ANL/ES/CP--84474

Conf-950186--2

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For inclusion in the proceedings of

The Second World Car Conference
University of California at Riverside
Riverside, CA

March 1995

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ABSTRACT

This paper summarizes the results of a lightweight materials study. Various lightweight materials are examined and the most cost effective are selected for further analysis. Aluminum and high-performance polymer matrix composites (PMCs) are found to have the highest potential for reducing the weight of automobiles and passenger-oriented light trucks. Weight reduction potential for aluminum and carbon fiber-based PMCs are computed based on a set of component-specific replacement criteria (such as stiffness and strength), and the consequent incremental cost scenarios are developed. We assume that a materials R&D program successfully reduces the cost of manufacturing aluminum and carbon fiber PMC-intensive vehicles. A vehicle choice model is used to project market shares for the lightweight vehicles. A vehicle survival and age-related usage model is employed to compute energy consumption over time for the vehicle stock. After a review of projected costs, the following two sets of vehicles are characterized to compete with the conventional materials vehicles: (1) aluminum vehicles with limited replacement providing 19% weight reduction (AIV-Mid), and (2) aluminum vehicles with the maximum replacement providing 31% weight reduction (AIV-Max). Assuming mass-market introduction in 2005, we project a national petroleum energy savings of 3% for AIV-Mid and 5% for AIV-Max in 2030.
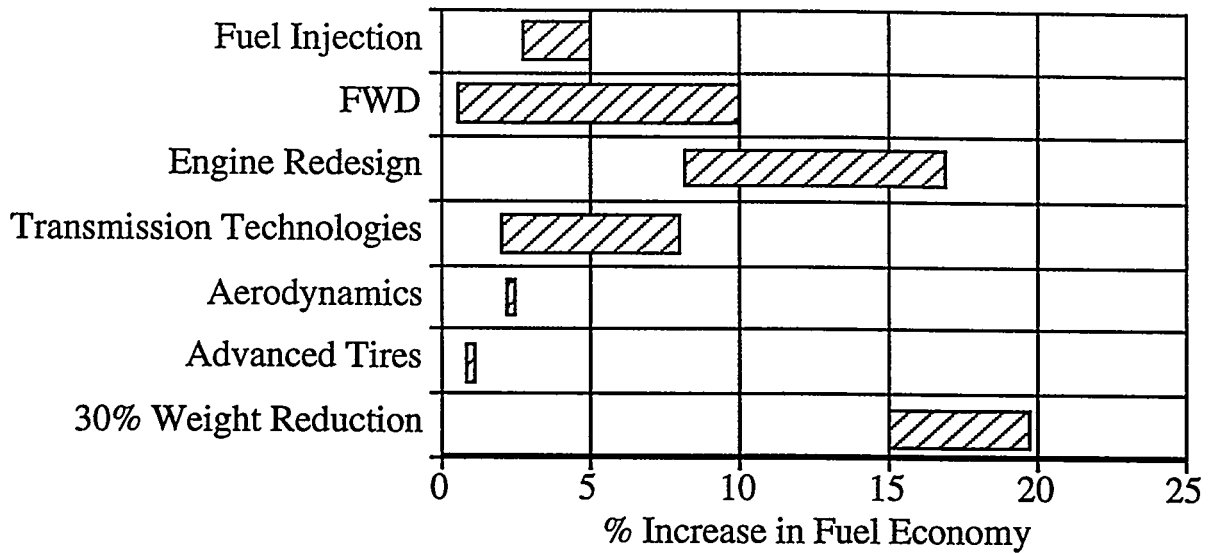
INTRODUCTION

Automobile fuel economy, adjusted for vehicle size, has improved markedly over the past 15 years, despite low oil prices. Technologies responsible for improved fuel economy include fuel injection, front wheel drive, improved engine aspiration (multi-valves/cylinder, turbo- and supercharging), transmission technologies (e.g., 4-speed automatic with lock-up), improved aerodynamics, tires with lower rolling resistance, and increased use of lightweight materials. While many of the above measures have been used in production vehicles, the only area that promises significant improvements in fuel economy in the future (aside from development of totally new powerplants and perhaps hybrid-electric vehicles) is the use of lightweight materials for body and chassis components . Figure 1 illustrates the potential for the various technologies to improve vehicle fuel economy (NRC [1]).

Automakers are constantly working on new design concepts and materials to reduce vehicle weight. They are motivated by potential cost reductions, Corporate Average Fuel Economy (CAFE) standards, and (most recently) electric vehicle mandates. Because current fuel prices are relatively low compared to the overall cost of vehicle ownership, consumers have opted for larger, more option-laden vehicles, resulting in no increase in fleet CAFE levels, in spite of advances by the automakers in achieving weight reductions, mainly using plastics and integrating parts.

Clearly, if CAFE standards are raised, or if oil prices rise sharply over an extended period of time, automakers will be faced with the need to further reduce vehicle weight. Downsizing is one option. However, automakers are keenly interested in cost-effective, lightweight materials to reduce vehicle weight without sacrificing vehicle

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Figure 1. Vehicle Fuel Economy Improvement Potential for Various Technologies

Fuel Injection					
FWD					
Engine Redesign					
Transmission Technologies					
Aerodynamics					
Advanced Tires					
30% Weight Reduction					

0   5   10   15   20   25

% Increase in Fuel Economy

utility.[1] In addition, the zero-emission vehicle requirements will encourage automakers to produce lightweight vehicle structures to improve the range of electric vehicles.

Some automakers currently use lightweight materials in the body structure for their high-performance, luxury vehicles that serve as "pace setters" for the main product line. These vehicles also may serve as a "test bed" for future designs. Lightweight materials are used mainly to improve acceleration performance or to add options while keeping the vehicle in the next lower weight class.   For example, Acura division of Honda Motor Company is producing the all-aluminum-body NSX; Audi AG, in cooperation with the Aluminum Company of America (Alcoa), is producing the aluminum-space-frame A8 (ME [2]).   At least one proposed limited-edition sports car, where cost is no object, will be made of carbon fiber PMCs (McConnell [3]).

While certain "niche" vehicles are being made with advanced lightweight materials, automakers are also interested in reducing weight in their main product line—mid-size passenger cars and light-duty trucks in particular.   However, based on current costs and fuel prices, it is not economically practical to significantly reduce vehicle weight (by 20-30%) using lightweight materials.   Substantial improvements are required to lower the costs of manufacturing (forming, joining, assembly, painting) using lightweight materials, and to reduce the costs of producing the materials themselves.

In this paper, we assume that R&D is successful in reducing the costs of manufacturing aluminum and PMCs for vehicle structures (body and chassis). We exclude other components such as glass and interior trim because they do not add significant weight to the vehicle. Future vehicles could have lightweight glazing (windows) and other lightweight components not mentioned in this study. We assess the impact of lower manufacturing costs on lightweight vehicle sales and energy savings over time as lightweight vehicles penetrate the vehicle fleet.   This paper is part of a more comprehensive study for the Office of Transportation Materials, U.S. Department of Energy (DOE).   In the more comprehensive study, begun in 1993 and scheduled for

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[1] In this study, vehicle utility is assessed using the following measures: (1) passenger and cargo volume, and (2) vehicle acceleration. We assume vehicle acceleration peformance is held constant, so for a lighter vehicle, the engine size is reduced accordingly. In actuality, incremental engine downsizing rarely, if ever, occurs because engines are normally produced in discrete sizes. Based on recent trends in engine horsepower ratings, passengers are demanding increased horsepower, so our assumption of constant acceleration performance implies that this trend will not continue.

publishing later this year, life-cycle energy impacts (including recycling) of lightweight materials, the impact of alternative powerplants, and macroeconomic impacts are investigated.

BACKGROUND

Many studies have been published that look at the potential impacts of using alternative materials such as aluminum and PMC instead of steel for vehicle components (NRC [1]; Kaiser [4]; Jahnle [5]; OTA [6]; Arnold et al. [7]). A variety of methods have been used to assess the relative merits of competing materials. Some studies looked at direct substitution of materials—that is, the vehicle was not redesigned from the ground up to take advantage of specific material properties (e.g., parts integration).

Other studies examined "mild" parts integration, where individual parts (e.g., liftgate, door, or structural member) are redesigned to reduce the parts count using alternative materials (Arnold et al. [7]). Past studies by the Office of Technology Assessment (OTA), U.S. Congress (OTA [6]), and the National Research Council (NRC [1]), focused on a broad range of technologies available for improving fuel economy. Neither study considered post model-year 2000 technologies (not yet commercially available in at least one mass-produced vehicle). The NRC study is perhaps the first of its kind that evaluates policy options while factoring in costs. (While the OTA study mentioned costs in an appendix, costs were not used to assess the rate of technology adoption in the study.) At least two studies are planned to evaluate the technical and economic impacts of extensive use of lightweight materials to substantially reduce vehicle weight and improve fuel economy (Eyring [8]; Kee [9]). We could not find any studies that investigate the market potential for vehicles with substantial amounts of lightweight materials.

The purpose of this paper is to assess the potential impact of lightweight structural and semi-structural materials on vehicle fuel economy and evaluate the potential market for lightweight vehicles, assuming that the manufacturing costs for these materials are reduced through R&D. We focus on body materials being considered by the Partnership for a New Generation of Vehicles (PNGV).[2] This paper, and our final report, attempt to place in perspective the relative feasibility of using lightweight structural materials to significantly reduce passenger car weight without having to downsize the vehicle. Because of inherent uncertainties in projecting technological feasibility and costs of processes not yet developed, we do not imply that this paper, or our final report, are the definitive works on this subject. Future studies, such as those planned by OTA (OTA [10]) and the U.S. Department of Transportation (DOT [11]) will provide additional insight. In future work for the Office of Transportation Materials, Argonne National Laboratory (ANL) will investigate the technical feasibility of extensive use of magnesium in automobiles and the life-cycle costs of traditional and advanced aluminum-forming technologies for vehicle bodies.

APPROACH

First, we estimate the weight reduction potential, incremental fuel economy improvement, and incremental costs of two mid-size aluminum-intensive vehicles (AIV-Mid and AIV-Max) and a mid-size carbon-fiber polymer matrix composite-intensive vehicle (PIV).[3] We assume the weight of the baseline vehicle is reduced over time as a result of improved vehicle design and increased use of high-strength steels, based on projections described in the 1992 Delphi survey conducted by the University of Michigan [12]. Cost of the baseline vehicle is estimated by adding the costs of technologies such as high-strength steel, four valves per cylinder, and nonstructural plastics, described in the NRC [1] study. We assume materials and processing-related R&D lowers the cost of fabrication, assembly, and painting (and associated capital costs) of the AIV to that of a comparable conventional vehicle. As a result, we assume the cost difference between the conventional vehicle and the AIV is due to the cost of the material (F.O.B. plant). For the PIV, we assume a projected decrease in carbon-fiber costs as a result of mass production, and we assume the costs of assembly and finishing are the

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[2] This study was initiated about one year before the formation of the partnership.

[3] The terms "aluminum-intensive" and "PMC-intensive" imply that other materials are also used in the vehicle body structure. For example, a vehicle with an aluminum space frame could have structural PMC and nonstructural plastics for body closures (doors, hood, trunk lid). Here, we use the terms to indicate the predominant material used for the body-in-white, by weight.

same as for the conventional vehicle. This assumption allows for lower processing times and higher costs for PMC fabrication on a per-vehicle basis. For each case, we conduct an extensive survey of prototype and limited-production vehicles to estimate potential weight reduction. After a review of the projected costs, the two sets of AIV vehicles, based on the AIV-Mid and AIV-Max mid-size vehicles, are characterized to compete with the conventional materials vehicles. The vehicle sets include compact, mid-size, large, and minivan/small utility vehicles. Next, a vehicle choice model is used to project market shares for the lightweight vehicles. Finally, a vehicle survival and age-related usage model is employed to compute energy consumption over time for the vehicle stock.

VEHICLE MASS REDUCTION POTENTIAL

The desire to increase the fuel economy of a vehicle creates a significant motivation for reducing its curb (empty) weight. There are at least three ways to decrease the empty weight of a vehicle: (1) reduce its size, (2) optimize its design to minimize weight, and (3) replace the materials used in its construction with lighter mass equivalents. The third alternative, use of lightweight materials, has been pursued to some extent, but greater gains are possible. In addition to taking advantage of the lighter mass of aluminum and PMCs compared to steel, further weight reduction is possible through parts integration and "holistic" design approaches, over and above what has been demonstrated in pure substitution exercises like the carbon-fiber composite 1979 Ford LTD (Cedar [13]). While incremental increases in the use of lightweight materials are predicted at least through the early part of the next century (University of Michigan [12]), advances in reducing the cost of manufacturing and the cost of the materials themselves could create large new markets for lightweight materials such as aluminum, magnesium, and PMCs.

Passenger Car Mass Distribution and Material Content

An analysis of the mass distribution in a passenger car (according to component groups) shows that the body, with about 43% of total vehicle mass, is the single heaviest group; the powertrain and chassis, in almost equal proportions (27% and 26%), follow behind (Table 1). Within the body group, the unit-body, or body-in-white (b-i-w), is the single largest component, with about 26% of the total vehicle mass. Within the powertrain group, the engine is the single heaviest component, with roughly half the group weight, or about 14% of total vehicle mass, while the transmission represents another 5% or so. The chassis group, on the other hand, is not dominated by any single component; the wheels and tires are usually the single heaviest system, but represent only around 6% of the entire vehicle mass.

Passenger cars are manufactured using a number of different materials, some of which perform highly specialized functions, while others, like steel and (to a lesser extent) cast iron and aluminum, usually perform a more general "structural" function. The estimated material content in a typical, current, American-made passenger car (Ward [14]), is shown in Table 2.

Analysis of the material content indicates that about 19% of the mass of the car is made up of special-function materials that would be very difficult to replace. The potential for significant weight reduction clearly involves replacement of the almost 68% of the mass constituted by ferrous materials. The single largest opportunity for lightweight material substitution lies with the body-in-white, which is made primarily from mild steel. There are two main structural material group candidates: light metals (aluminum, magnesium and titanium) and polymers (including composites).

Material Property Considerations

There are two ways to replace a given component with a lighter-weight equivalent: switch to a material with much lower density, or switch to one with far higher strength or rigidity. The key performance parameter for body structures is specific strength or rigidity, i.e., strength (or rigidity) per unit volume or unit mass. Energy absorption and denting are two other important commonly used criteria. Figure 2 compares elastic modulus (one characteristic that correlates with rigidity) and density of various materials relative to steel.
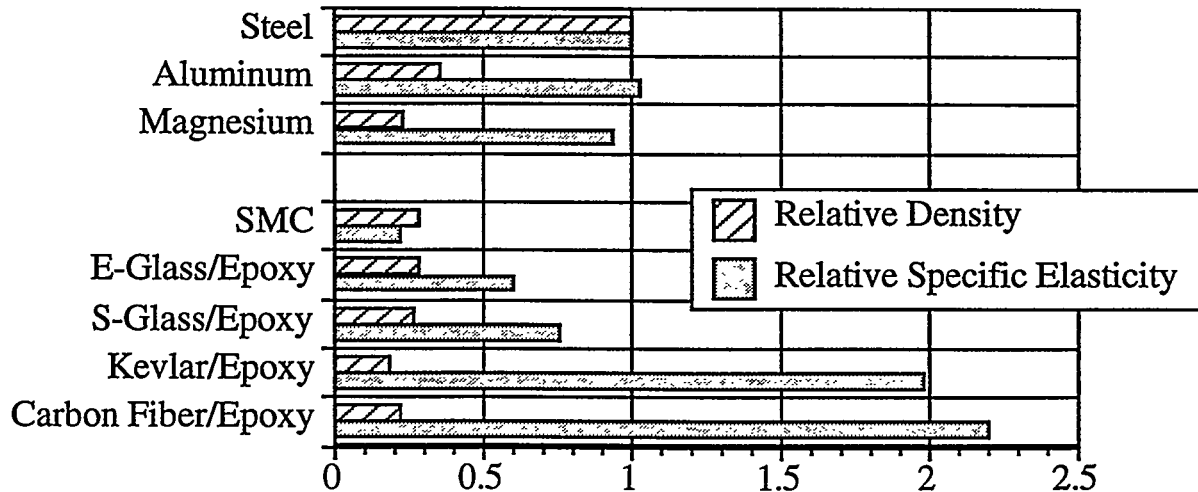
Table 1. Passenger Car Mass Distribution*

Body group	43%	
	b-i-w	26
	int. components	10
	glass	3
	other	4
Powertrain group	27%	
	engine	14
	transmission	5
	other	8
Chassis group	26%	
	wheels/tires	6
	brakes	5
	suspension	4
	bumpers	3
	other	8
Fluids	4%	
Total	100%	

*Average weights from several 1990 model passenger cars

Table 2. Material Content in Typical Passenger Car (1988)

	Mass (lb)	%
Mild steel	1,376	43.7
HSLA steel	259	8.2
Stainless steel	43.5	1.4
Other steels	48	1.5
Total steel	1726.5	54.8
Cast iron	411.5	13
Total ferrous	2,138	67.9
Plastics/composites	245	7.8
Aluminum	177	5.6
Rubber	134.5	4.3
Glass	88.5	2.8
Copper/elec. eq.	43.5	1.4
Powder metal	26	.8
Lead	24	.8
Zinc (die casting)	16	.5
Other materials	68.5	2.2
Fluids/lubricants	188.5	6
Total	3,149.5	100

Figure 2. Density and Elastic Modulus of Various Materials Relative to Steel

The primary physical characteristics or properties of a given material that provide good performance in automobile structural applications are high strength and high rigidity, plus low density. To make such a material attractive in automotive manufacture, it must also be relatively low in cost, available in large quantities, and amenable to a high-volume process that does not require excessive tooling costs. Ferrous materials are the most commonly used in automotive applications. They are characterized by high strength and rigidity but also by high density. The lightest metals (aluminum and magnesium) are characterized by medium strength and rigidity, but low density. The relative specific (RS) properties show the effect of the combination of these properties more clearly. HSLA steel, for instance, shows higher specific strength than mild steel, as one would expect because both have the same density, but by definition, HS steel has higher tensile strength. Because both have the same value for elastic modulus, as well as for density, their values for RS-elasticity are equal. In the case of the light metals, RS-strength is superior to that of the ferrous metals primarily because of the low density of these metals. On the other hand, RS-elasticity of the light metals is about the same as that for the ferrous metals, because the rather low elastic modulus of the light metals offsets most of the advantages of low density. This fact partially explains why aluminum performs better in replacing steel for applications where strength is the main design criterion, compared to applications where rigidity is the main design criterion.

Polymer-based composites are characterized by very low densities, outstanding strength (in the direction of the fibers), and rather low rigidity. Unreinforced (or low-reinforcement) polymers also show low density, but much lower strength and rigidity than composites. It is clear that composites, especially the higher-performance types (carbon, graphite[4] and Kevlar) have outstanding RS-strength (unidirectional), while RS-rigidity is merely good. Polymers and low-performance composites have only equal to good RS-strength, and rather poor RS-rigidity. This explains why structural composites are often used in conjunction with foam cores (to improve rigidity through larger cross-sections), and why high-performance composites are necessary on structures where rigidity is important.

Mass Reduction Potential Using Aluminum

Prototype aluminum-intensive vehicles based on mass-produced versions have been developed by most automakers. One of the best documented examples is the aluminum-body Mercury Sable recently developed by Ford. The vehicle is part of a design and production study aimed at evaluating the feasibility of a stamped aluminum body process for mass manufacture of passenger cars (Stuef [16]). The approach was to replace the material, (i.e., using aluminum alloy sheet instead of steel), while maintaining the current vehicle design (a 1993 Sable), and using basically the same body manufacturing process (spot welding and bonded sheet metal stampings). The mass reduction achieved on the body was 381 lbs.; about 47% less than the equivalent steel body. A comparison of the mass of individual key components as produced in both materials (Cornille [17]), is shown in Table 3.

In addition to the mass saved on the aluminum body, other changes in the powertrain and chassis (allowed by the lower mass of the body) could have resulted in a further reduction of about 200 lbs., for a total mass reduction of about 20% compared to the standard steel-intensive Sable. Therefore, use of aluminum for the body plus secondary weight savings could turn a 3,150-lb, four-door, mid-size sedan into a 2,540-lb curb-weight vehicle. This reduction in vehicle mass translates into a fuel economy improvement of about 12.5%, or to a projected combined U.S. Environmental Protection Agency (EPA) mileage increase from 25.1 to 28.2 mpg. We investigated other examples of using aluminum instead of steel. In all cases, the conclusions are very similar—an aluminum body results in a mass reduction of 40 to 47% over the comparable steel body, even when the design follows steel practice (i.e., the design of the vehicle is not completely optimized for aluminum manufacture).

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[4] We distinguish here between "carbon" and "graphite" fibers. Typically, polyacrylonitrile-based carbon fibers are 93 to 95% carbon by elemental analysis, whereas graphite fibers are usually 99%+ (Schwartz [15]). Graphite fibers go through an additional high-temperature graphitization process to produce fibers with higher tensile strength. Only rarely are carbon fibers ever converted into classic graphite regardless of heat treatment.

Table 3. Comparison of Steel and Aluminum Mercury Sable Body

Component	No.	Steel Mass (lb) Each	Total	Aluminum Mass (lb) Each	Total	Savings	(% Mass)
Fenders	2	7	14	3	6	8	57
Decklid	1	26.5	26.5	12	12	14.5	55
Hood	1	49	49	20	20	29	59
Front door	2	37.5	75	21.5	43	32	43
Rear door	2	28.5	57	18	36	21	37
Unit body	1	596	596	320	320	276	46
Total			818		437	381	47

Aluminum concept cars, of which there have been several examples recently, are free from the constraints of a previously designed steel vehicle. The Ford Synthesis 2010 is again one of the better-documented aluminum-intensive, stamped-body concept cars. Synthesis 2010 has the same interior dimensions as a Taurus/Sable, and is supposed to carry a similar payload, but has a curb weight of only about 2,300 lb (about 850 lb less, or almost 27% lower than the 3,150 lb comparable steel vehicle). True, the Synthesis vehicle is powered by an 80-HP, two-stroke, aluminum engine, which is undoubtedly much lighter than the standard Taurus/Sable powerplant. Still, the differences in mass savings between the aluminum Sable and the Synthesis indicate that there is indeed a somewhat higher potential for a lightweight vehicle that is designed from the beginning as an aluminum-intensive concept.

The stamped-sheet, spot-welded, aluminum body is not the only concept currently vying for replacement of the conventional steel passenger car body. The other aluminum-intensive passenger car concept is the space frame. One of the best examples of this technology is Audi's large, V8-powered sedan, the A8. This vehicle features an all-aluminum body for which Audi claims a mass roughly 40% (about 310 lb) lighter, a component count reduction of 30%, and a torsional stiffness about 40% higher than for its steel equivalent. The main characteristic of the space frame technology is that it relies primarily on extruded and die-cast (compared to stamped) components for integrating the basic body structure, which is an integral "bird cage" construction type. The basic structure is then clad with standard stamped aluminum sheet panels, although polymer panels could be used. Because the mass, strength, and rigidity of the aluminum space frame passenger car body appear to be similar to those of the stamped sheet and spot welded equivalent, we use the stamped-sheet, spot-welded, aluminum body for our analysis.

Experience with practical substitution of steel with aluminum shows that in components designed primarily for rigidity, as in the body-in-white, 1 lb of aluminum replaces between 1.66 (Komatsu et al. [18]) and 1.87 (Sherman [19]) lb of steel. On the other hand, for components that are designed primarily for strength, as in many chassis parts, 1 lb of aluminum replaces about 2 lb of steel (Komatsu et al. [20]). In cylinder heads, designed primarily for strength, the ratio is also about 1 to 2, while in cylinder blocks, where rigidity is also important, the ratio is about 1 to 1.7. In simpler castings, where geometry is governed by process rather than strength or rigidity (minimum cast thicknesses are larger than actually needed), the ratio is equal to the density ratio (i.e., 1 lb of aluminum replaces about 2.7 lb of cast iron). Aluminum has very high specific energy absorption, so it is not too difficult to make structures designed for rigidity that also meet safety (impact) requirements.

Our scenarios for aluminum-intensive vehicles are based on information available in the literature and on discussions with automakers. We assess two types of aluminum-intensive vehicles: (1) those with a body-in-white made of aluminum (e.g. Mercury Sable AIV) and (2) those on which aluminum castings are used extensively in addition to an optimized aluminum body-in-white (e.g., Synthesis 2010, excluding the effects of the 2-stroke engine). We call the first case AIV-Mid, and the second case AIV-Max. Table 4 summarizes the

Table 4. Aluminum-Intensive Vehicle Weight Scenarios

Material	Baseline Weight (lb)	AIV-Mid			AIV-Max		
		Primary Weight (lb)	Secondary Weight Savings (lb)	Net weight (lb)	Primary Weight (lb)	Secondary Weight Savings (lb)	Net Weight (lb)
Steels	1,727	908	(118)	790	408	(72)	336
Cast iron	412	412	(54)	358	120	(21)	99
Wrought aluminum	32	469		469	469		469
Cast aluminum	145	145	(19)	126	556	(98)	458
Reinforced plastics	30	30		30	30		30
Unreinforced plastics	215	215		215	215		215
Other	590	590	(19)	571	590	(46)	543
Total	3,150	2,769	(210)	2,559	2,387	(237)	2,150
Weight reduction	—	381	210	591	763	237	1,000

Notes:
Wrought aluminum includes 32 lb for radiator and other small components.

Assumptions:
Baseline vehicle uses a cast-iron engine block and aluminum cylinder head.
Plastics use remains the same on total mass basis, because most plastics (by mass) are used in interior components, which are assumed to remain unchanged from baseline vehicle.
Secondary weight savings of 0.5 lb/1 lb b-i-w weight reduction for engine and chassis components (steels, cast iron, cast aluminum).
Secondary weight savings in "Other" category reflects smaller fuel tank capacity (10% lighter for AIV-Mid and 20% lighter for AIV-Max) and 3% less mass of copper, zinc, glass, and rubber.

weight reduction potential for the two versions of aluminum mid-size vehicles compared to the typical mid-size vehicle described in Table 2, using the substitution ratios described above. Secondary weight reduction is estimated to be about 50% of primary weight savings (Marshall [21]; Steuf [16]).[5] For the AIV-Max case, we assume the engine size and horsepower rating are reduced to maintain the same horsepower-to-vehicle weight ratio as the conventional vehicle. (The impacts of alternative powerplants on weight and fuel economy are included in the more comprehensive study to be published later this year.)

Mass Reduction Potential Using PMCs

We have searched the literature for the best examples of application of composites in passenger cars and related vehicles, and have found very little to support the claim that use of anything other than a high-performance composite will result in a significant reduction of mass. The main reason why a fiberglass-based composite does not seem to be effective in achieving significant mass reduction is that the main design criteria for most body parts is rigidity (rather than strength), and fiberglass-based composites do not have a very high elastic

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[5] The value of 0.75 lb of secondary weight savings per lb of primary weight savings cited by Ford (Gjostein [22]) is based on a 1979 mid-size vehicle. Today's mid-size vehicle uses materials more efficiently (i.e., unitized body vs. separate frame). In our judgment, 0.75 lb of secondary weight savings per lb of primary weight savings is not possible in today's vehicle simply by redesigning current chassis components to account for the lighter load. We used a value of 0.5 for this assessment.

modulus. Most of the examples found in the literature where a fiberglass-based composite was used to replace a steel structural (body) member show that the mass saving, if any, is rather marginal. Weight reduction goals using glass fibers are typically in the order of 25 to 35% for structural members (Winter [23])—much less than the 47% weight savings now achieved with aluminum (Sherman [19]).

All the examples we found that exhibit significant weight savings, such as the all-composite version of a Ford LTD or the more recent GM "Ultralite" concept car, have made use of high-performance composites based on carbon (or in some cases, graphite) fibers and epoxy resin, and all have been made with aerospace-style prepregs (pre-impregnated tape—long strands of fibers or weaves impregnated with epoxy resin) by a hand lay-up process. It is interesting and revealing that the Ultralite did not use any fiberglass in its construction. Note that the size (passenger and cargo space) of the Ultralite is smaller than our mid-size sedan. This is due to the "backbone" structural design that limits the Ultralite to four passengers. Because of streamlining, the vehicle does not have any cargo space. On a volume basis, the Utralite is comparable in size to a Ford Escort.

We assume advances in monocoque design will allow construction of a PIV with cargo space comparable to that of our mid-size sedan. Table 5 summarizes our assumptions for the weight of a carbon-fiber PMC mid-size sedan, the PMC-intensive vehicle case. We assume design optimization and parts consolidation for the PIV b-i-w will reduce the weight from 420 lb (the weight of the GM Ultralite b-i-w) to 328 lb.

Table 5.   Carbon Fiber PMC-Intensive Vehicle Weight Scenario

Material	Baseline Weight (lb)	PIV Primary Weight (lb)	PIV Secondary Weight Savings (lb)	PIV Net Weight (lb)
Steels	1,727	408	(92)	315
Cast iron	412	120	(27)	93
Wrought aluminum	32	32		32
Cast aluminum	145	556	(126)	430
Reinforced plastics	30	358		358
Unreinforced plastics	215	108		108
Other	590	590	(56)	534
Total	3,150	2,171	(301)	1,870
Weight reduction	—	979	301	1,280

Assumptions:
PIV same as AIV-Max except for b-i-w material; b-i-w assumed to weigh 328 lbs.
Use of unreinforced plastics assumed to be reduced by 50% because trim function is integrated into the composite b-i-w.
Secondary weight savings of 0.5 lbs/1 lb b-i-w weight reduction for engine and chassis components (steels, cast iron, cast aluminum).
Secondary weight savings in "Other" category reflects smaller fuel tank capacity (25% lighter compared to baseline vehicle) and 3% less mass of copper, zinc, glass, and rubber.

PROJECTED COST OF SIGNIFICANT MASS REDUCTION

Volume-produced passenger cars are truly a bargain. In America, the typical family sedan can be purchased at the dealer's lot for about $5.00/lb. Such a vehicle is sold wholesale by the automaker at about $4.20/lb, and it comes out of the assembly plant at the direct cost of about $2.25/lb. Manufacturing cost includes roughly $1.35/lb for labor and plant overhead, and only about $0.90/lb for materials, including scrap. With this kind of cost structure, there is not much room for expensive materials in automobiles. Currently, about 68% of the mass of material used in the typical passenger car is represented by iron and steel, which are purchased at a cost of only $0.35 to $0.55/lb. Even considering that a pound of steel is replaced by a lesser amount of a lightweight substitute, it is clear that, to maintain current manufacturing costs, the maximum cost of any replacement material cannot be much above $1.00/lb. Aluminum sheet (the type needed for a stamped/welded body) sells for an average of about $1.50/lb. Therefore, unless significant labor and overhead savings are involved in fabrication of lightweight vehicles in high volumes, there will be significant increases in vehicle costs.

Aluminum-Intensive Vehicle

The difference between the aluminum-unitized body approach and aluminum space frame approach is not so much the performance of the structure, but the manufacturing process used, with potential consequences for optimal cost and volume. It appears that the space frame concept is more suitable for modest-volume production, perhaps up to about 50,000 units per year, while the stamped sheet process might be better for the higher production volumes—200,000 or more units per year. The tooling costs involved in the space frame concept are much lower (extrusion dies and die-cast molds are cheaper than stamping dies), and the process may be more amenable to outsourcing. Because we are interested in high-volume vehicles, we use the stamped sheet AIV in our cost analysis. In this study, we do not assess the potential of radically new forming methods, such as superplastic forming, for lowering costs; this is the subject of a new study scheduled for 1995.

The process for manufacturing a stamped sheet aluminum passenger car body is not much different from that used to produce a steel body. The aluminum is formed in the same type of presses, using very similar dies. Aluminum sheet, in general, does not form as well as steel, so for highly contoured panels, an extra strike (and an additional die) may be necessary. Aluminum is far softer than steel, so it has to be handled with greater care to prevent scratches, especially on A-class panels. None of these factors is going to make aluminum cheaper to form than steel, although the difference will not be that great either. Aluminum is a much better conductor than steel, and is therefore harder to spot weld (it requires much higher current) and demands greater separation between welds. On the other hand, aluminum bodies will likely rely more on adhesive bonding, and less on spot welds than equivalent steel components, so fabrication may be more or less the same, after all. Still, it is expected that stamped aluminum body manufacturing will require as much as 10% more labor than the equivalent steel process. All these factors point toward greater costs to manufacture a stamped aluminum body than its steel equivalent. If we assume that R&D lowers the labor and capital cost (per vehicle) of an AIV to that of the steel baseline vehicle, the only cost difference is that of the material itself, with proper accounting for scrap. We assume this scenario in order to assess the impact of a successful DOE materials R&D program.[6] Table 6 summarizes the cost assumptions for the AIV-Max case. A similar procedure was used for the AIV-Mid case. We estimate that the incremental price (manufacturers suggested retail price [MSRP]) of the AIV-Max vehicle would range between $1,100 and $1,300, depending on assumptions about overhead rates and other factors. For the market penetration analysis, we use an incremental price of $1,200. The incremental price of the AIV-Mid vehicle, calculated in a similar manner, is assumed to be about $800.

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[6] We do not assess the impact of lowering the cost of sheet via the slab cast process vs the ingot cast sheet process as currrently practiced.

Table 6. Projected Incremental Cost of AIV-Max vs Baseline Vehicle

| Material Replaced | Baseline Vehicle | | | | | AIV-Max | | | | |
| | Weight (lb) | | Cost (dollars) | | | Weight (lb) | | Cost (dollars) | | |
	Vehicle materials	Materials purchased	Materials purchased	Scrap value	Net cost	Vehicle materials	Materials purchased	Materials purchased	Scrap value	Net cost
Steels	1,727									
sheetmetal (b-i-w and other)	1,021	1704	596	34	562					
rod and other forms	370	462.5	208	5	204					
shafts, gears, fasteners	336	NRᵃ	NR							
Subtotal, steel cost					766					
Cast iron	412									
engine block, etc	313	454	182	0	182					
other--chassis	99	NR	NR							
Total, steel and cast iron					947					
Wrought aluminum	32	NR	NR			437	730	1095	132	963
Cast aluminum	145	NR	NR			200	290	464	32	433
Other aluminum forms						113	141	226	13	213
Total, aluminum										**1609**
Net cost of AIV materials at plant										661
High div overhead case, differential, MSRP (includes 45% div overhead, 20% gross margin, 15% dealer discount)										1323
Lower div overhead case, differential MSRP (20% div. overhead, 20% gross margin, 15% dealer discount)										1095
Mid value										**1209**

ᵃ NR = not replaced.

Carbon-Fiber PMC-Intensive Vehicle

The use of high-performance composites in passenger cars is severely restricted by two factors: the high cost of raw materials (reinforcing fibers, in particular), and the lack of an effective high-volume process. As previously shown, only the high-performance composites (those containing a greater proportion of oriented, high-strength reinforcing fibers, such as carbon, graphite, Kevlar, etc.) have adequate material properties to replace (and in fact, far outperform) steel in most structural applications. However, the cost of these high performance materials is extremely high: carbon fibers sell for between $10 and $30/lb, Kevlar for just over $10/lb, and epoxy resin for $2 to $3/lb (Bonsignore [24]). Pre-impregnated tape, or "prepreg" (long strands of fibers or weaves, impregnated with epoxy resin), the basic starting point for most advanced composite fabrications, sells for $30 to $40/lb.[7]

The usual manufacturing approach for advanced PMC products is the extremely labor-intensive manual lay-up process. This involves direct placement (by hand) of pre-cut pieces of prepreg in a mold, which is then placed in an autoclave for curing. This manufacturing process is not only inherently slow and labor intensive, but it also tends to generate a significant amount of scrap (approaching 50% in the case of complex parts), making the high material cost problem even worse. The rigidity of the parts is a strong function of the fiber content of the composite, which must be kept around the 60% level in order to obtain relatively high moduli. This of course, presents a serious problem for such popular processes as resin-transfer-molding because it is extremely difficult to achieve anywhere near 60% fiber reinforcement content by using such a process. Given these characteristics, it is not surprising that the average cost of advanced PMC components for the aerospace industry (the single largest market for these materials) is around $150/lb (Robinson [25]). Special racing car advanced PMC-based components are regularly sold at prices ranging from $108 to $400/lb (Applied Racing Technologies Group [26]).

We assume that, with R&D in the area of composite fabrication technologies (for example, manufacturing PMCs by liquid molding), the cost of PMC fabrication and finishing becomes comparable to the cost of fabricating and finishing a steel vehicle body (on a per-vehicle basis). This entails a fabrication and assembly cost reduction of almost two orders of magnitude over current methods used for high-performance PMCs. Assuming manufacturing barriers are overcome, the critical issue becomes the assumed selling price of carbon fibers. This issue greatly affects the final price of the PIV. Obviously, the scale of operation affects the manufacturing cost and selling price of carbon fibers. Current prices are dictated by aerospace and military requirements for quality and performance, and are affected by the relatively low production volumes of carbon fibers.

We performed a brief analysis of carbon fiber costs for this study. A more comprehensive analysis of the relationships among fiber production processes, scalability, fiber quality and moduli, and costs will be included in the final report. There are two precursors of carbon fiber: pitch and polyacrylonitrile (PAN) (Lin [27]). Pitch is derived from either petroleum or coal tar. While pitch is intrinsically low-cost, its purification and manufacturing processes are not (Reinhart and Clements [28]). In addition, the strengths of pitch-based fibers are relatively poor compared to PAN-based fibers. Therefore, we assume carbon fibers for vehicle structural applications are derived from PAN. The synthesis of high-modulus carbon fibers from low-cost precursors would be an important breakthrough.

Lowering the high cost of carbon fibers has been described as a "chicken or egg" problem. Increased demand will lower the price through economies of scale, but potential high-volume users are reluctant to commit to purchase the material unless costs are lowered significantly. A theoretical price of large-scale production (70 times the present production of 15 million lb/yr) of PAN-based carbon fibers has been estimated by the industry (DeLong [29]) to be about $3/lb. (Note that further processing of these fibers — weaving, pre-pregging, lay-up, and molding — would be required.) The $3/lb figure is derived by looking at the relationship

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[7] Note that "prepreg" includes partial fabrication costs, as well as refrigerated storage and delivery costs. Thus its cost per lb is well above that for the constituent materials, which are approximately 50% fiber and 50% resin.

between volume and cost for selected low-cost synthetic materials such as nylon fiber, with adjustments for carbon fiber yield from PAN precursors (DeLong [30]).

However, the costs of carbon fiber production may not necessarily be scaleable like nylon fiber production processes. (Detailed calculations on scaleablity are not available in the literature.) The PAN fibers must be stabilized at a temperature of 200-300°C in an oxygen-containing atmosphere while held under tension, adding to the processing cost (Schwartz [15]; Lin [27]). In the subsequent step of carbonization, the polymer enters a heated chamber (over 800°C) containing an inert atmosphere and is converted into ribbons of continuous carbon hexagonal rings via pyrolysis (Lin [27]; Schwartz[15]). In this step, the PAN fibers are converted to carbon fibers at a yield of about 50% (Schwartz [15]). The yield is inherently low because only the carbon from the PAN remains. Higher modulus graphite fibers can be produced from carbon fibers during the graphitization step that follows (temperatures above 2,500°C).

Many critical factors affect carbon fiber properties. Crystallite size, crystal orientation, fiber porosity, and impurities are major factors (Lin [27]). Structural defects, both on the surface and in the interior of the fiber, greatly affect performance. Major processing parameters in the stabilization process are homogeneity (skin-core texture), extent of applied tension, and rate of stabilization. Major processing parameters in the carbonization process include rate of temperature rise, atmosphere of processing, and dust-free environment within the carbonization chamber. Without further study, it is unclear whether the carbon fiber process has the same cost-scaleability potential as the nylon fiber process, which does not require multi-step processing involving highly controlled, high-temperature, inert atmospheres. Further, even if these difficult technical problems are resolved, the build-up in production volume necessary to reach a cost of $3/lb would take a few decades.

For our cost analysis, we assume that the cost of carbon fiber production is $10/lb. We assume that sufficient modulus is obtained from a 50% fiber, 50% epoxy resin matrix, and we assume high-performance epoxy is available for $2/lb. Table 7 summarizes the cost assumptions for the PIV case.

Based on these preliminary observations about the cost of carbon fiber PMC and the cost of the materials it replaces, we conclude there will be *no* demand for a vehicle whose fuel economy is about 27% greater (based on a weight savings of 41%), but which could cost between $4,850 and $5,250 more than a conventional mid-size vehicle (even assuming significant gains in manufacturing technology and carbon fiber cost reduction). (Early runs of the vehicle choice model showed this to be the case. The incremental cost of materials alone is about $2,900 based on our assumptions.) Clearly, the high price of carbon fibers is as formidable a barrier as manufacturability. It is interesting to note that a 1979 study by Jahnle [5] reached similar conclusions.

Unless there are breakthroughs in polymer science and polymer materials processing, for the foreseeable future, lightweight vehicles will most likely be constructed primarily from light metals. Our findings suggest that not only should ways to produce low-cost carbon fibers be pursued, but that a potentially more fruitful approach to ultralight vehicles would be to (1) develop new structural concepts for use of low-cost materials or to minimize the use of expensive materials, or (2) perform basic materials research to find low-cost, high modulus polymers using other formats such as whiskers or flakes (Economy [31]). In the following analysis of market potential, we limit our discussion to AIVs.

MARKET PENETRATION MODELING OF ALUMINUM-INTENSIVE VEHICLES

ANL characterized a set of vehicles by using data from the above mass reduction and incremental cost analysis. A vehicle choice model was executed under two fuel price scenarios for both the AIV-Mid and the AIV-Max technology vehicles, and a vehicle survival model was used to simulate impacts on on-road fuel economy and energy consumption.

The Disaggregate Vehicle Stock Allocation Model (DVSAM), a part of the ANL's Transportation Energy and Emissions Modeling System (TEEMS), used to compute the probability of purchasing a vehicle (i.e., AIV)

Table 7. Projected Incremental Cost of Carbon Fiber PIV vs Baseline Vehicle

| | Baseline Vehicle | | | | | PIV | | | | |
| | Weight (lb) | | Cost (dollars) | | | Weight (lb) | | Cost (dollars) | | |
Material Replaced	Vehicle materials	Materials purchased	Materials purchased	Scrap value	Net cost	Vehicle materials	Materials purchased	Materials purchased	Scrap value	Net cost
Steels	1,727									
sheetmetal (BIW and other)	1,042	1,739	609	35	574					
rod and other forms	370	462.5	208	5	204					
shafts, gears, fasteners	315	NR^a	NR							
Subtotal, steel cost					777					
Cast iron	412									
engine block, etc	319	463	186	0	186					
other--chassis	93	NR	NR							
Total, steel and cast iron					962					
Wrought aluminum	32	NR	NR							
Cast aluminum	145	NR	NR			172	249	399	27	372
Other aluminum forms						113	141	226	13	213
Total, aluminum										656
Carbon fiber PMC						328	548	3287	0	3,287
Unreinforced plastics	215	215	108		108	108	108	54		54
Total					1,070					3,996
Net cost of PIV materials at plant										2,926
High overhead case, differential, MSRP (includes 45% overhead, 20% gross margin, 15% dealer discount)										5,654
Lower overhead case, differential MSRP (20% overhead, 20% gross margin, 15% dealer discount)										4,846
Mid value										5,250

a NR = not replaced.

from a given set (i.e., AIV and conventional vehicles) (Vyas et al. [32]). The model evaluates characteristics of the vehicles offered and characteristics of the population that will make choices in computing probabilistic estimates. The model can handle various sizes and types of vehicles with alternative and conventional materials, engines, and fuels. The projected probabilities can be combined with new vehicle sales to generate estimates of the number of vehicles sold by size and type. The resulting vehicle sales estimates are used in a vehicle survival and usage model to develop estimates of vehicle registrations, vehicle miles of travel, and energy use.

Model Application

Fuel prices projected by the Energy Information Administration (EIA) in its 1993 Annual Energy Outlook (EIA [33]) are used for the first scenario, the Reference Fuel Price Scenario. Motor fuel prices are projected to increase 0.9% annually between 1990 and 2005, from $9.86 per million Btu to $11.30 (in 1991 dollars). The annual increase after 2005 is projected to be 1.3%, so the price in the year 2010 price will be $12.08 per million Btu and when extended to 2030, the projected motor fuel price is $15.12. A second scenario involving higher fuel prices was developed to evaluate changes in vehicle choices under such prices. Past experiences of higher fuel prices were evaluated for this purpose. The price of gasoline jumped 26.2% between 1973 and 1974, 26% between 1978 and 1979, and 27% between 1979 and 1980. The two-year price rise between 1978 and 1980 was 60%. The CAFE standards were just instituted during these years and were beginning to show some effects. Then the growth in U.S. motor fuel consumption slowed, which caused a reversal in price. Based on this analysis we developed a High Fuel Price Scenario assuming fuel prices would rise by 40% compared to the Reference Fuel Price Scenario.

Several alternative cases involving vehicles made of conventional materials and those made with varying degrees of lightweight materials were modeled within each fuel price scenario. These cases included various versions of automobiles and light trucks. They either combined several different versions of vehicles or used one exclusive version. A version was defined by assumptions relating to use of materials and/or engines, or fuel economy regulations. The four-stroke gasoline-powered engine was assumed to improve over time by using multi-valves, electronic controls, overhead cams, intake valve control, and accessory modifications. We assumed the conventional materials would continue to improve resulting in some reduction in vehicle weight even without any lightweight materials. Lightweight materials, when introduced, will improve vehicle fuel economy because of the reduced weight and associated reduction in engine size—less power will be required to maintain vehicle performance.

Market penetration of various sizes of light-duty vehicles was simulated for the years 2005, 2010, and 2030. The simulated market shares, together with the historical new light-duty vehicle sales by size (Murrell et al. [34]) were used in a separate model to estimate registration, vehicle miles of travel (VMT), and energy use. The model used for this purpose, the Integrated Market Penetration and Anticipated Cost of Transportation Technologies (IMPACTT), is based on capital survival and utilization concepts. The survival and usage models in this version of the IMPACTT model were adapted from related research (Greene and Rathi [35]). The original model's sensitivity to vehicle cost increases was retained and a modification was added to make it sensitive to fluctuations in vehicle sales. The version used here retards the rate of scrappage when vehicle sales dip below a rate-per million population. The VMT calculation procedure was also modified to include VMT elasticity to fuel cost per mile. An elasticity of -0.134 was incorporated for increasing values of cost per mile and the rebound effect from decreasing cost per mile was assumed to be zero (Greene [36]).

Development of Vehicle Characteristics

Vehicle characteristics used in the model include price, operating cost, seating capacity, curb weight, and horsepower. Four sizes of automobiles and four sizes of trucks were characterized in the modeling runs. The automobile sizes were small, compact, mid-size, and large; the light truck sizes were small pickup, standard pickup, minivan/small utility, and standard van/large utility. The vehicle choice model allows vehicle classification by technology and/or fuel. In the analysis presented here, we limited the technology and fuel choice to otto cycle engines powered by gasoline.

Three versions of each automobile size and minivan/small utility and one version of small pickup, standard pickup, and standard van/large utility were characterized. A version typically represented a conventional material vehicle with market oriented fuel economy, a vehicle with limited aluminum substitution (AIV-Mid), or vehicle with maximum aluminum substitution (AIV-Max). All four sizes of automobiles and minivan/small utility were candidates for aluminum substitution. The extent of aluminum substitution determined the changes in such vehicle characteristics as price, curb weight, and operating cost per mile. Vehicle performance, in terms of horsepower per pound, was kept unchanged from 1990 in all cases. The various versions characterized for the analysis are described below.

1. Conventional Material Vehicles with Market-Oriented Fuel Economy (CV-Mkt): A vehicle set containing the conventional material version of each of the eight vehicles with market oriented fuel economy was developed first. The future vehicles were characterized by updating the characteristics of 1990 vehicles (Automotive News [37]; Williams and Hu [38]) by using data and analyses from recent studies (NRC [1]; OTA [6]). The future conventional material vehicles will be slightly lighter, with moderate increases in fuel economy. The fuel economy of automobiles will increase 9% by 2005, 16.5% by 2010, and 26% by 2030 compared to the fuel economy in 1990. The corresponding fuel economy increases for trucks will be 7% by 2005, 13% by 2010, and 21% by 2030. These fuel economy gains will be achieved through such conventional materials improvements as high-strength steel and improved castings, reduced aerodynamic drag, improved four-stroke engines, and better vehicle designs. The vehicles were assumed to cost more because of engine and materials as well as safety and environmental improvements. The 2005 cars will cost $500-$700 more, pickup trucks $330-$350 more, and vans/utilities $500-$550 more compared to their 1990 counterparts in constant 1990 dollars. The price increases between 2005 and 2010 were $200-$300 for cars, $200-$250 for pickups, and $200-$250 for vans/utilities. The corresponding increases between 2010 and 2030 were $650-$700, $320-$350, and $620-$650.

2. Aluminum-Intensive Vehicles with Limited Aluminum Components (AIV-Mid): Four passenger-carrying vehicles (three sizes of automobiles [excluding small car] and the minivan/small utility), were assumed to have aluminum bodies as described in the preceding sections. Conventional material components that contribute 26% of vehicle weight can be replaced by aluminum components weighing 47% less. Nearly half a pound of reduction in accessory weight can be achieved per pound of body weight reduction. Thus, the total weight reduction will be 19% (Table 4), providing a 12.5% increase in fuel economy. We pro-rated the costs estimated for the mid-size vehicle to arrive at estimates for other vehicle sizes. These AIVs will cost more than their conventional material counterparts: $725 for a compact car, $800 for a midsize car, and $1,000 for a large car and minivan/small utility vehicle.

3. Aluminum-Intensive Vehicles with Maximum Aluminum Components (AIV-Max): Three vehicles, mid-size and large cars as well as the minivan/small utility, were characterized with maximum aluminum components beginning 2005. These three vehicles will weigh 31% less (Table 4) and have 20.5% higher fuel economy than their conventional material counterparts (CV-Mkt). The cost differential will be $1,200 for a mid-size car and $1,500 for a large car and minivan/small utility.

The extent of changes in the characteristics of a typical vehicle under various versions can be seen in Figures 3 through 5. The fuel economy, purchase price, and weight of the mid-size car are depicted in these figures.

Modeling Simulations

The three versions of cars and truck sizes were combined to form vehicle menus for simulation. These simulations, referred to as cases, represented base and alternative conditions under which light-weight materials would be introduced. A simulation case usually included eight or more vehicles combined.

Three cases were analyzed under the reference and High Fuel Price Scenarios. A Base Case that assumed no material substitution was established first. Other two cases included aluminum vehicles competing with the conventional material vehicles. The vehicle menus for these cases are described as follows.

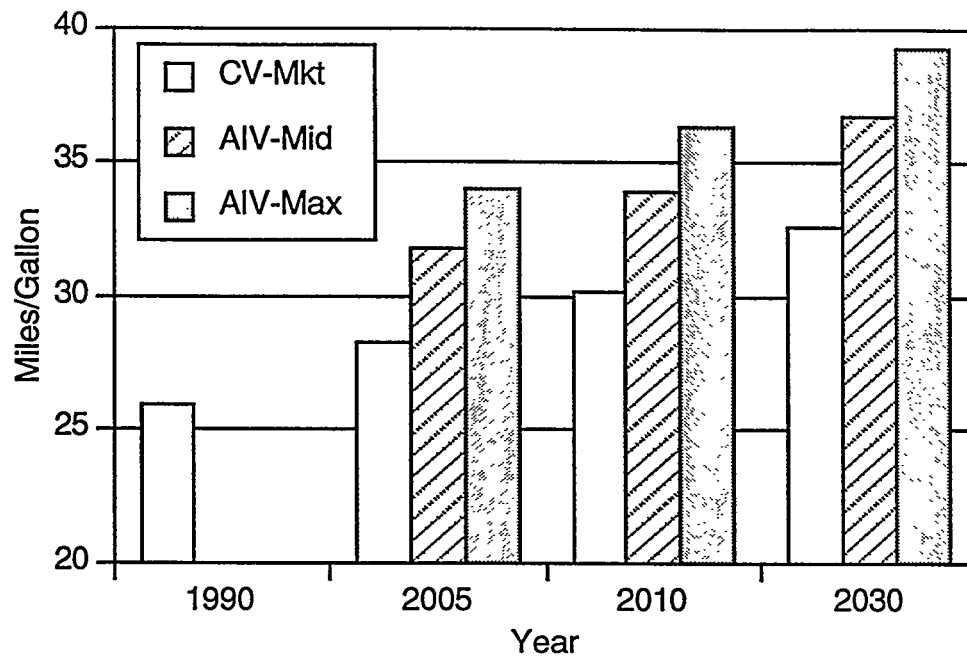**Figure 3   Characteristics of the Mid-Size Car: Fuel Economy**

Figure 4   Characteristics of the Mid-Size Car: % Increase in Purchase Price Compared to 1990
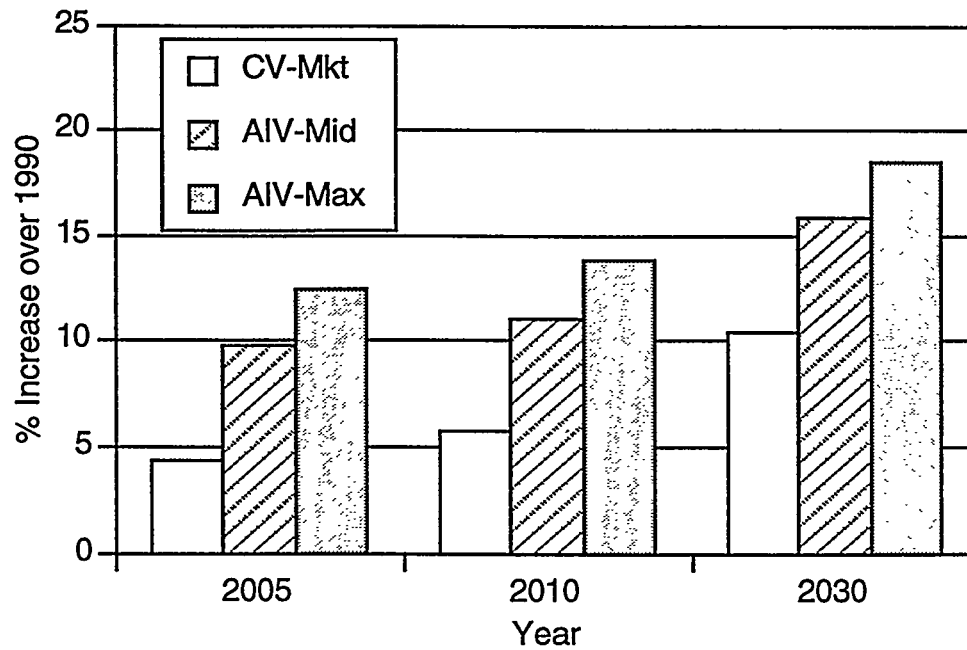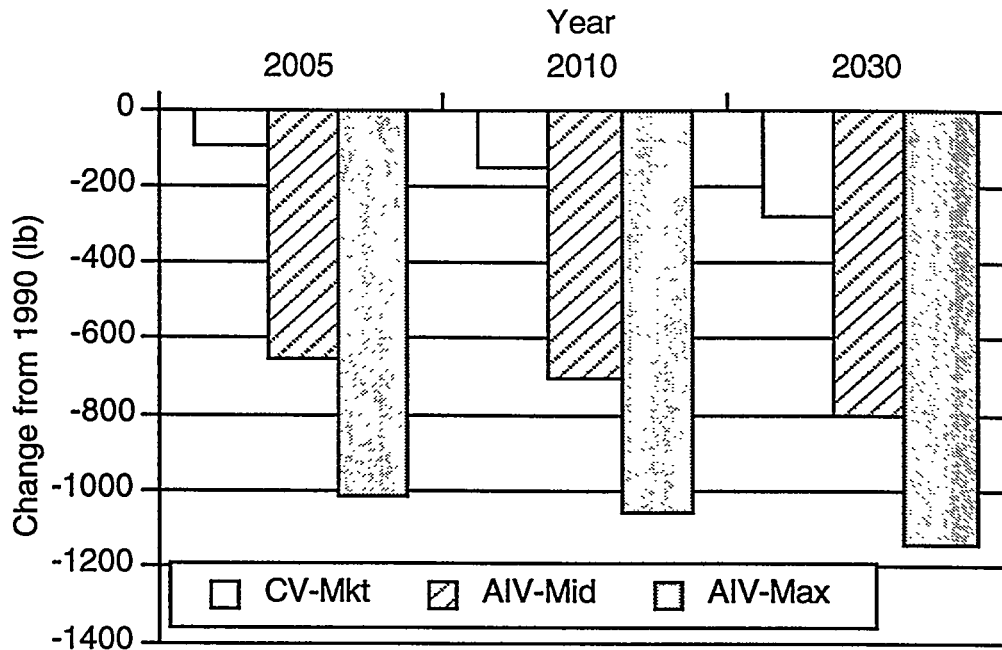
Figure 5 Characteristics of the Mid-Size Car: Weight Reduction from 1990

I. __No Substitution (Base) Case__: The vehicle menu for this case consisted of conventional material vehicles with market-oriented fuel economy (CV-Mkt). Eight vehicles (four cars and four trucks) were analyzed.

II. __Mid-Tech Aluminum and Conventional Material Case (AL-Mid)__: The vehicle menu for this case combined vehicles from CV-Mkt and AIV-Mid versions. Lightweight material vehicles were offered along with conventional material vehicles expanding the number of vehicles in the menu. Three AIV-Mid vehicles (mid-size car, large car, and the minivan/small utility) were introduced beginning in 2005. An AIV-Mid compact car was introduced beginning in 2010.

III __Max-Tech Aluminum and Conventional Material Case (AL-Max)__: The vehicle menu for this case combined vehicles from CV-Mkt and AIV-Max versions. Both conventional material vehicles and AIV-Max vehicles were included, expanding the Base Case vehicle menu. The AIV-Max versions of mid-size and large cars and the minivan/small utility were introduced beginning in 2005. An aluminum compact car was added beginning in 2010.

Market Penetration Analysis Results

The simulation results showed several tendencies, some caused by demographic changes. For example, future households are smaller and more affluent. The percentage of persons over 16 licensed to drive increases from 88% in 1990 to a saturation level of 96% before 2030. Households headed by a person over 64 years of age increase considerably, from 21.5% in 1990 to 25% in 2010 and 30% in 2030. Percent of households with two or more vehicles increases from 55.5% in 1990 to 62.8% in 2010 and 63.1% in 2030.

Simulation of the Reference Fuel Price Scenario

This scenario used fuel prices projected by the EIA in its 1993 Annual Energy Outlook. As mentioned earlier, fuel prices rise at a rate of 0.9% annually during 1990-2005 and 1.3% afterwards.

New Vehicle Sales: The effect of smaller household size and multi-vehicle ownership caused the market share of smaller cars (small and compact) to remain nearly unchanged under the No Substitution (Base) Case. Higher incomes did not result in increased market share for mid-size and large cars; however, they did not lose much of their share. Light trucks increased their share slightly from 33% in 1990 to 35.4% in 2030. The sales-weighted fuel economy of new cars rose from 27.7 mpg in 1990 to 30.5 mpg in 2005, 32.6 mpg in 2010, and 35.4 mpg in 2030. while that for light trucks rose from 20.7 mpg in 1990 to 22.4 mpg in 2005, 23.6 mpg in 2010, and 25.4 mpg in 2030. The automobile share of the light-duty market increased under the two aluminum cases. The increase was smaller for the maximum aluminum substitution case, where the price differential was slightly higher.

Shifts in automobile size shares were more noticeable under the alternative cases. Smaller cars (small and compact) lost their share of the automobile market under the two aluminum cases in 2005 and 2010, recovering a substantial part of the loss by 2030.

In terms of sales-weighted EPA-rated fuel economy of automobiles, some gains were observed with the two aluminum cases. Both the aluminum cases offer more fuel-efficient vehicles than the Base Case; however, shifts in the market shares between size classes (due to the higher prices of the aluminum vehicles) negated some of these gains.

Vehicle Stock: The introduction of new vehicles with higher-rated fuel economy will cause a gradual rise in the on-road fuel economy of all light-duty vehicles. The vehicle stock (representing total vehicles in use) is projected to increase with increased population and higher vehicle ownership rate (EIA [33]; Mintz and Vyas [39]). The light-duty vehicle use, in terms of miles traveled, is also projected to increase with increased income (EIA [33]). The effect of market penetration of the vehicle, their survival over time, their usage in terms of miles driven, and their impact over on-road fuel economy were analyzed. As described earlier, a model that uses a vintage-dependent vehicle survival and usage concept (IMPACTT) was employed to evaluate the impacts over time.

The projected on-road fuel economy of all vintages of cars under the three cases did not differ much until the year 2010. The on-road fuel economy rose from 22.1 mpg in 2005 to 22.6 mpg in 2010 for the Base Case, 22.7 mpg for the AL-Mid Case, and 22.9 mpg for the AL-Max Case. The effect of more aluminum-intensive vehicles in the vehicle stock was evident in the year 2030 as the automobile on-road fuel economy for the three cases differed markedly at 25.4 mpg, 25.8, and 26.5, respectively. Within the IMPACTT model, fuel economy is computed using miles driven by each vintage and is corrected for deterioration and congestion (Maples [40]; Mintz et al. [41]; Westbrook and Patterson [42]). The more expensive aluminum vehicles survive longer and are driven more miles resulting in a slightly lower fuel economy.

The on-road fuel economy of light trucks was markedly different than that of automobiles. All three cases showed very similar on-road fuel economy of 14.3 mpg in the year 2005 with differences of less than 0.05 mpg. The Base Case fuel economy increased to 14.4 mpg in 2010 and to 15.9 mpg in 2030; the AL-Mid Case fuel economy increased to 14.7 mpg in 2010 and to 16.5 mpg in 2030; and the AL-Max Case fuel economy increased to 14.8 mpg in 2010 and to 16.9 mpg in 2030.

The light-duty vehicle (combined auto and light truck) on-road fuel economy in 2005 was projected to increased very little, from 18.9 mpg under the Base Case to 19 mpg under the two aluminum cases, because very few new aluminum vehicles would have entered the market. The fuel economy rose to 19.2 mpg for the Base Case, 19.5 mpg for the AL-Mid Case, and 19.7 mpg for the AL-Max Case by 2010. By 2030 the on-road fuel economy was 21.3 mpg for the Base Case, 22.3 mpg for the AL-Mid Case, and 22.9 mpg for the AL-Max Case.

The total light-duty vehicle energy consumption showed the energy saving potential of aluminum. The 2005 energy consumption was nearly identical at 15.8 quadrillion Btu for all the three cases, except for small differences of the order of 0.04 to 0.06. The energy consumption rose to 17 quadrillion Btu in 2010 under the

Base Case, 16.8 under the AL-Mid Case, and 16.6 quadrillion Btu under the AL-Max Case. The light-duty energy consumption in the year 2030 ranged from a high of 19.4 quadrillion Btu under the Base Case, a middle of 18.9 quadrillion Btu under the AL-Mid Case, and a low of 18.5 quadrillion Btu under the AL-Max Case. The effect of lightweight materials can be seen as they reduce energy consumption even when relatively low aluminum-intensive (AIV-Mid) vehicles are offered.

Simulation of the High Fuel Price Scenario

The Reference Fuel Price simulations showed that introduction of aluminum will increase fuel economy and lower energy consumption. The extent of reduction in energy consumption depended on market penetration of aluminum vehicles. Because these vehicles cost more, their potential market share was restricted — the benefits derived from higher fuel economy were not substantial enough to induce wider acceptance of the higher-priced aluminum vehicles. We also simulated a High Fuel Price Scenario under which fuel prices were increased by 40% keeping all other vehicle characteristics unchanged. The effect of higher fuel prices were simulated in terms of market share changes only. The effects on the nation's economy and such demographics as household formation, income, and vehicle ownership were not simulated.

New Vehicle Sales: The automobile share of the light-duty market increased under the Base Case from 67% in 1990 to 70% in 2005, dropped slightly to 69% by 2010, and remained at that level in 2030. The sales-weighted, EPA-rated fuel economy of new cars increased from 27.7 mpg in 1990 to 30.6 mpg in 2005, 32.7 mpg in 2010, and 35.6 mpg in 2030. The corresponding fuel economy values for light trucks were 20.7, 22.6, 23.9, and 25.7 mpg. In the vehicle choice simulations, vehicle characteristics remained unchanged; the model evaluated the selection process in terms of shifts between conventional material vehicles and aluminum vehicles, between cars and trucks, and between size classes. The simulation showed very similar market shares, except for the slight changes caused by the increase in the fuel cost component of the operating cost. The resulting new vehicle fuel economy increases are not appreciable. Also, only the long-term steady-state effects of higher fuel prices were simulated here (as opposed to sudden escalation or price shock).

The introduction of aluminum vehicles resulted in increased automobile share of the light-duty vehicle market because more versions of aluminum cars (three) were offered compared to aluminum light trucks (one). The automobile share of the light-duty market in the year 2005 changed from 70% under the Base Case to 70.3% under the AL-Mid Case, and 70.4% under the AL-Max Case. The automobile share in the year 2010 was projected as 68.9% under the Base Case, 71% under the AL-Mid Case, and 70.6% under the AL-Max Case. The shares were 69.4%, 74.3%, and 73.7% in the year 2030.

The smaller car (small and compact) share of the automobile market declined under the aluminum cases as fuel efficient mid-size and large cars were made available. Smaller cars comprised 61.3% of the year 2005 automobile market under the Base Case, 53.6% under the AL-Mid Case, and 51.6% under the AL-Max Case. Their shares of the year 2010 automobile market were 61.1%, 50.9%, and 47% under the Base, AL-Mid, and AL-Max Case respectively. The shares increased to 63%, 59.4%, and 54.8% in the year 2030.
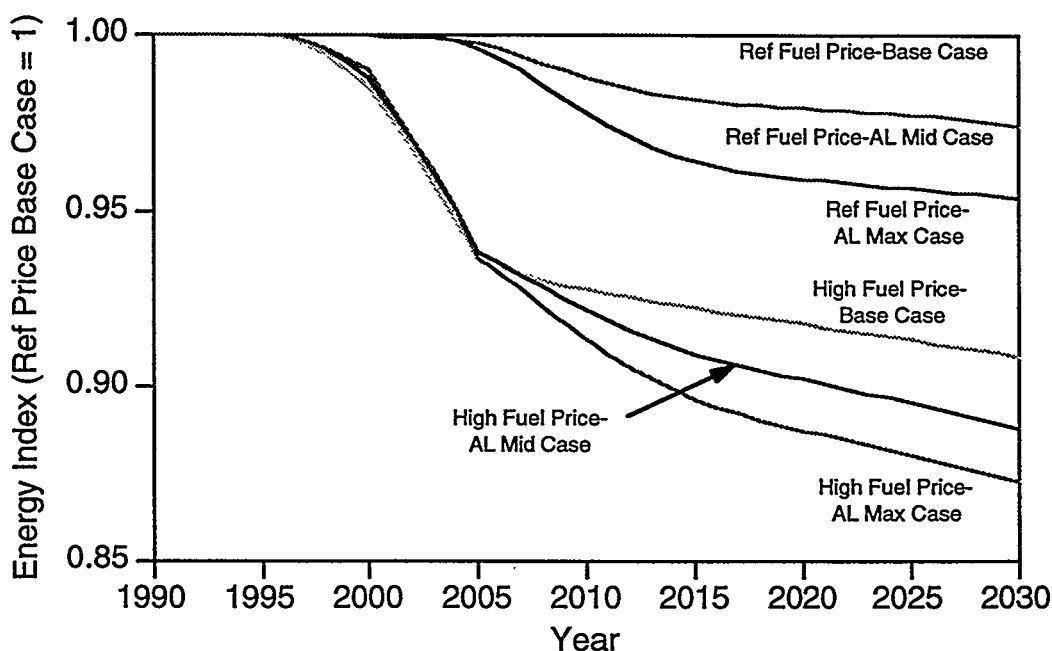
The sales-weighted, EPA-rated fuel economy of new cars increased very little, by 0.1 mpg, compared to the Reference Fuel Price Scenario, even though the fuel price was 40% higher. The consumers appear to opt for the larger cars when they become more fuel efficient. The sales-weighted fuel economy of light trucks increased by 0.2-0.5 mpg as the demand for less fuel-efficient trucks dropped.

Vehicle Stock: The on-road fuel economy of all vintages of cars improved slightly compared to the Reference Fuel Price Scenario; their energy consumption also decreased slightly. The small increase of 0.1 mpg is identical to the increase in the new car fuel economy. The on-road fuel economy of light trucks improved by a smaller margin, 0.2-0.3 mpg, even though their sales-weighted fuel economy showed a wider margin. The difference is partly caused by the late availability of more fuel-efficient light trucks toward the year 2030, and the decline in light truck share of the light-duty market resulting in lower miles. The combined on-road fuel

economy of cars and trucks showed greater improvement 0.5-0.7 mpg as miles traveled by more efficient cars increased.

The projected energy consumption by light-duty vehicles (auto and light trucks) declined substantially because of higher fuel prices. The year 2005 energy consumption declined by 1 quadrillion Btu under the Base Case, 0.9 quadrillion Btu under the AL-Mid Case, and 0.9 quadrillion Btu under the AL-Max Case relative to the Reference Fuel Price Scenario. The declines in 2010 were 1.2, 1.1, and 1.1 quadrillion Btu, respectively, for the three cases. The year 2030 energy consumption declined by 1.8 quadrillion Btu under the Base Case, 1.7 quadrillion Btu under the AL-Mid Case, and 1.6 quadrillion Btu under the AL-Max Case. Figure 6 compares the energy savings potential of aluminum-intensive vehicles.

Figure 6. Energy Savings Comparison of the Three Simulation Cases under Reference and High Fuel Price Scenarios

SUMMARY AND CONCLUSIONS

This study examined the weight reduction potential of aluminum and high-performance PMCs in the light-duty vehicle market. We estimated the incremental costs of these materials assuming that an R&D program is successful in significantly reducing manufacturing costs for aluminum-intensive and PMC-intensive vehicles. We found that, even under a very optimistic scenario for manufacturing improvements, and an assumed price of carbon fibers at the bottom of the near-term range, the projected cost of PMC vehicles is still too high for consumer acceptance. Therefore, we limited our subsequent analysis to estimating the extent of market penetration and the energy savings impacts of aluminum-intensive vehicles. We recognized the ongoing process of vehicle improvement in characterizing a "base case" that excluded the effects of lightweight materials but reflected the possible improvements in vehicle styling, engine technology, and conventional materials such as high-strength steel. Aside from the base case, we developed two alternative aluminum cases in which conventional-material vehicles and aluminum-intensive vehicles competed for market share. We recognize the impact of such regulatory actions as the enhancement of the CAFE standards in accelerating the development of

alternative processes for PMC as well as aluminum. However, we excluded such hypothesized action on the part of the U.S. Congress in light of the current petroleum prices and consumer preference. The results of the analysis can be summarized as follows.

- Lightweight materials such as aluminum and high-performance PMCs have potential to boost the fuel economy of vehicles, making it feasible for the manufacturers to increase their corporate average fuel economy even when larger vehicles are in demand.

- The projected low fuel prices under the Reference Fuel Price Scenario limit the market penetration of fuel-efficient but expensive lightweight material vehicles.

- R&D is needed to lower the cost of manufacturing aluminum-intensive vehicles so that the incremental price of a mid-size car does not exceed $800 to $1,200 over a conventional mid-size vehicle. The efforts to increase its viability should continue.

- Very high cost is an impediment to the market for PMC-intensive vehicles. A breakthrough in manufacturing processes and low-cost polymer synthesis is required. Research efforts to reduce costs and efforts to develop new structural formats (e.g., sandwich materials) using lower-modulus and lower-cost PMC should be encouraged.

- The product mix and pricing strategies are important. For example, the replacement of conventional material automobiles by lightweight versions that cost more will cause shifts to light trucks, thereby hurting overall fleet fuel economy.

- Lightweight material vehicles became more attractive when higher fuel prices were simulated.

ACKNOWLEDGMENTS

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