Energy Efficiency, Fuel Economy, and Policy Implications

Nicholas Lutsey and Daniel Sperling

In the past 20 years, the acceleration performance of light-duty vehicles in the United States has improved substantially while vehicles have gotten larger and heavier. Over the same period, fuel economy, measured as miles per gallon, has not improved. These data suggest that technological innovation in vehicles is not lagging but is not being used to improve vehicle fuel economy. This paper quantifies vehicle efficiency improvements in U.S. light-duty vehicles since 1975 as they relate to fuel consumption. Energy efficiency improvements have been strongly positive and relatively constant since 1975. The rapid rise in fuel economy in the late 1970s was due to a mix of efficiency improvements and downgrading of utility in the form of reduced size, power, and elimination of accessories and amenities (such as air conditioning). In contrast, since the mid-1980s, fuel economy has remained constant while the benefits of technological innovation were used to satisfy private desires (more power, size, and amenities), instead of the public interest (reduced greenhouse gas emissions and oil imports). An important policy question is how and to what extent future efficiency innovations might be directed to the public interest.

In the past 20 years, the average performance of light-duty vehicles in the United States (measured as 0- to 60-mph acceleration and maximum power output) has improved substantially, and vehicle weight and size have increased; over this time period fuel economy, measured as miles per gallon (mpg), has not improved at all (*1*). These trends suggest that vehicle efficiency, in a technical sense, continues to improve but that efficiency innovations are not being used to improve fuel economy. This paper quantifies vehicle efficiency improvements in U.S. light-duty vehicles since 1975 as they relate to fuel consumption.

This understanding of efficiency improvement can serve as a key input to policy and regulatory actions. It provides a baseline of what technological efficiency improvements are typical and serves as a guide to determine how aggressive fuel economy and greenhouse gas emissions policies can be without disrupting vehicle marketing and manufacturing plans and activities.

A number of regulatory initiatives have been adopted throughout the world that challenge major automobile manufacturers to achieve reductions in new vehicle fuel consumption and climate change emissions. In Europe, a voluntary agreement by automobile makers calls for a 25% reduction in carbon dioxide emissions per kilometer from light-duty vehicles between 1995 and 2008 (*2*). New standards in Japan are set to improve fuel economy by approximately 23% between 1995 and 2010 (*3*). China is moving toward instituting fuel consumption standards for the first time, with new light-duty vehicles from 2005 and later being regulated more stringently than in the United States (*4*). California's proposed climate change standard would reduce climate change emissions by about 30% for vehicles by model year 2016 (*5*), corresponding roughly to a 30% to 40% increase in fuel economy. New initiatives in Canada and some northeastern U.S. states modeled on the California law suggest the possibility that aggressive new greenhouse gas rules may be implemented more broadly in North America in the near term—even though U.S. corporate average fuel economy (CAFE) standards have not changed since 1990 for passenger cars (27.5 mpg) and since 1996 for light trucks (20.7 mpg). There are no plans currently to raise the passenger car CAFE standard, but the light-truck CAFE standard increases to 22.2 mpg (about 7%) for 2007 (*6*).

Regulatory initiatives toward improved fuel economy (and climate change emissions) in the new light-duty vehicle fleet have been supported by numerous studies that assessed the potential of emerging technologies (*7–12*). These studies generally assess the costs and benefits of particular emerging vehicle technologies (e.g., variable valve technologies, gasoline–electric hybridization, and transmission technologies) to determine fuel savings of the incremental technology cost to vehicle owner operators. In those studies, technical and economic feasibility of new technologies is assessed to investigate more stringent average levels of fuel consumption and climate change emissions for light-duty vehicles.

This paper examines historical vehicle performance and efficiency data to understand better the introduction of efficiency technologies and how the potential effects of these technologies have been traded for other vehicle attributes. Various vehicle characteristics are analyzed that affect vehicle fuel economy for vehicle model years 1975–2004. Trends are discerned primarily from publicly available data from the Environmental Protection Agency (EPA) on vehicle characteristics (*1*). A metric for engine and drivetrain efficiency is developed to differentiate between the various methods of improving fuel economy (i.e., vehicle load reduction and efficiency improvements), and a nuanced definition and interpretation of how CAFE standards have been "binding" over the years are offered to further highlight key attribute trade-offs since 1975.

HISTORICAL CONTEXT

CAFE standards were enacted by the U.S. Congress in 1975 to reduce passenger vehicle petroleum use. There has been considerable debate over many aspects of the standard, including its overall effect, associated costs, two-tiered structure (light trucks and cars), division between imported and domestic products, and effects on safety. More general examination of CAFE and its pros, cons, and general effects

---

Institute of Transportation Studies, University of California, Davis, 1 Shields Avenue, Davis, CA 95616.

Transportation Research Record: Journal of the Transportation Research Board, No. 1941, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 8–17.

on fuel consumption and the economy can be found elsewhere (*13, 14*) and are beyond the scope of this paper. Instead of studying U.S. fuel economy through an econometric lens, this paper looks at it from a technology perspective, investigating how vehicle technology has been deployed, with various consumer- and regulatory-driven demands pulling it in different directions over the past 30 years. Over this time period, vehicle product offerings, fuel price spikes, fuel economy standards, large changes in vehicle size preferences, and a growing desire for vehicle performance in acceleration and towing have all influenced the vehicle fleet and offer a rich data set for the examination of how technology attributes are traded off. First, key vehicle technology trends related to vehicle fuel efficiency are reviewed.

EPA uses a simple metric for vehicle energy efficiency: ton-mpg, the mass of the vehicle (ton) multiplied by the distance traveled (mile), divided by the fuel consumed (gallons of gasoline). This energy efficiency metric is plotted against fuel economy in Figure 1 for new vehicles from 1975 to 2004. This metric is a good measure of efficiency improvements, with some important exceptions. The metric does not disaggregate the effects of different efficiency technologies used in new vehicles, including improved load reduction (e.g., aerodynamics, rolling resistance) and engine and drivetrain efficiency technologies. It also does not account for how weight has fluctuated due to other technology advances over the past 30 years and thus affected fuel economy in different ways. By offering a metric that separates efficiency improvements from weight, this paper takes a step toward an enhanced explanation of all the attributes that most affect fuel economy. Efficiency improvements are examined more carefully and specifically than was done by EPA to understand better

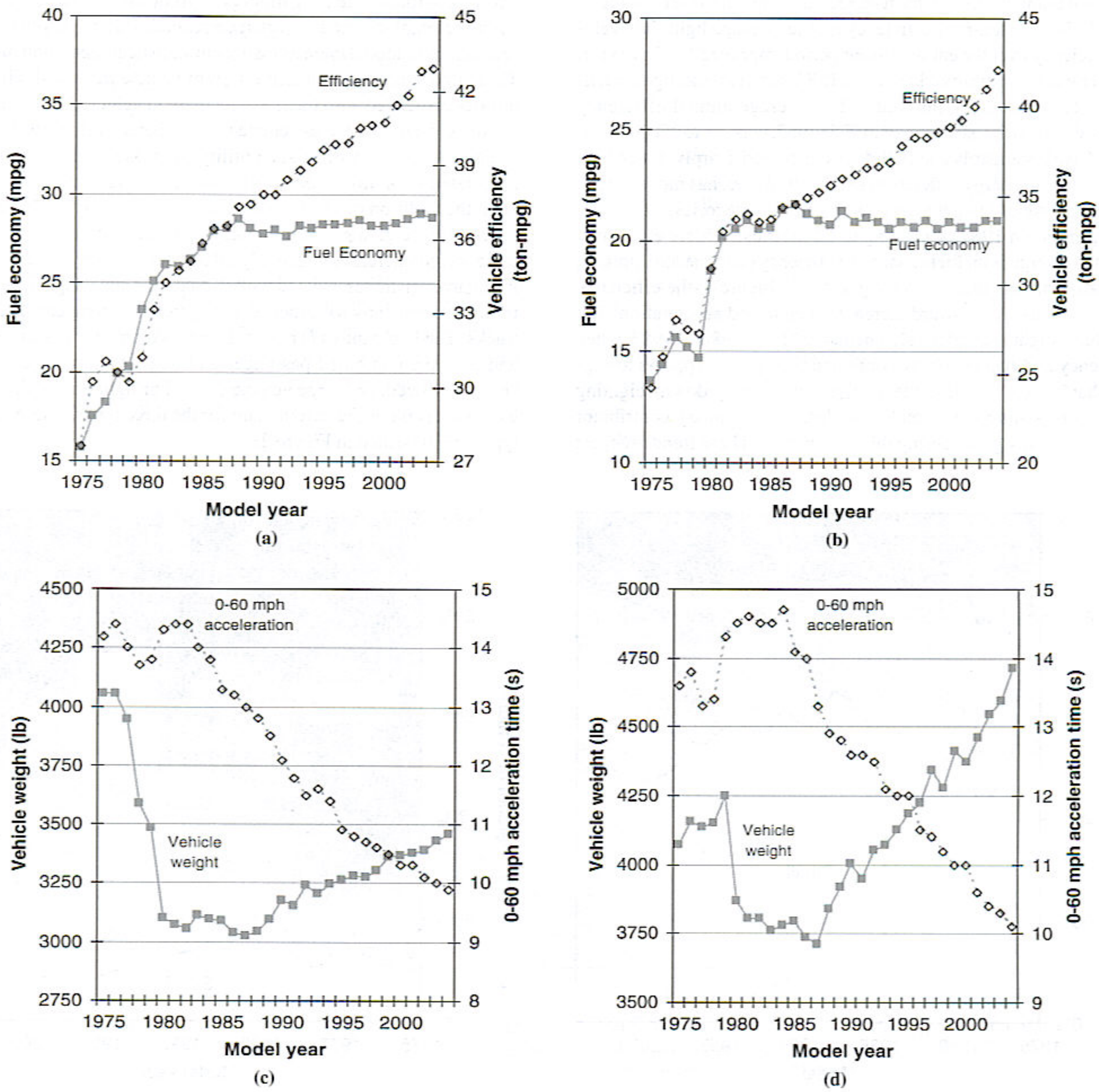


FIGURE 1 Fuel economy and other vehicle attribute trends for light-duty vehicles, 1975–2004 (*1*): (*a* and *c*) passenger cars and (*b* and *d*) light trucks.

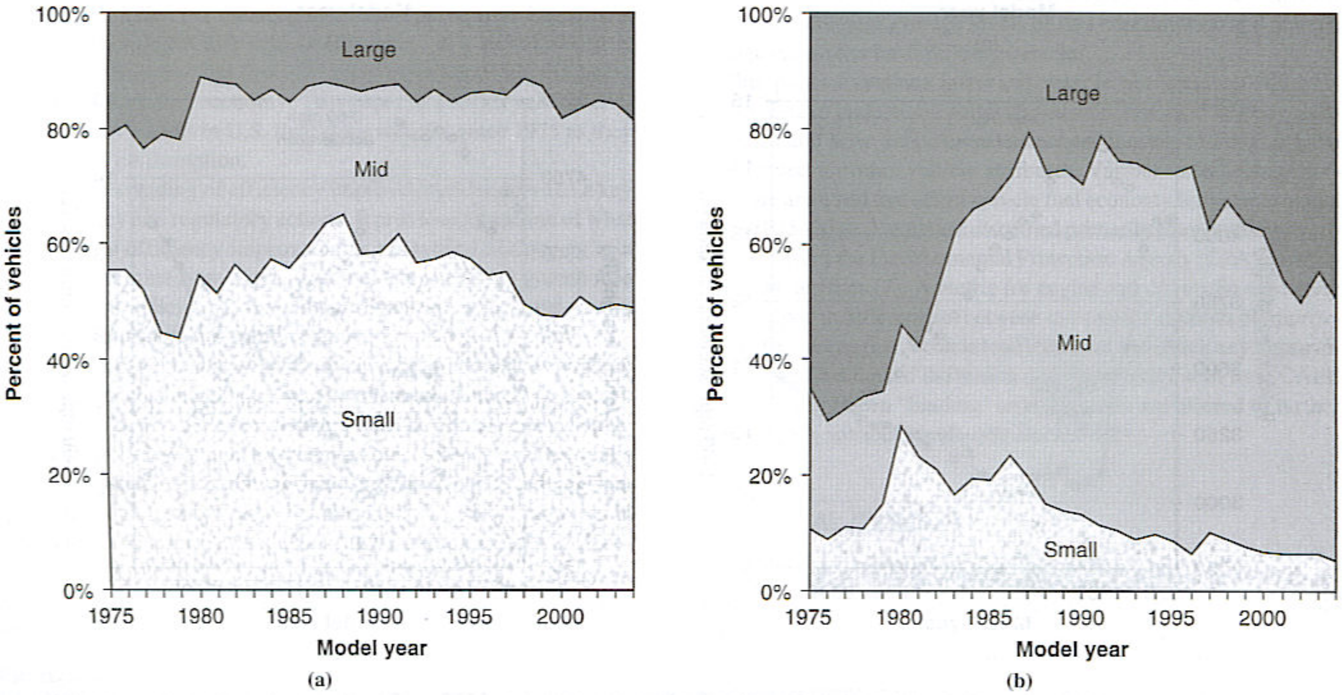
the technology innovation and deployment process of the automotive industry. The following three hypotheses are explored:

1. Vehicle efficiency improvements over the past 20 years have primarily gone to improved vehicle acceleration and vehicle size and weight increases (and not improved fuel economy).
2. CAFE standards have been decreasingly "binding" over the 30-year history of CAFE standards, with fewer vehicle attributes being constrained over the years to improve fuel economy.
3. As long as there is a competitive market and industry, energy efficiency improvements will be relatively constant over time.

This paper focuses on three time periods: 1975–1980, 1980–1987, and 1987–2004. In the first two time periods, fuel economy increased dramatically, and in the most recent period it was constant. In the first period, the EPA energy efficiency metric suggests that efficiency also increased dramatically but that it increased at a much slower rate thereafter. Using this ton-mpg efficiency metric, average light-duty vehicle efficiency over the entire 30-year period improved 1.6% per year. (Passenger cars improved at about 1.5% per year and light trucks improved about 2.0% per year.) The average annual efficiency improvement in the earlier years, 1975–1987, was 2% to 3% per year, when CAFE standards and fuel prices increased sharply. Since then the increase in energy efficiency, using this metric, has moderated to a constant rate of 1% per year in both vehicle categories.

Beginning in 1987, according to all metrics, vehicle efficiency began to diverge from fuel economy. Efficiency continued to improve, but fuel economy did not. As suggested in Figure 1, the efficiency improvements went toward increased weight and acceleration. The fact that weight was relatively unchanged from 1980 to 1987, when efficiency and fuel economy continued to improve, appears to suggest that vehicle efficiency technology, not simply downweighting vehicles or selling more small vehicles, was a primary contributor to fuel economy gains during this time period. These trends suggest that there have been distinctly different ways in which average fuel economy has kept pace with the CAFE standards. This point, that CAFE binds different attributes in different ways, provoked the hypothesis that the attribute binding effect of CAFE has differed over the years and that it has become decreasingly binding on automobile makers in deploying fuel efficiency technology. With the objective of CAFE to reduce petroleum usage via improved fuel economy, the authors are concerned with whether the cluster of technology attributes on vehicles is in fact actually bound to improve fuel economy. Although, in more recent years, CAFE standards have provided a floor that has constrained average fuel economy from decreasing in each vehicle category, its overall binding effect on the entire vehicle technology package has diminished by allowing efficiency improvements to be converted to advances in vehicle performance and size.

In addition to vehicle weight, vehicle size was considered in the analysis. Although these variables (weight and size) clearly bear a strong resemblance and are often correlated with one another, there are reasons to model them as distinct in statistical regression models. These two variables represent different vehicle traits with different utilities associated with them. An increase in vehicle size offers passenger and cargo space to vehicle users, whereas vehicle weight per se does not directly offer such utility. Increased vehicle weight is associated with utility indirectly when the weight increases result from the addition of safety features, towing capacity, or increased accessories (e.g., air conditioning, electronics); on the other hand, these weight increases negatively affect fuel economy. These differing characteristics associated with vehicle size and weight imply differing relationships with fuel economy trends among cars and light trucks. The EPA study (*1*) reports interior volume for passenger cars and uses the combined passenger and cargo volume to designate small, midsized, and large vehicle types. For light trucks, the report uses wheelbase as the determinant for the three types. These vehicle types are presented in Figure 2.



(a) (b)

FIGURE 2 Vehicle size classes for light-duty vehicles, 1975–2004 (*1*): (*a*) passenger cars and (*b*) light trucks.

ANALYSIS

Vehicle Efficiency Characteristics

In an effort to understand better the diverging fuel efficiency and fuel economy trends shown in Figure 1, the effects of various efficiency technologies were analyzed. Efficiency technologies were split into two basic categories: engine and drivetrain technologies and vehicle load reduction technologies. These two areas of vehicle energy use are presented schematically in Figure 3. Engine and drivetrain technology improvements improve the combustion of the fuel into useful mechanical energy and the efficient transfer of that energy to the vehicle's wheels for traction. Examples of these technologies include improved fuel–air mixing, increased control of valve timing, and reduced transmission losses by shifting to more gears. Load reduction technologies, on the other hand, involve reducing the amount of total work required to propel the vehicle. Areas for load reduction include the use of lower aerodynamic drag vehicle designs, reduction of tire rolling resistance, and reducing the weight of the vehicle. In this section, the trends in these different aspects of vehicle efficiency are analyzed.

Load Reduction

Estimations of aerodynamic and rolling resistance friction coefficients are presented in Figure 4. Because these coefficients are not published alongside EPA fuel economy data, these data were estimated from the available literature. For aerodynamic drag, the trend was estimated from textbook data from sedans from three major automobile makers (*15*). These data were extrapolated into recent years to match average drag coefficients of 0.31 for passenger cars and 0.41 for light trucks. A similar method was used to estimate the rolling resistance coefficient of new vehicles. Data were taken from Michelin sources (*16, 17*) and reconciled with values of 0.009 for current average cars and 0.012 for current light trucks.

In the case of load reduction via decreasing vehicle weight, few data were available to distinguish between several weight-related trends: (*a*) an overall increase in weight due to increased accessories and safety enhancements; (*b*) the decrease in weight due to the use of high-strength, lightweight materials or improved structural designs; and (*c*) weight changes due to sales mix trends to different size classes. Ideally, these separate trends would be disentangled, allowing analysis of the impacts of efficiency-oriented weight reduction; however, in the absence of appropriate data to do so, this task was forgone. To some extent, these sales mix changes are incorporated by the separation of cars and light trucks and the inclusion of a vehicle size variable in the analysis, but these effects were not further analyzed.

Engine and Drivetrain Efficiency

A metric was established to estimate vehicle efficiency based on publicly available vehicle fuel use and weight characteristics, theoretical road load equations, and average vehicle attributes. Efficiency generally is the percentage of energy input that contributes to any desired output. As defined here, a vehicle's engine and drivetrain efficiency is the percentage of fuel energy consumed that contributes to moving the vehicle or overcoming the vehicle road load. The energy required to propel the vehicle includes the inertial energy to accelerate the vehicle and the energy to maintain a given speed due to aerodynamic drag and rolling resistance at the wheels. Defining and evaluating efficiency in this way incorporate the operation of the fuel intake system, fuel combustion, engine friction, and the drivetrain.

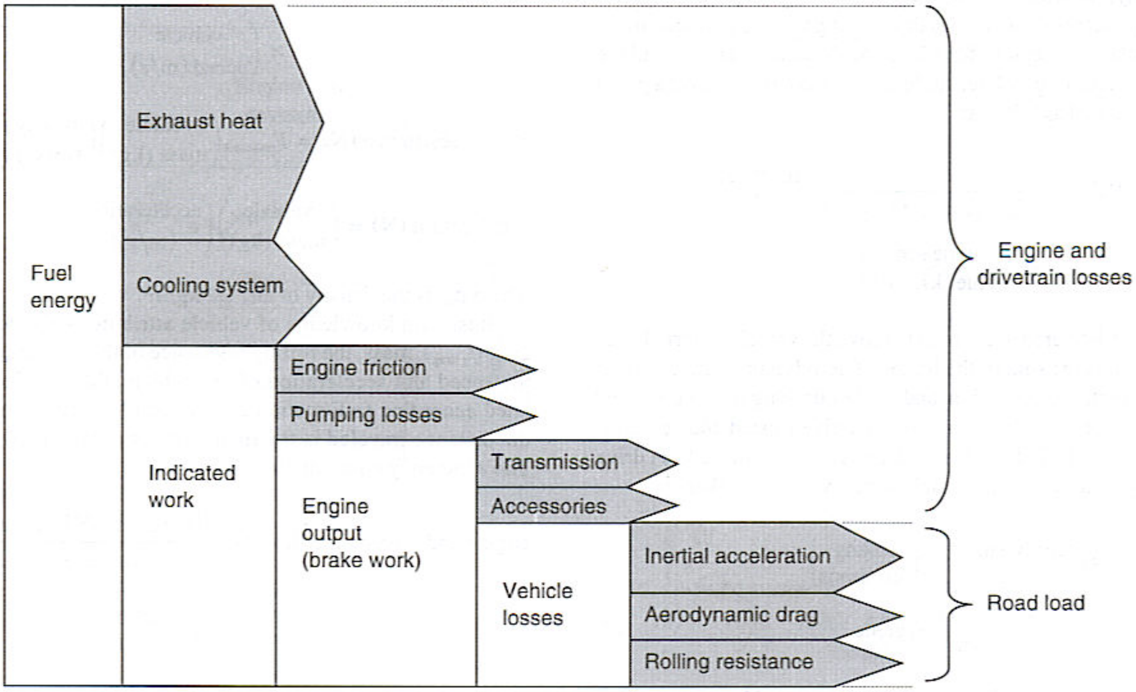
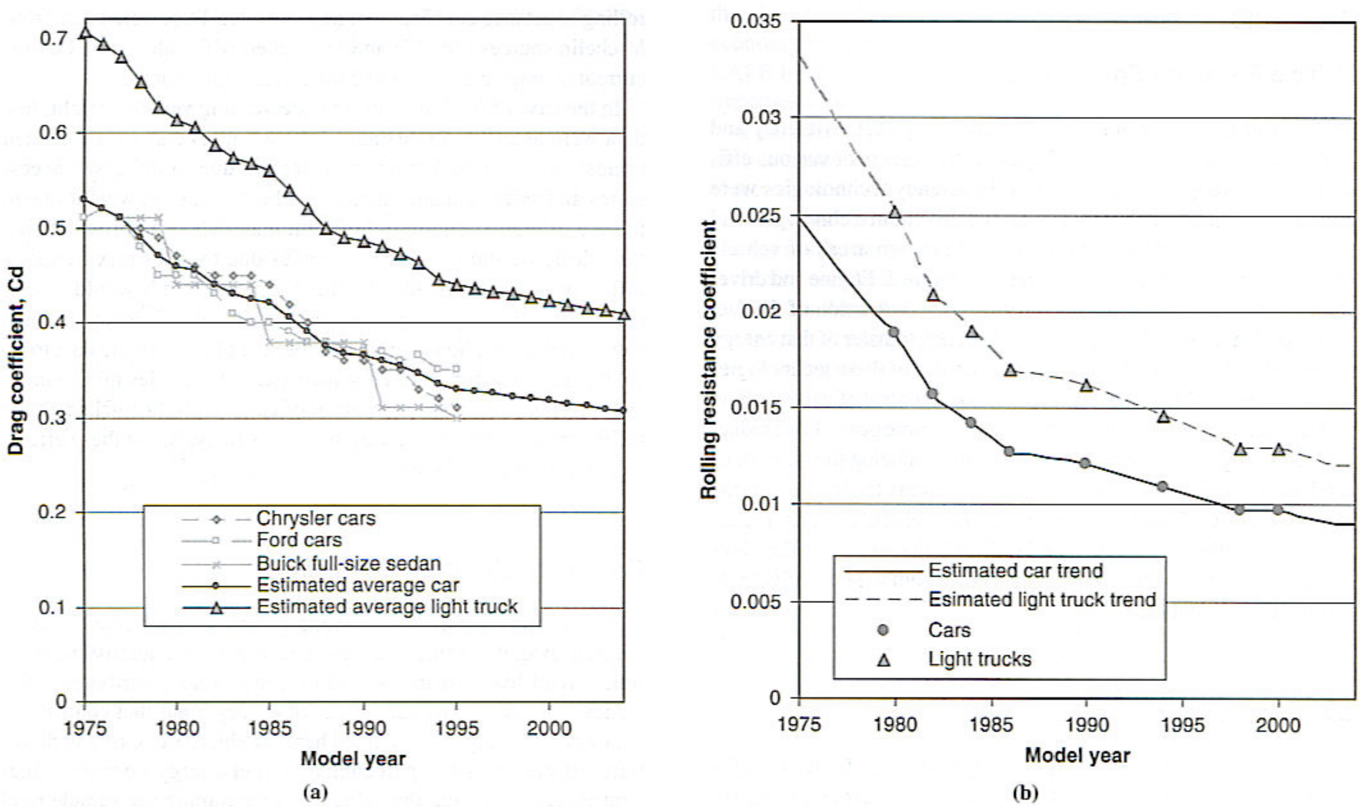


FIGURE 3 Qualitative vehicle energy breakdown [based on TRB (*7*)].



(a)

(b)

FIGURE 4 Estimated new vehicle aerodynamics and tire rolling resistance, 1975–2004: (*a*) aerodynamic drag [based on Hucho (*15*)] and (*b*) rolling resistance [based on California Energy Commission (*16*) and LaClair (*17*)].

Determining the amount of fuel that is consumed for vehicle travel is relatively straightforward based on EPA data on fuel economy over the "city," or federal test procedure, and "highway" drive cycles. Using fuel economy data in miles driven per gallon of gasoline (mpg) over particular drive cycles for which the distance is known and the low heating value of gasoline, the fuel energy consumed over a given cycle is calculated as follows:

$$\text{fuel energy (kJ)} = \left(\frac{1}{\text{fuel economy(mpg)}}\right)\left(\begin{matrix}\text{distance}\\ \text{(mi)}\end{matrix}\right) \times \left(\begin{matrix}\text{low heating}\\ \text{value (kJ/gal)}\end{matrix}\right) \qquad (1)$$

The power delivered to the road to move the vehicle, referred to as the road load, is the sum of the forces of aerodynamic drag, rolling resistance, inertial acceleration, and grade-climbing forces that must be overcome for the vehicle to move at a given speed and acceleration. Grade is not included because there is no grade in the EPA drive cycle test procedure on which fuel economy data are taken.

$$\text{road load (N)} = \left(\begin{matrix}\text{aerodynamic}\\ \text{drag}\end{matrix}\right) + \left(\begin{matrix}\text{rolling}\\ \text{resistance}\end{matrix}\right) + \left(\begin{matrix}\text{inertial}\\ \text{acceleration}\end{matrix}\right) + (\text{grade}) \qquad (2)$$

where the components of Equation 2 are determined by the following equations:

$$\text{aerodynamic drag (N)} = 0.5\left(\begin{matrix}\rho_{\text{air}}\\ (\text{kg/m}^3)\end{matrix}\right)(C_{\text{drag}})\left(\begin{matrix}\text{frontal}\\ \text{area (m}^2)\end{matrix}\right) \times \left(\begin{matrix}\text{vehicle}\\ \text{speed (m/s)}\end{matrix}\right)^2 \qquad (3)$$

$$\text{rolling resistance (N)} = F_{\text{resistance}}\left(\begin{matrix}\text{vehicle}\\ \text{mass (kg)}\end{matrix}\right)\left(\begin{matrix}\text{gravity}\\ (\text{m/s}^2)\end{matrix}\right) \qquad (4)$$

$$\text{acceleration (N)} = \left(\begin{matrix}\text{vehicle}\\ \text{mass (kg)}\end{matrix}\right)\left(\begin{matrix}\text{acceleration}\\ (\text{m/s}^2)\end{matrix}\right) \qquad (5)$$

where ρ_{air} is the density of air, 1.2 kg/m^3.

Thus, with knowledge of vehicle attributes—the coefficient of drag (C_{drag}), mass, the rolling resistance of the tires ($F_{\text{resistance}}$)—and the speed and acceleration of the vehicle, the road load is calculated according to Equation 2. The road load force multiplied by the distance traveled is the final work or energy used at the tires. The efficiency equation then becomes

$$\text{engine and drivetrain efficiency} = \frac{\{[\text{road load (N)}][\text{distance (m)}]\}}{\text{fuel energy (kJ)}} \times \left(\frac{\text{kJ}}{10^3\text{N m}}\right)100\% \qquad (6)$$

A series of averaging estimations are utilized to be able to use these theoretical equations to approximate vehicle efficiency for this analysis. Calculations for efficiency were done separately for the two drive cycles, highway and urban, for which data were available about the drive cycle characteristics (distance, time, speed, and acceleration) (*18*). The average amount of fuel consumed (mpg) for 2004 vehicles on each of the cycles was taken from the EPA trends report (*1*). Average vehicle characteristics of rolling resistance, drag coefficient, and vehicle inertial weight are used from the preceding figures for cars and light trucks. Although this methodology gives only a gross, nonrigorous estimation for the actual engine and drivetrain efficiency, the resulting changes in this measure of efficiency should be relatively accurate when comparing different years within the same population and data set of vehicles.

Figure 5 presents an estimation of engine and drivetrain efficiency with fuel economy. By inspection, the vehicle engine and drivetrain efficiency and fuel economy curves bear a resemblance to each other, showing strong upward trends in the late 1970s and being mostly flat through the 1990 model years. On the other hand, there are substantial differences between the curves in some of the earliest and latest model years. The increases in this efficiency metric encompass efficiency improvements in the vehicle engine (e.g., going from two to four valves per cylinder, reduced engine friction) and transmission (e.g., automatic three speed to automatic four speed). To some extent, the early fluctuations in efficiency from 1975 to 1980 are showing the effects of weight changes; vehicle downsizing (via sales mix, smaller within-class vehicles, and lightweighting) inherently affects efficiency based on the theoretical road load calculation. The largest engine and drivetrain increase for light trucks is from 1978 to 1982. This period coincides with a peaking of diesel sales at 10% and rapid replacement of carburetors with fuel injection technologies for light trucks.

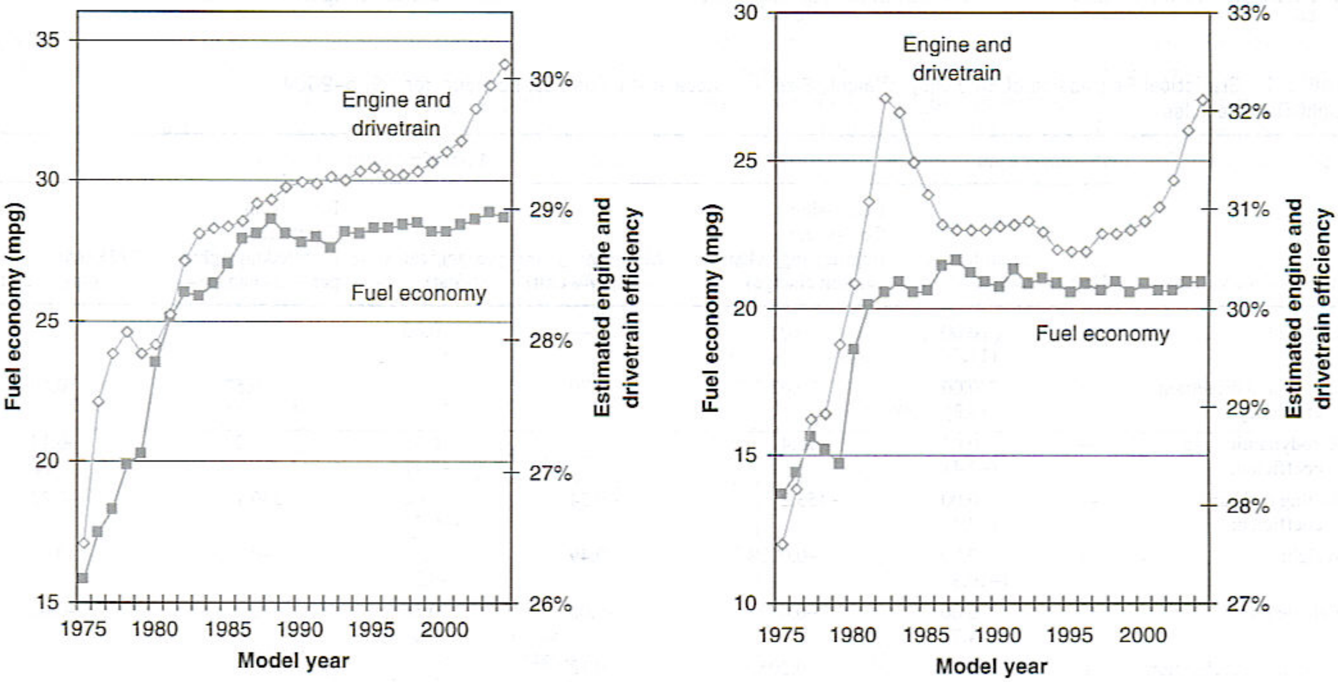
Some of the key technology trends that are likely contributors to the efficiency trends are presented in Figure 6. For both cars and light trucks, the 1980s saw the introductions of fuel injection in place of carburetors and torque converter lock-up for automatic transmissions. Through this time period, three-speed transmissions were being replaced with four-speed transmissions (for automatic) and five-speed transmissions (for manual). Car efficiency is also improving due to the switch from rear- to front-wheel drive. More recent efficiency improvements are to some extent driven by the increase in the number of valves per cylinder. Likely negative influences on engine and drivetrain efficiency are the slow increase of automatic transmissions, air conditioning systems, and four-wheel (or all-wheel) drive.

Statistical Analysis

A linear statistical regression was used to analyze the correlated effects of the three efficiency factors (engine and drivetrain efficiency, aerodynamics, and rolling resistance), vehicle weight, vehicle size, and acceleration on fuel economy. It is hypothesized that fuel economy is positively affected by efficiency and that the load reduction technologies of aerodynamics and tire friction are negatively correlated with fuel economy. As weight and size increase and as acceleration time is reduced, fuel economy will be negatively affected.

$$\begin{aligned}\begin{pmatrix}\text{fuel}\\ \text{economy}\\ \text{(mpg)}\end{pmatrix} = f\Bigg[&\begin{pmatrix}+\\ \text{engine and}\\ \text{drivetrain}\\ \text{efficiency}\end{pmatrix}, \begin{pmatrix}-\\ \text{aerodynamic}\\ \text{drag}\end{pmatrix} \begin{pmatrix}-\\ \text{rolling}\\ \text{resistance}\end{pmatrix}\\ &\times\begin{pmatrix}-\\ \text{vehicle}\\ \text{weight}\end{pmatrix}, \begin{pmatrix}-\\ \text{vehicle}\\ \text{size}\end{pmatrix}, \begin{pmatrix}+\\ \text{0–60 mph}\\ \text{acceleration}\end{pmatrix}\Bigg]\end{aligned}$$

The results from the statistical regression of efficiency, weight, size, and performance vehicle attributes on fuel economy are presented in Table 1. The statistical model conforms roughly to commonly held



(a) (b)

FIGURE 5 Fuel economy [data from EPA (*1*)] and engine and drivetrain efficiency, 1975–2004: (*a*) passenger cars and (*b*) light trucks.

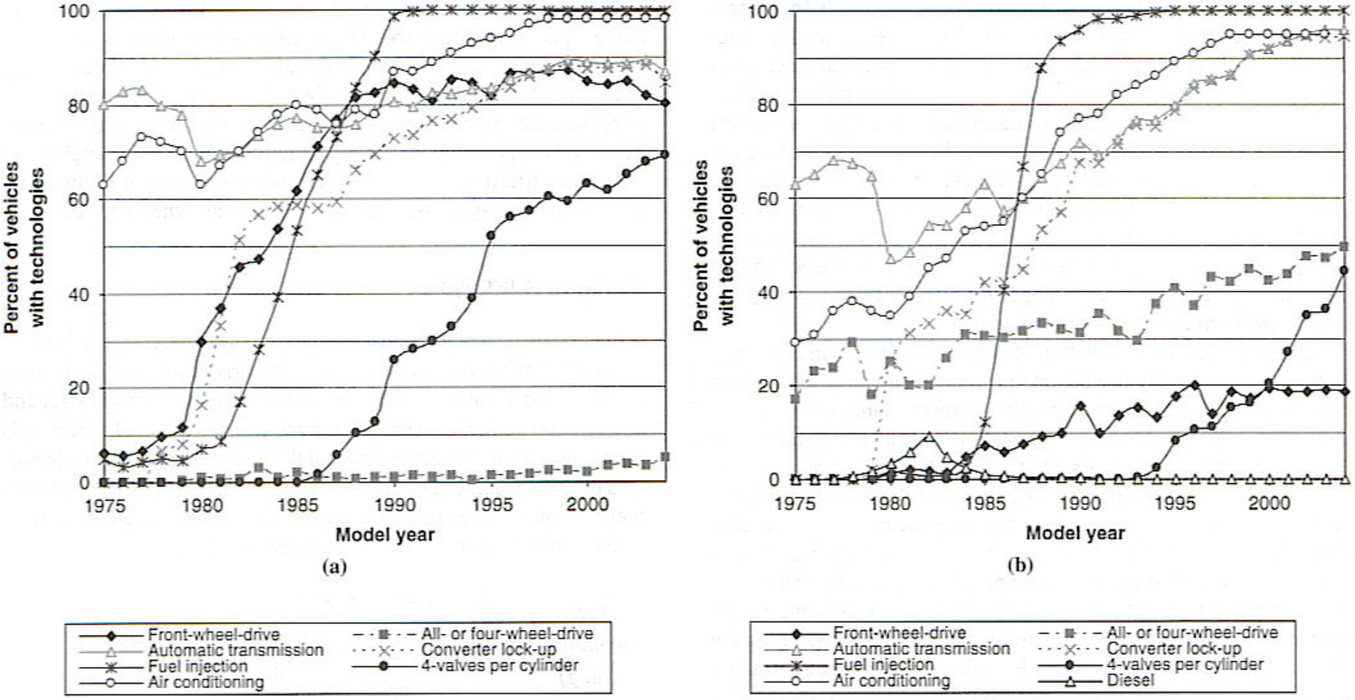


FIGURE 6 Technology deployment in new vehicles, 1975–2004 (*1*): (*a*) passenger cars, [data from EPA (*1*)] and (*b*) light trucks.

engineering rules of thumb. For example, the elasticities for the load reduction factors of weight (–0.5 to –0.7), aerodynamic drag (–0.14 to –0.17), and rolling resistance (–0.22 to –0.24) approximately match up with those relationships of an engineering handbook (*19*) and a recent vehicle simulation modeling study (*12*). Each percentage point change in engine and drivetrain technology correlates with a 0.6-mpg increase or an elasticity of 0.7 (cars) to 0.9 (light trucks). The least significant variable ($t = 1.3$, $\alpha = 0.2$) in the passenger car regression is the vehicle performance metric, the 0- to 60-mph acceleration time. This is likely because acceleration performance can, with some technologies, be complementary with efficiency improvements. One example of this is a variable valve timing fuel intake system that can simultaneously improve power output on demand while improving fuel efficiency during the less demanding driving periods of regulatory testing drive cycles. For the light-truck case, the size variable did not correlate highly ($t = -0.6$, $\alpha = 0.6$).

TABLE 1 Statistical Regression of Efficiency, Weight, Size, and Acceleration on Fuel Economy for 1975–2004 Light-Duty Vehicles

		Passenger Cars			Light Trucks		
Independent Variable	Unit	Significance (*t*-Stat)	Regression Coefficient (implied mpg change per unit change)	Elasticity (% mpg/% unit)	Significance (*t*-Stat)	Regression Coefficient (implied mpg change per unit change)	Elasticity (% mpg/% unit)
Constant	—	0.00 (11.7)	30.0	—	0.00 (8.0)	22.6	—
Engine and drivetrain efficiency	%	0.00 (8.3)	0.63	0.70	0.00 (15.3)	0.57	0.89
Aerodynamic drag coefficient	—	0.02 (−2.4)	−11.4	−0.17	0.03 (−2.4)	−5.2	−0.14
Rolling resistance coefficient	—	0.00 (−8.4)	−453.2	−0.24	0.00 (−9.2)	−240.1	−0.22
Weight	lb	0.00 (−10.8)	−0.0038	−0.49	0.00 (−8.5)	−0.0032	−0.66
Vehicle size*	%	0.00 (−4.7)	−0.032	−0.02	0.56 (−0.6)	−0.004	−0.01
0–60 mph acceleration	s	0.20 (1.3)	0.205	0.12			

*Percentage of cars defined as "midsized" and "large" and light trucks defined as "large" vehicles in EPA trends report (*1*) as in Figure 3.

Other studies have also sought to distinguish the different contributions of vehicle technology innovation, weight, and performance. These studies were motivated by the notion from CAFE critics that CAFE, through the mid-1980s, was simply spurring manufacturers to sell smaller cars (*14*). Three studies that used somewhat different methods over different time periods within 1975–1986 apportioned 65%, 40%, and two-thirds of mpg improvements to efficiency-oriented engineering and design changes for passenger cars (*20–22*). The fuel economy implications of the regression analysis of Table 1 are presented in Table 2. The results have been separated into the three distinct time periods since CAFE was installed, as discussed previously, to show the different ways the market for vehicle technologies has affected fuel economy differentially. This study has the benefits of working from a richer data set with more variation from which to determine regression coefficients and the value of hindsight to distinguish between the time periods with distinctively different attribute trends.

For cars, from 1975 to 1980, the combined effect of the efficiency technologies was to increase fuel economy by approximately 4.2 mpg (55% of the total fuel economy change), and weight reduction contributed to a 3.5-mpg (45% of the total fuel economy change) increase. A plausible explanation for this mixed "weight reduction plus technology" approach toward fuel economy improvements initially is that, although some readily available efficiency gains were to be taken in a previously unregulated market, consumer tolerance for smaller vehicles in a time of high fuel prices was also a viable compliance strategy.

However, from 1980 to 1987, efficiency technology improvements for cars were almost singularly responsible for fleet fuel economy increases, equating to about 93% of the implied fuel economy improvement. During this period, fuel economy improved by 4.6 mpg within 7 years, being driven by efficiency improvements (+4.2 mpg) and some reductions in weight (+0.3 mpg) and size (+0.3 mpg), with a slight offset by performance gains (–0.3 mpg). This period coincides with relatively rapid deployment of automatic transmission, torque converter lock-up, port fuel injection (in place of carburetors), and front-wheel drive technologies. This nearly "all-efficiency" approach toward fuel economy increases could equally signify (*a*) that automobile makers and suppliers had the research lead time, were sufficiently confident with, and could therefore ramp up production of these new drivetrain technologies at this point; or (*b*) that consumers' appetite for smaller vehicles had diminished with lower fuel prices and therefore automobile makers had no choice other than to meet CAFE standards via efficiency technologies.

The third distinct period analyzed, from 1987 to the present, was a period with comparatively little movement in the CAFE standards. During this period, new car fuel economy increased by 0.6 mpg, so the regression results are not so much dissecting where all the gains came from as analyzing the counteracting trends. Advances in efficiency correlate with a 3.5-mpg improvement. Weight increases correspond to a 1.7-mpg decrease, size increases with a 0.5-mpg decrease, and performance improves with a 0.7-mpg decrease.

This overall three-part trend was similar for light trucks. For light trucks from 1975 to 1987, efficiency was consistently a major correlate with fuel economy improvements. Both from 1975 to 1980 (with 87%) and from 1980 to 1987 (with 76%), the clusters of efficiency technologies are heavy contributors to fuel economy. It is reasonable to think that, especially in the earlier years of CAFE, light-truck buyers, compared with car buyers, would be less tolerant of size- and weight-related reductions in fuel economy considering the work-related functionality of these attributes in light trucks. Thus, the automobile industry could be more inclined to deliver fuel economy improvements in light trucks through technology innovation with less compromise in other attributes. Over these two earlier time periods, weight reductions (12% and 19%) and size reductions (1% and 5%) explain only a small amount of the variation in fuel economy. In the latest period, from 1987 to 2004, efficiency technologies equate to a 3.1-mpg increase, whereas weight (–3.6 mpg) and size (–0.1 mpg) correlate to deduct these efficiency gains.

The overall trend over these three time periods since 1975 is for CAFE to be less binding on new-vehicle attributes. The effect in the initial years of the fuel economy regulation was to bind technological efficiency improvements and to constrain average vehicle weight and hold acceleration performance nearly constant to accommodate the large increases in fuel economy. Reflecting the seriousness of the times when fuel shortages were a reality, the CAFE standard was stringent enough that neither efficiency advances nor fleet weight reduction alone would have resulted in meeting the CAFE standard. In the middle years of CAFE, 1980–1987, efficiency improvements contributed substantially to increasing fuel economy while average vehicle weight held roughly constant and acceleration improved only marginally. In the most recent years, efficiency has improved but not to the benefit of fuel economy. Instead, efficiency increases

TABLE 2 Correlated Effects of Efficiency, Weight, Size, and Acceleration on Fuel Economy

Vehicle Category	Vehicle Characteristic		Implied Fuel Economy Effect (mpg) for Given Time Period			Total Implied Fuel Economy (mpg) Effect
			1975–1980	1980–1987	1987–2004	1975–2004
Passenger cars	Efficiency technologies	Engine and drivetrain efficiency	1.0	0.6	0.8	12.0
		Aerodynamic drag coefficient	0.6	0.8	1.0	
		Rolling resistance coefficient	2.6	2.8	1.7	
	Weight		3.5	0.3	–1.7	2.1
	Size		0.0	0.3	–0.5	–0.2
	0–60 mph acceleration		0.0	–0.3	–0.7	–0.9
Light trucks	Efficiency technologies	Engine and drivetrain efficiency	2.2	–0.5	1.1	9.6
		Aerodynamic drag coefficient	0.3	0.5	0.7	
		Rolling resistance coefficient	1.8	2.2	1.3	
	Weight		0.6	0.6	–3.6	–2.4
	Size		0.0	0.2	–0.1	0.1

have served to partially counterbalance increasing size, weight, and performance.

From Table 2, efficiency technologies have resulted in implied (but unrealized in later years) fuel economy improvements in each of the three time periods. In each of these periods, the average mpg effect of efficiency gains in passenger cars has gone from 0.8 mpg/year (1975–1980) to 0.6 mpg/year (1980–1987) to 0.2 mpg/year (1987–2004). Similarly for light trucks, the average amount of implied efficiency-driven fuel economy gains went from 0.8 mpg/year (1975–1980) to 0.3 mpg/year (1980–1987) to 0.2 mpg/year (1987–2004). This trend could imply a lack of anticipation of any CAFE-mandated fuel economy increases from the perspective of automobile makers or perhaps a diminishing response to further fuel economy improvements by consumers.

From the preceding regression results, two hypothetical fuel economy scenarios were examined. Figure 7 presents a hypothetical scenario in which all efficiency improvements from 1987 to 2004 were realized in fuel economy improvements by assuming constant vehicle size, weight, and acceleration. Both cars and light-truck fuel economy would be approximately 12% higher than they were in 1987 (up to 31.4 mpg for cars and 24.3 mpg for light trucks). This is in contrast to the actual average fuel economy trends for cars, which increased by 2%, and light trucks, which decreased by 3%.

Figure 8 presents hypothetical projections of fuel economy under different trends for vehicle size, weight, and performance. The most recent period of 1987–2004 was used to determine the baseline (i.e., routine, without CAFE increases) efficiency-driven fuel economy increases of about 0.2 mpg per year. Three different trends (current attribute trends, constant attributes, and compromised attributes to 1990 levels) in the size, weight, and acceleration are considered for 2004–2020 to investigate these attributes' effects on projected fuel economy. Current trends in size, weight, and acceleration result in relatively unchanged fuel economy. If these attributes are held constant, fuel economy improves steadily; gradually compromising these vehicle attributes back to their 1990 levels results in further fuel economy gains.

CONCLUSIONS

Fuel economy increased sharply in the late 1970s and early 1980s, partly through energy efficiency improvements and partly through a reduction in "utility"—a shift to smaller cars, reductions in performance, and elimination of accessories. But since then, fuel economy has remained static, even as efficiency—the result of constant engineering and design innovations—has continued to improve. Fuel efficiency improvements have not been converted into fuel economy improvements for almost two decades in the United States.

Historical efficiency improvements in aerodynamics, rolling resistance, and engine and drivetrain efficiency have amounted to about 1% per year improvements in overall energy efficiency—equivalent to increases of about 0.2 mpg per year in new passenger cars and light trucks from the mid-1980s to today. There is good reason to think improvements of this scale are likely to continue for some time. New technologies such as hybridized electric–internal combustion engine technologies, diesel engines, regenerative braking, continuously variable transmissions, engine on-off controls, and continuing replacement of heavy hydraulic and mechanical systems with electrical systems, all provide substantial energy efficiency improvements. Further in the future, fuel cells will provide additional improvements.

In effect, efficiency improvements since the mid-1980s have been used in the United States to increase private benefits—more power, larger vehicles, and more accessories (including all-wheel drive)—and not for public benefits of reduced oil imports and greenhouse gas emissions. Europe and Japan have pursued a quite different approach. They are capturing most of these efficiency benefits for the public

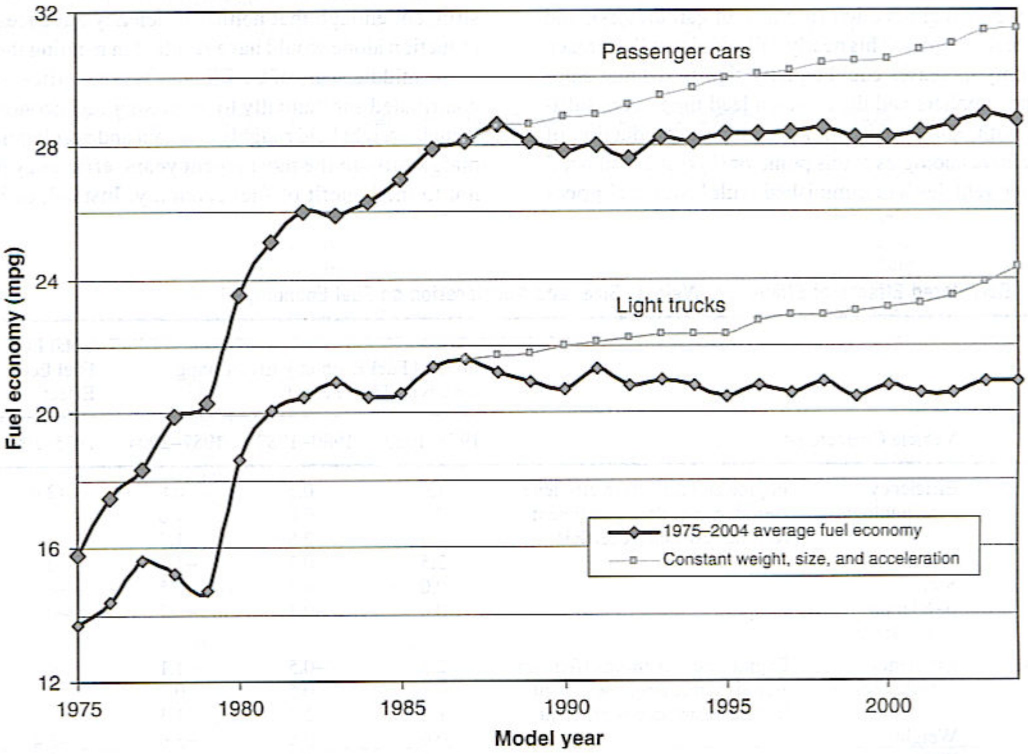


FIGURE 7 Fuel economy: actual versus hypothetical trend if vehicle weight, size, and acceleration are constant from 1987.

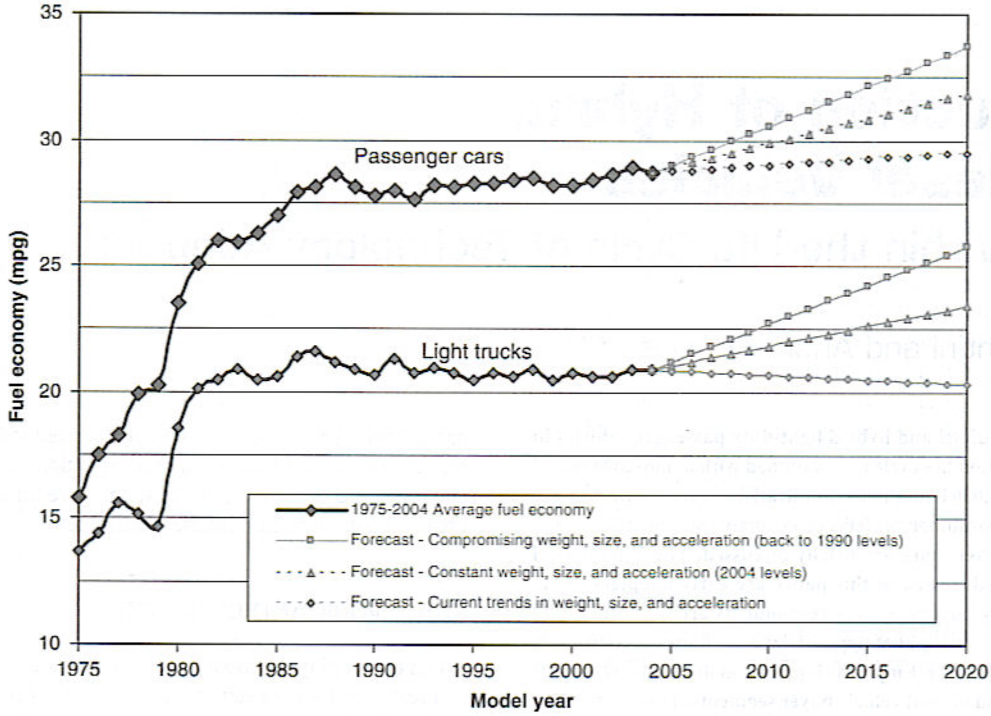


FIGURE 8 Projected fuel economy assuming current efficiency trend and various trends in weight, size, and acceleration.

good—through fuel economy standards in Japan and carbon dioxide reduction agreements in Europe. The question for regulators and lawmakers is whether to shift some or all of these efficiency improvements to overall public benefits.

REFERENCES

1. *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2004.* Report EPA420-R-04-001, Environmental Protection Agency, Washington, D.C., 2004. www.epa.gov/otaq/fetrends.htm. Accessed July 15, 2004.
2. *ACEA's CO₂ Commitment.* Association des Constructeurs Europeens D'Automobiles, Brussels, Belgium, 2004. www.acea.be/ACEA/brochure_co2.pdf. Accessed July 15, 2004.
3. Interim Report on Target Standards for Fuel Consumption. Ministry of Land, Infrastructure and Transport, Tokyo, Japan, 2001. www.mlit.go.jp/english/mot_news/mot_news_981014/mot_news_981014_2.html. Accessed July 15, 2004.
4. An, F. Proposed Chinese Motor Vehicle Fuel Consumption Standards—A Preliminary Analysis. Presentation to the California Air Resources Board, Sacramento, Dec. 17, 2003.
5. *Staff Proposal Regarding the Maximum Feasible and Cost-Effective Reduction of Greenhouse Gas Emissions from Motor Vehicles.* California Air Resources Board, Sacramento, 2004. www.arb.ca.gov/cc/cc.html. Accessed April 10, 2004.
6. *Light Truck Average Fuel Economy Standards Model Years 2005–2007.* RIN 2127-AI70. National Highway Traffic Safety Administration, U.S. Department of Transportation, 2002.
7. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards.* TRB, National Research Council, Washington, D.C., 2002.
8. Austin, T. C., R. G. Dulla, and T. R. Carlson. *Alternative and Future Technologies for Reducing Greenhouse Gas Emissions from Road Vehicles.* Prepared for Committee on Road Vehicle Technology and Fuels, Natural Resources Canada, Sierra Research, Inc., Sacramento, Calif., 1999.
9. DeCicco, J., F. An, and M. Ross. *Technical Options for Improving the Fuel Economy of US Cars and Light Trucks by 2010–2015.* American Council for an Energy-Efficient Economy, Washington, D.C., 2001.
10. Energy and Environmental Analysis, Inc. *Technology and Cost of Future Fuel Economy Improvements for Light-Duty Vehicles.* Draft Final Report. Prepared for the National Academies National Research Council Committee on Impact and Effectiveness of Corporate Average Fuel Economy Standards, Washington, D.C., 2001.
11. Weiss, M. A., J. B. Heywood, E. M. Drake, A. Schafer, and F. F. AuYeung. *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies.* Energy Laboratory Report MIT EL 00-003. Massachusetts Institute of Technology, Cambridge, 2000.
12. *Reducing Greenhouse Gases from Light-Duty Vehicles.* Interim Report. Northeast States Center for a Clean Air Future, Boston, Mass., 2004. bronze.nescaum.org/committees/mobile/rpt040316ghglightduty.pdf. Accessed March 15, 2004.
13. Greene, D. L. Why CAFE Worked. *Energy Policy,* Vol. 26, No. 8, 1998, pp. 595–613.
14. Nivola, P. S., and R. W. Crandall. *The Extra Mile: Rethinking Energy Policy for Automotive Transportation.* The Brookings Institution, Washington, D.C., 1995.
15. Hucho, W.-H. *Aerodynamics of Road Vehicles: From Fluid Mechanics to Vehicle Engineering,* 4th ed. Society of Automotive Engineers, Warrendale, Pa., 1998.
16. *California State Fuel-Efficient Tire Report: Volume II.* 600-03-001CR. California Energy Commission, Sacramento, 2003.
17. LaClair, T. J. Tire Rolling Resistance, Its Impact on Fuel Economy, and Measurement Standards. Presented at California State Fuel-Efficient Tire Program Workshop, Sacramento, Calif., Sept. 19, 2002.
18. *EPA Dynamometer Driver's Aid.* Environmental Protection Agency, Washington, D.C., 2004. www.epa.gov/otaq/labda.htm#vehcycles. Accessed June 13, 2004.
19. *Automotive Handbook,* 3rd ed. Society of Automotive Engineers, Warrendale, Pa., 1993.
20. Greene, D. L. *Efficiency-Related Changes in Automobile and Light Truck Markets, 1978–1986.* Society of Automotive Engineers Technical Paper Series, Society of Automotive Engineers, Warrendale, Pa., 1986.
21. Heavenrich, R. M., J. D. Murrell, J. P. Cheng, and S. L. Loos. *Light Duty Automotive Fuel Economy . . . Trends thru 1985.* Society of Automotive Engineers Technical Paper Series, Society of Automotive Engineers, Warrendale, Pa., 1985.
22. *Automotive Fuel Economy Program: Sixth Annual Report to Congress.* National Highway Traffic Safety Administration, U.S. Department of Transportation, 1982.

The Transportation Energy Committee sponsored publication of this paper.