

Strategic Materials Selection In The Automobile Body: Economic Opportunities for Polymer Composite Design

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Previous studies on materials choice in automotive bodies have looked at both composite and aluminum alternatives, but have always found steel to be the most cost-effective option at the production volumes found in the overwhelming majority of vehicle models. This study finds steel to no longer overwhelmingly dominate as the most cost-effective body material when considering potential advances in the polymer composite body-in-white design against the mild-grade steel body currently on the road. With the significant implications of a polymer-composite body for vehicle light-weighting and thereby improved fuel efficiency, these results come at a time when they are particularly pertinent.

The results presented in this paper are based on a consortium-developed, 25-part unibody design not available to previous studies. Also presented for the first time are data on competing alternatives in fiber-composite component assembly and implications of platform sharing across vehicle models. Finally, developments in process-based cost modeling capabilities are presented for a) fiber-reinforced composite component production, b) component assembly, and c) design implications of glass versus carbon reinforcement.

Materials Selection in Automotive Body-In-Whites: Technologies and Demands

Public concern about energy consumption has influenced vehicle development for over three decades. The issue came to the fore with the energy shocks of the 1970's. The U.S. government responded by passing the Corporate Average Fuel Economy (CAFE) standards in 1975. In response to these federal mandates, automakers began deploying alternative materials, architectures, and power trains to improve fuel economy while still satisfying consumer demand. Although CAFE requirements remained fixed between 1990 and 2006 [1],¹ automakers have

¹ As of March 2006, CAFÉ standards for light trucks of model years 2008-2011 have been increased to 24.1mpg. [2]

continued to explore technologies that improve vehicle fuel efficiency and accommodate consumer preferences for increased vehicle performance, size, and convenience features. With recent rises in oil prices, such technological advances have increasing importance for competitiveness in the global automobile market [3, 4]. One key technical design strategy for improving vehicle efficiency is the reduction of vehicle mass, or light-weighting.

Vehicle light-weighting not only enhances fuel efficiency, but also lowers vehicle emissions and improves driving performance.² Lightweight subsystems such as hoods and decklids are already employed throughout the industry to achieve small weight savings. However, significant improvements in vehicle efficiency will require larger changes in mass. A primary target for this mass reduction is the body-in-white, whose standard steel version comprises 20-25% of total vehicle curb weight.

The two main strategic approaches for reducing weight in the body-in-white are architectural changes and material substitution. Among architecture alternatives, the unibody is most mass efficient and is already ubiquitous. Consequently, the primary mechanism available for reducing the weight of the body-in-white is the use of alternative materials. This study examines the potential cost-competitiveness of two alternative body materials – carbon fiber (CFRP) and glass fiber reinforcement polymer (GFRP) composites.

Background: Current BIW Materials Use

Steel has been the material of choice for automobiles since Henry Ford's introduction of mass production in 1913. This history of steel in the automobile has led not only to numerous jobs in the U.S.,³ but also to a wealth of technological experience on body component design,

² Alternatively, lighter structures can allow for additional weight in the form of electrical conveniences such as DVD players, navigation systems, and additional motorized options.

³ According to the Center for Automotive Research, in 2001 the U.S. automotive industry accounted for 14% of U.S. steel consumption and 31.4% of U.S. iron consumption. The automotive industry's use of steel provided 15,475 jobs in the U.S. steel industry and 3,384 jobs in the U.S. iron industry. [5]

production, and assembly with steel. In 2004, the average light vehicle produced in North America contained 2233 pounds of steel, totaling 55% of the vehicle weight [6]. Another 331 pounds, or 8%, of the typical light vehicle in 2004 was iron[6].^{4,5}

The use of polymers in U.S. automotive applications has risen dramatically from an average of 18 pounds per vehicle in 1960[8]. Ward's Motor Vehicle Facts and Figures place plastics and composites at 335 pounds in the average light vehicle produced in 2004, or 8% of vehicle weight, and 4.5% of total U.S. plastic consumption. Most of the plastic applications in vehicles are lower-performance commodity polymers and short-fiber composites. These lower-performance polymers are used in sportside truck models in fascia, fenders, and trims, and in heavy truck applications for cab steps, bumpers, spoilers, doors, fenders, toolbox doors, and even full cabs. Low-performance polymers are also used in non-structural body applications of some passenger vehicles. Vehicles with non-structural polymer body panels have included GM's Saturn, EV1, Corvette, Firebird, and Camaro, as well as Ford's Taurus/Sable, Mustang, and Windstar. Advanced composites in structural vehicle body applications have been far less extensive. The two most well-known advanced composite applications are the GM 800 truckbox and the GM 805 tailgate, both of which are structural reaction injection molded. Recently, GM placed a polyester and carbon-fiber-reinforced floor in its Corvette Z06, and BMW has included a carbon-fiber-reinforced roof structure in its M6[9].

Previous Work

Most work on the competitiveness of polymer composite technology came out in the early- to mid-1990s along with the 1993 establishment of the Partnership for a New Generation of

⁴ These numbers, based on "Average Materials Content of North American Light Vehicles" in 2006 Ward's Automotive Vehicle Facts and Figures assume a total material content of 4026 pounds.

⁵ With ongoing pressures to light-weight vehicles, in March of 1998 the U.S. Iron and Steel Industry rolled out an Ultra Light Steel Auto Body (ULSAB) concept. In comparison to today's mid-size cars which weigh about 3,300 lbs., they estimate that a ULSAB-bodied car would weigh about 2,960 lbs [7]

Vehicles (PNGV) [10-15]. Little new work has emerged in the past decade re-evaluating the economic feasibility of structural polymer composite applications in automobile bodies-in-white. It is conventional wisdom within the industry that the use of polymer matrix composites in automobile structures cannot be defended on an economic basis [10, 16]. A 1995 study by IBIS and the Rocky Mountain Institute, based on GM's 100-day first cut ultra-light BIW concept car, argued that concerns over the economic viability of carbon fiber advanced composites in the BIW may be misplaced [10]. A 1999 study by the Rocky Mountain Institute has suggested that polymer composite BIW alternatives may be well-suited to platforming goals by providing a cheaper and more easily contoured alternative for the customized part of the vehicle [17].

The work presented in this paper differs from previous studies in several ways: (1) It is based on, up-to-date detailed data collection with resin and fiber reinforcement suppliers, polymer composite equipment suppliers, polymer composite component producers, and Ford, General Motors, and DaimlerChrysler; (2) It applies new component and assembly modeling techniques; (3) It evaluates the competitiveness of polymer composites against real North American car production volumes; and (4) It looks at how platform sharing changes the competitive position of polymer composites against steel in BIW applications.

Methods: Process-Based Cost Modeling

Since the late 1980's, models of the cost of ownership have been used widely in industry to support investment decisions. Activity-based costing [18] and other process-based cost research [19] have extended these methods to include the implications of both non-manufacture and individual process activities. These costing approaches, however, are unable to predict the cost-implications of technology advances while those advances are still in their early stages of development. Process-based (or technical) cost modeling was developed to address just such a

problem. Process-based cost modeling is a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial and error investigation [20]. Its application has been extended to analyzing the implications of alternative design specifications or process operating conditions on production costs within and across manufacturing processes [21]. In the same way that present-day mathematical models allow designers and manufacturing engineers to understand the physical consequences of their technical choices before those choices are put into action, technical cost models harness science and engineering principles to understand the economic consequences of technology choices prior to large product development and facility investments[21]. The relationships developed in a process-based cost model are shown in Figure 1A.

The mathematical framework of the component and assembly cost model are provided in the Appendix. The calculations in these models for the relationships between part design parameters and process requirements are presented in the next section.

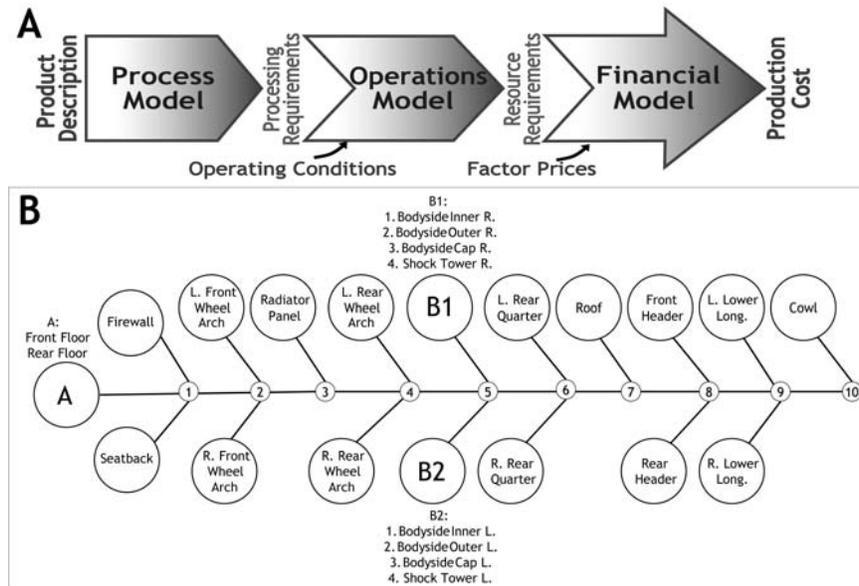


Figure 1. A) Process-based cost models reveal the economic properties of a materials decision by mapping materials and product characteristics to process and resource requirement and, thereby, manufacturing costs. B) Automotive Composites Consortium (modeled) vehicle assembly sequence for composite unibody designs. Identical assembly sequence was assumed for both carbon-fiber and glass-fiber designs.

A Three-Case Comparison

Product Design

This study evaluates the relative competitiveness of three design alternatives – a CFRP unibody, a GFRP unibody, and a steel unibody. Each design is described below.

Design 1: Carbon Fiber-Reinforced Polymer Composite Unibody

Design and processing information for the composite vehicles is drawn from the Automotive Composite Consortium's [22] Focal Project III, whose goal was to characterize the perspectives of industry experts on the near-term potential of composites technology.⁶ The specific design goal of the Focal Project III was to produce a body-in-white with minimum mass, while maintaining structural integrity and cost-competitiveness at medium to high production volumes (20,000-250,000 body units per year). The Focal Project III vehicle design is a four door mid-sized sedan. The sedan has a 108" wheelbase, is 186" long, 71" wide, and 54" high. The design consists of 25 components and 37 inserts. The components are 60 wt% of two-component polyurethane⁷ and 40% carbon fiber reinforcement. The joining inserts are mild steel. All of the components are designed to be produced using SRIM (structural reaction injection molding). The preforms for the bodyside inners, outers, and caps, the floor pieces, the firewall, the seatback, the front and rear wheel arches, the radiator, the front and rear headers, the right and left lower longitudines and the cowl are created using a robotic spray-up process.⁸ The preforms for the front floor, front lower longitude, rear floor, and roof are composed of layered carbon-fiber fabric to create the preform. The assembly of the 25 components and 37 inserts is achieved by joining the parts with a two-component adhesive.⁹ The joining inserts are mild steel.

⁶ The ACC was formed in August 1988 as a collaborative effort of Ford, GM, and Chrysler (now Daimler-Chrysler).

⁷ The two-component polyurethane polymer chosen by the ACC and used in this study was Bayer AG's Baydur 420.

⁸ The specific spray-up preforming process used is called P4 (programmable powder pre-form process).

⁹ The adhesive chosen by the ACC and used in this study was SIA's Plastilock 731SI.

Design 2: Glass-Fiber Reinforced Polymer Composite Unibody

In addition to the highly innovative carbon-fiber reinforced design, a second composite option is examined – a glass-reinforced fiber composite body. Because glass fiber is less stiff, less strong, and more dense than carbon fiber, glass fiber reinforced parts are typically thicker and heavier than comparable carbon fiber reinforced parts. The unit price of glass fiber, however, is five to ten times less than that of carbon fiber.

The glass-reinforced design has the same general layout as the carbon-reinforced ACC vehicle. For each of the 25 components, height and width are the same as for the carbon-reinforced BIW. The thickness of the glass-reinforced components, however, is increased. For the carbon-reinforced and glass-reinforced components to exhibit the same stiffness, their deflection under the same loading force must be equal. The required thickness (h_G) of each glass reinforced component is calculated by approximating the component as a centrally loaded, fixed beam:

$$h_G = \sqrt[3]{\frac{E_C}{E_G}} h_C \quad \text{Equation 1}$$

Here, E_C is the modulus of the carbon-reinforced material, E_G is the modulus of the glass-reinforced material, and h_C is the thickness of the carbon-reinforced component. These moduli are modeled as an average of the resin and the reinforcement moduli weighted by their respective volume fraction, as follows:

$$E_C = V_c E_c + V_r E_r, \quad E_G = V_g E_g + V_r E_r \quad \text{Equation 2}$$

where V_c is the volume fraction of carbon fiber, E_c is the modulus of the carbon fiber, V_g is the volume fraction of the glass fiber, E_g is the modulus of the glass fiber, V_r is the volume fraction of the resin, and E_r is the modulus of the resin. The volume fraction of glass reinforcement is

assumed to be equal to that used in the carbon-reinforced components. Here, $V_c=V_g = 35.1\%$, $V_r = 64.9\%$, $E_c = 230$ Gpa, $E_g = 72.4$ Gpa, and $E_r = 3.5$ Gpa.

The increase in thickness of the glass-reinforced parts has consequences throughout the SRIM process, affecting material quantities, preform spray times, molding cycle times, and line requirements. The methods by which these differences are accounted for in the process-based cost model are described in the next section of this paper on process design.

Design 3: Mild-Grade Steel Unibody

The third design, a steel unibody, is based on the typical steel body design currently on the market. This sedan has a 103" wheelbase, and is 185" long, 67" wide, and 57" high (compared with the 108" wheelbase, 186" long, 71" wide, and 54" high composite design). The minor dimensional differences between the steel and composite body designs are, for the purposes of this study, insignificant. The steel body is made up of 120 components and 130 inserts (compared with 25 components and 37 inserts for the composite design).

Process Design: Component Production and Assembly

Structural Reaction Injection Molding

The polymer composite fabrication process chosen for this study is structural reaction injection molding (SRIM). It was chosen because this process minimizes fiber scrap, accommodates part complexity, and is a relatively rapid process. SRIM is a four-step process: (1) pre-form making, (2) pre-form trimming, (3) injection molding, and (4) part trimming and inspection.

Preforming

Pre-form making shapes the reinforcement material into the form of the part. This study models two different performing methods: 1) spraying of fibers and 2) cutting and layering of

woven fiber fabric. The type of pre-form method most appropriate for each part was chosen by design engineers from the ACC team, and then actuated in the model.

The “spray method” creates the perform shape by spraying chopped fibers onto a screen in the shape of the part along with a powder or string binder. The screen is held in a press. Once the spraying is completed, the press closes, and the perform is heated to bind the fibers in place for handling.

As programmed, the model assumes a preform manufacturing line with a two-robot spray station at lower production volumes, and a six station carousel at higher production volumes. The cycle time for the spray station is modeled as comprising four stages: press opening (5 seconds), spraying, pre-form curing (2.5 minutes), and part unloading (30 seconds.) The spray time is a function of the mass of fiber required for each pre-form and the chopper gun operating rate. The chopper gun rate is modeled as 1.6 kg of carbon fiber reinforcement per minute and 2.29 kg of glass reinforcement per minute.

The cost of the screen for the spray system is estimated from a regression of actual screen costs against the weight and surface area of the part. For carbon this regression is as follows:

$$C_{screen,C} = 8000W_C + 5000SA_C + 73040 \quad \text{Equation 3}$$

where W_C is the weight of the carbon-reinforced part and SA_C is the surface area of the carbon reinforced part. For glass, this regression is

$$C_{screen,G} = 8000X * W_G + 5000SA_G + 73040 \quad \text{Equation 4}$$

with W_G the weight of the glass-reinforced part and SA_G the surface area of the glass-reinforced part. The additional multiplier, X , is required to take into account the difference in the density of glass-reinforced and carbon-reinforced parts.

$$X = \frac{\rho_C}{\rho_G} \frac{\sqrt[3]{E_C}}{\sqrt[3]{E_G}} \quad \text{Equation 5}$$

Component densities are calculated as follows:

$$\rho_C = V_c \rho_c + V_r \rho_r, \quad \rho_G = V_g \rho_g + V_r \rho_r \quad \text{Equation 6}$$

where ρ_C is the density of the carbon-reinforced composite, ρ_c is the density of the carbon reinforcement, ρ_G is the density of the glass-reinforced composite, ρ_g is the density of the glass reinforcement, and ρ_r is the density of the resin. The densities of carbon reinforcement (ρ_c) and glass reinforcement (ρ_g) are as follows $\rho_c = 1.6$ g/cc and $\rho_g = 2.55$ g/cc [23].

The “lay-up method” employs sheets of reinforcement in the form of dry fabric (note: not a pre-preg). The fabric is pulled directly from its roll onto the forming machine, where it is cut to the required pattern. The cut patterns composed of two to five sheets are then stacked directly onto the SRIM press. The number of fabric layers used depends on both the thickness and on the number of fiber orientations required to achieve the desired mechanical properties for the part.

To improve the formability of the stack of fabric, blocks in the reciprocal shape of the part, called conformers, are used to press the fabric into position. A vacuum is pulled to form the sheets into the shape of the mold. This entire process takes 2 ½ minutes to complete. Three-dimensional shaping of the pre-form occurs when the press closes during injection molding. The capital equipment and material cost assumptions for the two performing methods are shown in Table 1 in Appendix 2.

Pre-form Trimming

During pre-form trimming, the edges of the shape are refined, removing any unwanted material. This “trimming” is estimated to remove 4% of the fiber originally sprayed and banded into form, and to require 90 seconds per part.

Reaction Injection Molding

The SRIM step, as modeled in this study, consists of five stages: a 30 second load, a 20 second partial closing of the mold and injection of the resin, a 150 second completion of the closing of the mold and cure of the resin, a 30 second opening of the mold and unloading of the part, and a 10 second clean and prep before the loading of the next part. To reflect current practice in industry, injection time, closing time, and mold closed time are held constant, regardless of part dimensions, and the number of injection sites and dispensers are modified to accommodate the geometry of different parts. For the purposes of this study, the number of dispensers required for successful resin distribution was estimated by the ACC engineering team.¹⁰ The model assumes that a typical two component polyurethane thermoset resin is employed in the molding of structural automotive components. The cure time is modeled as 2.5 minutes or 4 minutes depending whether a powder or string binder, respectively, is needed. The cycle time breakdown described above is used for both the carbon- and the glass-reinforced parts in the model.

The model treats the cost of the injection molding press (C_{Press}) as a function of the maximum part length (L_{max}), maximum part width (W_{max}), and the maximum force required of the press (F_{max}). This press cost estimation was developed in a Ph.D. thesis by Paul Kang, and is independent of the component material[24]. Kang's regression is as follows:

$$C_{Press} = 49,400 + 590.0F_{max} + 94,000L_{max}W_{max} \quad \text{Equation 7}$$

The maximum required mold force (F_{max}) is calculated as follows:

¹⁰ Although not used in this analysis, the equation for fill time developed by Kang, provides a good approximation of the number of dispensers chosen by the ACC engineering team for each part. By setting the fill time (T_{fill}) constant instead of the number of injection ports ($P_{injection}$), Kang's equation to calculate fill time could be used in future studies to instead estimate the necessary number of injection ports.

$$P_{injection} = \frac{\phi\mu}{2KT_{fill}} \left(R_{initial}^2 \ln \left(\frac{R_{max}}{R_{initial}} \right) - \frac{R_{initial}^2 - R_{max}^2}{2} \right). \text{ In this equation, K is the permeability of the preform, and } \phi \text{ is the porosity of the preform.}$$

Kang, P. (1998). A Technical and Economic Analysis of Structural Composite Use in Automotive Body-in-White Applications. Materials Science and Engineering and Technology and Policy. Cambridge, MA, M.I.T.

$$F_{\max} = \pi P_{\text{injection}} \left(\frac{R_{\text{initial}}^2 - R_{\text{max}}^2}{2 * \ln \left(\frac{R_{\text{max}}}{R_{\text{initial}}} \right)} \right) \quad \text{Equation 8}$$

Here R_{initial} is the radius of the dispenser's injection port, R_{max} is the radius of the mold, and $P_{\text{injection}}$ is the number of injection ports. For a more detailed discussion see [24].

The tool cost estimate used in the model for the SRIM press was originally developed in Kang's study based on empirical production data for glass-reinforced parts. This equation, which is a function of part weight and surface area, is also used in this study:

$$C_{\text{tool,G}} = 26300 + 71350W_G^{0.67} + 24800SA_G \quad \text{Equation 9}$$

To estimate tool costs for the carbon-reinforced components, this study uses the following equation, where the coefficient, X (see Equation 5), is added to correct for the difference in material density between carbon- and glass-reinforced components:

$$C_{\text{tool,C}} = 26300 + 71350X^{-0.67}W_C^{0.67} + 24800SA_C \quad \text{Equation 10}$$

Final Trimming and Inspection

After being unloaded from the press, the part is ready for final trimming. Trimming removes the resin flash that escaped beyond the mold walls. The model assumes that trimming removes 10% of the original material and takes 120 seconds.

Assembly

Although there are some examples of composite sub-assemblies, there is to date no experience in medium- to high-volume production of a composite unibody. In developing the assembly model, the authors reviewed several assembly configurations and technologies, including technologies still under development. Based on this survey of methods, the authors have selected a set of methods that they view as most effective for use in the near future. This option

is described below. The interested reader should refer to [25] for a more detailed discussion of eliminated options.

The bonding step in assembly entails positioning the first part or already-joined sub-assembly, laying down adhesive, and then positioning subsequent parts or sub-assemblies on top of the adhesive (along the join). Bonding requires pumps, a metering system, adhesive guns, a heated hose, and switch-over pumps to dispense the adhesive. The carbon and glass composite bodies are modeled as being assembled using a heat-cure epoxy. There are several advantages to a heat-cure epoxy. Although heat curing requires additional equipment and time, the resulting bond has superior properties to the bond created by a room temperature epoxy. A heat cure epoxy also has the advantage of an infinite open time – the length of time between dispensing the adhesive and its curing. This infinite open time increases the number of parts that can be joined at a given station, and eliminates adhesive waste due to premature curing. This study assumes no primer and no pre-heating is necessary on the joining surfaces of the parts. Cure times within the model range between two and three minutes, depending on the length of the join.¹¹ The price of the adhesive used in this study is \$17.50/kg.

The researchers surveyed seven different cure methods: hot blocks, hot air impingement, RS induction cure, radio frequency cure, microwave frequency cure, and oven curing. Based on the recommendations of industry experts, this study uses hot air impingement. Heaters are generally placed every 50” along the join, with each heater costing between \$8K and \$12K. The system as a whole also requires a thermocouple sensor, as well as a control panel for the thermocoupler.

In addition to bonding and curing equipment, fiber reinforced polymer composite assembly also requires fixtures. The fixture costs used in this analysis are shown in Table 2 in Appendix 2 along with the curing systems for different sized sub-assemblies.

¹¹ The cure time for a heat cured epoxy can range between one and seven minutes depending on the magnitude of heat used for cure.

The assembly order is shown in Figure 1B. The layout of the assembly line is dependent on this order, as well as the number of parts, the type and intensity of joining, and the production rate. Higher production rates lead to more stations, more robots, and more automation, while smaller production runs assume fewer stations, more time at each station, and more manual labor.

Results

This section presents the model results for the three body-in-white (BIW) designs: a carbon fiber reinforced polyurethane composite (carbon), a glass fiber reinforced polyurethane composite (glass), and a mild-grade steel unibody (steel).

Baseline Results

Figure 2A shows the estimated unit cost of producing and assembling each of the three alternative BIW cases in the U.S. At annual production volumes under 105,000, the model results suggest that the glass-reinforced BIW is less costly than the steel, and at annual production volumes under 45,000, the carbon-reinforced BIW is also less costly than the steel.

The steel option is the least costly alternative when modeling high production volumes, because of sheet steel's low material costs and exceptionally fast cycle times. The steel design becomes less cost-competitive than composites at lower production volumes because of the carrying costs of expensive, under-utilized steel stamping equipment and tooling. As shown in Figure 2D, at annual production volumes (APV) of 100,000 units per year, machine, equipment, building, maintenance, and overhead – all fixed expenses – make up 59% of steel BIW costs. These fixed expenses account for only 24% of carbon, and 40% of glass BIW cost estimates.

Figures 2B and 2C isolate component production and assembly costs. Figure 2B shows that, although the composite BIW has far fewer total components than steel, the sum of the modeled composite component and insert costs is significantly larger than the sum of the steel component

and insert costs (so long as annual production volumes are above 30,000 for glass.) The estimated cost of assembling the composite BIW, however, is significantly cheaper than that of the steel BIW assembly, as shown in Figure 2C.

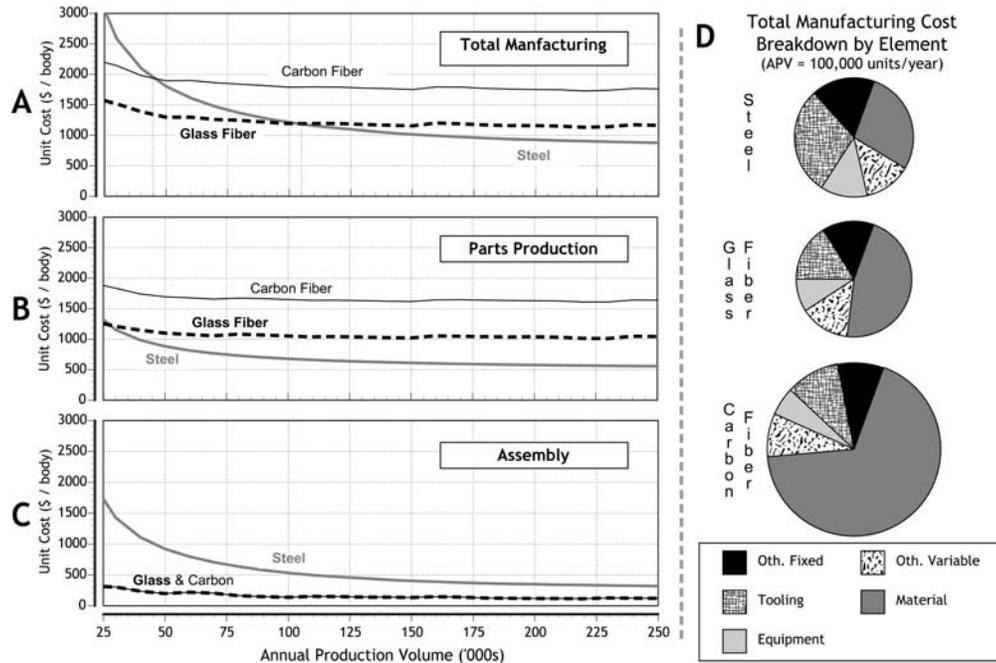


Figure 2. U.S. Body-in-white production cost sensitivity to production volume for (A) Total manufacturing cost; (B) Parts production, and (C) Assembly. (D) Total manufacturing unit-cost breakdown at 100,000 units per year.

Exploring the Sensitivity of Results

The results which follow show the sensitivity of the previous cost results to changes in carbon fiber price, performing scrap rate, molding reject rate, and assembly adhesive price. As can be seen in Figure 3A, variation in the carbon fiber price has by far the largest impact on final cost.

The market price of carbon fiber has a huge impact on the cost-feasibility of producing a carbon-fiber reinforced BIW. Car manufacturers claim to be willing to mass-produce carbon-fiber reinforced BIWs only when carbon fiber prices are at or below \$11/kg. Carbon fiber is currently \$22/kg, and can run as high as \$40/kg. The impact of fiber prices on the annual production volume of steel-carbon cost parity is shown in Figure 3B. The model results suggest

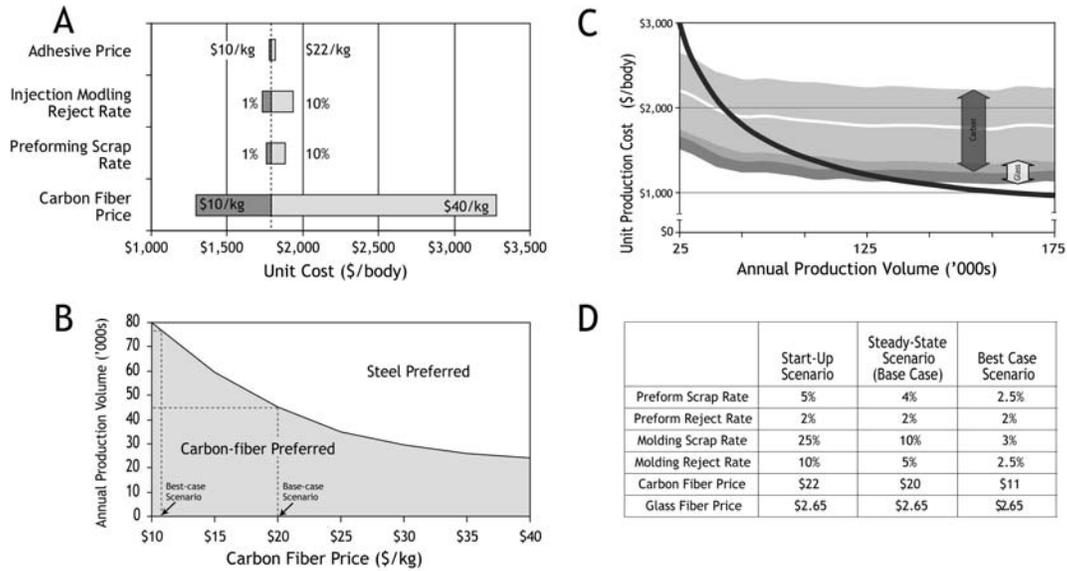


Figure 3(A) U.S. Body-in-white cost sensitivity to key production factors. (B) Sensitivity of steel-carbon cost parity to fiber price. (C) U.S. Body-in-white cost sensitivity to production volume across multiple production scenarios. (D) Details of alternative production scenarios.

that, at a market price of \$11/kg, the carbon composite BIW is less costly to produce than a steel BIW at annual production volumes below 75,000 units, given the base case assumptions.

So far, this paper has only explored the sensitivity of results when changing one or two variables. Figure 3C below presents three scenarios – a start-up scenario, a steady-state scenario, and a best case scenario – with alternative assumptions on how composite processing capabilities and carbon fiber prices may change over time. The start-up scenario represents processing characteristics automobile manufacturers believe would be achievable within a year of starting production. The steady-state scenario represents the base case assumptions used elsewhere in this publication. The best-case scenario represents most favorable conditions for composites. The inputs assigned to each of these scenarios are shown in Figure 3D.

As can be seen in Figure 3C, in the start-up scenario, glass is cheaper than steel at annual production volumes below 70,000 and carbon is cheaper than steel at production volumes below

30,000 units. In the best-case scenario, glass is cheaper than steel at production volumes below 120,000 and carbon is cheaper than steel at production volumes below 90,000 units annually.

Discussion

According to the results shown, composite technologies hold not only the potential to reduce vehicle mass, but also to do so in a cost effective manner. This economic advantage, however, is strongly dependent on production volume. Typical volumes on the U.S. market vary greatly. Figure 4A presents the distribution of 2005 production volumes for car models produced in the U.S. and Canada [6]. Figure 4A shows that 68% of car models in the US and Canada in 2005 – 29% of all cars produced in 2005 – were produced in volumes under 105,000, the base case cross-over point between glass and steel. Forty-five percent of 2005 car models – 10% of all cars produced – had annual production volumes under 45,000, the carbon cross-over point.

In many vehicle models, BIW components are shared across model platforms. Conventional wisdom in the auto world suggests that such platform sharing minimizes the competitiveness of composites. The production volumes of the car platforms produced in the U.S. and Canada, as reported in Automotive News' 2006 Market Data Book [6], can be seen below in Figure 4B. Even accounting for this sharing, composites maintain economic advantage over a large range of platforms. Specifically, 41% of car platforms produced and 8% of all cars produced in 2005 had platforms with 2005 production volumes under the estimated glass-steel cost parity. Similarly, 24% of car platforms and 2% of all cars produced in 2005 had platforms with annual production volumes under 45,000 (the carbon-steel cost parity.) Finally, only around 50% (by mass) of a given vehicle's body is typically shared across a platform[26].

The results presented in this section are for a BIW constructed entirely of a single material. Although there are manufacturing and performance advantages to such a solution, the economics

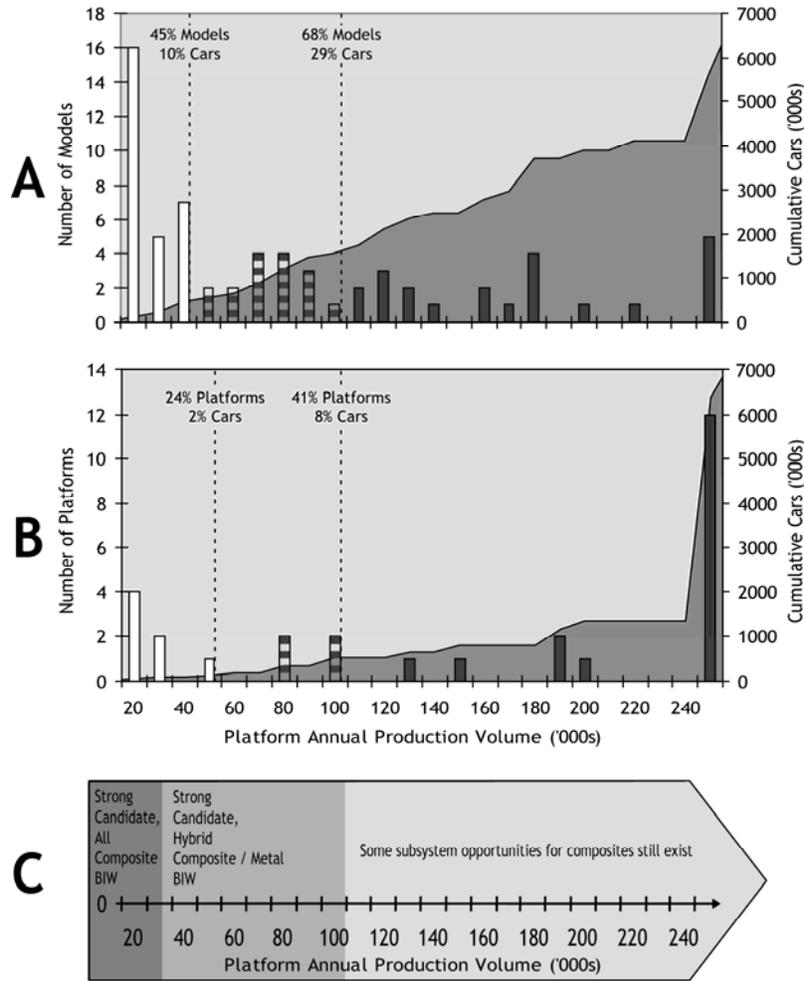


Figure 4. (A) Car models produced in U.S. and Canada with annual production volumes below composite-steel cost parity[27]. (B) Car platforms produced in the U.S. and Canada with annual volumes below composite-steel cost parity. [6] (C) Synthesis of all-composite and hybrid material opportunities within the North American fleet.

may favor a body using a hybrid set of materials. A more complete analysis will require exploring the economic competitiveness of composites at the subassembly level. Several insights, however, can be drawn from the present results. As shown in Figure 4C, this study’s analysis estimates that glass reinforced composite components are only cheaper than steel components at annual production volumes below 30,000 units. At annual production volumes of 30,000 or less substitutions of glass-reinforced composites for steel components in a body-in-white are likely to reduce costs. At higher production volumes, composites are only likely to gain cost-advantage at the sub-assembly level. This advantage does not exist within all sub-

assemblies. An initial schematic of how to think about composite competitiveness is provided in Figure 4C. Based on 2005 vehicle production in the U.S. and Canada, 68% of current car models (29% of all cars) could be strong candidates for composite-steel hybrid body-in-whites, and 32% of car models (5% of all cars) could be strong candidates for entirely composite bodies-in-white. Industry trends toward build-to-order and customization may mean a further increase in the economic competitiveness of composite components over time.

In addition to hybrid body analyses, two other scenarios would be of interest for future work. The first is the competitiveness of the composites against other light-weighting body materials, in particular, aluminum and high-strength steel. The second would be the cost-feasibility of composites in a setting with greenfield investment opportunities, such as a developing country.

Conclusions

Automobiles today are over 63% iron and steel by weight [27]. Fiber-reinforced polymer composite technologies offer a way of light-weighting the vehicle, both to increase fuel economy and to allow for the addition of other vehicle systems (and, thus, features). Several advances have occurred in the past decade in fiber-reinforced polymer composite body-in-white design, component processing, and assembly technology. This study uses process-based cost modeling, which allows the user to evaluate technology alternatives before investments are made, to gain insights into the manufacturing cost-feasibility of fiber-reinforced composite technology. The results show that the potential for fiber-reinforced composite bodies-in-white to be competitive against steel is greater than it has been in the past. Moreover, platforming only reduces, but does not eliminate, the potential cost competitiveness of composites. Considering platforming, the model results suggest that approximately 41% of car models and 8% of the cars produced in the U.S. and Canada in 2005 might have been cheaper if produced with a glass-fiber reinforced

composite rather than a steel unibody. In the end, any such materials substitution would need to be evaluated individually and against other light-weight materials options. These modeling results indicate that the polymer-composite industry's developments in process and design have kept composites technology a credible alternative for vehicle body applications.

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