

The Trade-off between Automobile Acceleration Performance, Weight, and Fuel Consumption

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ABSTRACT

This paper evaluates how the fuel consumption of the average new U.S. passenger car will be penalized if engine and vehicle improvements continue to be focused on developing bigger, heavier and more powerful automobiles. We quantify a parameter called the Emphasis on Reducing Fuel Consumption (ERFC) and find that there has been little focus on improving fuel consumption in the U.S. over the past twenty years. In contrast, Europe has seen significantly higher ERFC. By raising the ERFC over the next few decades, we can reduce the average U.S. new car's fuel consumption by up to some 40 percent and cut the light-duty vehicle fleet's fuel use by about a quarter. Achieving substantial fuel use reduction will remain a major challenge if automobile size, weight and power continue to dominate.

INTRODUCTION

Driven by the need to reduce greenhouse gas emissions and the reliance on petroleum imports, there are strong pressures to increase the fuel economy, or reduce the fuel consumption, of automobiles in the U.S. This calls for a departure from the historical trend of stagnant on-the-road fuel consumption (Fig. 1).

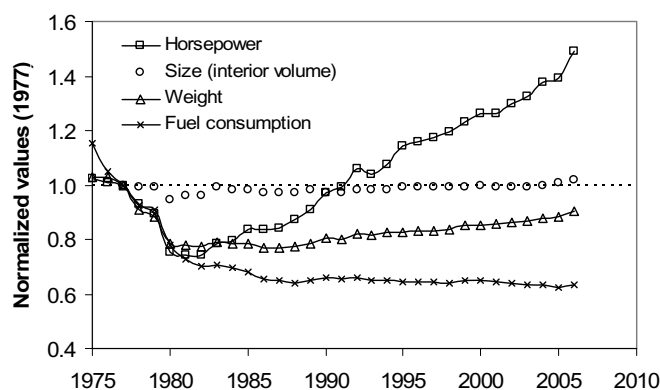


Figure 1: Relative change in horsepower, size, weight, and fuel consumption of the average new U.S. car, 1975-2006 [1]

This trend of unchanging vehicle fuel consumption since the mid-1980s should not be mistaken for a lack of advances in vehicle technology. The fuel efficiency of vehicles has improved steadily over the same period with engine improvements such as variable valve control, better lubrication to reduce friction, reduced vehicle rolling resistance and aerodynamic drag, and increased use of lighter materials. Most of these improvements, however, have not been dedicated to reducing fuel use. The gains in technical efficiency have instead been used to improve other attributes such as power, comfort, size, and safety. As seen in Fig. 1, automobile horsepower has been improving steadily since 1980, as weight has gradually crept upwards.

In general, improved technical efficiency can be used to reduce the fuel consumption of a vehicle or to improve performance attributes such as acceleration and power or some combination thereof. This is an explicit design decision. For example, reducing vehicle weight using lightweight materials leads to the possibility of downsizing the engine, which consumes less fuel while delivering the same level of performance. Or the engine size could be left unchanged in a lighter weight vehicle, resulting in better acceleration performance. In this paper, we focus on exploring this design trade-off in naturally-aspirated gasoline-powered passenger cars.

PERFORMANCE-SIZE-FUEL ECONOMY INDEX

Few studies have explicitly characterized the trade-off between vehicle fuel consumption and performance attributes [1,2]. An and DeCicco [3] defined a Performance-Size-Fuel economy Index (PSFI) to correlate trends in new vehicle characteristics and provide insight into where technical efficiency gains have been realized. For cars, the PSFI is defined as follows:

$$PSFI = P.S.F = (hp/lb).ft^3.mpg$$

P is the performance index, defined as the ratio of maximum engine horsepower to vehicle weight¹ (hp/lb).

¹ Inertia weight, which is the vehicle's curb weight plus 300 lb.

The size index, S , is defined as the interior volume of the car in cubic feet (ft^3). The fuel economy index, F , is defined as the fuel economy in miles per gallon (mpg). The EPA adjusted 55/45 combined fuel economy² is used.

Figure 2 shows the PSFI trend for cars from model years 1977 to 2006 and Fig. 3 shows variables P , S and F normalized to their 1977 values, along with the normalized PSFI trend. As noted by An and DeCicco, the PSFI shows a remarkable long-term linear trend and displays a steady compounded annual growth rate of 3.4%.

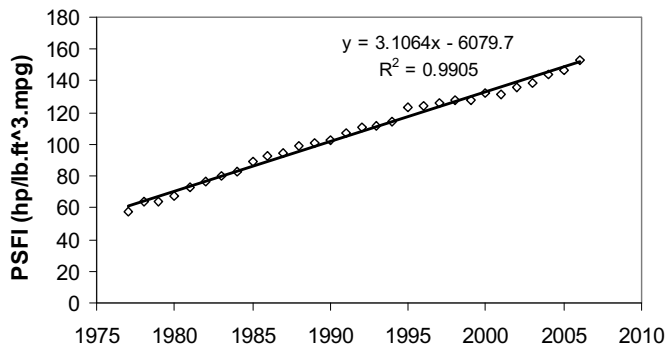


Figure 2: Performance-Size-Fuel Economy Index (PSFI) for U.S. cars, 1977-2006 [3]

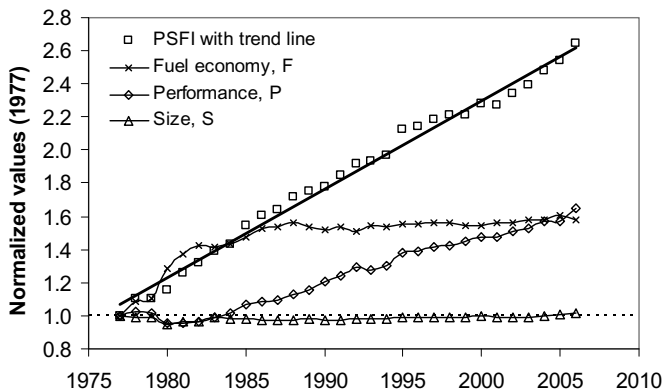


Figure 3: Normalized PSFI trend for U.S. cars, 1977-2006 [3]

This consistent PSFI trend can be extrapolated into the future and is useful for evaluating the trade-off between performance, size, and fuel consumption with one caveat. By using the ratio of horsepower to weight as a proxy for performance, the index does not distinguish between vehicles with different engine and vehicle weights, but with the same horsepower to weight ratio. As a result, the PSFI may not be able to consider the impact of reducing vehicle weight at constant vehicle size on decreasing fuel consumption appropriately.

² This reported fuel economy combines the laboratory mpg results using city (FTP-75) and highway (HWFET) drive cycles, weighted by the factors of 0.55 and 0.45 respectively. Correction factors of 0.9 and 0.78 are used to adjust the results to reflect on-road operation.

EMPHASIS ON REDUCING FUEL CONSUMPTION (ERFC)

For the purpose of understanding the influence of performance-size-fuel consumption trade-off, we introduce a parameter called *Emphasis on Reducing Fuel Consumption* or ERFC. In any improved vehicle offering, the degree of ERFC is defined to be the actual fuel consumption (FC) reduction realized, divided by the maximum fuel consumption reduction achievable during a specified time frame, and is expressed as a percentage, where:

$$\%ERFC = \frac{\text{Actual FC reduction realized}}{\text{FC reduction possible with constant size and performance}}$$

or

$$\%ERFC = \frac{FC_{\text{previous}} - FC_{\text{realized}}}{FC_{\text{previous}} - FC_{\text{potential}}}$$

ERFC measures the degree to which improvements in technology are realized for reducing actual fuel consumption. At 100% ERFC, all of the improvements in conventional technology over time are assumed to realize reduced fuel consumption, while vehicle size and performance attributes remain constant. In contrast, without any emphasis on reducing fuel consumption (0% ERFC), the fuel consumption of new vehicles will remain at current values, and all of the efficiency gains from technology improvements are channeled to increase the horsepower and acceleration performance instead.

So the degree of ERFC quantifies an explicit design decision to dedicate future advances in vehicle efficiency into reducing fuel consumption, as opposed to improving performance, or increasing vehicle size.

HISTORICAL ERFC

IN THE U.S. - We can use ERFC to describe and explore historical trends. For instance, to quantify where the historical emphasis has been in the U.S. for cars from model years 1995 to 2006, we calculate ERFC using the equation:

$$\%ERFC = \frac{FC_{1995} - FC_{2006}}{FC_{1995} - FC_{2006 \text{ potential}}}$$

Where $FC_{2006 \text{ potential}}$ is the minimum fuel consumption achievable today, defined to be the fuel consumption of today's car if it had the size and performance of a new car sold back in model year 1995. To determine this fuel consumption reduction potential, we turn to the expected Performance-Size-Fuel Economy Index (PSFI).

In 2006, the Index has a value of 153 (hp/lb). ft^3 .mpg. Fixing this, and replacing the performance (P) and size (S) indices with their 1995 values, the maximum potential fuel economy today is found to be 30 mpg, or equivalent to a minimum fuel consumption of 7.8 l/100km. Using

this, the ERFC in the U.S. from 1995 to 2006 is calculated to be only 8%.

Automobile characteristics	Average 1995 car	Average 2006 car	2006 car at 1995 weight, size and performance (calculated)
Max. horsepower, hp	152	198	152
Inertia weight, lb	3,263	3,563	3,263
Performance, P , hp/lb	0.047	0.056	0.047
Size index, S , ft ³	109	112	109
Fuel economy, F , mpg	24.2	24.6	30.2
Fuel consumption, L/100km	$FC_{1995} = 9.7$	$FC_{2006} = 9.6$	$FC_{2006 \text{ potential}} = 7.8$
PSFI, (hp/lb.ft ³ .mpg)	123	153	153

Table 1: Exploring the potential minimum fuel consumption of today's U.S. average new car using the expected Performance-Size-Fuel economy Index

In contrast, ERFC in the U.S. was much higher in the decade prior to 1987. Using the PSFI trend, ERFC reached 90% between 1977 and 1987, spurred by the oil crisis and the introduction of Corporate Average Fuel Economy (CAFE) standards.

IN EUROPE - Unlike in the U.S., the ERFC of both gasoline and diesel passenger vehicles sold in parts of Europe, particularly France, Germany, Italy and the United Kingdom (UK), have been much greater in recent history. This is evidenced by an upward trend in the fuel economy of new vehicles. For example, the average fuel economy of new gasoline cars sold in Germany increased from 29 mpg (8.2 L/100km) to 32 mpg (7.4 L/100km) between 1995 and 2006, when tested on the New European Driving Cycle [4,5].

Lacking appropriate size data and information on a typical European passenger vehicle, the historical ERFC for gasoline-powered passenger vehicles in these European countries are estimated solely using a Performance-Fuel Economy Index (PFI), which is similar to PSFI and was also introduced by An and DeCicco [3]. Figures 4(a)-(d) shows variables P and F normalized to their 1995 values, along with the normalized PFI trend for new gasoline passenger vehicles in different European markets. Similar to the U.S. results, the PFI shows a long-term linear trend. In contrast to the U.S., however, both P and F improved over the given time period.

Over the same period of 1995 to 2006, the historic ERFC values for new gasoline vehicles in France and Germany are calculated to have been 68% and 54%, respectively. For Italy and the UK, consistent vehicle data was only available up to 2001, so the ERFC for these markets were calculated for the time period of 1995-2001 only. These turned out to be 83% and 52%, respectively. These ERFC figures are calculated using the equation introduced earlier and the values in Tables 2(a)-2(d).

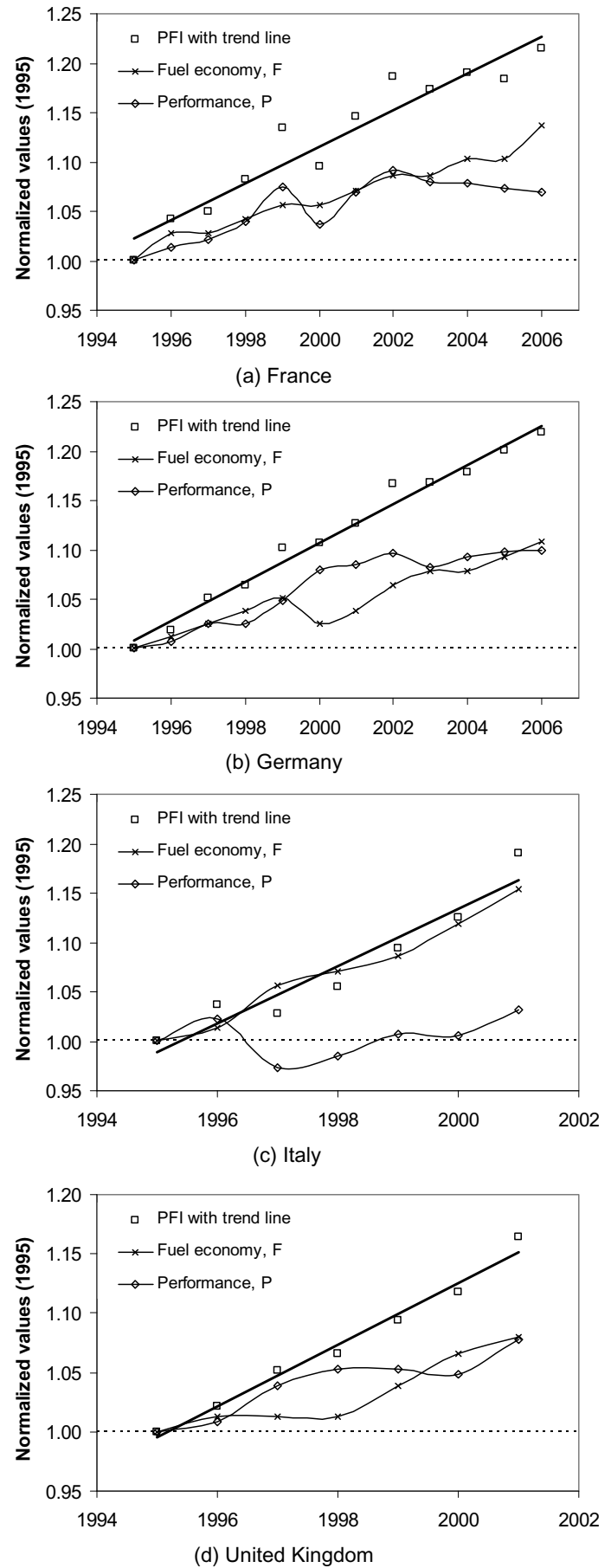


Figure 4: Performance-Fuel Economy Index (PFI) for gasoline passenger vehicles in various European markets [4,5]