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ABSTRACT

A framework for considering trade-offs between increased costs for lightweight materials and the attendant fuel savings accruing from weight reduction is developed in this paper.

Two quantitative estimates of lifetime fuel savings due to weight reduction of a vehicle are derived. For substitution on an ongoing vehicle, available data suggest savings of about 0.26 gallons for the vehicle lifetime per lb. of weight reduction. When long-term changes in vehicles follow lightweight material feasibility, a range of estimates must be quoted; viz: 0.55 to 1.07 gallons for the vehicle life per primary pound saved.

Considerations of trading these fuel savings against higher costs highlights two crucial issues: (1) the percentage weight reduction achieved in the substitution and (2) fabrication cost penalties. These technical issues largely determine whether a given application saves over-all resources. In a broad, approximate manner, the present trade-off analysis is found to be consistent with recent substitution practice and with apparent future trends.

ONE OF THE MOST CHALLENGING, exciting periods in automotive materials engineering is now well underway. Significant changes in material utilization are occurring partly driven by the well known changes in the U.S. and world energy supply and price situation. The purpose of this paper is to describe some of the changes and by identifying the relevant parameters to attempt a projection of further change. Identification of the important technical/economic issues also allows one to consider the factors that could significantly alter the projection.

The major thrust of the paper will be towards the material changes occurring because of changing energy supply and prices. This is not because other changes are insignificant - emerging materials will intersubstitute for one another in the future as in the past because of total resource efficiency, i.e. capital, labor and other total cost factors will continue to play a role despite relative changes in energy prices. Nonetheless, the relatively sudden change in U.S. awareness, vulnerability to import price, and concerted drive to change consumption habits, dictate that energy is currently dominating these other driving forces. In the energy saving arena, materials can play two major roles. The first is their influence on increased efficiency of power plants; for example, the appropriateness of wholly new engine systems (e.g. electric or turbine) may well hinge on materials technology. Indeed, the addition of platinum as catalysts and silicon in chips or micro-processors may well result in more overall fuel savings (at a given emissions level) than the total weight reduction from all material substitutions which have occurred or are highly likely. In the near term, the total weight reduction due to materials substitution will probably not exceed 20% of vehicle weight which translates to about 10% less fuel consumption. Nonetheless, it is this second role - the weight reduction thrust to reduce the energy consumed - which is causing the largest shifts in material volumes (literally millions of tons) and are thus the subject of most discussion and constitute the main theme of this paper.*

In treating the overall problem of materials substitution for weight reduction, an attempt is made to establish a quantitative framework for describing current and likely future events. Several findings or results of extensive past experience on automotive materials substitution should be listed as they are inherently assumed in much that will follow. Four can be noted:

1. Given enough time and/or money, almost all materials can be substituted for one another. As a most radical example, it is difficult for most people to even envision a nearly all ceramic car; nonetheless, it is this author's judgement that one would arise if only these materials were available (or even if they were the only ones available at "reasonable" cost). Such vehicles may well not be as comfortable or safe or even as fuel efficient as steel alternatives (and might cause a need for new highways). However, one would not know the full implications of ceramic cars without long, expensive technological development programs. Thus, if we consider large scale radical change, (including mass vs. private transport) "almost complete materials substitutability" may err from understatement.

2. The second important lesson derived from our experience is that in a highly developed product/industry, all material substitutions are difficult. The full product and manufacturing implications of change in the working material

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*A third materials role in automotive energy efficiency could be to reduce non-weight related power losses; however, materials are playing a relatively minor role in the ongoing reductions in aerodynamic drag.

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are almost never fully forecast without expensive and elaborate hardware and pilot studies. The time span for application is usually quite long. System redesign - especially manufacturing - is always necessary to "otpimize" substitution and is usually needed just to make it possible. (1)*

3. Technical and economic feasibility issues are closely interdependent in materials substitution problems. Our prime example is the effect world energy economics is having on U.S. automotive materials technology. However, it is just as significant that the economics of substitution hinge largely on technical issues. As we will see, improved material properties can significantly change the economic feasibility of substitution.

4. The fourth conclusion from experience (and it obviously follows from the first three) is that one must prioritize efforts reasonably carefully since the issue isn't what can be done but instead what should be done. Because of large interrelated changes in manufacturing and product necessitate long application time scales, it is also prudent to adopt a long-run point of view in such analyses.

In the present context, appropriate weight reducing applications are assumed to be those where the relevant fuel savings is worth any extra cost associated with application of weight reducing materials. Some applications will turn out to save cost and weight and thus need no detailed analysis to be seen as appropriate.** In this paper, we first consider the value of weight reduction in decreasing fuel consumption. This is a very difficult area to rigorously quantify, but arriving at estimates allows us to establish cost per pound saved as an excellent tool for prioritizing effectiveness of application. This allows the major technical issues to be identified - viz: percentage weight reduction (or substitution ratio) and fabrication costs. The analytical framework is then tested by reviewing material substitution in the past. Finally, the analysis is viewed as a projective tool and it allows sensitivity to various parameters to be ascertained and thus the relative value of potential future technological developments can be estimated.

INFLUENCE OF WEIGHT ON VEHICLE FUEL CONSUMPTION

Since a primary reason for reducing weight is to save fuel, a quantitative framework must include a method for calculating the lifetime fuel savings associated with weight reduction. Although the total vehicle mileage, mileage by year and discounting are important issues, the key uncertainties in calculating lifetime fuel savings resolve around determining the change in fuel consumed per mile per pound of weight saved. Issues include the time-frame of application, the level of secondary weight savings, the assumed level of powertrain efficiency, data correction due to aerodynamics and data correction due to vehicle performance and functional differences. The time-frame of application is important, first because it can affect the technological achievement possible and secondly because one must separately consider application on existing vs. "all-new" cars. In this latter rare event, powertrain sizing and other chassis systems can be reoptimized (2,3,4) to take advantage of the lower vehicle weight resulting from lightweight materials application. Based on the overall complexity of such total and coordinated change, such benefits are probably only practically realizable in a 10-year or more time-frame; thus, throughout this paper we refer to these as "long-range" estimates.

For determining changes in fuel consumed as a function of weight, it is useful to realize that in principle the weight of a vehicle should linearly (but not proportionally) increase the fuel consumed per mile travelled by that vehicle. The major problem is to obtain the appropriate data base for obtaining the change in fuel consumption with change in weight. Figure 1 shows date from 1979 cars simply plotted as fuel consumption*** vs. weight (5) and shows a simple straight line in agreement with expectation. The figure would indicate a slope of 1.4 x 10^{-5} gallons per mile per pound of vehicle and this estimate has been used in some analyses. (6,7) However, the result is not theoretically sound because all of the fuel consumption is now attributed to weight dependent terms. It is well known that aerodynamic drag factors are significant in the work done by real vehicles and thus the intercept on figure 1 should not be at zero.

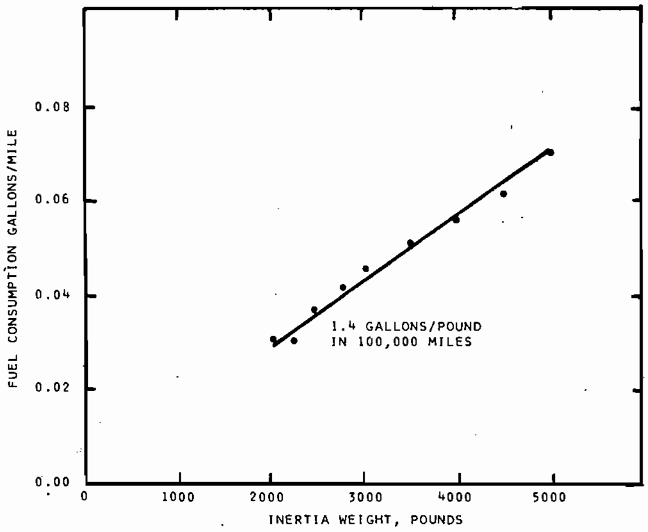

Fig. 1 - Fuel-consumption and inertia weight relationship for 1979 passenger cars after Cochran and McClure.

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*Abernathy (1) discusses in depth the effect of prior productivity increases on raising obstacles to further technical change.

**Investment costs are not treated in this paper but a full cost analysis would include them.

***Fuel consumption is simply the inverse of the more usual (in U.S.) "fuel economy" measures.

The data plotted in Figure 1 over the range of vehicle weights are not from comparable vehicles. The acceleration performance, transmission efficiency, and vehicle area and thus aerodynamic drag losses are not constant over the vehicle series considered. To obtain the change in fuel consumption with weight alone, one would want data from functionally equivalent cars having different masses. Unfortunately, every one of the functional changes act to reduce the apparent fuel consumption of low mass cars relative to those with higher masses. Thus, the theoretically incorrect result of no mass-independent fuel consumtpion can arise as in Figure 1. Apparently, the first publication which (implicitly) recognized that vehicle weight should linearly increase the fuel consumption is that due to Marshall (8). It is of interest that he applied an aerodynamic correction to his data and obtained a slope of 0.76×10^{-5} gallons per mile per pound.

An independent analysis of these factors was performed as part of this study and is briefly reviewed here. Working with data from 1978 to 1979 Ford cars and considering three terms as the key vehicle variables (Figures 2 and 3 explain the concepts and expected nature of graphs) we have derived slopes of 0.69×10^{-5} gallons per mile per pound for manual transmission vehicles and 0.92×10^{-5} for vehicles with automatic transmissions.

Fuel Consumption and Weight Concepts

A. Work done per unit time includes three terms:

1. Rolling resistance $= \beta_R \mu V \cdot W$
2. Inertia $= \beta_I \frac{aV}{g} \cdot W$
3. Aerodynamics $= \beta_A C_d A V^3$

- Two depend on weight W, thus

$$\text{Work} = B_o + B_W W$$

B. Therefore, fuel consumption depends similarly on weight since

$$\text{F.C.} = 1/\alpha \,.(\text{Work})$$

$$\alpha = \text{"Powertrain Efficiency"}$$

$$\text{F.C.} \ \frac{\text{gal.}}{\text{mile}} = A_o + A_W W \qquad A_o = k_1 C_d A_o \ \ \alpha$$

$$A_W = K_2 \ \alpha$$

C_d = Drag coefficient
A_o = frontal area
k_1, k_2 = Constants determined from data

C. For any vehicle α can be determined by measurement of fuel consumption and all parameters in A summing over the EPA cycle. Then other fuel consumptions can be calculated at other weights and the slope and intercept determined (Figs. 3 and 4).

Fig. 2 - Concepts used in studies of effect of weight on fuel-consumption

Thus, one can obtain different values or estimates for the change in fuel consumption with change in weight. All of these estimates assume that cars when weight reduced are then given reduced power engines and drivelines in order to obtain more fuel efficiency with constant acceleration performance. Since new design, development and putting into practice requires more than five years, this is clearly a long-run estimate. Table I summarizes the estimates from different sources. Also shown are shorter term or "application to esisting vehicle" estimates. The short term data reported in this study was on 1979 cars, where careful repetitive dynamometer tests were run with only inertia weight settings for the dynamometer changed. The "corrected" figures are estimates by the author of how rolling resistance changes (also weight-dependent) would alter these measurements. From the analysis done in this study, the slopes given in entry 10 on Table I are recommended. We will now consider other factors which affect estimates of lifetime fuel savings.

One further problem with the data base that should be considered is our use of EPA (chassis dynamometer tests) estimates of fuel consumption. The fuel consumptions are often lower than real-world experience which could lead to under-estimates of the weight dependent slope. In addition, the test methods probably even give incorrect relative values and the domination of the test mode by low speed city-like driving may well seriously underestimate the importance of aerodynamic drag and fuel efficiency while cruising. Because this latter uncertainty would lead to over-estimation of the "weight-dependent" slopes, we have approximated the net effect as unimportant and have made no correction because of the testing mode. Extensive real-world data on actual mass effects might allow for better estimates.

An additional important uncertainty is the future efficiency of powertrains. This is a particularly important point for the long term effects estimated above. It should be noted that any improvements in efficiency will directly reduce the weight-dependent slope since the amount of fuel required to perform a given function will decrease. A wide variety of efficiency increases have been discussed and their actual implementation and achievement is clearly a further uncertainty. For this analysis, we have assumed that future slopes will be about 70-85% of current ones. This is consistent with diesels currently being sold (see Figure 4). Thus, we retain 0.35×10^{-5} gallons per mile per pound as our short term slope estimate (average Table I-9B) and obtain 0.49 to 0.79×10^{-5} gallons per mile per pound as the range of our longer term estimates (from ranges in slope and future efficiency).

For the current analysis, we have assumed each vehicle will be driven 10,000 miles per year for 10 years and have discounted future fuel at 5% per year. Thus, we estimate the lifetime fuel savings for short term substitution of weight-reducing materials as .26 gallons per pound of weight saved. On the longer-range or full redesign application mode, our estimates for lifetime vehicle fuel savings per pound of weight save then range from 0.34 gallons to 0.56 gallons.

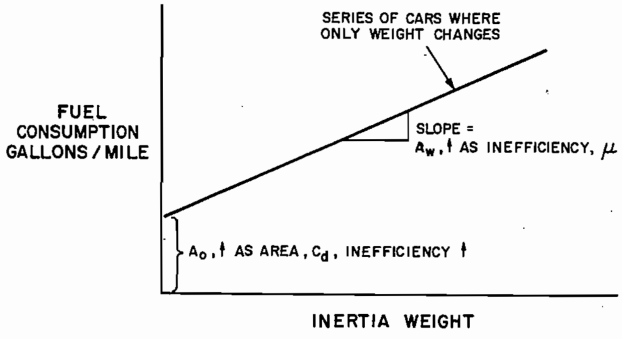

Fig. 3 - Expected plots for fuel consumption as a function of weight. Of particular interest in this analysis is the Slope A_w.

Finally, the issue of what can be changed when lightweight materials are used to reduce weight while maintaining other functions is also important in its own right. Since reduced weight powertrains and running gear are needed when weight reduction actions are taken, a "secondary" weight reduction is possible (2,3,4). The level of these secondary weights is clearly zero for very short term substitution but recent estimates using previous methods (2) indicate that an additional 0.6 to 0.9 pounds of weight will accompany a primary weight reduction when the planning horizon is sufficiently long-term to allow complete redesign and manufacturing investment.* Thus, our short term effect remains at 0.26 lifetime gallons for each vehicle pound but our long-run estimates now range between 0.55 and 1.07 lifetime gallons per primary pound saved (all estimates are ranged). These three estimates are clearly subject to reconsideration, but are the best we can do at the present time and are therefore utilized through the remainder of the analysis. When a single number is used for convenience, our lower long-range estimate (0.55 gallons per pound saved) is favored as the "middle" estimate.

FRAMEWORK FOR APPROPRIATE WEIGHT/COST TRADEOFFS

The estimates for lifetime vehicle fuel savings per pound of weight reduction allows one to obtain the lifetime fuel savings for any weight reduction action. Thus, it is possible to estimate the cost of fuel saved by various weight reduction scenarios that involve a cost penalty and so simultaneously calculate the fuel savings and cost penalty. Furthermore, if the cost penalty per pound saved is used as a measure of the appropriateness of substitution, one can calculate an equivalent price of fuel per gallon that any hypothesized weight reduction action entails. Figure 5 shows the calculated cost of the vehicle fuel saved for various weight-reducing actions. These fuel costs should be considered a "shadow" cost for fuel not used - it is paid for by cost increases in the vehicle because of weight reduction.

The three lines shown on Figure 5 are for the three estimates of lifetime fuel savings previously mentioned. We see that for a cost per pound saved of one dollar, our estimate of the short term fuel savings are such that it would be equivalent to paying about four dollars per gallon for the gasoline saved over the life of the vehicle. On the other hand, if we use the lower long-term number (0.55 gal./lb.), we see a much more reasonable price for the "saved" gasoline, namely about \$1.70 per gallon. We also see that in any case very expensive weight reductions are equivalent to buying fuel at very expensive prices.

The cost per pound saved is thus an important parameter because it is "equivalent" to a cost of fuel saved by the vehicle over its lifetime. Figure 6 shows a plot for a hypothetical material of the material cost penalty per pound saved as a function of the weight substitution ratio. The weight substitution ratio is the weight of the standard material for an equivalent functional characteristic. The important point of Figure 6 is that the cost penalty per pound saved is strongly and nonlinearly dependent on the weight substitution ratio because both the cost penalty and the amount of weight savings are each dependent on the substitution ratio. For example, we have assumed that the substitute material costs two dollars per pound whereas the standard material costs twenty cents per pound. For this hypothetical case, it is seen that a weight savings by substitution of forty percent is equivalent to buying gasoline for \$4.50 per gallon, whereas a seventy percent weight save for the same materials is equivalent to buying gasoline for less than one dollar per gallon. This strong influence of the substitution ratio is almost always ignored in discussions of materials substitution. Obviously, the material price ratio also plays a role and we will return to this shortly.

We should briefly consider what is known about weight substitution ratios. Generally, those interested in substituting a specific weight-reducing material assume a highly agressive and often unrealistic weight save. Let us consider a few facts in this difficult area. Table II considers the weight reduction possible in suspension springs with a variety of materials. The relationship at the top of the table shows the effects of design parameters and material parameters on the overall weight of a spring (14). The weight of the spring increases

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*Further complicating the achievement of secondary weight reduction is the practice of deriving a variety of vehicles from a common base.

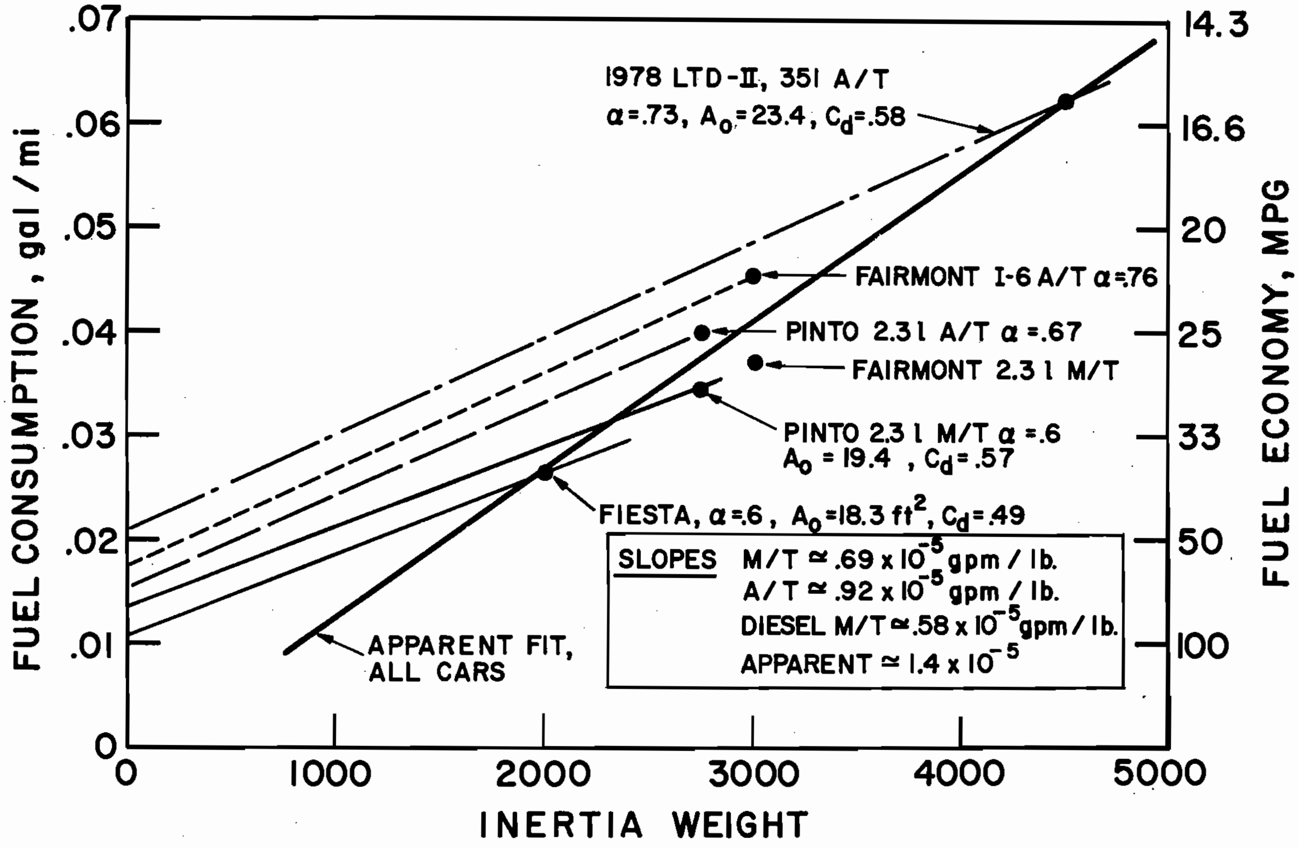

Fig. 4 - Calculated fuel-consumption-weight curves for some 1978 and 1979 Ford cars following the concepts in Figures 2 and 3. Slopes (A_w) are shown.

with density and modulus and is inversely proportional to the strength squared. Thus, high strength steel springs which are commonly used in vehicles weigh only one tenth (or less) as much as an equivalent mild steel spring. This "explains" why high strength steel suspension springs have long been used in the industry. To use mild steel would cause major redesign to a bulkier vehicle with less desirable ride quality. The other materials shown have various weight reductions (or increases as with aluminum) and show weight reduction percentages from forty-five to zero percent.

Table III shows other design cases that can be considered and gives estimated weight reduction percentages for different materials. Three points should be made. One, the weight reduction percentages are not well known even for these simple cases. Secondly, there are a variety of different percentages that can be quoted, depending on the assumed controlling design criteria.* The other point that should be noted is that the weight reduction percentage depends on the base material assumed. For example, in suspension springs, aluminum would show a seventy-five percent weight reduction

*Component and subsystem redesign usually accompany material substitution and so the true ratios are not particularly well known after the fact for most real-world cases.

Table 1 - Estimates of Change in Fuel Consumption with Weight

	Year	Reference	Gallons per 100,000 Miles per lb.	Method
1.	1970	Marshall (8)	0.7	Weight and aerodynamics considered
2.	1973	Cochran (7)	1.4	Sales weighted average (SWA)
3.	1976	Tien & Clark (9)	1.4	SWA (as #2)
4.	1975, 1977	Aluminum (6) Assoc., I & II	1.4	SWA
5.	1978	GM (11)	0.5 short term 1.09 long term	No technical discussion
6.	1979	Herridge and (12) Hole	2.2	All cars
7.	1979	Cochran & (5) McClure	0.55 short term 1.10 long term	Aero "Correction" Agree with #5
8.	1979	A. D. Little (13) (AISI)	0.5 short term 1.10 long term	Agree with #5 Aero & Dyno Correction
9.	1980	This study 9A	0.2 m/t short 0.32 a/t term	Experiments on Ford cars (no rolling resistance change)
		This study 9B	0.3 m/t short 0.4 a/t term	Correct for rolling resistance and use of automatic overdrive
		This study 9C	0.69 m/t long 0.92 a/t term	Aero, idle and rolling resistance considered
10.	Recommended slopes for weight effects on fuel consumption		0.35 short term	(average of 9B)
			0.76 to 0.92 long term	(range used due to uncertainties in various factors discussed in text)
11.	Estimates for weight effects on lifetime fuel savings used in later analysis		0.26 gal/lb. short term 0.55 to 1.07 gal/lb. long term	Future changes in powertrain efficiency, secondary weight and discounting cause range for uncertainty

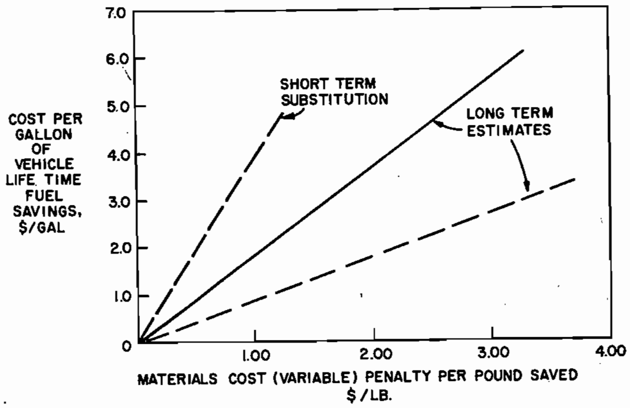

Fig. 5 - The "effective" cost of the gasoline saved by weight reduction as a function of the cost penalty (per pound) to achieve the weight reduction. The three lines are for the three estimates of the lifetime fuel savings.

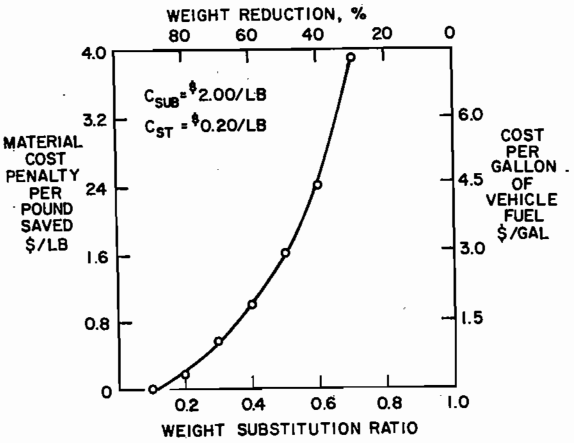

Fig. 6 - The material cost penalty per pound saved for a hypothetical substitute material as a function of the percentage weight reduction. The cost of the saved gasoline is based on the lower long-range estimate, 0.55 gal./lb.

Table 2 - Weight Reduction in Springs

$$\text{Weight of Spring } \alpha \ \frac{\rho \cdot E}{\sigma_{des}^2}\,(P_m \cdot \delta_m)$$

<u>Material Parameters</u>

ρ = density

E = elastic modulus

σ_{des} = design stress allowable (e.g. 10^6 cycle fatigue stress)

<u>Design Parameters</u>

P_m = maximum load

δ_m = maximum deflection

<u>Relative Spring Weight</u>

	H.S.S.* Steel	Mild Steel	Al	Ti	Composites
Relative Weight	10	150	20/30	4/5	3/8
Substitution Ratio	1	15	2.5	.45	.55

*Heat treated steel; σ_{uts} = 200 ksi

relative to mild steel, but relative to high strength steel it shows a 250 percent weight increase. It should also be reemphasized that the weight reduction percentage or weight substitution ratio is very dependent upon the particular component and design system chosen, as well as upon the material properties.

In the case where one limits himself to energy considerations alone, the weight substitution ratio (or weight reduction percentage) is still a very important variable. For substitution of a more energy-intensive material such as sheet aluminum for steel, <u>no</u> net energy savings are realized (even if the vehicle fuel economy increases as estimated herein) until some finite value of percent weight reduction. Figure 7 shows - for a crude estimate of the energy to produce the materials - that the tradeoffs for aluminum do not become favorable until about 30-40 percent weight reduction. The new production energy difference could be greatly reduced by assuming several recycling loops, but it is not yet clear that aluminum recycling from cars is (or will be) as economically effective as the current system from steel. Thus, the fraction of each material class that will, in fact, be recycled is not known.

To return to the main theme, the appropriate material substitutions for vehicle weight reduction here are hypothesized to be those whose cost ratio and weight substitution ratio are proper to give a reasonably low overall vehicle fuel price. Figure 8 shows a plot of the material cost ratio and the weight substitution ratio as a basis for comparing given materials in various applications. The lowest line which shows equal materials cost is the well known case where the weight substitution ratio is low enough to completely offset the higher materials price ratio (the so-called "cost wash"). We should note in passing that we assume materials that save weight and cost are automatically applied whereas those that save neither are not applied. Therefore, it is only in the case where the cost is higher and the weight is lower in which there is legitimate area for further analysis.

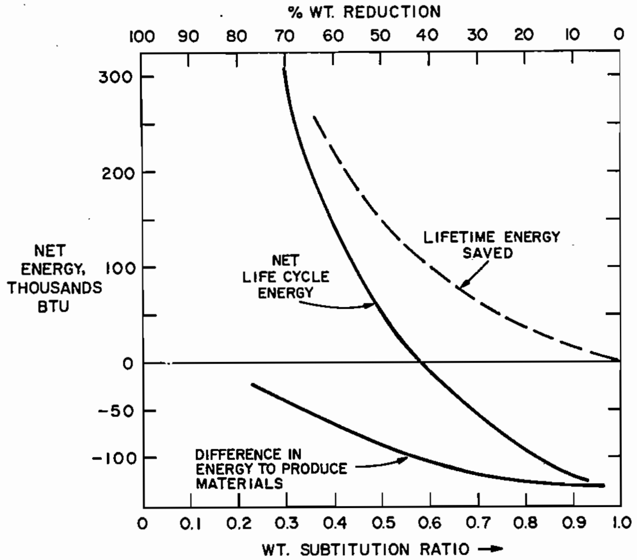

Fig. 7 - The net life cycle energy (no recycling) assumed) difference for <u>sheet</u> aluminum vs. sheet steel as a function of the percentage weight reduction achieved in application. The difference in energy to produce the materials is a simple average of two other estimates (6,13) and the lifetime energy savings is based on our lower long-range estimate.

In this case of interest, the materials cost and substitution ratio are such that the application involves a net cost increase and the point is above the bottom solid line in Figure 8. However, since there are vehicle fuel savings possible in an automotive application, it is possible to offset these by the value of the fuel saved. The three lines thereby drawn on Figure 8 include the value of this offsetting fuel savings. The solid line in the middle is from our lower estimate of the long-range vehicle fuel savings over the lifetime of the vehicle and the others are the short-term and maximum long-term estimates. The value of fuel per gallon in all three cases has been taken as six times the standard material price per pound. Thus, on our major example - current mild steel - this is roughly equivalent to gasoline at $1.50 per gallon and the formulation is not changed by <u>general</u> inflation. Indeed, Figure 9 indicates our estimate has been reasonable in the past.

Table 3 - Calculated Percent Weight Reduction for Idealized Design Situations
Brackets ( ) for Increase in Weight

Material Mild Steel	CASE 1 Fixed Size & Stiffness BASE	CASE 2 Fixed Size & Strength BASE	CASE 3 Fixed Collapse Load & Bending Stiffness BASE	CASE 4 Fixed Dent Resistance & Bending Stiffness BASE	CASE 5 Fixed Strength & Buckling Resistance BASE	CASE 6 Fixed Fatigue Resistance & Size BASE	CASE 7 Fixed Stiffness BASE	CASE 8 Fixed Dent Resistance BASE
50K steel	0	40%	18%	15.4%	27%	5%	0	22.5%
80K steel	0	62.5%	32%	28%	42%	30%	0	39%
150K steel	0	80%	46%	41%	59%	∿ 42%	0	55%
25K Al	< 1%	60%	50%	48%	52%	40%	52%	63%
55K Al	< 1%	81%	63%	60%	68%	∿ 45%	52%	75%
50K Ti	(1%)	67%	46%	45%	63%	--	33%	57%
200K Ti	(1%)	92%	68%	64%	78%	∿ 60%	33%	79%
15K FRP	(580%)	51%	(11%)	(10.7%)	(15.1%)	∿ (50%)	28%	60%
30K FRP	(400%)	75%	25%	22%	30%	--	38%	72%
100K CFRP	(120%)	92%	60%	56%	55%	∿ 30%	48%	80%
150K CGrFRP	60%	96%	83%	81%	80%	∿ 75%	75%	88%
Cast Fe	(16%)	(7.8%)	(34%)	(28%)	(54%)	--	--	--
Cast Al	(5%)	48%	24%	29%	10%	--	--	--
Cast Mg	(7%)	56%	39%	41%	18%	--	--	--
	HOLLOW BEAMS						PANELS (Variable Thickness Only)	

If we focus on any one of the three lines in Figure 8, it is then possible to determine whether an application for weight reduction with a more expensive material is indeed "appropriate". Substitutions whose cost and substitution ratios lie below the relevant line are effective in conserving total resources. In order to use this framework, it is necessary to attempt to place substitutions of interest at their actual cost and substitution ratios. Before doing so, however, it is important to briefly mention one further (and most important) area of ignorance.

For concepts and graphs such as displayed in Figure 8 to be truly effective in determining appropriateness, it would be necessary that the cost ratio become a fabricated part cost ratio per pound of structure. This, of course, is not accomplished by the current analysis as we have considered the cost differences upon materials substitution to be due only to materials costs. This is an oft-used assumption; however, it is clearly untenable. For example, it should be noted that the fabricated cost of a part is usually several times the base materials cost. Further evidence of the importance of fabrication resources arises if one considers the hand lay-up composite structures used in some aerospace applications. It is not unknown in these applications to utilize twenty man-hours per pound of structure as labor for fabrication. For such fabrication methods, one would have to utilize all the world's workers to produce the current world output of vehicles.* Thus, if we attempted to produce hand layed-up composite cars, all of the people in the world would be working to produce cars for those fortunate few--perhaps twenty percent of current population--who have access to them (and no one would be available for distributing cars or fuel). Indeed, the transition from metal to plastics that is occurring in many products is not occurring because of favorable material cost ratios (see Figure 10), but instead is due to superior fabrication costs (16). One final interesting example of materials change possible due to fabrication costs is the early transition in the automotive industry from a wood-based car to metal, at least partly, if not largely, because of the superior fabricability of metal structures at high volume.

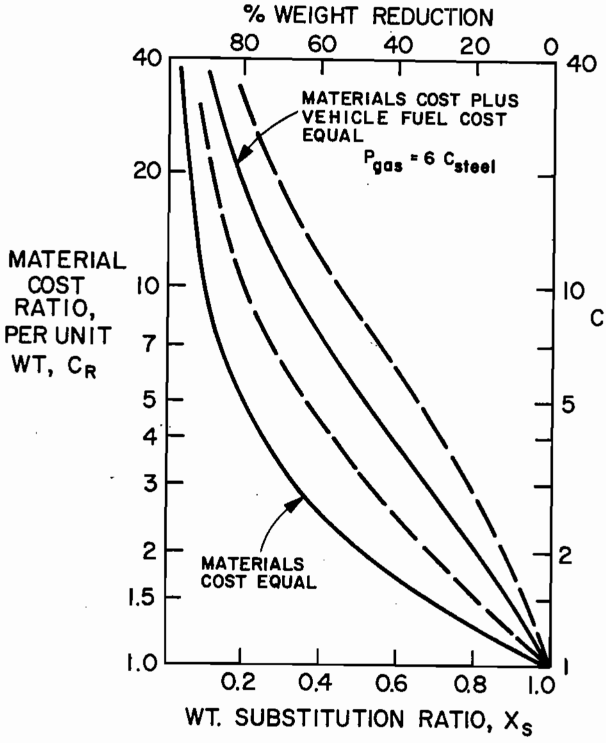

Fig. 8 - A plot of materials cost ratio (logarithmic scale) as a function of the substitution ratio showing lines for (1) equal materials cost (bottom line) and (2) three estimates of equal total cost (materials plus fuel saved) under an assumed ratio of the price of gas per gallon to steel per lb. of 6.

Thus, our conclusion about fabrication costs must be that they cannot be ignored in a proper framework. However, we also must recognize that there are no available means for calculating them. Thus, we remain in this analysis ignorant of fabrication costs and largely ignore them despite the clear evidence that this weakens our ability to predict or explain changes.

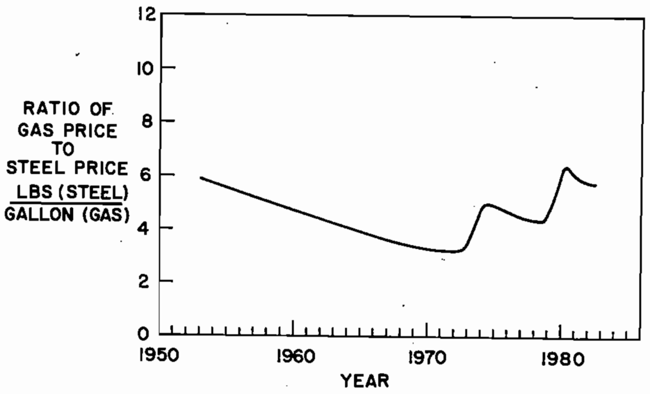

Fig. 9 - Historic trend in the ratio of the price of gasoline per gallon and the cost of sheet steel per lb. (15)

COMPARISONS AND PROJECTIONS

Figure 11 is the same as Figure 8 except that we have retained only the central solid line as our single "best" estimate of substitution appropriateness (more for simplicity than reality). We have also attempted to place a variety of potential material substitutions on this graph. Each is shown over a range of price ratios and substitution ratios** and because of all the uncertainties, only very rough estimates of appropriateness can be made. In comparing our framework to past applications, we assume that market forces work so as to cause appropriate change to occur. In using it to project future events, we assume the same mechanism despite "apparent" government intervention with fuel economy standards.

Figure 11 can now be used to compare how well the proposed framework has described the past while considering it as a basis for future

*(36 x 10^6 vehicle/yr. x 2500 lbs./vehicle x 20 man hrs./lb. ≃ 10^9 workers x 2000 hrs./worker)

**In reality, there are a variety of ratios and the most appropriate applications are those at the lowest substitution ratios. Finding these is the most challenging technical task before the materials and design communities.

projection. Among the favorable substitutes, we first note that cast aluminum as a replacement for cast iron is in fact a viable technology that is proceeding relatively rapidly in North America. Despite the need for foundry investment, the percentage of cast aluminum in North American vehicles will probably double from 1979 to 1987. Because of their higher fuel prices, the earlier utilization of cast aluminum in European vehicles is also consistent with the assumptions here. New casting alloys and wear prevention technology are major developments which have increased the effectiveness of such applications. The weight reductions are relatively large (up to 70%) because of aluminum's superiority as a heat-managing material in the engine-related applications (heads, blocks, manifolds) and because in castings weight is often determined by processing constraints on minimum dimensions so weight savings up to the density ratio are sometimes achieved.

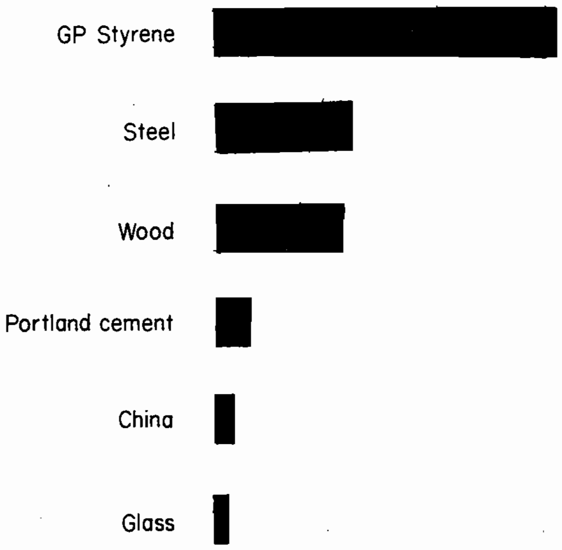

Fig. 10 - Comparative raw material prices after throne (16)

It is also consistent with current projections that the utility of sheet aluminum as a substitute for mild steel is still under question. At the weight reduction percentages normally attained (in this case, structural limits are present and results such as Tables 2 and 3 are expected) and at the cost ratio now found, the substitution represents relatively expensive gasoline prices. This is even ignoring the more difficult fabrication procedures which are indicated by the arrow on the wrought aluminum box in Figure 11. We also see that substitution of Titanium in springs, while offering very significant weight reduction, represents extremely expensive fuel savings. The same comments apply to application of graphite-based composites at current prices.

Among the most favored substitutions indicated by Figure 11 is the substitution of high strength sheet steel for mild steel. Indeed, the substitution appears so favorable that one could wonder why it did not occur before the recent changes in the energy supply/price or before now in Europe despite the neglected fabrication costs (see arrow on Figure 11). This view ignores the availability of new technology and in particular the newness of the high strength sheet technology (17) and the lead U.S. automotive and steel producers happen to enjoy in this technology. Figure 12 shows a previously published plot (17) of the penetration of HSS in vehicles over the past few years, including a speculative projection. We note that the extremely rapid rate of penetration of this material - compared to well-known plastics penetration - justifies our calling it the "quiet materials revolution." The current analysis strongly suggests that this substitution should eventually occur worldwide despite early disinterest because "we already have light cars."

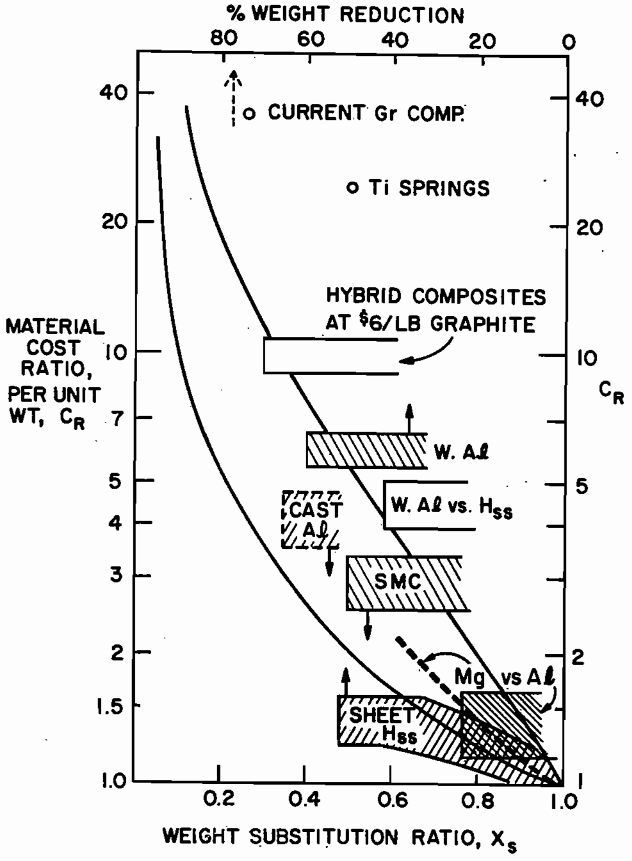

Fig. 11 - Materials cost ratio (logarithmic scale) against substitution ratio showing placement of various automotive applications on Figure 8. All cases except those indicated are versus mild steel as the base.

One further point to note from Figure 12 is that the HSS substitution explosion seems to be technologically rather than institutionally paced. The penetration began soon after the initial materials evolved and the simultaneous application driven materials invention and reinvention of the manufacturing process are going hand-in-hand with learning how to use the materials to reduce weight (17). It would seem that further relatively low cost fuel savings are possible and this can justify the difficulties that must be overcome. The role of fuel-economy standards seems unimportant.

The materials technology which has a longer proven track record in vehicle substitution are the plastics materials also shown on Figure 12. The relevant question is whether the major changes are finished and whether the percentages of plastics in vehicles can yet rise significantly. This question is particularly relevant because further substitution must involve more structural and functional applications. It seems obvious that reliability of these applications will result in need for use of continuous fiber composites. Some key issues are (1) whether competitive cost fabrication procedures can be developed (in SMC and injection molding technology, less expensive fabrication has been a key in the past penetration), (2) the degree of weight recuction achievable with glass-only composites, and (3) the development of glass-graphite hybrids and attainment of lower graphite prices. In general, the weight reduction, price-ratio analysis indicate the incentive to develop viable technologies and thus the projection that such will emerge. Nonetheless, we should expect the overall penetration rate to remain relatively slow (as in Figure 12) because of the limited knowledge and the extensive need for investment (new fabrication and assembly processes eventually needed for "plastic" cars).

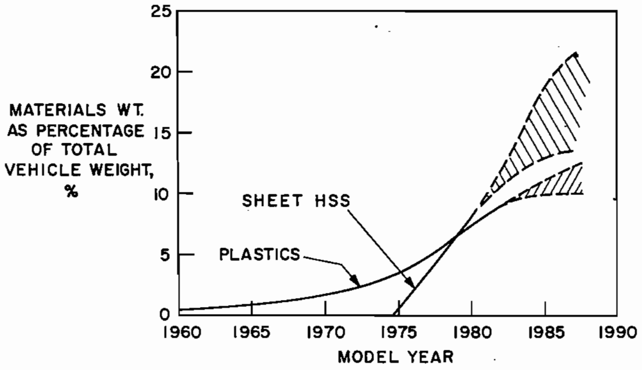

Fig. 12 - Plastics and high strength sheet steels in U.S. passenger cars as percent of vehicle weight over the last two decades. Data beyond 1980 model year is from a speculative projection (17)

CONCLUDING REMARKS

A final issue for consideration is the stability of the "predictions" given here relative to technological or even institutional changes. There are two sets of uncertainties in the predictions. First are those that are not material related. Among these are: 1) the future real cost of fuel, 2) future powertrain efficiency, 3) true future secondary weight factors, and 4) investment and other institutional constraints, including government standards, which prohibit or push particular materials. The analysis, in general, can be modified to deal with these, but clearly the uncertainties already considered are sufficient to preclude firm conclusions.

There are larger uncertainties relative to the predictions which hinge on the materials world. Among these are future and even current real material costs and availability questions. Most important, from our analysis we have seen the importance of fabrication costs and percent weight reduction on the appropriateness of substitution. Since these parameters both depend on material properties, new materials can have an enormous influence in our analysis. For example, fabricable higher strength aluminum alloys, allowing us to achieve higher weight reduction could easily make wrought aluminum a more effective candidate. Secondly, new fabrication processes for composites and new reliability for these materials to achieve their weight reduction potential could accelerate their application. In the area of weight reduction, new designs, new design systems, and new vehicle systems could uncover new weight reducing potentials which would be appropriate and effective.* Intercompetition among the weight reducing materials is also extremely important - see the wrought aluminum/HSS comparison in Figure 11.

In conclusion, the analysis "predicts" that high strength steels, cast aluminum, plastics and magnesium should and will continue to grow in their application in personal transportation vehicles. Wrought aluminum and hybrid composites will remain as uncertain candidates depending on weight reduction percentage, fabrication costs, and future material and fuel cost ratios. There are other substitutions (such as titanium) which will not occur widely without important material cost changes in the future. The last and most important conclusion is that all of these predictions are fortunately subject to technical change.

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*Conversely, more effective mild steel designs have often precluded what was originally viewed as an effective application of a weight-reducing material.

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