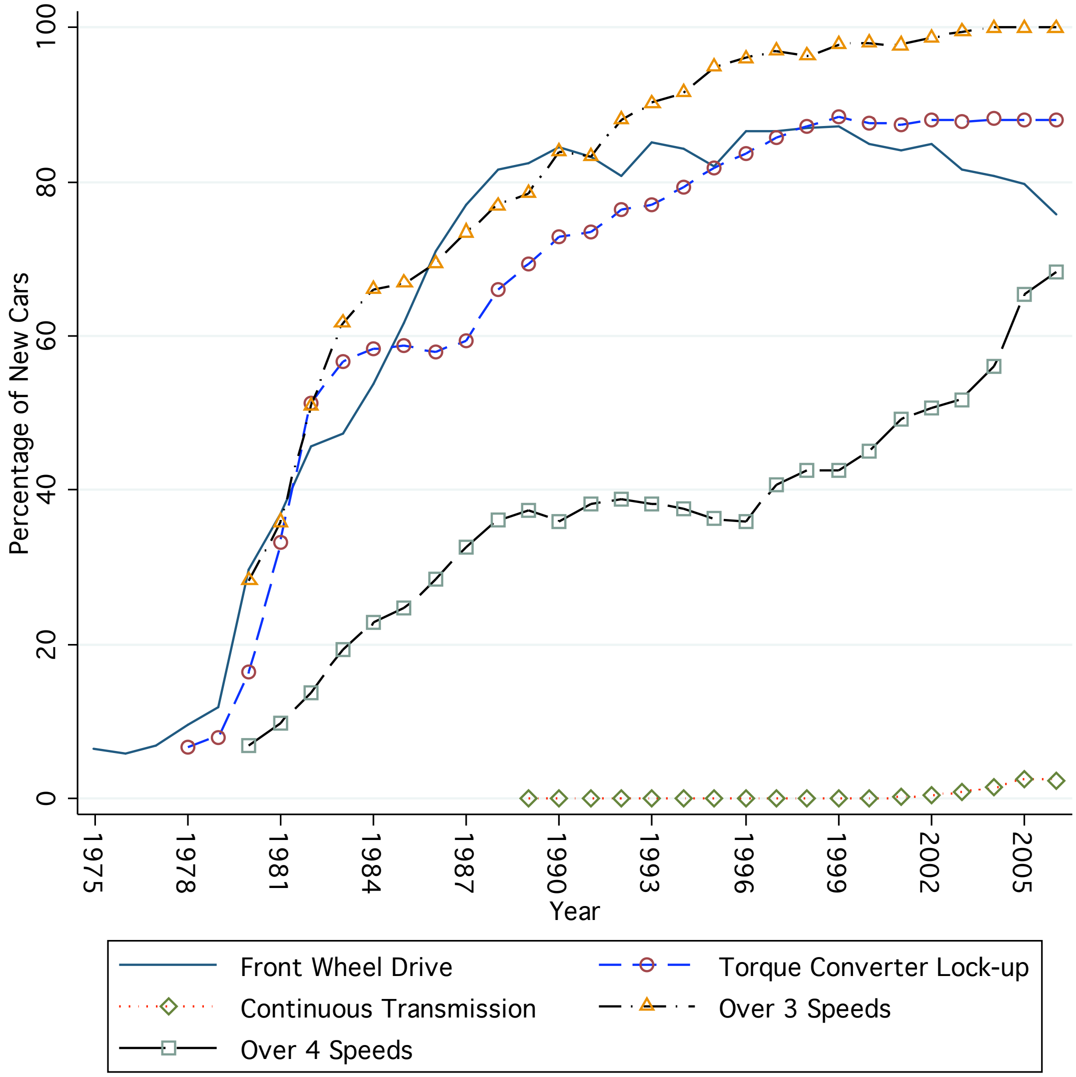

Figure 4: Distribution of Fuel Economy for Passenger Cars and Light Duty Trucks, 1980 and 2006

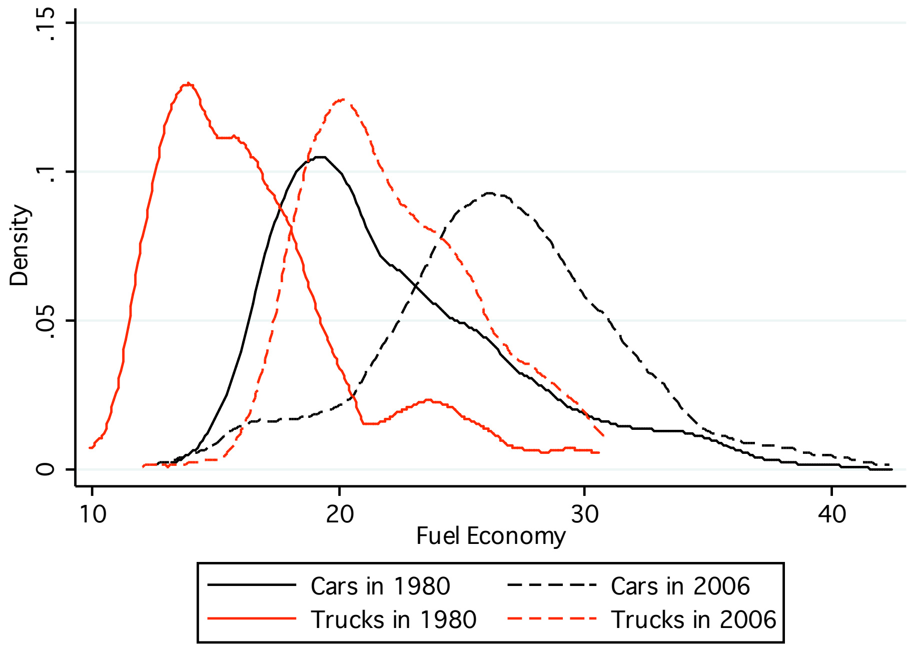

Figure 5: Distribution of Horsepower for Passenger Cars and Light Duty Trucks, 1980 and 2006

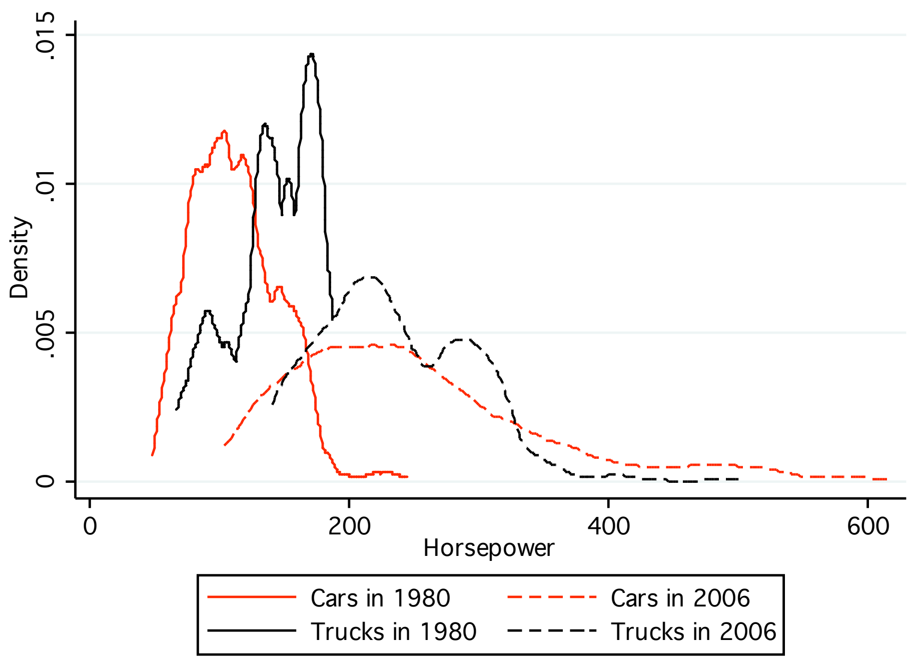

Figure 6: Distribution of Acceleration for Passenger Cars and Light Duty Trucks, 1980 and 2006

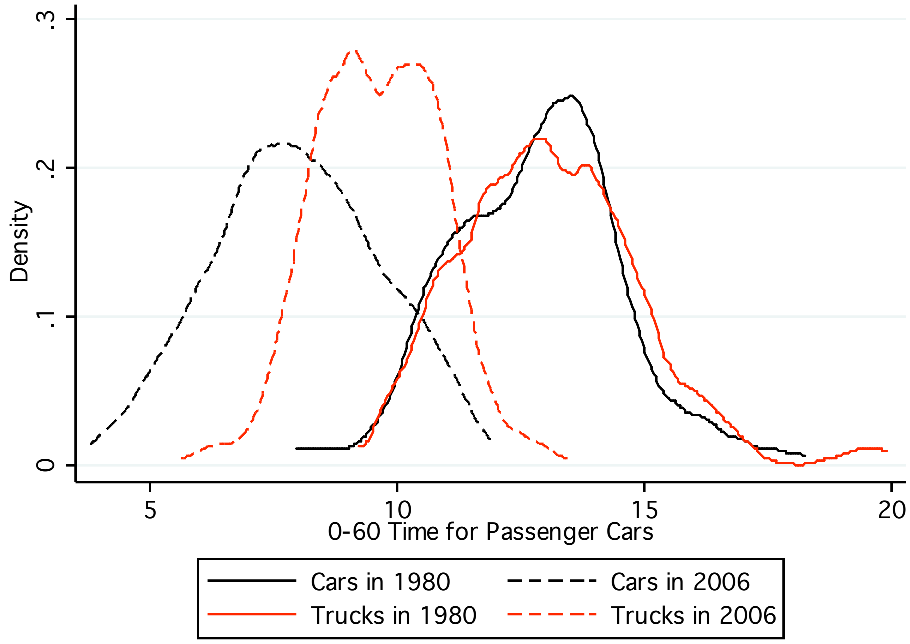

Figure 7: Fuel Economy versus Weight, 1980 and 2006, Passenger Cars

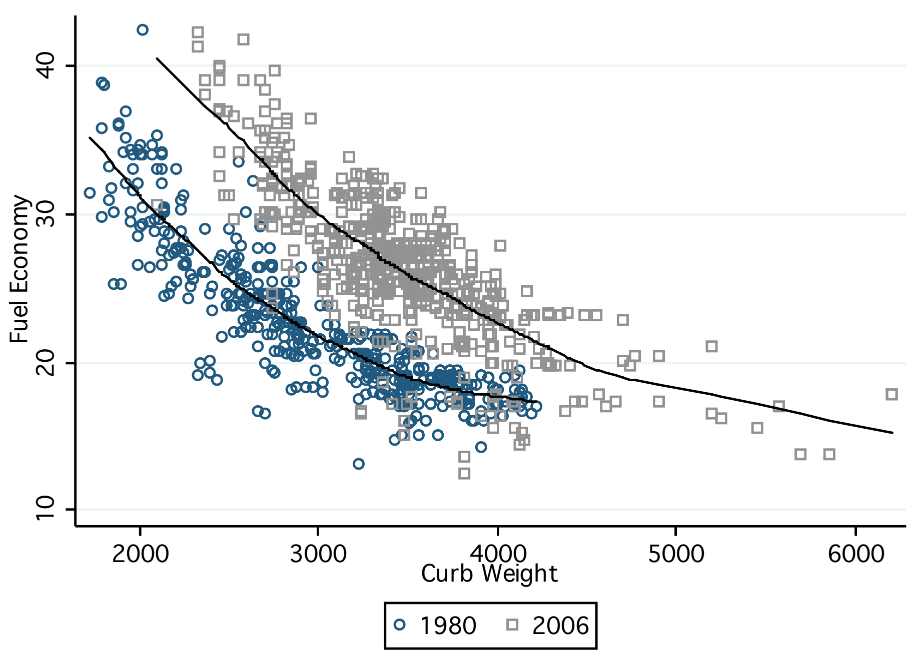

Figure 8: Fuel Economy versus Horsepower, 1980 and 2006, Passenger Cars

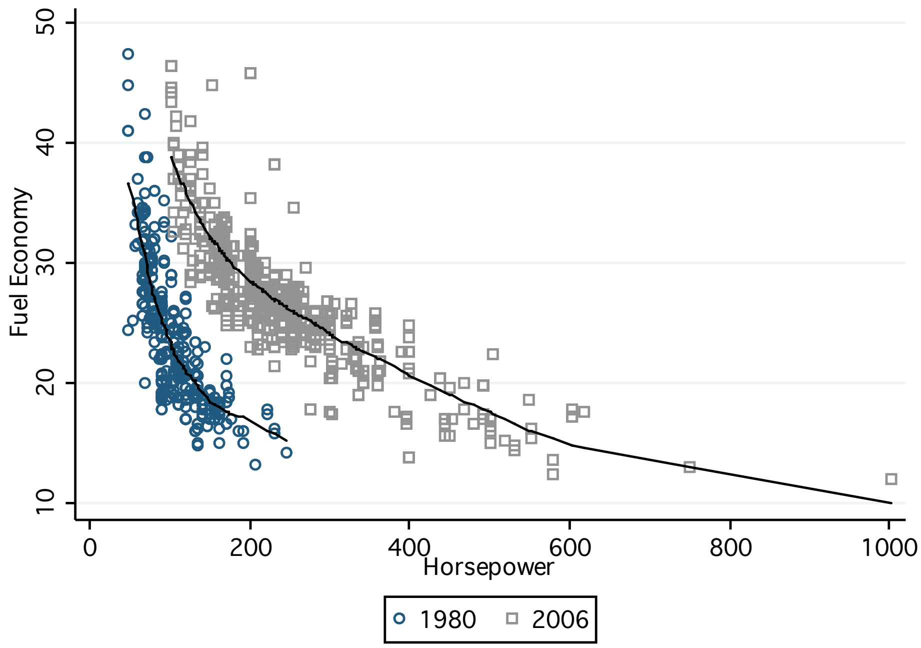

Figure 9: Fuel Economy versus Torque, 1980 and 2006, Passenger Cars

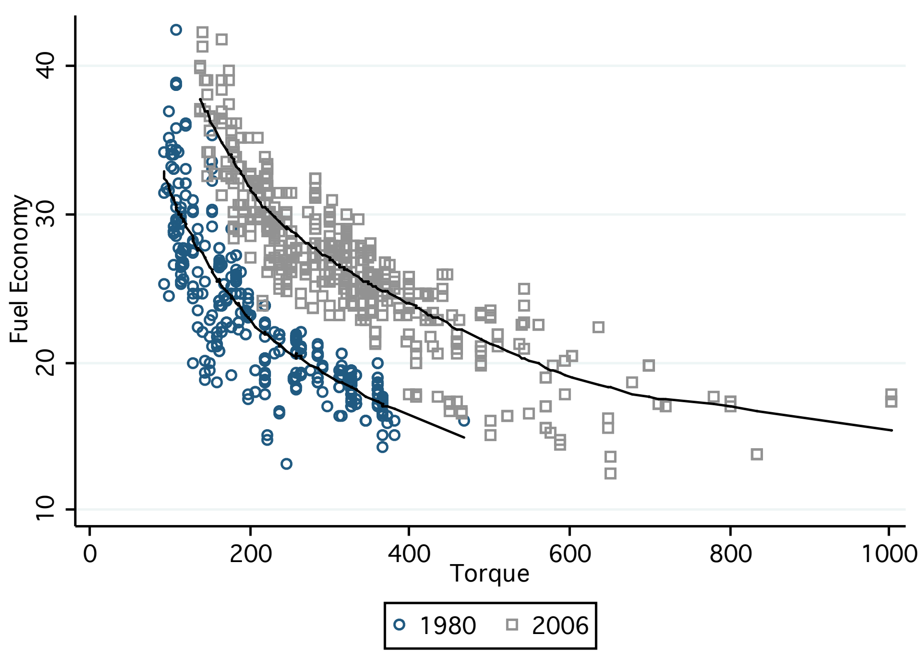

Figure 10: Fuel Economy versus Weight, 1980 and 2006, Light Duty Trucks

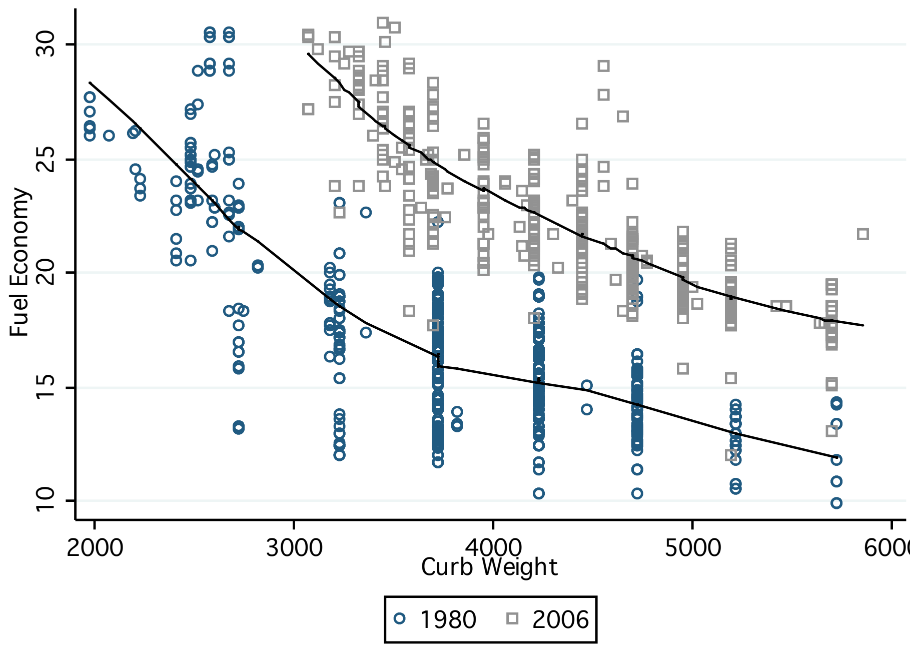

Figure 11: Fuel Economy versus Horsepower, 1980 and 2006, Light Duty Trucks

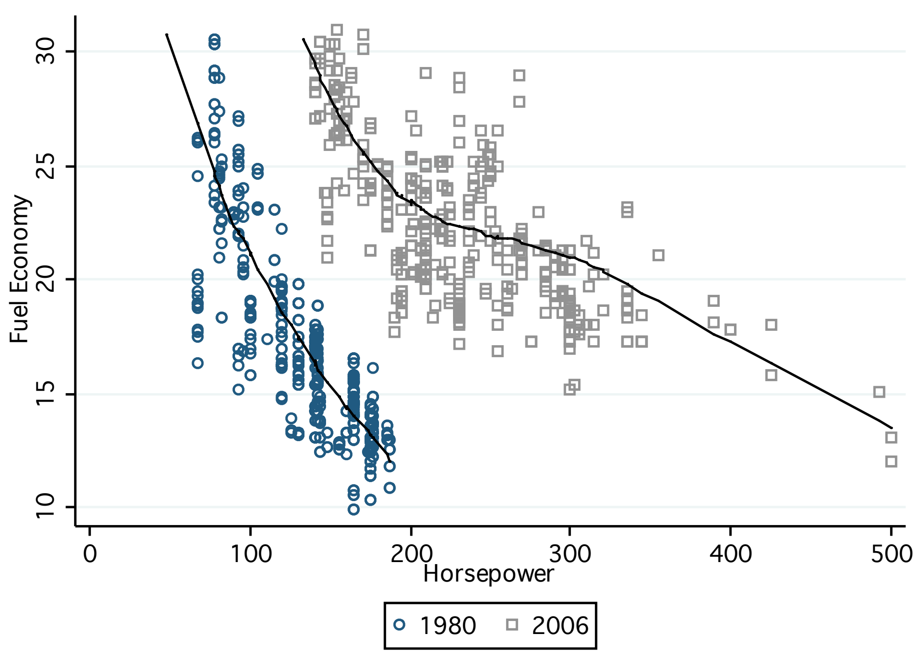

Figure 12: Fuel Economy versus Torque, 1980 and 2006, Light Duty Trucks

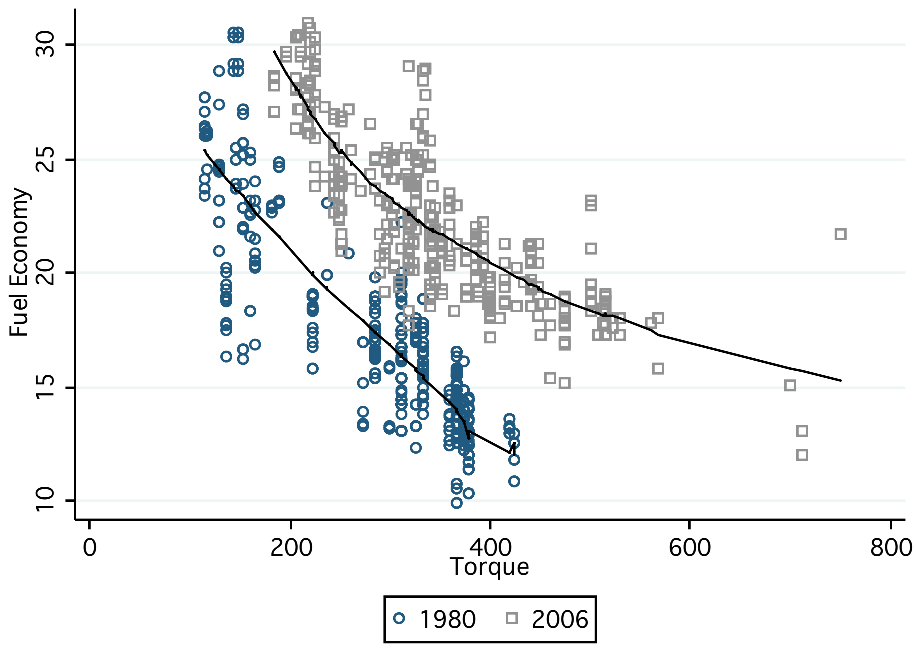

Figure 13: Passenger Car Technological Progress Measures from All Models

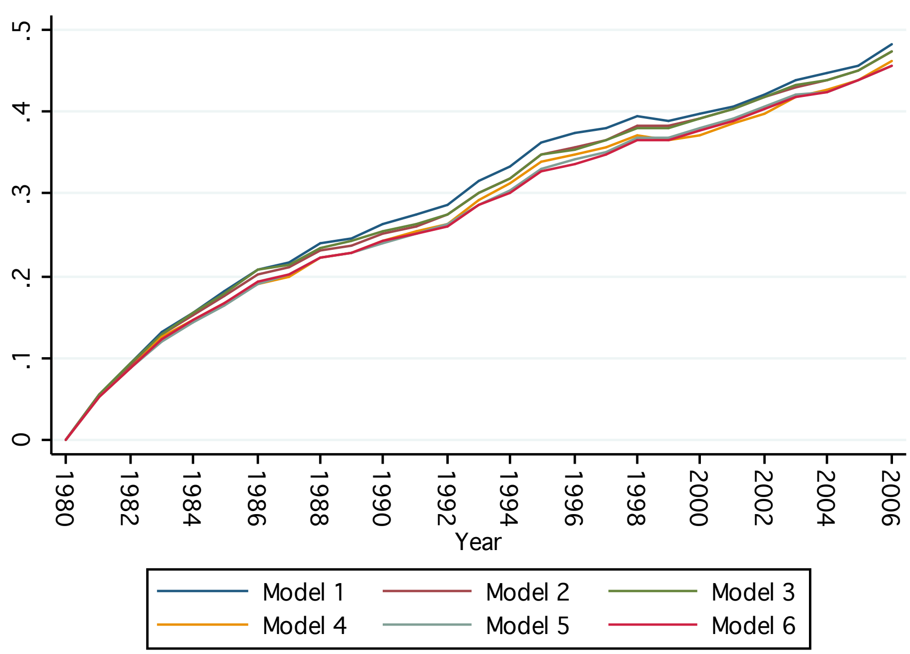

Figure 14: Passenger Car Technological Progress Measures from Model 3

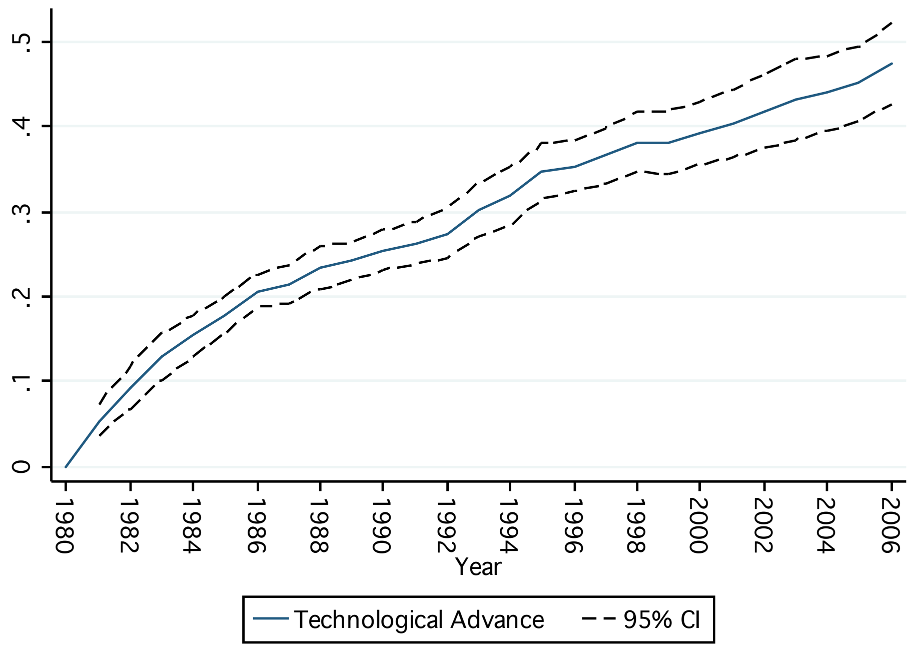

Figure 15: Passenger Car Annual Technological Progress and Annual CAFE Changes

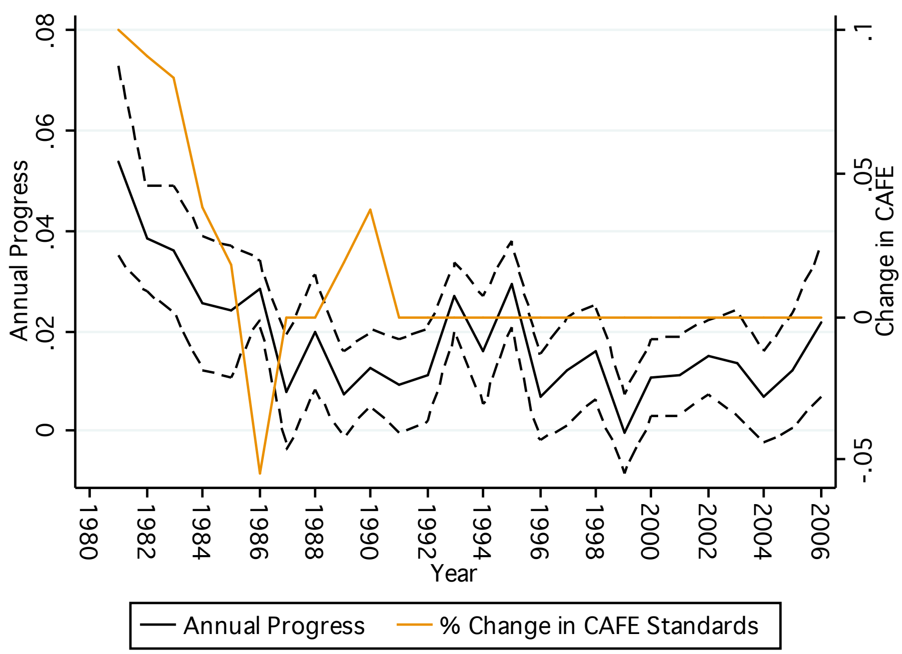

Figure 16: Light Truck Technological Progress Measures from All Models

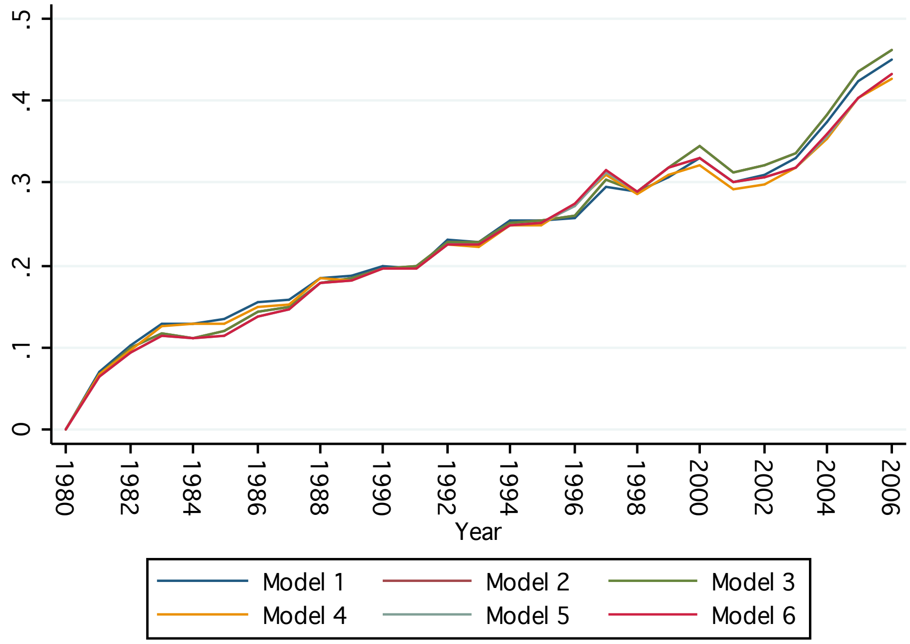

Figure 17: Light Truck Technological Progress Measures from Model 3

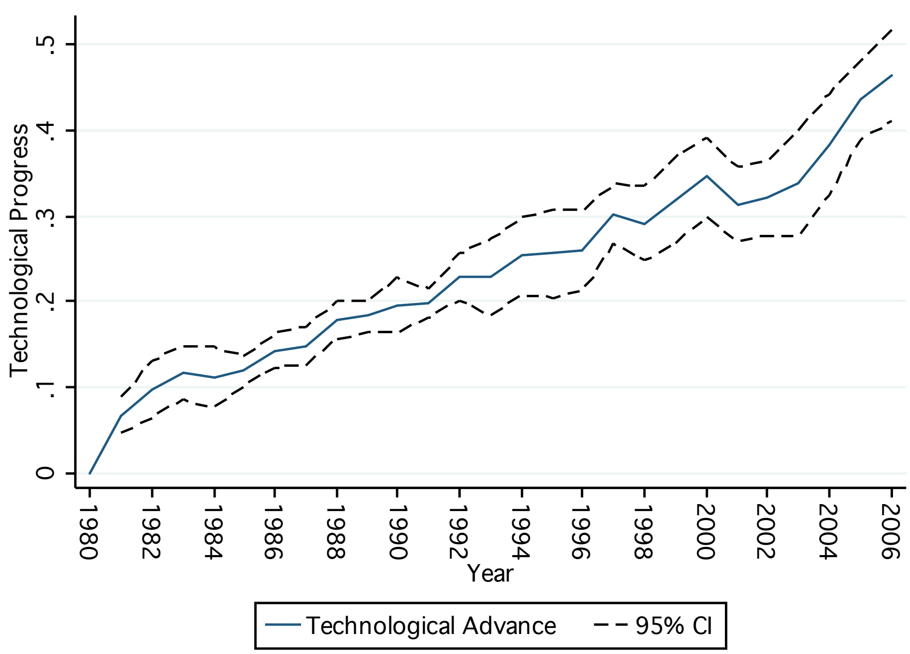

Figure 18: Passenger Car and Light Truck Technological Progress Measures from Model 3

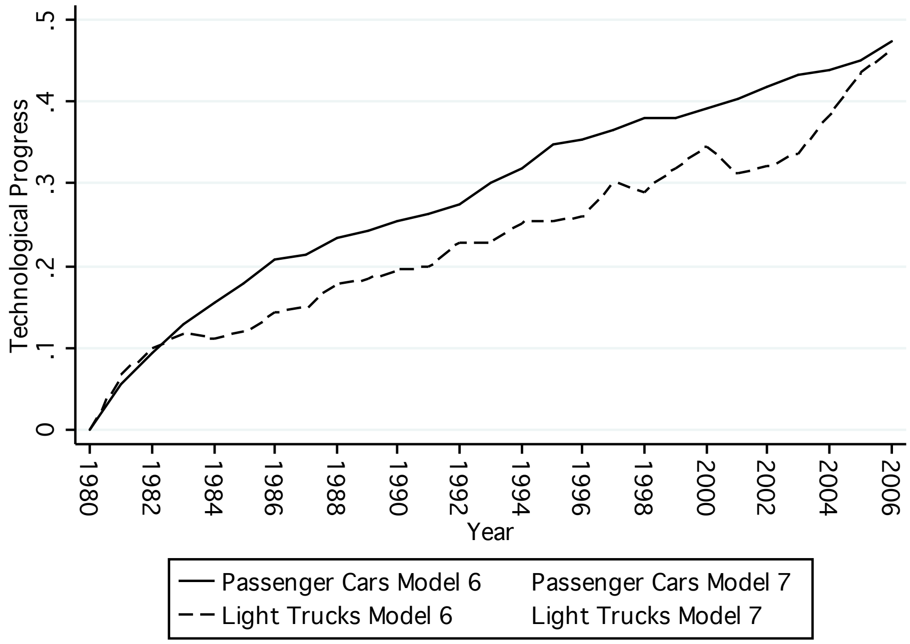

Figure 19: Light Truck Annual Technological Progress and Annual CAFE Changes

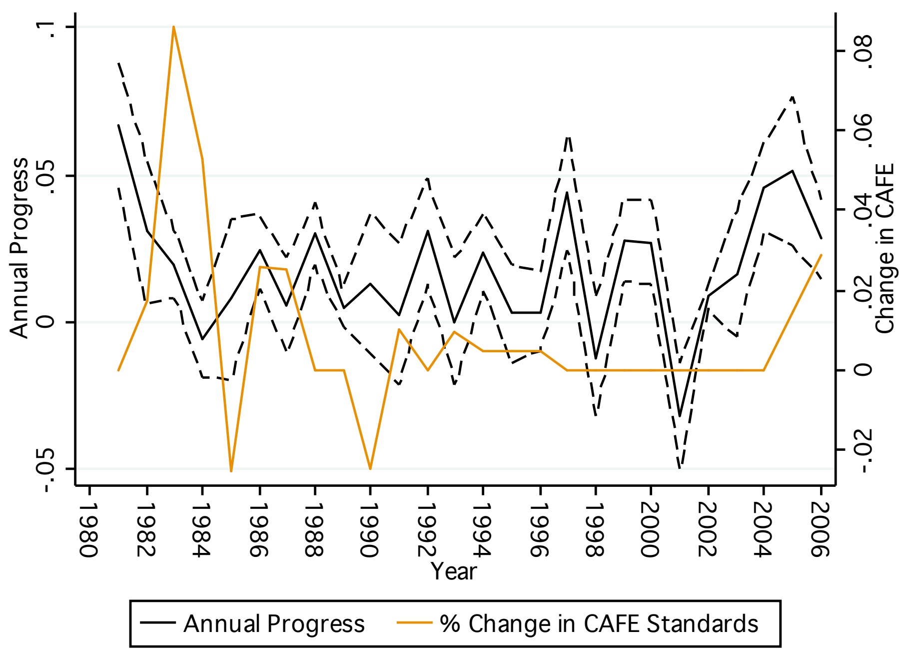

Figure 20: Firm-Level Productivity Measures for Passenger Cars

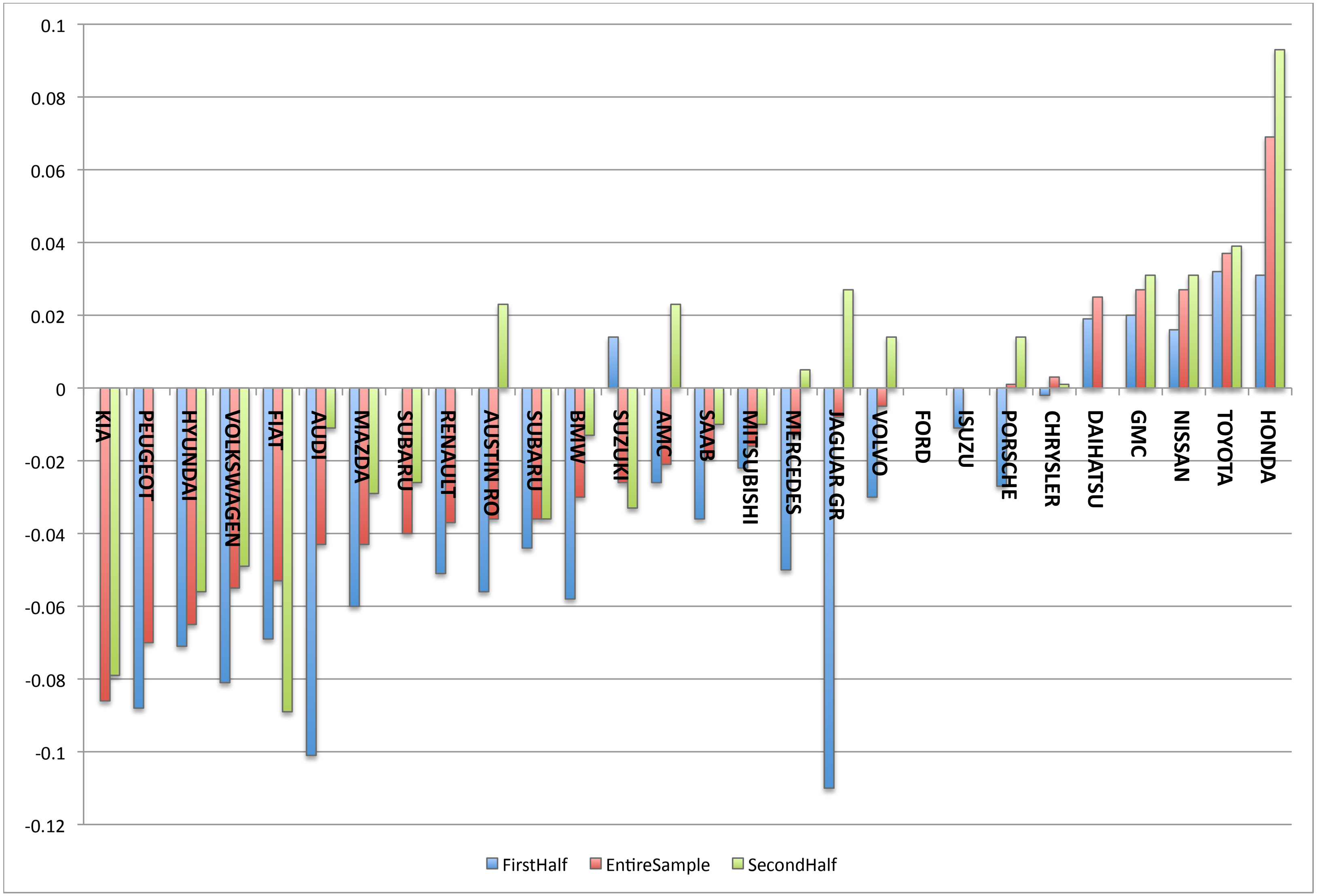

Figure 21: Firm-Level Productivity Measures by Passenger Cars and Light Duty Trucks

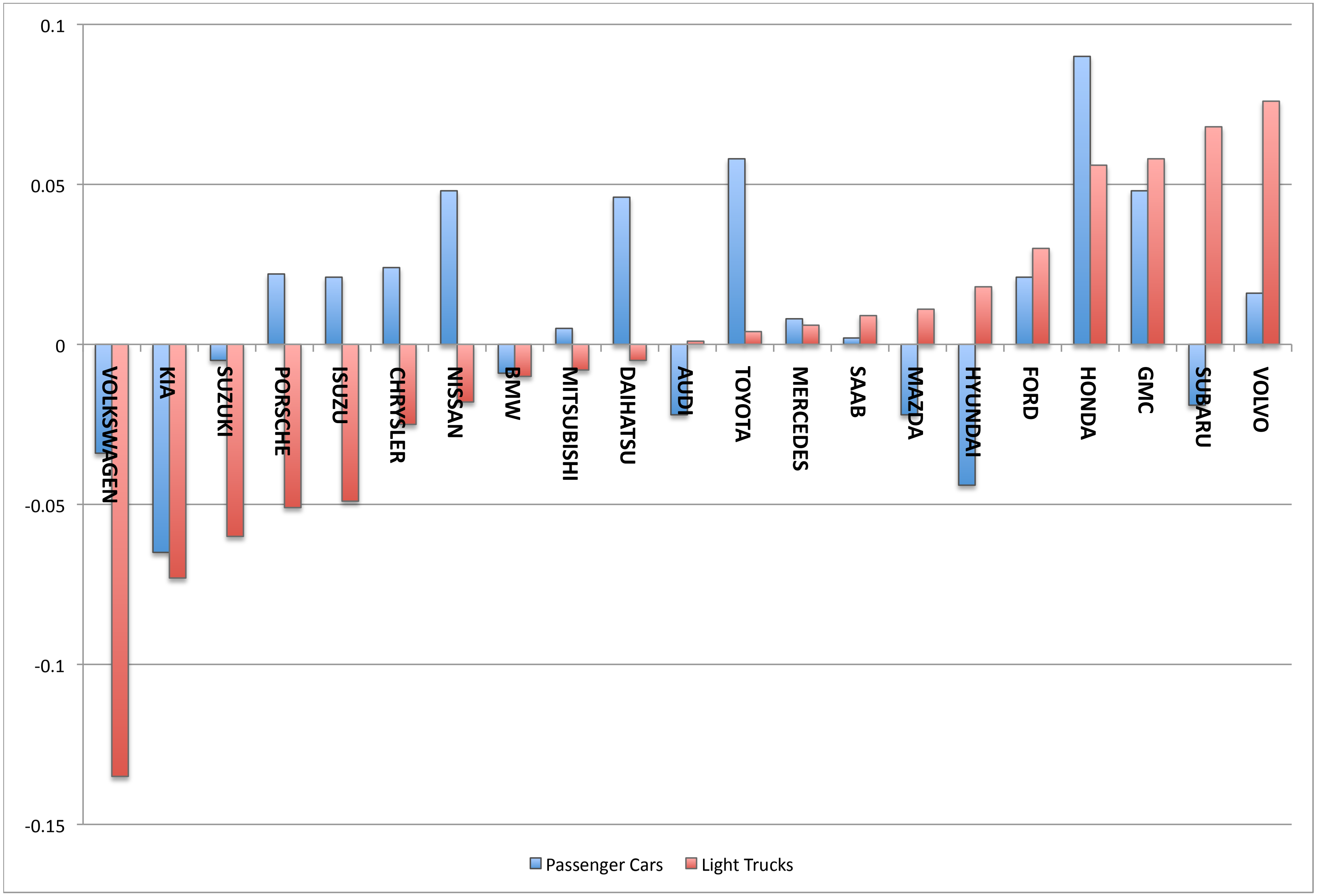

Figure 22: Firm-Level Productivity Measures for Light Duty Trucks Across Time