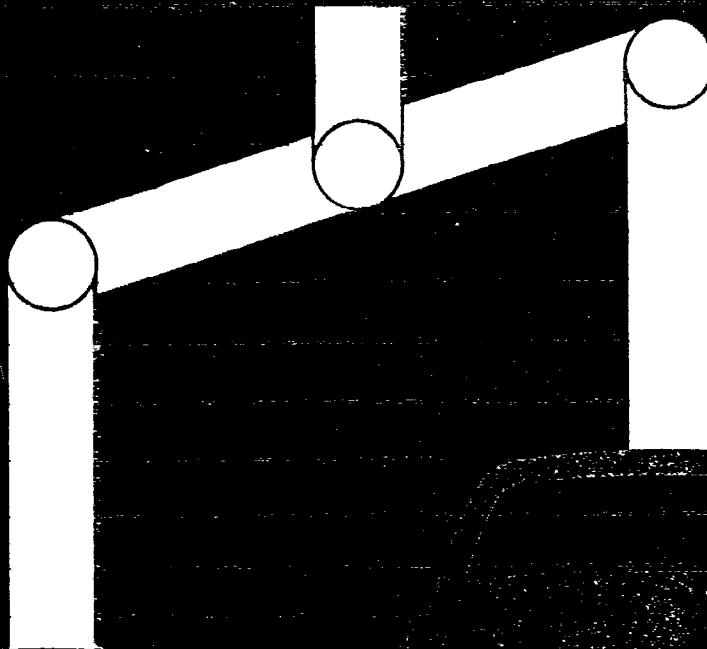


Use of aluminum in automobiles— Effect on the energy dilemma

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Content:

Summary	2
Background	3
Future Fuel Economy Requirements.....	4
Curb Weight and Inertia Weight.....	5
Weight Factors	5
Fuel Economy and Weight	7
Designing the 1985 Car	8
Energy Content.....	10
Energy Savings	12
Cost Effectiveness in Saving Fuel	12
Energy Case Studies in Materials	13
Conclusions	18
References	18
Glossary	19
Appendices.....	20

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Summary

From 1967 to 1974 cars increased in weight for a variety of safety, comfort and pollution control reasons. Fuel economy suffered accordingly. Since 1974 auto manufacturers have done an outstanding job of improving MPG. Even so, there is a lot yet to be done to meet the 1985 corporate average fuel economy (CAFE) goal of 27.5 miles per gallon as required by the Energy Policy and Conservation Act of 1975.

Because there is a direct correlation between vehicle weight and gas mileage (EPA figures for 1979 cars show that fuel economy improves in lighter weight classes) weight reduction is an attractive means of increasing gasoline mileage.

Weight reduction by using aluminum is an especially attractive alternative because it can often be accomplished at low capital costs without compromising comfort (size) and safety features mandated by law or desired by the buyer.

Further, the car buyer of tomorrow is expected to attach great importance to the effect of weight savings on fuel economy and to evaluate his investment on a per mile basis. The use of aluminum is important in both aspects because it not only increases fuel economy, but also may be used to extend the useful life of a car because of its durability.

If we are to come to grips with our energy dilemma, it seems apparent that we will have to make more efficient use of gasoline in our automobiles. Today, cars use over 25 percent of the U.S. annual petroleum supply and account for more than 13 percent of all our nation's energy consumption.

Aluminum, with a proven track record in weight reduction in automobiles and all other transportation vehicles over the years, continues to offer an ideal solution to auto weight problems.

The use of a single pound of aluminum in an auto part produces an immediate primary (direct) weight saving of 1.5 pounds on the average when substituted for traditional ferrous automotive materials.

In addition, this weight saving encourages redesign, allowing use of lighter supporting structure and reduced power requirement for comparable performance, saving at least an additional 50 percent of the direct or primary weight savings in the form of secondary savings.

Thus, a single pound of aluminum can reduce car weight by at least 2.25 pounds (1.5 pounds direct plus 0.75 pounds indirect). Since about 118 pounds of aluminum are used in the average 1979 model car, this has already cut car weight by as much as 265 pounds. This weight reduction translates into a savings of over 290 gallons of gasoline for the operator over the 100,000 mile lifetime of his or her car.

Put another way, each pound of aluminum used in a car could save the owner at least 2.5 gallons of gasoline over its lifetime. This works out to a total of about 2.9 billion gallons of gasoline that could be saved through use of aluminum in 1979 U.S. model automobiles.

If the average aluminum content were to be increased to 200 pounds per car for 1985 models, the total gasoline savings from the 450 pounds minimum weight

reduction would approximately be 500 gallons of gasoline for each car over its useful life.

Aluminum in cars is also effective on a lifetime energy basis. Gasoline energy savings resulting from the use of aluminum in place of steel or iron are much larger than the energy required to manufacture aluminum.

Total lifetime energy (all energy used to produce a component and to transport it during a car's lifetime)

is less than half the energy for a corresponding steel part, about one-fourth the lifetime total for a cast iron part, and equal to or less than the energy requirement for a plastic part.

Additionally, aluminum components can be easily recycled into new parts, which will allow even greater lifetime energy savings than realized at present. Recycling aluminum saves 95 per cent of the energy needed to make new metal from ore.

Background

Automobiles presently account for 95 percent of all urban and 85 percent of all intercity passenger traffic (based upon passenger miles)¹, and they consume about 25 percent of all petroleum used annually in the U.S.

In 1970 the production of U.S. oil peaked at just under 9,600,000 bpd. Domestic production has declined inexorably, falling to about 8,100,000 bpd. in 1976. While the Alaskan North Slope has increased production slightly (an average of almost 8,700,000 bpd was realized for 1978) this respite is considered temporary, so that any increase in demand can be filled only by expanding imports of foreign oil. (Figure 1)²

The automobile industry is attacking fuel consumption on a broad front-through mechanical modifications involving lower (numerical) rear axle ratios, improved automatic transmissions, standard transmissions with overdrive, more efficient air conditioners, improved carburetion, smaller engines, more efficient space utilization resulting in smaller exterior dimensions, improved aerodynamic characteristics to reduce drag, greater use of diesel engines, use of front wheel drive, radial tires, and reduced weight.

Together, all these modifications are helping to vastly improve fuel economy. (Figure 2)³ Especially significant is the relationship between fuel economy and weight. (Figure 3 and 4)³

The increased use of aluminum not only reduces weight, thereby saving critical petroleum fuel, but also aids in conserving material resources. In particular, it enhances the economic feasibility to recycle, not only for the valuable aluminum contained in an automobile, but also for other materials that, today, may not be of sufficient magnitude to justify being recycled.

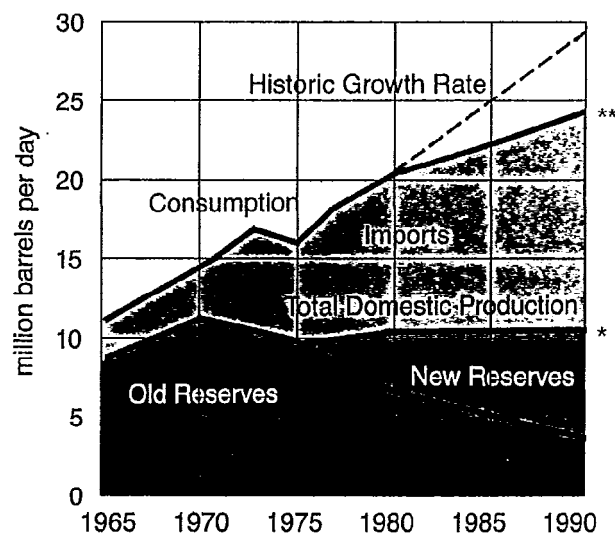
A major goal of manufacturers is to reduce weight while maintaining vehicle passenger capacity, thus ensuring better fuel economy with no loss in comfort, convenience, or accommodation in any class (full size, intermediate, compact, subcompact) of automobile.

Evaluating the energy saving potential of a material depends on three basic factors:

- weight differences between alternate materials
- relationship between fuel economy and weight
- energy content of both materials and fuel

Proper evaluation of these factors will reveal both fuel and lifetime energy potentials of alternate automotive materials.

Figure 1:
U.S. petroleum
consumption
and sources
over time *

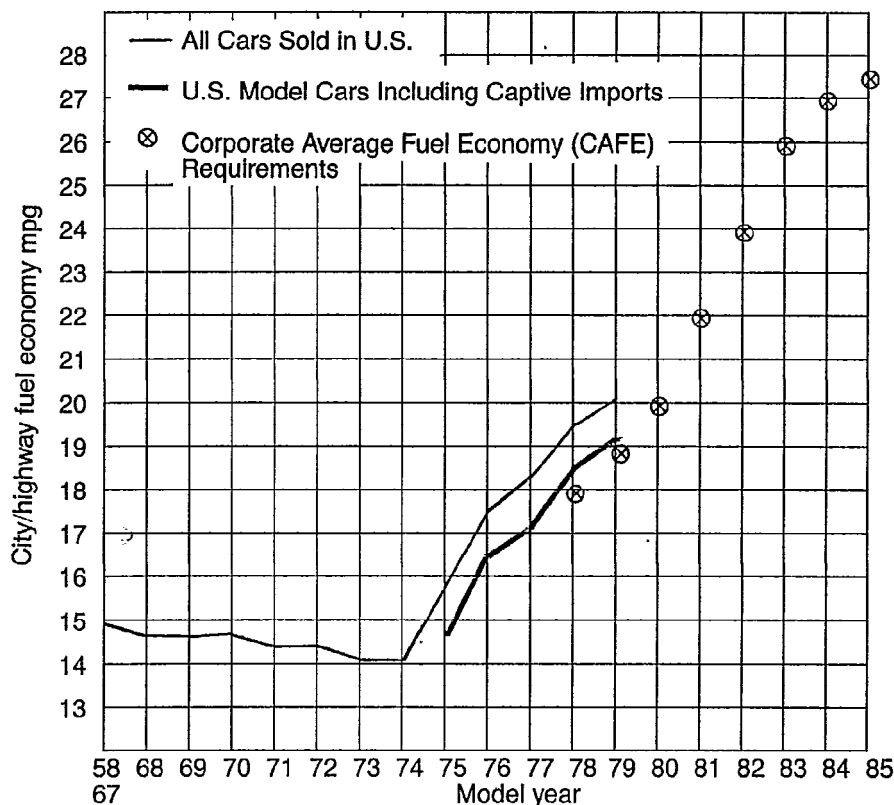


*Includes Natural Gas Liquids

**Assumes implementation of mandatory fuel efficiency standards and reductions induced by higher gasoline prices

Source: U.S. Bureau of Mines and Federal Energy Administration

**Figure 2:
Fuel economy
trends and
requirements**



Future fuel economy requirements

The Corporate Average Fuel Economy (CAFE) regulations require that by 1985 each car-maker's new car fleet have a sales-weighted city/highway fuel economy average of 27.5 MPG (Figure 2)^{3,4} with fuel economy values for each size of car in a fleet determined from its EPA inertia weight/test weight.

This will be a very difficult goal to meet: 1979 cars sold in the U.S. average 20.1 MPG, and U.S. models averaged only 19.2 MPG. (Figure 2)³ And, in the future, U.S. carmakers will not be permitted to include high MPG "captive" imports in their figures, as they do at present.

Additionally, the fact that CAFE must be calculated not on fuel economy but on fuel consumption will make it even more difficult to reach future goals.

A simplified example will demonstrate the difficulties facing car manufacturers in reaching future requirements. Let's say that a particular carmaker has only two 1985 car lines, a subcompact model which averages 35 MPG and a larger, family type car which averages 20 MPG based upon city/highway fuel economy. It would appear that if equal numbers of each model are sold, the company's CAFE number would be 27.5 MPG, the 1985 requirement.

However, such is not the case since fuel consumption (gallons/mile) governs. The formula used to calculate

each manufacturer's CAFE number is:

$$\frac{P_1 + P_2 + \dots + P_n}{M_1 + \frac{P_2}{M_2} + \dots + \frac{P_n}{M_n}} \quad \text{where } P = \text{production number} \quad \text{and } M = \text{MPG}$$

If, in this example, one million units of each model are built, the company's CAFE number would be:

$$\frac{1,000,000 + 1,000,000}{\frac{1,000,000}{35} + \frac{1,000,000}{20}} = 25.45 \text{ MPG}$$

The Corporate Average Fuel Economy of only 25.45 MPG, is more than 2 MPG below Federal requirements. If the company maintained the same sales mix, the larger cars would have to average nearly 23 MPG to obtain a corporate average of 27.5 MPG. Or, if the larger cars continued to average 20 MPG, with one million sales, sales of the high MPG subcompacts would have to be increased to 1,750,000 units to achieve the 27.5 MPG requirements.

This example indicates the need for all cars built in any significant number in the future to obtain high fuel economy. Under the CAFE system, it will be very difficult to build large numbers of low-MPG cars and still meet Federal requirements by building a similar number of high MPG subcompacts.

Obviously, if the family sized car is to exist in the future, lightweight materials must be used extensively to help achieve good fuel economy figures. And aluminum, with its light weight and high strength, is an excellent candidate to aid the car manufacturers in their quest for roomy high-economy cars.

Curb weight and inertia weight

Passenger car weight is usually measured in terms of curb weight, which is the actual weight of the vehicle including fuel, lubricants, and cooling fluids. The Environmental Protection Agency (EPA), however, employs vehicle inertia weight as its basis for fuel economy measurements.

Inertia weight, or test weight, refers to a vehicle's curb weight plus 300 pounds (representing the driver and one passenger), plus the added weight of any

options which are included in more than 33 percent of a model's sales.

For fuel economy test purposes EPA has developed inertia weight class intervals of between 250 and 500 pounds. Beginning in 1980 the boundaries of inertia weight classes will be altered slightly and the inertia weight classes themselves will be subdivided into test weight classes of 125 pounds to reduce weight-related test errors. Inertia Weight Classes as they are established, and as they will change beginning in 1980 are given in Appendix A.

In the report, vehicle weight will be referred to as either curb weight or inertia weight.

Weight factors

Weight reduction through the use of lighter materials includes:

- A primary saving resulting from the direct substitution of a lighter for a heavier material in a component.
- A secondary weight saving resulting from the lighter structural loads to be carried by the chassis and suspension system and/or from the substitution of smaller, lighter powertrains.

Primary and secondary weight savings combine to produce overall savings, or what is often referred to as weight compounding or compounded weight savings.

Precise estimates of weight reduction through substitution of lighter for heavier materials are difficult because of the variety of performance criteria that must be met by various automotive components (e.g., strength, stiffness, resistance to corrosion, heat conductivity, mass, appearance, dent and vibration resistance, etc).

For some wrought applications, one pound of aluminum replaces about two pounds of steel while in other cases one pound of aluminum replaces 2.5 pounds of steel. In castings, one pound replaces about 3.0 pounds of cast iron.

On an overall basis one pound of aluminum replaces at least 2.5 pounds of steel or iron in automotive applications. The 118 pounds of aluminum in the average 1979 car (Table 1) replaces about 295 pounds of ferrous materials for a direct savings of 177 pounds, or 1.5 pounds for each pound of aluminum used.

Secondary saving, can vary depending on several factors. The location of the component where primary weight savings are obtained will affect the amount of secondary savings generated. For example, lighter wheels will have no effect on upper body weight, but may have a slight effect on the car's powertrain, chassis, or frame.

Similar weight reduction, however, in a body or frame component may generate much greater secondary savings due to interaction with a greater number of subsystems on the vehicle.

Additionally, cars have to be designed to obtain full benefits of secondary weight savings. The primary weight reduction must be fairly large before redesign of supporting parts to obtain secondary weight savings can be justified. Usually, this only happens with considerable redesign of a car model.

The lightening of the upper body of an existing car

by 100 pounds will probably have little affect on the weight of the lower body or chassis since they will not be redesigned to take advantage of the lower imposed loads.

However, complete redesign enables weight reductions to be made in all interacting systems and subsystems. For example, advantage can be taken of the lighter body of a newly designed car to reduce frame and suspension weight thereby compounding the weight savings.

Research has indicated that secondary weight savings can range from zero, in the case of simple part substitution, to as much as 160 percent of primary savings. If cars are designed to take full advantage of component weight reduction, secondary savings may approach the latter value.^{5,6,7,8}

One manufacturer's comment on secondary weight follows:

"The secondary weight effect can be expected to be 1.1 to 1.6 times as large as the primary effect in an all-new vehicle design.

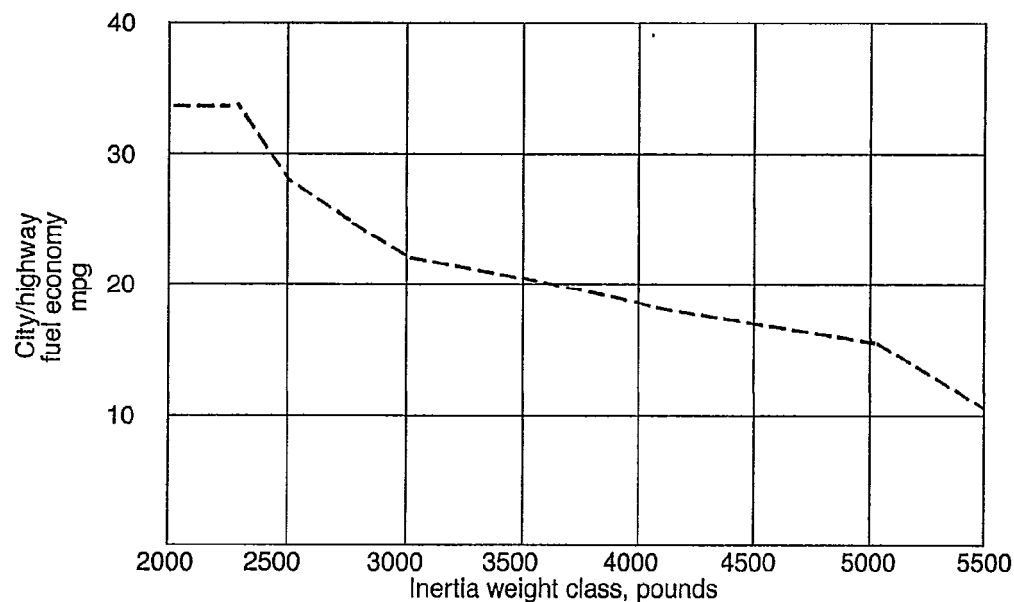
Secondary weight savings in the long run can significantly improve fuel economy and also result in substantial cost saving due to use of smaller and lighter engines, transmissions, wheels, tires, brakes, etc. . . These secondary changes are not fully achieved in the short run, particularly in carryover vehicles or components, but in the long run, when all new vehicles and components are designed, these secondary effects can be fully implemented."

It is recognized that some current aluminum applications do not generate secondary weight savings. On the other hand, increasing numbers of new weight efficient designs do take advantage of potential secondary weight savings. This study employs a value of 50 percent secondary weight savings because with redesign cars built in the next few years will yield secondary effects of this magnitude.

Thus, each pound of aluminum not only replaces 2.5 pounds of iron or steel for a primary savings of 1.5 pounds, but on a conservative basis, an additional 0.75 pounds, 50 percent of the primary reduction is also saved. Total savings average about 2.25 pounds for each pound of aluminum used in a car.

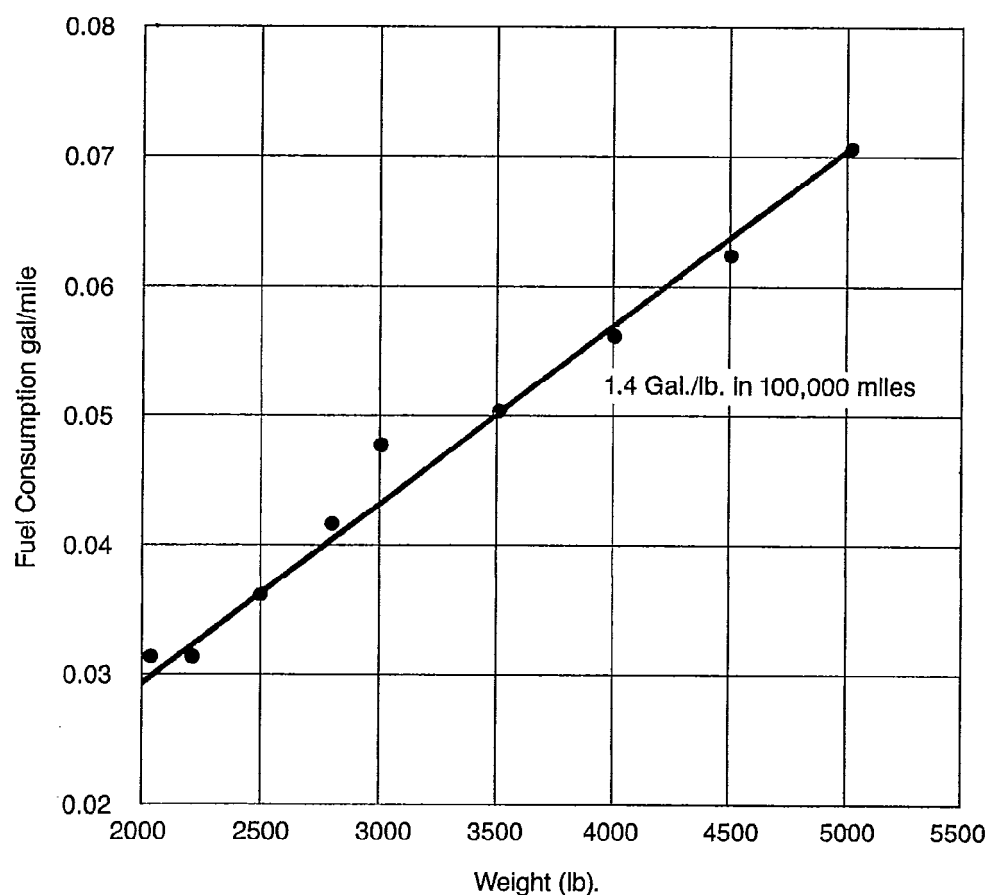
The estimated 200 pounds of aluminum in the typical 1985 car will generate about 300 pounds in primary weight savings, plus at least 150 pounds of secondary savings, for a total of compounded weight savings of at least 450 pounds. The intelligent use of this aluminum in cars will contribute greatly to attainment of future fuel economy requirements.

Figure 3:
1979 passenger
car fuel
economy, by
inertia weight
class



Source: "Light Duty Automotive Fuel Economy ... Trends Through 1979," SAE Paper No. 790225. J. D. Murrell, Environmental Protection Agency, February 1979.

Figure 4:
Fuel consumption
inertia weight
relationship for
1979 passenger
cars



Source: Based on data calculated from SAE Paper No. 790225.

Fuel economy and weight

The relationship between fuel economy and car inertia weight in Figure 3, reproduced from sales-weighted fuel economy data published by the Environmental Protection Agency, covers both city and highway driving cycles. Figure 3 shows that as cars become lighter, fuel economy improves.

From this data it can be calculated (Figure 4) that fuel consumption is directly proportional to changes in car weights. Figure 4 shows that, on the average, for 1979 cars about 1.4×10^{-5} gallons of gasoline is consumed in moving each pound of car weight one mile. Put another way, each pound of car weight will use about 1.4 gallons of fuel during the car's 100,000 mile lifetime.¹⁰ Correspondingly, each pound of weight reduction properly utilized, can save about 1.4 gallons in a car lifetime.

A short example will help clarify this concept. Figure 3 shows that the average 1979 car in the 3500 lb Inertia Weight Class obtains 20.0 EPA MPG in city/highway driving. In 100,000 miles 5000 gallons of gasoline will be consumed, or 1.43 gallons per pound of weight.

The average car in the 2500 lb. weight class averages 27.7 EPA MPG, using 3610 gallons in its lifetime, for an almost identical average of 1.44 gallons per pound. Thus, the 1,000 lb weight difference will save 1390 gallons, or 1.39 gal/lb of weight reduction. The fuel saving is generated by weight reduction and the resulting smaller engine and drivetrain, plus somewhat smaller surface areas.

A 1978 study¹¹ corroborates this consistent relationship between fuel consumption and vehicle weight. It also shows that weight reduction with vehicle and engine downsizing will result in average fuel consumption decreases of about 1.4×10^{-5} gallon/mile-pound. This study also estimates that by 1985 savings may decrease to about 1.2×10^{-5} gallon/mile-pound, due to greater engine and overall design efficiencies of future cars.

However, analyses of fuel economy improvements in one carmaker's downsized and lightened 1978 models have indicated slightly lower decreases of about 1.1×10^{-5} gallons per mile for each pound of weight reduction.^{12, 13}

Due to the documented fuel economy-fuel consumption changes in this family of cars as well as the consensus that future fuel consumption decreases for a specific weight reduction will be somewhat smaller than at present, this report employs a conservative fuel consumption-weight coefficient of 1.1×10^{-5} gallon/mile-pound. Thus, one pound of weight reduction will be considered to save 1.1 gallons of fuel in 100,000 miles; 100 pounds, about 110 gallons.

It is recognized that fuel savings are not generated solely by weight change, but by an interacting relationship between lower vehicle weight and related optimizing factors, mainly lower vehicle power needs, but also reduced mechanical friction losses and less air drag. These other factors are normal functions of vehicle redesign for lighter weight, and generally apply to new car designs.

For example, as weight decreases, rolling resistance declines proportionally. This change alone has a significant effect on fuel economy. Weight reduction also makes possible the substitution of smaller, lighter, and less powerful drive trains, which still deliver similar performance. This too adds significantly to fuel economy.

Weight and powertrain changes may also lead to decreased mechanical friction, allowing a small increase in mileage. Finally, significant amounts of weight reduction through redesign generally yield smaller cars with less frontal and side area, and therefore, less air drag. Again, the result is improved fuel economy.

The two cited automobile industry studies^{11, 13} indicate that no more than half of fuel economy improvements are directly and solely attributable to weight reduction, but that weight reduction interacting with the coordinated redesign of body and mechanical components will maximize fuel economy gains.

Since each pound of aluminum reduces vehicle weight by about 2.25 pounds (primary and secondary reduction), around 2.5 gallons of fuel will be saved in a car's lifetime for each pound of aluminum used. In cases where efficient redesign permits secondary savings to equal or exceed primary savings, as much as 4 gallons may be saved for each pound of aluminum.

Using an average of 50 percent secondary weight savings, about 2.5 gallons of fuel will be saved in a car's lifetime for each pound of aluminum used. The 118 pounds of aluminum in a typical 1979 model car has reduced vehicle weight about 265 pounds, which will result in fuel savings of about 295 gallons during the car's life.

It is estimated that the average 1985 model car, with a required city-highway fuel economy average of 27.5 MPG, will contain about 200 pounds of aluminum (Table 1). Such a car will be designed to offer the best combination of fuel economy and roominess within the low weight ceiling necessitated by fuel economy regulations. All major components in the car will be programmed to allow the greatest weight reductions in other related components.

Thus, this estimated 200 pounds of aluminum per car in 1985 models will contribute about 450 pounds of weight reduction. This represents an additional 185 pounds contribution compared to the 265 pounds saved by the 118 pounds of aluminum used in 1979 models.

Table 1:
Estimated net
average usage
of aluminum in
passenger cars,
weight saved
and weight of
replaced
materials

Factor	1979	Potential 1985
• Est. Aluminum Usage		
Casting*	68	120
Wrought*	50	80
Total	118	200
• Est. Weight Saved		
Primary	177	300
Secondary	88	150
Total	265	450
• Est. Weight of Replaced Materials	383	650

*Examples of castings include pistons, intake manifolds, automatic transmission housings, etc. Examples of wrought materials include sheet; (bumpers and bumper reinforcements, hoods, deck lids,

trim, wheels); extrusions; (bumpers, bumper reinforcements) forgings; (wheels); wire; (wiring harness); rod and bar; miscellaneous fasteners); and impact extrusions; (air conditioning components).

Designing the 1985 car.

The effects of weight reduction, secondary weight savings, and powertrain changes on fuel requirements for a typical 1985 passenger car are shown in Figure 5. All four vehicles compared in the figures have the same external dimensions, somewhat smaller than the average 1979 model car.

Each vehicle incorporates expected technological improvements which will help increase fuel economy. Differences between the four cars are restricted to the amount of aluminum used, secondary weight effects, and engine size and power.

Figure 5A represents a vehicle with the dimensions and performance of the typical 1985 car but which does not use any aluminum components. This hypothetical base car has been developed to demonstrate the weight and fuel economy penalties which would be incurred if aluminum were not used. Curb weight is 3150 pounds and EPA city/highway fuel economy is 24.1 mpg, 3 mpg below 1985 CAFE requirements.

In Figure 5B, 200 pounds of aluminum have been substituted for ferrous components to reduce weight only through direct substitution. Otherwise, the car is identical to Figure 5A. The largest aluminum components are highlighted in gray. Performance is higher because the powertrain (engine, transmission, differential gears, etc.) has not been modified to match the reduced curb weight of 2850 pounds.

Because the powertrain has not been optimized for the reduced weight, only about 0.55 lifetime gallons of fuel will be saved per pound of weight reduction. In conjunction with the direct substitution of aluminum, lifetime fuel savings will be about 0.83 gallons per pound of aluminum in the car. This results in an improvement of EPA fuel economy to 25.2 mpg.

The car in Figure 5C also has 200 pounds of aluminum but has had its powertrain modified. Engine displacement and power have decreased to maintain performance equal to the base car in Figure A. The optimized powertrain change is noted in light blue. As in Figure 5B, the car has not been redesigned to obtain the benefits of secondary weight reduction.

However, the combination of powertrain optimiza-

tion with direct aluminum substitution will save about 1.65 lifetime gallons of fuel for each pound of aluminum used in this car. Curb weight remains at 2850 pounds (assuming that the engine weighs the same as in Figures 5A and 5B), but EPA fuel economy rises to 26.3 mpg.

The car in Figure 5D combines the benefits of 200 pounds of aluminum usage, powertrain optimization, and redesign to obtain secondary weight reduction. Through effective redesign of key components and optimal distribution of weight reduction among body, supporting structure, and powertrain, a weight savings of 400 pounds is accomplished compared to the base car in Figure 5A.

Some, but by no means all, of the areas achieving secondary weight reduction benefits are highlighted in blue. Engine displacement and power is further reduced to maintain standard performance. This car has a curb weight of 2700 pounds and meets 1985 CAFE requirements of 27.5 mpg.

Figure 5 shows that only through the coordinated application of vehicle and powertrain downsizing, careful design for maximum weight reduction, material substitution, and mechanical improvements will future government fuel economy standards be met. In a well designed 1985 model car, 200 pounds of aluminum will save at least 500 gallons of fuel during its lifetime compared to a car of equal size and performance which does not use aluminum. About 295 gallons are saved using 118 pounds of aluminum, the 1979 average.

Assuming the fuel economy of the average 1979 U.S. model car is 19 mpg, the 118 pounds of aluminum used improves fuel economy by 1.1 mpg or nearly 6%. Applied to a production estimate of 10 million U.S. cars in 1979, this represents a savings of 2.9 billion gallons of gasoline worth more than \$2.9 billion in 1979 dollars over the next 10 years based on a fuel cost of \$1 per gallon.

An average of 200 pounds of aluminum per car would save nearly 5.0 billion gallons worth \$5 billion in 10 years based on the same production rate. Fuel savings of this magnitude would have considerable effect on the energy, oil, and financial dilemmas confronting the U.S.