
Determinants of U.S. passenger car weight

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Abstract: After a precipitous drop from 1976-1982, the weight of U.S. passenger cars has grown steadily. This paper examines multiple conflicting influences on vehicle weight in two categories: technological changes that reduce vehicle weight; and improvements in functionality that, *ceteris paribus*, add to vehicle weight. The widespread adoption of unibody construction, lightweight materials and smaller engines have been offset by growth in vehicle size and feature content. The best estimates from this work indicate that new features and functionality would have added at least 250 kg (550 lbs) to the weight of the average new car between 1975 and 2009, if not for offsetting improvements in technology. Over the same period, it is estimated that alternative materials, more weight-efficient vehicle architectures, and reduced engine sizes have taken 790 kg (1,700 lbs) out of the weight of the average car. These observable influences do not explain the full extent of the drop and subsequent growth in weight, suggesting that substantial non-observed technological improvements were made from 1976-1982, and that unobserved improvements in areas such as crashworthiness and NVH have added substantially to vehicle weight in the past two decades.

Keywords: weight; lightweighting; materials; unibody; features.

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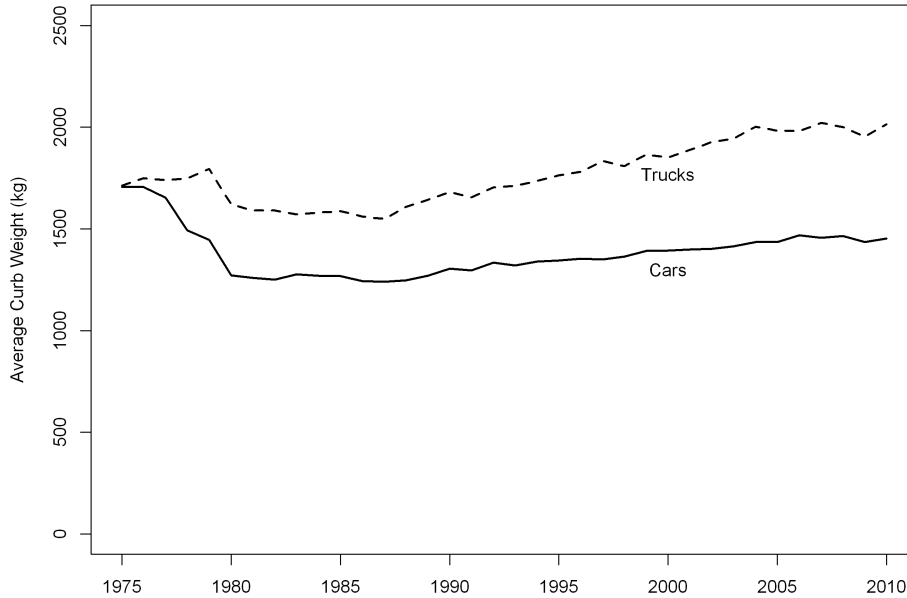
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1 Introduction

Between the late 1970s and the early 1980s, something remarkable happened to the cars sold in the United States: they shed more than 450 kg (1000 lbs) from their average curb weight. Even more remarkably, this 25% weight reduction occurred in only six years (and most of it in just four). Today, after nearly a decade of rising fuel prices and with Corporate Average Fuel Economy (CAFE) standards poised to jump sharply, the auto industry is once again looking to cut dramatically the weight of new vehicles. Ford has stated a goal of cutting 340 kg (750 lbs) off its vehicles by 2020, and announced plans to reduce the weight of the F-150 pickup by 320 kg (700 lbs) in its 2014 redesign. Renault and PSA Peugeot Citroen have established a goal of cutting 200 kg (440 lbs) by 2018, while Hyundai planned in 2010 to cut its average vehicle weight by 10% (150 kg or 330 lbs) over five years. One goal of this work, therefore, was to take a retrospective look at the specific changes that permitted the dramatic weight reductions that occurred between 1976 and 1982.

Following its rapid decline, the average weight of a new U.S. car remained essentially unchanged until the late 1980s, at which point it began to rise steadily, a trend that persisted until quite recently. A second objective of this work was to examine why weight increases resumed despite continued growth in the use of weight-saving technologies.

The general patterns described above were observed for both cars and light trucks. However, cars showed a more dramatic weight decrease in the early years, while trucks underwent a steeper increase in the later years. The focus of this work is on cars exclusively rather than light trucks, for several reasons. First, cars

Figure 1 Average weights of new U.S. vehicles since 1975 (EPA, 2012)

showed a more dramatic decline in weight than did trucks in the late 1970s – early 1980s. Second, some key data sources were more readily available for cars than for trucks. Finally, cars have remained fairly well defined as a class of vehicles over time, whereas the types of roles fulfilled by trucks have changed considerably over the last 35 years, in particular with the advent of the minivan, SUV, and crossover.

All else equal, a vehicle with a lower weight (and commensurate reductions in power to maintain constant performance) will consume less energy per kilometer traveled. The magnitude of this reduction is significant: Cheah (2010) finds that a 10% reduction in weight results in a 6-7% reduction in fuel consumption. Changes in curb weight are brought about by two fundamentally opposing forces. Improvements in vehicle capability, such as higher performance, larger size or carrying capacity, and greater levels of equipment add weight to a vehicle. Advances in materials, design and manufacturing technologies remove weight from a vehicle. Therefore manufacturers must carefully balance content added to vehicles against investments in weight-saving technology during the course of product development.

This analysis incorporates estimates of the above sources of weight increase and decrease that are observable (vehicle size, architecture, features, engine size, material content) using a bottom-up analysis that estimated the contributions to changes in average weight of various technologies, features, and vehicle size classes. First, the effects of weight-saving technologies on the weight of an individual car were estimated from model-level data and from the literature. Second, the weight-

increasing effects of adding features and changing car classes were estimated. Finally, these individual-level estimates were aggregated into overall effects on average vehicle weight based on the changes in market penetration of the various technologies and features.

2 Weight reduction: Technological improvements

Weight-reducing effects were estimated for both major architectural changes and for the incremental replacement of traditional steel and iron with lighter and stronger alternative materials. A broader definition of weight-reducing technology would include myriad other advances in engineering, design, and manufacturing practices that permit materials to be used more effectively in building vehicles, but these sorts of technologies were not represented in the data used in this work.

2.1 Major architectural changes

New cars in the United States underwent large architectural shifts between 1975 and 1990 that contributed substantially to reductions in weight. In 1975, about half the cars on the market in the U.S. used unitized body (unibody) construction, and fewer than one in 10 were front-wheel drive. By 1990, 85% were front-wheel drive and 95% used unibody construction. (EPA, 2012)

Unibody construction

Unibody construction reduces weight by eliminating the traditional frame and integrating its structural functions into the vehicle's body shell. Data compiled by Audatex North America indicate that the overwhelming majority of cars offered in the U.S. since 1975 have used either unibody or body-on-frame construction. In addition, a small number of cars have used space frame construction, which employs a 3-dimensional structure of welded tubes to which non-structural body panels are attached, primarily in low production high performance cars. A few others have used a mixed, unibody-on-frame construction that incorporates elements of both unibody and body-on-frame construction.

Estimates of the weight savings from unibody construction vary widely. Dupnick and Graham (1996) suggested a weight difference of more than 450 kg (1000 lbs) between unibody and body-on-frame cars, while a 1970s case study from Ford attributed only 87 kg (192 lbs) of weight reduction to the switch from body-on-frame to unibody (Gutherie, 1978).

In this work, the weight reduction due to switching from body-on-frame to unibody construction was estimated by creating matched sets of unibody cars and comparable body-on-frame cars using Mahalanobis matching. Size, transmission, drive, and model year data were obtained from a database maintained by the U.S. Environmental Protection Agency (U.S. EPA). Data on construction type by model and year were provided by Audatex North America, and were merged with the EPA database. The matched sets of vehicles were created by matching unibody cars with body-on-frame cars that had the same transmission type and drive type, similar interior volume (within 5 cubic feet or 0.14m³), and were of similar vintage (within 2 model years). The two matched groups had identical fractions

of transmissions and drive types, and were very well balanced on model year and interior volume. The difference between these groups indicated that the average unibody car weighs 280 kg (616 lbs) less than a body-on-frame car with the same drive type, transmission type, and size, from the same model year, would weigh. A similar analysis indicated that the average space frame car weighs 156 kg (344 lbs) less than a comparable unibody car would, and that cars using unibody-on-frame construction do not differ significantly in weight from comparable unibody cars. These results are summarized in Table 1.

A potential source of bias in these estimates is the possibility that vehicles employing more advanced construction techniques may also tend to make greater use of alternative materials. Such as bias would lead to inflated estimates of the weight savings associated with advanced construction techniques, but data on materials composition were not sufficient to support an exploration of this possibility.

Table 1 Estimated weight effects of different construction types.

Comparison	Relevant Group	Estimated Difference (kg)	Standard Error (kg)
<i>Construction</i>			
Unibody vs. Body-on-Frame	Unibody cars	-280	5
Space Frame vs. Unibody	Space frame cars	-156	19
Unibody-on-Frame vs. Unibody	Unibody-on-Frame cars	-39	35
<i>Drive</i>			
FWD vs RWD	FWD cars	-296	6

Front-wheel drive

A second major architectural change in U.S. cars is the transition from rear-wheel drive to front-wheel drive. Compared with rear-wheel drive, front-wheel drive yields both a direct weight reduction in the drivetrain, and an indirect weight reduction due to improved packaging of the drivetrain. Eliminating the need for a tunnel running the length of the vehicle allows for greater interior space, and so the exterior dimensions of the vehicle (and thus weight) can be reduced while maintaining interior space.

The weight effect of front-wheel drive relative to rear-wheel drive was estimated by matching front-wheel drive vehicles with rear-wheel drive vehicles that had the same transmission type and construction type, similar interior volume (within 5 cubic feet or 0.14m³), and were of similar vintage (within 2 model years). The matched groups had identical fractions of different construction types and transmission types, and were very similar in average interior volume and model year. Based on the difference between these groups, it was estimated that a front-wheel drive car weighs an average of 296 kg (653 lbs) less (standard error: 6 kg) than a rear-drive vehicle with the same transmission type, construction type, interior volume, and model year.

Engine cylinder counts

During the period of this analysis engine technology has matured in numerous ways, allowing manufacturers to extract more performance from a given engine mass. These changes are partly reflected in materials analysis discussed later: newer engines more commonly use aluminum blocks and heads than in 1975, and ancillary equipment (intake manifolds and accessories) are increasingly manufactured from composite materials.

This analysis attempts to quantify the improved power density, less materials changes, by assessing the mass impact of changes in engine cylinder counts as a proxy for materials-neutral power density. Nearly all production cars during this timeframe use 4, 6 or 8 cylinder engines—balanced configurations for which most production and reliability issues have been resolved. A few vehicles use 3, 5, 10, 12 and 16 cylinder engines in limited production.

Using a matching process that holds constant for vehicle model, model year, body style and transmission type, this analysis identified an average decrease in weight of 64 kg (142 lbs) by decreasing from 8 to 6 cylinders, and an average decrease of 67 kg (147 lbs) by decreasing from 6 to 4 cylinders.

2.2 Alternative (lighter / stronger) materials

Traditional low-carbon steel and iron now make up less than half the weight of a new vehicle, as they are increasingly displaced by alternatives such as high-strength steel, aluminum, plastics, and magnesium. Because the substitution of alternative materials into a vehicle's design is strongly dependent on the demands of the specific application in question, estimating a single figure for the amount of weight saved by these materials is difficult. Nevertheless, it is helpful to generate some rough approximations based on the properties of different materials and reports in the literature. Cheah (2010) and Wohlecker et al. (2006) provide relationships for estimating the weight ratios of parts made with alternative materials to those made with conventional materials, for a variety of generic load cases. These provide a useful starting point for estimating the weight reduction potential of various alternative materials. In addition, rules of thumb and case studies of vehicle designs using alternative materials have been reported by a variety of authors. The weight-saving characteristics assumed for key materials are summarized in Table 2 and more detailed discussions of the assumptions for each material are found in the following sections.

High-strength steel

Rule-of-thumb relationships like those mentioned above, when used with typical values for materials properties, indicate that parts made from high-strength steel (HSS) can be expected to weigh between 0 and 25% less than a conventional steel part, depending on the application. Salonitis et al. (2009) estimated a 10-30% weight reduction from using advanced high-strength steels, and Roth et al. (1998) reported an advanced steel unibody weighing 25% less than conventional unibodies. Das et al. (1997) assumed that high-strength steels could reduce weight by 50% relative to conventional steels, but the rationale for this high value was

Table 2 Assumed weight savings for alternative materials.

Material	Relative Savings (fraction of weight saved by replacing conventional steel or iron with alternative material)	Weight Weight Potential, (kg conventional displaced per kg alternative material)	Reduction P (kg material per kg)
Conventional Steel	0%	1.0	
Iron	0%	1.0	
High-Strength Steel	23%	1.3	
Aluminum	45%	1.8	
Magnesium	60%	2.5	
Plastics & Composites	50%	2.0	

unclear. A particular challenge in estimating a weight reduction potential for high-strength steel is that there is such a broad range of grades available, with widely varying properties. For purposes of this work, with its focus on assessing weight reduction to date, it was assumed that each kg of high-strength steel replaced 1.3 kg of conventional steel (a 23% weight reduction).

Aluminum

Rules of thumb based on generic load cases suggest that substituting aluminum for conventional steel can reduce weight by up to 70%, with a 50% reduction predicted in many applications. The trade press has noted that the greatest concentration of automotive aluminum use is in engines, and that aluminum engine blocks weigh half as much as iron blocks (Murphy, 2006). Stodolsky et al. (1995) estimated that in engine applications, aluminum reduced cylinder head weight by 50% and block weight by 40%. They also reviewed a number of studies and concluded that substituting aluminum for steel in the body reduces weight by about 40-47%, even when “the design of the vehicle is not completely optimized for aluminum manufacture.” Mayer et al. (1994) concluded that a 45% reduction in weight for the body-in-white was possible by substituting aluminum for steel in a BMW 3-series. Das et al. (1997) assumed that substituting aluminum for steel and cast iron delivers a 45% weight reduction, while Carle and Blount (1999) estimated a 40% reduction in weight relative to steel in automotive body applications. Although generic load cases suggest that replacing steel with aluminum can reduce weight by as much as 70%, most of the (considerable) literature on the topic suggests that a value of around 45% is more realistic (i.e. that each kg of aluminum can replace 1.8 kg of conventional iron or steel). The latter was the value assumed in this work.

Magnesium

Magnesium still represents a very small fraction (0.3% in 2009) of automotive materials usage, and fewer estimates of its weight reduction potential have been reported. Based on generic load cases, it is estimated that magnesium can reduce weight by up to 70% compared with conventional steel or iron. Luo (2002) calculated savings as high as 80% for some wrought magnesium alloys. Das et al.

(1997) assumed that substituting magnesium for steel and cast iron would deliver a 67% weight reduction. In this work, it was assumed that each kg of magnesium replaced 2.5 kg of conventional steel or iron (a 60% reduction).

Plastics & composites

Estimating weight reduction potential for plastics and composites is particularly difficult because of the wide range of materials included in this category. However, some rough calculations with typical ranges of values for materials properties indicate that weight reductions in excess of 80% could be possible, relative to conventional steel or iron. For example, Luo (2002) estimated a weight reduction potential of 35-70% for polycarbonate/ABS based on generic load cases. Das et al. (1997) assume a 30-60% weight reduction from substituting composites for steel. The American Chemistry Council (ACC, 2011) has estimated that each kg of plastics and composites replaces 2-3 kg of other materials (a 50-67% reduction). A report commissioned by Plastics Europe (Pilz et al., 2005) concluded that each kg of plastic replaces an average of 1.5 kg of heavier material (a 33% reduction in weight), but found reductions of up to 75% in some components. In the present analysis, it was assumed that each kg of plastic or composite has displaced 2 kg of traditional steel or iron (a 50% weight reduction).

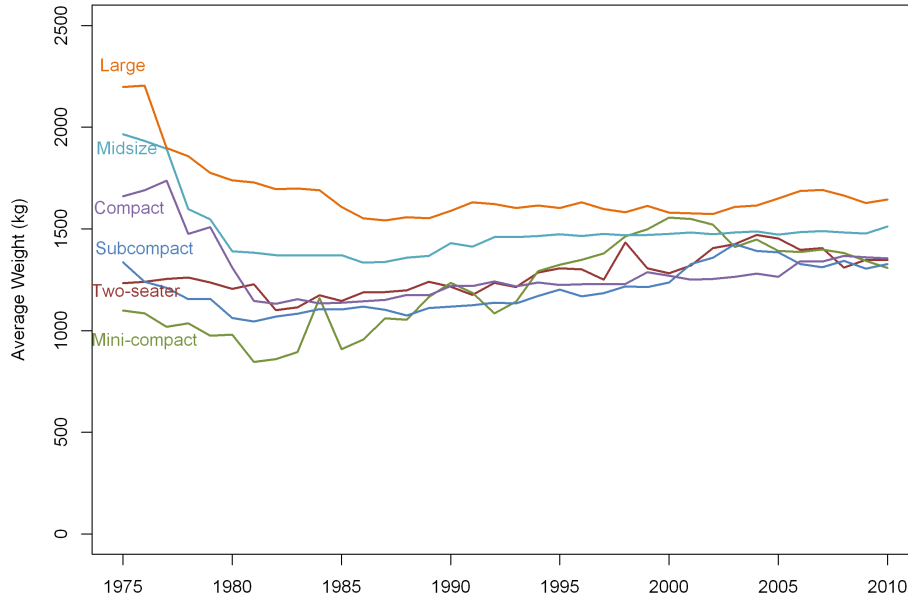
2.3 Other technological improvements

In addition to major architectural changes and increased use of alternative materials, several other sources of technological improvements may have contributed to weight reductions in new cars. Improvements in manufacturing processes and technologies, tighter tolerances, and the like may enable the production of parts that are more precisely designed to use material only where it is needed.

Concurrently, improvements in engineering methods and the availability of tools such as finite element analysis and computer-aided engineering may have enabled the design of parts and systems that make more effective use of materials, better optimizing component designs and interactions. There is clearly also the possibility of synergies between these two sets of improvements. The contributions of these tools to overall weight reduction is hard measure directly, but we will return to them later as a possible means to explain gaps between observed weight changes and those expected from materials substitution and architectural changes.

3 Weight growth: Functionality improvements

While the use of weight-saving technologies has steadily grown, it has been offset (and at times, more than offset) by increases in the deployment of weight-increasing features and a shift toward heavier (larger) car classes. In this section, the weight differences between various car classes are summarized, as are the subsystem weights associated with a variety of emissions, safety, and comfort & convenience features.

Figure 2 Average weights of new U.S. cars, by class. (EPA, 2012)

3.1 Weights by car class

In this work, the effects on weight of shifts in the vehicle size mix were estimated using data found in the U.S. EPA's annual Fuel Economy Trends Report. Figure 2 shows the average curb weight (average inertia weight minus 136 kg or 300 lbs) for each of six classes of cars tracked by EPA (weights for large, midsize, and small wagons tracked closely with those of the corresponding sedan classes, and are omitted from the figure for clarity). Several features visible in the figure are worth highlighting. First, weight decreases in the early years were much greater among the larger car classes than among the smaller classes. Second, since about 1980, the weights of compacts, subcompacts, and two seaters have been quite similar. Finally, the overall spread between classes has been shrinking over time, first due to weight decreases in the larger classes and more recently driven by weight increases in the smaller classes.

3.2 Feature content

One of the most readily observable changes to vehicles during the past four decades has been the widespread addition new features. For the purposes of this analysis, features included not only optional equipment (e.g. air conditioning) but also safety and emissions equipment such as airbags and catalytic converters that are required by regulation in new passenger cars.

This analysis is unable to capture all improvements in these areas—noise, vibration, and harshness (NVH), for example, has dramatically improved in new vehicles as a result of balance shafts, sound insulating materials and active noise cancelation. Other metrics such as reliability and body rigidity have also improved. This analysis does not attempt to quantify such metrics.

In total, features were estimated to add a total of 109 kg (240 lbs) to the average 1975 passenger car. In 2010, the estimated contribution grows to 223 kg (62 kg safety, 25 kg emissions, 136 kg comfort/convenience; a total of 491 lbs). These estimates do not include the contribution of secondary weight, discussed in the following section.

4 Secondary weight

Secondary weight represents the notion that for every unit of weight added to (or removed from) a vehicle, the supporting systems and structures also grow (or shrink) so that structural integrity and braking, acceleration and handling performance can be maintained. Typically, the secondary weight is expressed as some percentage an initial (primary) weight change. In the work reported here, secondary weight enters as the form of a percentage multiplier on bottom-up component analyses. In reality, the addition or removal of secondary weight may be discontinuous, as in the case where a discrete number of existing engines or transmissions are available for inclusion in a particular vehicle model. Moreover, secondary weight effects may vary depending on the subsystem in which the primary weight reduction occurs. Nevertheless, it is not uncommon to use a single secondary weight multiplier, and this approach is believed to be adequate for the type of analysis presented here, which relies mainly on fleet-wide data.

Cheah (2010) reviewed more than twenty published studies of secondary weight and identified estimates ranging from 23 – 129%, with a mean value of 79.6%. For the purposes of this study the secondary weight was assumed to be 80% of the primary weight added or removed. This secondary weight coefficient was applied to the bottom-up analyses of features and materials, in which the initial estimates of weight change were generated from component-level data. However, the secondary weight multiplier was not applied for mix shifting or architectural changes, since the weight effects of these changes had already been assessed at the whole-vehicle level.

5 Estimating fleet-level contributions of technologies and functionality

The general approach to estimating the effects of technologies and functionalities on average vehicle weight is captured in the question, “What would be the average weight of vehicles from some base year, if those vehicles instead had some future year’s combination of technologies and features?” The effects of changes in size mix, features, major architectural technologies, and alternative materials were estimated sequentially and added up as outlined in this section. In all cases, the

changes in size mix, features, and technologies are measured relative to a base year of 1975.

5.1 Mix shifting

The first step in estimating weight changes was to account for shifts in the mix of size classes between 1975 and each future year t up to and including 2009. Nine car classes based on body style and interior volume are tracked by U.S. EPA and were used as the basis of the mix shifting analysis in this work. For each year t , a weight value was calculated to represent the average weight of cars in that year, if the average weight within each class had been the same as in 1975 but the market share of each class were the same as the actual share in the year t .

$$W_t^s = \sum_i S_{it} \cdot W_{i,1975}$$

In the above expression, $W_{i,1975}$ is the average weight of cars in class i in 1975, S_{it} is the market share of class i in year t , and W_t^s is interpreted as the average weight in year t , adjusted only for changes in shares of various car classes since 1975.

The deployment rates of other major technologies considered in this analysis also tend to be correlated with car class. As a result, some changes in the market share of front-wheel drive, unibody construction, and different engine sizes would be expected to occur due to mix shifting. Therefore, the market share expected based on the change in mix was estimated as follows:

$$S_{jt}^s = \sum_i S_{it} \cdot S_{ij,1975}$$

In the above expression, S_{it} is the market share of class i in year t , $S_{ij,1975}$ is the market share of technology j within class i in 1975, and S_{jt}^s is interpreted as the market share of technology j in year t , adjusted only for the changes in class mix between 1975 and year t .

5.2 Architectural changes

After accounting for changes in weight and major technologies due to mix shifting, the next step was to estimate the aggregate weight effects of changes in major vehicle architectures. To do this, the per-vehicle weight effect of each architectural change (δ_j) was multiplied by the difference in market share of that architecture between the year t and 1975 (where the latter share has first been adjusted for mix shifting between 1975 and year t , as noted in the preceding section). The values obtained were then summed over all architectural changes:

$$W_t^{s,a} = W_t^s + \sum_j (S_{jt} - S_{jt}^s) \cdot \delta_j$$

The above expression, $W_t^{s,a}$ is interpreted as the average weight in year t , after adjusting for changes in both mix and the prevalence of major architectures

between 1975 and year t . Specifically, this approach was used to estimate the weight effects of the front-wheel drive and unibody transitions, as well as shifts in the prevalence of 4-, 6-, and 8-cylinder engines. As discussed in section 4, the weight differences associated with these architectural changes were estimated using vehicle-level data, and do not require further adjustment to account for secondary weight effects.

5.3 *Safety, comfort, & convenience features*

The next step was to estimate the weight effects of growth in the adoption of safety, comfort, and convenience features. Since the weights of the features were estimated based on teardown data for the associated components or subsystems, the secondary weight multiplier was included to estimate the effect of these features on overall vehicle weight:

$$W_t^{s,a,f} = W_t^{s,a} + (1 + \sigma) \sum_k (S_{kt} - S_{k,1975}) \cdot \delta_k$$

In the above expression, S_{kt} is the take rate of feature k in year t , $S_{k,1975}$ is the take rate of the feature in 1975, δ_k is the weight associated with the feature based on teardown analysis, σ is the secondary weight factor, and $W_t^{s,a,f}$ is interpreted as the average weight in year t , based on adjusting average weight in 1975 for changes in mix, major architectural changes, and features.

The component-level masses used in these analyses of feature mass are limited in their ability to embody technological improvements in the features themselves. The study of safety features referenced, (DOT, 2004) incorporates at best two point values for the mass of a given feature, while comfort and convenience feature weights are based on a single teardown of four MY2009 production vehicles.

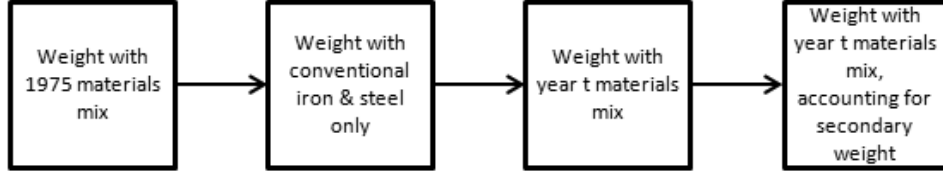
5.4 *Alternative materials*

The final step in estimating weight changes was to incorporate the effects of changes in alternative materials usage between 1975 and each future year. This was done by answering the question: “By how much would the weight of the average car change if the materials mix from 1975 were replaced with the materials mix from some future year t ?” This question was addressed in several steps, premised on an assumption that all materials substitution occurs among the materials in set C , which comprises conventional steel and iron, high-strength steel (HSS), aluminum, magnesium, and plastics.

The first step was to ask, “What would be the weight of iron and steel in a car if all of the steel, iron, high-strength steel (HSS), aluminum, magnesium, and plastics in it were replaced by only conventional steel and iron?” This estimate was made using the following expression:

$$W_t^{conv\ only} = W_t^{s,a,f} \sum_{l \in C} f_{l,1975} \cdot P_l$$

In the above expression, $W_t^{m,a,f}$ is the average weight adjusted for changes in size mix, major architectures, and features, as explained in the preceding sections;

Figure 3 Representation of modeling logic for weight-reducing materials.

$f_{l,1975}$ is the weight fraction of material l in 1975; P_l is that material's weight reduction potential (i.e. the weight of conventional material replaced per unit weight of material used, equal to 1 for conventional steel and iron and greater than 1 for weight-saving alternative materials); and set C includes those materials assumed to be subject to substitution. Other materials, such as glass, zinc, and fluids, were explicitly excluded at this stage.

The second step was to ask, "How would the resulting weight estimate change if the conventional steel and iron were replaced with HSS, aluminum, magnesium, and plastics in the proportions used in year t ?" The new weight using these proportions of alternative materials was estimated as:

$$W_t^{adv} = W_t^{conv \text{ only}} \frac{\sum_{l \in C} f_{lt}}{\sum_{l \in C} (f_{lt} \cdot P_l)}$$

Third, the weight of miscellaneous materials (the set D , including glass, zinc, fluids, etc), was assumed to be unaffected by the materials substitution, and was added to the estimated weight of steel, iron, HSS, aluminum, magnesium and plastics:

$$W_t^{s,a,f,m} = W_t^{adv} + W_t^{s,a,f} \sum_{l \in D} f_{lt}$$

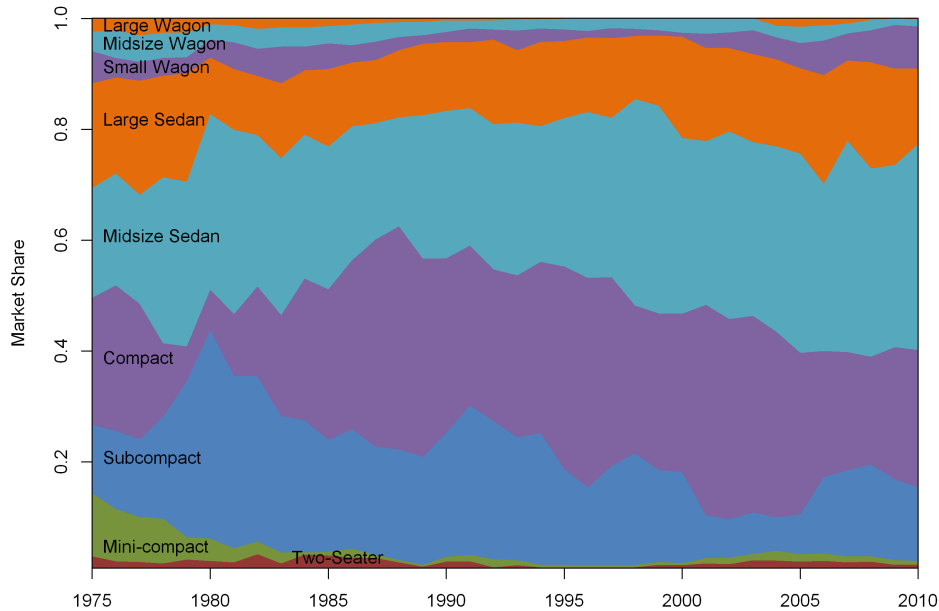
Finally, the weight was adjusted for the secondary weight effects resulting from the materials substitution:

$$W_t = W_t^{s,a,f,m} + (W_t^{s,a,f,m} - W_t^{s,a,f})(1 + \sigma)$$

The above weight, W_t , constitutes an estimate of the average car weight in year t , obtained by starting from the average weight in 1975 and adjusting for changes in size mix, major architectures, feature content, and materials composition between 1975 and year t . The logic for estimating the weight effects of alternative materials is summarized in Figure 3.

6 Examining weight trends since 1975

By combining all estimates of weight-reducing technologies and weight-increasing functionality improvements as shown in Figure 3, an estimate was developed for the net change in weight year over year. The results of these individual contributions are reported here, and in section 7 they are aggregated up and compared with actual net changes in average passenger car weight.

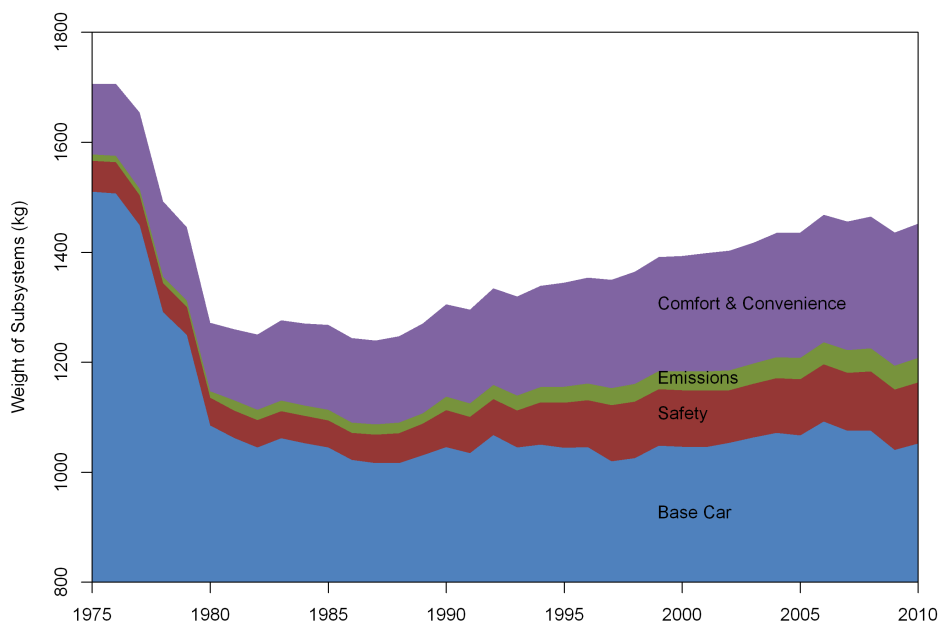
Figure 4 Historical sales mix of passenger cars by class.

6.1 Sources of weight increase

All else equal, adding functionality to a vehicle in the form of greater size or feature content will generally tend to increase weight. As will be shown in this section, changes in the size mix have added approximately 50-100 kg (110-220 lbs) to the average new car in recent years. The addition of new safety, comfort, and convenience features (and associated secondary weight increases) has added approximately 200 kg (440 lbs) to the average new car since 1975.

Figure 4 shows the mix of car classes, weighted by sales, reported by EPA (2012). In the late 1970s, there were noticeable shifts from the compact segment to subcompacts, and to a lesser degree from large sedans to midsize. Over the subsequent years, these trends were gradually reversed. More recently, subcompacts have once again regained share from compacts, as have midsize cars from large cars.

Figure 5 shows the estimated weight effects of safety, emissions, and comfort & convenience features for the average new car since 1975, including secondary weight effects. Comfort and convenience features have added more weight than either safety or emissions features, with the most significant contributions coming from near-universal application of air conditioning and automatic transmissions. Greater detail, including the market shares and weight effects of each specific feature considered, can be found in Zoepf (2011).

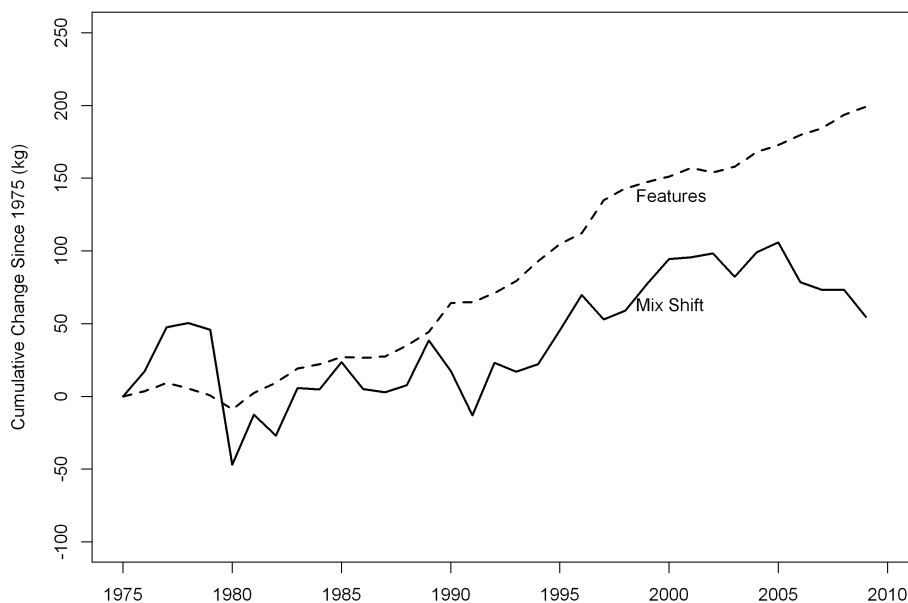
Figure 5 Weight effects of changes in since 1975, including secondary weight.

The estimated cumulative weight effects of additional features and mix shifting are summarized in Figure 6. There was little change in the weight of features between 1975 and 1980, but since 1980 the weight of features has steadily increased, and was estimated to account for approximately 200 kg (440 lbs) of additional vehicle weight in 2009, compared with 1975. The effect of mix shifting since 1975 peaked at an increase of 106 kg (233 lbs) in 2005, before falling back to +54 kg (120 lbs) by 2009 as the longstanding trend toward larger cars was reversed. The results in Figure 6 indicate that if not for the effects of weight-saving technologies, mix shifting and the adoption of new features would have increased the weight of the average car by approximately 250 kg (550 lbs) between 1975 and 2009.

6.2 Sources of weight reduction

Technological improvements, including greater use of front-wheel drive, unibody construction, lighter and stronger materials, and a shift from 8-cylinder to 4- and 6-cylinder engines, have all tended to reduce the average weight of new cars since 1975.

Figure 7 shows the fractions of cars using each construction type from 1975 through 2010. The shares in Figure 7 are based on data compiled by Audatex North America, and are based on available models rather than sales. About half of the cars offered for sale in the U.S. in 1975 used unibody construction, but this

Figure 6 Cumulative weight effects of feature changes and mix shifting.

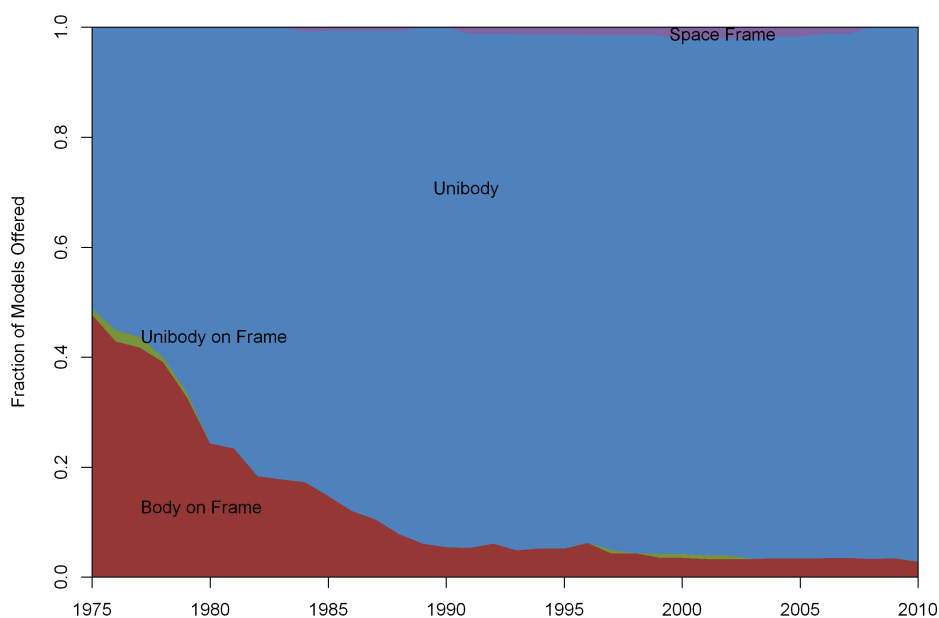
share rose steadily to more than 90% by 1990, and has changed only slightly since then.

Figure 8 shows the market share of front-wheel drive in U.S. cars from 1975 to 2010, as reported by EPA (2012). These values are sales-weighted. Less than 10% of new cars employed front-wheel drive in 1975. As with unibody construction, this share rose rapidly through 1990, but has remained fairly steady since then.

Figure 9 shows the sales-weighted shares of 4-, 6-, and 8-cylinder engines by year, which together account for the overwhelming majority of all engines in U.S. cars. Eight-cylinder engines suffered a huge loss in market share between the late 1970s and early 1980s, followed by slower declines in later years. After peaking in the mid-1980s, the share of 4-cylinder engines declined slightly and then held steady before recovering as fuel prices rose after 2005.

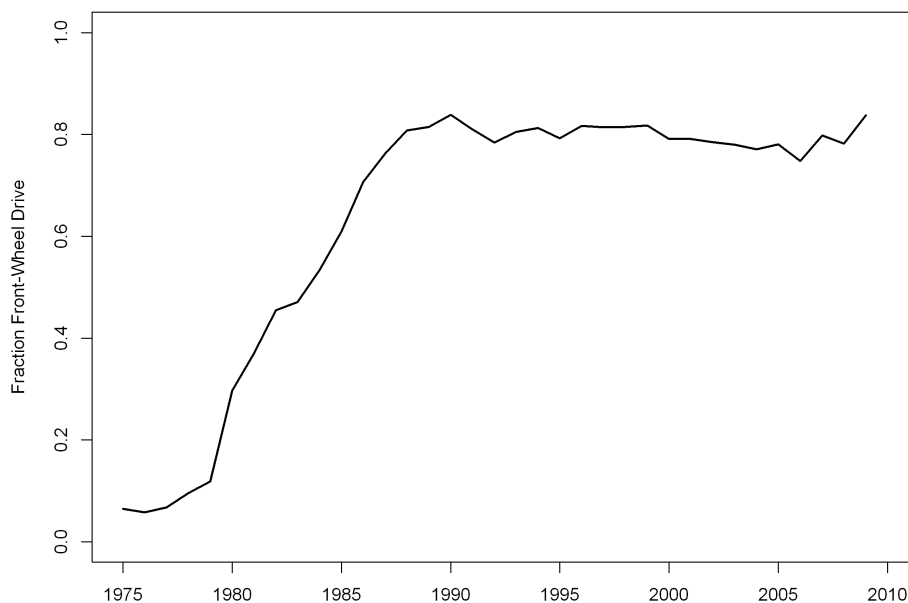
The materials content of cars was compiled from several related sources, primarily various editions of the Transportation Energy Data Book (TEDB) published by Oak Ridge National Laboratory. The scope of the materials analyses and the original sources of the data varied from year to year, but there was substantial overlap between the various time series. Table 3 summarizes the years included in each time series, and which of these were incorporated into the time series reported in this work. In years for which no data could be found, materials content was linearly interpolated.

The materials content data warrants additional discussion. Two potential issues are the changing scope used over the years (U.S.-built car, domestic car, domestic

Figure 7 Availability of major construction types in U.S. cars since 1975.**Table 3** Sources of material content data used in this analysis.

Series	Source	Scope	Years Available	Years Used
(1)	TEDB, Ed. 6 (citing Ward's)	U.S.-built car	1975-1981	1975-1981
(2)	TEDB, various (citing Ward's)	Domestic car	1978, 1984, 1985, 1992, 1993, 1994, 1996, 1997	1984, 1985, 1992, 1993, 1994, 1996, 1997
(3)	TEDB, various (citing American Metal Market)	Domestic car	1977, 1978, 1985, 1987, 1990, 1998, 1999, 2001, 2003, 2004	1987, 1990
(4)	TEDB, various (citing Ward's)	Domestic light vehicle	1995-2009	1998-2009
(5)	American Chemistry Council	Domestic light vehicle	1987-2005	None

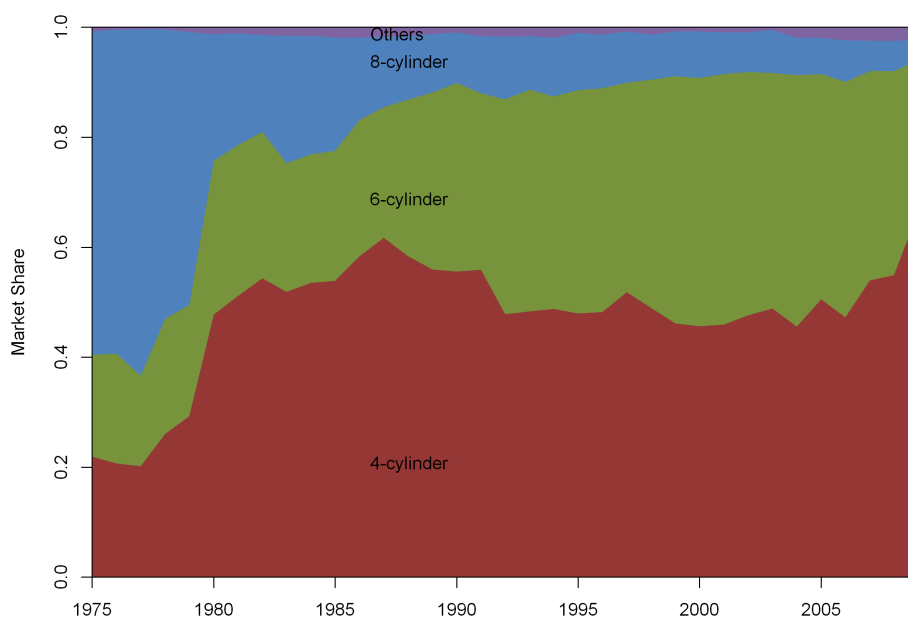
light vehicle), and the differing original sources of the data. Fortunately, there is substantial overlap between the different data sets, and in general the weight fractions of each of the key materials are very similar in the different data series. This helps to mitigate concerns over inconsistencies in the data over time. Moreover, personal communication with Ward's has confirmed that the American Chemistry Council is the original source of the Ward's data.

Figure 8 Sales-weighted penetration of front-wheel drive in passenger cars.

An additional issue is that these data are based on domestic vehicles, and not imports. This is a legitimate concern, but in the absence of any data on the materials composition of imported cars, the materials composition time series reported here were assumed to apply to all cars sold in the U.S.

Figure 10 charts the evolution of the materials composition of U.S. cars based on the composite data set described above. The share of conventional iron and steel in overall vehicle weight has shrunk by a third since 1975, with HSS, aluminum, and plastics rising to fill in the gap. Plastics & composites account for twice as large a share of weight as they did in 1975, while aluminum content has quadrupled and HSS content quintupled. Although magnesium's share has grown by a factor of 10, it still only accounted for about 0.3% of vehicle weight in 2009. Miscellaneous materials (rubber, glass, fluids & lubricants, etc.) have risen modestly, from 20% to 25% of overall vehicle weight.

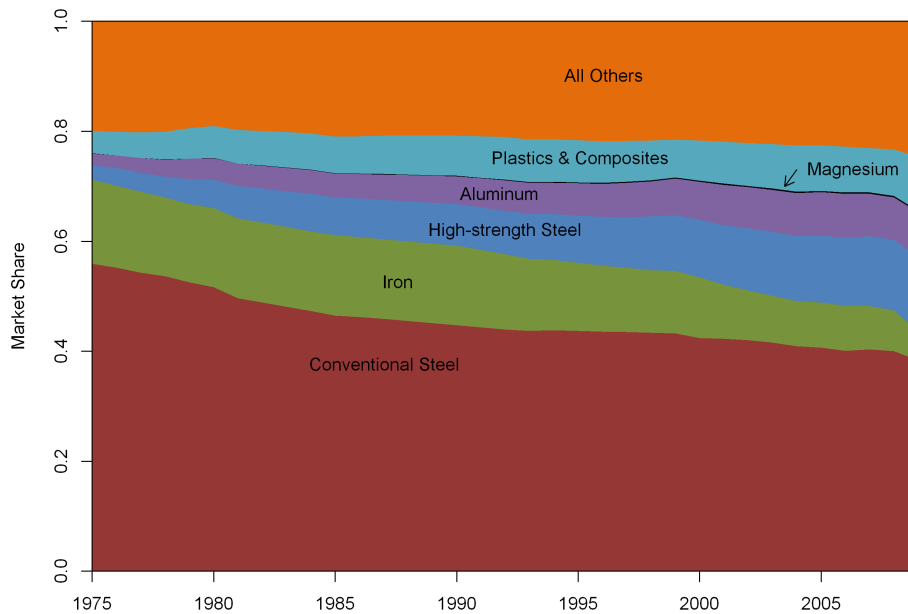
The estimated effects of the various technological improvements on average car weight are summarized in Figure 11. Each series corresponds to the estimated cumulative weight change relative to 1975. All of these technological changes contributed significantly to weight reduction, especially in the early years. Since 1990, weight reductions have largely been driven by alternative materials substitution, as the market has become saturated with front-wheel drive and unibody cars and the shift away from 8-cylinder engines slowed considerably. All told, the combined effects of technology are estimated to have reduced the weight of the average new car in the U.S. by 790 kg (1,700 lbs) versus 1975.

Figure 9 Market shares of 4, 6 and 8-cylinder engines in new U.S. passenger cars.

7 Estimating average weight

The effects of growing feature content, mix shifting, and weight-reducing technologies were summed up as outlined in section 5 (Estimating Fleet-Level Contributions of Technologies and Functionality). The resulting weight estimates for each year are plotted in Figure 12, along with the actual average weight of new cars as reported by U.S. EPA. The estimates developed here capture the general trends observed in the weight of the average new car between 1975 and 2000: namely, a large and abrupt decrease in the late 1970s - early 1980s, followed by a gradual reversal and increase. After 2000, actual average weight continued to climb, while the estimates of this work declined slightly, driven by growth in alternative materials. As with any change in new vehicles, changes in the application of features or weight-saving technologies will take several decades to fully permeate the in-use fleet, due to the dynamics of fleet turnover.

Although the results reported here reflect the general trends in average car weight, two key discrepancies are apparent in Figure 12. First, the estimates developed in this work are too high in the early years. Second, the estimates continue to fall while actual weights remained constant, and have not risen as quickly as actual weights have in recent years. These discrepancies are highlighted by a residual term, also plotted in Figure 12 and calculated as the difference between the actual average weight and the average weight predicted by this analysis. That the predicted values for weight would not perfectly agree with

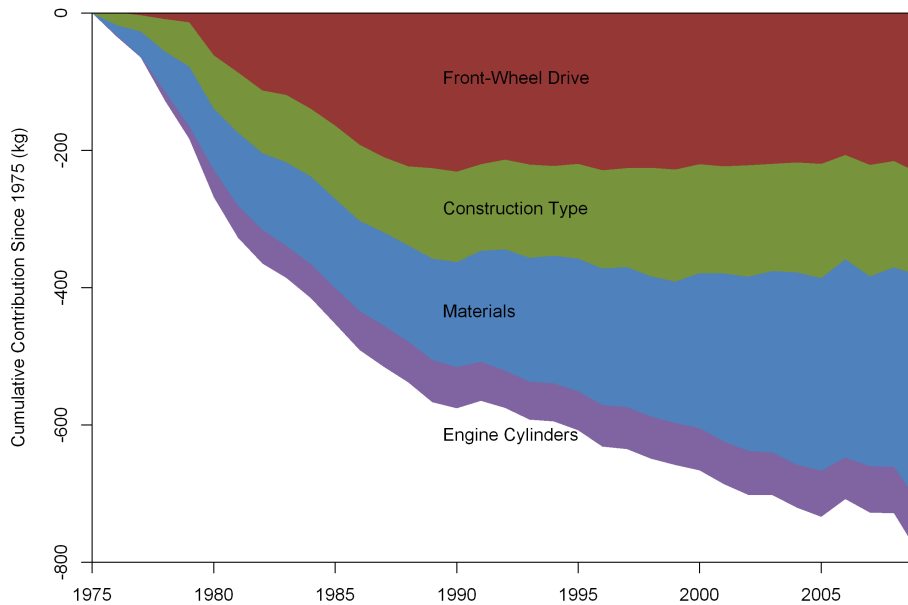
Figure 10 Materials composition of new U.S. cars since 1975.

the true averages should not be surprising, given the disparate and often highly aggregate nature of the data used to generate the estimates. Nonetheless, patterns in the actual and estimated weight trends may be due to a variety of causes, and deserve further discussion.

It appears that some substantial source of weight reduction has been omitted from the estimated values in 1976-78, which suggests that one of two things may have been happening at that time. There may have been additional technological improvements that served to reduce weight. Some of these were discussed in section 2, and might include improvements in design, engineering, and manufacturing practices. Another possibility is that design tradeoffs were made that sacrificed functionality in order to save weight, but that these sacrifices were not captured in the data on feature content or size mix. The latter explanation seems less plausible, given that there was so little change in weight due to feature content or size reductions during this period. Presumably, if design tradeoffs were being made to save weight, they would not be restricted to only those attributes that happen to be excluded from our data set.

A second feature of Figure 12 is that the estimated weight is approximately constant after 1988, but actual weight increased during this period. This suggests that additional features or functionality, not captured in the data on feature content, may have been added to cars during this period. Some possibilities were discussed in section 5, and include things like NVH improvements. It is also possible that the estimated weight reductions from technology in this latter period

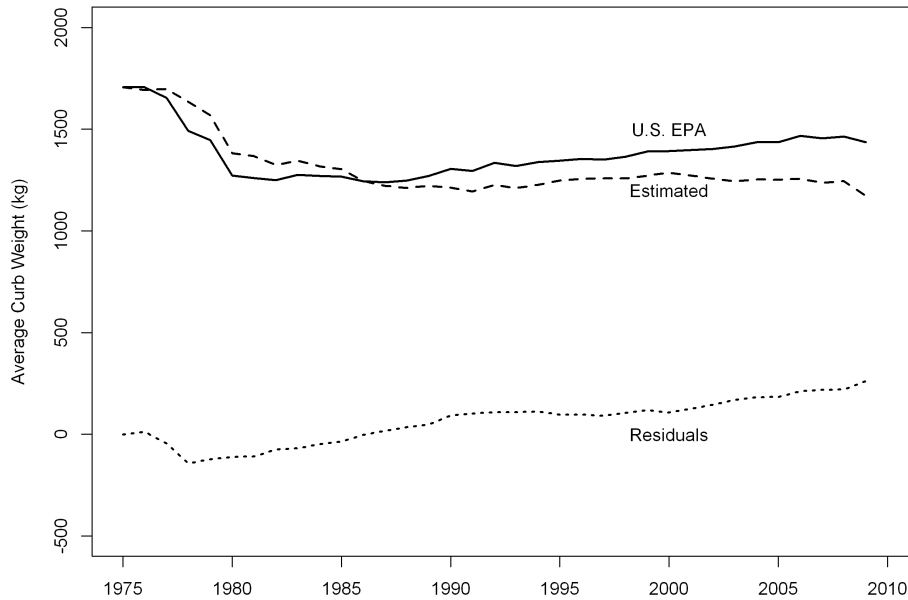
Figure 11 Estimated contributions of technological improvements to weight reduction in new U.S. cars, since 1975.



were too high. However, in order to fully explain the actual change in weight during this time, the weight savings from technology improvements (largely alternative materials during this period) would need to be essentially zero. Even if the true weight savings from alternative materials were lower than assumed, it is unlikely that they would be zero, since there would be no incentive to adopt more expensive materials if they didn't save weight (or equivalently, increase strength per unit weight).

An additional possible explanation for the discrepancies between the actual and predicted weights is that certain parameters assumed to be constant in this analysis may have actually varied over time. For example, it is plausible that the secondary weight factor might have been higher in earlier years and lower in more recent years. Alternatively, the weight savings from front-wheel drive or unibody construction may have declined over time. While these factors would tend to push the estimated weights closer to the actual weights (lower in the early years, higher in the later years), none of them on its own is adequate to resolve the discrepancies between the actual and estimated average weights.

Figure 12 Actual and estimated average weights of new U.S. cars since 1975, and differences between these (residuals).



8 Conclusions

In the work reported here, a bottom-up analysis was developed to explain as fully as possible the rapid decline and subsequent steady increase in the average weight of new U.S. cars since 1975. The weight effects of various technologies and features were estimated using reviews of available literature and analysis of model-level data. Weight trends across the fleet of new cars were estimated by aggregating up these vehicle-level data using fleet-wide penetration rates.

The best estimates from this work indicate that new features and functionality would have added at least 250 kg (550 lbs) to the weight of the average new car between 1975 and 2009, if not for offsetting improvements in technology. Over the same period, it is estimated that alternative materials, more weight-efficient vehicle architectures, and reduced engine sizes have taken 790 kg (1,700 lbs) out of the weight of the average car.

The switch to front-wheel drive, that from body-on-frame to unibody construction, and increased use of alternative materials all contributed significantly to historic weight reductions, and observed changes were able to explain about 80% of the weight reduction that occurred between 1975 and 1982. In later years, accounting for observed features and technology replicated the observed weight increases of the 1990s, but did not capture the continued weight increases since 2000.

Several explanations are possible for the observed patterns. First, there might be substantial unobserved technology improvements that could contribute to time-varying residuals. For example, the use of alternative materials – and especially combinations of such materials – requires substantial capabilities in forming, joining, and design that would change over time. Alternatively, time-varying engineering emphasis on reducing weight that could have been omitted from the data set, particularly concentrated in the early years. Such a theory is generally supported by anecdotal evidence from industry experts at the time (Lutz, 2011) who claim that CAFE regulations and economic conditions forced radical redesigns of domestic vehicles in the early 1980s. Such a shift in engineering emphasis could result in the discontinuity of the application of technology or diminishing marginal returns in unobserved weight-reducing technologies that are reflected in the residual error observed here. This effect could potentially be modeled using a non-fixed secondary weight multiplier that is higher in early years. Finally, our inability to accurately predict weight changes during late phases of the 1975-2009 period considered could indicate a shift in focus to improve the feature and functionality of vehicles in non-observed ways such as crashworthiness or reductions in NVH.

As noted at the outset, many automakers have recently announced a renewed focus on reducing the weight of their vehicles. An update to this work within the next few years will be particularly telling. Will automakers realize this weight reduction primarily through observable materials or structural changes, or will these reductions come through unobservable design and process changes? More importantly, however, will be whether these reductions are actually realized, or are offset by the continued growth in vehicle features and functionality witnessed over the past three decades.

References

- ACC. Chemistry & light vehicles. Technical report, American Chemistry Council, December 2011.
- D. Carle and G. Blount. The suitability of aluminium as an alternative material for car bodies. *Materials & design*, 20(5):267–272, 1999.
- L.W. Cheah. *Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the US*. PhD thesis, Massachusetts Institute of Technology, 2010.
- S. Das, T.R. Curlee, and S.M. Schexnayder. Materials used in new generation vehicles: supplies, shifts, and supporting infrastructure. Technical Report ORNL/TM-13491, Oak Ridge National Lab., TN (United States), 1997.
- DOT. Cost and weight added by the federal motor vehicle safety standards for model years 1968-2001 in passenger cars and light trucks. Technical Report DOT HS 809 834, U.S. Department of Transportation, December 2004.
- E. Dupnick and J. Graham. The demand for advanced materials in the automotive industry: Projections for the next decade. In *AIP conference proceedings*, volume 361, page 163, 1996.
- EPA. Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2011. Technical Report EPA-420-R-12-001a, U.S. Environmental Protection Agency, March 2012.

- AL Guthrie. Fairmont/zephyr-engineered for lightweight and improved fuel economy. Technical Report 780134, Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale, PA, 15096, USA,, 1978.
- A.A. Luo. Magnesium: current and potential automotive applications. *JOM Journal of the Minerals, Metals and Materials Society*, 54(2):42–48, 2002.
- R. Lutz. *Car Guys vs. Bean Counters: The Battle for the Soul of American Business*. Portfolio/Penguin, New York, NY, 2011.
- S. Mayer, AD Seeds, and Society of Automotive Engineers. BMW’s aluminum lightweight prototype car projects: Comparison of aluminum and steel performance. Technical Report 940154, Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale, PA, 15096, USA,, 1994.
- T. Murphy. Aluminum claims no. 2 ranking. WardsAuto.com, March 2006.
- H. Pilz, J. Schweighofer, and E. Kletzer. The contribution of plastic products to resource efficiency. Technical report, Plastics Europe - Association of Plastics Manufacturers, Brussels, Belgium, 2005.
- R. Roth, J.R. Dieffenbach, R. Koehr, and J.A. Isaacs. Economic analysis of the ultra light steel auto body. In *SAE Conference Proceedings P*, pages 285–290. Society of Automotive Engineers, 1998.
- K. Salonitis, J. Pandremenos, J. Paralikas, and G. Chryssolouris. Multifunctional materials used in automotive industry: A critical review. In *Engineering Against Fracture*, volume 1, page 59, 2009.
- F. Stodolsky, A. Vyas, R. Cuenca, and L. Gaines. Life-cycle energy savings potential from aluminum-intensive vehicles. In *1995 Total Life Cycle Conference & Exposition*, Vienna, Austria, October 1995.
- R. Wohlecker, H. Wallentowitz, R. Henn, and J. Leyers. Communication module–mass reduction. Technical Report 56690, Forschungsgesellschaft Kraftfahrwesen mbH Aachen, Body Department, November 2006.
- S. Zoepf. Automotive Features: Mass Impact and Deployment Characterization. Master’s thesis, Massachusetts Institute of Technology, 77 Massachusetts Ave. Cambridge, MA 02139, USA., 2011.