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**The Impact of CAFE Standards on Innovation
in the US Automobile Industry**

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The Impact of CAFE Standards on Innovation in the US Automobile Industry

Antonio M. Bento, Kevin D. Roth, Yiwei Wang¹

Abstract:

The Obama administration seeks to tighten the fuel economy standards in the US and the target is to almost double the miles per gallon (MPG) of vehicles by 2025 comparing to that of 2010. With this new aggressive movement, there is an ongoing discussion about whether auto makers could meet the new standards without providing consumers with vehicles that are much lighter and less powerful. In this paper, we investigate how historical changes in the fuel economy standards impacted technological innovation in the automobile industry and estimate the changes in the rate of innovation in response to the changes in the standards. By decomposing innovation growth into natural growth and growth induced by standard changes, we not only show that standard changes can increase innovation growth but are also able to quantify the induced growth rate with respect to the rate of changes in standards. Such method can provide a more precise prediction of the future technological innovation under new standards.

Key words: CAFE standards, technological growth, regulation and innovation, fuel economy, vehicle attributes

JEL Classification Codes: L2, L5, Q4, Q5

Global climate change has been a hot topic for years. Believed to be the major cause of the climate change, greenhouse gas (GHG) emissions gain increasing concern. Many countries adopted regulations and policies to reduce GHG emissions. As one of the major producer of GHG, emission cuts in the US could have large impact on global environment.

According to EPA estimates, US produces around 6,000 metric tons of energy related CO₂ emission every year. Light duty vehicles, including passenger cars and light duty trucks, are

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one of the major sources of GHG emissions and contributes around 20% of the total energy related GHG emission in the US. Not surprisingly, various policies had been introduced to reduce emissions and energy consumptions in this sector. One of the most important regulations relate to emission cuts is the corporate average fuel economy (CAFE) standard. CAFE was first enacted in 1975 as the response to the oil embargo in the early 1970s. CAFE standards target on the sales weighted average fuel economy, measured in miles per gallon (MPG), of automobiles in all automakers that run business in the US. The standards was first introduced to passenger cars in model year 1978 and to light duty trucks in model year 1979.

The standard for passenger cars was set at 18 MPG for model year 1978 and kept increasing in the next few year until it hit 27.5 in 1986. The standards was lowered to 26 in 1987 and raised back to 27.5 in 1990. The 27.5 MPG standard for cars remained stable since 1990 until 2010. Empirical studies in engineering show that automakers can sacrifice engine power and vehicle weight to get higher fuel economy. That is exact what firms did when CAFE first came into effect. Automakers reacted in the beginning by down-weighting their vehicles and using less powerful engines to improve fuel economy to meet the standards. Later when the standards were stable in the 90s, they kept MPG around the standards and produced heavier and more powerful vehicles with new innovations.

In 2011, President Obama announced new aggressive CAFE standards, which seek to almost double the overall fuel economy of passenger vehicles by 2025 compared to 2011. The goal is an average MPG of 54.5 in 2025 model year vehicles, passenger cars and light duty trucks combined, much higher than the 27.4 MPG in 2011. With the new aggressive change in the CAFE standards, there is an ongoing discussion about whether auto makers would provide consumers with much lighter and less powerful products, which might raise safety concerns.

In this paper, we analyze vehicle attributes data to answer two related questions. First, how was innovation affected by the changes in the CAFE standards in the automobile industry in the US? At what rate? Second, what would happen to innovation under the new standards? We use a broad definition of innovation. Following Joseph Schumpeter (1942), we consider all successful commercial application of invention, new ideas and designs, and adoptions of ideas or technologies from diffusion, as innovation. We focus on investigating the relationship between the growth rate of technological innovation related to fuel economy and the changes in the CAFE standards.

Our work mainly differs from previous literatures in two ways. First, instead of merely showing evidence of innovation growth in the automobile sector, we focus on the relationship between innovation and the changes in the standards. Previous studies show evidence that regulation can speed up innovation growth. We move one step forward and decompose innovation growth into two parts. One is the natural growth, which occurs regardless of regulation pushes. The other part is the induced growth, which is in direct response to the tightened standards. Therefore, we not only show that regulation changes can impact innovation but also show that the changes in the rate of innovation is proportionate to the changes in the CAFE standards.

Second, with our method of decomposing innovation growth, we turn innovation growth into a function of regulation changes. By doing that, we create a better tool to predict future innovation under new regulations. Instead of picking a random rate of growth from previous data, we can now adjust the predicted growth rate based on how tight the new regulation will be.

The results suggest that, automakers improved their technology over time at a natural growth rate. When the stringent level of standards changed, automakers also adjusted their innovation rate in response to the changes. They were able to innovate faster compared to the natural rate when facing pressure from tight standards. To be more specific, in the car sector, the natural innovation in fuel economy related technologies can increase the fuel economy of cars by 1.19% annually should vehicle weight and engine power were kept constant. Every 1% increase in the CAFE standard would induce an additional 0.32% improvement in total innovation. Likewise, in the light truck sector, there is a natural innovation rate of 0.67% annually and every 1% increase in the CAFE standards would induce an additional 0.62% in fuel economy related innovation. Using these results, we predict that additional innovation induced by the more stringent new standards would play a big role under the new aggressive standards. In the car sector, average fuel economy would increase by 41% if weight and engine power were kept at 2011 levels. However, such increase will still not be fast enough to meet the 2025 target so firms will have to downsize their product to gain higher fuel economy. We estimate that cars will have to be downsized to the late 90s' level to meet the aggressive target. In the light truck sector, average fuel economy would increase by 45% if weight and engine power remained at 2011 levels. Since the standard increase is relatively smaller in the truck sector compared to that of the car sector, we estimate that firms will only have to downsize their product to the late 2000s' level to meet the 2025 target. This is a more optimistic prediction compared to previous studies.

The method we use in this paper can also be applied to other industries where there are regulations whose stringent level change over time and impact innovation directly.

The remainder of the paper is organized as follows. Section I discusses the theoretical and empirical models. Section II introduces the data. Section III provides evidences of attributes tradeoffs and technological progress. Section IV reports the empirical results and interpretation of the estimates. Section V provide robustness checks using alternative models. In section VI, we predict future innovation under the new aggressive standards. Finally, section VII concludes.

I Theoretical and empirical models

Empirical studies in engineering show that the automobile attribute, such as weight, engine power, and fuel economy, are transferable to each other. Murrell (1999) estimates that each percent increase in 0–60 MPH time (i.e. slower acceleration performance) implies a 0.44% improvement in fleet average fuel economy. There is also a rich body of literature that studied the relationship between regulation and innovation. Newell, Jaffe, and Stavins (1999) use characteristics transformation surface of innovation to study the technology growth and trade-offs between energy usage and performance in energy consuming products. Their findings were that energy efficiency directed innovations response substantially during the period after energy-

efficient product labeling was required such as energy star in air-conditioners. Adopting the idea of “characteristics transformation surface” in Newell, Jaffe, and Stavins, Knittel (2011) studies the trade-off between light duty vehicle attributes including fuel economy, measured in miles per gallon (MPG), weight, horsepower and torque and builds a transformation surface. Then he estimates the growth of the technologies over time and thus estimates the potential of MPG increases of vehicles. In his analysis, he estimates that if weight, horsepower, and torque were fixed at their 1980 levels, MPG could have risen by 60% from 1980 to 2006. Also, to achieve Obama’s aggressive CAFE standard increase will require downsizing of vehicles. DeCicco and Ross (2001) estimate that by 2010-2015, there could be a 47% increase in overall fuel economy, which is measured in miles per gallon (MPG), from 24 to 35 with a curb weight cut of 14% at 2000 level. The overall MPG could even reach 44 with a curb weight cut of 26% compared with 2000 level. These empirical results are important supports of modeling fuel economy as a function of vehicle weight and engine power. In this paper, we adopt a similar frame work to Knittel’s model.

Our focus in this paper is on the relationship between innovation and changes in the CAFE standards. Following Knittel’s vehicle attribute surface framework, we model the technology growth under the CAFE standards as follows. Firms choose the attributes of their product, including engine power, hp_{it} , torque, tq_{it} , curb weight, w_{it} , fuel economy, mpg_{it} , other attributes that are related to MPG, X_{it} , attributes related to other aspects, Y_{it} , at time t given the profitable technologies available at time t . I represent it as:

$$(1) \quad K_{it} = f(mpg_{it}, w_{it}, hp_{it}, tq_{it}, X_{it}, Y_{it}, t)$$

The purpose of this study is to measure innovation that are related to fuel economy, that includes innovation that directly affects fuel economy, and innovation that affects attributes that are transferable to fuel economy, such as weight and engine power. So we assume that K is additively separable in fuel economy related attributes and non-fuel-economy related attributes, that is:

$$(2) \quad K_{it} = U_t(mpg_{it}, w_{it}, hp_{it}, tq_{it}, X_{it}) + D(Y_{it}, t)$$

Where U is the profitable technologies that are related to fuel economy available at time t , and D is technologies that are unrelated to fuel economy, such as safety, available at time t . Our focus is on the progress of U over time. The level set of U can be expressed as

$$(3) \quad mpg_{it} = g(w_{it}, hp_{it}, tq_{it}, X_{it} | U_t)$$

We model the innovation in U at year t with respect to year $t-1$ as

$$(4) \quad U_t / U_{t-1} = (S_t / S_{t-1})^m \text{EXP}(j + \varepsilon_t)$$

where S is the fuel economy standard, m is the innovate rate that is induced by standard changes, j is the average yearly innovate rate, and ε is a normally distributed zero mean error term, which represents fluctuation in the annual innovation under natural growth. We assume independency of ε in different model years. Then in each model year after CAFE was enacted, we have

$$(5) \quad U_t / U_0 = (S_t / S_0)^m \text{EXP}(t * j + \sum \varepsilon_t)$$

Following Knittel (2011), we assume Cobb-Douglas functional form for U. Then the fuel economy is modeled as

$$(6) \text{Mpg}_{it} = \beta_1 \ln W_{it} + \beta_2 \ln \text{HP}_{it} + \beta_3 \ln \text{TQ}_{it} + j^* t + m^* \ln \text{CAFET} + \beta_4 M_t + \beta_5 M_t^* t + X'_{it} B + e_{it}$$

II Data

We collect vehicle attribute of models that were sold on the US market from Ward's Automotive Yearbook (WAY) from 1975 to 2011 and automobile-catalog.com (AC) from 1975 to 2011. Both data have their advantage and disadvantages. The WAY covers a broader range of vehicles among 68 different makes. However, WAY does not provide complete information of torque in cars prior to 1997. Fuel type is also not reported directly in WAY. Therefore, we construct the fuel type of an internal combustion vehicle from the compression ratio reported in WAY. We assign fuel type to gasoline if the compression ratio of the engine is less than 12 and diesel if the compression ratio is above 12. We also construct transmission type for earlier years in WAY when several transmissions were reported for a same trim. We pick only the first provided transmission as the standard trim to determine whether the vehicle is manually transmitted or automatically transmitted.

In the WAY data, the MPG reported are the EPA adjusted MPG ratings. The EPA changed their methods of estimating MPG ratings over time. Also, only the combined adjusted MPG rating was reported before 1985. Beginning in 1985, adjusted MPGs were reported in 2 separate numbers, city MPG and highway MPG. The city MPG was calculated as $0.9 \times [\text{EPA tested city MPG}]$ and highway MPG was calculated as $0.78 \times [\text{EPA tested highway MPG}]$.

In 2008, the EPA adjusted their MPG rating methods again. The new methods took more variables such as outdoor temperature, air-conditioning into account. This change resulted a decrease in EPA adjusted MPG in most vehicles. The new formulas are shown as below

$$\text{Adjusted city MPG} = \frac{1}{0.003259 + \frac{1.1805}{\text{Tested city MPG}}}$$

$$\text{Adjusted highway MPG} = \frac{1}{0.001376 + \frac{1.3466}{\text{Tested highway MPG}}}$$

We use these formulas provided by the EPA and the adjusted MPG to reverse engineer the tested MPG and then apply the formulas used prior to 2008 to get adjusted MPG numbers that are comparable to those of previous model years. We then applied the same method EPA used to construct the combined MPG, which is the weighted harmonious mean of adjusted city MPG and adjusted highway MPG using a city/highway ratio of 0.55/0.45. We add a dummy in our regression specifications to control for this additional adjustment to the MPG in the WAY data as the tested fuel economy would be proportionately higher than the estimated actually fuel economy reported in the AC data.

The AC data that we have permission to use cover 23 major makes but provide more comprehensive information in vehicle MPG and torque. The AC data also provide full information of transmission type and fuel type. The MPG reported in the AC data are not EPA ratings but estimates made by engineers.

Vehicles that have gross weight above 8500 lbs, typically heavy duty trucks, are not regulated by the CAFE standards, therefore, we remove these vehicles from our analysis. We also remove hybrid vehicles and electric vehicles that have MPG above 70 from our analysis since these vehicles use very different technologies and we worry that our model for internal combustion engine automobiles might not be suitable in estimating technology growth and attributes tradeoffs in these vehicles.

III Evidences of attributes tradeoffs and technological progress

The fuel economy of vehicle models changed dramatically after the CAFE standards was enacted. Figure one shows the changes of the CAFE standards over time. The standards were effective starting in 1978 for cars and 1979 for trucks. The standards increased sharply at the beginning and then remained stable in the 1990s and 2000s. The Obama administration set aggressive new standards and the new standards after 2011 model year will be based on footprints of vehicles. The 2025 target of MPG is almost twice as high as that of 2010.

Goldberg (1998) uses a discrete choice model to study the effect of the CAFE standards on vehicle attribute. He shows that firms would produce cars with lower MPG at equilibrium had CAFE not been in place. Since firms are taking corner solutions in their MPG choice when CAFE standards are effective and binding, there is no incentive for firms to develop vehicles with better MPG. Instead, firms produce more small cars and less large cars to make sure the average MPG meets the standards. This could be the explanation of the almost flat average MPG curve after 1983, when the CAFE standards stayed stable. Figure two shows how the average weight, horsepower and fuel economy change from 1975 to 2011 in our data. Compared to passenger cars in model year 1975, average MPG almost doubled in 1986 and remained at that level till 2011. Average horsepower lowered by over 20% in 1982 compared to 1975 models and then kept increasing every year and was 90% higher than 1975 models in 2011. Similarly, average curb weight of cars decreased sharply during the period when CAFE standards were increasing. The average weight decreased by 25% from model year 1975 to 1986 and gradually increased and got back close to the 1975 level in 2011.

We observe similar trend in the light duty truck sector, whose CAFE standards were first introduced at 17.2 MPG for 2 wheel drive trucks and 15.8 MPG for 4 wheel drive trucks. The separate standards for 2 wheel drive trucks and 4 wheel drive trucks were disconnected after 1992. A combined standard was introduced later in 1982 at 17.5 MPG and all standards kept increasing till 1987, when the combined standard was at 20.5 MPG. The combined standard moved around 20.5 for a few years and remain stable at 20.7 MPG from 1996 to 2004. The truck standard increased slowly again since 2005 and kept increasing to 24.1 in 2011. During 1975-2011 model years, average weight of light trucks also dropped sharply in the first few years

when the standards came into effect and then increased to 20% higher than 1975 level in 2011. Average horsepower decreased slightly in the beginning and then increased to 110% higher than 1975 level during the same period.

These evidences show that, first, when standards increase faster than innovation, firms are capable of lowering weight and horsepower of their products to achieve higher MPG. The changes of average weight, horsepower and MPG during the late 70s and early 80s reflect such behavior. Second, as technologies advance over time, firms are capable of building vehicles that are better in every dimension. The changes of average CAFE standards were stable show that technological growth over time allow firms to build vehicles with similar MPG, but much more powerful and heavier. While horsepower and weight can be transferred to MPG, such changes show that firms were able to build vehicles that are more fuel efficient. Figure three compares the weight and fuel economy of car models in 1978 with models in 2008. Not surprisingly, firms were able to produce cars that are larger and more efficient in 2008 compared to 1978. Such shift in the plotting of attribute can also be seen in engine power and fuel economy and is clear evidence of innovation.

IV Empirical results

Tables one and two report the regression results of passenger cars and tables three and four report the regression results of light duty trucks. Table one and three also make comparisons between firms from different origins while table two and four compare among different vehicle classes.

A. Trade-offs of vehicle attributes

Coefficients of engine power, which includes torque and horsepower, and weight suggest that they are negatively correlated to fuel economy. This is consistent with empirical studies in engineering, which emphasize that firms can decrease weight or engine power to gain higher fuel efficiency. Vehicles with diesel engine usually have better fuel economy compared to vehicles with gasoline engines due to the higher efficiency of diesel engines. Another important factor that affects fuel economy is the type of transmission. Manually transmitted vehicles are normally more fuel efficient than automatically transmitted vehicles. However, the coefficients of the interaction terms of manual transmission and time trend show that the difference had been decreasing over time in both cars and trucks. In fact, some of the modern automatic transmissions, such as the CVT, have similar or even better performance than manual transmissions in terms of affecting fuel economy.

B. Natural rate of innovation

The coefficients of year trend estimate the average annual growth rate of fuel economy related technologies. The results suggest that on average, firms have an annual increase of 1.19 percent in the fuel economy of their passenger cars. Note that this is not saying the actual fuel

economy of the car models would be increasing every year. The interpretation is that the natural innovation would increase the fuel economy by 1.19 percent assuming that other vehicle attribute, including engine power and weight, were kept constant. Firms could choose to increase weight or engine power instead of fuel economy to make their product more attractive to their customers. And that is exactly what they did when the CAFE standards remained stable. Similarly, in the light duty truck sector, the natural innovation rate is 0.66 percent annually. These estimates are the average innovation rate of all firms. As shown in table one and two, the growth rate could vary across firms of different origins and different vehicle classes. For example, while the US automakers have annual innovation rates at 0.79 percent in cars and 0.56 percent in trucks, the Asian automakers have annual innovation rates at 1.3 percent in cars and 0.86 percent in trucks. Also, small cars appear to enjoy a higher innovation rate than large cars while SUV/CUVs lead in innovation rate among trucks.

C. Innovation in response to the CAFE standards

The induced innovation is the key focus of this paper. Our results show that in both the passenger car and light truck markets, the changes in the level of CAFE standards have significant effect on the MPG related innovation in addition to the natural innovation rate. Also, the truck sector responds more strongly than the car sector.

The coefficients of the log CAFE standards estimate the average technological increase with respect to changes in the CAFE standards. The estimates suggest that on average, 1 percent increase in the CAFE standards are associated with additional 0.32 percentage point increase in the innovation rate of fuel economy related technologies of cars. Likewise, 1 percent increase in the CAFE standards are associated with additional 0.62 percentage point increase in the innovation of trucks. There are two explanations to the different response to the CAFE standard changes among cars and trucks. The first explanation is that trucks started at a relatively low technology level. When the CAFE standards first came into effect, the market share of light duty trucks was only around 20 percent and there were very few international brands on the US market. The market of cars, however, were much more competitive. Second reason is that, as discussed in part B, the natural innovation rate of trucks are also lower than that of cars. Therefore, automakers were able to improve their technologies faster when they were pushed by the increases of standards since there were more rooms for improvements due to the two reasons discussed above.

We also break down our sample into various subgroups to explore the heterogeneity among different automakers and vehicle classes. As shown in table one, in the passenger car market, both US automakers and Asian automakers respond strongly to the standards. This is surprising at first glance since Asian makers had been producing cars with average fuel economy that were high above the CAFE standards. Slight increases of the CAFE standards should not have a direct pressure on the Asian makers. We explain this as the evidence of market competition. The US automakers had been producing cars with an average fuel economy that barely meets the CAFE standards. Every time the CAFE standards tightened up, US automakers had to push harder in their innovation to increase their fuel economy to meet the higher standards. They are reluctant to simply lower weight and engine power as these attributes are

what consumers demand in the US. The traditional advantage of Asian brand cars is fuel efficiency since they day they entered the US market. To defend their advantages in the market competition, Asian makers also had to increase the fuel efficiency of their products when US automakers improved their fuel economy. Therefore, though most of the time the tightening in the CAFE standards did not push Asian automakers directly, they still stimulated faster innovation rate of Asian brand cars through market competition.

There were also automakers who chose to not to comply with the CAFE standards and pay the fines. These were all European companies who were specialized in producing luxury cars. Unlike the US automakers and Asian automakers, European automakers do not have a significant response in innovation to the increases in the CAFE standards. We explain this as the evidence that these European companies were able to pass on the fines to their consumers who cared more about luxury features of their vehicles and were less sensitive to prices. We do not observe such behavior in the luxury cars in the US and Asian automakers. There are two explanations for this. First, though they are all luxury vehicles, the US and Asian luxury cars were normally cheaper than the European luxury cars, which suggest that consumers who chose to purchase European luxury cars are probably richer and less price sensitive than those who chose the US or Asian brand luxury cars. Second, the US and Asian automakers pushed their technological growth in response to increases in CAFE standards to either avoid paying fines or maintaining market advantages. These technological improvements can be applied to both economy cars and luxury cars without extra innovation costs. As a result, even though consumers of luxury cars could be less price sensitive, the US and Asian automakers still applied technologies that were already at their disposal.

V Robustness checks

In this section we discuss the potential concerns of the robustness of our results and we perform series of robustness checks to show that the estimates in the main specification are sound.

A. Correlation between vehicle attributes

The first concern of the empirical model we use is that vehicle attribute are correlated with each other. When automakers design their vehicles, the combinations of installed equipment are not random. For example, engine power is highly correlated with vehicle weight. Automakers typically install more powerful engines in heavier and larger vehicles. Therefore, horsepower and weight are clearly correlated with each other. Though the focus of this paper is not on the trade-off relationship between attributes but on the innovation rate, we still want to make sure that such correlation in attribute wouldn't bias our estimation of innovation responses. To address this concern, we use the translog functional form for the technology level U to test whether our estimates of innovation responses are sensitive to such correlations. Table five and six show the regression results using the translog functional form in specification III while showing the main specification in specification II. The annual innovation rate estimated using the translog model is very close to the estimates we have in the Cobb-Douglas model. The response rates of innovation

to the changes in the CAFE standards are also very close between the two specifications. Such results suggest that even though there are correlations between vehicle attribute, they do not appear to be a potential threat to the estimations of annual innovation rates and the response rates of innovation.

B. Engine power measurement

The second concern we have is the measure of engine power. We use both highest torque and highest horsepower in the analysis. However, these two measures are also closely related. We present the specification keeping only horsepower in specification one and the estimates of natural innovation rate and response rate increased compared to our main specification. The relationship between torque and horsepower is: $\text{Horsepower} = \text{Revolution per minute (rpm)} * \text{Torque} / 5252$ while torque is a function of rpm. So though highly correlated, keeping both maximum horsepower and maximum torque in the model still helps controlling more features of engine development over time. Therefore, we still chose the more conservative estimates in our main specification to proceed to predicting future innovation.

VI Future innovation prediction

We simulate innovation under the new standards using the estimated natural innovation rate and the induced innovation in response to the CAFE standards. The CAFE standards changed to footprint based standards starting in 2012. Instead of a single average fuel economy standard for cars or trucks, the footprint based standards set different standards for vehicles based on their size. To simplify the simulation, we use the average change rates of the footprint based standards for in the simulation.

Our calculation show that the average fuel economy standard increase from 2011 to 2025 in cars is 72%, or an increase of 0.542 in logarithm. We estimate the logarithm innovation rate comparing to 2011 as

$$(7) \text{Growth}_t = (T - 2011) * j + (\log S_t - \log S_{2011}) * m$$

where j is the average annual growth, T is the model year, S is the CAFE standards and m is the technological growth response to CAFE standards. In the car sector, as shown in section IV, $j = 0.0119$ and $m = 0.32$. Using the formula above and the estimates, we calculate that the total technological growth from the natural growth will be 0.167 in logarithm from 2011 to 2025 and the additional growth stimulated by standard increases will be 0.190 in logarithm as shown in table seven. The induced innovation exceeds the natural innovation in cars. This means that if firms keep the weight and engine power of their cars at the 2011 level, they will be able to build cars with 40.5% higher MPG than their 2011 products in 2025 or an increase of 0.340 in logarithm. However, the increases in the CAFE standards for cars is 0.542 in logarithm. This means that there will still be a 0.2 gap. Therefore, to meet the standards in 2025, automakers will have to decrease the weight and engine power of their cars comparing to 2011 level to gain better fuel economy. Comparing to the historical data, if we assume that firms decrease weight and engine power backward of the way they increased weight and engine power in the past, then cars

will have to be downsized to the 1995 to 1999 level to be able to comply with the 2025 standards.

Likewise, we calculate the future innovation in the light truck sector. The total induced innovation will be 37.4% in the truck sector or 0.318 in logarithm from 2011 to 2025 and the natural innovation will be 9.8% or 0.093 in logarithm. This leaves only 7.6% gap for firms to downsize to meet the 2025 targets. We estimate that firms only need to downsize to 2007 to 2009 levels to achieve that.

VII Conclusion

In this paper, we estimate the technology growth in the automobile industry under the pressure of the CAFE standards and then predict future vehicle attributes changes under the new aggressive standards. We find that automakers would have a higher innovation rate under the new standards. We estimate that automakers have a higher natural innovation rate in cars compared to the truck sector. In the truck sector, the innovation is more sensitive to changes in the standards than in the car sector. However, we cannot simply conclude that the overall effect of the new aggressive standards are positive. This is because we only looked at fuel economy related technologies in this analysis. Though we showed that firms have response positively to the changes in standards in fuel economy related innovation, we don't know if that's at the expense of innovation in other areas, such as safety technologies.

Our simulation of innovation under the new aggressive CAFE standards suggest that automakers will have to do moderate downsizing to meet the 2025 target in cars, and they only need minor downsizing in trucks to meet the standards. This is a much more optimistic prediction than previous studies have shown.

Finally, by modeling innovation as a function of changes in regulation stringency, we provide a tool that can more precisely predict future innovation under new regulation and compare between different scenarios of regulation by taking into account the changes in stringency levels. Such method can also be applied to other areas with similar standards or regulations that are quantifiable.

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Figure one. CAFE standards over time (MPG)

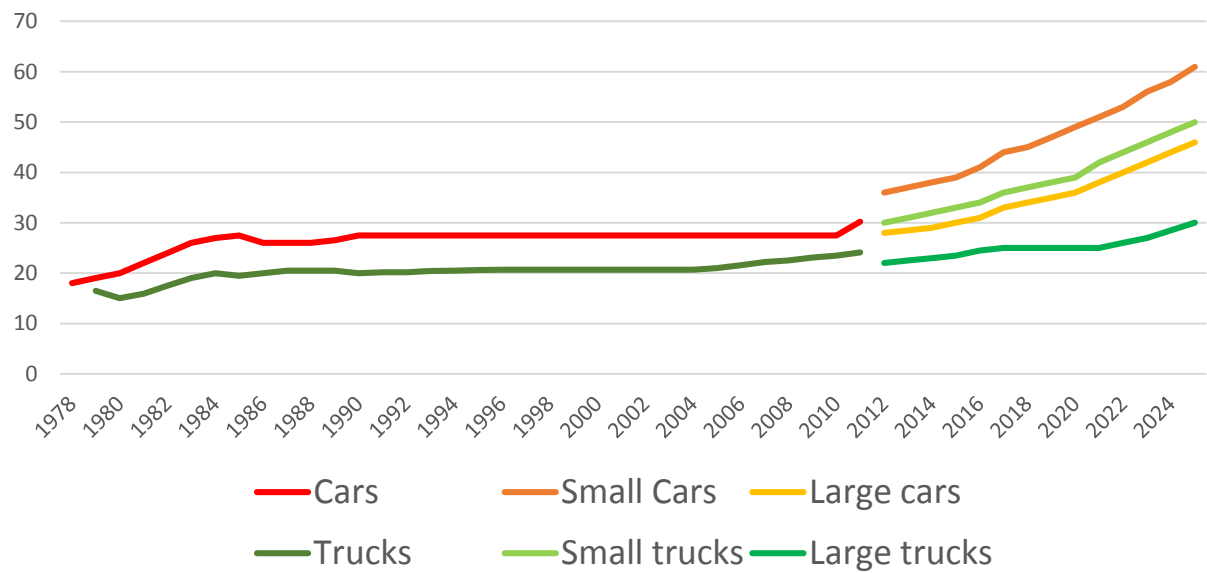


Figure two. Changes in car attribute from 1975 to 2011

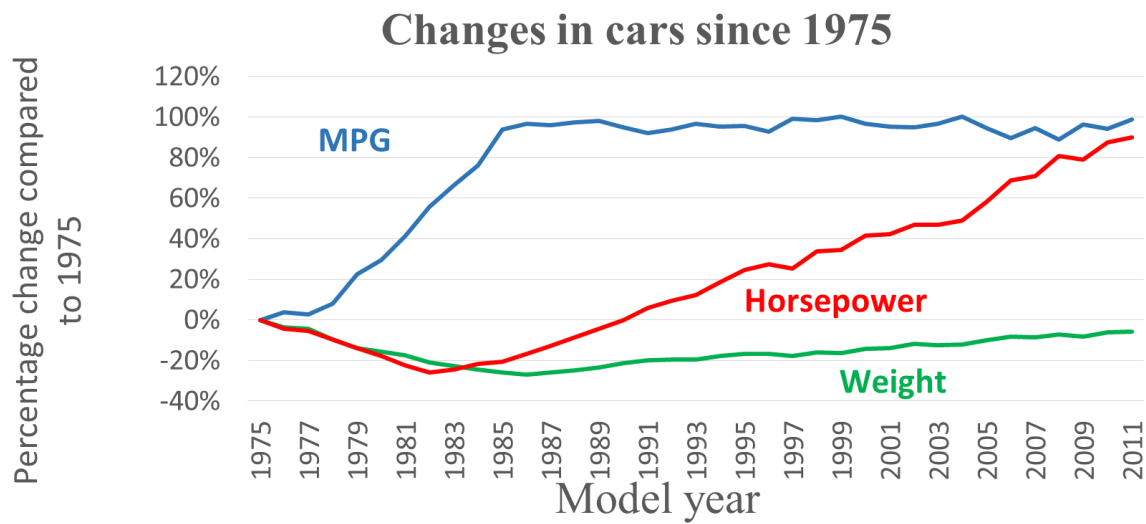


Figure three. Technological innovation of cars from 1978 to 2008

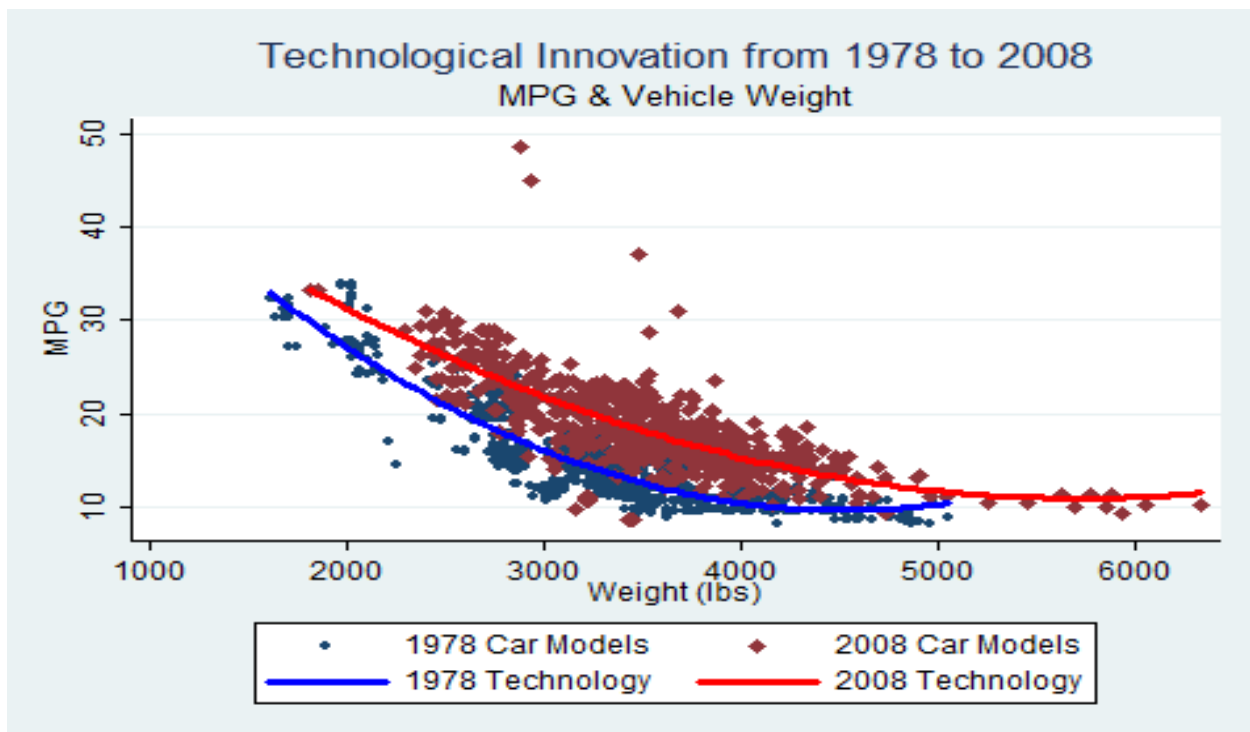


Table one. Innovation response in cars.

	All	US	Asian	EU
Log horsepower	-0.1378 (0.0732)	0.0492 (0.0389)	-0.4781*** (0.1063)	-0.6089 (0.0977)
Log curb weight	-0.3770*** (0.0355)	-0.2848*** (0.0331)	-0.3061*** (0.0728)	-0.3802*** (0.0423)
Log torque	-0.3533*** (0.0841)	-0.5881*** (0.0388)	-0.0245 (0.1320)	0.2657*** (0.1072)
Manual	0.1341*** (0.0186)	0.1157*** (0.0214)	0.0954*** (0.0196)	0.1142*** (0.0543)
Manual*trend	-0.0067*** (0.0007)	-0.0051*** (0.0007)	-0.0047*** (0.0010)	-0.0043*** (0.0021)
Diesel fuel	0.1637*** (0.0537)	0.1340*** (0.0185)	0.1999*** (0.0814)	0.1362*** (0.0298)
Turbocharged	0.1430*** (0.0161)	0.1405*** (0.0250)	0.1235*** (0.0201)	0.0213*** (0.0227)
wards	0.3977*** (0.0141)	0.4147*** (0.0115)	0.3360*** (0.0210)	0.4147*** (0.0234)
Log CAFE standards	0.3205*** (0.0353)	0.3089*** (0.0388)	0.4225*** (0.0799)	-0.2012 (0.1366)
Yearly trend	0.0119*** (0.0013)	0.0079*** (0.0005)	0.0130*** (0.0006)	0.0129*** (0.0011)
Firm fixed effect	Y	Y	Y	Y
R-squared	0.8971	0.9181	0.8553	0.7637
Obs	21656	12870	5501	3066

Table two. Innovation response comparison among car classes

	Small cars	Medium Cars	Large cars	Economy cars	Luxury cars
Log horsepower	-0.2300*** (0.0948)	-0.1275*** (0.0547)	0.0722 (0.0561)	-0.0867 (0.0651)	-0.2597*** (0.1269)
Log curb weight	-0.2994*** (0.0563)	-0.4589*** (0.0713)	-0.4882*** (0.0926)	-0.3788*** (0.0460)	-0.2921*** (0.0565)
Log torque	-0.2808*** (0.1162)	-0.3734*** (0.0519)	-0.4676*** (0.0859)	-0.4253*** (0.0650)	-0.1954 (0.1299)
Manual	0.1389*** (0.0132)	0.1014*** (0.0390)	0.0385 (0.0178)	0.1300*** (0.0157)	0.0831*** (0.0445)
Manual*trend	-0.0061*** (0.0006)	-0.0049*** (0.0016)	-0.0001*** (0.0008)	-0.0063*** (0.0005)	-0.0040*** (0.0017)
Diesel fuel	0.2490*** (0.0523)	0.0735 (0.0474)	0.2197*** (0.0185)	0.2118*** (0.0688)	0.0566 (0.0679)
Turbocharged	0.1271*** (0.0155)	0.1916*** (0.0182)	0.2609*** (0.0211)	0.0895*** (0.0237)	0.1331*** (0.0348)
wards	0.3543*** (0.0171)	0.4041*** (0.0131)	0.5065*** (0.0104)	0.3538*** (0.0133)	0.4833*** (0.0253)
Log CAFE standards	0.3456*** (0.0575)	0.3058*** (0.0594)	0.3101*** (0.1496)	0.2695*** (0.0382)	0.4373*** (0.1246)
Yearly trend	0.0129*** (0.0012)	0.0117*** (0.0012)	0.0052*** (0.0020)	0.0123*** (0.0012)	0.0101*** (0.0026)
Firm fixed effect	Y	Y	Y	Y	Y
R-squared	0.8609	0.8901	0.9336	0.9325	0.7971
Obs	10185	8525	2946	16287	5369

Table three. Innovation response in trucks.

	All	US	Asian	EU
Log horsepower	0.0589 (0.0431)	0.0927 (0.0711)	0.0253 (0.0716)	-0.0946 (0.0894)
Log curb weight	-0.3975*** (0.0295)	-0.3797*** (0.0507)	-0.4283*** (0.0412)	-0.5554*** (0.0737)
Log torque	-0.4318*** (0.0642)	-0.4788*** (0.1050)	-0.3781*** (0.0761)	-0.1819 (0.1146)
Manual	0.0783*** (0.0133)	0.0855*** (0.0191)	-0.0439*** (0.0415)	-0.0174*** (0.0433)
Manual*trend	-0.0043*** (0.0007)	-0.0045*** (0.0012)	-0.0002*** (0.0018)	-0.0001 (0.0013)
Diesel fuel	0.3468*** (0.0695)	0.3452*** (0.0991)	0.4524*** (0.0213)	0.3051*** (0.0540)
Turbocharged	0.1043*** (0.0182)		0.0648*** (0.0141)	0.0743*** (0.0277)
wards	0.4070*** (0.0136)	0.4259*** (0.0161)	0.3390*** (0.0198)	0.3699*** (0.0339)
Log CAFE standards	0.6239*** (0.1966)	0.6306*** (0.3151)	0.4530*** (0.1492)	1.1270*** (0.3600)
Yearly trend	0.0066*** (0.0015)	0.0056*** (0.0022)	0.0086*** (0.0030)	0.0046 (0.0068)
Firm fixed effect	Y	Y	Y	Y
R-squared	0.865	0.8612	0.8145	0.9191
Obs	14724	10369	3775	566

Table four. Innovation comparison among truck classes

	Pickups	CUV/SUV	Vans
Log horsepower	-0.0270 (0.0241)	0.0818 (0.0853)	0.0498 (0.0413)
Log curb weight	-0.2808*** (0.0195)	-0.4397*** (0.0244)	-0.7404*** (0.0403)
Log torque	-0.2736*** (0.0358)	-0.4617*** (0.0843)	-0.2448*** (0.0232)
Manual	0.0492 (0.0275)	0.0939 (0.0117)	0.2152 (0.0358)
Manual*trend	-0.0027*** (0.0013)	-0.0040*** (0.0009)	-0.0084*** (0.0021)
Diesel fuel	0.3086*** (0.0238)	0.3818*** (0.0790)	
Turbocharged	0.0259*** (0.0086)	0.1341*** (0.0145)	
wards	0.3768*** (0.0235)	0.4129*** (0.0163)	0.3337*** (0.0203)
Log CAFE standards	0.8959*** (0.0448)	0.4719*** (0.1726)	0.3913*** (0.1257)
Yearly trend	0.0009 (0.0022)	0.0088*** (0.0008)	0.0065*** (0.0018)
Firm fixed effect	Y	Y	Y
R-squared	0.7782	0.8904	0.8145
Obs	4267	8748	3775

Table five. Innovation response in cars, specification comparison

	Spec I	Spec II	Spec III
Log horsepower	-0.4122*** (0.0165)	-0.1378 (0.0732)	-1.0728 (1.3998)
Log horsepower squared			-0.4933*** (0.0875)
Log horsepower*Log weight			0.0195 (0.1733)
Log horsepower*Log torque			1.0932*** (0.1607)
Log curb weight	-0.5840*** (0.0311)	-0.3770*** (0.0355)	5.8616*** (1.4723)
Log weight squared			-0.5143*** (0.1320)
Log weight*Log torque			0.3847 (0.2608)
Log torque		-0.3533*** (0.0841)	-2.2422 (1.8252)
Log torque squared			-0.6405*** (0.1297)
Manual	0.1490*** (0.0184)	0.1341*** (0.0186)	0.1122*** (0.0197)
Manual*trend	-0.0074*** (0.0007)	-0.0067*** (0.0007)	-0.0050*** (0.0008)
Diesel fuel	0.1122*** (0.0501)	0.1637*** (0.0537)	0.2129*** (0.0521)
Turbocharged	0.1235*** (0.0268)	0.1430*** (0.0161)	0.1232*** (0.0186)
wards	0.3983*** (0.0148)	0.3977*** (0.0141)	0.3921*** (0.0139)
Log CAFE standards	0.3792*** (0.0289)	0.3205*** (0.0353)	0.2243*** (0.0353)
Yearly trend	0.0157*** (0.0004)	0.0119*** (0.0013)	0.0119*** (0.0010)
Firm fixed effect	Y	Y	Y
R-squared	0.8883	0.8971	0.9036
Obs	21656	21656	21656

Table six. Innovation response in trucks, specification comparison

	Spec I	Spec II	Spec III
Log horsepower	-0.2806*** (0.0215)	0.0589 (0.0431)	-0.0579 (1.0173)
Log horsepower squared			-0.2200*** (0.0959)
Log horsepower*Log weight			0.1241 (0.2097)
Log horsepower*Log torque			0.2585 (0.2780)
Log curb weight	-0.5980*** (0.0184)	-0.3975*** (0.0295)	2.8153*** (1.2335)
Log weight squared			-0.1609 (0.1096)
Log weight*Log torque			-0.2202 (0.2940)
Log torque		-0.4318*** (0.0642)	-1.7171 (1.3189)
Log torque squared			0.1617 (0.2392)
Manual	0.0825*** (0.0226)	0.0783*** (0.0133)	0.0841*** (0.0110)
Manual*trend	-0.0049*** (0.0012)	-0.0043*** (0.0007)	-0.0047*** (0.0005)
Diesel fuel	0.2309*** (0.0594)	0.3468*** (0.0695)	0.3315*** (0.0608)
Turbocharged	0.0397*** (0.0107)	0.1043*** (0.0182)	0.0381 (0.0234)
wards	0.3982*** (0.0130)	0.4070*** (0.0136)	0.4061*** (0.0141)
Log CAFE standards	0.8299*** (0.1295)	0.6239*** (0.1966)	0.6115*** (0.2003)
Yearly trend	0.0107*** (0.0017)	0.0066*** (0.0015)	0.0064*** (0.0018)
Firm fixed effect	Y	Y	Y
R-squared	0.8385	0.865	0.8697
Obs	14726	14724	14724

Table seven. Future innovation prediction from 2011 to 2025 under the new standards.

	Cars		Trucks	
	Percentage	logarithm	Percentage	logarithm
Average increase in the CAFE standards from 2011 to 2025	72.0%	0.542	55.6%	0.442
Average annual innovation	1.2%	0.012	0.7%	0.007
Innovation response rate to changes in CAFE standards	0.320		0.624	
Induced innovation	20.9%	0.190	37.4%	0.318
Total innovation from 2011 to 2025	40.5%	0.340	44.6%	0.369
Deficit to meet the 2025 targets	22.5%	0.203	7.6%	0.073