5.0 Fuel Consumption, Performance, and Weight Trade-Offs

Attempts to assess potential improvements in fuel consumption are confounded by simultaneous changes in vehicle acceleration performance, feature content, size, and weight. The prospects for fuel consumption reduction depend not only on what might happen to efficiency technology in the future, but also on assumptions about these other attributes. Further complicating the picture, these other attributes interact with not only fuel consumption, but also with one another. Thus, one key to understanding the prospects for fuel consumption reduction is to understand the trade-offs between various vehicle attributes.

Faster acceleration performance requires more powerful engines, which (ceteris paribus) end up being heavier and spending more time operating at inefficient, part-load conditions. These effects mean that all else being equal, vehicles with faster acceleration capabilities tend to consume more fuel per mile than those with slower acceleration capabilities.

Increasing vehicle size increases fuel consumption in several ways. First, greater size increases weight, which increases the amount of energy needed to accelerate the vehicle. Absent any regenerative braking capabilities, this energy is all lost when the brakes are engaged. Second, greater weight means increased rolling friction. Finally, larger vehicles may have a greater frontal area, which increases aerodynamic resistance.

Adding more features to a vehicle can increase fuel consumption in at least two ways as well. First, any feature that includes additional hardware will increase vehicle weight, increasing the energy needed to accelerate the vehicle and to overcome rolling resistance. Second, features that require power to operate will place parasitic loads on the engine, increasing average fuel consumption. In most cases, the former effect is thought to be dominant.

In order to assess the prospects for future fuel consumption, and to better understand historic improvements in efficiency technology, it is useful to quantify the relationships showing the ways that fuel consumption, acceleration performance, size, features, and weight relate to each other. As suggested by the discussion above, however, the variables’ interactions are somewhat complicated and nonlinear, making the exact nature of the trade-offs somewhat ambiguous. Estimates of these trade-offs can nevertheless be developed using one of two main approaches.

One approach to characterizing attribute trade-offs is to use vehicle simulation software to model fuel consumption while varying vehicle weight, power, and acceleration performance capabilities, but holding vehicle technology constant. This is the approach employed by Cheah et al. (2009), Shiau et al. (2009), and Whitefoot et al. (2011).

A simplified econometric model based on observed vehicle characteristics offers a tractable alternative approach to estimating attribute trade-offs and technological improvements based on the characteristics of vehicles that have actually been offered in the market. This is the approach taken by Knittel (2011) to characterize the trade-offs between power, weight, and fuel economy. A slightly different approach is to estimate the trade-offs between fuel consumption and weight and acceleration performance (rather than power), controlling for several covariates including engine and transmission type, engine specific power, body style, and all-wheel drive. Doing so yields the trade-off estimates reported in Table 5.1. More complete details of this work can be found in MacKenzie & Heywood (2015).
Table 5.1  Fuel consumption trade-offs associated with changing key attributes of cars, holding efficiency technology and other attributes constant.

<table>
<thead>
<tr>
<th>Design Change</th>
<th>Fuel Consumption Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% increase in inertia weight</td>
<td>+0.69%</td>
</tr>
<tr>
<td>1% increase in 0-97 km/h time</td>
<td>-0.44%</td>
</tr>
<tr>
<td>Manual transmission*</td>
<td>-5%</td>
</tr>
<tr>
<td>All-wheel drive*</td>
<td>+3%</td>
</tr>
</tbody>
</table>

*Manual transmission and all-wheel drive effects are estimates for 2012, and represent the additional fuel consumption changes beyond those expected from the weight change from a manual transmission or all-wheel drive system. The magnitude of these effects has been declining over time, by about 0.3% per year for manual transmissions and 0.2% per year for all-wheel drive.

The estimates reported in Table 5.1 are broadly consistent with results previously reported in the literature. They indicate that holding acceleration and vehicle technology constant, increasing vehicle weight by 1% will increase fuel consumption by about 0.7%. Cheah (2010) previously reviewed several studies on this topic 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.

Several investigations in the early 1990s addressed the trade-offs between weight and acceleration performance 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, identical to the results obtained here [OTA, 1991; DeCicco and Ross, 1993; Greene and Fan, 1994].

More recently, a number of authors have used vehicle simulations to explore the trade-offs between fuel consumption and power or acceleration performance. Figure 5.1 illustrates the results of several such exercises for midsize U.S. cars, along with the trade-off reported in this work. The trade-off identified in this chapter is very similar to that reported by Whitefoot et al. (2011). Compared with the results of Cheah et al. (2009), the present work and the findings of Whitefoot et al. imply a smaller fuel consumption penalty for decreasing acceleration time. The substantial variability in the estimated trade-offs between acceleration and fuel consumption point to the importance of vehicle-to-vehicle variation, and the need for caution when generalizing from trade-offs for a single vehicle model to the entire fleet.
Figure 5.1 Recent results from our group characterizing the trade-off between acceleration performance and fuel consumption, compared with results from other recent investigations.

5.1 Fuel Consumption Potential

As shown in the preceding section, changing the acceleration performance, size, or feature content of a vehicle changes its fuel consumption significantly, even if the efficiency technology used in the vehicle is unchanged. An important corollary of this is that improvements in vehicle technology will not necessarily lead to lower fuel consumption. Instead, technology improvements may be dedicated to offsetting the fuel consumption penalties that would otherwise have resulted from changes in feature content, size, and acceleration capabilities. To get an accurate picture of how much vehicle technology has improved over time, it is necessary to consider not only reductions in fuel consumption, but also any changes in related vehicle attributes over the same period. We use fuel consumption potential as such a measure of technology improvement.
Fuel consumption potential is used to characterize how much vehicle efficiency technologies have improved over time. It is simply the change in average fuel consumption that could have been achieved over some period of time, given actual improvements in technology but holding other vehicle attributes (acceleration performance, size, and feature content) at their initial levels. Fuel consumption potential is estimated by adjusting improvements in average fuel consumption to account for changes in acceleration performance, size, and feature content, based on the trade-off coefficients discussed previously.

Figure 5.2 shows the estimated progress in technology for cars manufactured in the United States between 1975 and 2009, expressed as fuel consumption potential. This highlights the vast improvements in fuel consumption potential that have been made since 1975. If acceleration, size, features, and functionality had remained constant, per-mile fuel consumption could have been reduced by approximately 70% between 1975 and 2009. Over the same period, the actual fuel consumption of the average new car was reduced by 50%. More details on this analysis can be found in MacKenzie & Heywood (2015).

Figure 5.2 Potential reductions in fuel consumption for new U.S. cars since 1975, if acceleration, size, features, and functionality had remained unchanged (blue). Also shown is the actual average fuel consumption of new U.S. cars (black).
While the improvements in technology since 1975, measured by fuel consumption potential, 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% per year.

5.2 Emphasis on Reducing Fuel Consumption

To enable a more quantitative analysis of the relationship between actual fuel consumption reductions and the technical potential, our research group has developed and previously reported on the concept of Emphasis on Reducing Fuel Consumption (ERFC) [Bandivadekar et al., 2008]. Intuitively, ERFC is simply the ratio of the actual reduction in fuel consumption over some interval to the potential reduction over the same period, if other attributes had remained unchanged. It is calculated as follows:

\[
ERFC = \frac{FC_t - FC_0}{FC_{t \text{ potential}} - FC_0}
\]

In the equation above, \(FC_0\) is the average fuel consumption in the base year, \(FC_t\) is the actual average fuel consumption in year \(t\), and \(FC_{t \text{ potential}}\) is the potential fuel consumption in year \(t\) if other vehicle attributes had remained at their base-year levels.\(^{14}\)

5.2.1 Emphasis on Reducing Fuel Consumption for U.S. Cars

Figure 5.3 summarizes the emphasis on reducing fuel consumption calculated for new cars in the United States between 1975 and 2009. Each bar represents the ERFC over a five-year interval.\(^{15}\) 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 suggests that there was some pull-back in the levels of other attributes that enabled the larger decrease in fuel consumption. 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 when fuel prices were increasing.

\(^{14}\)In past work [Bandivadekar et al., 2008], our group has defined ERFC as the ratio of the realized fuel consumption reduction to the reduction possible with constant performance and size. In the work reported here, the denominator is instead the potential reduction with constant performance, size, features, and functionality. As a result, ERFC values calculated here will be different (generally lower) and not directly comparable with those we have reported in the past. Although we have refined the details of our methodology over time, the results of all methods have yielded qualitatively similar trends. Moreover, the central point remains that technological improvements can be dedicated to reducing fuel consumption or to offsetting the fuel consumption effects of changes in other vehicle attributes, and ERFC enables quantification of the relative focus on each of these goals.

\(^{15}\)The last interval is four years, between 2005 and 2009.
5.3 Technology Sinks

While the ERFC tells us how much of the technically feasible reductions in fuel consumption were actually realized, it does not tell anything about the other ends to which the technology improvements were applied. However, by applying trade-off coefficients like those reported above to the changes in acceleration and to changes in weight due to size and feature content, it is possible to estimate how much fuel consumption might have been reduced if the changes in the other attributes had not occurred. This can provide an estimate of how much new technology was “consumed” by the need to offset the fuel consumption penalties of these other design changes.

Figure 5.4 summarizes the technology improvements that were needed to offset changes in acceleration, feature content, and size changes in the average new car sold in the United States since 1975. These figures are expressed as the equivalent fuel consumption reductions that could have been achieved if not for the changes in size, feature weight, and acceleration performance. 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. Above this, each wedge represents the potential fuel consumption reduction that could have been achieved if a certain attribute had remained at its 1975 level. (The light green wedge represents the technology that went into actual fuel consumption reductions.)
Figure 5.4  “Sinks” for technology improvements in new U.S. cars. Each of the top three bands represents the equivalent improvement in fuel consumption that could have been achieved if not for changes in another vehicle attribute. The light green, lowermost band represents the actual improvement in fuel consumption since 1975. The lower edge of the lower band represents the overall fuel consumption potential since 1975, i.e., the relative fuel consumption if size, feature content, and acceleration performance of the average new car had remained unchanged.

Apart from reductions in fuel consumption, the largest “sink” for efficiency technologies in new U.S. cars has been in offsetting the fuel consumption penalties of faster acceleration. Offsetting faster acceleration has consumed a large and continually growing amount of new efficiency technologies since the 1970s, as shown by the blue wedge in Figure 5.4. Between 1975 and 1990, the average acceleration time decreased by 30%, which “consumed” enough technology to have reduced fuel consumption by 15%. In contrast, shifts in car size and feature content have had little effect on fuel consumption. The dark green wedge shows that at its peak, offsetting the fuel consumption effects of greater size (among cars, but excluding the shift from cars to light trucks) consumed enough technology to have reduced fuel consumption by about 5% or less. Similarly, the ultimate effect of more feature content in new cars has been a single-digit percentage effect on fuel consumption.

Fuel consumption improvements have been the largest sink for new efficiency technologies since 1975. While foregoing acceleration improvements could have reduced fuel consumption by an additional 15% from 1975–1990, fuel consumption actually decreased by 43% over this period. Average fuel consumption changed much less after 1990, but nevertheless still accounted for the largest “sink” for technology changes from 1990–2009.
5.3.1 U.S. Vehicle Acceleration Trends

Recent reappraisals of the relationship among power, weight, and acceleration performance [MacKenzie & Heywood, 2012] indicate that acceleration performance has been improving even more rapidly than is indicated by commonly cited sources such as U.S. EPA’s Fuel Economy Trends Report [U.S. EPA, 2012]. The EPA relies on a simple correlation between power/weight ratio and acceleration performance. MacKenzie & Heywood showed that this relationship no longer holds, because of improvements in both vehicle attributes that are widely reported (e.g., transmission type and number of speeds) and in technologies that are not as commonly tracked and reported (such as aerodynamic improvements and driveline efficiency). Between 2006 and 2009, the average acceleration calculated using the EPA’s methods was approximately 1 second, or 11%, greater than the average of 8.8 seconds calculated using MacKenzie & Heywood’s model. Between 1982 and 2009, the estimated average 0–97 km/h acceleration time of new U.S. vehicles decreased from 16.6 seconds to 8.8 seconds. Over the same period, the average 0–48 km/h acceleration time decreased from 5.5 seconds to 3.2 seconds, and the average 72–105 km/h passing acceleration time fell from 10.9 seconds to 5.6 seconds.

Reductions in 0–97 km/h acceleration times occurred within both high- and low-performance vehicles. Figure 5.5 shows how 0–97 km/h acceleration times have changed since 1978 for the median vehicle as well as for vehicles at the fastest (5th percentile) and slowest (95th percentile) ends of the market.

![Figure 5.5](image-url)  
**Figure 5.5** Distribution and trends in acceleration performance among new U.S. vehicles.
Two features of Figure 5.5 are especially striking. First, 95% of vehicles sold today achieve a level of acceleration performance that beats the average from 1992, and would have put them in the top 5% in 1985. As an example, consider three venerable sports cars from the mid-1980s: the 1985 Mazda RX-7, Nissan 300ZX, and Toyota Supra. They all had 0–97 km/h times of 11.0 seconds. Three recent “econo-boxes”: the 2009 Honda Fit and Toyota Yaris, and the 2008 Nissan Versa, all had 0–97 km/h times between 10.9 and 11.1 seconds. This is virtually identical to the level of acceleration performance seen in sports cars of a generation ago.

Second, the chart shows that although acceleration times have been getting faster, the rate of change has been declining. In fact, the chart appears to suggest that acceleration performance may be asymptoting. A model of exponential decay toward an asymptote captures both the asymptotic acceleration level and the rate of approach toward that level:

$$Z_{97} = a \cdot e^{b(t-1980)} + c$$

Parameter $c$ in the equation above represents the estimated asymptotic performance level, while parameter $b$ captures the average rate at which acceleration performance has been approaching this level, and parameter $a$ is a constant. These parameters were estimated using least-squares estimation for the years 1982–2009, and the curves fitted in this manner for the median, 5th percentile, and 95th percentile performance levels have been added to Figure 5.5. The fitted parameters suggested, firstly, that the rate of decay, $b$, is fairly stable regardless of whether vehicles are high-performance, low-performance, or in the middle of the pack. In addition, the estimated asymptotic performance levels ranged from 6.1 seconds for vehicles in the 5th percentile to 10.1 seconds for vehicles in the 95th percentile. It is interesting to note that even high-performance vehicles are today within 1 second of their estimated asymptotic values. This is, of course, far from proof that reductions in acceleration times are going to stop anytime soon, but it at least suggests that Americans’ thirst for power in their cars may in fact be quenchable, and offers guidance for making future projections of acceleration performance levels.

### 5.4 Prospects for Future Vehicle Characteristics in the United States

#### 5.4.1 Fuel Consumption Potential

Assessments of future potential reductions in fuel consumption benefit from both historical perspectives on what has been achieved, and forward-looking assessments of available technologies.

As discussed in Chapter 4, automakers are currently talking about reducing vehicle weight at a rate of 2%–3% per year in the near term. These sorts of rates were observed in the late 1970s and early 1980s, but were only sustained for a few years. Over the longer term, sustained reductions of 1%–1.5% per year, totaling some 30%–45% weight reduction by 2050, appear more plausible. This weight reduction would lead to fuel consumption reductions of 0.6%–1% per year.

As discussed in Chapter 3, future improvements in aerodynamics and rolling resistance should each be able to deliver a potential fuel consumption reduction of close to 0.2% per year. Incremental powertrain improvements in naturally-aspirated, spark-ignition engines could contribute about 1% per year in potential fuel consumption reductions, while growth in more advanced powertrains, including turbocharged gasoline and hybrid electrics, might contribute an additional one-third to this.
Considering all of the above sources of improvement, our forward-looking assessment suggests that an overall rate of technology improvement of about 2%–2.5% per year is feasible. Comparing this projection with the historic rates of improvement documented in this chapter, we note that it is somewhat higher than the 2% per year measured between 1990 and 2009, but considerably less than the 5% per year observed between 1975 and 1990.

Note that our analysis in Chapter 3 incorporates two key assumptions. First, our estimates of the benefits of technology improvements are based on the average vehicle: i.e., all vehicles benefit (on average) from these improvements. Second, not all of the potential opportunities for improving the technology are implemented in practice. We assume that only some 75%–80% of the fuel consumption gains (again, on average) are realized.

**5.4.2 Emphasis on Reducing Fuel Consumption**

To assess the prospects for future emphasis on reducing fuel consumption in the United States, we can begin by estimating the amount of technology that will be needed just to offset future acceleration performance gains and new feature weight.

If historic trends hold, future increases in performance will be relatively modest compared with what we have seen over the last 30 years. Extrapolating the trends reported in the preceding section suggests that, relative to 2009 levels, 0–97 km/h acceleration times could decline about 5% by 2025, and 6% by 2050. Offsetting this reduction in acceleration time would require technology improvements equivalent to about a 2%–3% reduction in fuel consumption. In other words, technology (expressed as fuel consumption potential) would have to improve by about 0.1% per year to offset future acceleration gains. If we suppose that future acceleration gains were larger, reaching 10% through 2025 and 15% through 2050, offsetting the fuel consumption penalties of these changes would require improvements in technology of about 0.2%–0.3% per year.

As shown in Chapter 4, the average weight of feature content in new cars has increased steadily at about 7 kg/year since the early 1980s. If we assume that this rate continues, then features would add an additional 105 kg to the average car by 2025, and 280 kg by 2050, relative to 2009 levels. This would constitute an increase in inertia weight of 7% by 2025 and 18% by 2050. As reported above, each 1% increase in inertia weight is estimated to increase fuel consumption by 0.7%. This implies that improvements in fuel consumption potential of about 0.3% per year—totalling 5% by 2025 and 12% by 2050—would be required to offset the effects of increased feature content.

It appears that improvements in fuel consumption potential of approximately 0.5% per year would be needed to offset the effects of greater feature weight and faster acceleration, if feature content and acceleration performance continued to follow trends observed over the past 30 years. If overall fuel consumption potential continues to improve at about 2% per year, as it has since 1990, then ERFC values of 75% may result, and fuel consumption would fall by about 1.5% per year. Naturally, if acceleration performance or feature weight changes more slowly, ERFC will be higher, and if they change more quickly, ERFC will be lower. Similarly, if technology improves more quickly than the 2% per year assumed here, and the additional improvements are directed toward fuel consumption reduction, then ERFC would be higher.
5.5 Conclusions

Looking ahead toward 2050, overall rates of technology improvement sufficient to reduce fuel consumption by between 2% and 4% per year (holding size, feature content, and acceleration performance constant) appear to be feasible. The lower end of this range is consistent with the pace of improvements since 1990, and could be realized primarily through continued weight reduction at about 1% per year and incremental improvements in aerodynamics, rolling friction reduction, and conventional gasoline powertrains. The upper end of this range is closer to the rates of improvement that were observed between 1975 and 1990, and improvements at this rate will be required if 2025 Corporate Annual Fuel Economy (CAFE) standards are to be met without sacrificing other vehicle attributes. This rate of improvement could be realized through weight reduction targets announced by various automobile manufacturers, combined with incremental improvements in conventional gasoline engine technology and steady but manageable shifts toward higher-efficiency alternative powertrains.

Reductions in acceleration times have “consumed” more technology improvements than any other vehicle attribute since 1975, except for fuel consumption reduction. Technology needed to offset the fuel consumption penalties of continued reductions in acceleration times will likely amount to 0.1%–0.3% per year, while offsetting the weight of new features may require a further 0.3% per year. Thus, it appears likely that at least 70% of new technology improvements going forward will be dedicated to reducing fuel consumption.
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References


