Quantifying efficiency technology improvements in U.S. cars from 1975-2009

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Abstract

Quantitative measurements of historic improvements in fuel efficiency technology help to illuminate the feasibility of future fuel economy standards. Past investigations have produced widely varying estimates of this rate of improvement, though all seem to indicate that fuel consumption reductions implied by the 2025 U.S. CAFE standards cannot be met solely through technological improvements at historic rates. In this paper, we use the characteristics of U.S. cars between 1975 and 2009 to estimate that holding all else equal, a 1\% increase in weight increases a car’s fuel consumption by 0.69\%, and a 1\% reduction in 0–97 km/h acceleration time increases fuel consumption by 0.44\%. These tradeoff parameters are combined with the results of related work by the authors and others, yielding a more comprehensive measure of technological improvements than has been previously reported. When accounting for all of these sources of improvement, we conclude that the per-mile (or per-kilometer) fuel consumption of new cars in the U.S. could have been reduced by 5\% per year from 1975–1990, if acceleration, features, and functionality had remained at their 1975 levels. Approximately 80\% of this potential was realized as actual reductions in fuel consumption. Between 1990–2009, in contrast, technological improvement averaged just 2.1\% per year, only 34\% of which was realized as actual fuel consumption reductions. To meet the 2025 CAFE standards for cars without sacrificing capabilities that consumers have come to expect, technology must improve...
quickly enough to reduce fuel consumption by 4.3% per year for 14 years — considerably faster than has occurred since 1990, but consistent with the pace of improvements observed between 1975 and 1990.

Keywords: fuel economy, technology change, vehicle efficiency

1. Introduction

The United States government has recently finalized Corporate Average Fuel Economy (CAFE) standards for light-duty vehicles in the years 2017–2025. The standards will increase by 3.8–4.7% annually for cars, and by 2.5–4.9% annually for trucks, during these eight years. Combined with previously-announced increases for the years 2011–2016, the new rules are expected to yield fuel economy increases of 80% and 60% for cars and light trucks, respectively, over the 14 year period 2011–2025 [1, 2].

An important question for policymakers, researchers, and analysts is how ambitious these targets — equivalent to reductions in per-mile (or per-kilometer) fuel consumption averaging 3.4–4.3% per year for 14 years — really are, relative to historic rates of technology improvement in light-duty vehicles. If required rates of fuel consumption decrease are within historic rates of technology change — and provided that there are similar levels of efficiency improvements yet to be exploited — it would suggest that the standards can be met through business-as-usual technology improvements [3]. This might mean foregoing additional gains in other vehicle attributes such as features or performance, but would not require giving up levels of the attributes that consumers have already come to expect. If, on the other hand, the required rates of fuel consumption reduction exceed historic rates of technology change, it will mean that new technology gains must occur.

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1 Throughout this paper, we refer frequently to fuel consumption. We use fuel consumption to refer to the amount of fuel that a vehicle consumes for a specified distance traveled, in units such as liters per 100 km or gallons per 100 miles. Fuel consumption therefore is the inverse of fuel economy, which is commonly expressed as miles per gallon. Fuel consumption in this sense should not be confused with the total quantity of fuel consumed by all vehicles combined; even as average vehicle fuel consumption has fallen over the years, the total quantity of fuel consumed by the in-use vehicle fleet has increased as the number of vehicles has grown and their collective distance traveled has increased.
more rapidly than in the past, or that other vehicle attributes will have to be “taken back” from their current levels.

The constraint of maintaining functionality at current levels has been central to establishing technical feasibility and economic practicability in recent U.S. rulemakings on automotive greenhouse gas and fuel economy standards. The Final Rule setting standards for 2017–2025 states that:

[T]hese rules should not have a significant effect on the relative availability of different size vehicles in the fleet. The agencies’ analyses used a constraint of preserving all other aspects of vehicles’ functionality and performance, and the technology cost and effectiveness estimates developed in the analyses reflect this constraint. — EPA and NHTSA [2]

That is to say, the feasibility of recent fuel economy standards has been built on a premise of maintaining constant size, acceleration performance, and other measures of functionality.

There are two objectives to the work reported in this paper. The first is to quantify the historic rates of technology improvement in U.S. cars. Technology improvement is measured as how much the per-mile fuel consumption of the average new car could have been reduced over time, if not for changes in acceleration, size, features, and other attributes valued by consumers. The second objective is to quantify the degree to which efficiency technology improvements have been realized as reductions in fuel consumption, versus being used to offset the fuel consumption penalties of changes in other vehicle attributes.

Before proceeding, it is helpful to contrast two major views of technology improvement in motor vehicles (or in any sophisticated, energy-consuming system). The first view can be thought of as bottom-up, in that it focuses on the contributions of individual subsystems, vehicle loads, and “widgets” that can be adopted to incrementally improve efficiency. In contrast, there is a top-down view that focuses on the services and attributes that are provided to the user of the vehicle. This contrast can also be thought of as one between inputs (what goes into building the system) versus outputs (how well the system performs).

Much work, both retrospective and prospective, employs the bottom-up view. For example, the modeling system underlying the CAFE rulemaking process employs this view, evaluating the cost effectiveness of potential future technology packages. For example, works by EPA [1] and Zoepf and
Heywood [5] study the deployment of individual technologies. Kasseris [6] developed projections of future vehicle efficiency based on assumed values for road loads and efficiency parameters in various subsystems — many of which were informed by their historic trends. One challenge when working with the bottom-up view is the potential interdependence of the rates of adoption of multiple technologies at the same time. Zoepf and Heywood [5] examined the rates of adoption of individual features and engine technologies, but it is much harder to know how quickly multiple vehicle technologies can be integrated into the production system simultaneously.

The top-down view provides a simpler perspective on these subsystem interactions, by focusing on the efficiency with which the overall system delivers key services and utility attributes. In the case of vehicles, this may mean characterizing the fuel consumption of a vehicle for a given level of size, acceleration capability, and feature content. An and DeCicco [7] reviewed a number of studies of the U.S. market which have attempted to quantify past improvements in automotive technology, or technical efficiency in their parlance, using what amounts to a top-down perspective. They found widely varying estimates ranging from 1.0–3.8% per year (though mostly clustered between 1.5–2.2% per year). An and DeCicco noted that:

> Because the full range of features that interact both physically and economically with fuel economy cannot be observed with publicly available data, fully characterizing automotive technical efficiency trends is probably not possible. However, at least some portion of the trend can be quantified using attributes that are readily observable (such as size or mass) or calculable from public data. — An and DeCicco [7]

Attempting to get closer to this goal, they defined a performance-size-fuel economy index, which they interpret as “represent[ing] the ratio of moving a spatial carrying capacity a unit distance with a given performance capability per unit of fuel consumed.” An and DeCicco [7] emphasized the importance of shifting the focus from engineering metrics like ton-miles per gallon to more consumer-centric attributes like size and performance. Focusing on attributes that are most directly relevant to consumer utility will provide a more complete picture of all of the technological improvements occurring over time. Nonetheless, An and DeCicco chose to focus on power-to-weight ratio as their measure of
performance, rather than acceleration time, although the latter is arguably more directly related to consumers’ driving experience. As shown in MacKenzie and Heywood [8], the relationship between acceleration performance and power-to-weight ratio has changed over time, as newer vehicles tend to deliver faster acceleration than do older vehicles with comparable power and weight. A second downside to An and DeCicco’s approach is that they make a strong assumption about the relationship between size, power-to-weight ratio, and fuel economy. Namely, their performance-size-fuel economy index implies that for any given technology level, a proportional increase in size or power-to-weight ratio will be met with an equal and opposite proportional decrease in fuel economy. However, there is no theoretical or empirical reason to believe that this 1:1:1 tradeoff must hold.

Knittel [9] showed that the tradeoffs between engine power, vehicle weight, and fuel economy are not in fact 1:1. He also concluded that the fuel economy of new U.S. cars could have been increased by approximately 65% between 1980 and 2006, if weight and power had remained unchanged over this period. His approach was to empirically model the logarithm of fuel economy as a function of the logarithms of weight ($w$), power ($hp$), torque ($tq$), selected covariates ($X$), and a set of year fixed effects ($T$):

$$\ln mpg_{it} = T_t + \beta_1 \ln w_{it} + \beta_2 \ln hp_{it} + \beta_3 \ln tq_{it} + X'_{it}B + \epsilon_{it}$$  \hspace{1cm} (1)$$

In Equation (1), the $\beta$ coefficients represent the tradeoffs between fuel economy and the various independent variables, expressed as the elasticity of fuel economy with respect to each attribute. The year fixed effects, $T_t$, are interpreted as the cumulative change in technology between some base year and year $t$. Specifically, the change in technology is expressed as the change in the expected value of log fuel economy conditional on weight, power, torque, and covariate values. Holding power, weight, torque, and covariate values constant, the difference in expected fuel economy between the base year 0 and some future year $t$ would be:

$$\ln mpg_{it} - \ln mpg_{i0} = T_t$$  \hspace{1cm} (2)$$

In Equation (2), $T_0$ is normalized to zero. Rearranging and taking the exponential, we see that the ratio of expected fuel economy in year $t$ to the
that in year 0, if power, weight, torque, and covariates were unchanged, is:

\[ \frac{mp_{gt}}{mp_{g0}} = e^{T_t} \]  

Knittel’s methodology offers both advantages and disadvantages relative to the prior work. It is attractive because it allows the tradeoff parameters between power, weight, and fuel consumption to be estimated as parameters of the model, rather than assuming these values \textit{a priori}. However, a shortcoming is that by focusing on engineering attributes (power and weight) rather than consumer attributes (such as acceleration, size, and features) his definition of technology change may not capture all sources of technology improvement. Critically, since he conditions on power, his estimated effects for technology do not capture any improvements in how effectively vehicles turn engine power into acceleration performance. As shown in MacKenzie and Heywood, these improvements amount to a 20–30% reduction in acceleration time for modern vehicles, relative to a 1970s-vintage vehicle with the same weight, power, and other characteristics. Similarly, by conditioning on weight, Knittel’s specification will not capture technology improvements that allow newer vehicles to weigh less than comparable vehicles in the past. As shown by MacKenzie et al., modern weight-saving technologies would have allowed a reduction in weight of approximately 650 kg, or 40%, for the average new car between 1975 and 2009, if not for increases in size and features over that time. The fuel consumption reductions resulting from such a change in weight are substantial, but are not captured in Knittel’s estimates of technology change.

Several investigators have addressed similar questions for new cars in Europe. Kwon studied cars in the United Kingdom, but only controlled for a single covariate (engine displacement). Van den Brink and Van Wee considered cars in the Netherlands, relying on literature estimates of the tradeoff between weight and fuel consumption, and comparisons between similar vehicle models to estimate the effect of engine displacement. Sprei

\footnote{For small values of $T_t$, $e^{T_t} \approx 1 + T_t$, so $T_t$ represents the fractional increase in expected fuel economy, holding other attributes constant. However, as $T_t$ increases, this approximation no longer holds.}

\footnote{The relationship between power and other performance metrics, like towing capability or ability to hold speed on an uphill grade, may also have changed, though these are not investigated in this work.}
and coauthors [13, 14] used a combination of regression analysis of vehicle attributes and physics-based models of energy consumption to compare actual changes in fuel consumption over time with potential changes if technology had remained constant. Though details of their methods were vague, their general approach of considering consumer-centric attributes reflects that of An and DeCicco [7], as well as the work reported here.

The objective of this paper is to develop a more comprehensive estimate of how much efficiency technology has improved in U.S. cars since 1975. Our approach draws heavily on the empirical approach of [Knittel], while embracing the philosophy of [An and DeCicco] and Sprei et al. by focusing on attributes most relevant to consumers. The methodological approach is described in the next section. Section 3 briefly describes the data used in this paper. Section 4 presents the resulting estimates of technology change and compares them with values found in the literature, and the final section offers some conclusions against the backdrop of the required increases in Corporate Average Fuel Economy through 2025.

2. Methodology

This paper attempts to answer the question, “How much could the per-mile fuel consumption of new U.S. cars have been reduced between 1975 and 2009, if vehicle size, performance, features, and functionality had remained constant over this period?” Effectively, we are asking what would happen if we built a fleet of cars functionally equivalent to those sold in 1975, but using modern materials, designs, and powertrain technologies. Actually building these vehicles is clearly impractical, but engineering simulations offer one possible solution, as they might enable the application of contemporary technologies to the design of a vehicle with 1975-level performance, capacity, comfort, and safety specifications. While vastly simpler than actually building a vehicle, such simulations are nevertheless labor-intensive to develop and calibrate, and questions would likely persist over the representativeness of the specific vehicle model or models chosen for study.

Estimation of a simplified econometric model based on observed vehicle characteristics offers an alternative approach that is both tractable and can incorporate data on all vehicle models. This is the approach taken by
Knittel [9]. As discussed in Section 1, Knittel’s models may not capture all of the sources of technology improvement in new vehicles. Ideally, such a model would estimate the expected level of fuel consumption for a vehicle, conditional on all related attributes. These related attributes might include acceleration, towing, and handling capabilities, passenger and cargo capacity, some measure or measures of comfort and ride quality, and the presence of various convenience, emissions, and safety features.

In this work, detailed, model-level data on comfort, convenience, and safety features were not available, so an alternative, two-step methodology was adopted instead. First, technology change from a top-down perspective was estimated as the change in expected fuel consumption since 1975, holding weight, 0–97 km/h (0–60 mph) acceleration time, and selected covariates constant. Next, the resulting estimates of technology change were adjusted to account for the fuel consumption benefits of weight-saving technologies, based on the bottom-up analysis reported by MacKenzie et al. [10]. The weight analysis is intended to capture the weight reductions that would have occurred in the average new car if size, features, and functionality had remained at 1975 levels. The basic empirical model for implementing the first step was:

\[ \ln gpm_{it} = T_t + \beta_1 \ln IWT_{it} + \beta_2 \ln Z97_{it} + \mathbf{X}_it'\mathbf{B} + \epsilon_{it} \]  

In Equation 4, \( gpm_{it} \) is the fuel consumption of car model \( i \) in year \( t \) in gallons per mile, \( Z97_{it} \) is its 0–97 km/h acceleration time in seconds, \( IWT_{it} \) is its inertia weight in kg, and \( \mathbf{X}_it \) is a vector of dummy variables indicating whether the vehicle has a manual transmission or all-wheel or 4-wheel drive, whether it is a two-seater or a wagon body style. Also included were terms for the interactions of manual transmissions and all-wheel or 4-wheel drive with year. As in Equation 1, \( T_t \) is a set of year fixed effects representing the expected reduction in log fuel consumption for cars in each year \( t \) relative to some base year, if the other attribute levels had remained unchanged. The year fixed effects \( T_t \) will therefore be interpreted as the improvement in technology of the average new car between the base year and year \( t \).

\(^5\)Fuel consumption in l / 100 km can be obtained by multiplying gallons-per-mile by 235.2 (62.14 miles per 100 km * 3.785 liters per gallon). Therefore, to model fuel consumption in l / 100 km, simply add \( \ln 235.2 = 5.460 \) to the right hand side of Equation 4.
Some specifications also included dummy variables for powertrain type\footnote{Dummy variables were created for turbocharged gasoline, supercharged gasoline, naturally aspirated diesel, turbodiesel, and hybrid electric powertrains, with naturally aspirated gasoline engines representing the base case.} and engine specific power quintiles\footnote{The first quintile includes those cars with engine specific power values in the lowest one-fifth of all cars in their model year, the second quintile includes those vehicles with engine specific power values in the second fifth in their model year, etc.}. The reason for including specific power is to control for the possibility that more sophisticated engine technologies tend to be correlated with heavier vehicle weight or higher performance. Specific power (the ratio of engine peak power to displacement, often measured in kW/liter) is commonly used as a measure of the technical sophistication of an engine \cite{15}. If more sophisticated engines tended to be used in heavier or higher-performance vehicles, then ignoring differences in technology could lead to biased estimates of the coefficients on weight or acceleration performance ($\beta_1$ and $\beta_2$). Dummy variables for quintile were used to introduce specific power for two reasons. First, since engine specific power has generally increased over time, quintiles were used to provide a measure of specific power relative to other vehicles in the same model year. Controlling for the absolute level of specific power would bias the estimates of technological improvement downwards, since specific power increases over time are themselves a part of the overall technological improvement that we want to identify through the year fixed effects. A second reason for using dummy variables for specific power quintile is that it does not impose any assumption on the particular form of the relationship between specific power and fuel consumption.

The second step involves estimating the expected fuel consumption of a new car in year $t$ relative to year 0. This is done as in Equation $3$, but with an additional adjustment to account for the weight reduction that would have occurred in the absence of changes in size, features, and functionality:

$$gpm^\text{potential}_{t} = e^{T_t} \left( \frac{IWT_t}{IWT_0} \right)^{\beta_1}$$

(5)

In Equation $5$, $IWT_0$ is the inertia weight of an average new car in some base year, and $IWT_t$ is the estimated inertia weight of a similar car using weight-reducing technologies characteristic of year $t$, based on the work reported by MacKenzie et al. \cite{10}.
3. Data

The data used to estimate the model in this paper were obtained from the U.S. Environmental Protection Agency. The data include interior volume, inertia weight, body style, and powertrain characteristics for all cars offered for sale in the U.S. between 1975 and 2009. The 0–97 km/h acceleration times were estimated for these cars using the methods reported in MacKenzie and Heywood [8].

4. Results

4.1. Model Estimation Results

Table 1 contains results of the estimation of several different specifications of the general model provided in Equation 4. Multiple model specifications were explored in order to examine the effects of including different sets of control variables on the estimates of tradeoff parameters and technological progress. In each case, the coefficient on a continuous variable represents the partial derivative of log fuel consumption with respect to that variable. Since logs are also used for all continuous independent variables, each of these coefficients represents the elasticity of fuel consumption with respect to the corresponding variable. Model 1 employs a similar specification to that used by Knittel [9]. The remaining model specifications in Table 1 explore the effects of weight, acceleration performance, body style, powertrain type, and engine specific power on fuel consumption. Each model yields estimates of the degree of technological improvement (the year fixed effects) for each year since 1975, holding other variables in the model constant. In the interests of brevity, estimates of each year’s fixed effects are not reported here. Detailed fixed effect estimates, as well as additional model specifications, can be found in MacKenzie [16].

Model 1 provides a baseline comparison with the results of Knittel [9], and its specification is similar to that of Model 2 in Knittel’s work. The reported effects are similar in magnitude but opposite in sign to the results of Knittel, because Knittel used log of fuel economy (in miles per gallon) as

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8For example, in Model 5, the coefficient on log of inertia weight (\(\text{ln}\ W\)) indicates that the elasticity of fuel consumption with respect to inertia weight is 0.686. That is to say, according to this model, a 1% increase in inertia weight is expected to cause a 0.686% increase in fuel consumption.
the dependent variable, while the present work uses log of fuel consumption (gallons per mile) as the dependent variable. For our Model 1, the difference in the fixed effect estimates between 1980 and 2006 is equal to 0.503\(^9\), which is very close to the results reported by Knittel (0.512 between 1980 and 2006 in Knittel’s Model 2).

Our Model 2 controls for acceleration time instead of power, which leads to two important changes in the results. First, it increases the sensitivity of fuel consumption to weight. This is to be expected, since increasing weight at constant power generally leads to both higher fuel consumption and slower acceleration. To hold acceleration constant while increasing weight, an increase in power is required, which increases fuel consumption beyond what is expected from the weight change alone. The second notable change when controlling for acceleration performance instead of power is that the magnitude of the estimated technology changes (captured in the year fixed effects) increases. This is also to be expected, given the finding of MacKenzie and Heywood \[^8\] that newer vehicles can extract better acceleration performance from the same weight and power than could older vehicles.

Model 3 takes a further step toward controlling for attributes most relevant to consumer utility, introducing terms to control for all-wheel drive and for body styles (the presumed baseline body style is sedan/coupe). Not surprisingly, all-wheel drive is associated with higher fuel consumption, but this effect has been shrinking over time. Model 3 also drops the variables identifying different powertrain types. The reasoning behind this decision is that shifts toward more inherently efficient powertrain technologies are themselves a part of the overall process of technology change, so it is desirable to capture their contributions to overall efficiency in the year fixed effects.

Model 4 introduces the dummy variables for specific power quintiles. The coefficients on the specific power quintile variables decrease with increasing quintiles. This indicates that within a given year, vehicles with higher engine specific power tend to have lower expected fuel consumption, conditional on their other attributes. In addition, accounting for the specific power quintiles changes the coefficient estimates on weight and 0–97 km/h acceleration time. Since specific power is commonly used as a proxy for the technological

\[^9\] Specifically, the estimated year fixed effects were \(-0.153\) for 1980 and \(-0.656\) for 2006. Thus the expected change in log fuel consumption due to improved technology between 1980 and 2006, holding the other attributes in Model 1 constant, is \(-0.656 - (-0.153) = -0.503\).
The sophistication of the engine, this suggests that the relative sophistication of a vehicle’s engine (compared to others in the same model year) is correlated with weight and acceleration performance; new technologies are not applied uniformly across all vehicles.

In Model 5, the variables for powertrain type (diesel, hybrid, etc.) are reintroduced, in order to check whether the coefficient estimates on other variables are robust to their inclusion. Notably, the coefficient estimates on weight and acceleration performance change when the model includes powertrain type. This suggests that weight and acceleration also tend to be correlated with powertrain type, and that we may obtain biased estimates of the coefficients on weight and acceleration if we omit the variables indicating powertrain type. The estimates of technology change, reflected in the year fixed effects, also decrease in magnitude when powertrain type is included in the model. This latter result is consistent with the idea that growth in these powertrains (diesels, boosted gasoline engines, and hybrids) constitutes an increase in the technical efficiency of vehicles. Thus, when powertrain type is not explicitly controlled for, the fixed effects will capture the efficiency gains resulting from increased marked share of inherently more efficient powertrain types. However, when powertrain type is controlled for, efficiency gains stemming from the shifts in powertrain type will not be represented in the year fixed effects.

Models of fuel consumption that also include size (as measured by interior volume) have been documented in related work [16], and the corresponding findings are summarized here. Interior volume was found to have little effect on fuel consumption (outside of its effect on weight), and including it in the regression model did not significantly alter the coefficient estimates on other variables like acceleration time, weight, or powertrain type. Moreover, including interior volume in the regression did not significantly change the estimated year fixed effects.

Model 5 is the preferred specification among those investigated here, forming the basis of the technology potential calculated in the next section. Comparing Models 2–5, it is apparent that failing to account for body style, powertrain type, or engine specific power introduces biases into the estimates of the tradeoffs between fuel consumption, weight, and acceleration. Thus, Model 5 is preferred because it avoids the bias that would be introduced by omitting either engine specific power or powertrain type from the model specification (as in Models 2–4). Model 5 also has the greatest explanatory power (measured as the highest adjusted $R^2$ value) among all of the models.
investigated here, as well as among specifications that also included interior volume [10]. It should be emphasized, however, that since Model 5 controls for powertrain type, its estimates of technology improvement omit the gains due to the introduction of diesel and hybrid powertrains, and can thus be regarded as slightly conservative in this respect.
Table 1: Results of estimating regression models of car fuel consumption as a function of weight, size, power, acceleration performance, and related attributes. Standard errors for each estimate are listed in parentheses. All models also included fixed effects for year and manufacturer, but for the sake of brevity the estimates of these parameters are not reported here.

<table>
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<th>Model 1</th>
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<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
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<td>−6.153***</td>
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<td>ln Z97</td>
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<td>(0.006)</td>
<td></td>
</tr>
<tr>
<td>Turbo Gasoline</td>
<td>−0.038***</td>
<td>−0.052***</td>
<td></td>
<td>−0.040***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.002)</td>
<td>(0.002)</td>
<td></td>
<td>(0.002)</td>
<td></td>
</tr>
<tr>
<td>Hybrid Electric</td>
<td>−0.341***</td>
<td>−0.351***</td>
<td></td>
<td>−0.363***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
<td>(0.011)</td>
<td></td>
<td>(0.011)</td>
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</tr>
<tr>
<td>Specific Power Quintile 2</td>
<td></td>
<td></td>
<td></td>
<td>−0.010***</td>
<td>−0.020***</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>(0.002)</td>
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</tr>
</tbody>
</table>

Continued on next page
4.2. Overall Estimates of Technology Improvement

Figure 1 shows the actual average fuel consumption of new U.S. cars, along with several “potential fuel consumption” trajectories, each representing the estimated level of per-mile fuel consumption that could have been achieved if a particular set of attributes had remained constant at 1975 levels. The estimated year fixed effects from Model 1 (which are very similar to those of Knittel) are used to generate the red series in Figure 1. This series represents the expected fuel consumption, given estimated technology improvements, if the power and weight of new cars had remained at 1975 levels. The estimated year fixed effects from Model 5 represent the expected fuel consumption if acceleration performance, weight, and the market shares of wagons, two-seaters, all-wheel drive, and unconventional powertrains had all remained at 1975 levels. This scenario is represented by the green series in Figure 1. The blue series in Figure 1 represents the expected fuel consumption if acceleration, fraction of cars that were two-seaters, wagons and all-wheel drive, and the content of safety, emissions, and comfort & convenience features had remained constant since 1975.

Figure 1 highlights the vast improvements in automotive technical efficiency that have been made since 1975. In particular, it shows that:

- If power and weight had remained unchanged, per-mile fuel consumption could have been reduced by approximately 50% between 1975 and 2009. Between 1980 and 2006, the potential reduction is estimated to be about 40%, consistent with the results of Knittel [9].
- If acceleration and weight had remained unchanged, per-mile fuel consumption could have been reduced by nearly 60% between 1975 and 2009. In other
words, improvements in the ability to turn power into acceleration performance contributed the equivalent of a 16% fuel consumption reduction over this period.

• If acceleration, features, and functionality had remained constant, per-mile fuel consumption could have been reduced by approximately 70% between 1975 and 2009. In other words, new weight-saving technologies alone could have cut the average new car’s inertia weight by about 35%, and contributed the equivalent of a 25% reduction in per-mile fuel consumption over this
period.

- Between 1975 and 2009, the actual fuel consumption of the average new car was reduced by 50%.

Although the improvements in technical efficiency since 1975 have been impressive, they have not occurred consistently over time. Between 1975 and 1990, the potential reduction in fuel consumption averaged 5% per year. That is to say, per-mile fuel consumption could have been reduced by 5% annually over this period if not for changes in acceleration, features, and functionality of new cars. Between 1990 and 2009, however, the average rate of change was just 2.1% per year. This result is consistent with the findings of Knittel [9] that technology changed more rapidly in the 1980s than in subsequent years.

4.3. Sources and Sinks for Technology Gains

Up to this point, we have shown that improvements in technology have come from a number of sources: reductions in fuel consumption for a given level of power and weight; improvements in acceleration time, even for the same level of weight and power; and the introduction of vehicle architectures and materials that permit vehicle weight to be reduced while maintaining functionality. In this section, the relative contributions of each of these sources are first compared with one another over time. Then, we look at the major “sinks” for technology: the major attribute changes to which the technical efficiency improvements were applied.

Figure 2 shows the annual contribution of each major technology source to the overall potential reduction in fuel consumption. The red series represents the potential reduction in per-mile fuel consumption relative to the preceding year, that could have been realized if power and weight had remained unchanged. This is calculated as the year-over-year (percentage) change in the value of the red series in Figure 1. The green series represents the additional fuel consumption reduction that might have been realized each year if power had been reduced to maintain acceleration performance. This is calculated as the difference between the year-to-year changes in the green series in Figure 1 and the year-to-year changes in the red series in the same figure. The blue series represents the additional reduction that could have been realized if all weight-saving technologies had gone to reducing weight, rather than offsetting increased feature content. This is calculated as the difference between the year-to-year changes in the blue series in Figure 1 and the year-to-year changes in the green series in the same figure.

The red and blue series in Figure 2 move together; they both are higher in the earlier years and lower in more recent years. This is consistent with the intuition that when automakers are seeking to make efficiency improvements, they will encounter diminishing marginal returns in any one technology area and will seek to
equalize the marginal costs of efficiency improvement across multiple technology areas. The green series is much more volatile than the other sources of technology improvement. The volatility likely follows from the volatility in the acceleration analysis reported by MacKenzie and Heywood [8], which relied on only a sample of vehicles from each year. The volatility in the green series makes it difficult to determine whether there is any correlation between the green series and the other series.

Having assessed the contributions to overall efficiency improvement from various technology sources, we now turn to the question of where the efficiency im-

Figure 2: Contributions to potential reductions in per-mile fuel consumption from different technology areas.
provements have gone. To what design goals have the efficiency improvements been applied? To address this question quantitatively, Bandivadekar et al. [17] introduced a variable that they called Emphasis on Reducing Fuel Consumption (ERFC), which they defined as the ratio of the actual fuel consumption reduction realized over a certain period, and the potential reduction that could have been realized if size and acceleration performance had remained constant. Sperei and coauthors [13, 14] conducted similar analyses for new cars in Sweden. Adapting these concepts to the present context, ERFC is redefined here at the ratio of the actual reduction in fuel consumption of the average new car over some n-year interval, and the potential reduction that could have been achieved if acceleration performance, features, and functionality had remained unchanged:

\[ ERFC = \frac{gpm_{t} - gpm_{t+n}}{gpm_{t} - gpm_{t+n} \frac{gpm_{potential}}{potential}} \] (6)

In Equation 6, \( gpm \) denotes actual average fuel consumption, and \( gpm_{potential} \) denotes potential fuel consumption as calculated according to Equation 5. Figure 3 shows the ERFC over five-year intervals from 1975–2005 and over the four-year interval from 2005–09. Also shown are the annual average gasoline prices over the same period. Between 1975 and 1980, ERFC exceeded 100%, indicating that per-mile fuel consumption decreased by more than would have been expected at constant acceleration, features, and functionality. This is also evident in Figure 1 in which the black series decreases more rapidly than the other series in the early years. This suggests that either (1) actual technological improvement was greater over this period than has been estimated here, or (2) there was some pull-back in the levels of other attributes that enabled the larger decrease in fuel consumption. In fact, there was a slight decrease in acceleration times between 1975 and 1980, and a slight reduction in the weight associated with average size and feature content [8, 10]. These two effects appear to have approximately canceled one another out, so we can conclude that if it was a pull-back in attributes that enabled ERFC to exceed 100% over this period, it occurred in attributes other than acceleration performance and the size and feature content variables considered by MacKenzie et al. [10].

Between 1980 and 1985, ERFC fell to approximately 50%, and fell further in subsequent years, as gasoline prices remained low. Between 1995 and 2000, ERFC was negative, reflecting the fact that the average fuel consumption of new cars actually increased over this period. The emphasis on reducing fuel consumption became positive again between 2000 and 2005, and increased further between 2005 and 2009, a time when fuel prices were increasing.

Whereas ERFC addresses the question, “How much of the potential reduction
Figure 3: Emphasis on reducing fuel consumption among new U.S. cars, 1975–2009. The real price of regular unleaded gasoline is plotted on the secondary axis.

in fuel consumption has actually been realized?” a related question is “To what ends were the improvements in technology applied?” To answer the latter question quantitatively, it is possible to express the changes in acceleration, size, and feature content between two years, $t_1$ and $t_2$, in terms of equivalent reductions in fuel consumption. This was done based on the tradeoff coefficients from Equation 4 as shown in the following equations:
In the above equations, $Tech_{Size/Features}$ is the fractional reduction in per-mile fuel consumption that could have been realized in lieu of the observed change in weight from greater size or feature content, holding technology constant. $IWT_{t_1}$ is the average inertia weight of new cars in year $t_1$, and the $\Delta W_{t_1,t_2}$ is the change in weight between $t_1$ and $t_2$ that is attributed to either changes in the size mix or changes in feature content, as reported by [10]. Similarly, $Tech_{Z97}$ is the fractional reduction in fuel consumption that could have been achieved in lieu of changes in acceleration performance.

Let us consider a concrete example applying Equation 7 to the weight of new features. [10] estimated that the weight of features in the average new car increased by 135 kg between 1990 and 2009. Starting from a baseline inertia weight of 1,443 kg in 1990, this represents a 9.4% increase in weight. Applying the estimated value of $\beta_1 = 0.686$ from Model 5 in Table 1, we find that with the same technology needed to maintain constant per-mile fuel consumption while increasing weight by 9.4%, feature weight could have been maintained and fuel consumption reduced by 6.0%. Thus, the technology required to offset the weight of new features between 1990–2009 was the equivalent of a 6.0% reduction in fuel consumption.

Figure 4 summarizes the equivalent fuel consumption reductions that were needed to offset changes in acceleration, feature content, and size changes in the average new U.S. car from 1975–1990 and from 1990–2009. Between 1975 and 1990, the average per-mile fuel consumption of new cars decreased by 43%. Over the same period, the average acceleration time decreased by 30%, which “consumed” enough technology to have reduced fuel consumption by 15%. Greater feature content and size had relatively minor effects in this period. Comparing 1975–1990 with 1990–2009, the most striking difference is the large decrease in the actual fuel consumption change between the two periods. Average fuel consumption changed much less over the second period than over the first, but nevertheless still constituted the largest “sink” for technology changes over the second period. In the second period, slightly less technology was dedicated to offsetting faster acceleration times, while offsetting the weight impacts of new features consumed considerably more technology than in the first period (though this was still a smaller technological burden than faster acceleration times and fuel consumption reductions). The weight effects of increased size consumed very little technology in either period, reflecting the fact that net size shifts were relatively small over
these periods. (Throughout this paper, but especially here, the reader should bear in mind that the scope of the analysis is limited to new cars. Therefore, the size shift embodied in the transition from cars to light trucks is not reflected in the results reported here.)

Figure 4: Applications of technological improvements to fuel consumption reductions and to offsetting other attribute changes in new cars over two periods.

An alternative view of the technology sinks is provided in Figure 5. In this figure, the lower edge of the stacked areas represents the potential fuel consumption reduction that could have been achieved if size, acceleration performance, and feature content had remained unchanged at their 1975 levels. Each wedge represents
the potential fuel consumption reduction that could have been achieved if a certain attribute had remained at its 1975 level. For example, the red wedge shows that at its peak, offsetting the fuel consumption effects of greater size consumed enough technology to have reduced fuel consumption by about 5% or less. The figure illustrates how offsetting the fuel consumption penalties of faster acceleration has consumed a large and continually growing amount of new efficiency technologies.

Figure 5: Cumulative applications of technological improvements toward major attribute changes in new cars in five-year intervals. Each wedge represents the potential fuel consumption reduction that was dedicated to offsetting the fuel consumption penalties of other attribute changes.
4.4. Comparison with Other Published Results

In this section, some of the key results reported earlier in the paper are compared with analogous estimates previously reported by other authors. First, estimates of the tradeoff parameters between fuel consumption, acceleration performance, and weight are considered. Next, the estimates of the potential per-mile fuel consumption reduction since 1975 are compared with other authors’ estimates of this quantity.

4.4.1. Weight, Power, and Acceleration

Model specifications 2 – 5 in Table 1 indicated that holding acceleration constant, a 1% increase in weight is associated with a 0.60–0.73% increase in fuel consumption. Based on the preferred model specification (Model 5), a 1% increase in weight is expected to cause a 0.69% increase in fuel consumption. These results are consistent with literature, empirical, and simulation results presented by Cheah [18]. Cheah reviewed literature estimates and found estimates ranging from a 2–8% increase in fuel consumption for a 10% increase in weight. Her empirical analysis found that for a weight increase of 10%, fuel consumption of cars increases by about 5.6%, though she did not simultaneously control for other vehicle attributes. Finally, Cheah reported a set of vehicle simulation exercises, which yielded a 6.9% increase in fuel consumption for a 10% increase in weight, holding acceleration performance constant.

Knittel [9] estimated that holding power constant, a 1% increase in weight would cause a 0.4% decrease in fuel economy. As discussed in Section 4.1, it is not surprising that the sensitivity of fuel consumption to weight is higher when holding acceleration constant (as in the present work) than when holding power constant (as in Knittel’s work). Maintaining acceleration performance while increasing weight requires a commensurate increase in power. Thus, the overall effect of a weight increase on fuel consumption includes both the direct effect of greater weight, and the indirect effect of increasing power to maintain acceleration performance.

Several papers dating from the early 1990s addressed the tradeoff between weight and fuel consumption. Among these, typical effects of a 10% reduction in weight were a 3% increase in fuel economy at constant power, or a 6.6% increase in fuel economy at constant acceleration performance. Similarly, they used a value of a 0.44% increase in fuel consumption for a 1% decrease in the 0–97 km/h acceleration time [19, 20, 21].

More recently, a number of authors have used vehicle simulations to explore the tradeoffs between fuel consumption and power or acceleration performance. Figure 6 illustrates the results of several such exercises for midsize U.S. cars, along with the tradeoff calculated in this paper. The tradeoff identified in the present
analysis is very similar to that reported by Whitefoot et al. [22]. Compared with the results of Cheah et al. [23], the present work and the findings of Whitefoot et al. imply a smaller fuel consumption penalty for decreasing acceleration time. The discrepancy between the results of Cheah et al. and the others may be a result of the small number of vehicle simulations carried out by the former. The tradeoff estimated by Shiau et al. falls between the current results and those of Whitefoot et al. on the one hand, and those of Cheah et al. on the other.

Figure 6: Tradeoff between 0–97 km/h acceleration time and combined city/highway fuel consumption. Curves represent tradeoffs as estimated in this work and by other authors [22, 23, 24].
4.4.2. Powertrain Technologies

The results that were presented in Table 1 also contained estimates of the fuel consumption effects of various powertrain technologies. Holding acceleration and weight constant, a manual transmission was estimated to deliver a 12–14% reduction in fuel consumption in the base year (1975), though this advantage has been declining by about 0.3% per year. These results are similar to those reported by Knittel though slightly larger. This most likely reflects the fact that manual transmissions offer better acceleration performance than automatics, so the fuel consumption benefit of a manual is greater when controlling for acceleration performance than when controlling for power. Similarly, all-wheel drive or 4-wheel drive was estimated to incur a 8–11% fuel consumption penalty in 1975 (in addition to the associated weight penalty), though this has been declining by an estimated 0.2% per year. The shrinking fuel consumption penalties associated with automatic transmissions and all-wheel drive can be interpreted as an indication that automobile manufacturers are making technological improvements in these particular subsystems.

Naturally aspirated diesels delivered an estimated 18% fuel consumption reduction, and turbodiesels approximately a 25% reduction. This is within the range of 20–30% reported by EPA [4], and is similar to the 24% fuel consumption benefit of dieselization reported by Bandivadekar et al. [17]. In contrast, the fuel consumption benefits estimated here for boosted gasoline engines (3–5%) are lower than the 10% calculated by Bandivadekar et al. [17] for current turbocharged engines. This is most likely because boosted gasoline engines tend to have high specific power. Being in the top quintile for engine specific power is estimated to reduce fuel consumption by a further 2–4% relative to the middle quintile, so if boosted gasoline vehicles are all in the top quintile, then a more accurate estimate of their fuel consumption benefit would be 5–9% compared with the average new car. The estimated 30% fuel consumption benefit of hybridization was similar to the results of Bandivadekar et al. [17], and within the 20–40% range reported by EPA [4].

4.4.3. Technological Improvements

In this paper, estimates have been developed for the rate of technological improvement in new U.S. cars since 1975, expressed as the potential reductions in per-mile fuel consumption that would have been achieved if not for changes in

\[ \text{Bandivadekar et al. [17]} \] reported that current diesel cars offer about a 16% reduction in fuel consumption on an energy-equivalent basis, relative to a naturally aspirated gasoline car. Adjusting for the 10% greater energy content of diesel, this is equivalent to a 24% reduction in fuel consumption on a volumetric basis. The EPA fuel economy numbers used in this work are reported on a volumetric basis.
other vehicle attributes, namely acceleration, features, and functionality. Central to our approach is the estimation of expected changes in log fuel consumption over time while controlling for changes in other vehicle attributes, using the regression model in Equation 4. The regression outputs are translated into potential fuel consumption reductions according to Equation 5. Other investigators have addressed this question in the past, using different time periods, different methodologies, and controlling for different vehicle attributes. Table 2 summarizes some of these studies for the U.S. and compares their estimates of technology change with the results of the present analysis over the same time period.

Table 2: Annual rates of technology improvement* for the United States: comparisons between results of this analysis and literature estimates. Each literature study provided estimates of how much fuel consumption would have been reduced if other vehicle attributes had remained constant over time.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Controlled For</th>
<th>Years</th>
<th>Annual Technology Improvement</th>
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</thead>
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<tr>
<td>Greene and Fan [21]</td>
<td>hp/wt</td>
<td>1975–1993</td>
<td>3.6%</td>
</tr>
<tr>
<td>Greene and Fan [21]</td>
<td>hp/wt, wt</td>
<td>1975–1993</td>
<td>2.8%</td>
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<tr>
<td>Lutsey and Sperling [3]</td>
<td>size, wt, accel</td>
<td>1987–2004</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

* Defined as the potential reduction in fuel consumption if other attributes had remained constant.

Each row of Table 2 contains a reference to a prior estimate of annual technology improvement for new U.S. cars, expressed as the potential reduction in per-mile fuel consumption if other attributes had remained constant. Also listed are the particular attributes that were controlled for in each analysis, and the years that were considered. The last column contains the potential reduction in fuel consumption over the period in question as estimated in this paper. The estimates developed in this work are intended to reflect the potential improvements holding acceleration performance, features, and functionality (including size and comfort) constant.

Most of the literature estimates in Table 2 are smaller than the estimates...
developed here, reflecting the broader scope of technology improvements captured by the present work. The technology change estimates reported by An and DeCicco [7] come closest to the estimates developed here, but as discussed in Section 1 there are important disadvantages to An and DeCicco's assumption of a 1:1:1 tradeoff between fuel economy, interior volume, and power/weight ratio. When considering different time periods, An and DeCicco's estimates yield different results than the present work. For example, their method yields 4.2% per year from 1977–1990 and 2.3% per year from 1990–2005. In contrast, the current work indicates a sharper difference in the rate of technology change between these two periods: 4.9% per year from 1977–1990 versus 1.9% per year from 1990–2005.

Table 3 summarizes the rates of automotive technology improvement in several European countries as estimated by prior investigators. As with the U.S. estimates, methodological approaches varied between studies. The results of Sprei and coauthors [13, 14] are most analogous to the results of the present work, as they represent estimates of potential fuel consumption change after correcting for changes in acceleration, size, and feature content. In fact, our results indicate an annual rate of technology improvement of 2.5% per year for U.S. cars from 1985–2009, very similar to the estimated 2.4% per year improvement estimated for Sweden between 1985–2010.

Table 3: Annual rates of technology improvement* estimated for other countries. Each literature study provided estimates of how much fuel consumption would have been reduced if other vehicle attributes had remained constant over time.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Controlled For</th>
<th>Years</th>
<th>Country</th>
<th>Annual Improvement</th>
</tr>
</thead>
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<tr>
<td>Sprei et al. [13]</td>
<td>size, accel, features</td>
<td>1985–2002</td>
<td>Sweden</td>
<td>2.0%</td>
</tr>
<tr>
<td>Van den Brink and</td>
<td>weight, engine size</td>
<td>1985–1997</td>
<td>Netherlands</td>
<td>1.3%</td>
</tr>
<tr>
<td>Van Wee [12]</td>
<td></td>
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</tbody>
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* Defined as the potential reduction in fuel consumption if other attributes had remained constant.
5. Conclusions

In order to assess the feasibility of mandated fuel consumption reductions, it is helpful to quantify the tradeoffs between vehicle fuel consumption, weight, and acceleration performance. Empirical analysis of cars offered for sale in the U.S. since 1975 yielded an estimate of a 0.69% reduction in fuel consumption for a 1% reduction in inertia weight, which is consistent with values reported in the literature. The effect of a 1% increase in acceleration time was sensitive to model specification, but in the preferred model specification was estimated to cause a 0.44% decrease in fuel consumption, holding all else equal.

This paper developed a broader view of technology improvements than has been reported in previous studies of automotive technology improvement. Improvements in the fuel efficiency technology of new cars in the U.S. since 1975 have been impressive. The work reported in this paper has shown that between 1975 and 2009, per-mile fuel consumption could have been reduced by approximately 70%, or an average of 3.4% per year, if not for reductions in acceleration time and the introduction of new features and functionality to vehicles. However, this progress has not been uniform: improvements averaged 5% per year from 1975–1990, but only 2.1% per year from 1990–2009. These estimates of potential fuel consumption reductions are greater than estimates previously reported in the literature. This is because the present work takes a broader view of technology improvement than have previous investigations, and captures additional sources of improvement. These include improvements in acceleration performance for a given level of weight and power, and weight-saving technologies that enable more features and functionality to be added to a vehicle without increasing weight.

The ends to which technological improvements have been applied has varied over time. In the late 1970s, all of the improvements in car efficiency technology (and then some) were realized as reductions in per-mile fuel consumption. Since that time, the emphasis on reducing fuel consumption declined, and was even negative for a few years in the 1990s as the average fuel consumption of new cars actually increased. In recent years, it has again rebounded, and between 2005 and 2009 about 75% of the potential fuel consumption reduction was realized.

In light of these findings, the fuel economy standards recently finalized for 2025 appear to be ambitious. Even if features, functionality, and acceleration remain at current levels, cars would need to sustain average annual
improvements of 4.3% per year for 14 years in order to comply with the 2025 standards. This is much higher than has been observed in recent years, though it is within the range of the improvements that were achieved between 1975 and 1990. If automakers hope to further reduce acceleration times, or to increase features or functionality in any way that adds weight to their vehicles, they will need to improve their technology even faster to offset these changes while still meeting the standards. Alternatively, automakers may focus on improving functionality through what DeCicco [25] calls “virtual performance,” IT-based driver assistance and infotainment features that do not force tradeoffs against fuel economy. Continued reductions in acceleration times of 10–15%, consistent with the trends identified by MacKenzie and Heywood [8], would require an additional 0.3–0.5 percentage point increase in the annual rate of technology improvement. Continued increases in feature weight of 7 kg/year, consistent with the trend since 1980 [10], would require a further 0.4 percentage point increase in the rate of technology improvement. All told, meeting the 2025 CAFE standard while continuing historical trends in acceleration performance and feature content will require technology improvement of at least 5% per year, slightly exceeding the rates observed between 1975 and 1990.

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7. References


