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Automotive Applications of Composite Materials

ARGOS Associates, Inc, Winchester, MA

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Jul 78

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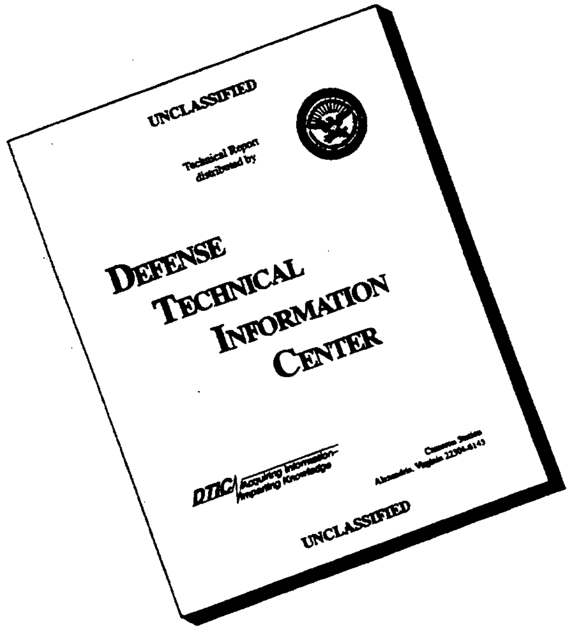

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AUTOMOTIVE APPLICATIONS OF COMPOSITE MATERIALS

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Under Subcontract to:
Corporate-Tech Planning Inc.
275 Wyman Street
Waltham, Massachusetts 02154

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JULY 1978
FINAL REPORT

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16. Abstract An analysis is presented of the potential use of advanced composite materials (ACM) in automotive structures based on the relative mechanical properties and costs of these materials and mild steel. The potential weight reduction obtainable by substituting ACM for steel in various components was analyzed on a functionally equivalent basis for a wide variety of fiber composites and system geometries. ACM considered were resin matrix, graphite fiber, graphite fiber/glass hybrid composites, and glass fiber composites. Continuous fiber glass composites can offer significant weight reduction in selected applications while potentially offering cost savings to the manufacturer. Graphite glass hybrids offer the potential for increased weight reduction but would currently cost more to manufacturers. However, at graphite prices of \$6/lb to \$10/lb, these hybrids would be competitive with steel in terms of manufacturing costs, and less expensive than either steel or fiber glass composites on a life cycle basis. If all graphite fiber composites were used, a further weight decrease would be obtained, but at a prohibitively high increase in manufacturing and life cycle vehicle costs. Additional problems and issues to be resolved prior to extensive use of ACM in production vehicles are also discussed.

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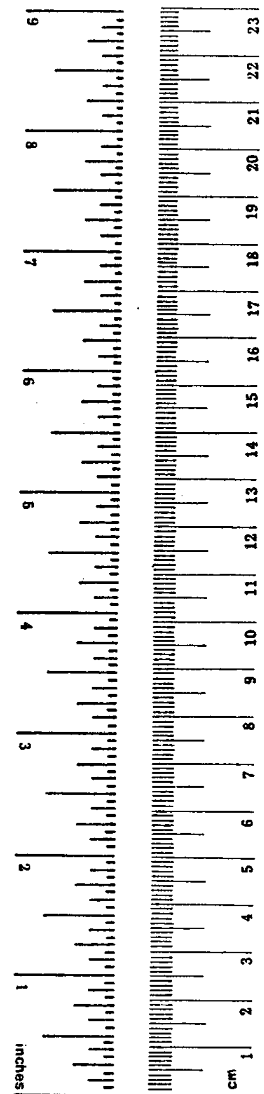
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

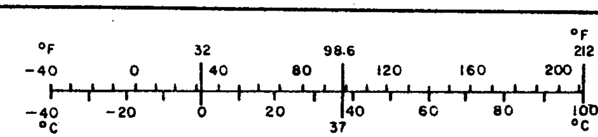
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This analysis was performed to assess the technology and long-term impact of composite materials on automobiles for NHTSA's Office of Passenger Vehicle Research.

This study was conducted under subcontract to Corporate-Tech Planning Inc., 275 Wyman Street, Waltham, Massachusetts as part of their Contract No. DOT-HS-7-01789 entitled "Augmentation of Research and Analysis Capabilities for Timely Support of Automotive Fuel Economy Activities".

The assistance, support and cooperation of Mr. William Basham, Technical Monitor for NHTSA, and Mr. Theodore Taylor, Jr., CTP Program Manager, in the execution and completion of this study are gratefully acknowledged.

Appreciation is also extended to the following individuals who provided advice and consultation in the indicated areas: Stress Analysis - Dr. Joseph Antebi, Simpson Gumpertz and Hager, Inc., Cambridge, Massachusetts; Review and Critique of the Draft Final Report - Dr. Frank Soliman, Ewald Associates, Inc., Detroit, Michigan; and Composites Technology - Dr. Val J. Krukonis, Arthur D. Little, Inc., Cambridge, Massachusetts.

In addition, the cooperation of Dr. Joseph Epel, Budd Plastics Research and Development Laboratory, Troy, Michigan; Mr. John Maxel, Armco Composites, St. Charles, Illinois; and Mr. Richard Schmidt, Great Lakes Carbon Co., Inc., New York, New York; who donated their time and provided some insights into the development of advanced composite material technology within the automotive industry, was of value to the study and greatly appreciated.

Robert Kaiser
Principal Investigator

ERRATA

PAGE	ITEM	CORRECTION TO BE MADE
30	Table 12-S	Weight ratio for Aluminum should read 0.55 instead of 0.74.
35	Table 15-S	Weight ratio Equation should read $\frac{W_c}{W_s} = \frac{\rho_c}{\rho_s} (\frac{E_s}{E_c})^m$ instead of $\frac{W_c}{W_s} = \frac{c}{s} (\frac{E_s}{E_c})^m$
35	Table 15-S	Weight ratio for Aluminum, H Case, should read 0.55 instead of 0.74.
39, 40	Tables 16-S and 17-S	Values for Aluminum, High Case should read 0.55 0.21 (0.15) (0.62) 0.03 (0.21) instead of 0.74 0.44 0.32 0.05 0.36 0.22
41	Line 2	...Aluminum is more expensive than 20/80 hybrid composites .. instead of ...Aluminum is more expensive than 40/60 hybrid composites...
A3-9	Table 19	Values of Equivalent Weight ratios for Equal Bending Moment with Fatigue (Last Column) should read 0.097 0.142 0.145 0.227 0.338 0.397 0.553 instead of 0.058 0.116 0.133 0.160 0.348 0.514 0.738
A3-18	Paragraph 2, 13th Line	...the weight ratio for aluminum (0.55) is higher because in this... instead of ...the weight ratio for aluminum (0.74) is much higher because in this...
A3-19	Table 25	Weight ratio for aluminum should read 0.55 instead of 0.74.
A4-9	Table 29	Weight ratio for aluminum H case should read 0.55 instead of 0.74.

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LIST OF ABBREVIATIONS

a	Scaling coefficient for engine characterization in fuel consumption equation.
a	Relative thickness of face sheets in hybrid composites.
A	Scaling coefficient for engine characterization in fuel consumption equation.
ACM	Advanced Composite Material.
AFER	Automobile Fuel Economy Regulation.
Al	Aluminum.
b	Scaling coefficient for engine characterization in fuel consumption equation.
B	Buckling Resistance Factor.
BTU	British Thermal Unit.
¢	Cent, U.S. currency.
cm	centimeter.
C	Crippling resistance Factor.
^oC	Degree Centigrade.
C*	Hypothetical CAFE credit per pound of steel replaced.
C_c	Unit cost of competing material.
$\overline{C}_c$	Average cost of materials in the baseline vehicle.
C_f	Adjusted value of fuel saved per pound of steel removed.
C_m	Change in materials costs per pound of steel replaced.
C_p	CAFE Penalty, $ per mile per gallon per vehicle produced.
C_s	Unit cost of steel.
CAFE	Corporate Average Fuel Economy.
D	Denting Resistance.
E_c	Modulus of Elasticity of Composite or other Alternate Material.
E_s	Modulus of Elasticity of Steel.
E_x	Longitudinal Modulus.
E_y	Transverse Modulus.
EHV	Electric Hybrid Vehicle.
EPA	Environmental Protection Agency.
EV	Electric Vehicle.
F	Vibration Frequency Factor.
^oF	Degree Fahrenheit

LIST OF ABBREVIATIONS(Continued)

FC Fuel Consumption, gallons per mile.

FE EPA Fuel Economy, miles per gallon.

G_{xy} Shear Modulus.

GPa Giga Pascal.

gpm gallons per mile.

H Designation for materials substitution case with a weight reduction potential that is HIGH in magnitude.

HM High Modulus, as in high modulus graphite.

HS (also Type A) High Strength, as in high strength graphite.

HSLA High Strength Low Alloy, as in HSLA steel.

ICCM-2 2nd International Conference on omposite Materials.

in inch.

^oK Degree Kelvin.

Ksi Thousand pounds per square inch.

L Designation for materials substitution case with a weight reduction potential that is LOW in magnitude.

L Local buckling resistance.

lb pound.

LTV Light Transportation Vehicle.

m meter.

m stiffness factor in weight reduction equation for materials substitution.

M Designation for materials substitution case with a weight reduction potential that is MEDIUM in magnitude.

M Bending Moment Resistance Factor.

M^F Bending Moment Resistance in Fatigue Factor.

MPa MegaPascal.

MPG miles per gallon.

Msi Million pounds per square inch.

Mtons Metric tons.

MY Model year.

n (subscript) subscript designating new material replacing old material.

NHTSA National Highway Traffic Safety Administration.

NSF National Science Foundation.

o (subscript) subscript designating old amterial (usually steel) being replaced.

LIST OF ABBREVIATIONS (Continued)

PAN polyacrylonitrile.

psi pounds per square inch.

QI quasi-isotropic.

$ Dollar, U.S. currency.

S Stiffness Factor.

S^b Bending Stiffness Factor for thin wall beams.

SAE Society of Automotive Engineers.

SMC Sheet Molding Compound.

t thickness.

T Torsional Strength Factor.

T^F Torsional Fatigue Strength Factor.

UHM Ultra High Modulus, as in Ultra high modulus graphite.

UMC^{tm} Sheet molding compound reinforced with continuous filaments (trademark of Armco Composites, Inc.).

U.S. United States.

W watts.

W Weight.

W_c Weight of Composite material, or other alternate material.

W_s Weight of Steel.

WT Test weight of a vehicle (Test weight = Curb weight plus 300 lb).

XMC^{tm} Filament wound continuous fiber sheet molding compound (trademark of PPG, Inc.).

Y Stress Yield Factor.

$\dot{\epsilon}$ strain rate

ρ_c Density of Composite or other alternate material.

ρ_s Density of Steel.

σ_c Ultimate tensile strength of composite or other alternate material.

σ_s Ultimate tensile strength of steel.

σ_x Ultimate longitudinal tensile strength.

σ_y Ultimate transverse tensile strength.

σ_{yc} Yield strength of Composite or other alternate material.

σ_{ys} Yield strength of steel.

LIST OF ABBREVIATIONS (Concluded)

τ_{xy} Ultimate shear strength.

ν_c Poisson's ratio, composte or other alternate material.

ν_x Poisson's ratio, steel.

1.0 BACKGROUND

Fuel economy and light weight vehicles have become vital concerns of the automotive industry because of the Energy Policy and Conservation Act that was passed into law on December 22, 1975. The legislation mandates a production weighted Corporate Average Fuel Economy (CAFE) for passenger automobiles that will increase from 18 mpg in 1978 to 27.5 mpg in 1985. It is most likely that these requirements will become even more stringent in the post-1985 period. This will require not only that the average inertial weight of an automobile be reduced from 4000 lbs. (1800 kg) to 3100 lbs. (1400 kg), but will also require major gains in power plant efficiency and packaging optimization, if the general attributes - space, ride, comfort - of American automobiles are to be maintained.

In order to reduce vehicle weight and still maintain sales attributes, automotive structures and materials are being closely examined. Greater use is being made of materials such as high strength low alloy (HSLA) steels, aluminum, and a variety of plastics materials, including fiber glass reinforced plastics. With extensive use of these materials, it should be possible for the manufacturers to produce an automobile that will meet the 1985 AFER (Automobile Fuel Economy Regulations) and still find market appeal.

The manufacturers are concerned about the likelihood that the AFER requirements after 1985 will become even more stringent. With current materials technology, it would be difficult to meet the increased AFER requirements without a significant level of downsizing, or without the introduction of alternate power plants, such as diesel engines, into the light transportation vehicle (LTV) fleet. In the longer terms, the automobile manufacturers are examining both the potentials and costs of new engine technology, and new materials technology. Among the novel materials being examined by the automotive industry, advanced composite materials (ACM) offer great promise for extensive reduction in the weight of LTV's.

Composite materials are combinations of two or more distinct solid materials that are bonded to each other to combine the properties of these materials in such a way as to obtain a material that has new or unique properties. Classic examples of composite materials that have been used for a long time include laminated wood, reinforced concrete, dispersion hardened metals, and a variety of plastics materials which contain low cost fillers, extenders, and short fiber reinforcements.

Approximately two decades ago, in order to meet the increasing performance requirements of advanced military systems, a number of low density fibers were produced that were very strong and very stiff. In the ensuing years, the category of high performance fibers has grown to include such diverse materials as boron, carbon, aramid (an organic compound), silicon carbide, boron nitride, and alumina, in addition to high strength glass fibers which have been the basis of the FRP (fiber reinforced plastics) industry. Incorporating one or more of these high performance filaments in a suitable matrix produces a class of composite materials that exhibit physical and structural properties not attainable with conventional engineering materials. The matrix, which is used to bond the fibers together, can be a thermosetting resin, such as an epoxy, polyester, or polyimide; a thermoplastic resin, such as nylon or polysulfone; a metal, such as aluminum; or a ceramic such as glass.

2.0 OBJECTIVE OF THE STUDY

The purpose of the present study is to estimate the potential impacts of ACM on LTV fleets in the 1985-1990 period, identifying, and quantifying where possible, weight reduction potentials, costs to the manufacturers of implementing suitable manufacturing processes, resulting costs to the consumer, and potential environmental effects. The potential use of ACM in LTV's in the 1985-1990 period was examined under two possible scenarios:

1) Revolutionary - Fuel economy standards are set in the time period at 32-40 mpg. and manufacturers must use composite materials technology to the maximum extent, almost independently of costs.

2) Evolutionary - Fuel economy standards are set at 28-31 mpg, and manufacturers will use composites only if the technology is well developed and cost tradeoffs are deemed reasonable.

In addition, an assessment was made of the likely evolution of the future use of ACM by the automotive industry in their LTV fleets over the next decade, up to 1990.

3.0 METHODOLOGY

3.1 Literature Search

A data base for ACM properties was first established by performing a search of the literature, and by contacting manufacturers of high performance fibers, fabricators of ACM parts for non-automotive uses, and potential users and fabricators of ACM components in the automotive industry. Much of this work was performed in the course of a prior Technology Assessment Study of ACM sponsored by the National Science Foundation (1).

3.2 Weight Reduction Potential of ACM

To assess the potential use of ACM in LTV structures, the relative weights of simple structures made from various ACM and other materials to functionally equivalent steel structures were calculated The study used the methodology and analysis developed by Chang and Justusson (2) to calculate the functionally equivalent weights of aluminum and HSLA steel when these materials are substituted for steel in simple structures. This analysis also extends similar work performed by Dharan (3). The analysis assumes that when steel is replaced by another material in a given structure, the resulting structure will match or exceed all the structural characteristics of the steel structure.

The analysis assumed that a mild steel structure would be replaced with an "equivalent" structure of the same major dimensions, geometrical design characteristics, and function, but of a different material, with a gauge thickness that would be adjusted to meet structural requirements such as stiffness, denting resistance, buckling resistance, and all the other design criteria listed in Table 1S. The structural geometries considered in the analysis included panels, thin walled beams, solid sections and thin walled tubes.

By considering similar geometries for equivalent structures, for any structural criterion, the relative weight of substituted material to that of steel reduces to being a function of the wall thickness of the material, and of its basic mechanical properties, namely the modulus of elasticity, ultimate strength, yield strength, fatigue strength, Poisson's ratio, and density. The calculations were performed for a wide variety of ACM of different composition and structure, for each of the four geometries mentioned above. For each case, the design criterion that resulted in the highest calculated value of the weight ratio was taken to be the design limiting criterion. The substituted structure is, therefore, overdesigned, in comparison to steel, in terms of all the other design criteria considered.

All the major automotive manufacturers, and many component and materials suppliers, have R and D programs exploring the potential uses of ACM in automotive structures. A wide variety of prototype parts and components have been made from different ACM and are currently being evaluated. A significant amount of data are, therefore, available on the relative weights of comparable ACM and steel automotive components. These data were collected, and the weight ratios actually obtained with different components as a result of materials substitution were compared to the theoretical values obtained for the simple structure most similar in shape (i.e. a hood was considered to be a panel, a driveshaft was considered to be a thin tube, a leaf spring was treated as a solid section, etc.). Comparable values established broad design criteria which allowed weight savings to be estimated for a wide category of parts and components, as a function of the types and properties of substitution materials being considered.

TABLE 1S

STRUCTURAL CRITERIA CONSIDERED

* BENDING STIFFNESS
* BENDING MOMENT RESISTANCE
* TORSIONAL STIFFNESS
* TORSIONAL STRENGTH
* FATIGUE CHARACTERISTICS
* OIL CANNING RESISTANCE
* DENTING RESISTANCE
* BUCKLING RESISTANCE
* STRESS YIELD FACTOR
* CRIPPLING RESISTANCE
* FREQUENCY RESPONSE

3.3 Economic Impact of ACM Substitution (unit weight basis)

The economic implications of materials substitution in LTVs were evaluated by examining the resulting changes in costs of raw materials to the manufacturer, the resulting impacts on the wholesale and retail prices of a vehicle, and on the life cycle costs to the user. The calculations were first performed on a normalized basis on the replacement of a unit weight of steel. These calculations are based on current (1978) costs and prices.

The Council on Wage and Price Stability (CWPS) publishes periodic reports (4) on various economic aspects of the U.S. automobile industry. These include average vehicle costs and prices. The CWPS reports are compiled from data obtained from the four major automobile manufacturers. CWPS data of interest to the study are summarized in Table 2S. This information was then used to develop proportionality factors between various cost/price elements as shown in Table 3S. In the analysis of the impact of ACM substitution on automobile costs and prices, it was assumed that the current ratios between manufacturers' costs, wholesale price, and retail price would remain unchanged.

3.4 Changes in Manufacturing Costs

In estimating the changes in manufacturing costs, it was assumed that the costs of purchased materials would be dominant, and that any cost changes due to variations in labor and capital requirements would be small in comparison. As long as the differences in unit raw material costs remain large, this is not a bad assumption. Changes in manufacturing costs were, therefore, assumed to be equal to the sum of the difference in the costs of the substituted material and that of the steel being replaced, and of the reduced material costs resulting from propagated weight reductions.

It was assumed that W pounds of ACM (or other substituted material) replace one pound of steel. This substitution results in a direct weight reduction of (1 - W) pounds. This direct weight reduction engenders additional weight reduction due to weight propagation. The argument used in developing weight propagation factors

TABLE 2S

CURRENT COST/PRICE STRUCTURE OF AN AVERAGE U.S. PASSENGER AUTOMOBILE*

	1977 Model Year	1978 Model Year
Retail Price, including delivery charges	$6,720	$7,130
Delivery Charges	170	190
Retail Price	6,550	6,940
Wholesale Price	5,335	5,700
Manufacturer's Costs	4,902	5,230**
Labor Costs	1,656	1,800
Material Costs	2,074	2,190
Other Costs	1,172	1,240

* With average options.

**Based on sales of 11 million vehicles in model year.

SOURCE: Executive Office of the President, Council on Wage and Price Stability, "Council Analyzes New Automobile Price Increases", November 14, 1977.

TABLE 3S

CALCULATED COST/PRICE RATIOS FOR AN AVERAGE U.S. PASSENGER AUTOMOBILE*

RATIO	1977 Model Year	1978 Model Year
Retail Price to Delivered Price	0.975	0.973
Wholesale Price to Retail Price	0.815	0.821
Manufacturer's Costs to Wholesale Price	0.919	0.918
Total Manufacturer's Costs		
Labor	0.338	0.334
Materials	0.423	0.419
Other	0.239	0.237
Manufacturer's Costs to Retail Price	0.748	0.754
Materials Costs to Wholesale Price	0.389	0.384

*With Average Options.

is that the weights of many components in a vehicle are a function of the gross vehicle weight. As specific components are made lighter, the gross vehicle weight decreases, so that other components now do not have to be as large, and as heavy, as they originally were. Values of weight propagation factors that have been published in the recent technical literature range from 1.4 (5) to 2.6 (5). These factors imply that there is a secondary weight reduction of 0.4 lb to 1.6 lb per pound of direct weight removed. The more conservative value of 1.4 for the weight propagation factor, suggested by Kennedy and Hoover (5) was used in this study. Therefore, in addition to the primary weight reduction of (1-W) pounds, there is a secondary weight reduction of 0.4 (1-W) pounds.

The net change in material costs to the manufacturer is, therefore,

$$C_m = W\,(C_c) - C_s - 0.4(1 - W)\overline{C} \qquad (1)$$

where:

C_m = net change in materials costs per pound of steel replaced

C_c = unit cost of composite material (or other substitute material)

C_s = unit cost of steel

$\overline{C}$ = average unit cost of materials in a baseline vehicle.

The unit costs of ACM used were treated as variable parameters. The unit costs of commodity materials, such as steel, were based on current published values obtained from the trade press. The unit average cost of materials in a baseline vehicle was assumed to be \$0.60/lb. This figure was obtained by dividing the average cost of materials in a 1978 passenger automobile, given as \$2,190 in Table 2S, by an estimated average weight of 3,650 lbs (1660 kg) for a 1978 model year passenger automobile.

3.5 Change in Wholesale Price

The net change in manufacturing costs, as developed above, is multiplied by 1.09 (obtained from Table 3S), to obtain the direct effect of materials substitution on the vehicle wholesale price on a per pound of steel replaced basis.

In order to take into account fuel economy resulting from weight reduction, a theoretical CAFE credit is substracted from the adjusted wholesale price to obtain the net change in the vehicle wholesale price. This factor represents the maximum value of weight savings deriving from the law to the manufacturer. It is used for accounting purposes in this study. In practice, a manufacturer may find it more advantageous to forego weight savings, and pay a penalty if this fleet does not meet the regulatory standard. This CAFE credit, C*, per pound of steel replaced is expressed as follows:

$$C^* = 1.4\ (1 - W)\ (\text{MPG})(C_p) \qquad (2)$$

where:

MPG = increase in fuel economy resulting from a unit weight reduction

C_p = CAFE penalty, currently \$50/mpg per vehicle produced.

The functional relationships between fuel economy and vehicle test weight that were used in this study are presented in Figure 1S. In this figure, curves are presented for a standard gasoline powered vehicle and for a diesel engine vehicle. These curves are based on the following equation published in the Motor Vehicle Goals Study (7):

$$FE = A\ (WT)^{-a}(HP/WT)^{-b} \qquad (3)$$

where:

FE = EPA Composite Fuel Economy in miles per gallon

WT = Test Weight of the Vehicle, defined as the curb weight plus 300 lb

HP/WT = ratio of the rated engine horsepower to the auto test weight

A,a,b = scaling coefficients which are functions of engine characteristics.

For a vehicle with a standard gasoline engine:

A = 6060 a = 0.88 b = 0.40

while for a vehicle with a diesel engine:

A = 2370 a = 0.69 b = 0.35

It was decided to examine both the case of a gasoline engine vehicle and of a diesel engine vehicle with an assumed value of 0.30

FUEL ECONOMY AS A FUNCTION OF TEST WEIGHT FOR MODEL GASOLINE AND DIESEL ENGINE VEHICLES

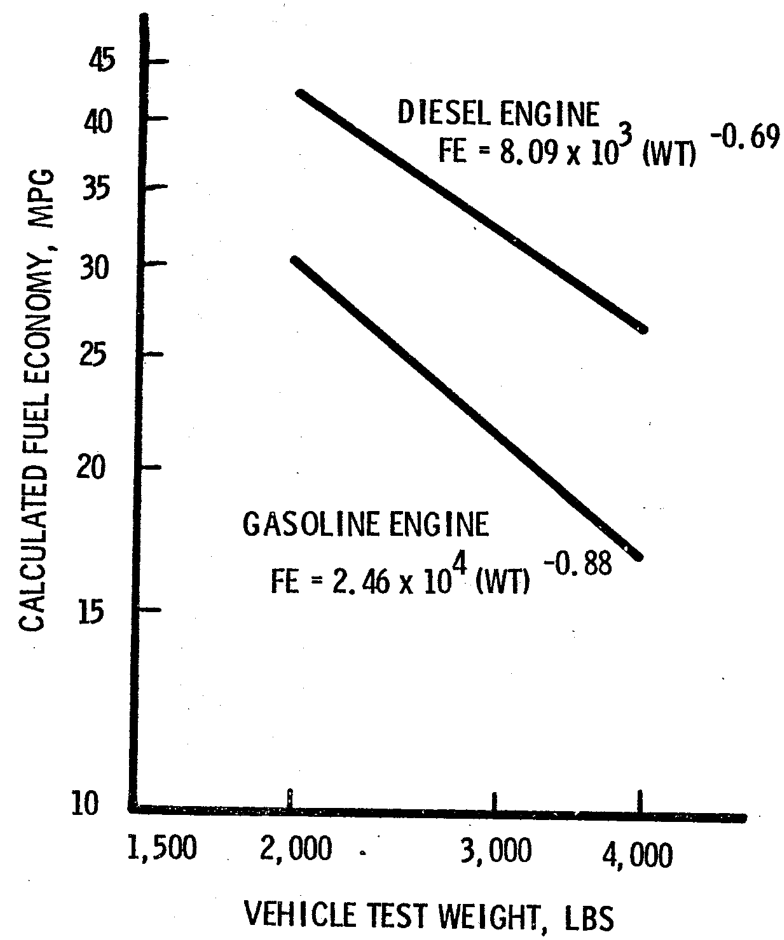


FIGURE 1S. FUEL ECONOMY AS A FUNCTION OF TEST WEIGHT FOR MODEL GASOLINE AND DIESEL ENGINE VEHICLES hp/lb as the performance parameter. This assumed value results in calculated fuel economies that are in reasonable agreement with the 1978 EPA composite fuel economy for gasoline powered vehicles of varying test weight (8). The replacement of gasoline engine vehicles by diesel engined vehicles is a fuel economy option that a manufacturer could use instead of, or in addition to, vehicle weight reduction by materials substitution. It seemed desirable to determine whether the characteristics of the power plant would have any major impact on the economics of ACM substitution as a result of differences in fuel economy.

In calculating C*, it is necessary to take into account the provision of AFER that a manufacturer's CAFE is based on the harmonic mean fuel economy of the vehicle fleet produced by that manufacturer. CAFE is actually based on the average fuel consumption of the vehicle fleet produced. By inverting Equation 3, the following relation between vehicle fuel consumption, FC, in gallons per mile, and vehicle test weight is obtained:

$$FC = \frac{(WT)^{a}(HP/WT)^{b}}{A} \tag{4}$$

By differentiating this equation the change in fuel economy per unit change in vehicle weight is obtained, for constant (HP/WT):

$$\frac{d(FC)}{dW} = \frac{a}{A}\,(WT)^{a-1}\,(HP/WT)^{b} \tag{5}$$

This change in fuel consumption with weight results in a monetary value for weight savings which is a function of the penalty assessed for not meeting the standard, and of the level of the fuel economy standard. As already noted, the penalty for not meeting the standard has been set at $50 per mile per gallon per vehicle produced.

The value of weight savings will increase as the fuel economy standard increases because the fuel consumed per mile decreases as the fuel economy increases. The differential of the fuel consumption to fuel economy varies as the inverse square of the fuel economy level. A 1 mpg average fuel economy difference results in a lower average gasoline consumption at 30 mpg than at 27.5 mpg. The level of the fuel economy standard will increase annually from a value of 18 mpg in 1978 to 27.5 mpg in 1985. It is quite probable that the fuel economy standard will increase in the post 1985 period to even higher levels. If the standard were to increase in annual increments of 0.5 mpg, the standard would be 30 mpg in 1990. If the annual increments were 1 mpg, the standard would reach 32.5 mpg in that year. If this were to occur, the value of weight reduction would increase with time in the post 1985 period.

The monetary value of saving one pound of vehicle weight is presented in Table 4S as a function of the mandated fuel economy level, for gasoline engine and diesel engine vehicles of varying weight. As shown in this table, the value of weight savings for a passenger automobile increases with the mandated fuel economy level, and varies with the assumed power plant. This value is, however, fairly insensitive to the test weight of the vehicle. In the subsequent calculations of this study, an assumed value of $0.61/lb for gasoline vehicles, and of $0.32/lb for diesel vehicles, was used for C*. These values correspond to an AFER standard of 30 mpg.

3.6 Changes in Retail Price

The net change in retail price is obtained by multiplying the adjusted wholesale price, as calculated above, by the current average ratio of retail price to wholesale price of 1.22 given in Table 3S.

3.7 Change in Life Cycle Costs

It was assumed that the major quantifiable change in operating costs due to materials substitution would result from lower fuel consumption. While materials substitution could result in improved maintenance characteristics and a longer vehicle life because of reduced corrosion, these factors are not easily quantifiable because of lack of substantiating evidence, and were, therefore, not included in the calculations.

The calculated decreases in fuel costs per pound of weight reduction are presented in Table 5S for gasoline and diesel engine vehicles of varying test weight. The following assumptions were made:

a) Fuel costs are \$0.70/gallon
b) A vehicle is driven 10,000 miles per year (16,000 km/yr)
c) Useful vehicle life is 10 years
d) Future expenditures are discounted at an annual rate of 5% to obtain their net present value.

It is to be noted that the decrease in fuel consumption per unit weight reduction is fairly insensitive to vehicle test weight. Reducing the weight of a gasoline engine vehicle by one pound decreases its lifetime fuel consumption by about 1.3-1.4 gallons. This is twice the savings that would be obtained with a diesel engine. For purposes of calculations, an assumed value of \$0.75/lb was used for a gasoline engine vehicle, and of \$0.40/lb for a diesel engine vehicle. In each case, the adjusted value of fuel saved per pound of steel removed, C_f, was obtained by multiplying the above factors by 1.4 (1-W). The life cycle cost change due to ACM substitution was obtained by substracting C_f from the adjusted retail price calculated above.

3.8 Substitution of ACM for Steel in a Model Vehicle

The potential reduction in the weight of a LTV that could be achieved by replacing steel components with equivalent ACM components was also analyzed. In this analysis, a model vehicle was chosen for which a detailed list of components, their weight, and composition, was available. The vehicle used in the analysis was a 1975 Chevelle Coupe with a curb weight of 3643 lb, because a detailed component breakdown of this vehicle was available from a recent NHTSA report (9). From all the components listed, candidate components that could be made from ACM were identified. The components selected included most of the body in white, a substantial part of the chassis, the bumpers, the drive shaft, and seat frames. It was assumed that ACM would not be used to replace plastics, nor

TABLE 4S

VALUES OF WEIGHT REDUCTION AS A FUNCTION OF AFER STANDARD AND VEHICLE CHARACTERISTICS

AFER STANDARD, mpg		27.5	30	32	34
EQUIVALENT FUEL CONSUMPTION, gpm		3.636×10^{-2}	3.333×10^{-2}	3.125×10^{-2}	2.941×10^{-2}
Differential	$\frac{\text{Fuel Consumption}}{\text{d(Fuel Economy)}}$ at AFER Standard $(\text{gpm})^2$	1.32×10^{-3}	1.11×10^{-3}	9.77×10^{-4}	8.65×10^{-4}
Vehicle Test Weight, lbs	dFc/dW gpm/lb test weight	Value of 1 lb Weight Reduction $/lb			
Gasoline Engine Vehicle					
4000	1.316×10^{-5}	0.50	0.59	0.67	0.76
3000	1.362×10^{-5}	0.52	0.61	0.70	0.79
2000	1.430×10^{-5}	0.54	0.64	0.73	0.83
Diesel Engine Vehicle					
4000	6.523×10^{-6}	0.25	0.29	0.33	0.38
3000	7.132×10^{-6}	0.27	0.32	0.36	0.41
2000	8.086×10^{-6}	0.30	0.36	0.41	0.47

TABLE 5S

NET PRESENT VALUE OF DECREASED FUEL CONSUMPTION PER UNIT WEIGHT REDUCTION

Vehicle Test Weight W, Lbs	Fuel Economy MPG	d(FC)/dw gpm/lb	Life Decrease in Consumption per Unit Weight Reduction-(1) gal/lb	Net Present Value Fuel Saved per Unit Weight Reduction-(2) $/lb
Gasoline Engine				
4000	16.7	1.32×10^{-5}	1.32	0.71
3000	21.5	1.36×10^{-5}	1.36	0.74
2000	30.8	1.43×10^{-5}	1.43	0.78
Diesel Engine				
4000	26.4	6.52×10^{-6}	0.65	0.35
3000	32.2	7.13×10^{-6}	0.71	0.38
2000	42.6	8.09×10^{-6}	0.81	0.44

(1) Based on 10,000 mi/yr for 10 years

(2) Based on Fuel cost of $0.70/gallon, and 5% annual discount rate.

engine components. The weight of each of these components on a functionally equivalent basis was then calculated for two types of ACM. The first was an all graphite fiber composite which would result in maximum weight savings, but would be very expensive to use. The second material was a graphite-glass hybrid composite that would result in less weight reduction, but would be significantly less expensive to use.

The total weight of a vehicle that made maximum use of the all graphite composite was obtained by assuming that all possible components for materials substitution in the model vehicle would be made from an all graphite composite. This vehicle would be representative of those the manufacturers would be required to make under a revolutionary scenario of very high AFER standards. The total weight of a vehicle that made selective use of a lower cost hybrid composite was calculated to represent the type of vehicle manufacturered under less stringent AFER standards. In all cases, a 1.4 weight propagation factor was assumed in the total vehicle weight calculations.

The economic implications of these substitutions were then analyzed. The changes in vehicle manufacturing costs, wholesale price, retail price and life cycle costs were calculated on a per vehicle basis, using the general methodology used to calculate changes on a per pound of steel replaced basis, and which was described above.

4.0 RESULTS

4.1 Composition and Properties of ACM

The principal physical properties of the high performance fibers that are currently commercially available in the U.S. are presented in Table 6S. The properties of E glass fibers, and S glass fibers, which are not normally considered as high performance fibers, are also presented in this Table. The fibers of current interest to the automotive industry include high strength graphite, high modulus graphite, aramid fiber, and E glass fiber, the last because of its low cost.

TABLE 6S PHYSICAL PROPERTIES OF COMMERCIALLY AVAILABLE HIGH STRENGTH FILAMENTS

Material	E-Glass Fiber	S-Glass Fiber	Aramid Fiber	Boron/Tungsten Fiber	Graphite Filaments: High Strength Fiber	Graphite Filaments: High Modulus Fiber	Graphite Filaments: Very High Modulus Fiber
Product	(Roving)	(Roving)	Kevlar 49	5.6 mil Diam.	Thornel 300 (WYP 15-1/0)	Magnamite HMS	Celion GY-70
Supplier			Dupont	Avco/CTI	Union Carbide	Hercules	Celanese
Density lbs/in^3	0.092	0.090	0.052	0.090	0.062	0.067	0.071
g/cm^3	2.54	2.48	1.44	2.48	1.72	1.86	1.96
Tensile Strength 10^3 psi	372	550	400	500	360	340	270
MPa	2500	3700	2800	3400	2600	2300	1900
Tensile Modulus 10^6 psi	10.5	12.4	18.0	58.0	32.5	50	75
GPa	73	86	124	406	225	350	520
Ultimate Elongation, %	4.8	5.4	2.5	0.8	1.1	0.58	0.38
Specific Strength, in	4.0×10^6	6.0×10^6	7.9×10^6	5.6×10^6	6.1×10^6	5.0×10^6	3.8×10^6
cm	9.8×10^6	1.5×10^7	1.9×10^7	1.4×10^7	1.5×10^7	1.2×10^9	9.7×10^6
Specific Modulus, in	1.1×10^8	1.4×10^8	3.5×10^8	6.4×10^8	5.2×10^8	7.5×10^8	1.1×10^9
cm	2.9×10^8	3.5×10^8	8.6×10^8	1.6×10^9	1.3×10^8	1.9×10^9	2.7×10^9
Filament Diameter, mils	0.20-0.55	0.35-0.40	0.47	5.6	0.3	0.3	0.33
cm	0.0005-0.014	0.0009	0.0012	0.014	0.0007	0.00075	0.00084
Thermal Conductivity BTU-ft/hr $(ft^2)(^\circ F)$	0.56				12	70	
$W/m\ ^\circ K$	0.97				20.8	121	
Electrical Resistivity Ω mil ft					9000	4500	3900
μΩcm					1500	750	650
Current Price, $/lb	0.49	2.00	8-10 & up to 27 for fine denier fiber	200	32	70	110-250

Epoxy resins have been the predominant matrix material used to make advanced composites. The resins that have been classically used have slow cure times and are relatively expensive. Other resin systems are being examined as candidate matrix materials to lower the costs of composites. Thermosetting polyesters are now being extensively examined as candidate materials for mass production applications of ACM. Unsaturated polyesters (and potentially, vinyl esters) are the matrix material of choice in the myriad consumer applications (including non-structural automotive parts) of chopped fiberglass reinforced plastics. These resins are relatively inexpensive (36¢/lb for general purpose resin) and formulations exist that cure rapidly (in minutes of less), and, therefore, are amenable to high speed mass production fabrication methods. There is also interest in thermoplastics that exhibit reasonably high temperature resistance (such as nylon) as matrix materials. These thermoplastic resins lend themselves to rapid processing and to post-forming which can result in significant cost reductions.

The mechanical properties of fibrous composites depend on the type(s) of fiber incorporated in the matrix, its volumetric concentration, and fiber lay up geometry. In general, the mechanical properties of a fibrous composite vary with the volumetric concentration of the incorporated fibers. The higher the fiber content, the stronger and stiffer the structure, up to the point where fiber contact impedes adhesion of the matrix to the fiber.

The mechanical properties tend to increase with increasing fiber length. A minimum fiber length to diameter ratio of at least 10/1 is desired. In general, the longer the fiber length in a given direction, the greater the continuity of stress transfer, and therefore, the greater the load bearing capability in that direction. Continuous fiber composites usually exhibit mechanical properties that are superior to those of discontinuous, or chopped fiber composites.

The geometric arrangement of fibers in a composite determines both the strength and stiffness of a composite in any given direction; and also the fiber content to a certain extent.

The effects of fiber orientation on the mechanical properties of various fibrous composites are presented in Table 7S, as are the comparable properties of aluminum and cold rolled steel. Unless otherwise specified, the nominal fiber loading is 60 percent by volume. The fibers considered include A type (high strength) graphite, HM type (high modulus) graphite, and UHM type (ultra high modulus) graphite, E-glass, S-glass and Kevlar 49. The fiber arrangements considered in this table include:

a) Unidirectional: In this arrangement all the fibers are parallel to each other, and are aligned in the direction of the applied stress (0^{o} orientation).

b) Crossply: In this arrangement, the composite consists of alternating perpendicular layers of parallel fibers. Such composites are usually either tested in a 0^{o}-90^{o} orientation, in which the direction of the applied stress is the same as the orientation of one of the fiber layers; or in a $\pm 45^{o}$ orientation, in which the fiber layers are at a 45^{o} angle to the applied stress.

c) Quasisotropic (isotropic): In this arrangement the composite consists of alternate layers of parallel fibers that are arranged at a relative angle of 45^{o}. With the first layer in the direction of the applied stress (0^{o}) succeeding layers are arranged in the $+45^{o}$, 90^{o}, and 135^{o} (or -45^{o}) directions.

d) Woven Patterns: The above arrangements apply to composites made with non-woven filaments. Different geometrical arrangements can be obtained with woven or braided filaments, and these will depend on the weaving pattern of the resulting cloth, and the relative orientation of different layers of cloth.

e) Chopped Fiber: The plastic is reinforced with chopped fiber that can be randomly oriented in three dimensions, or given a preferential orientation by an alignment process.

TABLE 7S MECHANICAL PROPERTIES OF VARIOUS FIBER REINFORCED EPOXY COMPOSITES AND OF METALS OF INTEREST

Material	Fiber Layup Geometry	Density gr/cm^3	Elastic Moduli, GPa Axial, Ex	Elastic Moduli, GPa Transverse, Ey	Elastic Moduli, GPa Shear Gxy	Ultimate Strength, MPa Axial, σ_x	Ultimate Strength, MPa Transverse, σ_y	Ultimate Strength, MPa Shear τ_{xy}	Yield Strength as Percent Ultimate Strength	Fatigue Strength as Percent Ultimate Strength
A type Graphite/Epoxy	Unidirectional (0^0)	1.57	138	6.9	4.5	1517	41	97		70
	Crossply (0^0, 90^0)	1.57	74	74	4.5	838	838	97		59
	Crossply ($\pm$45^0)	1.57	17.2	17.2	31.0	138	138	345		
	Isotropic (0^0, 90^0, $\pm$45^0)	1.57	48	48	17.8	604	604	221		
	Harness Satin Weave Cloth (Warp)	1.57	62	62		462	476			78
HM type Graphite/Epoxy	Unidirectional (0^0)	1.60	221	6.9	4.8	1206	34	69		
	Crossply (0^0, 90^0)	1.60			4.8			69		
	Crossply ($\pm$45^0)	1.60	17.2	17.2	44.8	124	124	290		
	Isotropic (0^0, 90^0, $\pm$45^0)	1.60	73	73	24.8	345	345	179		
UHM type Graphite/Epoxy	Unidirectional (0^0)	1.68	303	6.9	6.6	758	28	48		
	Crossply (0^0, 90^0)	1.68	159	159	6.6	402	402	48		
	Crossply ($\pm$45^0)	1.68	20.7	20.7	79.3	96.5	96.5	207		
	Isotropic (0^0, 90^0, $\pm$45^0)	1.68	103	103	42.8	242	242	128		
Kevlar 49/Epoxy	Unidirectional (0^0)	1.38	86(tens) 41(comp)	5.5	2.1	1517(tens) 276(comp)	28	41		70
	Crossply ($\pm$90^0)	1.38								
	Crossply ($\pm$45^0)		7.6	7.6	20.7	207	207	221		
	Isotropic (0^0, 90^0, $\pm$45^0)									
	181 Fabric (Warp)(50v/o)	1.33	31	31	2.0	517(tens) 172(comp)	517(tens) 172(comp)	110		
	Chopped Fiber (50v/o)	1.32	20	20		196	196			
S-Glass/Epoxy	Unidirectional (0^0)	1.88	48	6.9	3.4	1730	40	10		
	Crossply (0^0, 90^0)	1.88	31	31		980	980			
	Crossply ($\pm$45^0)	1.88	16	16		170	170			
	Isotropic (0^0, 90^0, $\pm$45^0)	1.88	25	25		730	730			
E-Glass/Epoxy	Unidirectional (0^0)	1.80	39	9.6	2.1	1104	20			23
	Crossply (0^0, 90^0)	1.80	25	25		518	518		32	22
	Crossply ($\pm$45^0)	1.80	11	11		152	152			
	Isotropic (0^0, 90^0, $\pm$45^0)	1.80	18	18		330	330		42	25
	Chopped Fiber (47% glass)	1.86	15	15		99	99			
Aluminum 6061-T-6		2.70	72	72	26.2	310	310	207	88	31
Steel, Cold Rolled (0.2% Carbon)		7.85	207	207	83	552	552	414	75(Tension) 60(Shear)	40-45

SOURCES: REFERENCES 10 - 18

The data presented in Table 7 indicate that fibrous composites can be put to greatest advantage in applications where the stress is applied in one direction, and the component can be made from a unidirectional composite in which all the fibers are aligned in the direction of this stress. As can be noted, unidirectional composites exhibit a very high tensile strength and tensile modulus along the 0° direction, but very low values of these properties in the transverse direction (90°). These are mainly a function of the mechanical peoperties of the resin.

Only rarely are applications found where the applied stresses are unidirectional, so that in most composite structures the fibers are arranged in more than one direction in order to provide better multi-directional strength properties. In bi-directional composites, laminates of fiber layers cross-plied at right angles to each other have improved transverse properties when compared to a unidirectional composite, but at the expense of the longitudinal properties. A $0^{\circ}/90^{\circ}$ cross ply composite has only half the longitudinal (0° direction) tensile properties of a unidirectional composite, but the transverse properties of a $0^{\circ}/90^{\circ}$ cross-ply composite are five times those of a 0° composite. However, with this arrangement the in-plane shear strength is not significantly better than that of the unidirectional composite. If the composite test sample is cut in such a way that the cross plies are at $\pm 45^{\circ}$ to the applied stress, significantly improved shear properties are obtained, but at the cost of longitudinal and transverse properties. A standard method of obtaining a composite with quasi-isotropic properties is to cross ply the fibers at $0^{\circ}/90^{\circ}/\pm45^{\circ}$. By arranging the fibers in this manner the properties of the composite are equal in all directions in the plane of the laminate.

Woven composite structures are similar in many respects to cross-plied laminate structures but are usually less stiff and less strong because of the weaving pattern. The advantages of fabrics is that they possess drapability and handling characteristics that allow the fabrication of geometrically complex components.

The attraction of graphite fiber composites as structural materials is because their strength and stiffness approach those of steel (depending on fiber lay up geometry as shown in Table 7S) while having only one fifth the density of steel. The high fatigue strength of graphite fiber composites further enhances the appeal of this class of materials to the designer.

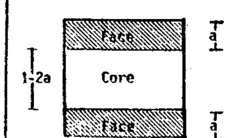
Continuous glass fiber composites have strengths that are comparable to, or can exceed, the strength of graphite fiber composites of similar fiber lay up geometry. Even on a unit weight basis, the specific strength of glass fiber composites compares favorably with the specific strength of graphite fiber composites. The density of glass fiber composites with a high fiber content is only 10% to 15% higher than that of comparable graphite composites. However, glass fiber composites do not have the stiffness and fatigue strength retention of graphite fiber composites. The stiffness of glass fiber composites ranges from one tenth that of steel for isotropic composites to one-fourth that of steel for unidirectional composites. On a unit weight basis, they are not as stiff as steel.

The mechanical properties of a fiber glass composite can be significantly improved by the selective incorporation of graphite fibers. A hybrid composite (a composite that contains more than one type of filament) that contains graphite fiber face sheets bonded to a glass fiber core, has significantly improved flexural properties when compared to a glass composite, but is significantly less expensive than an all graphite composite. As indicated in Table 8S, a sandwich structure that has graphite fiber face sheets that are each one tenth the total thickness of the composite (a=0.2), will be two to three times as stiff as a fiber glass composite. This composite will have about half the stiffness of an all graphite composite, but only one fifth the graphite content.

It is envisioned that the ACM used by the automobile industry will be hybrid composites because they appear to offer the most effective combination of cost and mechanical properties. Rapid

TABLE 8S EFFECTIVE FLEXURAL AND TENSILE MODULI OF GRAPHITE + GLASS HYBRID SANDWICH STRUCTURES

CORE MATERIAL	AXIAL MODULUS, CORE MATERIAL, GPa	FACE MATERIAL	AXIAL MODULUS FACE MATERIAL, GPa	RELATIVE THICKNESS OF FACE, a	EFFECTIVE FLEXURAL MODULUS, GPa	EFFECTIVE TENSILE MODULUS, GPa
Uniaxial E-glass/Epoxy Composite	39	Uniaxial Type A (high strength) Graphite Epoxy Composite	138	0	39	39
				0.05	66	49
				0.10	87	59
				0.20	117	79
				0.50	138	138
Uniaxial E-glass/Epoxy Composite	39	Uniaxial Type HM (high modulus) Graphite/Epoxy Composite	221	0	39	39
				0.05	88	57
				0.10	128	75
				0.20	176	112
				0.50	221	221
Chopped Glass/Epoxy Composite	15	Uniaxial Type HM (high modulus) Graphite/Epoxy Composite	221	0	15	15
				0.05	71	36
				0.10	116	56
				0.20	177	97
				0.50	221	221
Chopped Glass/Epoxy Composite	15	Quasi-Isotropic Type A Graphite Epoxy Composite	48	0	15	15
				0.05	24	18
				0.10	31	22
				0.20	41	28
				0.50	48	48
Chopped Glass/Epoxy Composite	15	Quasi-Isotropic Type HM Graphite-Epoxy Composite	73	0	15	15
				0.05	31	21
				0.10	43	27
				0.20	65	38
				0.50	73	73



HYBRID SANDWICH STRUCTURE

curing graphite-glass hybrid polyester composites have been successfully made by ARMCO Corporation. Armco has prepared hybrids that contain continuous graphite filaments by a method similar to the one used in the preparation of standard sheet molding compound, and that can then be compression molded to form ACM components.

4.2 Materials Substitution Weight Reduction Analysis

Using the material properties of the various ACM listed in Table 7S and Table 8S, the relative weights of panel members, solid sections, thin walled beams, and thin wall tubes made from these materials were calculated for the various design criteria suggested by Chang and Justusson (1), and by Dharan (2). The results of the analysis for panel members are presented in Table 9S. As can be seen by examining this table, the weight limiting criterion for panel members was oil canning, except for HM and UHM graphite composites for which local buckling was the limiting criterion by a very small margin. The weight ratio needed to meet this limiting criterion results in a structure that is overdesigned in terms of all other criteria. For any composite, the relative weight of a steel equivalent composite part depends strongly on the fiber lay up geometry. The lowest weight ratios are obtained for unidirectional composites, and the highest for $\pm 45^{\circ}$ crossplied composites. Since panels are likely to be subjected to directional stresses, it would not be likely that unidirectional composites would be used in this application. In practice, these structures would most likely be made from multidirectional fiber composites. The relative weights of steel equivalent panels made from various quasi-isotropic composites, and aluminum, are given in Table 10. Depending on the modulus of the graphite fiber, weight ratios for graphite panels range from about 0.30 to 0.42. In comparison, weight ratios for fiber panels range from 0.69 to 0.78, depending on the properties of the glass. For comparable hybrid composites, the steel equivalent weight ratios are about 0.5 to 0.6 or in the range of the value of 0.58 obtained for aluminum. Comparable results

TABLE 9S- DIRECT SUBSTITUTION OF MATERIALS

WEIGHT RATIOS (RELATIVE TO STEEL) REQUIRED TO OBTAIN EQUAL STRUCTURAL CHARACTERISTICS FOR PANEL MEMBERS

MATERIALS	FIBER LAYUP GEOMETRY	EQUAL STIFFNESS OIL CANNING $\frac{Wc}{Ws} = \frac{\rho c}{\rho s}\left(\frac{Es}{Ec}\right)^{1/3}$	EQUAL DENTING RESISTANCE $\frac{Wc}{Ws} = \left(\frac{\rho c}{\rho s}\right)\left(\frac{Ec}{Es}\right)^{1/3}\left(\frac{\sigma ys}{\sigma yc}\right)$	EQUAL BUCKLING RESISTANCE (x) $\frac{Wc}{Ws} = \left(\frac{\rho c}{\rho s}\right)\left(\frac{Es}{Ec}\,\frac{1-\nu s^2}{1-\nu c^2}\right)^{1/3}$	EQUAL STRESS YIELD FACTOR $\frac{Wc}{Ws} = \left(\frac{\rho c}{\rho s}\right)\left(\frac{Ec}{Es}\right)^{1/3}\left(\frac{\sigma ys}{\sigma yc}\right)$	EQUAL VIBRATION FREQUENCY $\frac{Wc}{Ws} = \left(\frac{\rho c}{\rho s}\right)^2\left(\frac{Es}{Ec}\right)$
A Type Graphite Epoxy	Unidirectional (0^o)	0.245	0.045	0.229	0.045	0.060
	Crossply (0^o, 90^o)	0.335	0.059	0.282	0.059	0.112
	Crossply ($\pm45^o$)	0.694	0.173	0.358	0.173	0.482
	Isotropic (0^o, 90^o, $\pm45^o$)	0.415	0.066	0.325	0.066	0.172
	Harness Satin Weavecloth	0.365	0.098	0.299	0.098	0.133
HM Type Graphite Epoxy	Unidirectional (0^o)	0.197	0.072	0.200	0.072	0.039
	Crossply (0^o, 90^o)					
	Crossply ($\pm45^o$)	0.708	0.196	0.468	0.196	0.501
	Isotropic (0^o, 90^o, $\pm45^o$)	0.343	0.145	0.289	0.145	0.113
UHM Type Graphite/Epoxy	Unidirectional (0^o)	0.177	0.141	0.188	0.141	0.031
	Crossply (0^o, 90^o)	0.244	0.193	0.234	0.193	0.060
	Crossply ($\pm45^o$)	0.677	0.290	0.461	0.290	0.458
	Isotropic (0^o, 90^o, $\pm45^o$)	0.303	0.259	0.270	0.259	0.092
E-Glass/Epoxy	Unidirectional (0^o)	0.528	0.037	0.400	0.037	0.279
	Crossply (0^o, 90^o)	0.661	0.159	0.463	0.159	0.433
	Crossply ($\pm45^o$)	0.995		0.610		0.985
	Isotropic (0^o, 90^o, $\pm45^o$)	0.776	0.202	0.517	0.202	0.603
	Chopped Fiber	0.883	0.355	0.570	0.355	0.780
S-Glass/Epoxy	Unidirectional (0^o)	0.496	0.028	0.389	0.028	0.246
	Crossply (0^o, 90^o)	0.617		0.450		0.381
	Crossply ($\pm45^o$)	0.861		0.562		0.742
	Isotropic (0^o, 90^o, $\pm45^o$)	0.687		0.483		0.472
Kevlar/Epoxy	Unidirectional (0^o) (Composite)	0.396	0.157	0.302	0.157	0.156
	Crossply (0^o, 90^o)					
	Crossply ($\pm45^o$)	0.915	0.090	0.528	0.090	0.837
	Isotropic (0^o, 90^o, $\pm45^o$)					
	181 Fabric (Warp) (50%)	0.454	0.218	0.331	0.218	0.207
	Chopped Fiber (50%)	0.539	0.147	0.366	0.147	0.291
Aluminum 6061-T6		0.583	0.308	0.489	0.308	0.340
Steel, Cold Rolled (0.2% Carbon)		1.0	1.0	1.0	1.0	1.0

(x) Assume $\nu c = \nu s$

TABLE 10S

ESTIMATED WEIGHT SAVINGS FOR PANEL MEMBERS DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF EQUIVALENT PANEL	EQUIVALENT WEIGHT SAVING %
Type UHM Graphite/Epoxy Q.I. Composite	0.303	69.7
Type HM Graphite/Epoxy Q.I. Composite	0.343	65.7
Type A Graphite/Epoxy Q.I. Composite	0.415	50.5
S Glass/Epoxy Q.I. Composite	0.687	31.3
E Glass/Epoxy Q.I. Composite	0.776	22.4
Aluminum	0.583	41.7
Steel	1.0	0

obtained for thin beam structures and solid sections are presented in Tables 11 and 12. The weight ratios obtained for solid sections and thin walled beams are also controlled by the modulus ratio. However, the weight ratios obtained for solid sections are lower than for panels (i.e. greater weight reduction is obtained) because the modulus ratio has an exponent of 0.33 as compared to the 0.50 for this ratio for panels. The weight ratios obtained for thin walled beams are higher than for panels because the modulus ratio has an exponent of 1.0. In this case, weight reduction occurs only for those composites that have a modulus that approaches the modulus of steel. Substitution of low modulus composites, such as glass or Kevlar^{R} composites for steel would result in a weight increase.

It is useful to compare these calculated values of weight ratios to the weight ratios that are obtained when the weights of various prototype ACM components are compared to the weights of the comparable components made from steel.

In a well publicized program, the Ford Motor Company is currently building an experimental automobile that uses ACM, mainly graphite composites, to as great an extent as possible, while retaining the appearance and performance characteristics of the Ford Grenada, an intermediate size automobile. The relative weights of some comparable graphite and steel components which have been released by Ford are presented in Table 13S. Similar data on ACM components made by other manufacturers are presented in Table 14S.

The reported values of the weight ratio, W_c/W_s, for the Ford hood (0.38), the Ford door frame (0.42) and a Hercules hood are not significantly different than the calculated value of 0.42 obtained for a quasi-isotropic Type A graphite-epoxy composite. The Hercules Fiesta hood has a reported weight ratio of 0.25, which is much lower than the above values. This hood, however, is known to be made up of 2 plies of unidirectional HM over two plies of Type A graphite cloth built up over a nomex^{R} core. The effective flexure modulus of this assembly was estimated to be 155 GPa, or 86.4% of the modulus of steel. Assuming that the oil canning criterion governs

TABLE 11S

ESTIMATED WEIGHT REDUCTION FOR THIN BEAM MEMBERS DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF STEEL EQUIVALENT PANELS Wc/Ws UNIDIRECTIONAL LAMINATE	ISOTROPIC LAMINATE
Type A (High Strength) Graphite-Epoxy	0.30	0.86
Type HM Graphite-Epoxy	0.20	0.58
Type UHM Graphite-Epoxy	0.19	0.43
Kevlar 49 - Epoxy	0.89	
S-Glass - Epoxy	1.03	1.89
E-Glass - Epoxy	1.22	2.63
Aluminum	0.99	0.99

TABLE 12S

ESTIMATED WEIGHT REDUCTION FOR
SOLID MEMBERS DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF STEEL EQUIVALENT STRUCTURE Wc/Ws *	
	Unidirectional Laminate	Isotropic Laminate
Type A (High Strength) Graphite-Epoxy	0.23	0.33
Type HM Graphite - Epoxy	0.20	0.29
Type UHM Graphite - Epoxy	0.19	0.27
Kevlar 49 - Epoxy	0.30	0.40-0.45 (est.)
S-Glass - Epoxy	0.39	0.48
E-Glass - Epoxy	0.40	0.52
Aluminum	—0.74—	

* Based on bending stiffness, except for aluminum, for which fatigue strength is calculated to be the weight limiting criterion.

TABLE 13 S

FORD LIGHTWEIGHT VEHICLE PROGRAM
GRAPHITE COMPONENT WEIGHT SUMMARY

COMPONENT	COMPONENT WEIGHT, lbs.		REDUCTION lbs.	WEIGHT RATIO*
	STEEL	GRAPHITE COMPOSITE		
Hood	40.0	15.0	25.0	0.38
Door, R.H. Rear	30.25	12.65	17.60	0.42
Hinge, Upper L.H. Front	2.25	.47	1.78	0.21
Hinge, Lower L.H. Front	2.67	.77	1.90	0.29
Door Guard Beam	3.85	2.40	1.45	0.62
Suspension Arm, Front Upper	3.85	1.68	2.17	0.44
Suspension Arm, Front Lower	2.90	1.27	1.63	0.44
Transmission Support	2.35	.55	1.80	0.23
Driveshaft	17.40	12.00	5.40	0.69
Air Conditioning, Lateral Brace	9.50	3.25	6.25	0.34
Air Conditioning, Compressor Bracket	5.63	1.35	4.28	0.24

$$\text{*Weight ratio} = \frac{\text{Weight graphite composite component}}{\text{Weight steel components}}$$

SOURCE: FORD MOTOR COMPANY

Reference 19

TABLE 14 REPRESENTATIVE LDV COMPONENTS MADE WITH ACM

AREA OF APPLICATION	COMPONENT	COMPOSITE STRUCTURE	COMPONENT STEEL Ws	WEIGHT, lbs. COMPOSITE Wc	WEIGHT REDUCTION lbs.	WEIGHT RATIO Wc/Ws	SOURCE OF DATA
Body Structure	Hood, Fiesta	4-ply graphite: 2 unidirectional (HM) + 2 0/90 fabric layers with Nomex honeycomb core buildup	23.6	6.0	17.6	0.25	Hercules, 1978 SAE Exhibition
	Hood	Graphite - not otherwise specified	40	16	24	0.40	Hercules Brochure (4/78)
	Door Intrusion Beam	Graphite/aluminum honeycomb	17	7	10	0.41	D. Hiler Union Carbide 1977 SAE Exposition
	Bumper Beam, Fiesta	Pultruded graphite/glass hybrid composites	12 lbs. alum. ≃30 lbs. steel	7	23 (over steel)	0.23	Hercules 1978 SAE Exposition
Chassis and Suspension	Leaf Spring, Auxillary Light Duty Truck	High strength graphite/epoxy - constant cross section	16.2	4.8	11.4	0.30	Dharan - ICCM-2
	Leaf Spring, auto	Graphite/glass composite	28	5	23	0.18	D. Hiler Union Carbide - 1977 SAE Exposition
	Leaf Spring, auto	1 leaf - not specified	---	---	---	0.30	Graftek
	Leaf Spring, auto	Not specified	28	5.5	22.5	0.20	Hercules - 1978 SAE Exposition
	Transmission Support Bracket	Graphite/polyester, Compression Molded	20.5	4.7	15.3	0.23	Hercules - 1978 SAE Exposition
	Engine Support Bracket (Fiesta)	Unidirectional HM Graphite and Type A Graphite cloth	5.2	1.3	3.9	0.25	Hercules - 1978 SAE Exposition
	Air conditioner Support Bracket for 1980 Mustang	Continuous graphite/chopped glass polyester composite	7.0	1.9	5.1	0.27	R. Schmidt Great Lakes Carbon, Pers. Communication
	Air Conditioner Bracket	Graphite composite	12.0	2.5	9.5	0.21	Hercules 1978 SAE Exhibition
Power Train	Drive Shaft, (no yokes)	Graphite-epoxy	7.4	2.4	5.0	0.32	Dharan - ICCM-2
	Drive Shaft, auto	Graphite composite	12.6	6.5	6.1	0.52	Hercules - 1978 SAE Exhibition
	Drive Shaft, truck	Graphite composite	165	50	115	0.30	Hercules - 1978 SAE Exhibition
	Drive Shaft, light truck with fittings)	Graphite/glass composite	32.9	17.9	15	0.54	Shakespeare - 1978 SAE Exhibition
	Drive Shaft, 64 in. long (no fittings)	All graphite composite	15.7	5.3	10.4	0.34	Graftek - 1978 SAE Exhibition
		Aluminum + graphite composite	17.5	5.5 Aℓ +0.5 graphite	9.7	0.38	Graftek - 1978 SAE Exhibition
	Drive Shaft (with metal end fittings)	Graphite composite	22.6	9.5	13.1	0.42	
Engine Components	Push Rods	Graphite composite				0.30	Hercules Brochure

the design, a weight ratio of 0.23 is calculated. This value is only slightly lower than the number reported above.

The weight ratios of the lower door hinge (0.21), the bumper backup beam (0.23), air conditioner brackets (0.21 for a graphite composite and 0.27 for a continuous graphite/chopped glass hybrid) and a number of leaf springs (0.18 to 0.30) compare closely with the weight ratios that would be expected for a uni-axial composite solid section of HM graphite (0.20), Type A graphite (0.23) or hybrid structure (0.25-0.40).

The door guard beams, the suspension arms and the transmission supports reported in Tables 13 and 14 can be considered to be thin beam structures. The values reported for these components range widely from 0.23 for the transmission support to 0.62 for an intrusion beam. Since the fiber lay up in these structures is not public knowledge, it is not possible to calculate theoretical values of the weight ratios. Based on the reported values of the weight ratios, it is possible to speculate that the transmission support consists mainly of HM fiber. The weight ratio for the suspension arms (0.44) indicates the use of some cross-plying, or more likely, the use of a hybrid composite with a significant glass fiber content.

4.3 Weight Reduction Model

In general, the steel equivalent weight of a composite structure can be expressed by the following equation:

$$\frac{W_c}{W_s} = \frac{P_s}{P_c} \left(\frac{E_s}{E_c}\right)$$

where:

W_c = weight of the composite
P_c = density of the composite
E_c = modulus of the composite
m = geometrical factor.

W_s = weight of steel
P_s = density of steel
E_s = modulus of steel

The term $(E_{s/E_c})^m$ depends on system geometry with E_c and m varying with characteristics of the structure under consideration. E_c depends on the orientation of the fibers in the structure, which in turn is a function of the applied loads, which are in part controlled by system geometry. Based on Justusson and Chang's (2) theoretical analysis the factor m can vary between 0.33 and 1 depending on the structural shape. The factor m has a numerical value of 0.33 for a solid section, 0.50 for a panel, and 1 for a thin walled beam.

To simplify the analysis, the potential for weight reduction by materials substitution for any component was classified as being either high, medium or low depending on its geometry and on the presumed fiber lay up. A high potential for weight reduction was deemed to exist for thick components, such as a leaf spring, that could be treated as solid sections (m = 0.33) and where uni-directional composites could be used (E_c is high). A medium potential for weight reduction was deemed to exist for panel structures such as a hood, where oil canning would be the critical criterion (m = 0.50) and where cross-plied composites would be required (E_c is low). A low potential for weight reduction was considered to exist for thin beam structures, such as suspension support arms, especially those subjected to multidirectional stresses which would have to be cross plied.

The weight ratio will also depend on the composition of the particular composite under consideration. The weight ratios for various continuous fiber composites with a 60% by volume fiber content, for the different cases, are presented in Table 15S. weight ratios for aluminum are also presented in this table. It is to be noted that the weight ratio for aluminum for H case is determined by fatigue, and not by the stiffness criterion used for the fibrous composites.

4.4 Value of Weight Reduction

Removing one pound of steel from a vehicle, without materials substitution, results in a total weight reduction of 1.4 lbs due to weight propagation. At the manufacturing level, this weight

TABLE 15S

ASSUMED VALUES OF WEIGHT RATIOS OF EQUIVALENT STRUCTURES
FOR VARIOUS SUBSTITUTION MATERIALS OF INTEREST

$$\frac{W_c}{W_s} = \frac{c}{s} \left(\frac{E_s}{E_c} \right)^m$$

CASE GEOMETRY m	High (H) Solid Section 0.33	Medium (M) Panel 0.50	Low (L) Thin Wall Beam 1.00
MATERIAL	NOMINAL WEIGHT RATIO, W_c/W_s		
HM GRAPHITE COMPOSITE	0.20	0.30	0.40
HS GRAPHITE COMPOSITE (TYPE A)	0.25	0.35	0.60
GLASS FIBER COMPOSITE	0.40	0.75	1.90
HYBRID COMPOSITES (HM GRAPHITE/GLASS)			
10/90	0.35	0.60	1.50
20/80	0.30	0.50	1.20
40/60	0.25	0.40	0.90
ALUMINUM	0.74(*)	0.60	1.00
STEEL	1.00	1.00	1.00

(*) Fatigue Limiting

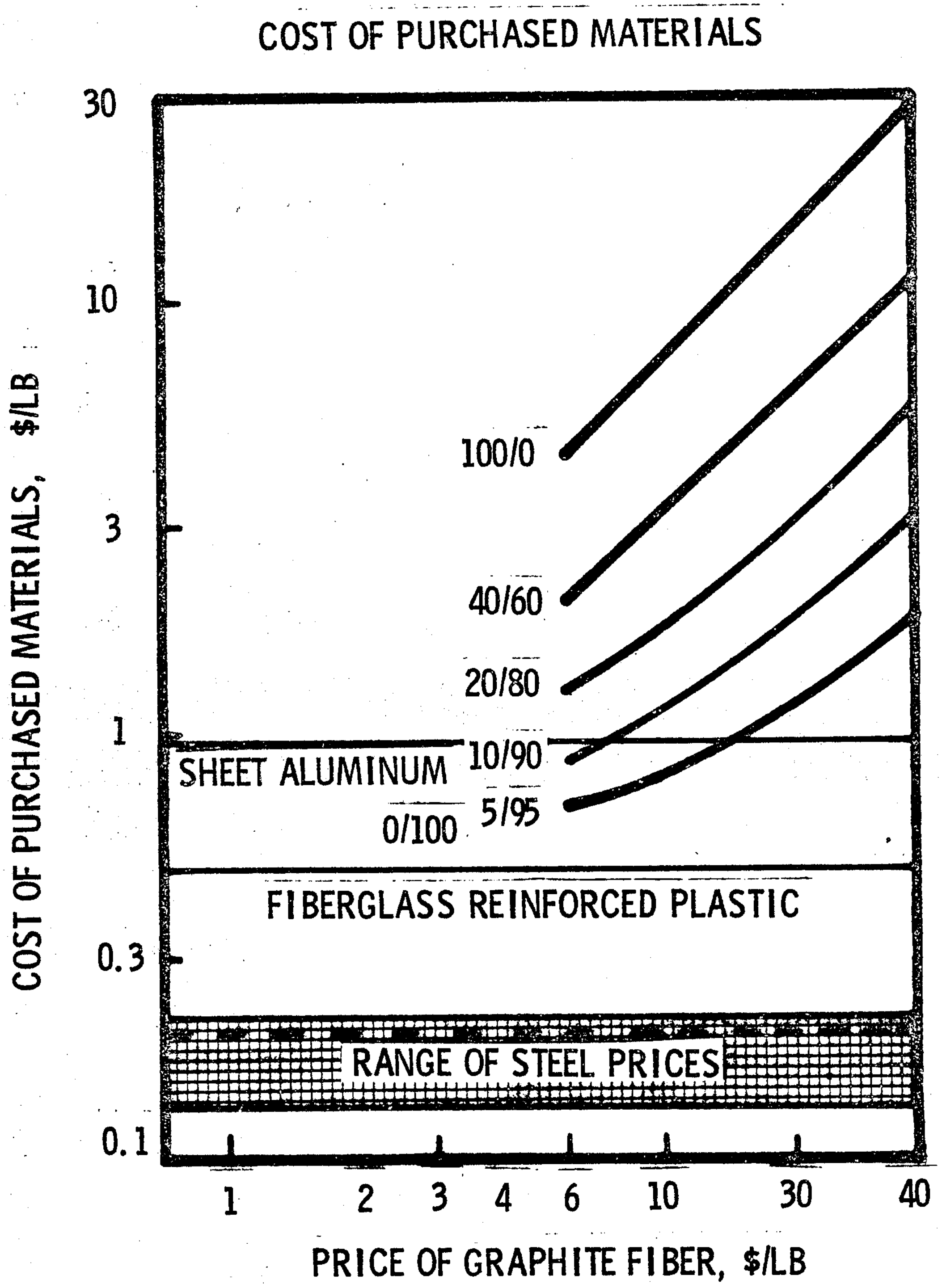


Figure 2S- Cost of Purchased Materials including Hybrid Composites as a Function of the Price of Graphite Fiber and the Graphite Fiber to Glass Fiber Ratio reduction is worth \$0.44, 20¢ for the pound of steel removed, and 24¢ for the 0.4 lbs of propagated materials.

At the wholesale price level, because of the CAFE credit, this weight reduction has an additional value of \$1.05 for a gasoline engine vehicle, and of \$0.45 for a diesel engine vehicle. The total difference of \$1.49 for a gasoline vehicle, and of \$0.93 for a diesel engine vehicle represents the total value of weight reduction to an auto manufacturer. It is to be noted that because of the better fuel economy obtained with a diesel engine, weight reduction is less valuable for diesel than for a gasoline engine vehicle.

These values are 22% higher at the retail price level which includes the dealer mark-up. At this level, removing one pound of steel has a value of \$1.82 for a gasoline engine vehicle, and of \$1.13 for a diesel vehicle.

The difference in the values of weight reduction for the types of vehicles is further accentuated on the basis of life cycle costs. Removing one pound of steel results in reduced lifetime fuel costs of \$1.05 for a gasoline engine vehicle and of \$0.56 for a diesel engine vehicle. Therefore, the total value on a life cycle basis of removing one pound of steel from a vehicle is \$2.87 for a gasoline engine vehicle and \$1.69 for a diesel engine vehicle.

4.5 Economic Impact of Materials Substitution

The economic impact of materials substitution was obtained by comparing the relative costs, per unit weight of steel replaced, of replacing steel by the various materials listed in Table 15S. The calculations were performed for each of the three cases (high, medium, low) outlined in Table 15S which have different values of functionally equivalent weight ratios. The analysis was not performed for those cases where materials substitution results in a weight ratio larger than one, and a corresponding weight increase.

The purchased costs of materials used are given in Figure 2S. An average purchase price of \$0.20/lb was assumed for steel. The current price of \$0.95/lb for 6061 aluminum sheets was used as the representative price for this material. The costs of the fibrous composites are based on a total fiber content of 60% by volume, a resin price of \$0.40/lb, and assume no compounding charges for the preparation of the composite from the fiber and resin. A price of \$0.50/lb was used for fibrous glass. The price of graphite fiber was considered a variable parameter. Cost calculations were based on assumed graphite fiber prices of \$10/lb, the highest price which the automotive industry would pay for this material, and of \$6/lb, a reasonable lower limit for the price of this material in mass production. This price range is significantly lower than the current graphite fiber price range of \$18/lb to \$50/lb or even more for specialty grades.

The results are presented in Tables 16S and 17S. In Table 16S, the comparisons are based on an assumed graphite fiber price of \$10/lb. In Table 17S, a price of \$6/lb was used for graphite fiber.

4.6 Changes in Manufacturing Costs

Even at a price of \$6/lb, all graphite composites are significantly more expensive than steel on a per pound of steel replaced basis. Depending on the type of component and of fiber, a cost increase of \$0.45/lb to \$2.23/lb would result from the use of graphite at this price. At \$10/lb graphite fiber, the cost increases will be about twice as high.

Fiber glass composites (assumed to be continuous fiber) are the only materials that would result in both weight reduction and lowered manufacturing costs, at least for solid sections (H case). Hybridization with HM graphite results in composites that have lower weight ratios, but are more expensive than all glass fiber composites. The increase in costs are minor for 10/90 and 20/80 hybrids, but they become significant for 40/60 hybrids. These hybrids, in the case of thin wall beams (L case) are even more expensive than the all HM graphite composites because of their low weight ratios. With \$6/lb graphite fiber, unidirectional hybrids are competitive with steel in terms of manufacturing

TABLE 16S

AUTOMOB LE COST/PRICE CHANGES DUE TO MATERIALS SUBSTITUTION (Graphite Fiber = $10/LB)

Material	Case	Weight Ratio	Change in Manufacturing Costs $/LB*	Gasoline Engine Vehicle: Change in Retail Price $/LB*	Gasoline Engine Vehicle: Change in Life Cycle Costs $/LB*	Diesel Engine Vehicle: Change in Retail Price $/LB*	Diesel Engine Vehicle: Change in Life Cycle Costs $/LB*
HM Graphite Composite	High	0.20	1.00	0.51	(0.32)	0.89	0.45
	Medium	0.30	1.72	1.57	0.84	1.91	1.52
	Low	0.40	2.43	2.62	2.00	2.90	2.57
Type A Graphite Composite	High	0.30	1.36	1.09	0.36	1.43	1.04
	Medium	0.35	2.07	2.08	1.40	2.40	2.04
	Low	0.40	3.86	4.73	4.31	4.91	4.69
E Glass Fiber Composite	High	0.40	(0.15)	(0.81)	(1.43)	(0.53)	(0.86)
	Medium	0.75	0.10	(0.12)	(0.38)	0.00	(0.13)
	Low	1.90	weight gain				
HM Graphite/Glass Hybrids 10/90	High	0.35	0.04	(0.62)	(1.30)	(0.30)	(0.66)
	Medium	0.60	0.38	0.10	(0.32)	0.29	0.07
	Low	1.50	weight gain				
20/80	High	0.30	0.17	(0.49)	(1.22)	(0.15)	(0.54)
	Medium	0.50	0.57	0.25	(0.27)	0.49	0.21
	Low	1.20	weight gain				
40/60	High	0.25	0.39	(0.25)	(1.03)	0.10	(0.31)
	Medium	0.40	0.88	0.56	(0.06)	0.75	0.42
	Low	0.90	2.53	3.27	3.17	3.32	3.27
Aluminum	High	0.74	0.44	0.32	0.05	0.36	0.22
	Medium	0.60	0.27	(0.04)	(0.46)	0.14	(0.08)
	Low	1.00	0.75	1.00	1.00	1.00	1.00
Steel		1.0	0	0	0	0	0

*Per pound of Steel Replaced

TABLE 17 S

AUTOMOTIVE COST/PRICE CHANGES DUE TO MATERIALS SUBSTITUTION (Graphite Fiber = $6/LB)

Material	Case	Weight Ratio	Change in Manufacturing Cost $/LB*	Gasoline Engine Vehicle: Change in Retail Price $/LB*	Gasoline Engine Vehicle: Change in Life Cycle Costs $/LB*	Diesel Engine Vehicle: Change in Retail Price $/LB*	Diesel Engine Vehicle: Change in Life Cycle Costs $/LB*
HM Graphite Composite	High	0.20	0.45	(0.22)	(1.05)	0.16	(0.28)
	Medium	0.30	0.90	0.48	(0.25)	0.82	0.43
	Low	0.40	1.34	1.17	0.55	1.45	1.12
Type A Graphite Composite	High	0.30	0.67	0.17	(0.56)	0.51	0.12
	Medium	0.35	1.12	0.82	0.14	1.14	0.78
	Low	0.60	2.23	2.56	2.14	2.75	2.53
E Glass Fiber Composite	High	0.40	(0.15)	(0.81)	(1.43)	(0.53)	(0.86)
	Medium	0.75	0.10	(0.12)	(0.38)	0.00	(0.13)
	Low	1.90	weight gain				
HM Graphite/Glass Hybrids 10/90	High	0.35	(0.05)	(0.74)	(1.42)	(0.42)	(0.78)
	Medium	0.60	0.21	(0.12)	(0.54)	0.06	(0.16)
	Low	1.50	weight gain				
20/80	High	0.30	0.00	(0.72)	(1.45)	(0.38)	(0.77)
	Medium	0.50	0.29	(0.13)	(0.65)	0.12	(0.16)
	Low	1.20	weight gain				
40/60	High	0.25	0.11	(0.62)	(1.40)	(0.27)	(0.68)
	Medium	0.40	0.45	(0.01)	(0.63)	0.27	(0.06)
	Low	0.90	1.55	1.96	1.86	2.01	1.96
Aluminum	High	0.74	0.44	0.32	0.05	0.36	0.22
	Medium	0.60	0.27	(0.04)	(0.46)	0.14	(0.08)
	Low	1.00	0.75	1.00	1.00	1.00	1.00
Steel		1.0	0	0	0	0	0

* Per pound of Steel Replaced

costs. Aluminum is more expensive than steel in all cases. Aluminum is also more expensive than 40/60 hybrid composites in H type components even at a graphite price of $10/lb. At this price for graphite panel members (M type components), aluminum is less expensive than even a 10/90 hybrid composite. However, at $6/lb for graphite, the 10/90 hybrids are less expensive than aluminum, while the 20/80 are competitive.

4.7 Changes in Retail Price

Materials substitution will have a different impact on the retail prices of gasoline and diesel vehicles because the lower values of weight reduction for the latter in terms of CAFE credits, as discussed in a prior section. The present discussion will limit itself to the gasoline case for which weight reduction has more value.

Unidirectional fiberglass composites in H components result in the greatest cost reduction, and a very significant weight reduction as well. Greater weight reduction can be obtained by using unidirectional graphite glass hybrids of increasing graphite content, but at an increasing vehicle price. At $10/lb, the hybrids in H applications are competitive with steel, while the all graphite composites are more expensive. At $6/lb for graphite, HM graphite composites can be less expensive than steel in these applications. Aluminum is more expensive than the fiberglass and high glass content hybrids.

For panel applications (M type components), isotropic fiberglass composites which could result in a 25% weight reduction, would be about $0.12/lb less than steel. Aluminum, which would result in a 40% weight reduction, would be about $0.04/lb less expensive than steel. At a $10/lb graphite fiber price, all the graphite fiber containing composites would be more expensive than steel. At a $6/lb graphite fiber price, 10/90 and 20/80 hybrids result in the same vehicle price as fiberglass composites, while offering significantly more weight reduction potential. The 40/60 hybrids, which would offer a 60% weight reduction potential, would be competitive with steel.

The all graphite composites, which would offer a weight reduction potential of 65%-75%, would increase the vehicle price about $0.50-$0.80 per pound of steel removed.

The use of graphite composites in thin beam components would result in a significant price increase, as would 40/60 hybrids, which offer little weight savings.

4.8 Changes in Life Cycle Costs

The differences noted above between gasoline and diesel engine vehicles become even greater when life cycle costs are included because of the differences in the amounts of fuel consumed. Material substitution has impact on the life costs of a gasoline engine vehicle.

Using unidirectional E glass composites in H type applications results in the greatest reduction in life cycle costs per pound of steel replaced. At $10/lb for graphite fiber, life cycle costs are only slightly higher for 10/90 and 20/80 composites than for glass composites. These costs increase with increasing graphite content, but even an all HM graphite composite is less expensive than steel in these applications. At a graphite fiber price of $6/lb, 20/80 graphite hybrids appear to result in slightly lower costs than even the fiber glass composites. In fact, there is very little difference between all fiber glass composites and even the 40/60 hybrid composites on a life cycle cost bases in H applications. All graphite composites would be intermediate to the hybrids and steel in terms of life cycle costs. In comparison, aluminum would be more expensive than steel.

For panel applications (M type components), at a graphite fiber price of $10/lb, aluminum results in the lowest life cycle costs. It is slightly less expensive than glass composites for gasoline engine vehicles (the reverse applies for diesel engine vehicles in this instance). However, at a graphite fiber price of $6/lb, 20/80 graphite/glass hybrids are the least expensive material. The differences between 10/90, 20/80, and 40/60 hybrids are however small. All HM graphite hybrids are more expensive than these hybrids, but less expensive than steel. A type graphite hybrids remain more expensive than steel.

For thin beam components (low weight reduction potential) the use of all graphite composites remains more expensive than steel, even at a graphite fiber price of $6/lb. It is to be noted that the 40/60 hybrids are more costly than all the all graphite composites because of the relatively low weight reduction engendered by these hybrids. In these applications, aluminum results in no weight savings, so its use would increase life cycle costs.

<u>General Discussion</u>

Based on the results presented in Tables 16S and 17S, it is clear that the type of fibrous composites that would be used in automotive applications depends on the type of application and the cost of graphite fiber.

Fibrous composites can be used most effectively in H type components where largely unidirectional composites can be used. In these applications, fiberglass composites are very attractive, and appear to offer both weight and cost reductions. However, there is an increase in weight reduction with little cost penalty if low graphite content hybrids are used, especially at $6/lb for the graphite fiber. The use of high graphite content hybrids or all graphite composites does not appear to be warranted. There is a significant increase in costs with only a slight weight reduction. Aluminum does not appear to be a very attractive material for these applications.

In contrast, at a graphite fiber price of $10/lb, aluminum appears to be a very attractive material for panels (M type components It would compete with fiberglass composites which offer slightly less weight reduction potential. However, at a graphite fiber price of $6/lb, 20/80 graphite/glass hybrids appear to offer the best cost/ weight reduction combination and would tend to displace all glass composites or aluminum.

None of the materials considered appeared to be likely to displace steel in thin wall beam components (L type components). In these applications, only high graphite content hybrids and all graphit composites offer any weight saving potential. However, use of these materials in these applications results in significant cost and price increases, even at a graphite fiber price of $6/lb.

A point to be made is that these conclusions assume no change in design or shape of the part. A part design optimized for steel may not be necessarily the optimum design for another material. A slight change in configuration could result in a comparison that would be more favorable to composites. These calculations are, therefore, very conservative estimates of the potential benefits that could be derived from materials substitution with ACM.

4.9 Use of ACM in a Model LTV

The weight reduction potential of ACM in a model automobile is illustrated in Table 18. After examining the component breakdown of a 1975 Chevelle, a number of components were identified as candidates for materials substitution. Table 18 presents the list of these candidate components. ACM prototypes of these components, or very similar components have been built and tested, as discussed in prior sections of this report. This list contains most of the structural elements of the body, and of the chassis that operate at ambient conditions. The only components listed in this table for which no supporting data were found are the road wheels and the coiled suspension springs. As far as the road wheels are concerned, there is a significant amount of work being performed on the design and fabrication of fiberglass and graphite fiber composite wheels (20,21). While the composite wheels that have been made to date are less than completely satisfactory, it is not unlikely that such wheels will be in use in the not too distant future. The assumption that coil springs could be made from ACM is purely speculative at the present time. The model vehicle unfortunately does not have leaf springs, which appear to be a very attractive use of ACM, so it was assumed that coil springs could be made from ACM in order to include an ACM suspension member.

Table 18S also presents the current weights of the components reported by Pioneer (9). For many of the components, it was evident

TABLE 18 S

WEIGHT REDUCTION BY ACM SUBSTITUTION OF STEEL AUTOMOTIVE COMPONENTS

COMPONENTS		TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT 20-80% HYBRID COMPOSITE COMPONENTS, LBS. I	II
Body in White							
Underbody		148	140	M	42		70
Windshield Cowl & Dash		97	80	L	32		
Quarter Panels		173	150	L	60		
Deck Opening		42	30	L	12		
Roof		62	60	M	18		30
Doors Front (2 ea)	Panels & Reinforcements	104	104	M	31		52
	Rails	28	28	L	11		
	Impact Rails	13	13	L	5		
	Hinges	12	12	H	3	4	4
	Other	30	---	-	--		
Deck Lid Assembly		30	28	M	9		14
Front Fender Assembly		93	76	L	30		
Hood Assembly		70	70	M	21		
Hood Hinge & Latch Assemblies		14	10	H	2	3	3
Radiator Supports & Brackets		39	39	H	8	12	12
Miscellaneous Supports & Brackets		6	6	H	1	2	2
Sub Total - Body in White		961	846		285	21	187

Notes:

Reference Vehicle : 1975 Chevelle 2 door Sedan, as per Ref. 9

Weight Reduction Assumes Substitution is Based on Stiffness Criterion

H = High Weight Reduction Potential with Unidirectional Fiber Layup and m= 0.33

M = Medium Weight Reduction Potential with Isotropic Fiber Layup and m= 0.50

L = Low Weight Reduction Potential with Isotropic Fiber Layup and m= 1.0

m = Exponent on modulus ratio

TABLE 18 S Cont.

COMPONENT	TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS.	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT 20-80% HYBRID COMPOSITE COMPONENTS, LBS. I	II
Chassis						
Frame Assembly	290	280	L	112		
Engine Rear Cross Member Assembly	27	27	H	5	8	8
Engine Supports	6	6	H	1	2	2
Front Suspension						
Upper Control Arm	19	19	L	8		
Lower Control Arm	33	33	L	13		
Coil Springs	25	25	L	10		
Rear Suspension						
Upper Control Arm	6	6	L	2		
Lower Control Arm	10	10	L	4		
Coil Springs	15	15	L	6		
Anti Sway Bar	13	13	M	4		6
Road Wheels (5 ea)	115	115	M	35		58
Sub total	559	549		200	10	74

TABLE 18.S Cont.

COMPONENT	TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT HYBRID COMPOSITE COMPONENT, LBS. I	II
Interior						
Front Seat Frame	44	34	H	7	10	10
Sub Total	44	34		7	10	10
Final Drive						
Propulsion Shaft	16	16	L	6		
Sub Total	16	16		6		
Bumpers						
Front Bumper	107	107	M	32		53
Rear Bumper	91	91	M	27		46
Sub Total	198	198		59		99
Total of Above	1778	1643		557	41	370
Current Curb Weight	3643					
Direct Weight Reduction due to Composition Substitution, lbs.				1086	96	425
Indirect Weight Reduction (0.4 Δ W)				434	38	170
Total Weight Reduction				1520	134	595
Curb Weight Composite Equivalent Auto				2123	3509	3048

that a small fraction of the current component weight could not be replaced by ACM. This weight included low density non-metallics, or steel inserts or fasteners, that would also be required in the ACM replacement component. The weight of these components was substracted from the total component weight in order to obtain the weight of steel subject to materials substitution.

The various components were then classified as having either a high, medium or low weight substitution factor, using the terminology of Table 15S. This ranking is also presented in Table 18S.

4.10 Three Case Analyses

In the first case, it was assumed that maximum use would be made of HM graphite composites in order to obtain the greatest possible amount of weight reduction. HM graphite composites are the highest modulus material that the automotive industry would be likely to use. In this scenario it was assumed that all components listed in Table 18S would be made of HM graphite composite. The weight ratios used for the H, M and L structures with this composite are those given in Table 15S. In the second case, it was assumed that only H type components, which offer maximum weight saving, would be made from a 20/80 HM graphite-glass composite. In the third case, it was assumed that both H and M components would be made from the 20/80 hybrid composite.

4.10.1 Case 1: All Graphite Composite Substitution

If all the components identified in Table 18S are made with graphite composites, 547 lb (248 kg) of HM composite replace 1643 lb (746 kg) of steel, for a direct weight reduction of 1086 lb (493 kg). Secondary weight reduction that would accrue as a result is estimated to be 434 lb (197 kg). The total reduction in vehicle weight is 1520 lb (690 kg). The graphite equivalent vehicle has a curb weight of 2123 lb (964 kg), or 58% of the curb weight of 3643 lb (1654 kg) of the base vehicle. These weight levels are in general agreement with the relative weights of a standard Ford Granada, which has a curb weight of 3767 lb (1800 kg) and of the projected weight of 2517 lb (1143 kg) for the "graphite" light weight vehicle that will be exhibited at the 1979 SAE meeting in Detroit, Michigan.

TABLE 19 S

IMPACT OF ACM SUBSTITUTION FOR STEEL ON THE CHARACTERISTICS OF A REFERENCE LTV (1975 CHEVELLE WITH A GASOLINE ENGINE)

ACM Assumed	HM Graphite Composite	HM Graphite/ Glass Hybrid (20/80)	HM Graphite/ Glass Hybrid (20/80)
Extent of substitution	H,M,L, components	H components only	H & M components
Test weight (lb)			
Original vehicle,	3943	3943	3943
Modified vehicle,	2423	3809	3348
Difference,	(1520)	(134)	(495)
Fuel Economy (mpg)			
Original vehicle	16.9	16.9	16.9
Modified vehicle	25.9	17.4	19.5
Difference	9.0	0.5	2.6
Lifetime Fuel Consumption* (gallons)			
Original vehicle	5910	5910	5910
Modified vehicle	3860	5750	5130
Difference	(2050)	(160)	(780)

*for 100,000 miles of use

The fuel economies of the 1975 Chevelle and of the equivalent vehicle were estimated from their test weights (curb weight + 300 lbs) by Equation 3. These results are presented in Table 19S. This extensive weight reduction results in a fuel economy improvement of 9 mpg which corresponds to a reduction in fuel consumption of 2050 gallons over the lifetime of the vehicle.

The economic impacts of this substitution are summarized in the first columns of Table 20S. Even at a graphite fiber price of $6/lb, the cost of the composites used would be higher than the current total purchased materials cost for a 1978 automobile. Extensive graphite substitution results in a total purchased materials cost increase of $1756/vehicle. This value overshadows the decrease in penalty accrued from the improved fuel economy of $450 for 9 mpg. Even after taking into account the NPV of reduced fuel expenses, the graphite vehicles would cost abour $680 more than the original vehicle on a life cycle basis. At a graphite price of $10/lb, the life cycle cost difference is about $2700, or four times as much.

4.10.2 Case 2: Selective Substitution with a Unidirectional Hybrid Composite

In this case the selective substitution of H type components with a 20/80 hybrid composite is analyzed, to present the most favorable situation for the use of graphite fiber containing composites. In this instance, materials substitution is limited to seven components in which 41 lbs (18 kg) of 20/80 hybrid composite replace 137 lb (62 kg) of steel, for a direct weight reduction of 96 (44 kg). Taking into account a secondary weight reduction of 38 lb (17 kg), a total weight reduction of 134 lb (61 kg), is obtained. This corresponds to a curb weight reduction of 3.7%. As shown in Table 19 S, this weight saving results in a fuel economy improvement of 0.5 mpg, and a reduced lifetime fuel consumption of 160 gallons.

The cost/price changes resulting from this substitution are given in Table 20S. At a graphite fiber price of $10/lb, this substitution results in an increase in purchased materials costs of $23, which is slightly less than an offsetting CAFE credit of $25.

TABLE 20 S

Impact of ACM Substitutions for Steel on the Cost/Price of a Reference LTV (1975 Chevelle with a gasoline engine)

ACM Assumed	HM Graphite Composite		HM Graphite/ Glass Hybrid (20/80)		HM Graphite/ Glass Hybrid (20/80)	
Extent of Substitution	H,M,L, Components		H Components Only		H+M Components	
Price of Graphite Fibers,$/lb	10	6	10	6	10	6
Cost of Composites Used, $	3860	2345	73	50	655	451
Value of Steel Replaced, $	(329)	(329)	(27)	(27)	(159)	(159)
Value of Propagated Materials,$	(260)	(260)	(23)	(23)	(102)	(102)
Net change in Materials Costs,$	3271	1756	23	0	394	261
Equivalent Change in Wholesale Price, $	3565	1914	25	0	429	284
CAFE Credit @ $50/mpg, $	(450)	(450)	(25)	(25)	(130)	(130)
Net Change in Wholesale Price,$	3115	1464	0	(25)	299	154
Equivalent Change in Retail Price, $	3800	1786	0	(31)	365	188
NPV of Reduced Fuel, $	(1108)	(1108)	(87)	(87)	(424)	(424)
Net Change in Life Cycle Costs,$	2692	678	(87)	(118)	(59)	(236)

At the retail price level, the vehicles are competitive. However, the composite containing vehicle is less expensive than the original on a lifecycle basis because it consumes less fuel. At a graphite fiber price of $6/lb, the composite materials are cost competitive with steel. Once the CAFE credit and reduced fuel consumption are taken into account, the composite containing vehicles cost the consumer less, both in terms of purchase price and operating costs.

4.10.3 Case 3: Substitution with Hubrid Composites

In this case, the components that would be made from a 20/80 hybrid composite include M type components (panels) in addition to the H type components considered in Case 2. This case considers all the components where the replacement of steel by a hybrid composite would result in a significant degree of weight reduction.

In this case, 370 lb (168 kg) of 20/80 hybrid composite replace 795 lb (361 kg) of steel in fifteen components, for a direct weight reduction of 425 lb (193 kg). Taking into account a secondary weight reduction of 170 lb (77 kg), a total weight reduction of 595 lb (270 kg) is obtained. This corresponds to a reduction of 16% of the original vehicle curb weight. As shown in Table 19S, this weight saving results in a fuel economy improvement of 2.6 mpg, and a reduced lifetime fuel consumption of 780 gallons.

The cost/price changes resulting from the substitution are also given in Table 20S.

More extensive use of hybrid composites results in increases in materials costs of $394 ($10/lb graphite fiber) to $261 ($6/lb graphite fiber), and in retail prices of $365 ($10/lb graphite fiber) to $188 ($6/lb graphite fiber). However, life cycle costs would decrease by $59 ($10/lb graphite fiber) to $236 ($6/lb graphite fiber).

General Discussion

The above results indicate that it will be very unlikely that a production automobile will ever be made that will contain extensive amounts of all graphite fiber composites. Even at $6/lb, they are too expensive to use effectively. This statement does not imply that graphite fibers will not be found on production vehicles. On the contrary, it is quite likely that graphite/glass hybrids would be used extensively if the cost of the graphite fiber were $10/lb or lower. Based on the costs presented in Table 20S, it is quite likely that hybrid composites would be used on a fleet-wide basis in a variety of H type components. In these applications, ACM would be cost competitive with steel at the manufacturing level.

The increase in retail price resulting from the use of 20/80 hybrids in M type components makes it unlikely that these hybrids would be used in all vehicles, especially the less expensive, smaller models. However, materials substitution allows the manufacturer to make a large, relatively light weight vehicle by using a hybrid composite, that is less expensive than a heavier steel vehicle on a life cycle basis. As previously noted, aluminum and fiberglass are less costly than 20/80 hybrids in panel applications at a graphite fiber price of $10/lb, but that the converse would hold if the price of graphite were $6/lb. Case II then represents the potential applications of hybrids at a graphite fiber cost of $10/lb, while case III represents the potential applications of hybrids at an assumed graphite fiber cost of $6/lb.

A limitation of the calculations presented in this section is that they are based on a heavy vehicle of obsolete design. The absolute values of weight reduction presented in Table 18S are likely to be higher than the values that would be obtained if the same analysis were to be performed on a more modern vehicle that was redesigned for weight reduction. However, the relative weights of a modern steel automobile and of the equivalent ACM vehicle would be about the same as those found for the 1975 Chevelle and ACM equivalent vehicle in this study. As already mentioned a number of times, further weight reductions, and possibly cost reductions, would be achieved with a total vehicle redesign that would take into account all the properties of ACM.

5.0 PROBLEMS AND ISSUES

A number of problems and issues have to be addressed and solved in order for advanced composite materials to be considered as materials of construction for production automobiles. These include:

a) Cost of raw materials. At current prices, advanced composites are prohibitively expensive for nearly all automotive uses. Specific applications would become attractive at graphite filament prices of less than $10/lb., and many applications could be considered if filament price dropped to $6/lb.

b) Manufacturing. Most of the experimental advanced composite automotive components have been made with all graphite composites formed by aerospace fabrication techniques that are too expensive and too slow to be considered for high volume automotive applications. It will be necessary to adapt, and improve upon, existing fiberglass reinforced plastic manufacturing technology to the manufacture of hybrid composites. The conductivity of graphite filaments will require that provisions be made for containing these fibers during shipping, storage, and manufacture of composite structures. There may also be some assembling problems with fibrous composites. Fibrous composites do not yield as metals do, and therefore, cannot be pounded into place. This may require large automotive structures to be fabricated to much closer tolerances.

c) Durability. There has been no demonstration that ACM components can survive 50,000 miles (80,000 km) of actual automotive use, over an extended period of years.

d) Damageability and Crashworthiness. The failure mode of fibrous composites, which are brittle materials is very different from the failure of metals which can yield. Composites are less likely to deform under light loads than metals, but could shatter and form jagged edges upon severe impact in some cases, or simply delaminate in other instances.

e) Repair Upon Damage. The ability of being able to repair major structural components made of any reinforced plastic is an open issue. It would be desirable to be able to repair rather than replace large components.

f) Noise Vibrations and Handling. The road handling characteristics of a large, low weight automobile are not known at the moment and it may be necessary to include load leveling provisions into the design of an automobile if the maximum payload becomes a significant fraction of the gross vehicle weight.

g) Recycling. Reinforced thermosetting resins can not be economically recycled at the moment, so that land fill of scrap advanced composite parts is the only current available option.

h) Graphite Fiber Release. The uncontrolled release of graphite fibers or lint from burning graphite-organic matrix composites is a problem of current concern. Graphite fibers are less flammable than organic matrices, such as an epoxy resin. The matrix can be preferentially consumed in a burning composite, resulting in the formation of an uncontained graphite fiber skeleton, from which fibers can break off and diffuse. This diffusion problem can be compounded if the fire is accompanied by an explosion.

With the emerging interest in the use of graphite fiber reinforced plastics in non-military applications, an interagency task force, under the technical leadership of NASA, has been established to examine the ramifications of this problem. Until recently the topic was classified, and much of the test data obtained by the military agencies are not, as of yet (7/78), available to the public. At the moment, there are insufficient data to arrive at any valid conclusion, and it is possible only to speculate as to the severity of the problem, especially for fiberglass hybrid composites where fusing the glass could result in a coherent mass.

6.0 PROJECTED FUTURE ACTIVITIES AND USES

Future development work will address itself to these issues. Current costs are not a major consideration because of the leverage of the automotive industry. The average use of only 1 lb. of graphite filament per automobile will create a demand for 10 million lbs. of graphite a year. At this level, graphite could be sold for less than $10/lb. The cost of graphite would be further diluted by extensive use of hybrid composites.

Developments over the next few years will focus on manufacturing technology and proof testing of selected components in actual service. One or two selected advanced composite components will be introduced by the major manufacturers in a limited production automobile or light truck in model year 1980. The first production use of advanced composites will most probably be an air conditioner support bracket for the Ford 2.3 liter engine which will be used on vehicles such as the Mustang. This part will most likely be made by Armco Composites of St. Charles, Illinois by compression molding of a modified polyester sheet molding compound. The UMC™ sheet will contain continuous graphite fiber reinforcement in addition to chopped glass. Great Lakes Carbon Company will most likely be the graphite fiber supplier. Based on a test production run of 1,000 brackets which will weigh 2.5 lbs. and contain approximately 20% graphite by weight, approximately 500 lbs. of graphite fiber will be required for this program. This is a conservative approach to introducing a new material in that the support bracket is a non-safety critical part that can be easily removed if it does function properly in service.

Both Chrysler Corporation and General Motors Corporation will have test programs under way in Model Year 1980 or Model Year 1981. Chrysler activities are focused on an unspecified bracket as well.

It is quite likely that the first production use of advanced composites by General Motors Corporation will be on the Chevrolet Corvette.

Over the next few model years, additional advanced composite parts will be introduced for service evaluation if no difficulties are encountered in the first series. Most of these parts will be structural parts that will weigh less than 5 lbs. (2.3 kg). A graphite reinforced hood or deck lid may be included to evaluate an external painted part. By 1985, there may be as many as 10 different parts in service. Assuming an average weight of 3 lbs. per part, a 10% graphite content, and an average of two test parts on 10% of the vehicles produced, the production of 10 million autos would result in a demand of 600,000 lbs. (273 metric tons) of graphite fiber.

Advanced composites usage in automobiles beyond 1985 will depend mainly on CAFE requirements imposed on the manufacturers. If these do not become much more stringent than 27.5 mpg, (i.e., less than 30 mpg) use of advanced composites will remain limited to brackets; hinges and a variety of similar small parts that will find general application, and to larger components for selected automobiles. By 1990, the combined weight of the small (H type) components in an average car could be as much as 40 lbs. Again, assuming a 10 million car/year production rate and a 10% graphite content, a graphite fiber consumption of 40 million lbs/year is envisioned.

Advanced composites will also be used to transfer automobiles from one inertia weight category to a lower one. For example, currently for EPA test purposes all automobiles that have an actual inertia weight (curb weight + 300 lbs.) of 2751 lbs. to 3250 lbs. are grouped in the 3000 lbs. inertia weight class; those that have an inertia weight of 3251 lbs. to 3750 lbs. are grouped in the 3500 lb. inertia weight class, etc. Thus a vehicle that has an inertia weight of 3249 lb will have a much better EPA fuel rating than a comparable vehicle that has an inertia weight of 3251 lb.

The first vehicle, which will be tested in the 3000 lb. class, will have a rated fuel economy about 10% higher than that of the second vehicle which will be tested in the 3500 lb. class. This difference could be as much as 2 to 3 mpg.

In the future, EPA will narrow the bandwidth of the inertia weight classes to 125 lbs. which will reduce the incentive to drop from one weight class to another by a factor of 4. In 1985 the difference in apparent fuel economy would be 0.8 to 1.2 mpg. Given the structure of the law ($50/automobile for every mile CAFE), a one mpg improvement in fuel economy in a production run of 100,000 automobiles, is worth $5 million. Under these circumstances, replacing a steel component with a graphite component has a value well beyond the costs of the components. A weight savings of 10 lb/car can be construed to be worth $5/lb. of weight saved.

This situation may arise in only a small percentage of the vehicles produced. Assuming the use of additional 40 pounds of hybrid composites to save 10 pounds of vehicle weight, on 5% of the fleet, an additional graphite usage of 2 million lb/yr. is calculated.

If the AFER requirements become significantly more stringent than 20 mpg in the post 1985 period, then advanced composites will find much more extensive use in the automotive industry, particularly in larger luxury vehicles. For example, increasing AFER will not have much impact on the use of materials in small vehicles that would already be fuel efficient; however, large automobiles would be vulnerable to a higher AFER level unless high performance composites would be used extensively. Approximately 8 to 10% of the current new car market is for luxury vehicles that sell for more than $10,000 apiece. The market for these status vehicles will continue to exist, nearly irrespective of the price of the vehicles (within limits of course). It is not unreasonable to assume that the larger luxury vehicles may make more extensive use of hybrid reinforced plastics than the average car. If it is assumed that the large cars will contain M and H type components made of hybrids, according to the analysis presented here, an average larger automobile would contain about 400 lbs. of hybrids. Based on a graphite content of 10% by weight, the larger vehicles would each contain 40 lbs. of graphite filaments. These would add $260 to $400 (constant dollars) to the manufacturing cost of the car. While this added cost would be prohibitive in an average $4000 automobile, it could be considered as providing optional luxury and space in a $12,000 vehicle. A million larger automobiles a year, each containing 40 lbs. of graphite filament, would consume a total of 40 million pounds of graphite filament a year.

Electric vehicles would be another group of automobiles in which advanced composites would be used extensively. Increasing the weight of the chassis and body of a vehicle by a given amount is more detrimental to an electric vehicle (EV) than to an internal combustion engine (ICE) vehicle. This is due to the fact that the weight of the power generating group (motor and fuel or battery) is a much greater fraction of the gross vehicle weight for an electric vehicle than for an ICE vehicle. Furthermore, the unit cost of the power generating group is much higher for an EV than an ICE vehicle. Weight reduction is three times as valuable in an electric vehicle as in an ICE. At the moment, there are few EVs in service, but DOE is funding a demonstration program which will result in 10,000 EVs being in service by 1986. An optimistic projection would assume an order of magnitude increase in EV population by 1990 which corresponds to a production rate of 25,000 vehicles a year. It is estimated that an EV could consume 600 lbs. to 800 lbs. of advanced hybrid composite in its body and chassis components. This EV production would consume approximately 1 to 2 million pounds a year of high performance fiber.

Based on the above discussion, the total projected consumption of high performance fiber by the automobile industry in 1990 is estimated to range from about 10 million to slightly over 80 million pounds per year (10,000 to 40,000 metric tons/year). This market would dominate the consumption of high performance fibers. These projections are summarized in Table 21S. Since the hybrids may contain less than 10% graphite fiber these figures are considered to be maximum values.

TABLE 21 S

PROJECTION MAXIMUM 1990 AUTOMOBILE CONSUMPTION OF ADVANCED COMPOSITE MATERIALS

VEHICLE	ANNUAL PRODUCTION 10^6 VEHICLES/YR	HYBRID COMPOSITE USE PER VEHICLE LBS/VEHICLE	AUTOMOBILE CONSUMPTION OF HYBRID COMPOSITES 10^6 LBS/YEAR	EQUIVALENT HIGH PERFORMANCE FIBER REQUIREMENTS(*) 10^6 LBS/YR
All Passenger Autos	10.0	40	400	40
Passenger Autos Subject to Inertial Weight Class Shift	0.5	80	20	2
Luxury Passenger Autos	1.0	0-400	0-400	0-40
EV/EHV	0.025	400-800	10-20	1-2
TOTAL			430-840	43-84

(*) 10% high performance fiber content.

The projected high performance fiber consumption by the 1990 automobile market represents one hundred fold expansion of the current (1977) market for these fibers. It is estimated that the additional manufacturing facility needed to produce the high performance fiber (e.g., graphite) could require $500 million to $1 billion in capital.

There would also be an associated demand for an additional 300 million to 600 million pounds per year (140,000 to 270,000 metric tons/year) of glass fibers; and of 150 million to 300 million pounds per year (78,000 to 140,000 metric tons/year) of polymeric resin, presumably unsaturated polyesters. For comparison, in 1976, fibrous glass consumption in the U.S. was 280,000 metric tons (22), while polyester resin consumption was 436,000 metric tons (23). Extensive use of hybrid composites would require expansion of facilities for these two commodities.

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APPENDIX A. DETAILED ASSESSMENT

1.0 INTRODUCTION

1.1 Background

Fuel economy and light weight vehicles have become vital concerns of the automotive industry because of the Energy Policy and Conservation Act that was passed into law on December 22, 1975. This legislation mandates a production weighted corporate average fuel economy (CAFE) for passenger automobiles that increases from 18 miles per gallon in 1978 to 27.5 miles per gallon in 1985, and it is likely that these requirements may become even more stringent in the post-1985 period. The fuel economy of nonpassenger autos with a gross vehicle weight of less than 8,500 pounds will also be regulated, and by 1981 will have to be at least 15.5 miles per gallon for four wheel drive vehicles, and 18 miles per gallon for two wheel drive vehicles. Current regulations have not concerned themselves with heavy trucks and buses, but with those vehicles, economic circumstances associated with rising fuel costs dictate that they be fuel efficient. Reducing vehicle weight and fuel consumption result in lowered operating costs and in increased hauling capacity.

The requirement of 27.5 miles per gallon in 1985 will require not only that the average weight of automobile be reduced from 4,000 pounds (1,800 kg) to 3,100 pounds (1,400 kg), but will also require major gains in power plant efficiency and packaging optimization, if the general attributes - space, ride, comfort - of American automobiles are to be maintained. General downsizing of all automobiles is not an attractive option to the manufacturer because it entails a major marketing risk in that small cars may not sell as readily as current larger cars.

In order to reduce vehicle weight and still maintain sales attributes, automotive structures and materials are being closely examined. Greater use is being made of materials such as high strength low alloy (HSLA) steels, aluminum, and both fiberglass reinforced and non-reinforced plastics. With extensive use of these materials, it should be possible for the manufacturers to produce an automobile that will meet the 1985 CAFE requirements and still find market appeal.

Preliminary NHTSA analysis indicates that significant fuel economy improvements will occur in the 1985-1990 time period only with the mass introduction of the diesel power plant in the LDV (light duty vehicle) fleet and a large decrease in the average weight of the fleet. Recent reports both by the automotive industry and the government indicate that significant reduction in the weight of LDV are possible with the substitution of advanced composite materials (ACM) for steel in automotive structures. ACM are currently used extensively in aerospace applications because of their excellent stiffness and strength to weight ratios.

The use of ACM to achieve weight savings is currently an important area of investigation. Table 1 is a list of the structural components on an automobile that could potentially be made from ACM.

In a well publicized program, the Ford Motor Company is currently building an experimental automobile that uses ACM, mainly graphite composites, to as great an extent as possible but which will retain the appearance and performance characteristics of the Granada, an intermediate size six passenger automobile. This prototype will be on display at the 1979 SAE Exposition in Detroit, Michigan. A cut-out of this vehicle is shown in Figure 1, and a list of ACM components in Table 2. This "Light Weight Vehicle" (LWV) will have a curb weight of 2,517 pounds (1,143 kg) and an inertia weight of 2,750 pounds (1,250 kg), or 1,250 pounds (657 kg) less inertia weight than the standard Granada. Because of lower structural weight, a smaller engine (a 2.8 ℓ V-6 instead of a 5.8 ℓ V-8) can be used without changing performance (0-60 miles per hour, (100 km/hr) in 12 seconds). Fuel economy (metro/highway) increases from 17 miles per gallon for the standard Granada to 23 miles per gallon for the LMV. In summary, substituting ACM for steel in this automobile should result in a 31% reduction in inertial weight and a 35% increase in fuel economy.

Ford Motor Company is not the only company investigating these

TABLE 1

SUGGESTED STRUCTURAL AUTOMOTIVE APPLICATIONS OF ADVANCED COMPOSITE MATERIALS

BODY STRUCTURE

Hood - outer and inner liners
Deck - outer and inner liners
Quarterpanel - outer and inner liners
Door - outer and inner liners
Door hinges
Side intrusion beams
Bumper beams

CHASSIS AND SUSPENSION

Leaf springs
Frames and cross members
Engine support
Radiator support
Transmission support
A/C support
Suspension arms
Wheels

POWER TRAIN

Drive shaft
Universal yoke
Axle and axle housing
Transmission housing

ENGINE

Push Rods
Connecting Rods
Rocker arms
Oil pan
Water pump impeller

SOURCE: D. C. Hiler, SAE International Automotive Congress, March 1, 1977.

TABLE 2

FORD LIGHTWEIGHT VEHICLE PROGRAM
GRAPHITE COMPONENT WEIGHT SUMMARY

COMPONENT	COMPONENT WEIGHT, lbs. STEEL	COMPONENT WEIGHT, lbs. GRAPHITE COMPOSITE	REDUCTION lbs.	WEIGHT RATIO*
Hood	40.0	15.0	25.0	0.38
Door, R.H. Rear	30.25	12.65	17.60	0.42
Hinge, Upper L.H. Front	2.25	0.47	1.78	0.21
Hinge, Lower L.H. Front	2.67	0.77	1.90	0.29
Door Guard Beam	3.85	2.40	1.45	0.62
Suspension Arm, Front Upper	3.85	1.68	2.17	0.44
Suspension Arm, Front Lower	2.90	1.27	1.63	0.44
Transmission Support	2.35	0.55	1.80	0.23
Driveshaft	17.40	12.00	5.40	0.69
Air Conditioning, Lateral Brace	9.50	3.25	6.25	0.34
Air Conditioning, Compressor Bracket	5.63	1.35	4.28	0.24

$$*\text{Weight ratio} = \frac{\text{Weight graphite composite component}}{\text{Weight steel component}}$$

SOURCE: FORD MOTOR COMPANY
AUTOMOTIVE INDUSTRIES 157 (no. 8), Dec. 1, 1977, p. 39.

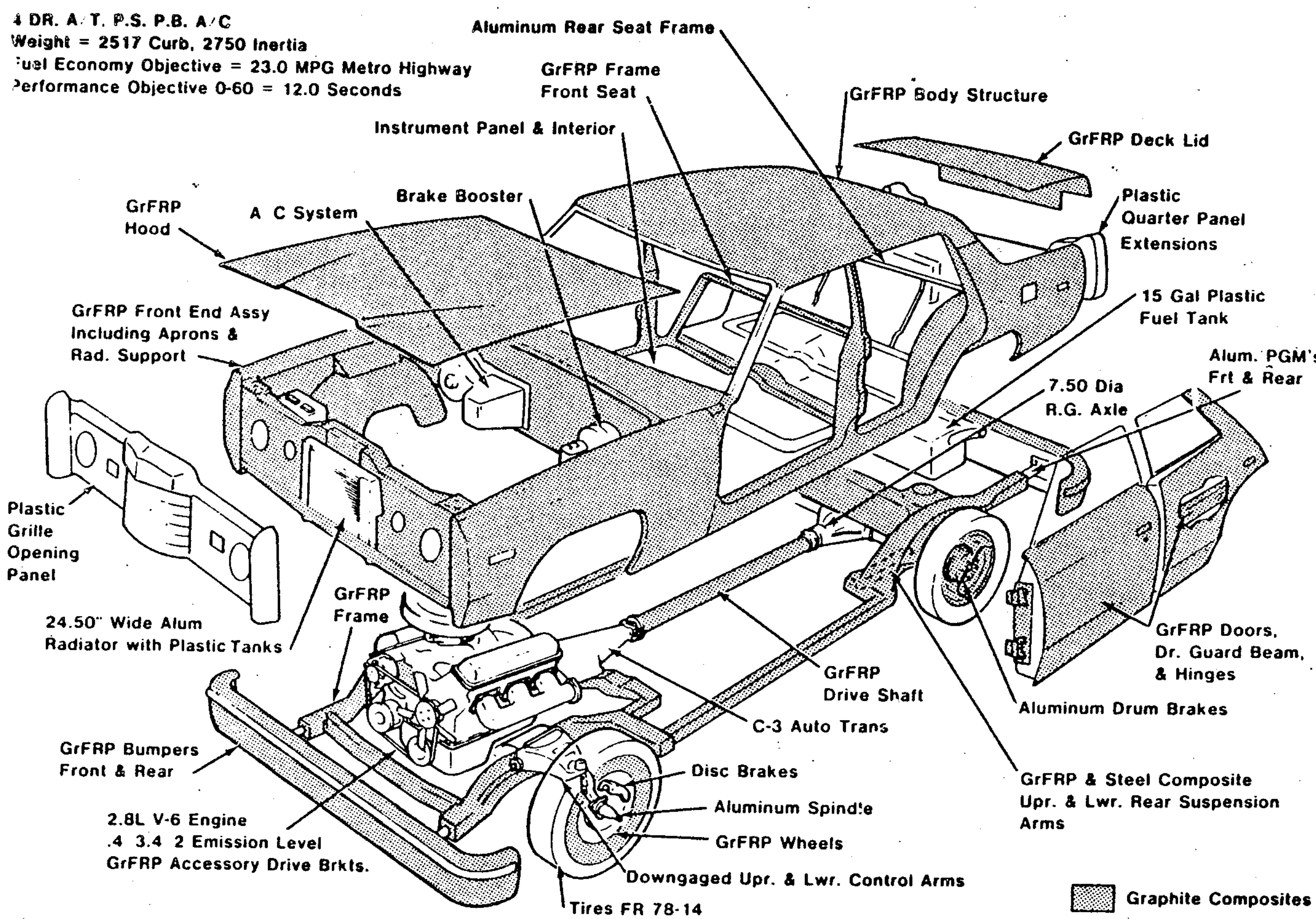

FIGURE 1

FORD LIGHTWEIGHT VEHICLE PROGRAM

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materials, and all the major automotive manufacturers, and many component and material suppliers have R&D programs exploring the potential automotive uses of Advanced Composite Materials. A wide variety of prototype parts and components have been made in which ACM are used in lieu of steel. These parts are currently being evaluated. Data on representative parts that have been discussed in the recent technical literature (including manufacturer's brochures, and/or presented at recent trade shows) are presented in Table 3.

There are, however, no ACM automotive components in production use at the present time. A number of problems and issues have to be addressed and solved before advanced composites can be considered as accepted materials of construction for production automobiles. These issues include the costs of raw materials, the lack of suitable manufacturing techniques, a general lack of experience with regards to the behavior of actual automotive use, and some reservations as to the recyclability and environmental compatability of ACM.

1.2 Objective of the Study

The purpose of the present study is to estimate the impacts of ACM on LTV fleets (passenger automobiles, and light trucks and vans) in the 1985-1990 period; identifying, and quantifying where possible, weight reduction potentials, costs to the manufacturers of implementing suitable manufacturing processes, resulting costs to the consumer and potential environmental effects.

1.3 Scope of the Study

The major focus of the study was a theoretical analysis of the potential use of ACM in LTV's in the 1985-1990 period. Two scenarios were investigated:

a) Revolution. - Fuel economy standards are set in the time period at 33-40 mpg, and manufacturers must use composite materials technology to the maximum extent, almost independently of costs.

TABLE 3 - REPRESENTATIVE LDV COMPONENTS MADE WITH ACM

AREA OF APPLICATION	COMPONENT	COMPOSITE STRUCTURE	COMPONENT STEEL Ws	WEIGHT, lbs. COMPOSITE Wc	WEIGHT REDUCTION lbs.	WEIGHT RATIO Wc/Ws	SOURCE OF DATA
Body Structure	Hood, Fiesta	4-ply graphite: 2 unidirectional (HM) + 2 0/90 fabric layers with Nomex honeycomb core buildup	23.6	6.0	17.6	0.25	Hercules, 1978 SAE Exhibition
	Hood	Graphite - not otherwise specified	40	16	24	0.40	Hercules Brochure (4/78)
	Door Intrusion Beam	Graphite/aluminum honeycomb	17	7	10	0.41	D. Hiler Union Carbide 1977 SAE Exposition
	Bumper Beam, Fiesta	Pultruded graphite/glass hybrid composites	12 lbs. alum. ≃30 lbs. steel	7	23 (over steel)	0.23	Hercules 1978 SAE Exposition
Chassis and Suspension	Leaf Spring, Auxillary Light Duty Truck	High strength graphite/epoxy - constant cross section	16.2	4.8	11.4	0.30	Dharan - ICCM-2
	Leaf Spring, auto	Graphite/glass composite	28	5	23	0.18	D. Hiler Union Carbide - 1977 SAE Exposition
	Leaf Spring, auto	1 leaf - not specified	---	---	---	0.30	Graftek
	Leaf Spring, auto	Not specified	28	5.5	22.5	0.20	Hercules - 1978 SAE Exposition
	Transmission Support Bracket	Graphite/polyester, Compression Molded	20.5	4.7	15.3	0.23	Hercules - 1978 SAE Exposition
	Engine Support Bracket (Fiesta)	Unidirectional HM Graphite and Type A Graphite cloth	5.2	1.3	3.9	0.25	Hercules - 1978 SAE Exposition
	Air conditioner Support Bracket for 1980 Mustang	Continuous graphite/chopped glass polyester composite	7.0	1.9	5.1	0.27	R. Schmidt Great Lakes Carbon, Pers. Communication
	Air Conditioner Bracket	Graphite composite	12.0	2.5	9.5	0.21	Hercules 1978 SAE Exhibition

TABLE 3 (CONTINUED) - REPRESENTATIVE LDV COMPONENTS MADE WITH ACM

AREA OF APPLICATION	COMPONENT	COMPOSITE STRUCTURE	COMPONENT STEEL Ws	WEIGHT lbs. COMPOSITE Wc	WEIGHT REDUCTION lbs.	WEIGHT RATIO Wc/Ws	SOURCE OF DATA
Power Train	Drive Shaft, (no yokes)	Graphite-epoxy	7.4	2.4	5.0	0.32	Dharan - ICCM-2
	Drive Shaft, auto	Graphite composite	12.6	6.5	6.1	0.52	Hercules - 1978 SAE Exhibition
	Drive Shaft, truck	Graphite composite	165	50	115	0.30	Hercules - 1978 SAE Exhibition
	Drive Shaft, light truck with fittings)	Graphite/glass composite	32.9	17.9	15	0.54	Shakespeare - 1978 SAE Exhibition
	Drive Shaft, 64 in. long (no fittings)	All graphite composite	15.7	5.3	10.4	0.34	Graftek - 1978 SAE Exhibition
		Aluminum + graphite composite	17.5	5.5 Aℓ +0.5 graphite	9.7	0.38	Graftek - 1978 SAE Exhibition
	Drive Shaft (with metal end fittings)	Graphite composite	22.6	9.5	13.1	0.42	
Engine Components	Push Rods	Graphite composite				0.30	Hercules Brochure

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b) Evolution. - Fuel economy standards are set at 28-31 mpg, and manufacturers will use composites only if technology is fully developed and cost trade offs are deemed reasonable.

In addition, an assessment was made of the likely development of the future use of ACM by the automotive vehicle industry through 1990. The following factors were investigated, with quantitative estimates provided where possible:

a) Identify parts and components where ACM are likely to be used. Estimate total weight savings, including propagating effects on the total vehicle.

b) Identify future manufacturing processes to make above parts and components. Estimate the cost of the ACM to the manufacturer as a function of volume. Also estimate capital requirements, labor and potential cost to the consumer.

c) Project total use of ACM, auto industry wide. Discuss potential availability problems.

d) Discuss issues and problems areas which have to be overcome in order for ACM to be utilized in the LTV fleet.

1.4 Methodology

The analysis of the potential use of ACM in LTV structures considered the substitution of ACM for steel in structurally equivalent functional components. The general methodology developed by Chang and Justesson (1), as well as by Dharan (2), was used to calculate the ratio of the weight of a simple structure made from a given advanced composite material to the weight of a functionally equivalent steel structure. The weight substitution calculations performed by Chang and Justusson for aluminum and HSLA steel were performed in this study for a series of ACM which contained different reinforcing fibers and different reinforcing fiber layup geometries.

A significant amount of information is available on the weight savings that can be achieved when a specific component is made from an ACM instead of steel. These data were collected and the weight ratios attained by materials substitution for various specific components were compared to theoretical values obtained for the most similar simple structure (i.e., a hood was considered to be a panel, a drive shaft to be a thin tube, and a leaf spring to be a thick beam) with the same material properties. Comparable values established broad design criteria which allowed weight savings to be estimated for wide categories of parts and components. Total vehicle weight savings were then calculated both as the sum of the individual weight savings that would be achieved simply by substituting ACM components for steel components, not taking into account secondary weight savings; and also when the secondary weight savings due to the reduction in size of non ACM parts on a vehicle are taken into account. Scenario I calculations are based on the maximum use of those types of ACM that would be expected, on the basis of their physical properties, to result in the greatest degree of weight reduction. Scenario II calculations were based on the more realistic assumption that hybrid composites would be used selectively. In general, hybrid composites are composite materials that contain more than one type of reinforcing fiber in a common matrix. More spcifically for the purpose of this study, hybrid composites are fiberglass reinforced plastics which also contain small amounts of selectively placed high performance fibers which enhance the overall properties of the structure.

The quantitative analysis referred to above does not include any engine components which would be expected to be operating at elevated temperatures. At present, because of high temperature requirements, it appears unlikely that advanced composite materials will find major use in production engine structures by 1990. However, on a longer term, it is possible that the state of the art of either metal matrix composites or high temperature organic resin matrix composites will be sufficiently advanced to warrant the use of these materials in engine parts. This potential area of application of ACM is discussed qualitatively in Appendix B.

The assessment of the likely evolution of the future use of ACM by the automotive vehicle industry through 1990 was based, in part, on discussions with members of the ACM community who are currently actively interested in automotive structures made out of ACM, attendance at a number of technical meetings at which the current state of the art of automotive use of ACM's was discussed, and site visits to the facilities of manufacturers of composite fabrication equipment, and of some of the leading developers of ACM automotive components.

The basis of the current assessment was an overall assessment of advanced composite materials that was recently completed by the author (3). The final report of this previous study, which was sponsored by the National Science Foundation, provides general background on ACM technology, a discussion of a broad scope of applications (including automotive applications) of ACM, and an assessment of the potential economic and social impacts of this technology through 1990.

2.0 PROPERTIES OF ADVANCED COMPOSITE MATERIALS

2.1 Introduction

Composite materials are combinations of two or more distinct solid materials that are bonded to each other in order to combine the properties of the component parts, to obtain composite properties which may be new or unique. They have long been used to fabricate useful artifacts and products.

At present, a myriad of combinations of metals, ceramics, and nonmetallic materials, all of which can properly be called composites, are in engineering use. Fiberglass reinforced plastics are noteworthy examples of a class of composite materials that have reached commercial fruition.

Approximately two decades ago, in order to meet the increasing requirements of advanced military systems, a number of low density fibers were produced that were significantly stiffer than glass fibers with comparable, or superior, strength properties. In the ensuing years, the category of high performance fibers, has grown to include such diverse materials as boron, carbon (graphite), aramid (an organic compound), silicon carbide, and alumina. Incorporating one or more of these high performance filaments in a suitable matrix produces a class of composite materials, herein called advanced composite materials (ACM), that exhibit physical and structural properties not unattainable with conventional engineering materials. The matrix (or bonding agent) can be a thermoplastic resin, such as nylon or polysulfone; a metal, such as aluminum or titanium; or a ceramic such as glass.

Advanced composite materials are composite materials that exhibit a very high specific strength and a very high specific modulus. The specific strength is defined as the ratio of the tensile strength to the density of the material, while the specific modulus is defined as the ratio of the tensile modulus to the density of the material. It has been suggested that ACM are those composite materials that have a specific strength and a specific modulus that are at least three times those of steel (4).

Since the mechanical properties of fibrous composites depend on the relative orientation and volumetric concentration of the fibers, a given composite material may or may not fulfill the above definition depending on the orientation of the applied stress and on the microstructure of the composite. More generally ACM could be defined as composite materials that contain at least one type of continuous high performance fiber dispersed in a suitable matrix.

2.2 High Performance Fibers of Interest

The principal physical properties of the high performance fibers that are currently commercially available in the U.S. are presented in Table 4. The properties of E-glass fiber most commonly used in reinforced plastics, and of higher strength S-glass fibers developed for the aerospace market, are also included in Table 4 for purposes of comparison. The principal physical properties of high performance fibers presently under development and that may be commercially available in the future are presented in Table 5.

Graphitized carbon (herein called graphite) fibers are the high performance reinforced filaments of greatest current interest to the automotive industry. The current prices of PAN (polyacryonitrile) base graphite fiber ranges from \$22/lb to \$250/lb. The price of high strength graphite ranges from \$22/lb for 160,000 filament tow to \$105/lb for 1,000 filament tow, with 6000 and 3000 filament tow material selling at \$32/lb and \$35/lb respecitively. The tow count is a measure of the number of individual filaments per strand of fiber. This price schedule reflects increasing manufacturing costs associated with lower filament tow material. The lower the tow count, the more expensive the raw material, from more than \$3.00/lb for low tow count precursor to less than \$1.00/lb for high tow count precursor.

High modulus graphite, such as Hercules HMS and Union Carbide's Thornel 50 sell for \$70/lb to \$125/lb, the price variation depending on the tow count. Very high modulus graphite (Celanese GY70) currently sells for \$145/lb to \$250/lb depending on the quantity purchased and product specifications.

TABLE 4

PHYSICAL PROPERTIES OF COMMERCIALLY AVAILABLE HIGH STRENGTH FILAMENTS

Material	E-Glass Fiber	S-Glass Fiber	Aramid Fiber	Boron/Tungsten Fiber	Graphite Filaments: High Strength Fiber	Graphite Filaments: High Modulus Fiber	Graphite Filaments: Very High Modulus Fiber
Product	(Roving)	(Roving)	Kevlar 49	5.6 mil Diam.	Thornel 300 (WYP 15-1/0)	Magnamite HMS	Celion GY-70
Supplier			Dupont	Avco/CTI	Union Carbide	Hercules	Celanese
Density lbs/in^3	0.092	0.090	0.052	0.090	0.062	0.067	0.071
g/cm^3	2.54	2.48	1.44	2.48	1.72	1.86	1.96
Tensile Strength 10^3 psi	372	550	400	500	360	340	270
MPa	2500	3700	2800	3400	2600	2300	1900
Tensile Modulus 10^6 psi	10.5	12.4	18.0	58.0	32.5	50	75
GPa	73	86	124	406	225	350	520
Ultimate Elongation, %	4.8	5.4	2.5	0.8	1.1	0.58	0.38
Specific Strength, in	$4.0x10^6$	$6.0x10^6$	$7.9x10^6$	$5.6x10^6$	$6.1x10^6$	$5.0x10^6$	$3.8x10^6$
cm	$9.8x10^6$	$1.5x10^7$	$1.9x10^7$	$1.4x10^7$	$1.5x10^7$	$1.2x10^9$	$9.7x10^6$
Specific Modulus, in	$1.1x10^8$	$1.4x10^8$	$3.5x10^8$	$6.4x10^8$	$5.2x10^8$	$7.5x10^8$	$1.1x10^9$
cm	$2.9x10^8$	$3.5x10^8$	$8.6x10^8$	$1.6x10^9$	$1.3x10^8$	$1.9x10^9$	$2.7x10^9$
Filament Diameter, mils	0.20-0.55	0.35-0.40	0.47	5.6	0.3	0.3	0.33
cm	0.0005-0.014	0.0009	0.0012	0.014	0.0007	0.00075	0.00084
Thermal Conductivity BTU-ft/hr $(ft^2)(^oF)$	0.56				12	70	
$W/m\ ^oK$	0.97				20.8	121	
Electrical Resistivity Ω mil ft					9000	4500	3900
μΩcm					1500	750	650
Current Price, $/lb	0.49	2.00	8-10 & up to 27 for fine denier fiber	200	20-32	70	140-250

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TABLE 5

Physical Properties of Developmental High Strength Fibers

Material	Pitchbase Graphite	Boron/Carbon	Silicon Carbide/Carbon	Alumina	Boron Nitride
Product	Thornel P-VSB-32			FP	
Manufacturer	Union Carbide	AVCO	AVCO	DuPont	Carborundum
Density lbs/in^3	0.073	0.082	0.113	0.143	0.065-0.069
g/cm^3	2.02	2.26	3.11	3.95	1.8-1.9
Tensile Strength 10^3psi	200	475	450	200	120 (ave.)
MPa	1380	3300	3100		830
Tensile Modulus 10^6psi	50	53	62	55	30 (ave.)
Gpa	345	363	425	377	210
Ultimate Elongation %	0.4			0.4	
Specific Strength in.	2.8×10^6	5.8×10^6	4.0×10^6	1.4×10^6	1.8×10^6 (ave.)
cm	6.8×10^6	1.5×10^7	1.0×10^7	3.6×10^6	4.7×10^6
Specific Modulus in.	6.8×10^8	6.4×10^8	5.5×10^8	3.5×10^8	4.6×10^8 (ave.)
cm	1.7×10^9	1.6×10^9	1.4×10^9	8.9×10^8	1.2×10^9
Filament diameter mils	0.44	5.6	5.6	1.0	0.24
cm	0.0011	0.014	0.014	0.002	0.0006
Thermal Conductivity BTU ft/hr(ft^2)($^\circ$F)	48			0.074	1.7
W/m$^\circ$K	83			0.13	3.0
Electrical Resistivity, ohm-cm					10^{14}
Current Price $/lb	20	250	450	200	

Union Carbide's pitch base material currently sells for \$20/lb in fiber form, and \$7.50/lb-\$8.50/lb in mat form.

The current price structure of graphite fibers reflects the relatively small current demand for this material (currently about 150 metric ton/yr). Since the market is divided between a number of suppliers who each produce a number of grades as fibers, production on any one fiber grade is presently only a pilot operation. As a result, unit costs and prices are high.

Figure 2 presents some price-volume productions obtained from different manufacturers for PAN base graphite. The production volume indicated in this figure is for a particular fiber grade in a single plant. The total market would exceed the indicated production level by a significant amount.

At 200,000 lbs/year (90 metric tons/year), the price of high strength PAN graphite is projected to range from \$14/lb for a 40,000 filament tow, to \$20/lb for 3000 filament tow. At a production volume of 10^6 lbs/year (450 M tons/year) the price would range from \$10/lb to \$13/lb, and at a production volume of 10^7 lbs/year (4500 M tons/yr) the prices would range from about \$6/lb to \$8/lb.

High modulus and very high modulus PAN based graphite fiber would be more expensive than the high strength fiber because of higher processing costs. A projected price for very high modulus PAN base graphite fiber is also given in Figure 2. This projection is based on current price for material and the range of slopes presented for the high strength graphite in the same figure.

Pitch base graphite fiber could potentially be made available at a lower price than PAN based graphite because of the lower cost of the precursor material; less than \$1 per pound of graphite for pitch base, as compared to \$2 to \$10 per pound of graphite for PAN base material. A price of \$5/lb for pitch base graphite has been projected if a sufficient (unspecified) volume develops. This projected price is also indicated in Figure 2.

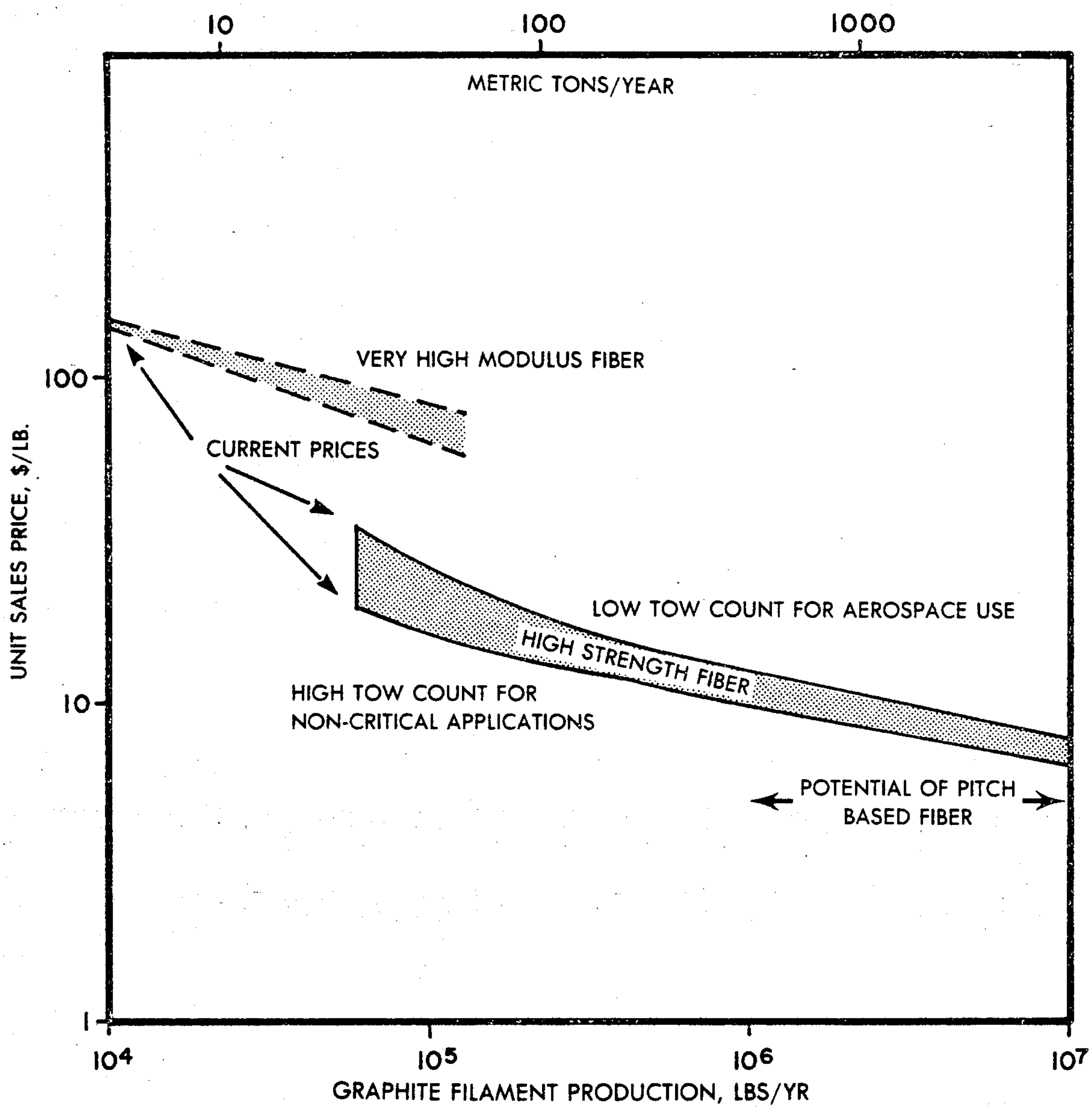

FIGURE 2
PROJECTIONS OF GRAPHITE FILAMENT PRICE AS A FUNCTION OF A MANUFACTURER'S PRODUCTION LEVEL

Aramid is the generic name assigned by the Federal Trade Commission to high strength, high modulus aromatic polyamide fibers introduced by E. I. du Pont de Nemours & Company, Inc. in 1972. Among these fibers is Kevlar 49 (R) which is a resin reinforcing material.

The current price of Kevlar fibers range from $4.50/lb. for chopped fiber to $27/lb. for fine, 200 denier filament. Most grades of Kevlar-49 used for reinforcement range from $8/lb. to $10/lb. The price structure is considered stable and no further economies of scale are envisioned.

Of the other fibers mentioned in Tables 4 and 5, only alumina FP, a product of E. I. du Pont de Nemours could potentially be used in automotive structures. The current price of alumina FP fibers reflects the developmental status of this material. Cost of production and price would drop as the fibers were made in large quantities, with $8/lb. being forecasted by the manufacturer for a 5,000,000 lb/year plant output.

A more detailed discussion on the manufacture and availability of the various high performance filaments that are currently available is presented in the aforementioned NSF study (3).

2.3 Organic Resin Matrices

Plastic resins have been the predominant matrix materials used to make advanced composites to date, and most of the current production applications of advanced composites use resin matrix systems. A major reason for the predominance of resin matrix systems, as compared to metal matrix systems, for example, is that much of the fabrication technology developed for fiberglass reinforced plastics was directly applicable, or at least adaptable, to the fabrication of advanced composite systems. High performance fibers can be combined with most of the conventional thermosetting and thermoplastic resins quite successfully, often with no special fiber finish (or size) being required. Key properties of the principal resin systems that have been used to make advanced composites are summarized in Table 6.

Epoxy resins have been the predominant matrix material for advanced composites. Two classes of epoxy resins have been used: high temperature resins which retain their mechanical properties at 350°F (176°C) and the general purpose resins which can be used at temperatures of up to 180°F (82°C). The high temperature grades are principally used in aerospace applications, whereas the general purpose resins are principally used in commercial applications which find principal use at ambient temperature. The general purpose resins are significantly less expensive than the high temperature resins, and also are easier to process, both in terms of lower cure temperature, 200°F (90°C) vs. 400°F (200°C), and faster cycle time (1 to 2 hours cure cycle vs. 4 to 6 hour cure cycle).

Other resin systems are being extensively examined as candidate matrix materials to achieve two totally different goals. The first is to lower significantly the costs of composites. This entails using resin systems which in themselves are significantly cheaper than the high performance epoxy resins, and which also lend themselves to lower fabrication costs. Thermosetting polyesters are now being extensively examined as candidate matrix materials for mass production applications of advanced composites. Unsaturated polyesters are the matrix material of choice in the myriad consumer applications of fiberglass reinforced plastics. While the polyesters do not exhibit all the mechanical properties of the higher performance engineering plastics, they are significantly less exensive (36¢/lb for general purpose resin) than the engineering plastics. Furthermore, polyester formulations currently exist that cure rapidly (in minutes or less) and, therefore, are amenable to high speed, mass production fabrication methods.

The second major thrust is to obtain resin matrix composites that can withstand significantly higher temperatures than the 350°F operational limit of the high termperature epoxies that represent the current state-of-the-art. The leading candidate systems being considered are thermosetting polyimides, such as Thermid 600, manufactured by Gulf Oil Chemicals Company or PMR-15 resin developed

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TABLE 6

Resins Used as Matrices in Advanced Composites

Resin		Epoxy	Phenolic	Polyester (Rigid)	Poly-imide	Nylon 6-6	Poly-sulfone	Polyaryl Sulfone	Polyether Sulfone	Polyphe-nylene Sulfide	Poly-Amide/ Imide
Property	ASTM Test Method	THERMOSETTING RESINS				THERMOPLASTIC RESINS					
Specific Gravity	D 792	1.1-1.4	1.25-1.30	1.10-1.46	1.37	1.14	1.24	1.36	1.37	1.34	1.40
RT Mechanical Properties											
Flexural Strength Ksi	D 790	13-21	12-15	8.5-23	19	15.0	15.4	17.2	18.7	20	30.7
Flexural Modulus Msi	D 790				0.6	0.4	0.4	0.4	0.4	0.6	0.6
Tensile Strength Ksi	D 638	4-13	7-8	6-13	12	12	10	13	12	10	27
Tensile Modulus Msi	D 638	0.4-0.6	0.7-1.0	0.3-0.6	0.6	0.5	0.4	0.4	0.4	0.5	0.7
Distortion Temperature @ 264 psi, °F	D 648	115-550	240-260	140-400		150	345	525	397	275	525
Resistance to Heat Continuous Exposure, °F		250-500	250	250	>600	180	300	500	300	400-500	>650
Flammability	D 635	slow	very slow	Burns to self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Non-burning	Self extin-guishing
Representative Cure/ Molding Conditions											
Temperature		250-450	270-360	270-350	400-700	520-620	250-325	720-750	610-710	550-675	600-625
Pressure psi			2000-4000	300-1200	2000	variable	100-3000	1000-2000	1000-1500	1000-1500	20,000 (inj. mold)
Price $/lb		0.70 to 10	0.47	0.36 (gen. purpose)	75-100 (cur.) 25(proj.)	1.16	2.95-4.75	20-40	6.50-11.00	2.05	9.75
Suppliers		7	31	19	2	13 (incl. other nylons)	Union Carbide Corp.	Carbor-undum Corp., Plastics Division	ICI America	Phillips Petro-leum Co.	Amoco Chemicals Corp.

by NASA Lewis Research Center. The polyimide resins are currently expensive (up to \$100/lb), and difficult to cure, with high pressures (up to 2150 psi), high temperatures (up to 700°F) and long cycle times (2 hour mold time with 16 hours post cure) being required. However, these resins allow composites to be considered for aerospace applications which now normally use titanium as a material of construction. With time, the cost of these resins is expected to drop significantly (less than \$10/lb) and if the chemistry can be modified to reduce cure time, these resins could find application in mass markets as well.

There is also interest in thermoplastic resins, that exhibit reasonably high temperature resistance as composite matrices. These thermoplastic resins lend themselves to rapid processing and to post-forming which can result in significant cost reductions in the manufacture of complex parts. These thermoformable resins can be reprocessed, which can result in a lower reject rate. This property also has implications in terms of the recycling of either industrial or post-consumer scrap composite parts.

2.4 Mechanical Properties of Fibrous Composites

The mechanical properties of fibrous composites depend on the type of fiber incorporated in the matrix, its volumetric concentration and the relative orientation of the applied stress to the fibers. Fibrous composites are strongest and stiffest in the direction of the alignment of the fibers, where the mechanical properties of the fibers predominate, and fairly weak in the direction normal to the fibers where the allowable stresses are determined by the mechanical properties of the matrix material. This is a very different situation than that which exists for standard homogeneous materials of construction, such as aluminum or steel, that exhibit essentially isotropic mechanical properties. Because of the directional characteristics of properties of composites, the design of components to be made from composites is more difficult, and a better understanding of the stresses this component will be exposed to in service, is required than would be the case if the components were to be made from a homogeneous material. The non-homogeneous, non-isotropic characteristics, however, can also be an asset to a designer who can tailor a composite by selectively positioning the reinforcing fibers to meet specific requirements.

In general, the mechanical properties of a fibrous composite will vary with the volumetric concentration of the incorporated fibers. The higher the fiber content, the stronger and stiffer the part, up to the point where contact and adhesion of the matrix to the fibers is impeded. If there is insufficient matrix present, voids are created which weaken the composite.

The mechanical properties tend to increase with increasing fiber length. A minimum fiber length to diameter ratio of at least 10/1 is desired. In general, the longer the fiber length in a given direction, the greater the continuity of stress transfer in that direction, and therefore, the greater the load bearing capability in that direction.

The geometric arrangement of the fibers in a composite determines both the strength and the stiffness of a composite in any given direction, as well as to a certain extent, the fiber content, and hence, the levels of mechanical properties that can be achieved.

The effects of fiber orientation on the mechanical properties of various fibrous composites are presented in Table 7, as are the comparable properties of aluminum and cold rolled steel. Unless otherwise specified, the nominal fiber loading is 60 percent by volume. The fibers considered include A type (high strength) graphite, HM type (high modulus) graphite, and UHM type (ultra high modulus) graphite, E-glass, S-glass, and Kevlar 49. The fiber arrangements considered in this table include:

a) Unidirectional: In this arrangement all the fibers are parallel to each other, and are aligned in the direction of the applied stress (0^{o} orientation).

b) Crossply: In this arrangement, the composite consists of alternating perpendicular layers of parallel fibers. Such composites are usually either tested in a 0°-90° orientation, in which the direction of the applied stress is the same as the orientation of one of the fiber layers; or in a $\pm 45^{\circ}$ orientation, in which the fiber layers are at a 45° angle to the applied stress.

c) Quasiisotropic (isotropic): In this arrangement the composite consists of alternate layers of parallel fibers that are arranged at a relative angle of 45°. With the first layer in the direction of the applied stress (0°) succeeding layers are arranged in the $+45^{\circ}$, 90°, and 135° (or -45°) directions.

d) Woven Patterns: The above arrangements apply to composites made with non-woven filaments. Different geometrical arrangements can be obtained with woven or braided filaments, and these will depend on the weaving pattern of the resulting cloth, and the relative orientation of different layers of cloth.

e) Chopped Fiber: The plastic is reinforced with chopped fiber that can be randomly oriented in three dimensions, or given a preferential orientation by an alignment process.

The data presented in Table 7 indicate that fibrous composites can be put to greatest advantage in applications where the stress is applied in one direction, and the component can be made from a unidirectional composite in which all the fibers are aligned in the direction of this stress. As can be noted, unidirectional composites exhibit a very high tensile strength and tensile modulus along the 0° direction, but very low values of these properties in the transverse direction (90°). These are mainly a function of the mechanical properties of the resin.

Only rarely are applications found where the applied stresses are unidirectional, so that in most composite structures the fibers are arranged in more than one direction in order to provide better multi-directional strength properties. In bi-directional composites, laminates of fiber layers cross-plied at right angles to each other have improved transverse properties when compared to a unidirectional composite, but at the expense of the longitudinal properties. A $0^{o}/90^{o}$ cross ply composite has only half the longitudinal (0^{o} direction) tensile properties of a unidirectional composite, but the transverse properties of a $0^{o}/90^{o}$ cross-ply composite are five times those of a 0^{o} composite. However, with this arrangement the in-plane shear strength is not significantly better than that of the unidirectional composite. If the composite test sample is cut in such a way that the cross plies are at $\pm 45^{o}$ to the applied stress, significantly improved shear properties are obtained, but at the cost of longitudinal and transverse properties. A standard method of obtaining a composite with quasi-isotropic properties is to cross ply the fibers at $0^{o}/90^{o}/\pm 45^{o}$. By arranging the fibers in this manner the properties of the composite are equal in all directions in the plane of the laminate.

Woven composite structures are similar in many respects to cross-plied laminate structures but are usually less stiff and less strong because of the weaving pattern. The advantages of fabrics is that they possess drapability and handling characteristics that allow the fabrication of geometrically complex components.

Multidirectional composites are usually made by placing fiber strands randomly in the matrix so as to achieve isotropic properties. Such composites are usually made by incorporating a fiber mat of chopped strand in the matrix. While incorporating chopped fibers into the matrix will significantly improve the mechanical properties of the resulting composite over those of the matrix, the mechanical properties of this type of composite are lower than those attained with directional continuous epoxy composites. The chopped fiber data presented in Table 7 are limited to Kevlar/epoxy and E-glass/epoxy systems. Data on chopped glass-polyester composites are given

TABLE 7 - MECHANICAL PROPERTIES OF VARIOUS FIBER REINFORCED EPOXY COMPOSITES AND OF METALS OF INTEREST

Material	Fiber Lay Up Geometry	Density gr/cm³	Elastic Moduli, GPa Longitudinal E_x	Elastic Moduli, GPa Transverse, E_y	Elastic Moduli, GPa Shear G_{xy}	Ultimate Strength, MPa Longitudinal σ_x	Ultimate Strength, MPa Transverse, σ_y	Ultimate Strength, MPa Shear τ_{xy}	Yield Strength as Percent Ultimate Strength	Fatigue Strength as Percent Ultimate Strength
A type Graphite/Epoxy	Unidirectional (0°)	1.57	138	6.9	4.5	1517	41	97		70
	Crossply (0°, 90°)	1.57	74	74	4.5	838	838	97		59
	Crossply (±45°)	1.57	17.2	17.2	31.0	138	138	345		
	Isotropic (0°, 90°, ±45°)	1.57	48	48	17.8	604	604	221		78
	Harness Satin Weave Cloth (Warp)	1.57	62	62		462	476			
HM type Graphite/Epoxy	Unidirectional (0°)	1.60	221	6.9	4.8	1206	34	69		
	Crossply (0°, 90°)	1.60			4.8			69		
	Crossply (±45°)	1.60	17.2	17.2	44.8	124	124	290		
	Isotropic (0°, 90°, ±45°)	1.60	73	73	24.8	345	345	179		
UHM type Graphite/Epoxy	Unidirectional (0°)	1.68	303	6.9	6.6	758	28	48		
	Crossply (0°, 90°)	1.68	159	159	6.6	402	402	48		
	Crossply (±45°)	1.68	20.7	20.7	79.3	96.5	96.5	207		
	Isotropic (0°, 90°, ±45°)	1.68	103	103	42.8	242	242	128		
Kevlar 49/Epoxy	Unidirectional (0°)	1.38	86(tens) 41(comp)	5.5	2.1	1517(tens) 276(comp)	28	41		70
	Crossply (±90°)	1.38								
	Crossply (±45°)		7.6	7.6	20.7	207	207	221		
	Isotropic (0°, 90°, ±45°)									
	181 Fabric (Warp)(50v/o)	1.33	31	31	2.0	517(tens) 172(comp)	517(tens) 172(comp)	110		
	Chopped Fiber (50v/o)	1.32	20	20		196	196			
S-Glass/Epoxy	Unidirectional (0°)	1.88	48	6.9	3.4	1730	40	10		
	Crossply (0°, 90°)	1.88	31	31		980	900			
	Crossply (±45°)	1.88	16	16		170	170			
	Isotropic (0°, 90°, ±45°)	1.88	25	25		730	730			
E-Glass/Epoxy	Unidirectional (0°)	1.80	39	9.6	2.1	1104	20			23
	Crossply (0°, 90°)	1.80	25	25		518	518		32	22
	Crossply (±45°)	1.80	11	11		152	152			
	Isotropic (0°, 90°, ±45°)	1.80	18	18		330	330		42	25
	Chopped Fiber (47% glass)	1.86	15	15		99	99			
Aluminum 6061-T-6		2.70	72	72	26.2	310	310	207	88	31
Steel, Cold Rolled (0.2% Carbon)		7.85	207	207	83	552	552	414	75(Tension) 60(Shear)	40-45

Sources: References 5, 6, 7, 8, 9, 10, 11, 12, 13.

in Table 11. Data on chopped fiber thermoplastic composites are presented in Table 8 in which the effects of reinforcement with chopped carbon fibers that have a Young's modulus of 207 GPA are compared with the effects of reinforcement with fiberglass with a Young's modulus of 73 GPA.

The properties of the various composites normalized to those of steel are presented in Table 9. These values were obtained by dividing the value of the composite property given in Table 7 by the value of the same property for steel. The comparison is also made for aluminum. Aluminum has a density of approximately one third of that of steel, but its modulus is also one third that of steel. The ultimate strength of aluminum is roughly half of that of steel.

The strength and modulus of the graphite fiber composites vary with fiber type and lay-up geometry. A unidirectional graphite composite is stronger than steel in the direction of the fibers, while it has less than one tenth the strength of steel in the transverse direction. The ultimate strength of quasi-isotropic cross-plied graphite composites vary from about half that of steel for UHM type graphite composites, to that of steel for Type A graphite composites. The modulus of graphite fiber composites can exceed that of steel in the case of unidirectional HM type of UHM type graphite fiber composites. For quasi-isotropic cross-plied composites, the moduli of the composites range from a fourth to one half that of steel.

The attraction of graphite fiber composites as structural material is because they exhibit strength and stiffness characteristics that approach those of steel (within the limits described above and in Table 9), while being significantly less dense than steel. The density of the graphite fiber composites being considered is only one fifth the density of steel. Therefore, these graphite composites exhibit significantly higher mechanical properties per unit weight of material than does steel. The high fatigue strength of graphite fiber composites further enhances the appeal of this class of materials to a designer. In Tables 7 and 9, fatigue data are

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TABLE 8

Properties of Various Thermoplastic Composites

RESIN		NYLON 6-6					POLYSULFONE			POLYESTER			FIBERS	
Reinforcement		Unreinforced	Carbon	Carbon	Carbon	Glass	Unreinforced	Carbon	Glass	Unreinforced	Carbon	Glass	Carbon	Glass
Loading, %		0	20	30	40	40	0	30	30	0	30	30		
Specific Gravity		1.14	1.23	1.28	1.34	1.46	1.24	1.45	1.37	1.32	1.52	1.47	1.8	2.54
Tensile Strength	Ksi	11.8	28.0	35.0	40.0	31.0	10.2	18.0	23.0	8.0	19.5	20.0	300	500
	M Pa	81	193	242	276	214	70	124	159	55	135	138	2510	3450
Tensile Elongation	%	10	3-4	3-4	3-4	2-3	50-100	3-4	2-3	10	3-5	2-3	1.2	4.8
Flexural Strength	Ksi	15	42	51	60	42	15.4	24.0	32.0	13.0	28.0	29.0		
	M Pa	104	290	352	414	290	106	166	221	90	193	200		
Flexural Modulus	10^6 psi	0.4	2.4	2.9	3.4	1.6	0.4	1.2	2.1	0.4	1.4	2.0		
	M Pa	2800	16000	20000	2300	1100	2800	8300	1450	2800	9600	14000		
Shear Strength	Ksi	9.6	12.0	13.0	14.0	12.0	9.0	9.5	9.5	7.0	8.0	8.0		
	M Pa	66	83	90	97	83	62	66	66	48	55	56		
Heat Distortion Temperature at 264 psi	°F	150	495	495	500	500	345	365	365	155	430	430		

Source: "Carbon Fibers Add Muscle to Plastics", Machine Design, February 7, 1974

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TABLE 9 - PROPERTIES OF FIBER REINFORCED EPOXY COMPOSITES NORMALIZED TO THE PROPERTIES OF STEEL

MATERIAL	Fiber Lay Up Geometry	DENSITY RATIO ρ_c/ρ_s	ELASTIC MODULI RATIO E_{xc}/E_s		ULTIMATE STRENGTH RATIO $\sigma_{xyc}/\sigma_{xys}$				YIELD STRENGTH RATIO σ^*_c/σ^*_s	FATIGUE STRENGTH RATIO σ_{FC}/σ_{FS}
			E_{xc}/E_s	E_{yc}/E_s	$\sigma_{xyc}/\sigma_{xys}$	σ_{xc}/σ_s	σ_{yc}/σ_s	τ_{xyc}/τ_s		
A Type Graphite Epoxy	Unidirectional (0°)	0.200	0.667	0.033	0.054	2.748	0.074	0.234		4.275
	Crossply (0°, 90°)	0.200	0.357	0.357	0.054	1.512	1.512	0.234		1.990
	Crossply (±45°)	0.200	0.083	0.083	0.373	0.250	0.250	0.833		
	Isotropic (0°, 90°, ±45°)	0.200	0.232	0.232	0.214	1.094	1.094	0.534		1.897
	Harness Satin Weavecloth	0.200	0.300	0.300		0.837	0.862			
HN Type Graphite Epoxy	Unidirectional (0°)	0.204	1.068	0.033	0.058	2.185	0.062	0.167		
	Crossply (0°, 90°)	0.204			0.058			0.167		
	Crossply (±45°)	0.204	0.083	0.083	0.540	0.225	0.225	0.700		
	Isotropic (0°, 90°, ±45°)	0.204	0.353	0.353	0.299	0.625	0.625	0.432		
UHM Type Graphite Epoxy	Unidirectional (0°)	0.214	1.464	0.033	0.080	1.373	0.051	0.116		
	Crossply (0°, 90°)	0.214	0.768	0.768	0.080	0.728	0.728	0.116		
	Crossply (±45°)	0.214	0.100	0.100	0.955	0.175	0.175	0.500		
	Isotropic (0°, 90°, ±45°)	0.214	0.498	0.498	0.516	0.438	0.438	0.309		
Kevlar 49[n]/Epoxy	Unidirectional (0°)	0.176	0.415(t) 0.198(c)	0.027	0.027	2.748(t) 0.500(c)	0.054	0.099		4.875
	Crossply (0°, 90°)	0.176								
	Crossply (±45°)	0.176	0.037	0.037	0.249	0.375	0.375	0.534		
	Isotropic (0°, 90°, ±45°)	0.176								
	181 Fabric Warp (50%)	0.176	0.150	0.150		0.937(t) 0.312(c)	0.937(t) 0.312(c)	0.199		
	Chopped Fiber	0.168	0.097	0.097		0.355	0.355			
S-glass/Epoxy	Unidirectional (0°)	0.239	0.232	0.033	0.041	3.134	0.127	0.024		
	Crossply (0°, 90°)	0.239	0.150	0.150		1.775	1.775			
	Crossply (±45°)	0.239	0.077	0.077		0.308	0.308			
	Isotropic (0°, 90°, ±45°)	0.239	0.121	0.121		1.322	1.322			
E-glass/Epoxy	Unidirectional (0°)	0.229	0.188	0.046	0.025	2.000	0.036			1.022
	Crossply (0°, 90°)	0.229	0.121	0.121		0.938	0.938		0.400	0.459
	Crossply (±45°)	0.229	0.053	0.053		0.275	0.275			
	Isotropic (0°, 90°, ±45°)	0.229	0.087	0.087		0.598	0.598		0.335	0.332
	Chopped Fiber (47% glass)	0.237	0.072	0.072		0.179	0.179			
Aluminum 6061-T-6		0.344	0.348	0.348	0.316	0.562	0.562	0.500	0.659	0.387
Steel, Cold Rolled (0.2% carbon)		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

2-16

only given for Type A graphite fiber composites. No data are presented for the fatigue strength of HM or UHM type graphite composites because the data obtained were not comparable to the rest of the information presented in Tables 7 and 8. In general, the data noted indicate that these materials also have excellent fatigue properties (7).

Continuous glass fiber composites have strengths that are comparable to, or can exceed, the strength of graphite fiber composites of similar fiber lay-up geometry. Even on a unit weight basis, the specific strength of glass fiber composites compares favorably with the specific strength of graphite fiber composites. The density of glass fiber composites with a high fiber content is only 10% to 15% higher than that of comparable graphite fiber composites. Where continuous glass fiber composites falter in comparison to graphite fiber composites is in their stiffness and fatigue properties. Depending on the grade of graphite fiber considered, glass fiber composites are only one third to one fifth as stiff. When compared to steel, glass fiber composites are, at best, less than 25% as stiff as steel. Quasi-isotropic glass composites are more typically 10% as stiff as steel. On a unit weight basis, these composites are not as effective a material as steel if the specific modulus is the controlling criterion. Furthermore, glass fiber composites do not have the resistance to fatigue that is characteristic of the higher modulus fiber composites. The fatigue strength of a given glass fiber composite is only about 25% of the fatigue strength of a graphite fiber composite of comparable geometry.

Kevlar 49(R) fiber composites exhibit the lowest densities of any of the fiber composites discussed here. They have mechanical properties intermediate to those of graphite and glass, in tension at least. Kevlar 49 (R) fiber composites are fairly weak in compression, which is not a characteristic of the other fiber composites discussed here. For these reasons, Kevlar 49 (R) fiber composites are mainly used in applications which require a high specific tensile strength.

Data are also presented for chopped glass fiber and chopped Kevlar 49(R) composites. These chopped fiber composites are significantly weaker and less stiff than comparable density continuous fiber composites. These chopped fiber composites, however, offer the not insignificant advantages of being fairly isotropic in all directions of space, and of lending themselves to a wide variety of fabrication techniques which could not be used with continuous fiber composite systems.

The great variation in mechanical properties of fiber composites with fiber lay-up geometry is to be noted. Depending on the relative orientation of the fibers and the applied stress, there is a four to five fold variation in the apparent strength and stiffness of orthogannally cross-plied composites. This predicates a need for careful stress analysis of any component for which the use of ACM as materials of construction is contemplated.

2.5 Mechanical Properties of Hybrid Composites

All the composite materials discussed in the previous sections are single fiber systems. In practice, however, the material properties desired for a given component may best be achieved with hybrid composites which are mixtures of different fibers in a common matrix. Hybridization greatly expands the range of properties that can be achieved with reinforced plastic systems, and also has important economic implications.

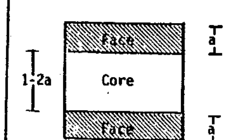
Reinforcing a composite solely with graphite fibers is usually too expensive and may not be necessary in many applications. In bending, the effective flexural modulus of a structure is related to the square of the distance of a fiber from the centroidal axis. In these applications replacing the glass filament furthest from the central axis with graphite filaments would greatly increase the bending stiffness of the structure, disproportionately to the amount of graphite added. A hybrid composite which has two graphite epoxy face sheets and a fiberglass epoxy core is significantly stiffer in bending than an all fiberglass structure as shown in Table 10. Graphite/glass hybrid composites that contain 20% graphite/80% glass (a=0.10) can be two to seven times as stiff as an all fiberglass composite. Hybridization in this manner results in a composite that has significantly improved flexural properties at significantly less cost than would be incurred with an all graphite composite. It should be noted that the effective tensile modulus of the hybrid is a function of the relative cross sections of the faces and the core and is not affected by the moment of inertia as indicated as well in Table 10.

It is envisioned that hybrids such as the ones described above will be used by the automotive industry. Depending upon the required mechanical properties, the core could be standard chopped random glass mat, high glass fiber chopped mat, filament wound continous glass such as XMC™ or fabric. The face sheets could vary as to graphite filament type, content, thickness and orientation. Design nomographs for various structural arrangements have been recently published by Kliger (14, 15).

Rapid curing graphite-glass hybrid polyester composites have been successfully made by Armco Corporation. In the Armco UMC™ process, chopped fibers and continuous reinforcing fibers are combined with polyester resins by a technique similar to the one used in the preparation of standard sheet molding compound, to produce a hybrid composite that can be compression molded to form components with excellent structural properties. The properties of representative UMC hybrid composites are presented in Table 11. The values of these materials normalized to those of steel are presented in Table 12. A UMC-graphite composites discussed in Tables 7 and 9 has an axial flexural modulus comparable to that of aluminum, and an axial flexural modulus comparable to that of steel, while being only one fifth as dense as steel. It is not as stiff as a unidirectional HM graphite laminate in the axial direction, but exhibits better transverse properties because of the contained chopped glass fibers.

TABLE 10 - EFFECTIVE FLEXURAL AND TENSILE MODULI OF GRAPHITE + GLASS HYBRID SANDWICH STRUCTURES

CORE MATERIAL	Longitudinal Mod. CORE MATERIAL, GPa	FACE MATERIAL	Longiqudinal Mod. FACE MATERIAL, GPa	RELATIVE THICKNESS OF FACE, a	EFFECTIVE FLEXURAL MODULUS, GPa	EFFECTIVE TENSILE MODULUS, GPa
Uniaxial E-glass/Epoxy Composite	39	Uniaxial Type A (high strength) Graphite Epoxy Composite	138	0	39	39
				0.05	66	49
				0.10	87	59
				0.20	117	79
				0.50	138	138
Uniaxial E-glass/Epoxy Composite	39	Uniaxial Type HM (high modulus) Graphite/Epoxy Composite	221	0	39	39
				0.05	88	57
				0.10	128	75
				0.20	176	112
				0.50	221	221
Chopped Glass/Epoxy Composite	15	Uniaxial Type HM (high modulus) Graphite/Epoxy Composite	221	0	15	15
				0.05	71	36
				0.10	116	56
				0.20	177	97
				0.50	221	221
Chopped Glass/Epoxy Composite	15	Quasi-Isotropic Type A Graphite Epoxy Composite	48	0	15	15
				0.05	24	18
				0.10	31	22
				0.20	41	28
				0.50	48	48
Chopped Glass/Epoxy Composite	15	Quasi-Isotropic Type HM Graphite Epoxy Composite	73	0	15	15
				0.05	31	21
				0.10	43	27
				0.20	65	38
				0.50	73	73



HYBRID SANDWICH STRUCTURE

TABLE 11 MECHANICAL PROPERTIES OF VARIOUS POLYESTER SMC COMPOSITES OF INTEREST

MATERIAL	STANDARD LOW PROFILE SMC	HIGH GLASS SMC	CONTINUOUS GLASS UMC	CONTINUOUS GLASS/ CHOPPED GLASS UMC	CONTINUOUS GRAPHITE/ CHOPPED GLASS UMC
Weight % Roving	0	0	70	40	30
Weight % Chopped	30	60	0	20	45
Weight % Total Fiber	30	60	70	60	75
Density, gr/cm^3	1.9	1.8	1.83	1.8	1.74
<u>AXIAL PROPERTIES</u>					
Flexural Strength, MPa	190	370	710	500	660
Flexural Modulus, GPa	11	15	35	29	55
Tensile Strength, MPa	90	170	430	340	520
Tensile Modulus, GPa	12	17	No Data	26	86
<u>TRANSVERSE PROPERTIES</u>					
Flexural Strength MPa	190	370	No Data	120	190
Flexural Modulus, GPa	11	15	No Data	9	9
Tensile Strength, MPa	90	170	No Data	42	90
Tensile Modulus, GPa	12	17	No Data	8	10

Source: Armo Composites Corporation, St. Charles, Illinois, July 21, 1978.

TABLE 12 NORMALIZED PROPERTIES OF VARIOUS POLYESTER SMC COMPOSITES OF INTEREST

MATERIAL	STANDARD LOW PROFILE SMC	HIGH GLASS SMC	CONTINUOUS GLASS UMC	CONTINUOUS GLASS/ CHOPPED GLASS UMC	CONTINUOUS GRAPHIT CHOPPED GLASS UMC
Weight % Roving	0	0	70	40	30
Weight % Chopped	30	60	0	20	45
Weight % Total Fiber	30	60	70	60	75
Density Ratio	0.24	0.23	0.23	0.23	0.22
AXIAL PROPERTIES					
Flexural Strength Ratio	0.34	0.67	1.29	0.91	1.20
Flexural Modulus Ratio	0.05	0.07	0.17	0.14	0.27
Tensile Strength Ratio	0.16	0.31	0.78	0.62	0.94
Tensile Modulus Ratio	0.06	0.08	----	0.13	0.42
TRANSVERSE PROPERTIES					
Flexural Strength Ratio	0.34	0.67	----	0.22	0.34
Flexural Modulus Ratio	0.05	0.07	----	0.04	0.04
Tensile Strength Ratio	0.16	0.31	----	0.08	0.16
Tensile Modulus Ratio	0.06	0.08	----	0.04	0.05

NOTE: Flexural properties of steel assumed equal to tensile properties of steel.

APPENDIX A. DETAILED ASSESSMENT

3.0 MATERIALS SUBSTITUTION ANALYSIS

3.1 Introduction

The potential weight saving that can be obtained by using ACM structures instead of steel structures in automobiles can be estimated by assuming that materials substitution will be made on a functional basis, and that the ACM structure will match or exceed the structural characteristics of the mild steel structure it replaces. The approach used in this report is an expansion of the methods developed by Chang and Justusson (1), who considered the substitution of mild steel by aluminum and HSLA steel in their analysis, and by Dharan (2), who considered a limited number of advanced composite structures. The method developed is limited to materials substitution for structurally equivalent components, and how functional and performance requirements place restrictions on those material substitutions. It does not consider design changes, even though an optimum lightweight design with ACM would realistically entail such design changes. The analysis, furthermore, does not take into account other considerations such as cost, ease of fabrication and durability.

The analysis focused on the replacement of a production mild steel structure with an "equivalent" structure of the same major dimensions, geometrical design characteristics and function, but of different material where gauge thickness can be adjusted to meet structural performance requirements such as stiffness, strength, fatigue strength, denting resistance, buckling resistance, and vibration response. The method, furthermore, assumes that the entire vehicle structure consists of simple elements that can be classified by structural functions either as:

a) panel members

b) thin-walled beam members

c) solid section members

d) thin walled tubes

Panel members (e.g., hood, roof panel and door panels) and thin walled beam members (e.g., chassis frame, pillars and rocker panels) are made from sheet stock and make up most of the vehicle structure. Solid section members (e.g., various reinforcement brackets, hinges, the hood latch support, as well as leaf springs) are used mainly as reinforcements, supports and linkages. Thin wall tubes are considered mainly in terms of rotating parts such as the drive shaft, but could also be used instead of open thin beam in structural supports.

By considering similar geometries for equivalent structures, for any structural criterion, the relative weight of a substituted material to that of steel reduces to being a function of the basic materials properties, namely the modulus of Elasticity, ultimate strength, yield strength, fatigue strength, Poisson's ratio, and density; and of the wall thickness. These relations are given in Tables 13 to 16 for the various geometries considered.

Using the material properties of the various ACM listed in Table 7, the relative weights of panel members, thin beams, solid sections and thin wall tubes, made from these materials to functionally equivalent structures made of steel, were calculated for the various design criteria listed in Tables 13 to 16.

The results of the analysis for the various materials listed in Table 7 are presented for the various geometries in Tables 17 to 20 respectively, and are discussed in the sections below.

3.2 Panel Members

As can be seen by examining Table 17, the weight limiting design criterion for panel members is oil canning, except for HM type and UHM type graphite epoxy composites for which local buckling was the limiting criterion. The structural weight necessary to meet these criteria results in a structure that is overdesigned in terms of all the other criteria. In calculating the buckling resistance, it was assumed that Poisson's ratio for the substituted material was equal to that of steel. This is not a bad assumption for unidirectional composites, but can result in errors in estimating

TABLE 13

COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS

FOR PANEL MEMBERS

- DIRECT SUBSTITUTION OF MATERIALS -

Structural Characteristic	Ratio of Structural Characteristics*	Thickness Ratio Required for Equal Structural Characteristics	Weight Ratio Required for Equal Structural Characteristics
Stiffness, S (Oil Canning Resistance)	$\frac{S_n}{S_o} = \frac{E_n}{E_o}\left(\frac{t_n}{t_o}\right)^2$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\right)^{1/2}$	$\frac{W_n}{W_o} = \frac{p_n}{p_o}\left(\frac{E_o}{E_n}\right)^{1/2}$
Denting Resistance, D	$\frac{D_n}{D_o} = \left(\frac{\sigma_{yn}(\dot{\epsilon})t_n^2}{\sigma_{yo}(\dot{\epsilon})t_o^2}\right)^2 \frac{S_o}{S_n}$	$\frac{t_n}{t_o} = \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}\left(\frac{E_n}{E_o}\right)^{1/2}$	$\frac{W_n}{W_o} = \frac{p_n}{p_o}\ \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}\left(\frac{E_n}{E_o}\right)^{1/2}$
Buckling Resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o}\ \frac{1-\nu_o^2}{1-\nu_n^2}\left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\nu_o^2}{1-\nu_n^2}\ \frac{E_o}{E_n}\right)^{1/3}$	$\frac{W_n}{W_o} = \frac{p_n}{p_o}\left(\frac{1-\nu_o^2}{1-\nu_n^2}\ \frac{E_o}{E_n}\right)^{1/3}$
Stress Yield Factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\epsilon})}{\sigma_{yo}(\dot{\epsilon})}\ \frac{E_o}{E_n}\ \frac{\bar{S}_n}{\bar{S}_o}$	$\frac{S_n}{S_o} = \frac{E_n}{E_o}\ \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}$	$\frac{W_n}{W_o} = \frac{p_n}{p_o}\left(\frac{E_n}{E_o}\right)^{1/2}\frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}$
Vibration Frequency	$\frac{F_n}{F_o} = \left(\frac{E_n\ t_n\ p_o}{E_o\ t_o\ p_n}\right)^{1/2}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}\ \frac{p_n}{p_o}$	$\frac{W_n}{W_o} = \left(\frac{p_n}{p_o}\right)^2\frac{E_o}{E_n}$

* Subscripts n and o refer to new material and original material

SOURCE: Reference 1.

TABLE 14

COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS

FOR THIN-WALLED BEAM MEMBERS

- DIRECT SUBSTITUTION OF MATERIAL -

Structural Characteristic	Ratio of Structural Characteristics*	Thickness Ratio Required for Equal Structural Characteristics	Weight Ratio Required for Equal Structural Characteristics
Bending Stiffness, S^b Buckling Resistance, B	$\frac{S_n^b}{S_o^b} = \frac{B_n}{B_o} = \frac{E_n}{E_o}\frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$	$\frac{W_n}{W_o} = \frac{P_n}{P_o} \cdot \frac{E_o}{E_n}$
Local Buckling Resistance, L	$\frac{L_n}{L_o} = \frac{E_n}{E_o}\frac{1-\nu_o^2}{1-\nu_n^2}\left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\nu_o^2}{1-\nu_n^2}\frac{E_o}{E_n}\right)^{1/3}$	$\frac{W_n}{W_o} = \frac{P_n}{P_o}\left(\frac{1-\nu_o^2}{1-\nu_n^2} \cdot \frac{E_o}{E_n}\right)^{1/3}$
Crippling Resistance, C	$\frac{C_n}{C_o} = \left(\frac{E_n}{E_o}\frac{\sigma_{yn}}{\sigma_{yo}}\right)^{\frac{1}{2}}\left(\frac{t_n}{t_o}\right)^{1.75}$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\frac{\sigma_{yo}}{\sigma_{yn}}\right)^{1/3.5}$	$\frac{W_n}{W_o} = \frac{P_n}{P_o}\left(\frac{E_o}{E_n}\frac{\sigma_{yo}}{\sigma_{yn}}\right)^{1/3.5}$
Stress Yield Factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\varepsilon)}{\sigma_{yo}(\varepsilon)}\frac{E_o}{E_n}\frac{\bar{S}_n}{\bar{S}_o}$	$\frac{\bar{S}_n}{\bar{S}_o} = \frac{E_n}{E_o}\frac{\sigma_{yo}(\varepsilon)}{\sigma_{yn}(\varepsilon)}$	$\frac{W_n}{W_o} = \frac{P_n}{P_o}\frac{\sigma_{yo}(\dot{\varepsilon})}{\sigma_{yn}(\dot{\varepsilon})}$
Vibration Frequency, F	$\frac{F_n}{F_o} = \left(\frac{E_n}{E_o}\frac{P_o}{P_n}\right)^{\frac{1}{2}}$	---	---

* Subscripts n and o refer to new material and original material

SOURCE: Reference 1.

TABLE 15

COMPARISON OF REQUIRED STRUTURAL CHARACTERISTICS

FOR SOLID SECTIONS

DIRECT SUBSTITUTION OF MATERIAL

STRUCTURAL CHARACTERISTICS	RATIO OF STRUCTURAL CHARACTERISTICS*	THICKNESS RATIO REQUIRED FOR EQUAL STRUCTURAL CHARACTERISTICS	WEIGHT RATIO REQUIRED FOR EQUAL STRUCTURAL CHARACTERISTICS
Equal Bending Stiffness	$\frac{Sn}{So} = \frac{En}{Eo} \left(\frac{tn}{to}\right)^3$	$\frac{tn}{to} = \left(\frac{Eo}{En}\right)^{1/3}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right) \left(\frac{Eo}{En}\right)^{1/3}$
Equal Bending Moment Resistance	$\frac{Mn}{Mo} = \frac{\sigma n}{\sigma o} \left(\frac{tn}{to}\right)^2$	$\frac{tn}{to} = \left(\frac{\sigma o}{\sigma n}\right)^{1/2}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right) \left(\frac{\sigma o}{\sigma n}\right)^{1/2}$
Equal Bending Moment Resistance in Fatigue	$\frac{M^F n}{M^F a} = \frac{\sigma n^F}{\sigma o^F} \left(\frac{tn}{to}\right)^2$	$\frac{tn}{to} = \left(\frac{\sigma o^F}{\sigma n^F}\right)^{1/2}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right) \left(\frac{\sigma o^F}{\sigma n^F}\right)^{1/2}$

* Subscripts n and o refer to new material and original material

SOURCE: Reference 2.

TABLE 16

COMPARISON OF REQUIRED STRUCTURAL CHARACTERISTICS FOR THIN TUBES DIRECT SUBSTITUTION OF MATERIALS

Structural Characteristics	Ratio of Structural Characteristics*	Thickness Ratio Required for Equal Structural Characteristics	Weight Ratio Required for Equal Structural Characteristics
Torsional Stiffness	$\frac{Sn}{So} = \left(\frac{tn}{to}\right)\left(\frac{Gn}{Go}\right)$	$\frac{tn}{to} = \frac{Go}{Gn}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right)\left(\frac{Go}{Gn}\right)$
Torsional Strength	$\frac{Tn}{To} = \left(\frac{tn}{to}\right)\left(\frac{\tau n}{\tau o}\right)$	$\frac{tn}{to} = \frac{\tau o}{\tau n}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right)\left(\frac{\tau o}{\tau n}\right)$
Torsional Fatigue Strength	$\frac{Tn^F}{To^F} = \left(\frac{tn}{to}\right)\left(\frac{\tau n^F}{\tau o^F}\right)$	$\frac{tn}{to} = \frac{\tau o^F}{\tau n^F}$	$\frac{Wn}{Wo} = \left(\frac{Pn}{Po}\right)\left(\frac{\tau o^F}{\tau n^F}\right)$

* Subscripts n and o refer to new material and original material

SOURCE: References 1, 2.

TABLE 17 - DIRECT SUBSTITUTION OF MATERIALS

WEIGHT RATIOS (RELATIVE TO STEEL) REQUIRED TO OBTAIN EQUAL STRUCTURAL CHARACTERISTICS FOR PANEL MEMBERS

MATERIALS	Fiber Lay Up Geometry	EQUAL STIFFNESS OIL CANNING $\frac{Wc}{Ws} = \frac{Pc}{Ps}\left(\frac{Es}{Ec}\right)^{1/2}$	EQUAL DENTING RESISTANCE $\frac{Wc}{Ws} = \left(\frac{Pc}{Ps}\right)\left(\frac{Ec}{Es}\right)^{1/2}\left(\frac{\sigma ys}{\sigma yc}\right)$	EQUAL BUCKLING RESISTANCE (x) $\frac{Wc}{Ws} = \left(\frac{Pc}{Ps}\right)\left(\frac{Es}{Ec}\frac{1-\nu s^2}{1-\nu c^2}\right)^{1/3}$	EQUAL STRESS YIELD FACTOR $\frac{Wc}{Ws} = \left(\frac{Pc}{Ps}\right)\left(\frac{Ec}{Es}\right)^{1/2}\left(\frac{\sigma ys}{\sigma yc}\right)$	EQUAL VIBRATION FREQUENCY $\frac{Wc}{Ws} = \left(\frac{Pc}{Ps}\right)^2\left(\frac{Es}{Ec}\right)$
A Type Graphite Epoxy	Unidirectional (0°)	0.245	0.045	0.229	0.045	0.060
	Crossply (0°, 90°)	0.335	0.059	0.282	0.059	0.112
	Crossply (+45°)	0.694	0.173	0.358	0.173	0.482
	Isotropic (0°, 90°, ±45°)	0.415	0.066	0.325	0.056	0.172
	Harness Satin Weavecloth	0.365	0.098	0.299	0.093	0.133
HM Type Graphite Epoxy	Unidirectional (0°)	0.197	0.072	0.200	0.072	0.039
	Crossply (0°, 90°)					
	Crossply (±45°)	0.708	0.196	0.468	0.196	0.501
	Isotropic (0°, 90°, ±45°)	0.343	0.145	0.289	0.145	0.118
UHM Type Graphite/Epoxy	Unidirectional (0°)	0.177	0.141	0.188	0.141	0.031
	Crossply (0°, 90°)	0.244	0.193	0.234	0.193	0.060
	Crossply (±45°)	0.677	0.290	0.461	0.290	0.458
	Isotropic (0°, 90°, ±45°)	0.303	0.259	0.270	0.259	0.092
E-Glass/Epoxy	Unidirectional (0°)	0.528	0.037	0.400	0.037	0.279
	Crossply (0°, 90°)	0.661	0.159	0.463	0.159	0.433
	Crossply (±45°)	0.995		0.610		0.989
	Isotropic (0°, 90°, ±45°)	0.776	0.202	0.517	0.202	0.603
	Chopped Fiber	0.883	0.355	0.570	0.355	0.780
S-Glass/Epoxy	Unidirectional (0°)	0.496	0.028	0.389	0.028	0.246
	Crossply (0°, 90°)	0.617		0.450		0.381
	Crossply (+45°)	0.861		0.562		0.742
	Isotropic (0°, 90°, ±45°)	0.687		0.483		0.472
Kevlar/Epoxy	Unidirectional (0°) (Composite)	0.396	0.157	0.302	0.157	0.156
	Crossply (0°, 90°)					
	Crossply (±45°)	0.915	0.090	0.528	0.090	0.837
	Isotropic (0°, 90°, ±45°)					
	181 Fabric (Warp) (50%)	0.454	0.218	0.331	0.218	0.207
	Chopped Fiber (50%)	0.539	0.147	0.366	0.147	0.291
Aluminum 6061-T6		0.583	0.308	0.489	0.308	0.340
Steel, Cold Rolled (0.2% Carbon)		1.0	1.0	1.0	1.0	1.0

(x) Assume $\nu c = \nu s$

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TABLE 18 - DIRECT SUBSTITUTION OF MATERIALS

WEIGHT RATIOS (RELATIVE TO STEEL) REQUIRED TO OBTAIN EQUAL STRUCTURAL CHARACTERISTICS FOR THIN WALLED BEAM MEMBERS

MATERIAL	Fiber Lay Up Geometry	EQUAL BENDING STIFFNESS BUCKLING RESISTANCE $\frac{Wc}{Ws} = (\frac{Pc}{Ps})(\frac{Es}{Ec})$	EQUAL LOCAL BUCKLING* RESISTANCE $\frac{Wc}{Ws} = \frac{Pc}{Ps}(\frac{1-v_s^2}{1-v_c^2})\frac{Es}{Ec}^{1/3}$	EQUAL CRIPPLING RESISTANCE $\frac{Wc}{Ws} = \frac{Pc}{Ps}(\frac{Es}{Ec}\frac{\sigma^*s}{\sigma^*c})^{1/3.5}$	EQUAL STRESS YIELD FACTOR $\frac{Wc}{Ws} = (\frac{Pc}{Ps})(\frac{\sigma^*s}{\sigma^*c})$
A Type Graphite Epoxy	Unidirectional (0°)	0.300	0.229	0.155	0.055
	Crossply (0°, 90°)	0.560	0.282	0.220	0.099
	Crossply (±45°)	2.410	0.458	0.557	0.600
	Isotropic (0°, 90°, ±45°)	0.862	0.325	0.273	0.137
	Harness Satin Weavecloth	0.667	0.299	0.273	0.179
HM Type Graphite Epoxy	Unidirectional (0°)	0.191	0.200	0.147	0.093
	Crossply (0°, 90°)				
	Crossply (±45°)	2.458	0.468	0.586	0.907
	Isotropic (0°, 90°, ±45°)	0.578	0.289	0.289	0.326
UHM Type Graphite Epoxy	Unidirectional (0°)	0.146	0.188	0.161	0.156
	Crossply (0°, 90°)	0.278	0.234	0.233	0.294
	Crossply (±45°)	2.140	0.461	0.626	1.223
	Isotropic (0°, 90°, ±45°)	0.430	0.270	0.305	0.489
Kevlar/Epoxy	Unidirectional (0°)	0.889(compression)	0.302	0.314	0.264
	Crossply (0°, 90°)				
	Crossply (±45°)	4.757	0.528	0.550	0.352
	Isotropic (0°, 90°, ±45°)				
	181 Fabric Warp (50%)	1.173	0.331	0.422	0.564
	Chopped Fiber	1.732	0.366	0.440	0.473
S-Glass/Epoxy	Unidirectional (0°)	1.030	0.389	0.241	0.057
	Crossply (0°, 90°)	1.593	0.450		
	Crossply (±45°)	3.104	0.562		
	Isotropic (0°, 90°, ±45°)	1.975	0.483		
E-Glass/Epoxy	Unidirectional (0°)	1.218	0.400	0.279	0.086
	Crossply (0°, 90°)	1.893	0.463	0.578	0.570
	Crossply (±45°)	4.321	0.610		
	Isotropic (0°, 90°, ±45°)	2.632	0.517	0.822	1.068
	Chopped Fiber	3.292	0.570	0.241	1.324
Aluminum 6061 T6		0.989	0.489	0.618	0.929
Steel, Cold Rolled, (0.2% Carbon)		1.0	1.0	1.0	1.0

* Assume $V_c = V_s$

TABLE 19 - DIRECT SUBSTITUTION OF MATERIALS

WEIGHT RATIOS (RELATIVE TO STEEL) REQUIVED TO OBTAIN EQUAL STRUCTURAL CHARACTERISITCS FOR SOLID SECTIONS

MATERIAL	Fiber Lay Up Geometry	EQUAL BENDING STIFFNESS $\frac{Wc}{Ws} = (\frac{Pc}{Ps}) (\frac{Es}{Ec})^{1/3}$	EQUAL BENDING MOMENT $\frac{Wc}{Ws} = (\frac{Pc}{Ps}) (\frac{\sigma s}{\sigma c})^{1/2}$	EQUAL BENDING MOMENT WITH FATIGUE $\frac{Wc}{Ws} = (\frac{Pc}{Ps}) (\frac{\sigma fs}{\sigma fc})^{1/2}$
A Type Graphite-Epoxy	Unidirectional (0^0)	0.229	0.121	0.058
	Crossply (0^0, 90^0)	0.282	0.163	0.116
	Crossply ($\pm45^0$)	0.458	0.400	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.325	0.191	0.133
	Harness Satin Weavecloth	0.299	0.219	
IM Type Graphite-Epoxy	Unidirectional (0^0)	0.200	0.138	
	Crossply (0^0, 90^0)			
	Crossply ($\pm45^0$)	0.468	0.430	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.289	0.258	
UHM Type Graphite-Epoxy	Unidirectional (0^0)	0.188	0.183	
	Crossply (0^0, 90^0)	0.234	0.251	
	Crossply ($\pm45^0$)	0.461	0.512	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.270	0.323	
Kevlar 49/Epoxy	Unidirectional (0^0)	0.302	0.249	
	Crossply (0^0, 90^0)			
	Crossply ($+45^0$)	0.528	0.287	
	Isotropic (0^0, 90^0, $\pm45^0$)			
	181 Fabric Warp (50%)	0.331	0.315	
	Chopped Fiber (50%)	0.266	0.282	
S-Glass/Epoxy	Unidirectional (0^0)	0.389	0.135	
	Crossply (0^0, 90^0)	0.450	0.179	
	Crossply ($\pm45^0$)	0.562	0.431	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.483	0.208	
E-Glass/Epoxy	Unidirectional (0^0)	0.400	0.162	0.160
	Crossply (0^0, 90^0)	0.463	0.236	0.348
	Crossply ($\pm45^0$)	0.610	0.437	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.517	0.296	0.514
	Chopped Fiber	0.570	0.560	
Aluminum	6061 T-6	0.489	0.459	0.738
Steel, Cold Rolled (0.2% carbon)		1.0	1.0	1.0

TABLE 20 - DIRECT SUBSTITUTION OF MATERIALS

WEIGHT RATIOS (RELATIVE TO STEEL) TO OBTAIN EQUAL STRUCTURAL CHARACTERISTICS FOR CONSTANT DIAMETER THIN WALLED TUBES

Materials	Fiber Lay Up Geometry	EQUAL TORSIONAL STIFFNESS $\frac{W_c}{W_s} = (\frac{\rho_c}{\rho_s})(\frac{G_s}{G_c})$	EQUAL TORSIONAL STRENGTH $\frac{W_c}{W_s} = (\frac{\rho_c}{\rho_s})(\frac{\tau_s}{\tau_c})$	EQUAL TORSIONAL FATIGUE STRENGTH $\frac{W_c}{W_s} = (\frac{\rho_c}{\rho_s})(\frac{\tau_s^f}{\tau_c^f})$
A Type Graphite Epoxy	Unidirectional (0^0)	3.704	0.855	0.200
	Crossply (0^0, 90^0)	3.704	0.855	0.430
	Crossply ($\pm45^0$)	0.536	0.240	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.935	0.375	0.198
	Harness Satin Weavecloth			
HM Type Graphite Epoxy	Unidirectional (0^0)	3.517	1.222	
	Crossply (0^0, 90^0)	3.517	1.222	
	Crossply ($\pm45^0$)	0.378	0.291	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.682	0.472	
UHM Type Graphite Epoxy	Unidirectional (0^0)	2.675	1.845	1.805
	Crossply (0^0, 90^0)	2.675	1.845	3.922
	Crossply ($\pm45^0$)	0.224	0.428	
	Isotropic (0^0, 90^0, $\pm45^0$)	0.415	0.693	2.087
Kelvar 49/Epoxy	Unidirectional (0^0)	7.56	1.78	0.365
	Crossply (0^0, 90^0)			
	Crossply ($\pm45^0$)	0.707	0.330	
	Isotropic (0^0, 90^0, $\pm45^0$)			
	181 Fabric			
	Chopped Fiber			
S-Glass/Epoxy	Unidirectional (0^0)	5.83	9.95	
	Crossply (0^0, 90^0)			
	Crossply ($\pm45^0$)			
	Isotropic (0^0, 90^0, $\pm45^0$)			
E-Glass/Epoxy	Unidirectional (0^0)	9.16		
	Crossply (0^0, 90^0)			
	Crossply ($\pm45^0$)			
	Isotropic (0^0, 90^0, $\pm45^0$)			
	Chopped Fiber			
Aluminum	6061 T-6	1.089	0.688	1.778
Steel, Cold Rolled (0.2% Carbon)		1.0	1.0	1.0

the equivalent structural weight for buckling of the order of 15% for cross-plied composites. However, for these materials, the weight needed to meet the oil canning criterion is much larger than the possible error in the calculated weight needed to meet buckling requirements, so the issue becomes of little consequence.

For any composite, the relative weight of an equivalent composite part depends strongly on the lay-up of the composite. The lowest weight ratios are obtained with unidirectional composites, and the highest weight ratios obtained for composite panels at $\pm 45^{\circ}$. Since panels are likely to be subjected to omnidirectional stresses in use, it is unlikely that unidirectional composites would be used in panel members. These structures would most likely be made from multidirectional fiber composites.

The relative weights of panels made from various quasi-isotropic composites, and aluminum, that are equivalent to steel panels are presented in Table 21. Depending on the modulus of the graphite fiber, weight ratios for graphite panels range from about 0.30 to 0.42. In comparison, for fiberglass reinforced panels, these ratios range from about 0.69 to 0.78 depending on the properties of the fiberglass; and would be approximately 0.58 for aluminum.

It is expected that the steel equivalent weight ratio for a comparable hybrid composite would be of the order of 0.5 to 0.6. Weight savings that would be obtainable by using hybrid composites in a structure were calculated for the two quasi-isotropic graphite faced/chopped glass core hybrids presented in Table 10. These results are presented in Table 22. Using HM graphite in a hybrid results in greater weight reduction than using HS graphite. The weight reduction available with a 10% HM graphite hybrid is equivalent to that which would be obtained with 20% Type A graphite hybrid or with aluminum.

It is useful to compare these calculated values with the weight ratios actually obtained with the prototype components listed in Tables 1 and 2 that can be treated as panel members. The reported

TABLE 21

ESTIMATED WEIGHT SAVINGS FOR PANEL MEMBERS DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF EQUIVALENT PANEL	EQUIVALENT WEIGHT SAVING %
Type UHM Graphite/Epoxy Q.I. Composite	0.303	69.7
Type HM Graphite/Epoxy Q.I. Composite	0.343	65.7
Type A Graphite/Epoxy Q.I. Composite	0.415	50.5
S Glass/Epoxy Q.I. Composite	0.687	31.3
E Glass/Epoxy Q.I. Composite	0.776	22.4
Aluminum	0.583	41.7
Steel	1.0	0

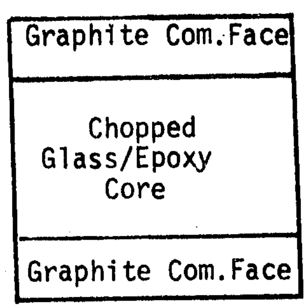
TABLE 22

WEIGHT REDUCTION* ATTAINABLE WITH

REPRESENTATIVE GRAPHITE/GLASS HYBRID COMPOSITES

PERCENT GRAPHITE	ISOTROPIC TYPE A GRAPHITE/EPOXY FACE	ISOTROPIC TYPE HM GRAPHITE/EPOXY FACE
	Wc/Ws	Wc/Ws
0	0.89	0.89
10	0.68	0.59
20	0.59	0.50
40	0.49	0.39
100	0.42	0.34

*Assuming $\frac{W_c}{W_s} = \frac{\rho_c}{\rho_s} \left(\frac{E_s}{E_c}\right)^{\frac{1}{2}}$ (oil canning criterion)



Hybrid
Composite
Structure

values of W_c/W_s for the Ford hood (0.38), and the Ford door frame (0.42), and a Hercules hood (0.40) are not significantly different than the calculated value of 0.42 obtained for a quasi-isotropic Type A graphite epoxy composite.

The Hercules Fiesta hood has a much lower value of $\frac{Wc}{Ws} = 0.25$. This hood is made of 4-ply graphite composite - 2 plies of unidirectional HM type graphite and two plies of Type A graphite cloth built up selectively over a Nomex[R] core. Assuming that the unidirectional plies are on the outside, the effective flexure modulus of this assembly is calculated to be 155 GPA, so that Ec/Es = 0.864. Assuming that the oil canning criterion governs the design, a weight ratio of 0.23 is calculated. This value is only slightly lower than the reported value given above.

3.3 Thin Beam Structures

As can be seen by examining Table 18, the weight limiting design criterion is bending resistance, except for HM and UHM graphite composites, in which case local buckling is the limiting criterion.

There is little difference in the weight ratios calculated of HM and UHM graphite composites because the relative strengths and moduli for these grades of graphite appear to balance out.

While the weight of a steel equivalent composite thin beam structure decreases with increasing modulus of the composite, it also is strongly dependent on the lay-up of the composite, as outlined in Table 23. The range of practical options ranges from a unidirectional fiber composite if the component is loaded in a single direction, to isotropic laminates which would be needed if the component were subjected to torsion and buckling. If the structure can be made with a unidirectional composite, a graphite composite structure would weigh only 0.2 to 0.3 times as much as the equivalent steel structure, depending on the modulus of the fiber.

If isotropic laminates are considered, much more modest weight savings can be expected. Very modest weight savings would be obtained with Type A graphite isotropic composite structures, while reduction of 40% and 60% could be obtained with Type HM and UHM structures respectively. Since most of the components would not be stressed uniformly, the structure would be designed with a preferential orientation. Therefore, in practice, it is expected that actual weight savings with any material system would be intermediate to the values presented in Table 23.

Thin beams, as defined in this study, are not effective applications for the other materials listed in Table 23: Kevlar 49-epoxy composites, glass-epoxy composites, and aluminum. With the fibrous composites, unidirectional laminates only result in a minor weight reduction (Kevlar 49), or a modest weight increase. If isotropic laminates are used in lieu of steel, a significant weight increase occurs. The equivalent weight of aluminum is about the same as the weight of the original steel.

The weights of steel equivalent hybrid composite thin beams for different fiber lay-ups, are presented in Table 24. The calculated weight ratios assume that bending resistance is the design criterion. With hybrids, weight savings are achieved only if the face sheets contain uniaxial graphite fibers. If the face sheets contain isotropic graphite fibers, hybrid substitution will result in a weight gain. The amount of hybrid required decreases as the thickness of the face sheets increase, and with the modulus of the graphite fiber in the face sheet, and as previously implied, with the geometry of the fiber lay-up.

These results reflect the sensitivity of the calculations to the relative value of the modulus of steel to the modulus of the substituted material, as well as to the relative value of the density of the substituted material to the density of steel. In the bending resistance criterion, both these ratios appear to the first power. Except for the high modulus graphite composites, the low values of the density ratio are offset by high values of the modulus ratio. For other structural shapes, criteria which are a function of the modulus ratio vary less because this ratio appears to a fractional power, typically 0.5 or 0.33. In these cases, the value of the density ratio dominates, so that substitution can result in more significant weight savings.

TABLE 23

ESTIMATED WEIGHT REDUCTION FOR THIN BEAM MEMBERS
DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF STEEL EQUIVALENT PANELS Wc/Ws	
	UNIDIRECTIONAL LAMINATE	ISOTROPIC LAMINATE
Type A (High Strength) Graphite-Epoxy	0.30	0.86
Type HM Graphite-Epoxy	0.20	0.58
Type UHM Graphite-Epoxy	0.19	0.43
Kevlar 49 - Epoxy	0.89	
S-Glass - Epoxy	1.03	1.89
E-Glass - Epoxy	1.22	2.63
Aluminum	0.99	0.99

TABLE 24

ESTIMATED WEIGHT SAVINGS FOR SELECTED EPOXY HYBRID COMPOSITE THIN BEAM MEMBERS

FACE SHEET REINFORCEMENT	CORE REIN-FORCEMENT	THICKNESS FACE SHEETS	BENDING RELATIVE WEIGHT OF COMPOSITE WITH EQUIVALENT BENDING RESISTANCE, W_c/W_s
Uniaxial Type A/ Graphite	Uniaxial E-Glass	0.10	0.72
Uniaxial Type A/ Graphite	Uniaxial E-Glass	0.20	0.55
Uniaxial Type HM/ Graphite	Uniaxial E-Glass	0.10	0.54
Uniaxial Type HM/ Graphite	Uniaxial E-Glass	0.20	0.37
Uniaxial Type HM/ Graphite	Chopped Glass	0.10	0.67
Uniaxial Type HM/ Graphite	Chopped Glass	0.20	0.41
Isotropic Type A/ Graphite	Chopped Glass	0.10	1.98
Isotropic Type A/ Graphite	Chopped Glass	0.20	1.54
Isotropic Type HM/ Graphite	Chopped Glass	0.10	1.54
Isotropic Type HM/ Graphite	Chopped Glass	0.20	1.11

The door guard beams, the suspension arms, and the transmission supports reported in Tables 1 and 2 can be considered to be thin beam structures in terms of the present discussion. For these members, the reported values of Wc/Ws vary. They are 0.23 for the transmission support, 0.34 for the AC brace, 0.44 for the suspension arms, and 0.62 for an intrusion beam. Since the fiber arrangement of these structures is not public knowledge, it is not possible to calculate model values of the weight ratios. The weight ratio for the transmission support indicates that it contains mainly unidirectional HM fiber. The weight ratio for the suspension arm indicates the use of some crossplies in a predominantly unidirectional composite. The high value of Wc/Ws reported for the intrusion beam indicates either significant crossplying or the use of a hybrid composite with a high fiberglass content.

3.4 Solid Section Members

As can be seen by examining Table 19, the weight limiting criterion for solid sections is bending stiffness. Because of the cube root relationship of the modulus ratio, weight reduction is dominated by the density ratio. As summarized in Table 25, all the light weight composite materials listed in Table 19 can result in significant weight reduction. Furthermore, the spread in weight reduction between unidirectional and crossplied composites is smaller than in the cases previously considered. The weight ratios for graphite composites range from about 0.2 for unidirectional composites to 0.3 for isotropic composites, with a $\pm 10\%$ variation due to differences in fiber modulus. For fiberglass composites the comparable weight ratios are about 0.4 and 0.5. It is to be noted that the weight ratio for aluminum (0.74) is much higher because in this case, it appears that fatigue strength is the limiting criterion. In the worst case, if bending stiffness were limiting, the aluminum weight ratio would be 0.49.

The weight reductions that are achieved with the graphite/glass hybrid composites listed in Table 10 are summarized in Table 26. While glass composite structures are much lighter than the

TABLE 25

ESTIMATED WEIGHT REDUCTION FOR
SOLID MEMBERS DUE TO MATERIALS SUBSTITUTION

MATERIAL	RELATIVE WEIGHT OF STEEL EQUIVALENT STRUCTURE Wc/Ws*	
	Unidirectional Laminate	Isotropic Laminate
Type A (High Strength) Graphite-Epoxy	0.23	0.33
Type HM Graphite - Epoxy	0.20	0.29
Type UHM Graphite - Epoxy	0.19	0.27
Kevlar 49 - Epoxy	0.30	0.40-0.45 (est.)
S-Glass - Epoxy	0.39	0.48
E-Glass - Epoxy	0.40	0.52
Aluminum	← 0.74 →	

* Based on bending stiffness, except for aluminum for which fatigue strength is calculated to be the limiting criterion.

TABLE 26

ESTIMATED WEIGHT REDUCTION FOR SOLID MEMBERS DUE TO MATERIALS SUBSTITUTION WITH SELECTED GRAPHITE/GLASS HYBRID EPOXY COMPOSITES

TOTAL THICKNESS OF FACES (2a)		0	0.1	0.2	0.4	1.0
FACE MATERIAL	CORE MATERIAL	RELATIVE WEIGHT OF STEEL EQUIVALENT STRUCTURE Wc/Ws				
Unidirectional Type A Graphite	Unidirectional E-Glass Fiber	0.40	0.34	0.31	0.28	0.23
Unidirectional Type HM Graphite	Unidirectional E-Glass Fiber	0.40	0.31	0.27	0.24	0.20
Unidirectional Type HM Graphite	Chopped E-Glass Fiber	0.58	0.33	0.28	0.24	0.20
Quasi Isotropic Type A Graphite	Chopped E-Glass Fiber	0.58	0.47	0.43	0.40	0.33
Quasi Isotropic Type HM Graphite	Chopped E-Glass Fiber	0.58	0.43	0.39	0.34	0.29

equivalent steel structures, significant further weight reductions can be achieved by the use of even small amounts of graphite fibers, especially HM type graphite.

Many of the prototype automotive components that have been developed to date can be classified as solid section members. These include door hinges ($\frac{Wc}{Ws}$ = 0.21 (lower hinge) and $\frac{Wc}{Ws}$ = 0.29 (upper hinge)), a bumper backup beam ($\frac{Wc}{Ws}$ = 0.23), air conditioner support brackets ($\frac{Wc}{Ws}$ = 0.21 for a graphite composite, and $\frac{Wc}{Ws}$ = 0.27 for a continuous graphite/chopped glass hybrid), and a number of leaf springs (for which reported values of $\frac{Wc}{Ws}$ range from 0.18 to 0.30).

All these components have a weight ratio, when compared to the steel equivalent structure, of less than 0.30, which agrees well with the expected values of weight ratio presented in Tables 24 and 25.

Leaf springs are mainly stressed along their longidudinal axes. The value of Wc/Ws = 0.20 for a unidirectional HM graphite epoxy laminate is the same as the value of $\frac{Wc}{Ws}$ reported by Hercules for prototype leaf spring. The value of $\frac{Wc}{Ws}$ = 0.30 for a graphite/glass hybrid spring correspond closely to the values expected for typical graphite/glass hybrids.

The relative weight (Wc/Ws = 0.30) of the high strength graphite leaf spring developed by Dharan (2) is larger than the value $\frac{Wc}{Ws}$ = 0.23) predicted for this type of composite in Table 24. According to Dharan, this is because the composite prototype leaf spring had a constant cross-section whereas the steel leaf spring was tapered, and thus the two designs are not strictly comparable.

The value of $\frac{Wc}{Ws}$ = 0.18 reported by Union Carbide for a glass/graphite hybrid leaf spring is much lower than the value expected from the calculations. It may be that this particular composite spring replaced an overdesigned steel spring.

3.5 Thin Wall Tubes

Table 20 considers the case of thin walled tubes subjected to a significant torsional load, where equal torsional stiffness becomes the weight limiting criterion. Substitution of steel by fibrous composites leads to significant weight reduction only if $\pm 45^{\circ}$ crossplied composites are used. Unidirectional composites are significantly less effective than steel in torsion and their use results in a significant weight penalty. A difficulty in using $\pm 45^{\circ}$ crossplied alone is that these materials exhibit relatively poor axial stiffness characteristics, as indicated in Table 18 which also applies to thin wall tubes. If both axial stiffness and torsional stiffness are of concern, it is necessary to consider using quasi-isotropic composites. In this instance, it is necessary to consider Type HM or Type UHM composites to attain significant weight reduction.

The above criteria apply to tubes subjected to static loads. When dealing with a rotating tube, as in the case of an automotive drive shaft, the parameters that control the design are the first bending mode resonant frequency, fatigue torque and impact torque. As shown by the following equation, the first natural frequency in bending of a thin walled tube is (2):

$$F = \frac{1}{2\pi} \left(\frac{\pi^2}{\ell^2}\right) R \left(\frac{E_L}{2\rho}\right)^{\frac{1}{2}}$$

where:

F = resonant frequency
ℓ = length of the tube between supports
R = tube radius, internal
E_L = longitudinal modulus of the tube
ρ = density of tube material.

The above equation indicates that, for a homogeneous isotropic material, the resonant frequency is proportional to the shaft diameter, inversely proportional to the square of the shaft length, and is independent of the wall thickness. It is also proportional to the square root of the specific modulus (E/ρ). This characteristic leads to considering a uniaxial graphite composite, with its high stiffness to weight ratio, in this application. However, as noted in Table 20, the uniaxial composite has poor torsional strength when compared to $\pm 45^{\circ}$ crossplied materials or even aluminum. In order to obtain both the torsional strength and the bending stiffness that are required, hybrid tubes have been developed in which the inner layers are designed to provide the required torsional strength, with the outer layers providing the desired bending stiffness.

The various approaches to the design of composite driveshafts that have been taken differ mainly in the choice of materials used to provide the torsional strength. As outlined in Table 3, Dharan used an inner graphite composite structure, Exxon/Graphtek is a proponent of aluminum, while Shakespeare uses fiberglass-graphite hybrids. In all cases, the stiffness is provided by an external layer of uniaxial graphite composite. As indicated by Exxon/Graphtek, the graphite composite represents only a small fraction (10%) of the weight of the shaft (16).

The relative weight of a drive shaft containing graphite when compared to a steel drive shaft depends in large on the basis of comparison. When the weight of the tubes alone are considered, typical weight ratios range from 0.32 (all graphite shafts) to 0.38 (aluminum-graphite hybrids). However, when the fittings and mountings are included, the weight ratios are higher (0.42 to 0.54), since the metal end fittings represent a significant part of the weight of a graphite containing drive shaft.

An important factor in considering the use of graphite composites in a drive shaft, is that it might be possible to increase the length between supports without reaching the critical frequency. In many truck applications, this results in a one piece graphite reinforced shaft replacing a two piece steel shaft. Calculated weight savings then will take into account the weight of the intermediate support structure that was eliminated. This also has significant cost considerations.

APPENDIX A. DETAILED ASSESSMENT

4.0 PROJECTED USE OF ACM IN COMPONENTS FOR LTV

4.1 Introduction

In this section, the potential reduction in the weight of a LTV that can be achieved by replacing steel components with equivalent components made of ACM is analyzed. This analysis considers two scenarios. In the first case, all out use of ACM in automotive structures is considered so as to establish the maximum weight reduction that is technically feasible with this technology, without any considerations given to the associated costs. The second scenario considers that the actual use of ACM will be constrained by cost considerations. Within these constraints, it is expected that ACM will find widespread use in those components where this results in significant weight reduction when compared to steel but at no additional cost to the manufacturer. In addition, it is also expected that ACM materials will also be used less extensively in structures that can be economically justified on a life cycle cost basis. The manufacturer provides the consumer a larger, more fuel efficient vehicle that is less costly to operate, even though it may be more expensive to purchase.

4.2 Methodology

The analysis was based on the replacement of steel components of known weight in a given automobile by selected ACM. The weight of the equivalent composite component was then calculated on the basis of the relative material properties, taking into account component geometry. The sum of the weights of the steel components minus the sum of the weights of the equivalent composites is the direct weight reduction achieved. This direct weight reduction, obtained by substituting lighter materials, is further augmented by secondary weight reductions in the rest of the vehicle. Thus, the substitution of a lighter body structure results in smaller brakes, tires, engine, fuel tank, etc., which, in turn, lead to additional weight reduction. This secondary weight reduction is usually expressed as a factor proportional to the direct weight reduction. The sum of the two weights is then the total weight reduction obtained as a result of the use of ACM.

4.2.1 Reference Automobile

The vehicle used in the analysis was a 1975 Chevelle Coupe, specifically a Model 1AC37 Malibu Colonnade HTR Coupe equipped with a 250-1BBL L6 engine and a three speed transmission, with essentially no optional equipment. This vehicle has a curb weight of 3643 lbs. This was the vehicle described in great detail by Harvey and Chupinsky of Pioneer Engineering and Manufacturing Company in a recent report prepared for NHTSA (17). This report lists the various components and subcomponents of the car, detailing among other information, their weight and materials of construction.

4.2.2 Candidate Components for Materials Substitution

The components of the reference vehicle that were considered candidates for materials substitution are listed in Table 27. ACM prototypes of these components, or very similar components have been built and tested, as described in prior sections of this report. The list basically consists of structural steel elements of the vehicle body and of the chassis that operate at ambient conditions. The only components presented in Table 27 for which no literature data were obtained are road wheels and the coiled suspension springs. There is currently a significant amount of on-going work on the design and fabrication of road wheels from fibrous composites. The work entails fiberglass reinforced wheels (18) as well as graphite fiber reinforced wheels (19). While little data have been released as of yet, fiber reinforced plastic wheels are a good candidate application.

The assumption that coil springs could be made from ACM is purely speculative at the present time. It is to be noted that there are no leaf springs on the reference auto. In view of the extensive work carried out to date on leaf springs, it was assumed that the technology could be extended to coil springs in order to include a use of ACM in suspension members.

TABLE 27

WEIGHT REDUCTION BY ACM SUBSTITUTION OF STEEL AUTOMOTIVE COMPONENTS

COMPONENTS		TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT 20-80% HYBRID COMPOSITE COMPONENTS, LBS. I	II
Body in White							
Underbody		148	140	M	42		70
Windshield Cowl & Dash		97	80	L	32		
Quarter Panels		173	150	L	60		
Deck Opening		42	30	L	12		
Roof		62	60	M	18		30
Doors Front (zes)	Panels & Reinforcements	104	104	M	31		52
	Rails	28	28	L	11		
	Impact Rails	13	13	L	5		
	Hinges	12	12	H	3	4	4
	Other	30	---	-	--		
Deck Lid Assembly		30	28	M	9		14
Front Fender Assembly		93	76	L	30		
Hood Assembly		70	70	M	21		
Hood Hinge & Latch Assemblies		14	10	H	2	3	3
Radiator Supports & Brackets		39	39	H	8	12	12
Miscellaneous Supports & Brackets		6	6	H	1	2	2
Sub Total - Body in White		961	846		285	21	187

A4-3

Notes:

Reference Vehicle : 1975 Chevelle 2 door Sedan, as per Ref. 9

Weight Reduction Assumes Substitution is Based on Stiffness Criterion

H = High Weight Reduction Potential with Unidirectional Fiber Layup and m= 0.33

M = Medium Weight Reduction Potential with Isotropic Fiber Layup and m= 0.50

L = Low Weight Reduction Potential with Isotropic Fiber Layup and m= 1.0

m = Exponent on modulus ratio

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TABLE 27 Cont.

COMPONENT	TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS.	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT 20-80% HYBRID COMPOSITE COMPONENTS, LBS. I	II
Chassis						
Frame Assembly	290	280	L	112		
Engine Rear Cross Member Assembly	27	27	H	5	8	8
Engine Supports	6	6	H	1	2	2
Front Suspension						
Upper Control Arm	19	19	L	8		
Lower Control Arm	33	33	L	13		
Coil Springs	25	25	L	10		
Rear Suspension						
Upper Control Arm	6	6	L	2		
Lower Control Arm	10	10	L	4		
Coil Springs	15	15	L	6		
Anti Sway Bar	13	13	M	4		6
Road Wheels (5 ea)	115	115	M	35		58
Sub total	559	549		200	10	74

TABLE 27 Cont.

COMPONENT	TOTAL CURRENT WEIGHT, LBS.	WEIGHT OF STEEL BEING SUBSTITUTED, LBS	WEIGHT REDUCTION CRITERION	WEIGHT OF EQUIVALENT HM GRAPHITE COMPOSITE COMPONENT, LBS.	WEIGHT OF EQUIVALENT HYBRID COMPOSITE COMPONENT, LBS. I	II
Interior						
Front Seat Frame	44	34	H	7	10	10
Sub Total	44	34		7	10	10
Final Drive						
Propulsion Shaft	16	16	L	6		
Sub Total	16	16		6		
Bumpers						
Front Bumper	107	107	M	32		53
Rear Bumper	91	91	M	27		46
Sub Total	198	198		59		99
Total of Above	1778	1643		557	41	370
Current Curb Weight	3643					
Direct Weight Reduction due to Composition Substitution, lbs.				1086	96	425
Indirect Weight Reduction (0.4 Δ W)				434	38	170
Total Weight Reduction				1520	134	595
Curb Weight Composite Equivalent Auto				2123	3509	3048

Table 27 does not list any component from the engine, transmission, the axle and differential, the braking and steering systems. It was assumed that ACM would not be used to any significant extent in these applications during the 1985-1990 period because there has been very little prototype work performed in these areas to date.

The current weights of the components listed in Table 27, as reported by Pioneer, are also presented in this Table. For many of the components, it was evident that a small fraction of current component weight could not be reduced by substituting ACM for steel, because of the presence of non-metallics or of special fasteners, in the structure, or because of the presence of metallic (steel) inserts that would have to be included in the ACM replacement component. The estimated steel replacement weight listed in Table 27 is arrived at by substituting sufficient weight from the present components in order to take these factors into account.

4.2.3 Weight Reduction Calculations

The information developed in the previous section provides a basis for projecting the potential for weight reduction by using ACM in lieu of steel for the various components listed in Table 27. As was discussed, the weight reduction that can be achieved by using ACM in lieu of steel is principally a function of the ratios of densities and of the moduli of elasticity of these materials, as expressed by the following equation:

$$\frac{W_c}{W_s} = \frac{\rho_s}{\rho_c} \times \left(\frac{E_s}{E_c}\right)^m$$

where:

W_c = weight of composite	W_s = weight of steel
ρ_c = density of composite	ρ_s = density of steel
E_c = modulus of composite	E_s = modulus of steel
m = geometrical factor	

As outlined in Appendix Section 3, the term $(Es/Ec)^m$ depends on system geometry, with Ec and m varying with characteristics of the structure under consideration. Ec depends on the orientation of the fibers in the strucutre which in turn is a function of the applied loads which are in part controlled by structure geometry. The factor m can vary between 0.33 and 1 depending on the structural shape.

To simplify the analysis, the potential for weight reduction by materials substitution for any component, was classified as either being high, medium or low based on the data presented in the previous section. As outlined in Table 28, a high potential for weight reduction would be deemed to exist for thick components ($m \simeq 0.33$) where unidirectional composites can be used (Ec is high). For example, a leaf spring would have a high potential for weight reduction. A medium potential for weight reduction would be considered to exist for panel structures where oil canning would be a critical criterion (m = 0.50) and where cross plied composite laminates would be required (Ec is low). A low potential for weight reduction would be considered to exist for thin beam structures (m=1), especially those subjected to multidirectional stresses (Ec is low).

The extent of weight reduction would also vary with the choice of the materials considered as outlined in Table 29. These values are based on the calculations presented in the previous section. The low value for aluminum in the H case is due to the low fatigue strength which establishes the limiting value of $\frac{Wn}{Wo}$.

4.2.4 Weight Propagation Factor

Values of weight propagation factors that have been published in the recent technical literature have ranged from 1.4 (20), to 2.0 (21) to as much as 2.6 (22). These factors imply an additional reduction of 0.4 lbs. to 1.6 lbs. per pound of direct weight removed.

Rearrangement of the data published in the Motor Vehicle Goal

TABLE 28

GENERAL CATEGORIES OF WEIGHT REDUCTION POTENTIAL OBTAINABLE WITH ACM

WEIGHT REDUCTION POTENTIAL	FIBER LAY-UP GEOMETRY	EXPONENT m	EXAMPLES
HIGH (H)	UNIDIRECTIONAL	0.33	LEAF SPRING SUPPORT BRACKET
MEDIUM (M)	ISOTROPIC	0.50	HOOD DOOR PANEL
LOW (L)	CROSSPLIED/ ISOTROPIC	1.00	DOOR BEAM (?)

TABLE 29

ASSUMED VALUES OF WEIGHT RATIOS OF EQUIVALENT STRUCTURES

FOR VARIOUS SUBSTITUTION MATERIALS OF INTEREST

$$\frac{W_c}{W_s} = \frac{\rho_c}{\rho_s}\left(\frac{E_s}{E_c}\right)^m$$

CASE GEOMETRY m	High (H) Solid Section 0.33	Medium (M) Panel 0.50	Low (L) Thin Wall Beam 1.00
MATERIAL	NOMINAL WEIGHT RATIO, W_c/W_s		
HM GRAPHITE COMPOSITE	0.20	0.30	0.40
HS GRAPHITE COMPOSITE (TYPE A)	0.25	0.35	0.60
GLASS FIBER COMPOSITE	0.40	0.75	1.90
HYBRID COMPOSITES (HM GRAPHITE/GLASS)			
10/90	0.35	0.60	1.50
20/80	0.30	0.50	1.20
40/60	0.25	0.40	0.90
ALUMINUM	0.74(*)	0.60	1.00
STEEL	1.00	1.00	1.00

(*) Fatigue Limiting

Study (23) on the relative weights of different subsystems of an automobile indicate that there is a consistent pattern in the relative weights of these subsystems as outlined in Table 30. Based on this information, it is estimated that the reduction in weight of the body and chassis of an automobile results in a further weight reduction due to downsizing of other components of an additional 40% to 70%. The argument used in developing these weight propagation factors is that, as the weight of the body and chassis are reduced, the ratio of the weights of the vehicle system to the sum of the weights of the body and chassis, and of the maximum payload are constant. Typically this ratio has a value of 35/65 (0.54), but due to the indicated variations, can range from 29/71 (0.41) to 41/59 (0.69.

In this study, the more conservative value of 0.4, suggested by Kennedy and Hoover (20), is used to estimate propagated weight reduction.

4.3 Scenario I - Revolution

This scenario considers a hypothetical case in which ACM materials are used to the utmost in order to maximize vehicle weight reduction. The purpose of this exercise is to establish the technical limits in weight reduction achievable with ACM technology.

4.3.1 Assumptions

In this instance, it was assumed that HM type graphite fiber composites would be used, exclusively. Refering to Table 4, it is to be noted that the strength of a graphite decreases as its modulus increases. HM graphite fibers offer the best balance of stiffness and strength of the three major types of graphite fibers now available. While HM type graphite is significantly stiffer than the Type A (high strength) graphite, it is still strong enough so that strength considerations do not limit the design of the resulting component. At the moment, most of the prototype work has been carried out with Type A graphite composites, even though HM fiber composites can result in greater weight reduction. This

TABLE 30

RELATIVE WEIGHTS OF VEHICLE SUBSYSTEMS AS A FUNCTION OF GROSS VEHICLE WEIGHT

	PERCENT GROSS VEHICLE WEIGHT
Maximum Payload	30 ± 3
Body and Frame	35 ± 3
Steering and Suspension	15 ± 3
Power System	18 ± 2
Miscellaneous	Balance
TOTAL	100

Source of Data: The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980, Vol. 2, Task Force Report Table 5B-4, page 5B-5, September, 2, 1976.

is believed to be due mainly to economic reasons. As mentioned in Section 2.2, HM fiber is currently two to three times as expensive as high strength fiber. It is to be noted that all the fiber manufacturers are also developing graphite fibers with a modulus in the range of 50×10^6 psi for the commercial (i.e., automotive) market.

At the same time, it was considered unlikely that extensive use would be made of UHM type graphite fibers. The additional weight reduction potential due to higher stiffness may be compromised by the lower strength of this fiber. Its very low elongation to failure characteristics make it difficult to handle and incorporate into a composite. Finally, the price of this fiber is currently twice that of HM fiber, and will remain higher because of the extremely high temperatures needed to achieve the high modulus.

The numerical values for the direct weight reduction ratios (Wc/Ws) for the various components listed in Table 27 were assigned as follows:

Weight Reduction Potential	Wc/Ws
High (H)	0.20
Medium (M)	0.30
Low (L)	0.40

These ratios, taken from Table 29, were used to calculate the weights of the steel equivalent ACM components from the weights of the steel components also listed in Table 27.

The calculated ACM component weights in this instance are also presented in Table 27.

4.3.2 Vehicular Weight Reduction Estimate

According to this exercise, 547 lb (248 kg) of HM composite components replace 1643 lb (746 kg) of equivalent steel components for a direct weight reduction of 1086 lb (493 kg). Secondary weight reduction that could accrue as a result is estimated to be 434 lb (197 kg), resulting in a total reduction in vehicle weight of 1520 lbs (690 kg). The resulting equivalent vehicle has a curb weight of 2123 lb (964 kg), or 58% of the curb weight of 3643 lb (1654 kg) of the base vehicle.

The weight of this modified Chevelle is about 400 lb (182 kg) less than the 2517 lb (1143 kg) curb weight projected for the Ford Light Weight Vehicle. This vehicle will weigh 1260 lb (657 kg) less than the equivalent steel Granada which has a curb weight of 3767 lb (1800 kg). In this case, the ratio of vehicle weights is 67 percent.

The results of the present study are considered in general agreement with the Ford projections. The 400 lb difference is due in part to the difference in the initial weights of the base vehicles, and in factors that are inherent in trying to compare theory with hardware. In the present study, it was assumed that stiffness alone was the weight limiting criterion, and that HM graphite composites would be used exclusively. In the Ford vehicle, many of the components will be made with other composites that will contain either high strength graphite, or graphite/glass mixtures, and which will have a different balance of properties. In terms of stiffness as a weight limiting criterion, these composites will not result in as large a weight savings as the HM graphite composites. Furthermore, the Ford vehicle design was undoubtedly constrained by other criteria, such as manufacturing or safety considerations, which could result in lower weight savings than those projected on the basis of structural requirements alone.

4.3.3 Projected Improvement in Vehicle Fuel Economy

The functional relationship between fuel economy, vehicle weight, and vehicle power to weight ratio can be approximated by the following equation (24):

$$FE = A.wt^{-a} (HP/WT)^{-b}$$

where:

FE	is the EPA composite fuel economy in miles per gallon
WT	is the test weight of the auto, defined as the curb weight plus 300 pounds
HP/WT	is the ratio of the rated engine horsepower to the auto test weight
A, a, b	are scaling coefficients which are functions of engine characteristics

For a standard 1975 gasoline engine,

$$A = 6060, \quad a = 0.88 \quad b = 0.40$$

For a diesel engine,

$$A = 2370 \quad a = 0.69 \quad b = 0.35$$

The above equation was used to calculate the improved fuel economy derived from the weight reduction resulting from extensive use of ACM in the vehicle structure, but not otherwise changing the level of vehicle technology. Figure 3 is a graphical representation of the variation in fuel economy with vehicle test weight for both modes of power, as calculated by the above equation with an assumed performance rating of 0.02 HP/lb vehicle test weight. This performance rating was obtained by dividing the estimated horsepower of the reference Chevelle by the test weight of this vehicle. Based on a typical power generation of 1 HP per 3 CID, the horsepower of the 250 CID engine in the Chevelle was estimated to be 83 HP. * Based on these values, the reference Chevelle has a

---

*This performance ratio is lower than the value of 0.03 HP/lb characteristically observed for 1978 model year vehicle, (34) and therefore results in values of vehicle fuel economy as a function of test weight that are higher than would be expected in production vehicles. It is to be noted that the calculations in the body of this report are based on a performance ratio of 0.03 HP/lb, and therefore are not in direct agreement with the values presented in this Appendix section.

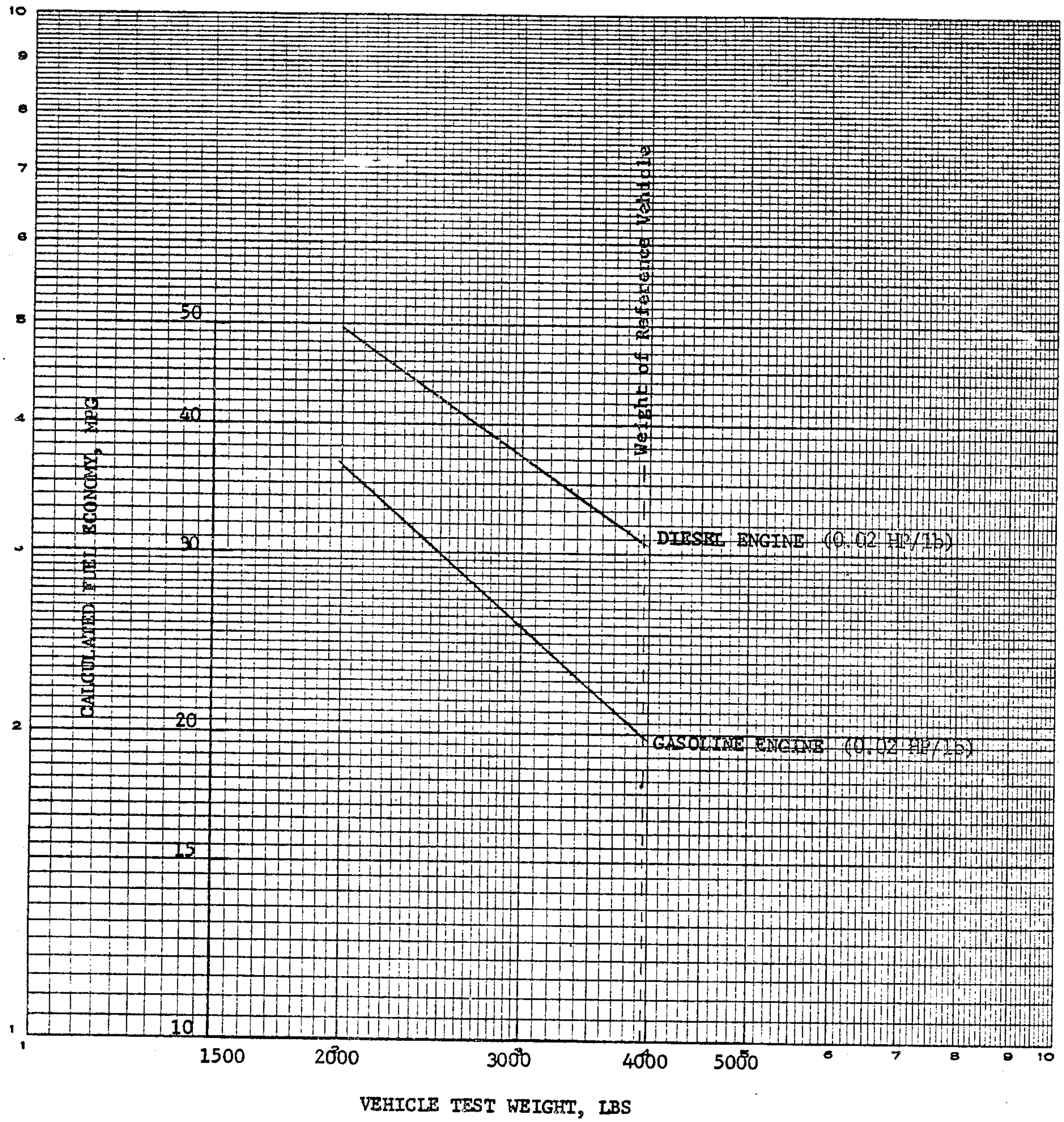

FIGURE 3

FUEL ECONOMY AS A FUNCTION OF TEST WEIGHT OF MODEL VEHICLE calculated fuel economy of 19.9 miles per gallon. The equivalent composite vehicle, based on a test weight of 2423 lbs, and a constant value of HP/WT of 0.02 HP/LB, has a calculated fuel economy of 27.4 miles per gallon; 9.5 miles per gallon or 53% more than that of the reference vehicle.

These calculations are only meant to imply that extensive substitution of high modulus graphite composite components for equivalent steel components can result in reductions in vehicle test weights of about 40%, which in turn, can lead to improvements in fuel economy of the order of 40% to 50% depending on engine characteristics.

4.4 Economics of Materials Substitution

4.4.1 Introduction

In this section, the potential impacts of the substitution of ACM for steel in a LTV are analyzed. The calculations are based on current (1978) costs and prices. In the calculation of the impact of fuel economy on the ownership costs of an automobile, it will be assumed that:

a) fuel costs are 70¢/gallon

b) the vehicle is driven 10,000 miles/year (16,000 km)

c) useful vehicle life is 10 years.

d) future expenditures are discounted at an annual rate of 5% to obtain their current net present value

4.4.2 Current Cost/Price Structure of U.S. Passenger Automobiles

The Council on Wage and Price Stability (CWPS) publishes periodic reports (25) on various economic aspects of the U.S. automobile industry. These reports are compiled from unpublished background data on prices, costs, sales and profits which the Council requests (but could legally demand) from the four domestic producers. Information pertinent to this study is summarized in Table 31. This information was used to develop proportionality

TABLE 31

CURRENT COST/PRICE STRUCTURE OF AN AVERAGE U.S. PASSENGER AUTOMOBILE

	1977 Model Year	1978 Model Year
Retail Price, including delivery charges	$ 6720	$ 7130
Delivery Charges	$ 170	$ 190
Retail Price	$ 6550	$ 6940
Wholesale Price	$ 5335	$ 5700
Manufacturer's Costs	$ 4902	$ 5230**
Labor Costs	$ 1656	$ 1800
Materials Costs	$ 2074	$ 2190
Other Costs	$ 1172	$ 1240

* with average options

** based on sales of 11 million vehicles in model year

SOURCE: Executive Office of the President, Council on Wage and Price Stability, "Council Analyzes New Automobile Price Increases", November 14, 1977.

factors between various cost/price elements, as shown in Table 32. In particular, it is to be noted that currently (M.Y. 1978) the ratio of manufacturers' costs to retail price is 0.754.

In the subsequent analysis of the economic impact of ACM on automobile costs and prices, it will be assumed that the current ratios between manufacturers' costs, wholesale price, and retail price will remain unchanged. The cost to the consumer as a result of any changes in manufacturing costs will be assumed to be the adjusted retail price (adjusted manufacturing cost divided by 0.754) plus $190 in delivery charges.

As shown in Table 33, based on an average cost of materials of $2074 (CWPS data), and an estimated average curb weight of 3890 lb (1766 kg), (26) the average unit cost of materials in the 1977 automobile was $0.53/lb. With the expanded sale of a significant number of lighter weight vehicles in MY 1978, it is estimated that the average sales weighted curb weight of MY 1978 U.S. passenger automobiles will be 3650 lb (1657 kg). Based on the cost of materials projected by the CWPS, the average unit cost of materials will be $0.60 for MY 1978 passenger autos.

4.4.3 Methodology

4.4.3.1 Introduction

The costs of materials substitution are first calculated parametrically as a function of the weight substitution ratio, W_c/W_s, on a per pound of steel removed basis. The analysis considers the net changes in the cost of materials to the manufacturer separately from other potential manufacturing cost changes that result in a total manufacturing cost change. By multiplying by the current ratio of wholesale price to manufacturer's cost, an adjusted wholesale price which reflects these cost changes is obtained.

In order to obtain the impact of materials substitution on the retail price of the vehicle, the wholesale price is further adjusted by a credit towards the manufacturer's potential CAFE

TABLE 32

CALCULATED COST/PRICE RATIOS FOR AN AVERAGE U.S. PASSENGER AUTOMOBILE

Ratio	1977 Model Year	1978 Model Year
Retail Price to Delivered Price	0.975	0.973
Wholesale Price to Retail Price	0.815	0.821
Manufacturer's Costs to Wholesale Price	0.919	0.918
Manufacturer's Cost Components to Total Manufacturer's Costs		
Labor	0.338	0.334
Materials	0.423	0.419
Other	0.239	0.237
Manufacturer's Costs to Retail Price	0.748	0.754
Materials Costs to Wholesale Price	0.389	0.384

TABLE 33

AVERAGE COST OF MATERIALS FOR CURRENT U.S. PASSENGER AUTOMOBILES

	1977 Model Year	1978 Model Year
Average Cost of Materials in U.S. Passenger Auto	$ 2074[a]	$ 2190[a]
Estimated Average Curb Weight of U.S. Passenger Auto, lbs	3890[b]	3650[c]
Average Unit Cost of Materials in U.S. Passenger Auto, $/lb	0.53	0.60

SOURCES:

a. Council on Wage and Price Stability, November 14, 1977
b. H. Gould, Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA, Personal Communication-July 17, 1978
c. Estimate

(Corporate Average Fuel Economy) penalty. This credit is equal to the original fuel economy improvement as a result of weight reduction obtained by materials substitution per unit weight of steel replaced, times the value of the tax penalty of $50/mpg.

The adjusted wholesale price, after taking a CAFE credit, is then multiplied by the current ratio of retail price to wholesale price, to obtain the effective change in vehicle retail price as a result of materials substitution. Materials substitution has a further impact on the consumer to the extent that it results in improved fuel economy and reduced vehicle ownership costs due to lower fuel consumption. A credit equal to the reduced cost of fuel consumption is added to the retail price adjustment calculated above to obtain the total impact of materials substitution on vehicle ownership costs.

The changes in vehicle retail price and in consumer ownership costs are a function of the change in fuel economy of the vehicles, which are a function of the extent of weight reduction, and of the type of engine assumed for the vehicle. The impact of materials substitution is different for a diesel engine powered auto than for a gasoline engine powered auto, so that separate calculations were performed for each case.

The cost changes resulting from the substitution of these various materials were then compared on a functionally equivalent basis for high, medium, and low weight reduction potentials, using the weight ratios outlined in Table 29. These results indicated that all graphite composites would be too expensive to be used in mass produced automobiles. The use of ACM under evolutionary conditions in the industry would be limited to graphite/glass hybrid composites with a low graphite content, in H type, and possibly also M type applications. To exemplify this evolution, the selective replacement of steel components by equivalent graphite/glass hybrid composite compounds in the 1975 Chevelle model vehicle is considered, and the resulting weight changes calculated.

The cost of ACM substitution on a per vehicle basis is then calculated for the various scenarios assumed, and the costs of extensive substitution by all graphite composites with maximum vehicle weight reduction, are compared to the costs of selective substitution by a 20/80 hybrid composite.

4.4.3.2 Net Change in Material Costs

It is assumed that W pounds of ACM (or other replacement material) replace one pound of steel. This substitution results in a direct weight reduction of (1-W) pounds, and therefore, in a secondary weight reduction of 0.4 (1-W) pounds. The net change in material costs to the manufacturer is therefore:

$$Cm = W\ (Cc) - Cs - 0.4\ (1-W)\ \overline{C}m$$

where:

Cm = net change in material costs per pound of steel replaced

Cc = unit cost of composite material

Cs = unit cost of steel

$\overline{C}m$ = average unit cost of materials in base automobile

Based on Table 33, $\overline{C}m$ is assumed to be \$0.60/lb. Other unit materials costs are discussed in the next section.

4.4.3.3 Cost of Raw Materials

Steel. - The current prices for carbon steel automotive products range from 13.7¢ per pound for hot rolled carbon bars to 22.7¢ per pound for cold rolled strip steel (27). For purposes of comparison, a steel price of 20¢/lb, will be assumed, in this study. This value is close to the current price of cold rolled sheet steel and galvanized sheet steel that are used extensively in automotive structures.

Fiberglass. - The price of fibrous glass of 50¢/lb was used in the study. This price is representative of the current price range of E-glass rovings (28), the standard grade of fibrous glass used in general reinforced plastics applications. Due to the tight supply situation for glass fibers, their price may rise by approximately 10¢/lb by the end of the year. Current prices should be checked in future calculations.

Resin Matrix. - The resins that are most likely to be used as matrix materials in major automotive applications of ACM include thermosetting polyesters, vinyl esters or epoxy resins. The current average price of the three resins ranges from 36¢/lb for general purpose thermosetting polyester to 79¢/lb for general purpose epoxy resin (29). For purposes of calculation, a price of 40¢/lb was assumed for the price of resin matrix material.

Graphite Fiber. - The price of graphite fiber is considered a variable parameter. However, it is unlikely that there will be any extensive use of graphite fiber composites by the automobile industry unless the price of graphite fiber in continuous lengths drops from the current range of $20/lb to $70/lb (for graphite fiber grades of potential interest to the automotive industry) to the range of $6/lb to $10/lb.

Cost of Composite Materials. - The cost of various fibrous composite materials of interest to the study are summarized in Table 34 and in Figure 4. These costs are based on a total fiber content of 60 volume-percent. They assume no compounding charges for the preparation of the composite from the fiber and the resin.

Aluminum. - The current price for aluminum in ingot form of 60¢/lb was assumed for the raw material price of components that would be made by casting (27). For the compounds that would require wrought aluminum such as sheet stock, a price of 95¢/lb (representative of 6061 sheet aluminum), was used. This price includes the recent increases on major flat rolled aluminum goods announced by ALCOA (30).

Scrappage. - In these calculations no provisions are made for scrappage losses since these will vary significantly with different components. This assumption may result in a bias in favor of steel components which would be expected to have a higher rate of scrappage in operations such as stamping than plastic composites which can be molded to near net shape. In balance, however, steel scrap has commercial value (currently $80 to $90 per ton for No. 1 factory bundles) whereas plastic scrap is currently worthless.

TABLE 34

RAW MATERIALS COSTS OF HYBRID COMPOSITE
AS A FUNCTION OF GRAPHITE PRICE AND CONTENT

Graphite Fiber/Glass Fiber (Volume Ratio)	100/0	40/60	20/80	10/90	5/95	0/100
Price of Graphite Fiber $/lb.	PRICE OF COMPOSITE MATERIAL $/lb.					
6	4.21	1.97	1.22	0.85	0.67	0.48
10	6.93	3.06	1.77	1.13	0.80	0.48
20	13.73	5.78	3.13	1.81	1.15	0.48
40	27.33	11.22	5.85	3.17	1.83	0.48

Assumptions: Total Fiber Content: 60 v/o — Graphite S. G. = 1.8
Glass Fiber Cost: $0.50/lb. — Glass S. G. = 2.5
Resin Cost: $0.40/lb. — Resin S. G. = 1.3

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Cost of Materials Contained in Hybrid Composites
As a Function of the Price of Graphite Fibers and
The Relative Graphite Fiber to Glass Fiber Content
(Total Fiber Content = 60 v/o)

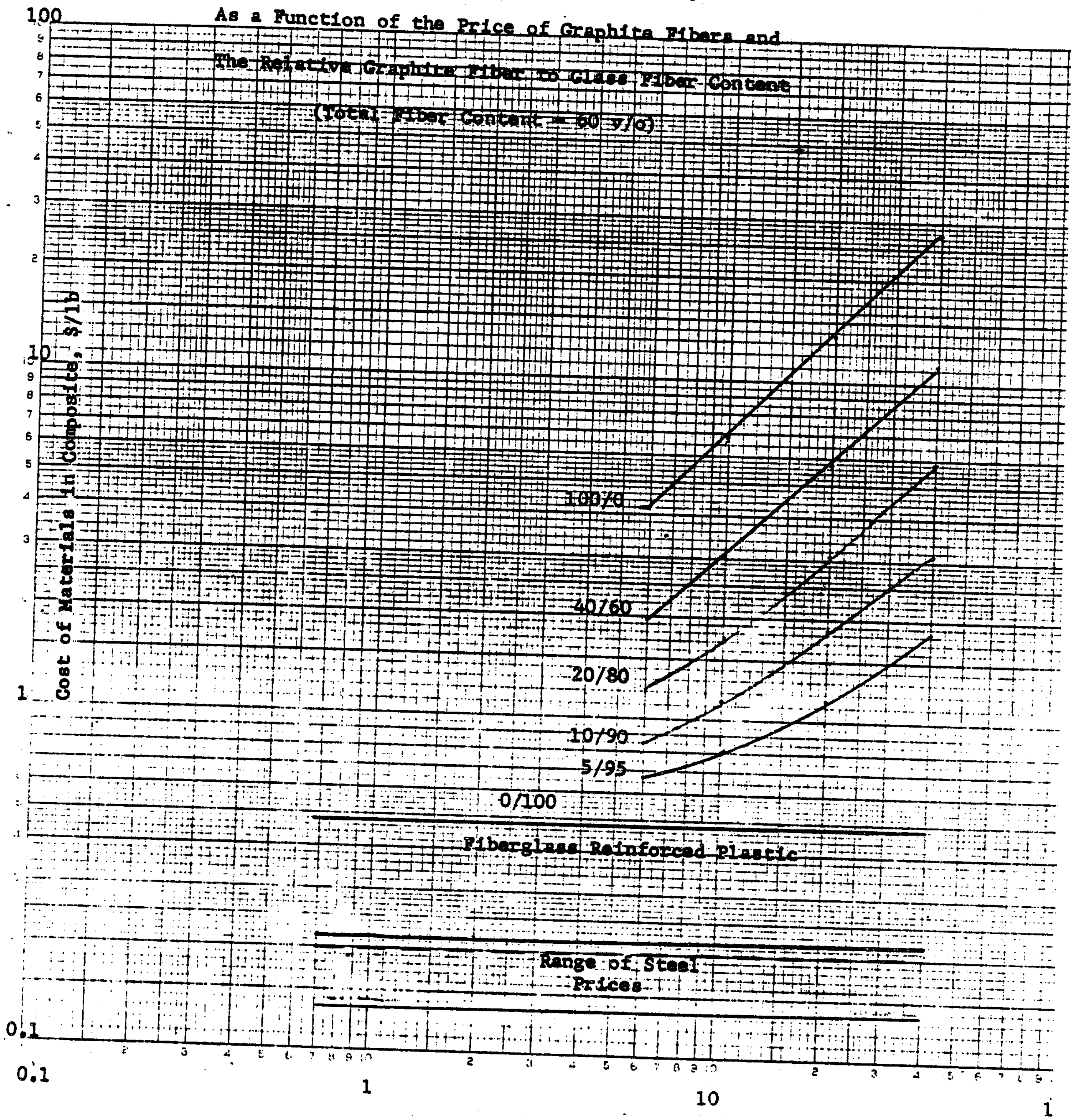

FIGURE 4

Full Logarithmic, 3 × 3 Cycles

4.4.3.4 Net Change in Other Manufacturing Costs

Since totally different manufacturing processes are used to make a component out of reinforced plastics than out of metal, materials substitution will impact a manufacturer's labor costs and capital investment. ACM automobile components will most likely be made by compression molding of a SMC type pre-preg, by pultrusion, or by tape layup, depending on the part. These changes can only be accurately compared on a specific component basis. Very complex structures can be molded to near net shape in reinforced plastics. There are numerous automotive components that consist of a number of individual metal parts that have to be machined and then assembled. In some instances, an equivalent ACM component could be molded as an integral unit. In these cases, lower labor costs, and possibly lower capital costs, could offset higher new materials costs.

On the average, however, it is expected that the changes in the cost structure will be small when compared to the changes in the raw material costs that would result from the use of ACM. Based on statistics published by the Society of the Plastics Industry (31), it is estimated that the costs of labor and factory overhead currently range from about \$0.40 to \$1.00 per pound of plastic processed. These numbers are for compression molders and molders of reinforced plastics. Based on the CWPS data published in Table 31, it was estimated that the other comparable costs for current fabrication of a typical automotive part were about 40¢/lb. The resulting differences in manufacturing costs become small and are of the same order of magnitude as the uncertainties in these costs. It was assumed that changes in labor and overhead costs would be secondary to changes in raw materials costs, and therefore, could be neglected for the purposes of the current study.

4.4.3.5 Net Change on Manufacturer's Wholesale Price*

Based on the results presented in Table 30, the net change in manufacturing costs developed above is multiplied by 1.09 to obtain their direct effect on the wholesale price of the vehicle.

A CAFE credit is subtracted from this value to obtain the net change in the vehicle wholesale price. The CAFE credit is expressed as follows:

$$C^* = (1.4)(1-W)(\Delta MPG)(C_P)$$

with

$$\Delta MPG = \frac{FE_2 - FE_1}{W_1^* - W_2^*}$$

In the above,

C_P = CAFE penalty, currently \$50/mpg

FE_1 = Fuel Economy of a vehicle with a test weight of W_1/mpg

FE_2 = Fuel Economy of a vehicle with a test weight of W_2/mpg

so that ΔMPG is the change improvement in fuel economy due to a weight change $W_1^* - W_2^*$.

Changes in vehicle fuel economy for different values of $W_1 - W_2^*$ are presented in Table 35A for a vehicle assumed to have a diesel engine, and in Table 35B for one with a gasoline engine. These values were calculated from the fuel economy relations presented

*Further analysis performed after the completion of the draft of this report results in a different methodology for calculating the CAFE credit a manufacturer might assume. This methodology which is presented in Section 3 of the report takes into account that the CAFE penalty is based on the harmonic mean fuel economy of the vehicle fleet produced by a manufacturer. The discussion in Section 3.5 is also based on vehicle fuel economies derived from a performance rating of 0.3HP/lb.

TABLE 35

CAFE CREDIT AS A FUNCTION OF THE EXTENT OF WEIGHT REDUCTION*

A. DIESEL ENGINE CASE

B. GAS ENGINE CASE

VEHICLE TEST WEIGHT, LBS.	VEHICLE WEIGHT REDUCTION, LBS.	FUEL ECONOMY MPG	FUEL ECONOMY IMPROVEMENT ,MPG	EQUIVALENT CAFE CREDIT $	EQUIVALENT CAFE CREDIT PER POUND WEIGHT REDUCTION, LBS.
A) DIESEL ENGINE CASE					
3943	0	30.8	0	0	0
3500	443	33.4	2.6	130	0.29
3000	943	37.2	6.4	320	0.34
2500	1443	41.9	11.1	555	0.38
2000	1943	49.2	18.4	920	0.47
B) GASOLINE ENGINE CASE					
3943	0	19.9	0	0	0
3500	443	22.0	2.1	105	0.24
3000	943	25.2	5.3	265	0.28
2500	1443	19.6	9.7	485	0.34
2000	1943	36.1	16.2	810	0.42

* Note these values have been revised.

in Appendix Section 3.3. The resulting CAFE credits are also summariz in this table. They depend on the extent of weight reduction, ranging from $0.29/lb to $0.47/lb (diesel case), and $0.24/lb to $0.42/lb (gasoline engine case), respectively for weight reductions of from 443 lbs. to 1943 lbs. For purposes of this analysis, the lower values in each case were used in the calculations.

4.4.3.6 Net Change In Vehicle Retail Price

The net change in vehicle retail price is obtained by multiplying the adjusted wholesale price, as calculated above, by a factor of 1.22, the current average ratio of retail price to wholesale price according to the data of the CWPS, as outlined in Table 32.

4.4.3.7 Net Change In Vehicle Life Cycle Costs*

It was assumed that the major quantifiable change in vehicle operating costs that would result from materials substitution would be the lower fuel consumption derived from weight reduction. The calculated decrease in fuel costs per pound of weight reduction are presented in Table 36A for a diesel engined vehicle, and in Table 36B for a gasoline engined vehicle. The lowest of the values presented in these tables were used in the calculations, namely $0.31/lb. for the diesel engined vehicle, and $0.58/lb. for the gasoline engine vehicle. It is to be noted that while there is a greater increase in mpg for a given amount of weight reduction for a diesel engined vehicle than for a gasoline engined vehicle, there is a significantly greater decrease in fuel consumption with the gasoline engine vehicle, for a given level of weight reduction, because of the lower initial level of fuel economy.

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*Note: The methodology and results presented in this section were revised after the preparation of the draft, and are discussed in Section 3.7 of the main report.

TABLE 36

REDUCTION IN FUEL COSTS AS A FUNCTION OF VEHICLE TEST WEIGHT*

VEHICLE TEST WEIGHT, LBS.	VEHICLE TEST WEIGHT REDUCTION LBS.	FUEL ECONOMY MPG	LIFETIME FUEL COSTS MPV $(*)	DECREASE IN LIFETIME FUEL COSTS NPV $	DECREASE IN FUEL COSTS PER POUND OF WEIGHT REDUCTION $/lb.
A) DIESEL					
3943	0	30.8	1755	0	0
3500	443	33.4	1618	137	0.31
3000	943	37.2	1453	302	0.32
2500	1443	41.9	1290	465	0.32
2000	1943	49.2	1099	656	0.34
B) GASOLINE					
3943	0	19.9	2715	0	0
3500	443	22.0	2456	259	0.58
3000	943	25.2	2144	570	0.61
2500	1443	29.6	1825	889	0.62
2000	1943	36.1	1497	1218	0.63

(*) Assumes 10,000 miles/year vehicle use, 10 year vehicle life, a cost of fuel of $0.70/gallon, and a 5% annual discount rate.

Note: These values have been revised.

Adjustment for fuel saved per pound of steel removed, C_F, was calculated as

$$C_F = 0.31(1-W)(1.4)$$

for the diesel engine case, and

$$C_F = 0.58(1-W)(1.4)$$

for the gasoline engine case.

The life cycle cost change due to ACM substitution is obtained by subtracting C_F from the adjusted retail price calculated in the previous section.

4.4.4 Results Cost/Price Changes Per Pound of Steel Replaced *

The changes in automotive costs/prices were calculated on a per pound of steel removed basis, for the materials listed in Table 29, for values of W_c/W_s ranging from 0 to 1. The results are summarized in Figure 5 to 15, as follows:

Figure 5: Impact of materials substitution on total materials costs, for various graphite/glass composites, assuming a cost of graphite fiber of $10/lb.

Figure 6: Impact of materials substitution on the retail costs of a diesel engined vehicle, for various graphite/glass composites, assuming a cost of graphite fiber of $10/lb.

Figure 7: Impact of materials substitution on the life cycle costs of a diesel engined vehicle, for various graphite/glass composites, assuming a cost of graphite fiber of $10/lb.

The corresponding data for a gasoline engined vehicle are presented in Figures 8 and 9.

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*The results presented in this section are based on the original methodology presented in Appendix Sections 4.3.3 and 4.4.3.

Graphite Fiber Price: $10/LB

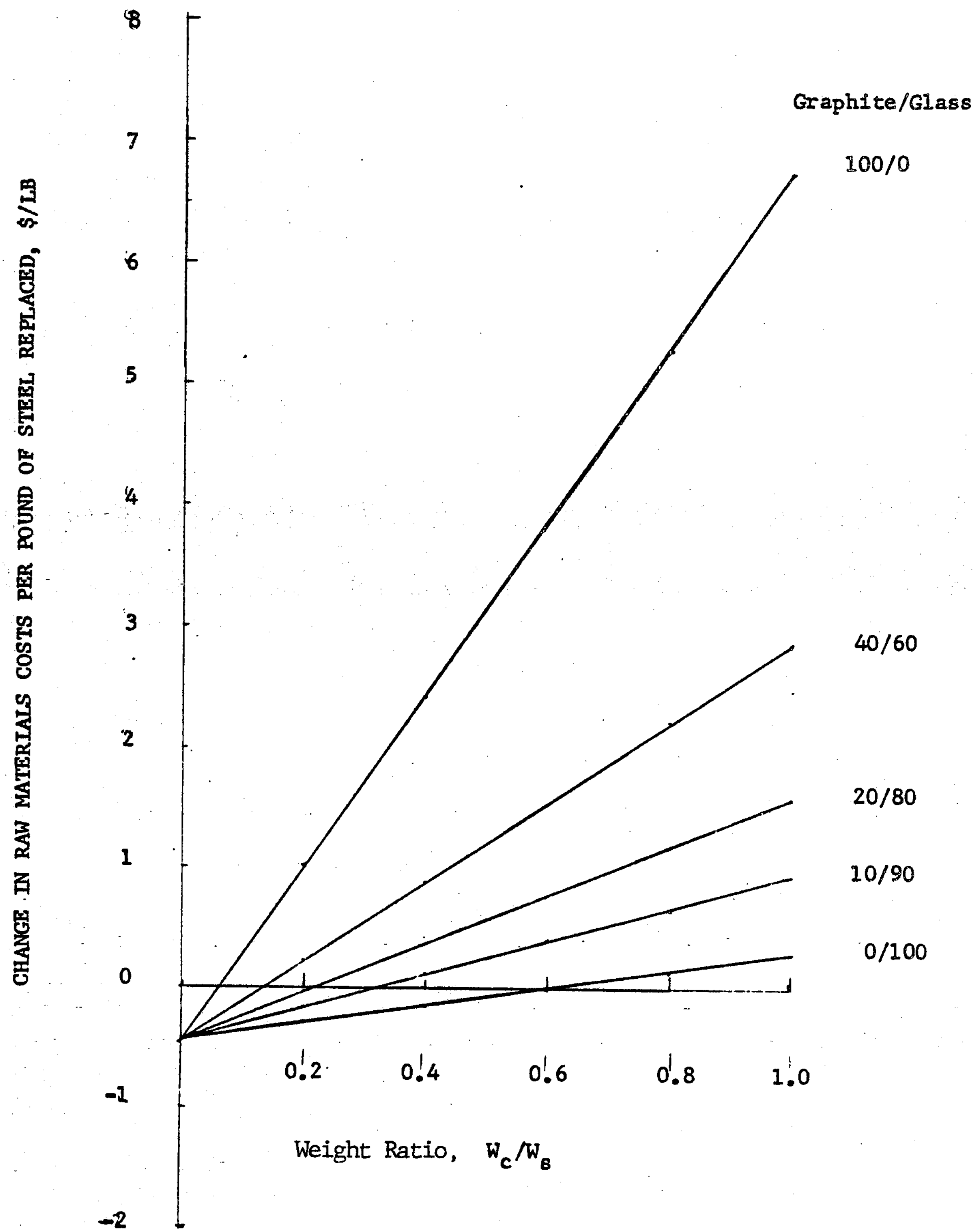

FIGURE 5 - CHANGE IN RAW MATERIAL COSTS OF MODEL VEHICLE DUE TO ACM SUBSTITUTION

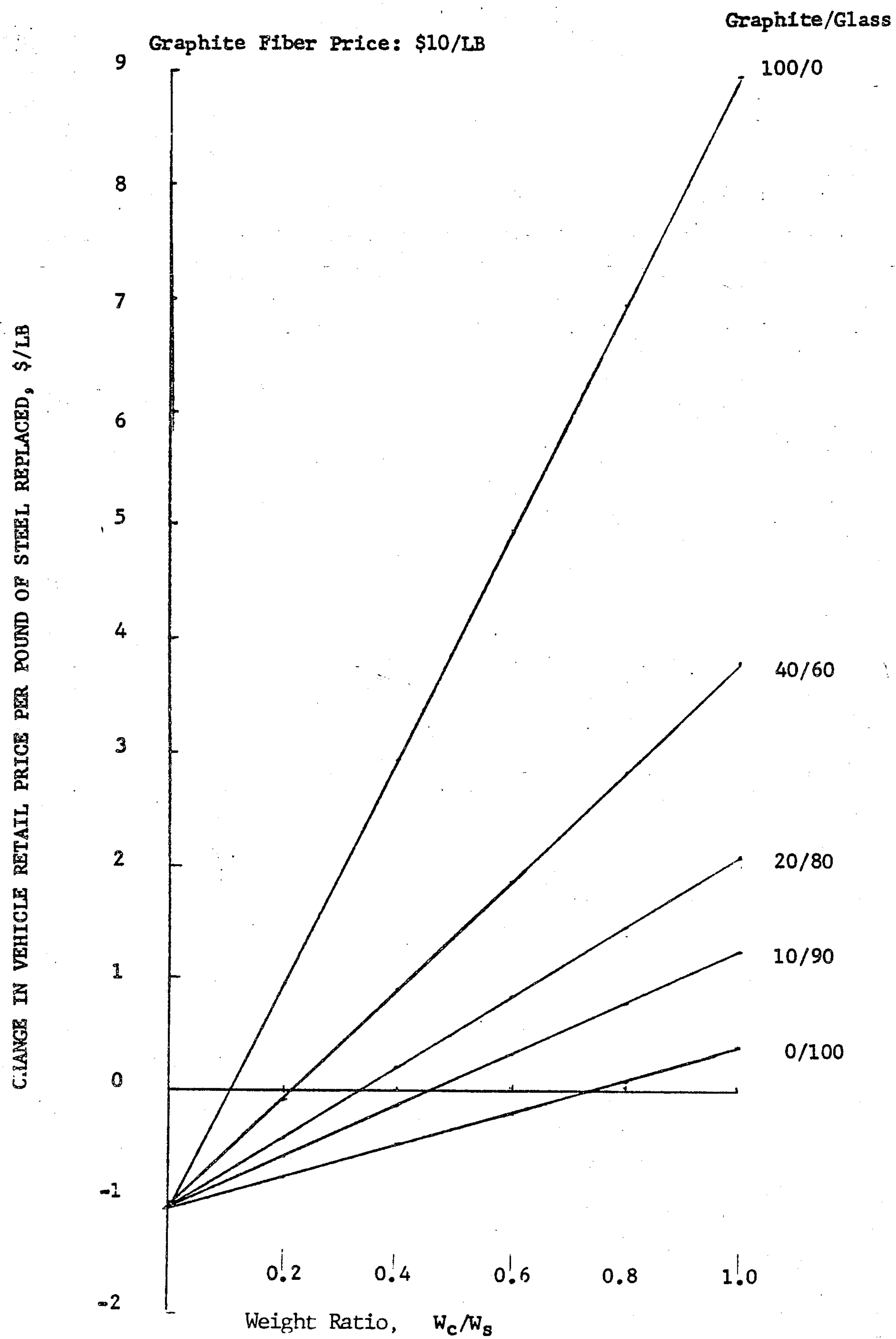

FIGURE 6 - CHANGE IN RETAIL PRICE OF MODEL DIESEL VEHICLE BY ACM SUBSTITUTION

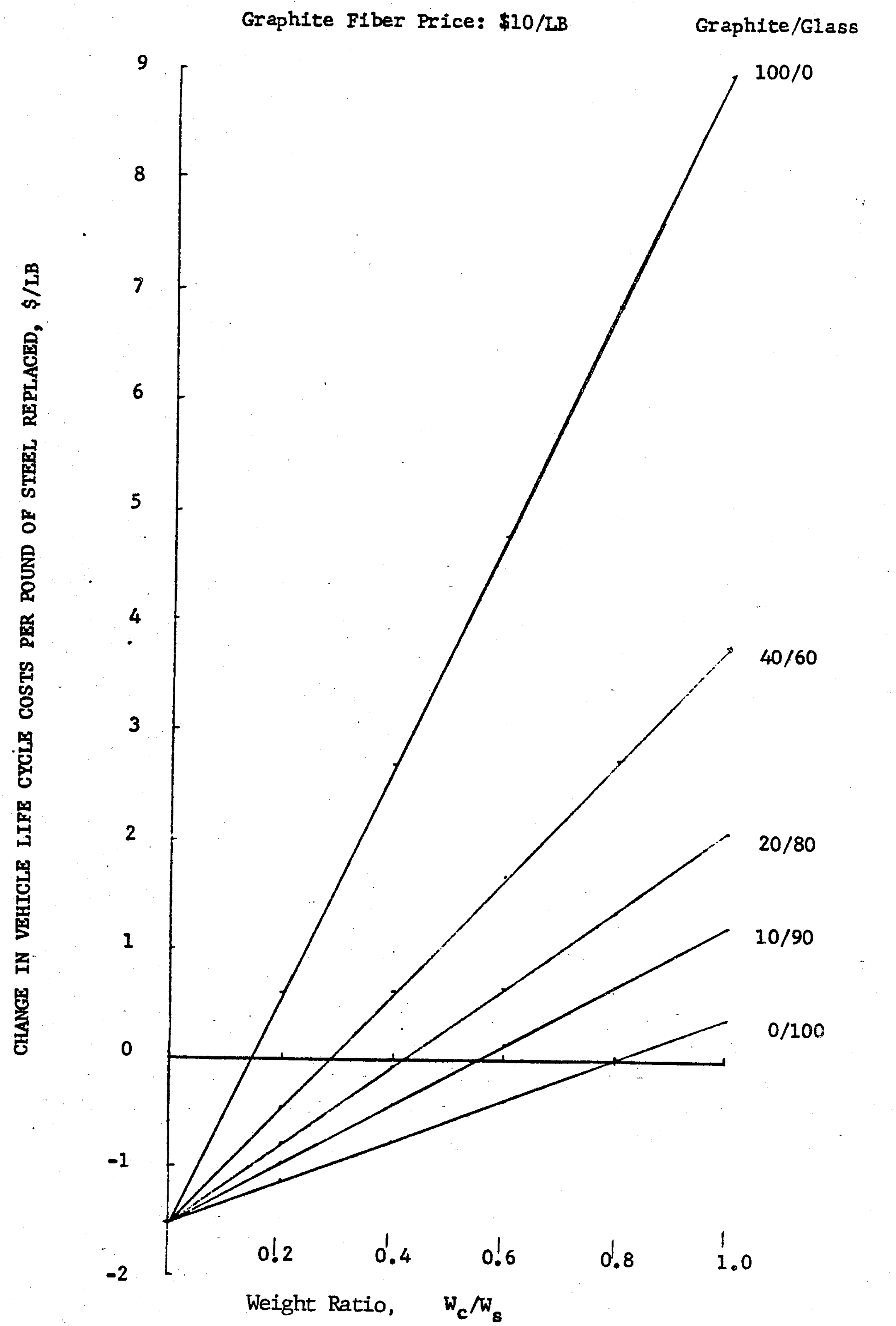

FIGURE 7 - CHANGE IN LIFE CYCLE COSTS OF MODEL DIESEL VEHICLE BY ACM SUBSTITUTION

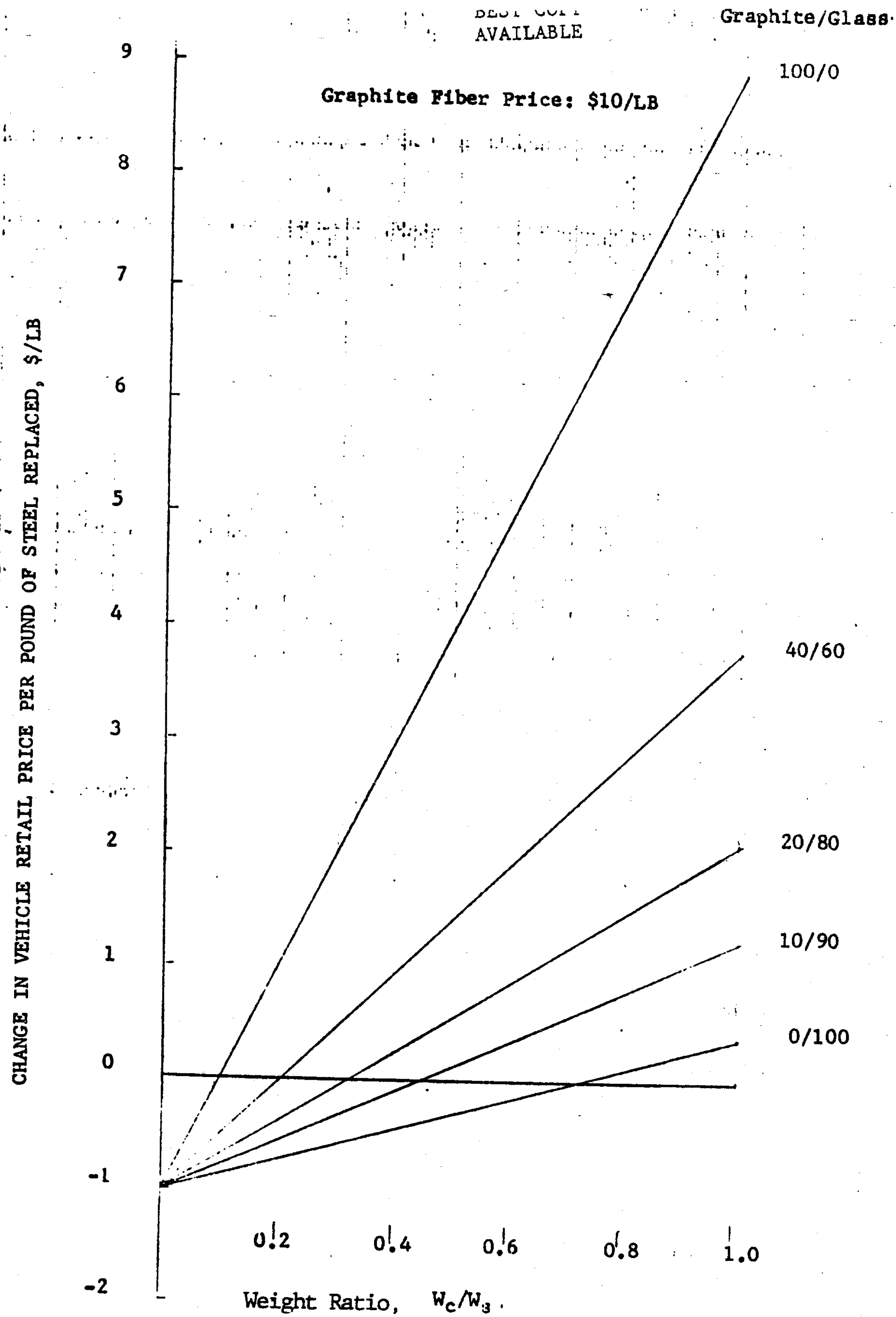

FIGURE 8 CHANGE IN RETAIL PRICE OF MODEL GASOLINE VEHICLE BY ACM SUBSITUTION

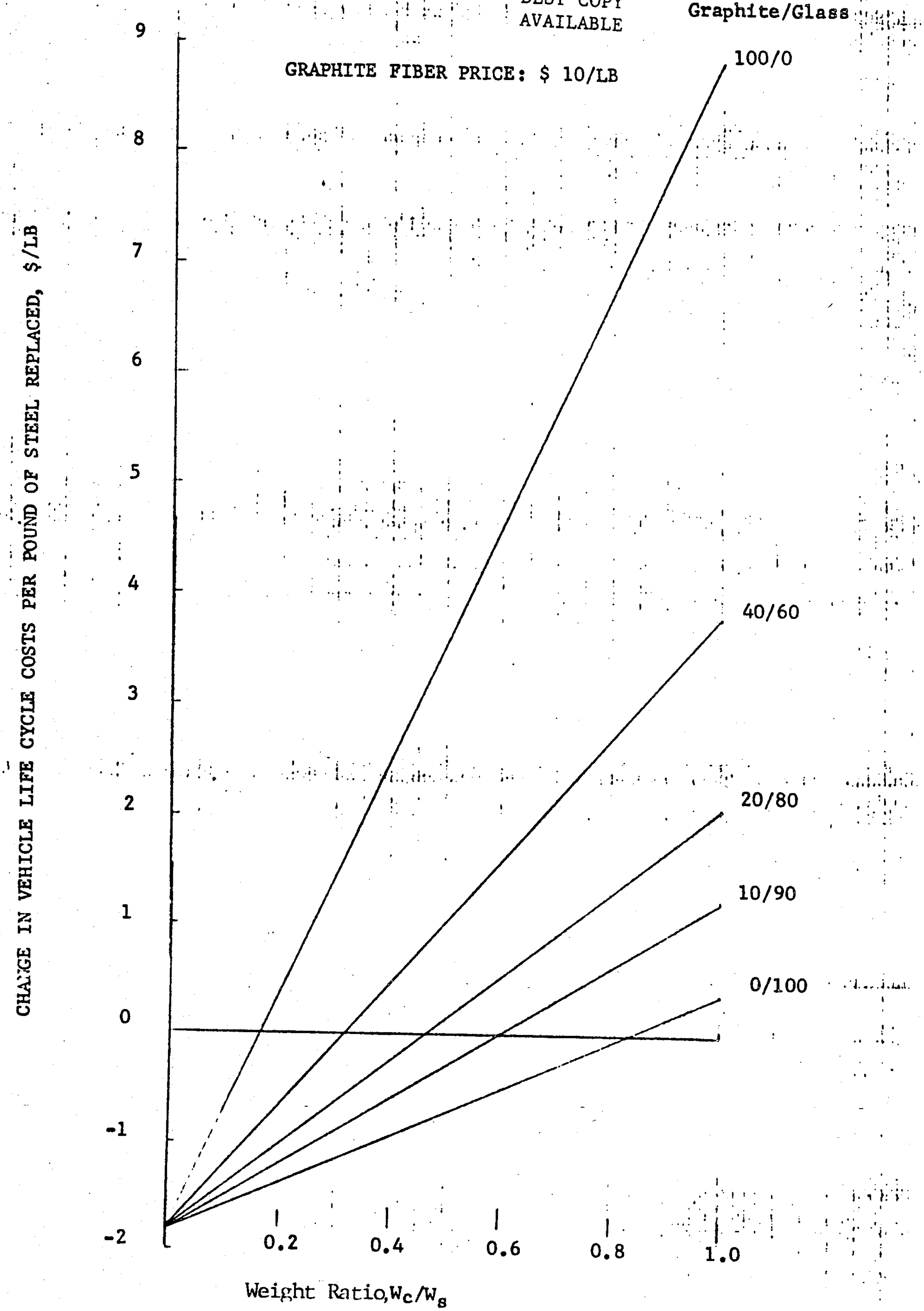

FIGURE 9 CHANGE IN LIFE CYCLE COSTS OF MODEL GASOLINE VEHICLE BY ACM SUBSTITUION

Figures 10 to 14 summarize the corresponding results for an assumed graphite fiber price of $6/lb.

The data for cast and wrought aluminum are summarized in Figure 15.

Details of the above data are summarized in Tables C-1 to C-11 of Appendix C.

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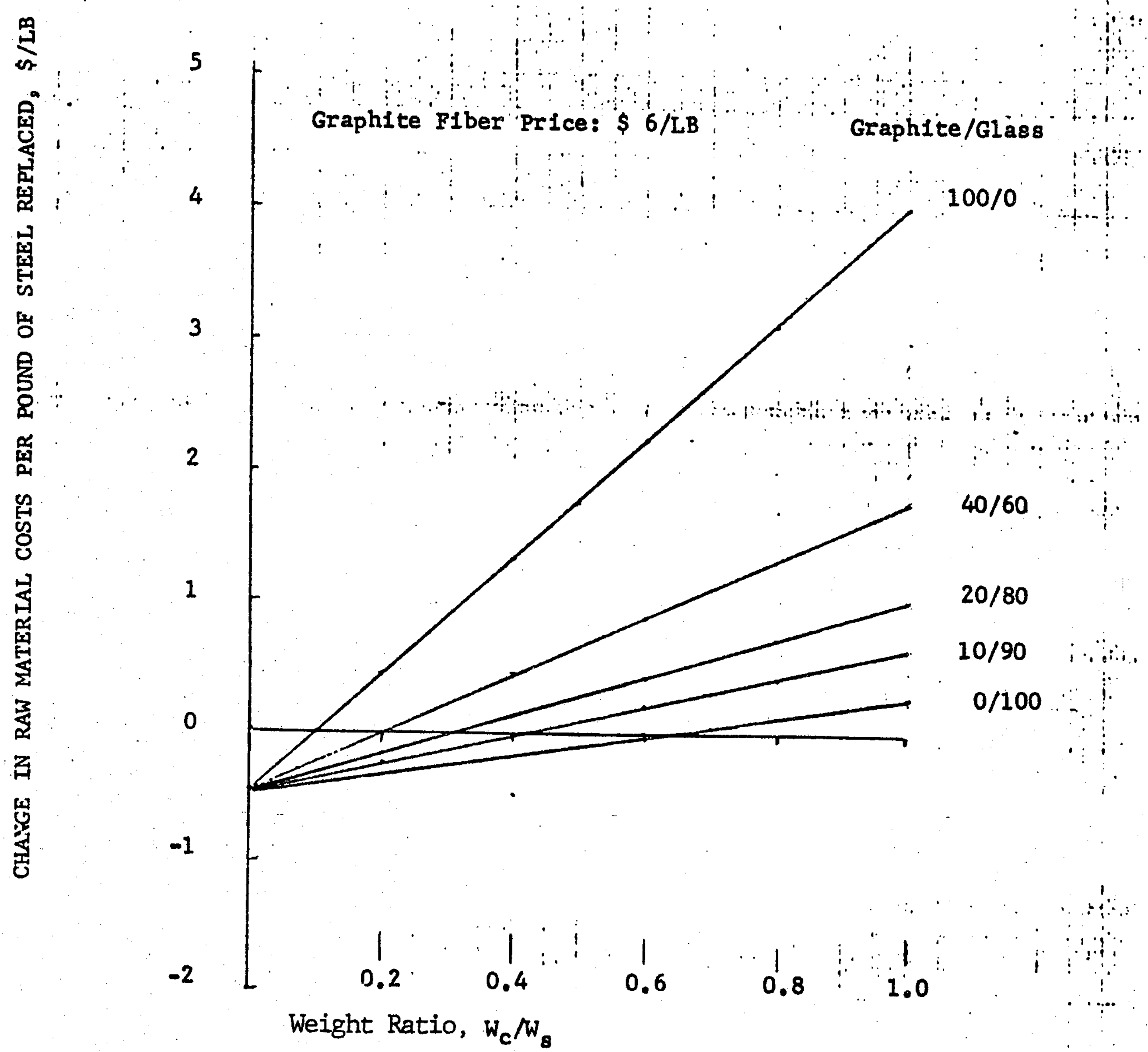

FIGURE 10 CHANGE IN RAW MATERIAL COSTS OF MODEL VEHICLE DUE TO ACM SUBSTITUTION (B)

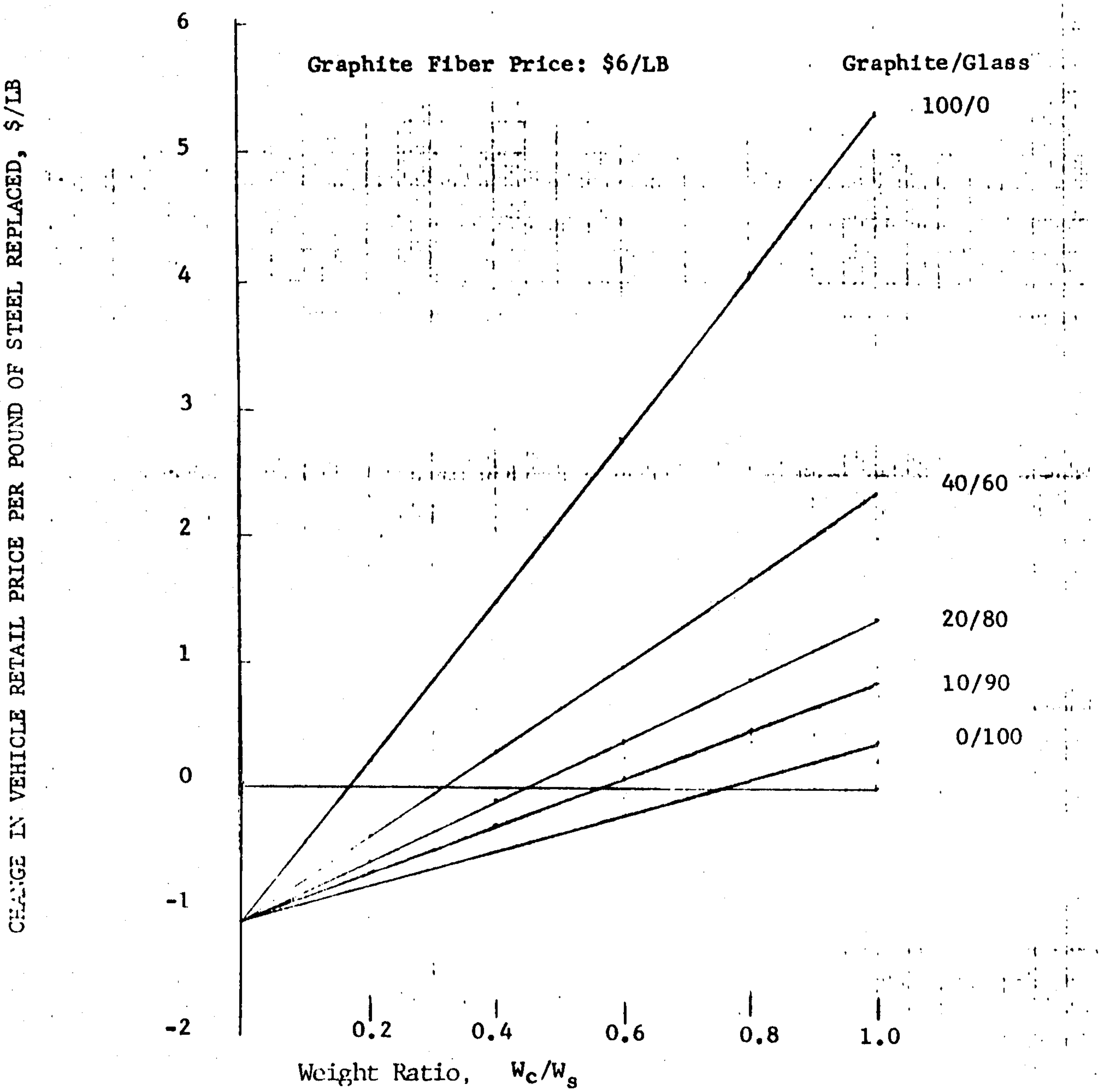

FIGURE 11 CHANGE IN RETAIL PRICE OF MODEL DIESEL VEHICLE BY ACM SUBSTITUTION (B)

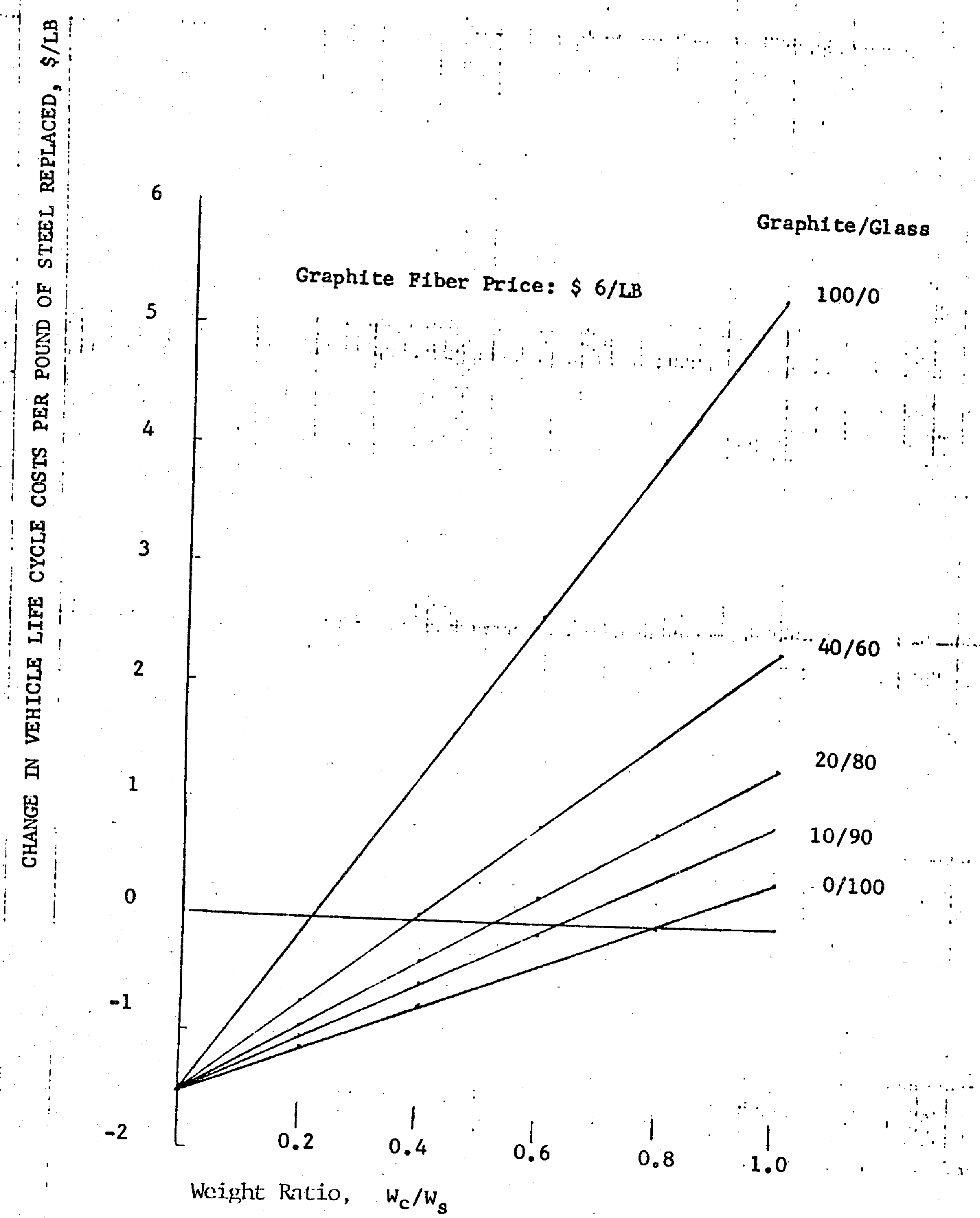

FIGURE 12 CHANGE IN LIFE CYCLE COSTS OF MODEL DIESEL VEHICLE BY ACM SUBSTITUTION (B)

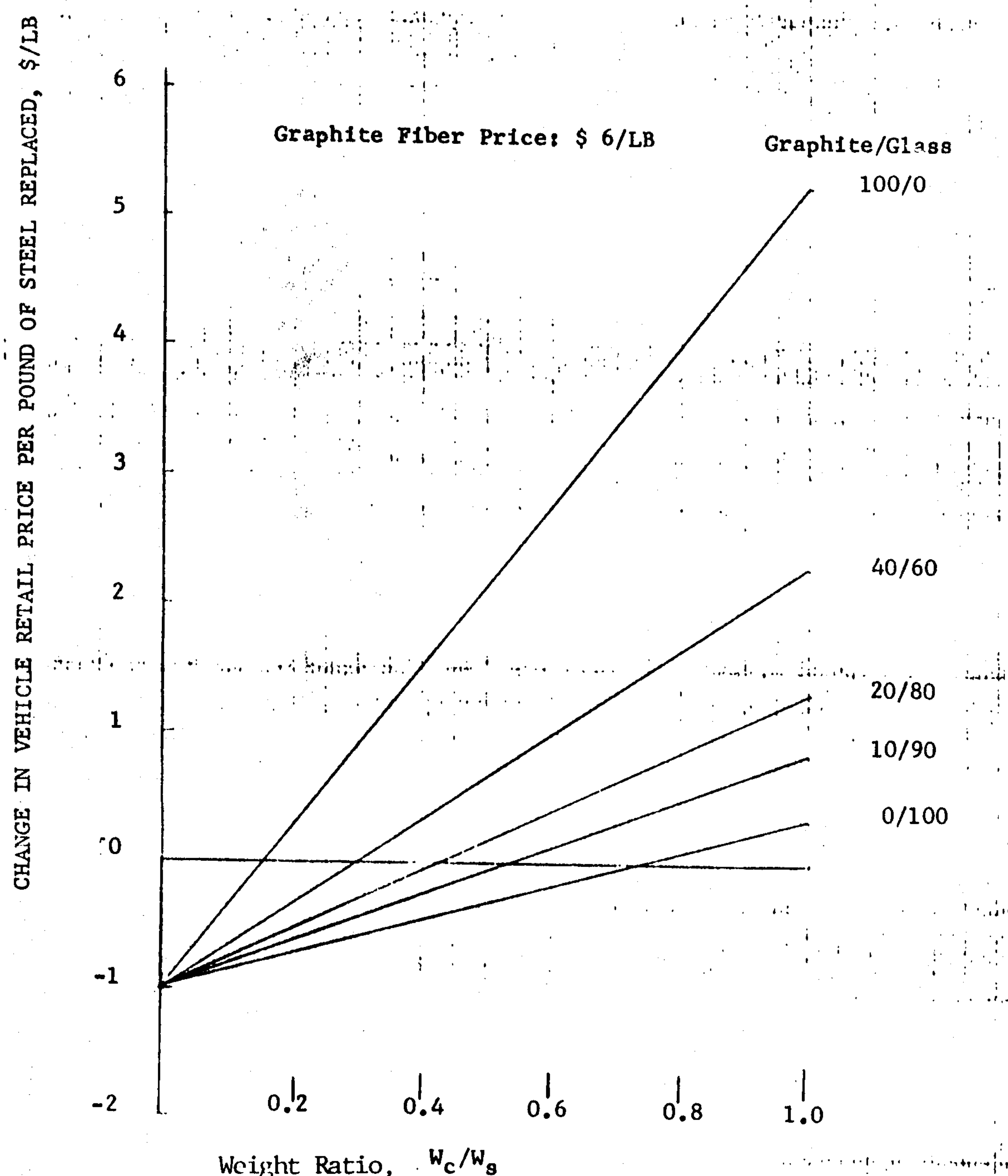

FIGURE 13 CHANGE IN RETAIL PRICE OF MODEL GASOLINE VEHICLE BY ACM SUBSTITUTION

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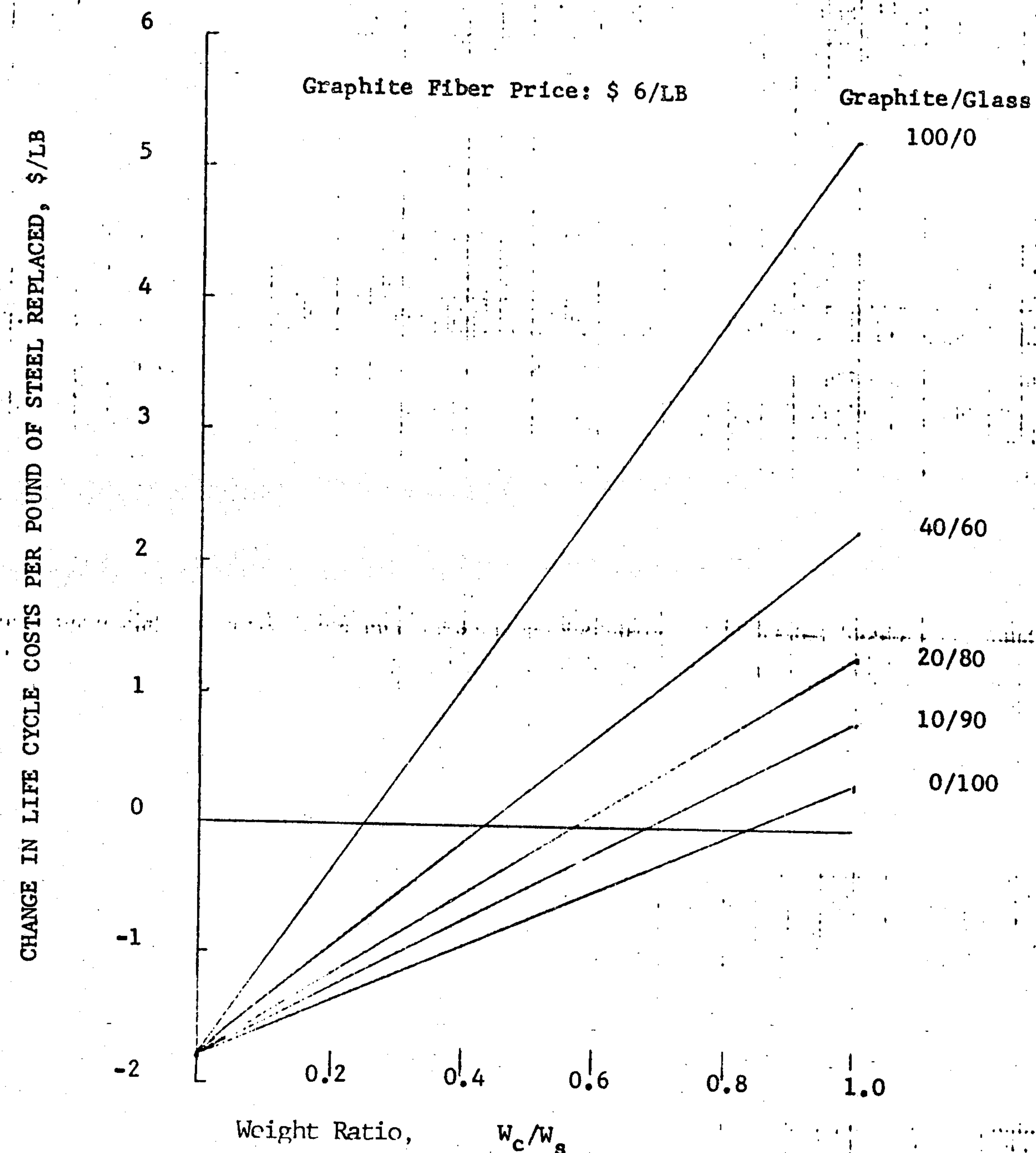

FIGURE 14 CHANGE IN LIFE CYCLE COST OF MODEL GASOLINE VEHICLE BY ACM SUBSTITUTION (B)

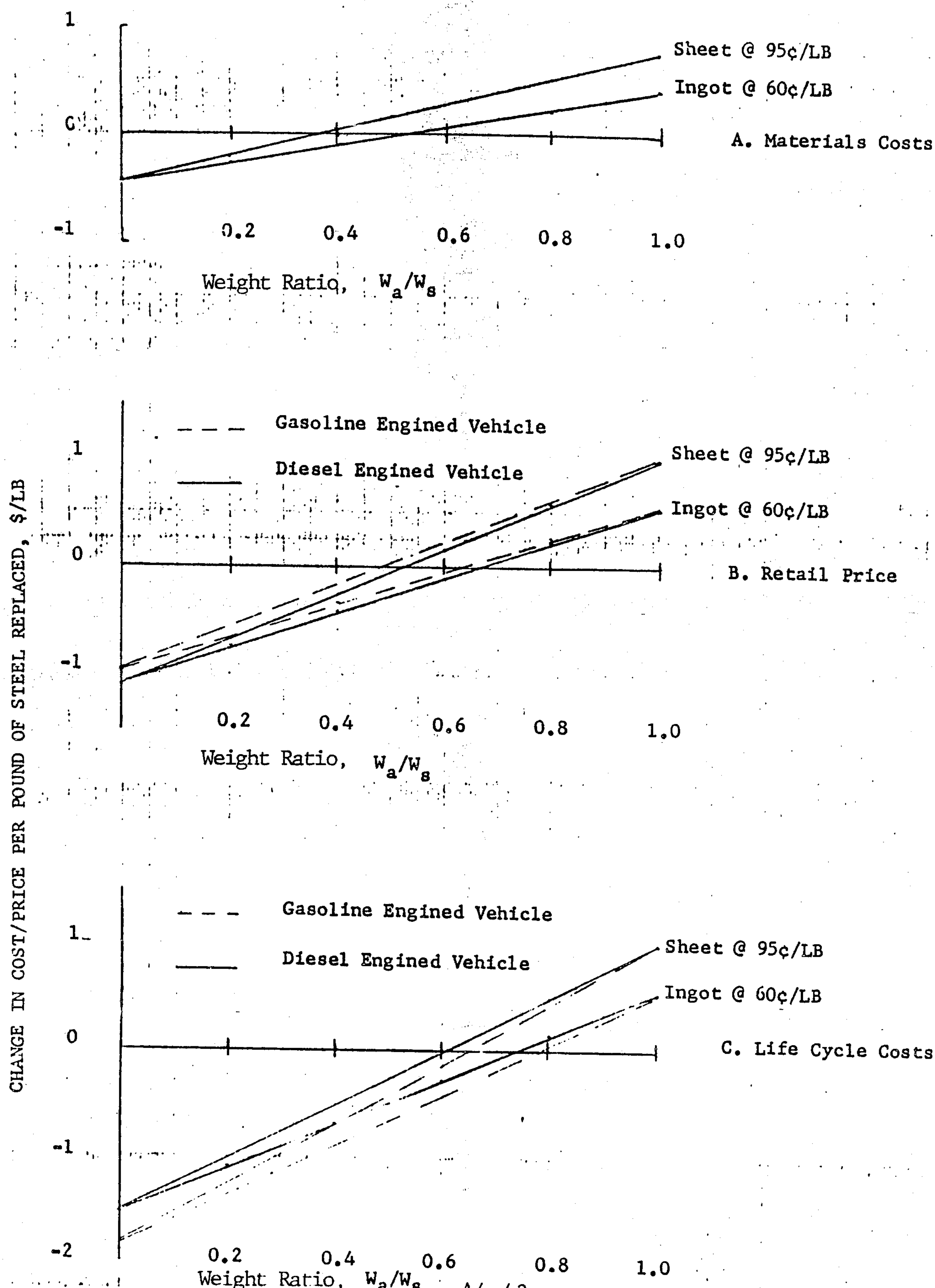

FIGURE 15 CHANGE IN COSTS/PRICES OF MODEL VEHICLES BY ALUMINUM SUBSTITUTION

The comparative impacts of substituting various materials for steel on a functionally equivalent basis are summarized in Tables 37 to 41. The cost/price changes presented in these tables are based on the values of W_c/W_s presented in Table 29 for the various materials and cases. Table 37 and 39 present the impact of materials substitution on the retail price and lifecycle costs of a diesel engined system. Tables 40 and 41 present the impact of materials substitution on the retail price and life cycle of a gasoline engined vehicle.

4.4.5 Discussion of Results

4.4.5.1 Value of Weight Reduction

The methodology developed indicates that weight reduction, per se, has a value that can range from \$0.50/lb to nearly \$2.00/lb. depending on the perspective taken. These savings correspond to the numerical values obtained for an assumed value of $W_c/W_s = 0$, which are presented in the figures presented in the previous section, or in the first column of any of the tables presented in Appendix C.

At the manufacturing level, weight reduction has a value of \$0.48/lb. which is the sum of the values of direct steel, and of propagated materials not used.

At the retail level, weight reduction has a value of about \$1.00 because of potential CAFE credits and dealer mark-up. The calculated values are \$1.09 for the diesel case and \$1.00 for gasoline engine case. It should be noted that these are conservative numbers based on the lower values presented in Table 33. If the higher values presented in the table were used (\$0.47/lbs for the diesel engine case, \$0.42/lbs. for the gasoline engine case), the CAFE credit per pound of steel removed would have been \$0.66/lbs. for the diesel engine case, and \$0.59/lb. for the gasoline engine case. The use of these numbers would have resulted in retail price reductions of \$1.39/lb steel (diesel engine case) and \$1.31/lb steel (gasoline engine case).

TABLE 37

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE MATERIALS COSTS

Assumed Price of Graphite Fiber	$10/lb			$6/lb		
Weight Reduction Potential	High	Medium	Low	High	Medium	Low
Material	Increase (Decrease) in Net Raw Materials Costs per pound of Steel Replaced, $/lb					
HM Graphite Comp.	1.00	1.72	2.43	0.45	0.90	1.34
A Graphite Comp.	1.36	2.07	3.86	0.67	1.12	2.23
Glass Fiber Comp.	(0.15)	0.10	weight gain	(0.15)	0.10	weight gain
Hybrid Composites (HM Graphite/Glass)						
10/90	0.04	0.33	weight gain	(0.05)	0.21	weight gain
20/80	0.17	0.57	weight gain	0.00	0.29	weight gain
40/60	0.39	0.88	2.53	0.11	0.45	1.55
Cast Aluminum (60 ¢/lb)	0.18	0.06	0.40	0.18	0.06	0.40
Wrought Aluminum (95 ¢/lb)	0.44	0.27	0.75	0.44	0.27	0.75
Steel	0	0	0	0	0	0

TABLE 38

IMPACT OF MATERIALS SUBSTITUTION ON DIESEL LDV RETAIL PRICE

Assumed Price of Graphite Fiber	$10/1b			$6/1b		
Weight Reduction Potential	High	Medium	Low	High	Medium	Low
Material	Increase (Decrease) in Diesel LDV Retail Price per pound of Steel Replaced, $/1b					
HM Graphite Comp.	0.94	1.94	2.94	0.21	0.85	1.49
A Graphite Comp.	1.44	2.44	4.94	0.53	1.17	2.77
Glass Fiber Comp.	(0.49)	0.00	weight gain	(0.49)	0.00	weight gain
Hybrid Composites (HM Graphite/Glass)						
10/90	(0.26)	0.31	weight gain	(0.39)	0.09	weight gain
20/80	(0.12)	0.51	weight gain	(0.34)	0.14	weight gain
40/60	0.14	0.88	3.31	(0.23)	0.30	2.01
Cast Aluminum (60 ¢/1b)	0.14	(0.11)	0.53	0.14	(0.11)	0.53
Wrought Aluminum (95 ¢/1b)	0.46	0.16	1.00	0.46	0.16	1.00
Steel	0	0	0	0	0	0

TABLE 39

IMPACT OF MATERIALS SUBSTITUTION ON DIESEL LDV LIFE CYCLE COSTS

Assumed Price of Graphite Fiber	$10/lb			$6/lb		
Weight Reduction Potential	High	Medium	Low	High	Medium	Low
Material	Increase (Decrease) in Life Cycle Costs per pound of Steel Replaced, $/lb					
HM Graphite Comp.	0.60	1.64	2.68	(0.13)	0.55	1.23
A Graphite Comp.	1.12	2.16	4.77	0.21	0.89	2.60
Glass Fiber Comp.	(0.75)	(0.11)	weight gain	(0.75)	(0.11)	weight gain
Hybrid Composites (HM Graphite/Glass)						
10/90	(0.54)	0.14	weight gain	(0.67)	(0.08)	weight gain
20/80	(0.42)	0.30	weight gain	(0.65)	(0.08)	weight gain
40/60	(0.18)	0.62	3.27	(0.54)	0.04	1.96
Cast Aluminum (60 ¢/lb)	0.03	(0.28)	0.53	0.03	(0.28)	0.53
Wrought Aluminum (95 ¢/lb)	0.35	(0.01)	1.00	0.35	(0.01)	1.00
Steel	0	0	0	0	0	0

TABLE 40

IMPACT OF MATERIALS SUBSTITUTION ON GASOLINE ENGINE LDV RETAIL PRICE

Assumed Price of Graphite Fiber	$10/lb			$6/lb		
Weight Reduction Potential	High	Medium	Low	High	Medium	Low
Material	Increase (Decrease) in Retail Price per pound of Steel Replaced, $/lb					
HM Graphite Comp.	1.00	2.00	3.00	0.27	0.91	1.54
A Graphite Comp.	1.50	2.50	4.98	0.59	1.23	2.81
Glass Fiber Comp.	(0.44)	0.02	weight gain	(0.44)	0.02	weight gain
Hybrid Composites (HM Graphite/Glass)						
10/90	(0.21)	0.34	weight gain	(0.34)	0.12	weight gain
20/80	(0.07)	0.55	weight gain	(0.29)	0.18	weight gain
40/60	0.20	0.94	3.32	(0.16)	0.35	2.02
Cast Aluminum (60 ¢/lb)	0.15	(0.07)	0.53	0.15	(0.07)	0.53
Wrought Aluminum (95 ¢/lb)	0.47	0.20	1.00	0.47	0.20	1.00
Steel	0	0	0	0	0	0

TABLE 41

IMPACT OF MATERIALS SUBSTITUTION ON GASOLINE ENGINE LDV LIFE CYCLE COSTS

Assumed Price of Graphite Fiber	$10/lb			$6/lb		
Weight Reduction Potential	High	Medium	Low	High	Medium	Low
Material	Increase (Decrease) in Life Cycle Costs per pound of Steel Replaced, $/lb					
HM Graphite Comp.	0.35	1.45	2.50	(0.38)	0.34	1.05
A Graphite Comp.	0.90	1.97	4.66	(0.02)	0.70	2.49
Glass Fiber Comp.	(0.93)	(0.21)	weight gain	(0.93)	(0.21)	weight gain
Hybrid Composites (HM Graphite/Glass)						
10/90	(0.74)	0.02	weight gain	(0.87)	(0.20)	weight gain
20/80	(0.64)	0.14	weight gain	(0.86)	(0.23)	weight gain
40/60	(0.41)	0.44	3.24	(0.77)	(0.14)	1.93
Cast Aluminum (60 ¢/lb)	(0.08)	(0.39)	0.53	(0.08)	(0.39)	0.53
Wrought Aluminum (95 ¢/lb)	0.25	(0.12)	1.00	0.25	(0.12)	1.00
Steel	0	0	0	0	0	0

On a life cycle basis, weight reduction has a still higher value because of its contribution to reduced fuel costs. Fuel reduction contributes an additional savings of $0.43/lb steel removed for the diesel engine case, and of $0.81/lb steel removed for the gasoline engine case. Depending on the CAFE credit assumed, the total life cycle test saving ranges from $1.52/lb steel removed to $1.82 lb/steel removed for the diesel engine case, and $1.81/lb steel removed to $2.12/lb steel removed for the gasoline engine case.

In summary, removing one lb. of steel from a vehicle component results in a total weight reduction of 1.4 lb, and in approximate savings of half a dollar at the manufacturing level, one dollar at the retail level, and as much as two dollars on a life cycle basis. On a relative basis, the variations for a diesel engined vehicle and a gasoline engined vehicle, are comparable, though the absolute values will differ.

4.4.5.2 Parametric Analysis

The results of the parametric analysis are presented in Figures 5 through 15, which are self explanatory. For a given material, in any set of three figures which present the results for manufacturing costs, retail price and life cycle costs, the point where the curve crosses the X axis shifts to the right as one progresses from manufacturing costs to retail price, to life cycle cost changes, because of the CAFE benefits and fuel economy benefits derived from weight reduction. The sensitivity of the slopes of the lines for those composites that contain some graphite fiber to the assumed price of graphite fiber is to be noted.

4.4.5.3 Comparison of Materials on a Functionally Equivalent Basis

The cost advantages or penalties to the manufacturer of using various materials in lieu of steel are summarized in Table 37. As can be noted in this table, the cost of materials substitution varies with the type of components being considered. For H case components, where a high degree of weight reduction can be achieved, materials substitution is least costly, and may result in cost savings. For M components, materials substitution can result in significant weight saving, but at an increase in materials costs. For L type components, little or no weight saving is achieved, except for graphite composites, while material costs increase significantly. For these L type components, it is unlikely that steel will be displaced, and that any degree of materials substitution will occur. Concurrently, there is a good probability that steel will be displaced in H type components by fiberglass or possibly graphite/glass hybrids, since these materials could result in both cost and weight savings. Aluminum is not competitive in the H applications because of its assumed fatigue limitations.

In M type applications, materials substitution results in weight reduction, but an increase in manufacturing. The extent of materials substitution in these applications will depend to a significant extent on the impact of CAFE penalties on vehicle cost structure, and to a secondary extent, on the benefits to the consumer of lower fuel utilization as a result of weight reduction. Referring to Table 37 to 41, aluminum at $0.60/lb is the most cost effective replacement material. At that price, it would only add $0.06 to the manufacturer's materials costs over steel, but result in lower retail price and life cycle costs to the consumer because of the reduced weight of the components ($\frac{Wal}{Wst} = 0.6$). The indicated price of $0.60/lb is for aluminum ingots, used mainly for castings. Many of the M type components are panels which would use aluminum sheet which is $0.95/lb. At this higher price for aluminum, fiberglass reinforced plastics and hybrids become more cost effective, especially if graphite is available at $6/lb.

The change in the material costs as a function of the weight ratio for composites with a varying ratio of HM graphite fibers and glass fibers are presented in Figure 16. As can be seen in this figure, for H components, an all glass composite can result in a weight ratio of 0.40 (60% weight reduction) and a net cost reduc-

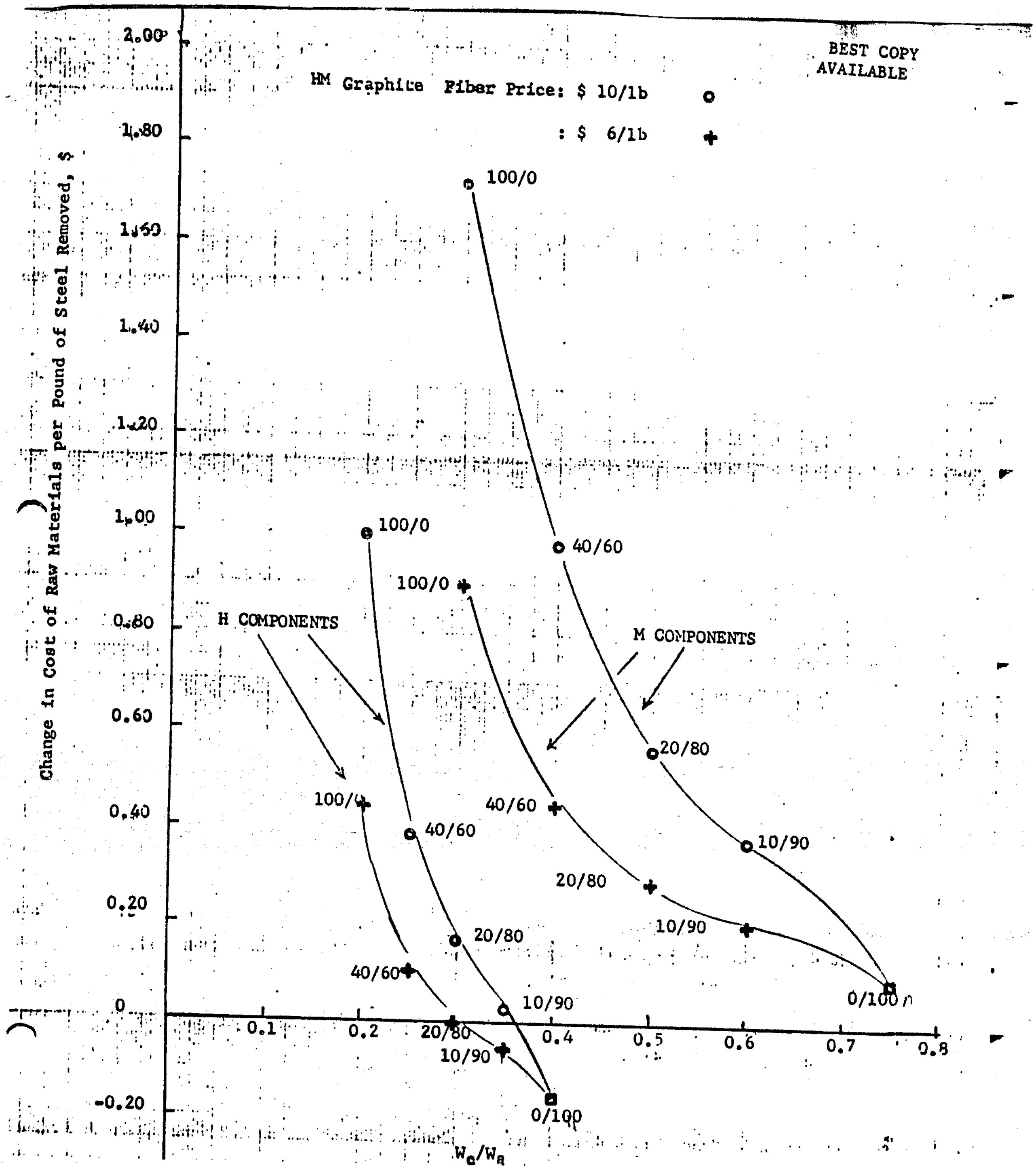

Figure 16

Change in Cost of Materials as a Function of the Weight Substitution Ratio for Graphite, Graphite/Glass Hybrids, and Glass Composites tion. Adding graphite results in further weight reduction, but at costs that rapidly increase with the graphite content. For M components, an all glass composite results in a cost increase of 10¢/lb steel removed, and a weight ratio of 0.75. Adding graphite results in a reduction in the weight ratio and in a price increase.

At $10/lb, for all HS graphite composites, the increase in the retail price per pound of steel replaced is higher than the increases in materials costs described in Table 37.

The impact of hybridization on the retail price/weight reduction relationship is shown graphically for the diesel engined vehicle in Figure 17. For H components, the lowest costs are attained with all glass composites, but hybrid composites are competitive, and at $6/lb graphite, the breakeven graphite content is estimated to be 70/30. In M applications, the cost of weight reduction is sensitive to the price of graphite. At $10/lb graphite, even 10/90 composites are relatively expensive. At $6/lb graphite, 20/80 hybrids offer a potential for a significant weight reduction as compared to glass, at a relatively small cost differential.

The impacts of materials substitution on vehicle life cycle costs for the diesel engine case are presented in Table 39. These results are similar to the results presented in Table 38 except that the values for the light weight materials are lowered relative to steel because of the credit for reduced fuel costs. These results are shown graphically for the fibrous composites in Figure 18.

In H components, fiberglass composites should reduce net life cycle costs by 75¢/lb of steel replaced. With graphite fiber at $10/lb, hybrids are competitive with steel. However, all graphite composites would be significantly more expensive than a 20/80 hybrid and offer relatively little reduction in weight.

In M compounds, substitution of steel by all fiberglass composites should result in lower life cycle costs. At a graphite fiber price of $10/lb, even a 10/90 hybrid is more ex-

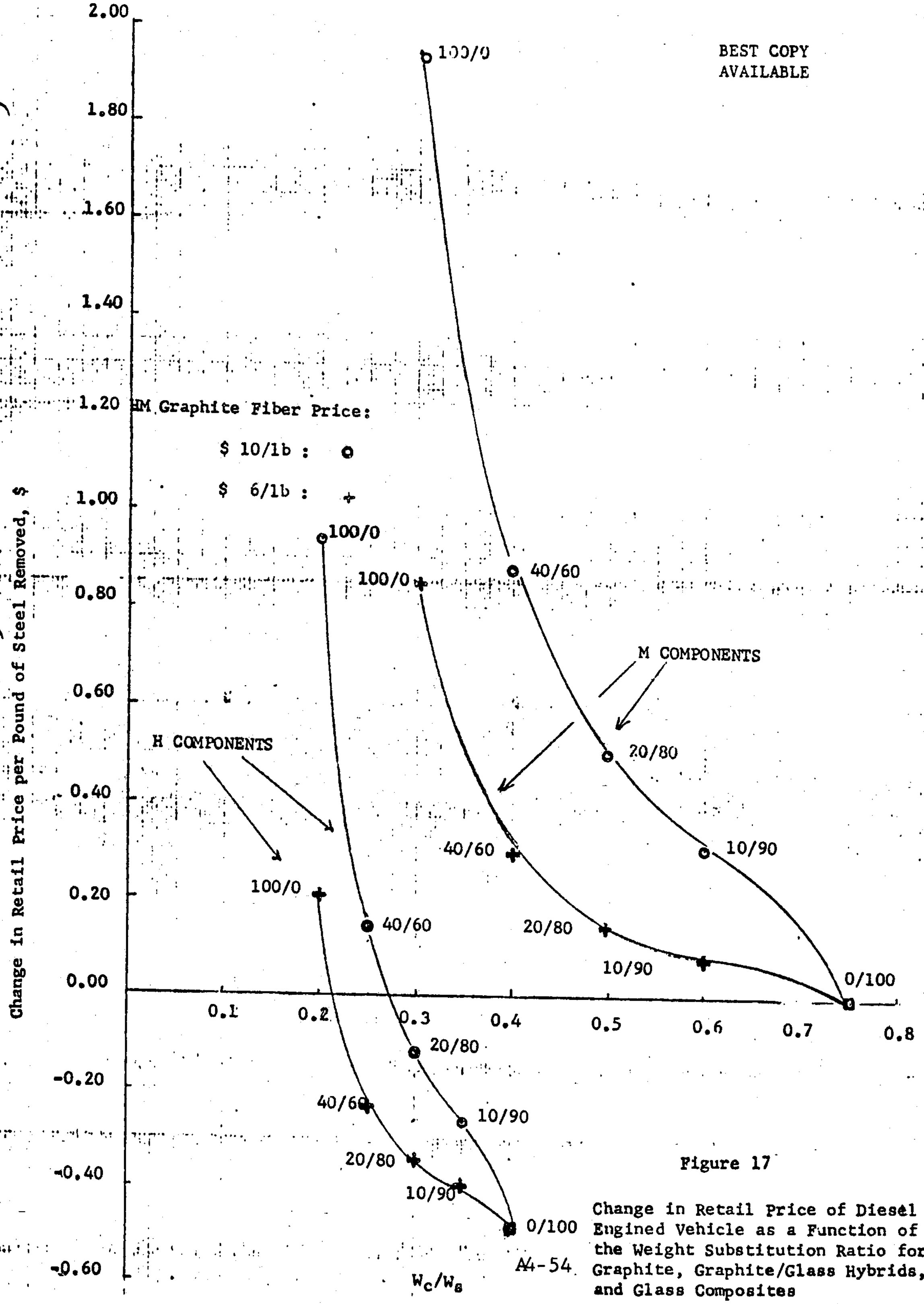

Figure 17

Change in Retail Price of Diesel Engined Vehicle as a Function of the Weight Substitution Ratio for Graphite, Graphite/Glass Hybrids, and Glass Composites

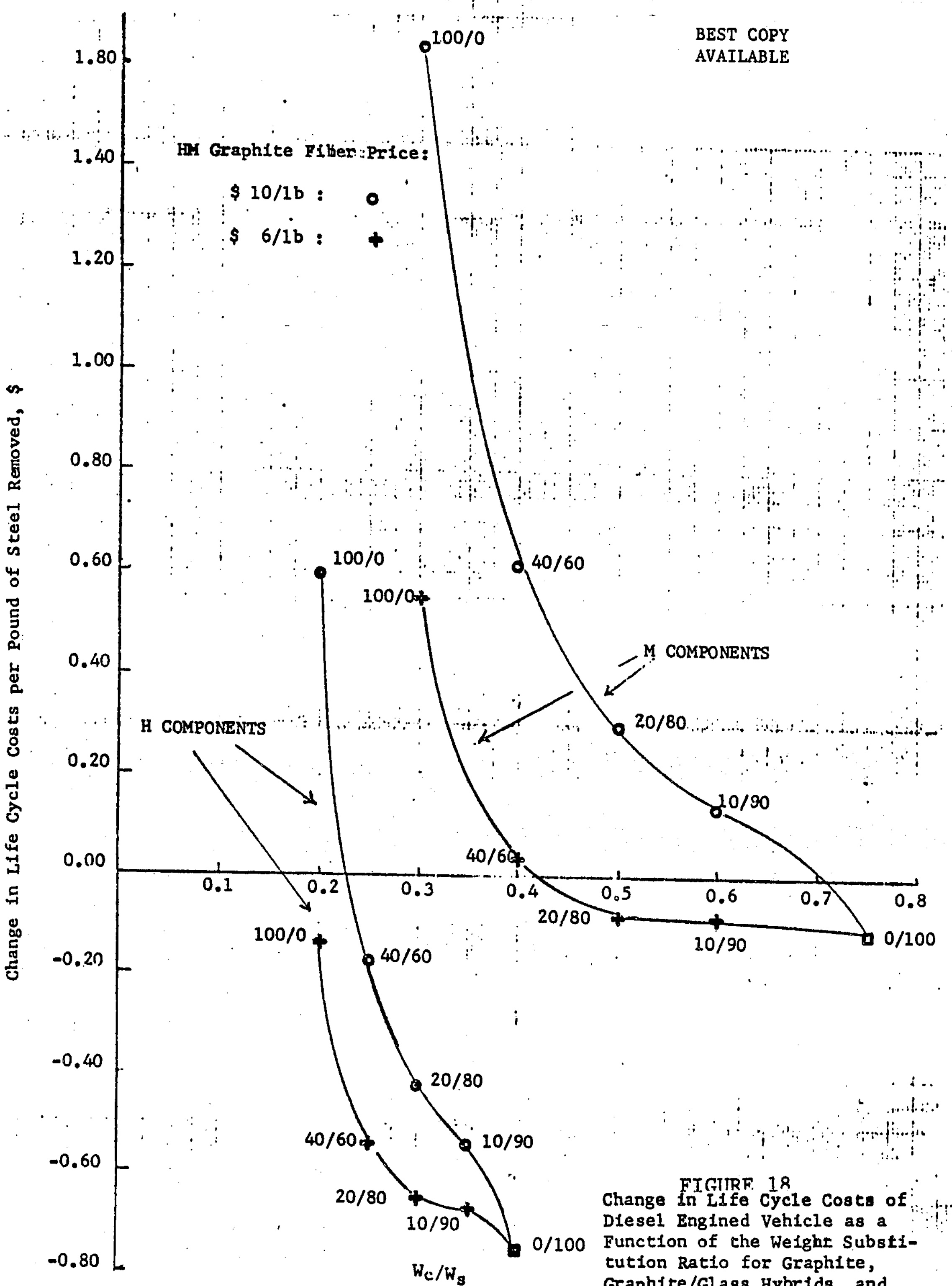

FIGURE 18
Change in Life Cycle Costs of Diesel Engined Vehicle as a Function of the Weight Substitution Ratio for Graphite, Graphite/Glass Hybrids, and Glass Composites

pensive than steel on a life cycle basis. However, at a graphite fiber price of $6/lb, replacing steel with 10/90 hybrids and 20/80 hybrids would reduce life cycle costs to within pennies of the life cycle costs of an all fiberglass composite structure.

The results for a gasoline engined vehicle presented in Tables 40 and 41 are qualitatively similar to those presented in Tables 38 and 39 for a diesel engined vehicle. This indicates that the nature of the power plant is a secondary variable as far as this analysis is concerned, and has little effect on the marginal impact of ACM on vehicle weight and cost/price structure.

4.5 Scenario II - Evolution

4.5.1 Introduction

In this section, the introduction of ACM in the real automotive world is considered. Based on the previous discussion, the more extensive use of fiberglass reinforced plastics (FRP) should result in H type automotive structures of significantly lower weight and costs (at all levels) than the equivalent steel structures. In M type structures, FRP result in modest weight reduction, slightly higher materials costs, but lower costs to the consumer than steel. All graphite reinforced plastic (GRP) composite structures result in weight ratios that are about half of those attained with FRP. Even with the most optimistic projections that can be reasonably made as to future graphite prices, GRP substitution of steel results in significantly greater costs to the manufacturer and to the consumer relative to steel. Hybrid fiber reinforced plastics (HRP), which contain graphite and glass fibers, result in weight reduction levels intermediate to those attainable with FRP and GRP. Costs are also intermediate to those of FRP and GRP systems. However, because of the non-linear relation between the weight reduction achievable with HRP systems, and their cost, it is possible to use hybrids with a low graphite fiber content that result in structures that are significantly lighter than the equivalent FRP structure, but only marginally more expensive than this FRP structure. The graphite fiber content in the component would be of the order of 10% by weight of the composite, or less. In the examples used in the previous section, a 10/90 hybrid composite only contains 5.5% graphite fiber by weight, and 20/80 hybrid composite contains 11% graphite fiber by weight.

It is envisioned that FRP will be used extensively in H type components on all LDV in the not too distant future. In many instances, the manufacturers will find it advantageous to selectively reinforce those components with judiciously placed graphite fibers to reduce the size of the components, improve fatigue properties, simplify manufacturing, etc. The amount of graphite fiber used will depend on the price of the fiber, but even at $6/lb graphite, it is doubtful that more than 10% by weight graphite will be used. The additional weight reduction attained by using more graphite fiber than this would be very small, and the costs become very large.

FRP and HRP composites may be used selectively on components of larger vehicles of the LDV fleet to the extent that these would result in lower life cycle costs to the owner. While replacement of steel with composites would increase manufacturing costs and vehicle retail price, life cycle costs would be reduced because the improved fuel economy derived from lower vehicle weight. If graphite fibers become available at $6/lb the increase in life cycle costs resulting from HRP (10% graphite or less) substitution are only slightly higher than those resulting from FRP substitution, but with significantly greater weight saving. The use of fibrous composites in M type components would occur later than in H type components.

4.5.2 Assumptions

In order to arrive at an estimate of the amount of ACM that would be used in the LDV fleet, the following assumptions were made:

1) H Type components on all vehicles would be made from ACM.

2) In addition, M Type components on the larger, more expensive vehicles would be made from ACM. These vehicles may represent 10% of the LDV Fleet population.

3) HRP composites would be used extensively. These composites would be selectively reinforced with graphite fibers, and would generally have a graphite content of less than 10% by weight. For purposes of calculation, a 20/80 graphite/glass hybrid is assumed as a model hybrid. This material which contains 11% graphite by weight, would give a measure of the maximum use of graphite in a LDV fleet application.

4) ACM use per vehicle is estimated on a component by component replacement basis for the 1975 Chevelle already used as a model vehicle to estimate the weight reduction potential of HM graphite composites. (See Appendix section 3.3). Exactly the same methodology is used as before, except that the replacement was limited to H components, in one case, and to H and M components, in a second case. From Table 29, the assumed values of Wc/Ws were 0.30 for H components, and 0.50 for M components.

5) As previously outlined in Appendix section 3.3, total vehicle weight reduction is the sum of direct weight reduction due to component substitution, plus secondary weight reduction which is assumed equal to 40% of direct weight reduction.

6) The relationship between vehicle fuel economy and vehicle test weight is described by the curves for diesel and engine vehicles presented in Figure 3.

4.5.3 Estimated Vehicle Weight Reduction

The specific steel components that were assumed to have been replaced by equivalent components made from a 20/80 hybrid composite are identified in Table 27, which presents the detailed data for the two cases considered here, as well as the results for the assumed substitution by HM graphite composites, previously discussed.

The results for the various cases presented in Table 27 are summarized in Table 42. By restricting substitution by 20/80 hybrid composites to H components, a weight reduction of 134 lbs. is attained. Extending substitution to M components results in an overall vehicle weight reduction of 595 lbs. Hybrid consumption was 41 lbs. and 370 lbs. for those two cases, respectively. The extent of weight reduction achieved in those two instances is significantly less than the 1520 lbs. obtained by extensive (H, M, and L components) use of HM graphite composte, but, as discussed in the next section, at significantly lower costs.

4.5.4 Impact of ACM Substitution on Vehicle Costs

The impact of materials substitution for the three cases considered in the analysis on materials costs to the manufacturer are presented in Table 42, based on an assumed price for graphite fiber of \$10/lb. The resulting impacts on the consumer are presented in Table 43 for a diesel engined vehicle and in Table 44 for a gasoline engined vehicle. Tables 45, 46, and 47 are equivalent tables based on an assumed price of \$6/lb. for graphite fiber.

4.5.4.1 All Graphite Substitution

At \$10/lb. graphite, extensive use of HM graphite composites results in an increase in materials costs of \$3271/vehicle. This is nearly one and a half times current total materials costs. To accommodate this cost increase, vehicle wholesale price would increase by about \$3000, after having taken a liberal CAFE credit.

TABLE 42

VEHICLE WEIGHT REDUCTION BY SUBSTITUTION OF ACM FOR STEEL

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
CURB WEIGHT, INITIAL VEHICLE, LBS	3643	3643	3643
WEIGHT OF STEEL REMOVED, LBS	1643	137	795
WEIGHT OF ACM USED, LBS	557	41	370
DIRECT WEIGHT REDUCTION, LBS	1086	96	425
SECONDARY WEIGHT REDUCTION, LBS	434	38	170
TOTAL WEIGHT REDUCTION, LBS	1520	134	595
CURB WEIGHT OF MODIFIED VEHICLE, LBS	2123	3509	3048
MATERIALS COSTS CHANGES (*)		$/VEHICLE	
COST OF COMPOSITES USED	3860	73	655
VALUE OF STEEL RELACED	(329)	(27)	(159)
VALUE OF PROPAGATED MATERIALS	(260)	(23)	(102)
NET CHANGE IN MATERIALS COSTS	3271	23	394
EQUIVALENT CHANGE IN WHOLESALE PRICE	3565	25	429

(*) Graphite Fiber = $10/LB

TABLE 43

IMPACT OF ACM SUBSTITUTION FOR STEEL

ON THE COST/PRICE STRUCTURE OF A REFERENCE LTV

(1975 CHEVELLE - DIESEL ENGINE MODEL)

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
ORIGINAL VEHICLE, TEST WEIGHT (LBS)	3943	3943	3943
ORIGINAL VEHICLE, FUEL ECONOMY (MPG)	30.8	30.8	30.8
ORIGINAL VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	3250	3250	3250
MODIFIED VEHICLE, TEST WEIGHT (LBS)	2423	3809	3348
MODIFIED VEHICLE, FUEL ECONOMY (MPG)	43.1	31.5	34.5
MODIFIED VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	2320	3175	2900
CHANGE IN VEHICLE TEST WEIGHT (LBS)	(1520)	(132)	(495)
CHANGE IN VEHICLE FUEL ECONOMY (MPG)	12.3	0.7	3.7
CHANGE IN LIFETIME FUEL CONSUMPTION (GALLONS)	(930)	(75)	(350)
INCREASE IN WHOLESALE PRICE DUE TO MATERIAL COST CHANGE	3565	25	429
CAFE CREDIT @ $50/ mpg	(615)	(35)	(185)
NET CHANGE IN WHOLESALE PRICE	2950	(10)	244
EQUIVALENT CHANGE IN RETAIL PRICE	3599	(12)	298
NPV OF REDUCED FUEL CONSUMED	(501)	(41)	(189)
NET CHANGE IN VEHICLE LIFE CYCLE COSTS	3098	(53)	109

TABLE 44

IMPACT OF ACM SUBSTITUTION FOR STEEL

ON THE COST/PRICE STRUCTURE OF A REFERENCE LTV

(1975 CHEVELLE - GAS ENGINE MODEL)

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
ORIGINAL VEHICLE, TEST WEIGHT (LBS)	3943	3943	3943
ORIGINAL VEHICLE, FUEL ECONOMY (MPG)	19.9	19.9	19.9
ORIGINAL VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	5025	5025	5025
MODIFIED VEHICLE, TEST WEIGHT (LBS)	2423	3809	3348
MODIFIED VEHICLE, FUEL ECONOMY (MPG)	30.5	20.5	22.9
MODIFIED VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	3280	4880	4370
CHANGE IN VEHICLE TEST WEIGHT (LBS)	(1520)	(132)	(495)
CHANGE IN VEHICLE FUEL ECONOMY (MPG)	10.6	0.6	3.0
CHANGE IN LIFETIME FUEL CONSUMPTION (GALLONS)	(1745)	(145)	(655)
INCREASE IN WHOLESALE PRICE DUE TO MATERIAL COST CHANGE	3565	25	429
CAFE CREDIT @ $50/ mpg	(530)	(30)	(150)
NET CHANGE IN WHOLESALE PRICE	3035	(5)	279
EQUIVALENT CHANGE IN RETAIL PRICE	3703	(6)	340
NPV OF REDUCED FUEL CONSUMED	(943)	(79)	(356)
NET CHANGE IN VEHICLE LIFE CYCLE COSTS	2760	(85)	(16)

TABLE 45

VEHICLE WEIGHT REDUCTION BY SUBSTITUTION OF ACM FOR STEEL (B)

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
CURB WEIGHT, INITIAL VEHICLE, LBS	3643	3643	3643
WEIGHT OF STEEL REMOVED, LBS	1643	137	795
WEIGHT OF ACM USED, LBS	557	41	370
DIRECT WEIGHT REDUCTION, LBS	1086	96	425
SECONDARY WEIGHT REDUCTION, LBS	434	38	170
TOTAL WEIGHT REDUCTION, LBS	1520	134	595
CURB WEIGHT OF MODIFIED VEHICLE, LBS	2123	3509	3048
MATERIALS COSTS CHANGES(*)		$/VEHICLE	
COST OF COMPOSITES USED	2345	50	451
VALUE OF STEEL RELACED	(329)	(27)	(159)
VALUE OF PROPAGATED MATERIALS	(260)	(23)	(102)
NET CHANGE IN MATERIALS COSTS	1756	0	261
EQUIVALENT CHANGE IN WHOLESALE PRICE	1914	0	284

(*) Graphite Fiber = $6/LB

TABLE 46

IMPACT OF ACM SUBSTITUTION FOR STEEL ON THE COST/PRICE STRUCTURE OF A REFERENCE LTV (1975 CHEVELLE - DIESEL ENGINE MODEL)

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
ORIGINAL VEHICLE, TEST WEIGHT (LBS)	3943	3943	3943
ORIGINAL VEHICLE, FUEL ECONOMY (MPG)	30.8	30.8	30.8
ORIGINAL VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	3250	3250	3250
MODIFIED VEHICLE, TEST WEIGHT (LBS)	2423	3809	3348
MODIFIED VEHICLE, FUEL ECONOMY (MPG)	43.1	31.5	34.5
MODIFIED VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	2320	3175	2900
CHANGE IN VEHICLE TEST WEIGHT (LBS)	(1520)	(132)	(495)
CHANGE IN VEHICLE FUEL ECONOMY (MPG)	12.3	0.7	3.7
CHANGE IN LIFETIME FUEL CONSUMPTION (GALLONS)	(930)	(75)	(350)
INCREASE IN WHOLESALE PRICE DUE TO MATERIAL COST CHANGE	$1914	$ 0	$284
CAFE CREDIT @ $50/ mpg	($ 615)	($35)	($185)
NET CHANGE IN WHOLESALE PRICE	$1299	($35)	$ 99
EQUIVALENT CHANGE IN RETAIL PRICE	$1585	($43)	$121
NPV OF REDUCED FUEL CONSUMED	($ 501)	($41)	($189)
NET CHANGE IN VEHICLE LIFE CYCLE COSTS	$1084	($84)	($ 68)

TABLE 47

IMPACT OF ACM SUBSTITUTION FOR STEEL ON THE COST/PRICE STRUCTURE OF A REFERENCE LTV (1975 CHEVELLE - GAS ENGINE MODEL)

ACM ASSUMED	HM GRAPHITE COMPOSITE	HM GRAPHITE/ GLASS HYBRID (20/80)	HM GRAPHITE/ GLASS HYBRID (20/80)
EXTENT OF SUBSTITUTION	H,M,L	H	H,M
ORIGINAL VEHICLE, TEST WEIGHT (LBS)	3943	3943	3943
ORIGINAL VEHICLE, FUEL ECONOMY (MPG)	19.9	19.9	19.9
ORIGINAL VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	5025	5025	5025
MODIFIED VEHICLE, TEST WEIGHT (LBS)	2423	3809	3348
MODIFIED VEHICLE, FUEL ECONOMY (MPG)	30.5	20.5	22.9
MODIFIED VEHICLE, LIFETIME FUEL CONSUMPTION (GALLONS)	3280	4880	4370
CHANGE IN VEHICLE TEST WEIGHT (LBS)	(1520)	(132)	(495)
CHANGE IN VEHICLE FUEL ECONOMY (MPG)	10.6	0.6	3.0
CHANGE IN LIFETIME FUEL CONSUMPTION (GALLONS)	(1745)	(145)	(655)
INCREASE IN WHOLESALE PRICE DUE TO MATERIAL COST CHANGE	$1914	$ 0	$284
CAFE CREDIT @ $50/ mpg	($ 530)	($ 30)	($150)
NET CHANGE IN WHOLESALE PRICE	$1384	($ 30)	$134
EQUIVALENT CHANGE IN RETAIL PRICE	$1688	($ 37)	$163
NPV OF REDUCED FUEL CONSUMED	($943)	($ 79)	($356)
NET CHANGE IN VEHICLE LIFE CYCLE COSTS	$ 745	($116)	($193)

Retail price would increase by about $3600 to $3700, and life cycle costs would increase by $2800 to $3100, depending upon the assumed mode of propulsion.

Even if HM graphite were to drop to $6/lb. (which is unlikely unless an improved pitch derived filament is obtained) cost of materials would still increase by over $1700. Even after taking a CAFE credit, vehicle retail price would increase by $1600 to $1700, and vehicle life cycle costs would increase by $750 to $1100.

These unfavorable economics are the reason why it is very unlikely that there will not be extensive use of all graphite composites in the LDV fleet of the future.

4.5.4.2 Selective Hybrid Substitution

Limiting the use of hybrid composites to H components results in an increase of materials costs of $23/car at an assumed graphite fiber price of $10/lb., and there is no increase in materials costs at an assumed graphite fiber price of $6/lb. Even at $10/lb. for graphite fiber the retail cost of the vehicle is less than that of the base case because the CAFE credits resulting from improved fuel economy are higher than the increase in wholesale price due to the materials cost increase. Both diesel and gasoline vehicles are cheaper for the consumer to buy, and to operate.

Substitution of steel by hybrid composites limited to H components results in a lower retail price of about $10 to $40, lower life cycle costs of from about $50 to $120, and a lower fuel consumption of about 130 gallons per vehicle over 10 years. These are all favorable impacts which indicate extensive use of fibrous composites in these applications.

4.5.4.3 Extensive Hybrid Substitution

Expanded use of hybrid composites can result in weight reductions of about 500 lbs./vehicle, and in fuel economy improvements of 3.0 to 3.7 mpg. A diesel engined vehicle, with extensive hybrid substitution equivalent in size and performance to the 1975 Chevelle would have a fuel economy of 34.5 mpg.

More extensive use of hybrid composites would result in materials cost increases of $261 ($6/lb. graphite fiber) to $394 ($10/lb. graphite fiber). At $10/lb. for graphite fiber the retail price of the vehicle would increase by about $300 to $350 depending on the type of engine used. Again, life cycle costs would be about the same as for the base case: a gasoline engine vehicle would be slightly lower, a diesel engined vehicle about $100 higher.

If graphite fibers were available at $6/lb., vehicle retail price would still increase by $120 to $160, but vehicle life cycle costs would decrease by $70 to $190 depending on the type of engine used.

The increase in retail price resulting from materials substitution makes it unlikely that the hybrids would be used in all vehicles, especially the less expensive, smaller models. However, hybrid substitution allows the manufacturer to make a large, light weight vehicle that is competitive with a heavier vehicle on a life cycle cost basis. The higher first costs relegate substitution to the larger, more expensive vehicles that would sell to more financially sophisticated, but also "status" conscious buyers, who would not mind paying slightly more for a distinctive vehicle, that in the long run, would not cost more to operate.

4.6 Problems and Issues

A number of problems and issues have to be addressed and solved in order for advanced composite materials to be considered as materials of construction for production automobiles. These include:

a) Cost of raw materials. At current prices, advanced composites are prohibitively expensive for nearly all automotive uses. Specific applications would become attractive at graphite filament prices of less than \$10/lb., and many applications could be considered if filament price dropped to \$6/lb.

b) Manufacturing. Most of the experimental advanced composite automotive components have been made with all graphite composites formed by aerospace fabrication techniques that are too expensive and too slow to be considered for high volume automotive applications. It will be necessary to adapt, and improve upon, existing fiberglass reinforced plastic manufacturing technology to the manufacture of hybrid composites. The conductivity of graphite filaments will require that provisions be made for containing these fibers during shipping, storage, and manufacture of composite structures. There may also be some assembling problems with fibrous composites. Fibrous composites do not yield as metals do, and therefore cannot be pounded into place. This may require large automotive structures to be fabricated to much closer tolerances.

c) Durability. There has been no demonstration that ACM components can survive 50,000 miles (80,000 km) of actual automotive use, over an extended period of years.

d) Damageability. The failure mode of fibrous composites, which are brittle materials is very different from the failure of metals which can yield. Composites are less likely to deform under light loads than metals, but could shatter and form jagged edges upon severe impact in some cases, or simply delaminate in other instances.

e) Crashworthiness. See Damageability above.

f) Repair Upon Damage. The ability of being able to repair major structural components made of any reinforced plastic is an open issue. It would be desirable to be able to repair rather than replace large components.

g) Noise Vibrations and Handling. The road handling characteristics of a large, low weight automobile are not known at the moment and it may be necessary to include load leveling provisions into the design of an automobile if the maximum payload becomes a significant fraction of the gross vehicle weight.

h) Recycling. Reinforced thermosetting resins can not be economically recycled at the moment, so that land fill of scrap advanced composite parts is the only current available option.

i) Graphite Fiber Release. The uncontrolled release of graphite fibers or lint from burning graphite-organic matrix composites is a problem of current concern. Graphite fibers are less flammable than organic matrices, such as an epoxy resin. The matrix can be preferentially consumed in a burning composite, resulting in the formation of an uncontained graphite fiber skeleton, from which fibers can break off and diffuse. This diffusion problem can be compounded if the fire is accompanied by an explosion.

With the emerging interest in the use of graphite fiber reinforced plastics in non-military applications, an interagency task force, under the technical leadership of NASA, has been established to examine the ramifications of this problem. Until recently the topic was classified, and much of the test data obtained by the military agencies is not, as of yet (7/78), available to the public. At the moment, there is insufficient data to arrive at any valid conclusion, and it is possible only to speculate as to the severity of the problem, especially for fiberglass hybrid composites where fusing the glass could result in a coherent mass.

4.7 Projected Future Activities and Uses

Future development work will address itself to these issues. Current costs are not a major consideration because of the leverage of the automotive industry. The average use of only 1 lb. of graphite filament per automobile will create a demand for 10 million lbs. of graphite a year. At this level, graphite could be sold for less than $10/lb. (see Figure 2). The cost of graphite would be further diluted by extensive use of hybrid composites.

Developments over the next few years will focus on manufacturing technology and proof testing of selected components in actual service. One or two selected advanced composite components will be introduced by the major manufacturers in a limited production automobile or light truck in model year 1980. The first production use of advanced composites will most probably be an air conditioner support bracket for the Ford 2.3 liter engine which will be used on vehicles such as the Mustang. This part will most likely be made by Armco Composites of St. Charles, Illinois by compression molding of a modified polyester sheet molding compound. The UMC™ sheet will contain continuous graphite fiber reinforcement in addition to chopped glass. Great Lakes Carbon Company will most likely be the graphite fiber supplier. Based on a test production run of 30,000 brackets which will weigh 2.5 lbs. and contain approximately 20% graphite by weight, approximately 15,000 lbs. of graphite fiber will be required for this program. This is a conservative approach to introducing a new material in that the support bracket is a non-safety critical part that can be easily removed if it does not function properly in service.

Both Chrysler Corporation and General Motors Corporation will have test programs under way in Model Year 1980 or Model Year 1981.

Chrysler activities are focused on an unspecified bracket as well. It is quite likely that the first production use of advanced composites by General Motors Corporation will be on the Chevrolet Corvette.

Over the next few model years, additional advanced composite parts will be introduced for service evaluation if no difficulties are encountered in the first series. Most of these parts will be structural parts that will weigh less than 5 lbs. (2.3 kg). A graphite reinforced hood or deck lid may be included to evaluate an external painted part. By 1985, there may be as many as 10 different parts in service. Assuming an average weight of 3 lbs. per part, a 10% graphite content, the production of 10 million autos, and an average of two test parts on 10% of the vehicles produced, would result in a demand of 600,000 lbs. (273 metric tons) of graphite fiber by the automobiles in 1985.

Advanced composites usage in automobiles beyond 1985 will depend mainly on CAFE requirements imposed on the manufacturers. If these do not become much more stringent than 27.5 mpg, (i.e., less than 30 mpg) use of advanced composites will remain limited to brackets, hinges and a variety of similar small parts that will find general application, and to larger components for selected automobiles. By 1990, the combined weight of the small (H type) components in an average car could be as much as 40 lbs. Again, assuming a 10 million car/year production rate and a 10% graphite content, a graphite fiber consumption of 40 million lbs/year is envisioned.

Advanced composites will also be used to transfer automobiles from one inertia weight category to a lower one. For example, currently for EPA test purposes all automobiles that have an actual inertia weight (curb weight + 300 lbs.) of 2751 lbs. to 3250 lbs. are grouped in the 3000 lbs. inertia weight class; those that have an inertia weight of 3251 lbs. to 3750 lbs. are grouped in the 3500 lb. inertia weight class, etc. The reported fuel economy of a vehicle is a function of its inertia weight as reported in Figure 3. Thus a vehicle that has an inertia weight of 3249 lb will have a much better EPA fuel rating than a comparable vehicle that has an inertia weight of 3251 lb. The first vehicle, which will be tested in the 3000 lb. class will have a rated fuel economy that is 10% higher than the second vehicle which will be tested in the 3500 lb. class, and this difference could be as much as 2 to 3 mpg.

In the future, EPA will narrow the bandwidth of the inertial weight classes to 125 lbs. which will reduce the incentive to drop from one weight class to another by a factor of 4. In 1985 the difference in apparent fuel economy would be 0.8 to 1.2 mpg. Given the structures of the law ($50/automobile for every mile above (CAFE)) a one mpg improvement in fuel economy in a production run of 100,000 automobiles, is worth $5 million. Under these circumstances, replacing a steel component with a graphite component has a value well beyond the costs of the components. A weight savings of 10 lb/car can be construed to be worth $5/lb of weight saved.

This situation may arise in only a small percentage of the vehicles produced. Assuming the use of additonal 40 pounds of hybrid composites to save 10 pounds of vehicle weight, on 5% of the fleet, an additional graphite usage of 2 million lb/yr. is calculated.

If the CAFE requirements become significantly more stringent than 30 mpg in the post 1985 period, then advanced composites will find much more extensive use in the automotive industry, particularly in larger luxury vehicles. For example, increasing CAFE will not have much impact on the use of materials in small vehicles that would already be fuel efficient; however, large automobiles would be vulnerable to a higher CAFE unless high performance composites would be used extensively. Approximately 8 to 10% of the current new car market is for luxury vehicles that sell for more than $10,000 apiece. The market for these status vehicles will continue to exist, nearly irrespective of the price of the vehicles (within limits of course). It is not unreasonable to assume that the larger luxury vehicles may make more extensive use of hybrid reinforced plastics than the average car. If it is assumed that the large cars will contain M and H type components made of HRP, according to the analysis presented here, an average larger automobile would contain about 400 lbs. of HRP. Based on a graphite content of 10% by weight, the larger vehicles would each contain 40 lbs. of graphite filaments. These would add $300 to $400 (constant dollars) to the manufacturing cost of the car. While this added cost would be prohibitive in an average $4000 automobile, it could be considered as providing optional luxury and space in a $12,000 vehicle. A million larger automobiles a year, each containing 40 lbs. of graphite filament, would consume a total of 40 million pounds of graphite filament a year.

Electric vehicles would be another group of automobiles in which advanced composites would be used extensively. Increasing the weight of the chassis and body of a vehicle by a given amount is more detrimental to an electric vehicle (EV) than to an internal combustion engine (ICE) vehicle. This is due to the fact that the weight of the power generating group (motor and fuel or battery) is a much greater fraction of the gross vehicle weight for an electric vehicle than for an ICE vehicle. Furthermore, the unit cost of the power generating group is much higher for an EV than an ICE vehicle. Weight reduction is three times as valuable in an electric vehicle as in an ICE. At the moment, there are few EVs in service, but DOE is funding a demonstration program which will result in 10,000 EVs being in service by 1986. An optimistic projection would assume an an order of magnitude increase in EV population by 1990 which corresponds to a production rate of 25,000 vehicles a year. It is estimated that an EV could consume 600 lbs. to 800 lbs. of advanced hybrid composite in its body and chassis components. This EV production would consume approximately 1 to 2 million pounds a year of high performance fiber.

Based on the above discussion, the total projected consumption of high performance fiber by the automobile industry in 1990 is estimated to range from about 10 million to slightly over 80 million pounds per year (10,000 to 40,000 metric tons/year). This market would dominate the consumption of high performance fibers. These projections are summarized in Table 48. Since the hybrids may contain less than 10% graphite fiber these figures are considered to be maximum values.

The projected high performance fiber consumption by the 1990 automobile market represents one hundred fold expansion of the current (1977) market for these fibers. It is estimated that the additional manufacturing facility needed to produce the high performance fiber (e.g., graphite) could require $500 million to $1 billion in capital.

There would also be an associated demand for an additional 300 million to 600 million pounds per year (140,000 to 270,000 metric tons/year) of glass fibers; and of 150 million to 300 million pounds per year (78,000 to 140,000 metric tons/year) of polymeric resin, presumably, in the main, unsaturated polyesters. For comparison, in 1976, fibrous glass consumption in the U.S. was 280,000 metric tons (32), while polyester resin consumption was 436,000 metric tons (33). Extensive use of hybrid composites would require expansion of facilities for these two commodities.

TABLE 48

PROJECTION MAXIMUM 1990 AUTOMOBILE CONSUMPTION OF ADVANCED COMPOSITE MATERIALS

VEHICLE	ANNUAL PRODUCTION 10^6 VEHICLES/YR	HYBRID COMPOSITE USE PER VEHICLE LBS/VEHICLE	AUTOMOBILE CONSUMPTION OF HYBRID COMPOSITES 10^6 LBS/YEAR	EQUIVALENT HIGH PERFORMANCE FIBER REQUIREMENTS(*) 10^6 LBS/YR
All Passenger Autos	10.0	40	400	40
Passenger Autos Subject to Inertial Weight Class Shift	0.5	40	20	2
Luxury Passenger Autos	1.0	0-400	0- 400	0-40
EV/EHV	0.025	400-800	10-20	1-2
TOTAL			430-840	43-84

(*) 10% high performance fiber content.

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APPENDIX B

ADVANCED COMPOSITE MATERIALS IN ENGINES OF THE FUTURE

The majority of engine components are produced from castings and forgings, with ferrous castings being predominant. In most cases, the components are overdesigned in terms of contained metal because of manufacturing and reliability considerations. A significant amount of weight reduction is already being obtained by redesigning the engine components so as to eliminate parasitic metal.

Beyond these efforts, weight reduction of engine components may be obtained by materials substitution. In the nearer term, this entails the replacement of ferrous castings by light metal alloy castings, principally aluminum, or by molded plastics. Cast aluminum is now replacing cast iron in cylinder heads. The engine cooling fan is made of fiberglass reinforced nylon on the Ford Fairmont/Zephyr, and of fiberglass reinforced polypropylene on the Plymouth Horizon (Dodge Omni), instead of steel. On many of the Fiat models, nylon pulleys are used instead of steel pulleys. Most of these developments are directed towards those components of an engine that operate under the more benign environmental conditions that exist under the hood of an automobile. Ferrous metals are still the materials of choice for those components that are most highly stressed, and that are exposed to the more severe environmental conditions, particularly higher temperatures. These include crankshafts, camshafts, connecting rods, etc.

In the longer term, the requirements of high rigidity, stability at elevated temperatures (up to 500°F), environmental resistance, and low weight, may be met by some novel composite materials that are presently far from commercialization.

Graphite fiber reinforced epoxy and polyester resins are currently being explored as lightweight structural materials for body and chassis applications. They have limited use in engine applications because of the temperature limitations of plastic matrix materials (up to 350°F for selected polyester and epoxy resins).

A number of plastics have been introduced into commerce that have distortion temperatures well in excess of 500°F. These include thermosetting resins such as Thermid 600 (Gulf Specialty Chemicals) and thermoplastic resins such as Torlon (Amoco), a thermoplastic poly (amide-imide). Reinforcing resins such as these with graphite fibers should result in materials that can be used in functional parts currently limited to ferrous metals.

These would include push rods which would be 70% lighter than the equivalent metal push rods. The composite push rod should also increase engine efficiency and reduce vibration noise. Using graphite fiber reinforced composites in other engine components such as connecting rods, wrist pins, and rocker arms, makes possible a reduction in counterweights on the crankshaft. The total effect of extensive use of ACM engine components would be to significantly reduce the weight of the engine required for a desired horsepower output.

Short fiber metal matrix composites could potentially also be used in the applications. In this case one would be dealing with aluminum or magnesium reinforced with either alumina or silicon carbide fibers. The presence of 15% reinforcing fibers in the metal matrix significantly increases the strength and the stiffness of the matrix metal without seriously affecting the metal density, nor the ability of the metal to be worked by standard fabrication techniques. (B1, B2).

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APPENDIX C

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE COSTS/PRICES PER POUND OF STEEL REPLACED FOR VARIOUS MATERIALS OF INTEREST

TABLE C-1

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IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: Glass Fiber Composite

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	Dollars per Pound of Steel Replaced					
Price of Composite Used,	0.00					
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.29)	(0.15)	(0.01)	0.13	0.28
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.32)	(0.16)	(0.01)	0.14	0.31
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.64)	(0.40)	(0.17)	0.06	0.31
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.78)	(0.49)	(0.21)	0.07	0.38
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(1.12)	(0.75)	(0.38)	(0.02)	0.38
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.59)	(0.36)	(0.14)	0.07	0.31
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.72)	(0.44)	(0.17)	0.09	0.38
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.37)	(0.93)	(0.49)	(0.07)	0.38

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TABLE C-2

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 10% Graphite/Glass Hybrid (Graphite = $10/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	←Dollars per Pound of Steel Replaced→					
Price of Composite Used,	0.00	0.23	0.45	0.63	0.90	1.13
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.16)	0.11	0.38	0.65	0.93
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.18)	0.12	0.41	0.71	1.01
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.50)	(0.12)	0.25	0.63	1.01
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.61)	(0.15)	0.31	0.77	1.24
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.95)	(0.41)	0.14	0.68	1.24
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.45)	(0.08)	0.28	0.64	1.01
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.55)	(0.10)	0.34	0.78	1.24
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.20)	(0.59)	0.02	0.62	1.24

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TABLE C-3

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 20% Graphite/Glass Hybrid (Graphite Fiber = $10/lb)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	←Dollars per Pound of Steel Replaced→					
Price of Composite Used,	0.00	0.35	0.71	1.06	1.42	1.77
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.04)	0.37	0.76	1.17	1.57
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.04)	0.40	0.83	1.27	1.71
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.36)	0.16	0.67	1.19	1.71
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.44)	0.20	0.82	1.45	2.09
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.78)	(0.06)	(0.65)	1.36	2.09
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.31)	0.20	0.70	1.20	1.71
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.38)	0.24	0.85	1.46	2.09
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.03)	(0.25)	0.53	1.30	2.09

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TABLE C-4

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 40% Graphite/Glass Hybrid (Graphite Fiber = $10/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.61	1.22	1.84	2.45	3.06
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	0.22	0.88	1.54	2.20	2.86
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	0.24	0.96	1.67	2.40	3.12
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.08)	0.72	1.51	2.32	3.12
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.10)	0.88	1.85	2.83	3.80
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.44)	0.62	1.68	2.74	3.80
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.03)	0.76	1.54	2.33	3.12
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.04)	0.93	1.88	2.84	3.80
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(0.69)	0.44	1.56	2.68	3.80

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TABLE C-5

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: Graphite Composite (Graphite Fiber = $10/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	←Dollars per Pound of Steel Replaced→					
Price of Composite Used,	0.00	1.39	2.77	4.16	5.54	6.93
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	1.00	2.43	3.86	5.29	6.73
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	1.09	2.65	4.21	5.77	7.34
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	0.77	2.41	4.05	5.69	7.34
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	0.94	2.94	4.94	6.94	8.95
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	0.60	2.68	4.77	6.85	8.95
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	0.82	2.45	4.08	5.70	7.34
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	1.00	2.99	4.98	6.95	8.95
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	0.35	2.50	4.66	6.79	8.95

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TABLE C-6

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 10% Graphite/Glass Hybrid
(Graphite Fiber: $6/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.17	0.34	0.51	0.68	0.85
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.22)	0	0.21	0.43	0.65
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.24)	0	0.23	0.47	0.71
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.56)	(0.24)	0.07	0.39	0.71
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.68)	(0.29)	0.09	0.48	0.86
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(1.02)	(0.55)	(0.08)	0.39	0.86
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.51)	(0.20)	0.10	0.40	0.71
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.62)	(0.24)	0.12	0.49	0.86
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.27)	(0.73)	(0.20)	0.33	0.86

TABLE C-7

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 20% Graphite/Glass Hybrid (Graphite Fiber = $6/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.24	0.49	0.73	0.98	1.22
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.15)	0.15	0.43	0.73	1.02
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.16)	0.16	0.47	0.79	1.11
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.48)	(0.08)	0.31	0.71	1.11
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.59)	(0.10)	0.38	0.87	1.36
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.93)	(0.36)	0.21	0.78	1.36
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.43)	(0.04)	0.34	0.72	1.11
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.52)	(0.05)	0.41	0.88	1.36
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.17)	(0.54)	0.09	0.72	1.36

TABLE C-8

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: 40% Graphite/Glass Hybrid (Graphite Fiber $6/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.39	0.79	1.18	1.58	1.97
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w)(0.4)(0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	0	0.45	0.88	1.33	1.77
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	0	0.49	0.96	1.45	1.93
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29)(1-w)(1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.32)	0.25	0.80	1.37	1.93
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.39)	0.30	0.98	1.67	2.35
Adjustment for Fuel Saved = (0.31)(1-w)(1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.73)	0.04	0.81	1.58	2.35
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24)(1-w)(1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.27)	0.29	0.83	1.38	1.93
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.33)	0.35	1.01	1.68	2.35
Adjustment for Fuel Saved = (0.58)(1-w)(1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(0.98)	(0.14)	0.69	1.52	2.35

TABLE C-9

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: Graphite Composite
(Graphite Fiber = \$6/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.84	1.68	2.53	3.37	4.21
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	0.45	1.34	2.23	3.12	4.01
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	0.49	1.46	2.43	3.40	4.37
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	0.17	1.22	2.27	3.32	4.37
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	0.21	1.49	2.77	4.05	5.33
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(0.13)	1.23	2.60	3.96	5.33
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	0.22	1.26	2.30	3.33	4.37
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	0.27	1.54	2.81	4.06	5.33
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(0.38)	1.05	2.49	3.90	5.33

TABLE C-10

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: Aluminum Ingot ($0.60/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.12	0.24	0.36	0.48	0.60
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.27	(0.10)	0.06	0.23	0.40
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.29)	(0.11)	0.07	0.28	0.44
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.61)	(0.35)	(0.09)	0.20	0.44
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.74)	(0.43)	(0.11)	0.24	0.53
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(1.08)	(0.69)	(0.28)	0.15	0.53
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.56)	(0.31)	(0.06)	0.21	0.44
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.68)	(0.38)	(0.07)	0.26	0.53
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.33)	(0.87)	(0.39)	0.10	0.53

TABLE C-11

IMPACT OF MATERIALS SUBSTITUTION ON AUTOMOTIVE

COSTS/PRICES PER POUND OF STEEL REPLACED

Substitution Material: Aluminum Sheet ($0.95/lb.)

W_c/W_s	0	0.2	0.4	0.6	0.8	1.0
	← Dollars per Pound of Steel Replaced →					
Price of Composite Used,	0.00	0.19	0.38	0.57	0.76	0.95
Price of Steel Replaced,	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Value of Propagated Matl. (1-w) (0.4) (0.60)	(0.24)	(0.19)	(0.14)	(0.10)	(0.05)	0.00
Total Matls. Cost Change	(0.44)	(0.20)	0.04	0.27	0.51	0.75
Equivalent Wholesale Price Change = 1.09X Costs Change	(0.48)	(0.22)	0.04	0.29	0.56	0.82
DIESEL CASE						
CAFE Credit to Wholesale Price = (0.29) (1-w) (1.4)	(0.41)	(0.32)	(0.24)	(0.16)	(0.08)	0.00
Adjusted Wholesale Price	(0.89)	(0.54)	(0.28)	0.13	0.48	0.82
Adjusted Retail Price =1.22X Wholesale Price	(1.09)	(0.66)	(0.34)	0.16	0.59	1.00
Adjustment for Fuel Saved = (0.31) (1-w) (1.4)	(0.43)	(0.34)	(0.26)	(0.17)	(0.09)	0.00
Net Change In Life Cycle Costs	(1.52)	(1.00	(0.60)	(0.10)	0.50	1.00
GASOLINE ENGINE CASE						
CAFE Credit to Wholesale Price = (0.24) (1-w) (1.4)	(0.34)	(0.27)	(0.20)	(0.13)	(0.07)	0.00
Adjusted Wholesale Price	(0.82)	(0.49)	(0.16)	0.16	0.49	0.82
Adjusted Retail Price = 1.22X Wholesale Price	(1.00)	(0.60)	(0.20)	0.20	0.60	1.00
Adjustment for Fuel Saved = (0.58) (1-w) (1.4)	(0.81)	(0.65)	(0.49)	(0.32)	(0.16)	0.00
Net Change in Life Cycle Costs	(1.81)	(1.25)	(0.69)	(0.12)	0.44	1.00

APPENDIX D

REPORT OF INVENTIONS

After a thorough review of the work performed under this contract, no new innovations, discoveries, improvements or inventions were made or patents submitted.

The program did result in a better understanding of the automotive industry and its capacity to meet fuel economy goals due to the assessment of the feasibility, costs, and nature of advanced composite materials in automotive applications.