Costing the Ultralite in Volume Production: Can Advanced Composite Bodies-in-White Be Affordable?

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Abstract

Advances in materials engineering, powerplant technology, systems integration, and fabrication processes now enable the automotive industry to design and prototype vehicles with improved performance and far better efficiency than current production platforms. The hypercar advanced vehicle concept, developed by Rocky Mountain Institute (RMI) since 1991, embodies this technological potential. However, for hypercars to benefit society significantly, they must be manufacturable in large production volumes at a cost broadly competitive with conventional automobiles. In addition to manufacturing costs, environmental concerns have forced lifecycle cost to the forefront. This paper examines both manufacturing and lifecycle costs for an important component of advanced vehicle design—an ultra-lightweight body-in-white (BIW).

The BIW lifecycle includes: A. manufacturing (fabrication, assembly, and secondary effects), B. operation (fuel consumption and repair), and C. post-use (recycling and disposal). These costs are assessed for volume production of a case-study BIW, the carbon-fiber composite GM Ultralite, using a lifecycle implementation of a technique called Technical Cost Modeling. This paper gives an overview of the hypercar; discusses materials, manufacturing, operation, and post-use issues for composite BIWs; describes the lifecycle cost assessment methodology; and analyzes the costs for volume production of the case-study BIW. The manufacturing and lifecycle costs for various manufacturing scenarios lead to encouraging conclusions about the applicability and future of lightweight advanced-composite BIW designs.

Introduction

Hypercar Overview

The artful fusion of ultralight, ultra-slippery car bodies with hybrid-electric propulsion emerged during the early 1990s as an unfamiliar but strikingly effective innovation in automotive design. With demonstrated technology, it can yield a family "hypercar" able to achieve dramatic gains in fuel efficiency with better safety, acceleration, comfort, refinement, and (by orders of magnitude) emissions than today's production cars (Lovins *et al*. 1993, Lovins 1995).

The improvements result from synergies between ultralight-and-slippery construction and hybrid-electric drive. Specifically, the design package referred to here as "ultralight" involves a curb mass M around 500–600 kg, a coefficient of rolling resistance $r0 \leq 0.007$, a coefficient of aerodynamic drag $C_D \leq 0.2$, and frontal area $A \leq 1.8$ m^2 for 4+ passengers or ~1.95 m^2 for 5–6. Together, these parameters can improve fuel efficiency by a factor around 2.0–2.5. Hybrid drive, using electricity generated from liquid or gaseous fuel carried onboard, ordinarily improves fuel efficiency by a factor of ~1.5 (or slightly more with ultracapacitor buffering: Burke 1995). However, combining a hybrid drive with an ultralight platform allows for fuel efficiencies 3–4 fold greater with current technology, 6–8 fold greater with polymer-exchange membrane (PEM) fuel cells and

This ultralight/hybrid synergy has two main causes: A. Reducing aerodynamic drag by ~2–3-fold and road and tire drag by ~2.5–3-fold greatly decreases the two irrecoverable losses of tractive energy, whose only other destination is braking energy. However, this braking energy is also reduced by ~2–3-fold in proportion to gross mass and then is largely recovered by the hybrid drive's electronic regenerative braking. B. Mass decompounding (the snowballing of saved mass) is typically greater with ultralights than with heavy platforms, greater with hybrid than with non-hybrid drivelines, and greatest of all with both.

Mass decompounding in ultralight hybrids was not previously observed because traditional hybrid development simply adds a hybrid driveline to a heavy platform. Mass, cost, and complexity then tend to compound. However, they tend to *de*compound in ultralights, because structural and propulsion elements not only become smaller with lighter loads, but may even become superfluous and disappear altogether (Moore & Lovins 1995). This accounts for the < 600-kg curb masses (for 4 passengers) found both empirically and by bottom-up line-item mass-budgeting benchmarked to existing designs (*id.*, Lovins 1995a). Achieving optimal mass decompounding naturally requires whole-system engineering with meticulous attention to detail—a "leapfrog" mentality and design organization quite different from traditional automaking (*id.*, Lovins 1995). Moreover, within the < 600-kg ultralight mass range, mass reduction is driven much less by fuel economy than by the need to reduce the power rating, cost, and complexity of driveline components (Moore & Lovins 1995), as well as to reduce the amount of costly reinforcing fibers, an hypothesis this paper will specifically examine.

Hypercars' basic engineering performance and feasibility, increasingly validated by empirical prototypes and by substantial proprietary development efforts, are no longer seriously questioned. Still often questioned, however, is the *cost* of mass-producing such platforms. This paper explores one fundamental element of hypercar economics by using an established production-costing model to simulate the manufacturing and lifecycle costs of a hypercar body-in-white compared with its conventional metal competitor, the modern steel unibody.

The body-in-white of a hypercar will probably be a monocoque made by molding advanced polymer composites into a small number (~2–20) of relatively large parts minimized by integration and joined by adhesives. Its materials and manufacturing methods are therefore relatively unfamiliar to automakers whose exquisite metal-forming skills have evolved over nearly a century. The Big Three automakers' entire 1995 headcount of advanced-composites experts is at most a few dozen, of whom only a few have much production manufacturing experience with these materials. Thus the widespread assumption that composite monocoques will be prohibitively costly is not surprising: it comes simply from noting that advanced fibers (*e.g.*, carbon or aramid) are far costlier per kg than steel. This is true but misleading, because people buy cars by the car, not by the kg, and there are crucial differences between a mass of fibers and a finished car. Specifically, we hypothesize that:

1. severalfold fewer kg of a typical advanced fiber than of steel are needed for the same strength;
2. much cheaper fibers (*e.g.*, E-glass) may be usable or even preferable for many reinforcing applications;
3. the utterly different manufacturing processes used to form the composite body can save major tooling, equipment, and assembly costs, potentially offsetting the costlier materials;

4. further savings may be available in color-coating (*i.e.*, through lay-in-the-mold color that could be cheaper than painting) and in the rest of the car; and
5. if the hypercar does achieve much lower tooling and equipment costs, permitting smaller-scale and more localized production, it could better lend itself to a streamlined market structure (direct sales, zero-inventory just-in-time manufacturing-to-order, direct delivery, onsite maintenance) that would greatly reduce mark-ups—thus potentially permitting a lower retail price and higher profit margin even if total production costs were somewhat higher than for the conventional car.

This analysis tests steps 1–3, emphasizing 3. Steps 4–5 are treated elsewhere (Lovins *et al.* 1996) and in forthcoming analyses by RMI's Hypercar Center. We begin with a brief summary of Step 1 (see also *id.*, Moore & Lovins 1995, Lovins 1995a): How heavy does the hypercar's BIW need to be?

Composite BIW Mass

Table 1 offers some helpful comparisons of BIW masses, *italicizing* the base-case assumptions used in this analysis. Unless otherwise noted, the BIW is conventionally defined as including all body panels and structures and any frame or chassis but no paint, trim, interiors, bumpers, seats, or elements of the driveline, suspension, or wheels; doors and the hood and trunk lids (collectively "closures") are either excluded or included as shown in the table.

The case-study BIW uses the 1991 GM Ultralite concept-car design (as distinguished from RMI's broader term *ultralight*) as the basis of its cost modeling. There are several reasons for the case-study choice: the Ultralite is a tangible vehicle, was built by a major automaker, and has well-known physical parameters. However, Table 1 suggests that the 190.5-kg mass of the GM Ultralite's BIW including closures is unnecessarily heavy, as many members of the design team have acknowledged (Coates 1992): its large parts were made largely of biaxial carbon-fiber cloth (which could provide more strength in some directions than necessary), its overall "first-mode" body stiffness was ~45 Hz (about twice the Avcar's or ~50% above that of luxury sedans), and it probably used a higher-than-optimal proportion of carbon as against lighter fibers (*e.g.*, aramid, polyethylene). Indeed, two leading automakers' senior composites experts (Eusebi 1995, Gjostein 1995) agree that a carbon BIW can cut standard steel-unibody mass by up to 67%, not the Ultralite's ~50%. This would imply, for a 1995 average production car (see footnote "a" in Table 1), ~89 kg without or ~123 kg with closures.

Compared with the IBIS steel unibody assumed as the base case in this paper, a 67% reduction would yield 89 kg without doors (but, as mentioned in footnote "a" in Table 1, including hood and trunk pieces), or 51 kg lighter than the Ultralite. For further comparison:

1. The 200-kg Electric Car Company (a collaboration of the Swiss firms ESORO, Horlacher, and PASOL AG) CoupÉ BIW is with closures 10-kg heavier than the Ultralite, but it is made completely from glass-fiber composites and is a 5–6 seater. Substituting carbon, whose specific strength and stiffness are superior to glass's, and downsizing the vehicle to Ultralite's dimensions would make the BIW significantly lighter.
2. The Western Washington University Viking 23's 93-kg carbon and aramid BIW including closures could require less than the 98-kg difference below the Ultralite to make it equivalent in size and function.
3. The 72-kg ESORO H301 BIW, with the same number of seats as the H301 but slightly smaller, was ~49% lighter without closures even though it was three-fourths glass. According to its chief designer, substituting carbon and aramid for glass would make the H301 as big and functional as the Ultralite without adding mass.

The composite case-study will therefore be based on the original GM Ultralite BIW mass, but will also provide a sensitivity test so that readers can readily substitute lighter BIW masses as desired. Alternatively, a BIW mass somewhat closer to but possibly less than the Ultralite's might be considered reasonable for the full 6-seat (3+3) configuration assumed by PNGV (Moore & Lovins 1995). Moreover, using a BIW mass below the Ultralite's would normally imply a *curb* mass still lower, because of mass decompounding. PNGV's assumed curb mass in Table 1, a quarter-tonne heavier than the Ultralite, is hard to justify on the basis of the hybrid driveline, as shown by bottom-up mass budgets (*id.*, Lovins *et al.* 1996).

The safety design of ultralight composite monocoques is quite different than that of steel unibodies, but safety performance can be equivalent or superior for most collision conditions within RMI's assumed mass budgets: better design and more energy-absorbing materials can more than offset reduced mass, and the structures required to protect people can weigh very little (Moore & Lovins 1995, Lovins 1995, 1995a). Exceptionally, equivalent safety in collisions with much heavier vehicles could require special (though light) safety structures; but if added, those may provide better safety than steel unibodies. Thus mass comparisons of platforms with quite different safety designs are necessarily inexact, although a close enough approximation for present purposes. Fuller treatment of ultralight safety is deferred to later Hypercar Center work.

Modeling Methodology

Manufacturing, operation, and post-use costs are simulated throughout this study using a technique called Technical Cost Modeling (Dieffenbach & Mascarin 1993). Technical Cost Models (TCMs) are computer spreadsheets developed and applied by IBIS Associates for the simulation of manufacturing costs. Inputs into TCMs include material, design, and process specifications. Outputs include cost summaries, which correspond to the unit operations of the process. Cost is assigned to each unit operation in a process flow diagram. Each unit operation represents one or several pieces of equipment operating at a common production rate determined by the production volume. Together, the process equipment makes up a station characterized by factors including number of laborers, equipment and tooling investment, power consumption, and floorspace requirement. Based on these factors as well as other cost specifications, TCMs account for product cost in terms of specific variable and fixed cost elements, which are shown in Table 6 in *Results and Analyses.*

Table 1. Selected body-in-white and curb masses (Lovins 1995a)

builder & model	date	seats	materials	body-in-white mass (kg) with closures... excluded	included	curb mass (kg)	remarks
IBIS steel base	~1994	4–5	steel	270[a]	304	~1,470	smaller than AVCAR
Advanced unibody est.	~1994	4–5	steel	~195–220	–	~1,363–1,388	assuming no component optimization or mass decompounding
Ford AIV Taurus	1994	4–5	Al, etc.	148	198	1,250	same
IBIS comp base	1992	4–5	E-glass, etc.		236[b]	1,218	"tub" chassis + panels, not monocoque
GM Ultralite	*1991*	*4*	*C, etc.*	*~140*	*190.5*	635	analysis curb mass slightly lower due to *fuel eff.* assumptions
PNGV target	1994	5–6	C, etc.	138	186 (–50%)	854 (–40%)	
Electric Car Company CoupÉ	1996	5–6	E-glass	–	200	800[d]	
ESORO H301 (designed to European safety standards)	XI.94 (updated I.95)	4	75% glass, 20% aramid, 5% C	72	~120	~490[c]	Curb mass and BIW w/closures exclude ~30 kg excess bumper & double-hinged-door mass, but *include* 2 bumpers and 4 seats
RMI mass budget (Lovins *et al.* 1995)	VI.95	4–5	C, etc.	–	123	520 near-term, 410 midterm	without special safety structures (see text)
RMI mass budget (Moore & Lovins 1995)	VI.95	5–6	C, etc.	–	170	698	without special safety structures (see text)
Western Washington U. Viking 23	1994	2+[e]	C, a little aramid	–	93	864	curb mass includes 314 kg of batteries, some safety structures

[a] The MY1995 Ford Taurus (as a proxy for the Chrysler/Ford/GM AVCAR) body-in-white without closures is ~271 kg, with closures ~372 kg. For comparability with the composite base case, the IBIS unibody (without closures) includes hood and trunk pieces, but no doors. However, the Taurus, with hood and trunk pieces, weighs 305 kg. The 34 kg (68 kg with closures) difference between the Avcar and IBIS unibodies is due to the IBIS vehicle's smaller size. Since the Ultralite is also smaller than AVCAR, the IBIS BIW mass is used for comparison throughout the analysis.

[b] This mass was incorrectly placed in the "excluded" column in the original October 1995 paper.

[c] If redesigned from a 670-kg range-extender parallel hybrid (= actual 700 kg– ~30 kg as noted) with 230 kg of batteries to a series hybrid with 50 kg of batteries.

[d] If redesigned from a 1000-kg battery-electric with 320 kg of batteries to a series hybrid with 50 kg of high-power batteries, a 65-kg auxiliary-power unit (APU) with cooling system, and a 5-kg APU controller.

[e] A series hybrid not needing this design's large battery, 0.9-liter IC engine, and glass/aluminum CNG tank might instead use the same structural mass budget to carry 4+ passengers.

This analysis does not attempt to quantify all costs associated with the BIW lifecycle, but only those that are likely to vary as a result of different materials or processes. Costs that could vary according to material and process but are not incorporated include overhead (shipping, receiving, inventory, administrative, and other related functions) and production costs after the BIW stage, such as painting and final assembly (see *Model Conservatisms*).

Lifecycle costs are broken into three main categories, each with two subcategories, listed in Table 2:

Table 2. Lifecycle cost categories

Manufacturing	Operation	Post-use
Fabrication cost	Fuel consumption	Recycling cost
Assembly cost	Repair cost	Disposal cost

Manufacturing costs and values are those realized by manufacturers and materials suppliers. Operation costs are those realized by the consumer. Post-use costs and values are those realized by recyclers and disposers, and by communities that operate disposal sites. Operation and post-use costs, incurred over the lifetime of the vehicle, are discounted at a 10%/y real rate to account for the time value of money. All costs are in 1995 dollars.

Case-Study Background

Materials

In this case-study, the body-in-white is made almost entirely of an advanced (*i.e.*, stronger than fiberglass) polymer composite—a plastic matrix reinforced by strong, fine fibers, combined to achieve the best properties of both. For example, the plastic matrix has a low density but is not very strong or stiff. The fibrous reinforcement can be very strong and stiff, but needs a medium to protect the fibers and transfer loads among them. The combination can offset its constituents' weaknesses and be very light, strong, and durable. Moreover, modifying the choice, proportions, and geometry of the constituents can vary the resulting engineering properties anisotropically and over a vast range.

Key advantages of advanced composites for the BIW include specific strength and stiffness up to five times those of steel or aluminum (Noton 1987). As a result, advanced composites can save much weight without sacrificing safety or mechanical performance. In

addition, being anisotropic and heterogeneous, composites can be specifically tailored, *e.g.*, maximizing strength by optimally orienting fibers to match structural loads, and minimizing cost by using less costly fibers where lower strength suffices. Finally, composites can be molded into large, complex, highly integrated shapes that dramatically reduce parts count and assembly effort.

However, advanced composites, being less industrially mature than metals, require careful attention to certain issues in design and manufacture (Lovins *et al.* 1996)—especially in high-volume, low-cost applications such as the BIW, where consistency and quality cannot be sacrificed for throughput. High-volume production issues requiring greater experience and innovation include resin rheology, porosity, fiber/matrix adhesion, and mechanical degradation during processing, among others (*id.*).

The GM Ultralite's BIW uses carbon fiber embedded in thermoset epoxy and sandwiching a layer of polyurethane foam core (GM 1992). The carbon fiber is chiefly biaxial fabric, reinforced by uniaxial roving (*id.*). We assume the fibers represent half of the weight of the composite; for carbon, 50% by weight translates to roughly 40% by volume. While prepreg can achieve fiber volumes of up to 70% and RTM up to 60%, our assumption correlates to a midpoint in the range experienced by competition vehicle manufacturers.

Variant model runs substitute other fibers for carbon; for simplicity we consider only various combinations of carbon and glass, rather than such other options as aramid or polyethylene (Lovins *et al.* 1996). Carbon fibers are generally the strongest and stiffest kind, and have excellent fatigue resistance and thermal conductivity (*id.*), but are relatively costly (even for commodity-grade fibers) and can have undesirable failure modes, chiefly brittle fracture. Glass fibers, specifically E-glass, while weaker and heavier, are also much cheaper and tougher, and can complement carbon by masking its fractures under extreme loads. Overlays or interweaves of various fibers (often aramid) are commonly used for this purpose, but elaborating such possibilities is unnecessary for this analysis, which is meant to elucidate costs, not to optimize detailed engineering design.

In addition, the model substitutes a lower-cost commodity resin, vinyl ester, for epoxy. Vinyl ester has mechanical properties similar to epoxy but is more frequently used in high-volume composite applications. However, the resin, as a variant of polyester, can have problems adhering to carbon fibers (Reinhart & Clements 1987). While the adherence problem has heretofore limited vinyl ester's use in advanced materials applications, it is not intractable (Dudgeon 1987).

Resin Transfer Molding

The modeled manufacturing method for the composite BIW is resin transfer molding (RTM). RTM is a thermoset liquid composite molding (LCM) process similar to structural reaction injection molding (SRIM) but with a different resin system (epoxy, polyester, or vinyl ester, rather than polyurethane or polyurea). Both of these LCM processes combine resin with fiber rovings, fiber mat preforms, foam core preforms, or other mold inserts. RTM and SRIM can be used to make both structural components and exterior panels.

The process, based on reactive chemistry, starts with a resin/catalyst mixture from any of various polymer systems, including polyesters, epoxies, and acrylics. The metering/dispensing unit prepares a shot of a suitable size and ratio, then injects it into a closed mold containing reinforcements. Depending on the resin chemistry, the mold is used, the filled mold cures for a set time and then is removed. Four major types of reinforcements are in use today: spray-up preforms, thermoformable continuous-strand mat, woven rovings, and stitch-bonded fabrics. RTM also allows for the insertion of ribs and cores within the mold if required by the part design. Both RTM and SRIM are low-pressure processes (1 MPa, 150 psi) employing low-force presses (890–1,780 kN, 100–200 short tons).

Cycle times for automotive RTM can be on the order of 30 minutes, although emerging variations (*e.g.*, "high"-speed RTM, or HSRTM) have demonstrated times under 10 minutes and advanced processes (*e.g.*, "ultra-high"-speed RTM, or UHSRTM) promise times of 2 minutes or less (Lovins *et al.* 1996). Overall cycle time depends mainly on resin-cure time; controlled injection that does not displace the preforms is also a factor. Technologies that use electromagnetic radiation (*e.g.*, UV) or high-energy electron beams (E-beam) could dramatically decrease resin-cure time for automotive structural parts (*id.*); these rapid-cure methods are currently used for curing coatings and a few aerospace components. Rapid-cure technologies, however, are presently incompatible with metal tooling (see *Tooling*, below).

As a result, this analysis assumes a "conventional" RTM cycle time for a large, complex part of ~30 minutes for the steel- and nickel-tooling scenarios (see *Results and Analyses*) and ~7 minutes for the soft-tooling scenario that models electron-beam curing.

Tooling

The choice of tooling for composite materials is paramount for optimal part performance and cost-effective production. Some tool requirements are relatively immutable, such as dimensional stability, reliability, nonreactivity with the resin or fibers, and a coefficient of thermal expansion compatible with the part. Other attributes, such as longevity and fabrication time, could be tailored to specific business goals. For example, a soft tool that wears out after a ten thousand parts, but that is inexpensive and can be quickly refurbished or remade, could allow the producer to refine the design inexpensively. This can be valuable in markets demanding nimbleness, short runs, high product differentiation, and continuous improvement—all increasingly common automotive requirements. Moreover, soft tooling may be roughly formable by automated processes (such as stereolithography) far faster than hard tooling can be machined. If soft tooling shortens product cycle times, it may yield critical competitive advantages even if it costs no less or slightly more (Lovins *et al.* 1996, Romm 1991).

This paper models three tooling types: steel, nickel, and composite (see *Results and Analyses*). Steel tools are costly to fabricate but very durable, and can produce Class A surfaces. A conventional tool material, steel is widely used because it is familiar and well understood, not because it is necessarily optimal or even suitable. Incompatible coefficients of thermal expansion, for example, may make certain types of steel tools unable to release carbon-fiber parts. The nickel shell tooling modeled is generally less expensive than steel, especially when using multiple sets of the same tool (Jerry Smith [Weber Tool & Mold], personal communication, July 1995)—a common tactic for producing slow-curing composite parts in high volume on parallel lines. Nickel tools can also produce Class A surfaces and last as long as steel tools.

Composite soft tooling, made of materials similar to the hypercar BIW itself, is less durable and hence is traditionally used in small production runs or to fabricate prototypes. However, several reasons indicate that soft tooling could be the best choice for high-volume applications on a manufacturing cost basis alone: A. soft tooling is

is compatible with rapid-curing technologies, reducing the number of parallel fabrication lines for a given production volume.

Despite its promise, soft tooling has difficulty in directly producing Class A surfaces. However, lay-in-the-mold thermoplastic or stick-on color-coatings already developed by several manufacturers could provide Class A surfaces. Soft tooling is also untested in high-volume applications, so many issues such as part consistency over time, feasible service life, long-term wear characteristics, and effects of thermal cycling remain unknown. More engineering knowledge is required before the soft tooling strategy can be adopted with confidence. However, GM's use of epoxy tooling for the EV1 aluminum spaceframe is an indication that automakers are on the learning curve for manufacturing with soft tooling.

Fuel Efficiency

To determine how BIW mass affects fuel use and hence lifecycle cost, fuel efficiencies are modeled here using the Rohde & Schilke (1981) bulk-parameter efficiency model and then conservatively renormalizing downward to approximate the slightly lower efficiencies found with the more complex SIMPLEV model developed at Idaho National Engineering Laboratory (Moore & Lovins 1995). To compare all vehicles uniformly, we set aside the original efficiency assumptions of the steel and aluminum bodies-in-white, which range from 33 mpg for the steel unibody to 38 mpg for aluminum. Instead, we "optimized" each vehicle to the exterior dimensions of the GM Ultralite and the powertrain efficiencies of Moore & Lovins's (*id.*) PNGV design scenario (Table 3).

To obtain vehicle masses for the efficiency model, we add a *non*-BIW mass equal to that of Moore & Lovins's (*id.*) "further optimized" scenario (Table 1, 4–5 passengers). Because this mass is optimized for a BIW of only 123 kg with closures, the case-study vehicles would compound the non-BIW mass to some degree (*e.g.*, by requiring a heavier suspension, powertrain, etc.); for this reason we assume a 75% compounding factor, so that for every kg by which the case-studies' BIW outweighs the "further optimized" scenario's BIW, a further 0.75 kg is *added*.

Table 3. Parameters assumed for applying the Rohde & Schilke (1981) model to steel and composite vehicles

Frontal area A (m^2)	1.71
C_D	0.19
APU efficiency	35%
Driveline efficiency	78%
Regenerative efficiency	60%
r_0 *(tires & parasitics)*	0.0065
Accessory average load	250 W

The assumed parameter modifications roughly triple fuel economy compared with the original IBIS study (Dieffenbach & Mascarin 1993) to 103 mpg for the steel unibody and to 119 mpg for the composite monocoque. However, the steel BIW fuel efficiency, due to conservative mass and performance assumptions, is overoptimistic (see *Model Conservatisms* below).

Repair Costs

The expected annual repair cost for a BIW is the sum of the average repair costs of its components, multiplied by the percentage of claims involving the respective components, times the likelihood of a claim for a given year. The present value of the lifecycle repair cost is the expected lifetime repair cost (equal to the annual repair cost times the vehicle life) discounted to present value.

There is uncertainty in the cost of advanced composite repair, as it has not had high-volume experience. However, for SMC body panels, where repair experience exists, there are no clear indications that repairing polymeric composites ends up costing more or less than steel. Empirically, the markups involved in the component, labor, and insurance aspects of the repair operations dwarf the actual material-dependent costs. Therefore, despite the lack of specific knowledge regarding the cost of composite repair, the repair costs for the steel and composite cars in the model are the same.

Recycling/Scrap

It would be inconsistent to make a very fuel-efficient hypercar from nonrecyclable materials. Even a favorable lifecycle energy balance could then be offset by rising landfill fees or poor public acceptance. Conversely, the potential for profitable recycling of composite manufacturing scrap would improve production economics and motivate development of suitable recycling techniques before they would be needed to cope with an aging fleet of hypercars.

Fortunately, polymeric composites are becoming increasingly recyclable as a result of innovations in chemical processing of scrap (Allred & Salas 1994, Lovins *et al.* 1996). While many of these processes are still in the lab or being demonstrated in pilot-scale projects, the groundwork is being laid for a timely, economically viable composite recycling industry. For continuous fiber-reinforced applications like a composite-monocoque BIW, further development is needed in the mechanical recovery of the fibers without damaging them, but chopped fiber can be valuable. (Lovins, *et al.* 1996)

The recycling technology used in this analysis is a proprietary process under development by Adherent Technologies (Albuquerque, New Mexico). The process separates the resin matrix from the fiber through low-temperature catalytic pyrolysis (Allred & Salas 1995). Currently, the composite scrap is chopped into small pieces before being pyrolized, which results in chopped fiber that is more easily recoverable. This process is used commercially overseas to recycle scrapped tires, and tests in the lab have demonstrated the process's ability to separate and recover the constituents of advanced composites (Allred [Adherent Technologies], personal communication, July 1995). Issues remain to be resolved regarding applicability to auto recycling, profitability with a mixed waste stream, sensitivity to fiber price, and adoption by the automobile recycling industry, but none precludes illustrative adoption of the Adherent process in our model.

Main Assumptions

Certain global assumptions were used to generate the manufacturing and lifecycle costs. The primary economic cost factors are listed in Table 4.

Table 4. Global TCM assumptions

Manufacturing Specifications		
Annual Production Volume	100,000	/year
Length of Production Run	4	years
Building Recovery Life	20	years
Working Capital Period	3	months
Capital Recovery Rate	10%	per year
Cost of Building Space	$800	/m^2
Price of Electricity	$0.080	/kWh
Lifecycle Specifications		
Average Vehicle Life	12.6	years
Real Discount Rate	10.0%	per year
Non-BIW Vehicle Mass	444	kg
Fuel cost specifications		
Annual Driving Distance	10,372	miles
Fuel Price	$1.25	/U.S. gallon
Repair Specification		
Frequency of Claims	7.7%	/vehicle-year
Post-Use Specifications		
Landfill Tip Fee	$25	/metric ton
Steel Recycle Value	$0.12	/kg
CFRP Recycle Value	$0.55	/kg
Polyurea/Glass Recycle Value	$0.18	/kg

Table 5 presents the assumptions specific to the base-case steel unibody and composite-monocoque BIW analyzed in this study. For the sake of comparison, the steel vehicle is assumed to take advantage of the same driveline technologies and ratings, non-BIW weight reductions, and physical characteristics as the composite car (see *Model Conservatisms*).

Table 5. Specific assumptions for case-studies

	Steel Unibody	**Composite Monocoque**
Total BIW mass	304 kg	190 kg
BIW mass w/o doors	270 kg	140 kg
Curb Mass	837 kg	637 kg
Piece count	266	8
Material	Steel	Carbon–Vinyl-Ester–Glass
Material Price	$0.75/kg	$17.60–$2.50–$2.20 /kg

Results and Analyses

The first analysis presented is the effect of alternative tooling technologies. Figure 1 presents manufacturing costs calculated for the steel unibody with traditional steel tooling and for the composite monocoque with three tooling options: steel RTM tooling, lower-cost nickel tooling, and "soft" composite tooling plus electron-beam curing. Figure 1 shows that at high volumes, the value of the soft-tooling/E-beam scenario stems more from the reduced equipment and labor costs (due to rapid cycle times) than from a decrease in overall tooling investment. Even though the soft tools cost significantly less per tool, many more must be purchased for the same high production rate. Because it has the lowest overall cost, however, the soft tooling scenario is used for the remainder of our composite manufacturing analyses (see *Soft-Tooling Life*).

Figure 1. Calculated manufacturing costs for base-case steel and composite bodies-in-white

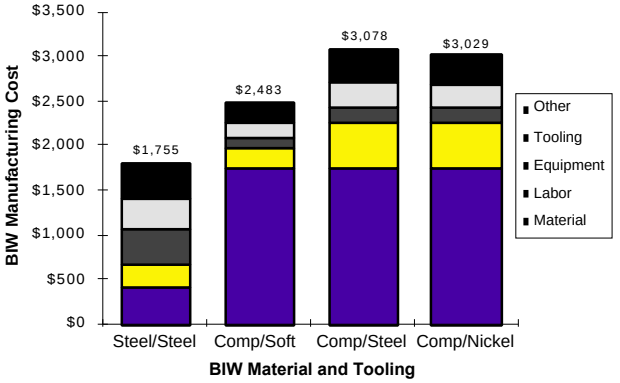
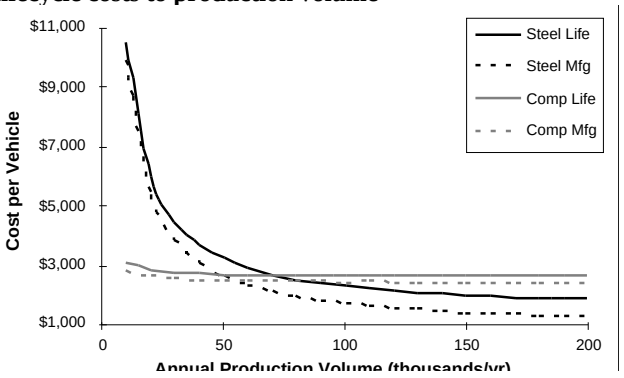


Table 6 shows the calculated structure of lifecycle costs, including manufacturing, fuel use, and recycling, for the steel and nickel-tooling scenario composite BIWs. These costs' sensitivity to annual production volume is summarized in Figure 2, which shows that using base-case assumptions (Table 4), the expensive steel tooling makes the composite BIW cheaper to manufacture than the steel BIW at under 55,000 units per year, and competitive in lifecycle cost at under 75,000 units per year. At the baseline 100,000 units per year, the total capital investment was $350 million for the steel unibody and $240 million for the composite monocoque.

Table 6. Calculated structure of lifecycle costs

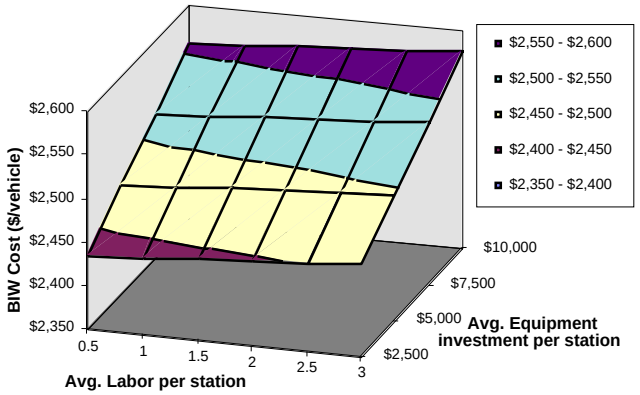
	Steel Unibody	**Composite Monocoque (soft tooling base case)**	**Composite Monocoque (Ni tooling for com-parison)**
MANUFACTURING			
Material Cost	$353	$1,753	$1,753
Labor Cost	$259	$240	$510
Equipment Cost	$423	$110	$161
Tooling Cost	$325	$172	$271
Other Cost	$395	$208	$333
MFG. SUBTOTAL	$1,755	$2,483	$3,029
Total Operation	$593	$264	$273
Total Post-Use	($7)	($29)	($29)
TOTAL LIFECYCLE	$2,341	$2,719	$3,246

Figure 2. Calculated sensitivity of base-case manufacturing and lifecycle costs to production volume



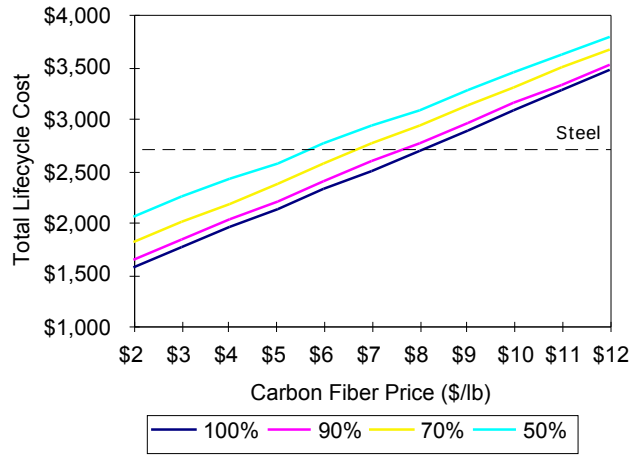
Assuming in all subsequent analyses the baseline production volume of 100,000 units per year, the effect of labor and equipment investment is shown in Figure 3 (see *Manufacturing Labor*). Figure 4

Figure 3. Calculated sensitivity of manufacturing costs to labor and equipment investment



shows the results of using lower-cost glass fiber to replace some of the carbon, adjusting total BIW mass to maintain stiffness: carbon is more cost-effective than glass on a stiffness basis. However, as discussed in *Fiber Choice*, if one assumed that the base-case Ultralite BIW were unnecessarily stiff or that certain areas of the BIW were not stiffness critical, then the BIW would experience more modest, if any, mass increases when the cheaper fibers were substituted.

Figure 4. Calculated sensitivity of lifecycle costs to varying fiber composition (assuming constant stiffness)



The preceding analyses show clearly that materials cost dominates composite BIW manufacturing cost. Figure 5 displays the results of an analysis of varying both carbon-fiber price *and* BIW mass reduction from the baseline Ultralite. Figure 6 presents the same data in a format that highlights the combinations of carbon price and mass reduction that yield a manufacturing-cost advantage over steel.

Figure 5. Calculated sensitivity of manufacturing costs to variation of carbon-fiber price and BIW mass reduction

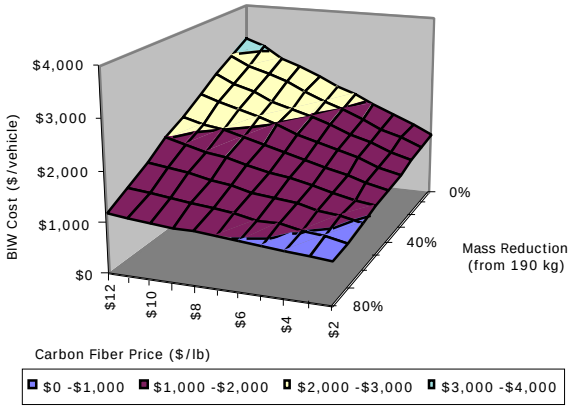
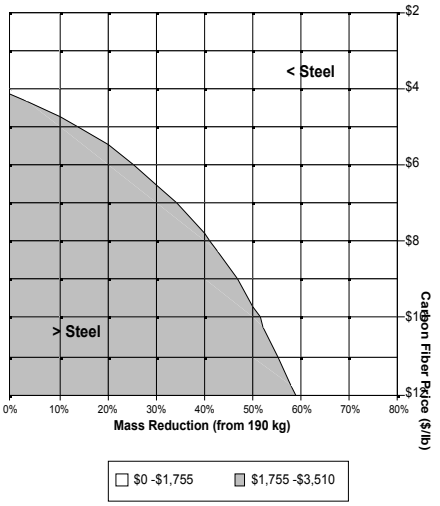


Figure 6. Carbon-fiber prices and BIW mass reductions: break-even manufacturing cost against steel unibody



Sensitivity Tests

While the TCM incorporates hundreds of variables, certain ones profoundly affect the feasibility of high-volume composite monocoque production. We discuss five of these variables in greater detail—carbon-fiber price, BIW mass, fiber choice, manufacturing labor, and soft-tooling life—and test how each affects BIW manufacturing and/or lifecycle costs.

Carbon-Fiber Price

The most sensitive variable in our model is the cost of materials, and by far its largest component is the price of carbon fiber. The baseline model assumes a fiber price of $17.60/kg ($8/lb)—the low end of the late-1994/early-1995 bulk purchase price of high-tow (50k or greater, *vs.* the aerospace standard of 12k), low- to intermediate-modulus, PAN-based continuous fiber, such as Akzo Nobel's Fortafil and Zoltec's PANEX. These fibers are of adequate performance (~230 GPa tensile modulus, ~3.7 GPa tensile strength) and should be compatible with the modeled RTM process, despite their large tow size. While they may have a 14–28% lower modulus than that used in the GM Ultralite (depending on whether its unpublished fiber choice was medium- or high-modulus respectively), the resulting difference in stiffness should be smaller than the degree of excess in the Ultralite BIW (see *Introduction*).

Sensitivity analysis of the cost of manufacturing composite BIWs at various carbon-fiber prices while holding all other design and production variables constant suggest that the monocoques are cost-competitive with steel at carbon-fiber prices of around $9.15/kg

($4.15/lb) with soft tooling. With a modest ~15% mass reduction (162 kg with closures, 119 without) from the suboptimized Ultralite design, the breakeven carbon-fiber price becomes $11/kg ($5/lb). Coincidentally, many have long considered the $5/lb price to be the threshold where carbon becomes the reinforcement of choice for high-volume applications not only in transportation but also in civil infrastructure such as beams and girders (Prescott 1995).

While some predict that $11/kg ($5/lb) carbon fiber is feasible at high production volumes of around 45 million kg/y (100 million lb/y) (*id.*), this target evokes understandable skepticism, as the coming of low-cost carbon has been touted for at least a decade. However, scale potentially can decrease costs through the phenomenon quantified by the progress ratio or "experience curve" (Lovins *et al.* 1996). DeLong (1994) of Amoco Performance Products, Inc. quantifies the learning curve for the carbon-fiber industry by expressing carbon fiber's selling price (at the minimum competitive profit margin consistent with attracting new investment for future production) as a function of manufacturing scale. His findings (Table 7) assume a production process with high fixed cost (which DeLong defines as labor, maintenance, safety, quality assurance, shipping, etc.) and medium capital cost. Although the most important factor affecting fiber price is manufacturing scale, DeLong's analysis (*id.*) suggests that possible variations in fixed and capital costs can affect price by 10–25%. Lower fixed costs could therefore reduce by 35–55% the production volume shown in Table 7 for a given fiber price (*id.*).

Table 7. Predicted fall in carbon-fiber price with increasing production volume (Cols. 1–2: DeLong 1994; cols. 3–5: authors)

fiber price (1994 $/lb)	*Production Volume (10^6 lb/y)*[a]	*# Ultralites @ 95 kg C (thousands)*[b]	*# hypercars @ 61.5 kg C (thousands)*[c]	*HC % of 1993 US Car Sales*[d]
$7	35	167	258	3%
$6	55	263	406	5%
$5	120	573	885	10%
$4	300	1,432	2,213	26%

[a] From DeLong (1994), for high fixed cost (labor, etc.) and medium capital cost. Cols. 3–5 assume for illustration that automotive BIWs are the only market for carbon fiber.
[b] GM Ultralite, with closures, at assumed 50% fiber by weight.
[c] "Further optimized scenario" without special crash structures (Moore and Lovins 1995), assuming 50% fiber by weight.
[d] Col. 4 hypercars as percentage of total passenger car sales, which were 8,517,862 in 1993.

The 100k-Ultralite/y production volume assumed in this paper as a basis for cost comparisons would consume, with closures, 21 million pounds of carbon fiber per year. With 1992 world production at 15 million pounds per year (*id.*), the marginal demand increase from this production would, according to DeLong's analysis, drop the price of carbon fiber to $7/lb (none the less, our base-case assumption remains at $8/lb). Moreover, if we assume our baseline production run is only *part* of a larger market share for composite monocoques, the price of carbon fiber should drop further. Table 7 shows, for example, that if ultralight cars are optimized to hypercar mass (lighter than the GM Ultralite assumed in this analysis), then a 10% nationwide market share, equivalent to California's ZEV/VZEV requirement for 2003, would bring carbon-fiber prices down to $5/lb. At this price, moderately well-designed ultralights would be cost-competitive with steel at model runs of 100,000 BIWs/y. That in turn could soon lead to a greater market share for composite vehicles, further reducing the price of carbon fiber and potentially

Such dramatic potential for higher volumes raises many issues about the speed of scaling up production of carbon-fiber-based hypercars. For instance, coordination between fiber users and producers would be needed for volume to grow quickly but with minimal risk. Constraints involve both economic risk and the logistics of investment, construction, capacity, and quality. Constraints do not, however, include availability of the carbon-fiber precursor, acrylonitrile. Having many common uses, this material's global 1993 production totalled over 8 billion pounds, which was only 80% of the global capacity available; and it takes only ~2 lb of acrylonitrile to make 1 lb of carbon fiber. Of note, at least one aggressive carbon-fiber producer plans to overcome the constraints and sell bulk continuous fiber at a nominal $5/lb by 2000—well under $5/lb in 1995$—regardless of automotive demand (Lovins *et al.* 1996).

BIW Mass

As discussed in the *Introduction*, the composite monocoque BIW mass, a key determinant of lifecycle cost, is assumed to be conservatively high in our base-case assumption, then sensitivity-tested for lower mass. Based on auto-industry estimates (Gjostein 1995; Eusebi 1995) and on masses of the other composite prototypes presented in Table 1, the base-case mass could conceivably be reduced by ~36% (~30% compared to AVCAR) to possibly ~50% (ESORO H301), or perhaps by slightly less if additional special safety features beyond those in the H301 were required. At our base-case price of $8/lb for carbon fiber, the mass reduction required to break even with steel would be ~40%, in the middle of that range. Specifically, the industry estimate of 67% potential mass reduction would break even at around $16.50/kg ($7.50/lb), implying an aggregate production volume of composite BIWs (not necessarily a single design) about 20% more than our base case (Table 7). In addition, this breakeven calculation assumes that lower BIW mass changes only materials usage (by far the largest component of manufacturing cost), not other manufacturing costs such as tooling and equipment, which might decrease costs a little further.

Fiber Choice

Our analysis includes designs where E-glass replaces part of the carbon-fiber reinforcement in the base-case Ultralite. Such fiber combinations can mitigate brittle fracture or otherwise improve performance as well as reducing fiber cost. However, we assume mechanical performance, specifically fiber strength and stiffness, to be paramount. We therefore normalize for the more conservative parameter, constant stiffness, using specific modulus as a proxy for overall performance. Glass has roughly a fifth the specific stiffness (and half the specific strength) of carbon, so the BIW becomes heavier as the E-glass fraction rises. For example, with a mix of 80% carbon and 20% glass (by volume) in a composite containing 50% fiber (by weight), an equally stiff Ultralite BIW would become ~30 kg heavier.

Adding glass using the above assumptions also *increases* the calculated materials cost of the BIW—a testament to the superior mechanical properties of carbon. In practice, however, glass would probably *decrease* the cost, because: A. the Ultralite is superfluously stiff (see *Introduction* and *Model Conservatisms*); B. the Ultralite could also better take advantage of mechanical anisotropy, lowering its mass (see *Introduction*); and C. The single-mechanical-parameter-as-proxy method ignores properties where glass has advantages over carbon, such as toughness and elongation. However, directly substituting glass for carbon without accounting for the overall decrease in mechanical performance would alter the characteristics of the Ultralite in complex ways. Thus feasible fiber

stant-stiffness assumption and a direct kilogram-for-kilogram fiber replacement.

Manufacturing Labor

Low-cost, high-volume advanced composites are generally assumed to require highly automated manufacturing in order to reduce costs. RMI hypothesized that, on the contrary, lower capital and investment costs for manufacturing composite monocoques might reduce sensitivity to costs such as labor. To investigate this hypothesis, we performed a multivariate test of sensitivity to both manufacturing labor intensity and equipment investment. As illustrated in Figure 3, labor intensity affects the overall cost of a composite BIW relatively little as compared to equipment investment and, most importantly, the materials cost.

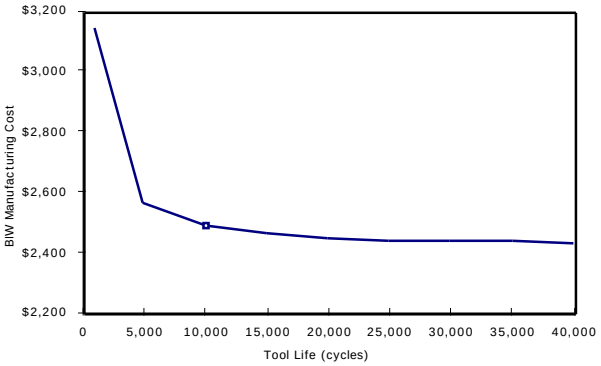
While this sensitivity test assumes that manufacturing throughput is constant for all levels of labor intensity, greater automation may allow faster cycle times. However, as the shift from chemical curing to E-beam curing shows, faster curing is even more important for raising throughput.

Soft-Tooling Life

Because it can be fabricated inexpensively and is compatable with high-speed curing technologies, composite tooling is the cheapest tooling scenario in our model runs. For our baseline model, we assume that each soft tool lasts 10,000 cycles on average—a projection based on proprietary discussions with soft-tooling manufacturers. Lifetimes of greater than 40,000 have been realized with heavy-duty soft tools, but some incertitude exists whether this can be attained for complex shapes and with sufficiently high consistency. Thus our assumed average cycle life for soft tools carries a degree of uncertainty.

To gauge this uncertainty, we performed a test of manufacturing cost sensitivity to soft tooling life (Figure 7). For soft tooling lives of under 5,000 cycles, manufacturing costs are fairly sensitive: increasing the average tool life from 1,000 to 5,000 cycles decreases manufacturing cost by almost $600. However, further increases in soft-tooling life quickly experience diminishing returns. An additional 5,000 cycles (to our base-case 10,000) lowers cost by $75; while quadrupling our base-case assumption lowers cost by only $55. Nonetheless, soft tooling, if feasible, remains the least expensive option for average tool lives above 1,100 cycles. As a result, our manufacturing cost analysis for soft tooling holds even for an

Figure 7. Calculated sensitivity of manufacturing costs to variations in soft tooling life



average tool life of half our base-case assumption, and soft tooling remains the cheapest option for a life ~90% lower than our assumption.

Moreover, soft tooling is given no credit for inducing lower equipment, labor, and auxiliary (such as energy) costs compared to metal tooling. For example, the lighter composite tools could require less support equipment and handling time (Harmon 1987). Also, soft tools require a third as much thermal energy per cubic foot as steel tools during part fabrication (*id.*). These advantages could provide an added buffer for variations in tool life.

Discussion

Model Conservatisms

This analysis contains conservatisms that could understate composite BIWs' potential economic advantages. While many are deliberate to account for the uncertainties in high-volume, low-cost advanced composite manufacturing and lifecycle issues, others are the result of forcing a direct comparison of the Ultralite with steel in the steel-optimized BIW industry structure.

1. Production volume. The baseline model compares BIW costs at a uniform production rate of 100k bodies per year. This assumption is driven by industry custom arising from the inherent attributes of steel BIWs made with steel tooling. It is *not* optimal for composite-BIW production—on the contrary, it tests the ability of composite BIWs to compete squarely in the middle of steel's most favorable territory—and it may also be far from optimal for overall production strategy. In fact, large production volumes can have negative marketing and strategic benefits and can significantly increase financial risk. More agile, small-run, fast-product-cycle manufacturing may be far more advantageous than anything now possible with steel's ponderous tooling and manufacturing methods but is not considered in this analysis.

2. Economies of scale. Conventional wisdom holds that processes with high fixed costs and low variable costs will be prone to economies of scale: the more units a firm produces, the more its fixed costs are spread over its production. Thus steel BIWs, with their rapid cycle times and large investments in tooling, equipment, and factory space, gain a much larger benefit in the model from increasing production volumes than do composite BIWs, whose volume/cost curve is practically flat.

However, composite BIWs should also experience economies of scale, because their predominant cost—materials—is a variable cost that is sensitive to production volume (see *Carbon-Fiber Price*). In fact, carbon fiber should become cheaper at larger volumes for the same reason steel BIWs do: both are very capital-intensive. As mentioned, the precursor for carbon fiber is abundant and relatively cheap, with a production cost of ~$1.50/kg (~$3.00 per kg of carbon fiber at 50% yield) (Prescott 1991). Carbon fiber's cost depends rather on the capital intensity required by its high-temperature and inert-atmosphere processing, hard-to-handle raw materials, and unique process equipment (DeLong 1994). That capital intensity gives composite BIWs economies of scale, both at a plant as well as an industry level, as is partly accounted for in the *Carbon-Fiber Price* sensitivity.

3. Production downtime and assembly speed. As steel parts require several contiguous processing steps, welded metal BIWs are produced on fast serial manufacturing and assembly lines. Composite parts, as near net-shape materials, can be produced on a larger number of slower parallel lines. The parallel lines should be far less vulnerable to shutdown if a problem arises anywhere in a given line. (Production will be lost in any case, but more units are lost per hour of downtime in a faster line.) To the extent that such failures are random (e.g., equipment failure) and not common-mode or cause-

this should give composite BIW production an uptime advantage. The model nonetheless assumes 25% aggregate downtime regardless of the number of lines.

Specifically, assuming all equipment has equal reliability, an equipment station in a serial line with *x* stations would have a downtime rate of 25/*x%*. For the same equipment set up in parallel, the *entire* downtime would equal the downtime for a single station: 25/*x%*. Considering that many steel parts require 4–7 processing steps (thus *x* could vary from 4 to 7), the parallel formation could significantly reduce downtime. However, the processing equipment ensembles for steel and composites are quite different, both in maturity and in their technological nature. Thus it is difficult to estimate the composite BIW's exact effect on downtime.

In addition, both slow and fast curing variants are assumed in the manufacturing model, for hard and soft tooling respectively. However, joining is assumed to take 600 seconds in all cases. It could be made an order of magnitude faster by curing the joints with light, microwaves, or electron beams. This would correspondingly speed assembly, reduce the number of parallel assembly lines, and decrease costs.

4. Parts overhead. The method of estimating factory space probably understates the saving in space and equipment for in-plant parts storage and delivery when the BIW-without-closures parts count falls by 44-fold, from 266 for the steel unibody to 6 for the Ultralite BIW (however, unlike steel, a composite part is an aggregate of several sub-components—see *Resin Transfer Molding*.) More fundamentally, this dramatic decrease should in principle reduce exposure to mishaps in external production, storage, and delivery to the plant, which the model does not count.

5. Composite BIW mass. Our base-case BIW, the 1991 GM Ultralite, is probably stiffer and heavier than necessary, as noted in the *Introduction*. This could be true even if it were a full-sized, PNGV-style 6-seat sedan (Moore & Lovins 1995). It would therefore be appropriate to interpret the model's results using a mass reduction beyond 0% from that base case. A mass reduction of ~36% (~30% for AVCAR) from the base-case Ultralite would reflect the maximum (67%) BIW mass reduction from steel unibody acknowledged as feasible by two leading automakers' senior composites experts. The ESORO concept car (Table 1), developed without the vast resources of a major automaker, suggest that even this 67% reduction from steel may not reflect the full mass savings available by careful anisotropic design, fiber-mix optimization, and internal mass decompounding within the BIW.

6. A steel hypercar? In order to isolate the effects of BIW mass and not confound them with other design changes, we assume that the hybrid driveline, aerodynamics, and performance remain constant regardless of the BIW material and mass. However, in practice these parameters would be far from constant: A. Steel BIWs with the assumed hybrid drivelines would actually experience the problems common to all heavy hybrids, including an expanded engine map (decreasing auxiliary-power-unit [APU] efficiency) and increased power generated in braking (probably decreasing regenerative efficiency). B. A steel BIW would have less interior space within the assumed constant frontal area (because of bigger drivelines, and hence reduced scope for better packaging) and a higher coefficient of drag (*e.g.*, because of more numerous and less uniformly thin seams). C. Heavier BIWs would have greater peak power requirements, causing sluggish performance with the assumed constant driveline power rating. D. Ultralight BIWs would have additional advantages over their heavier metallic counterparts, such as greater thermal and acoustic comfort, reduced noise/vibration/harshness, more refined handling, and perhaps enhanced safety. Thus in order not to confuse the comparison between composite and steel BIWs (the purpose of this analysis) with the comparison between hypercars and conventional automobiles in general (see *Future Tasks*), we *assume* a steel hypercar, but assuming it doesn't make it feasible or attractive.

7. Fuel efficiency. For the reasons discussed in Conservatism (6) above, and because of the underestimation of case-study driveline masses, our model greatly overstates the fuel economy of the steel BIW. Thus the 75% mass compounding factor for the steel BIW is probably too low, overstating the steel car's fuel economy and hence understating its lifecycle cost. Readers are therefore cautioned not to treat the simulated steel-BIW fuel efficiency as real.

8. Lifecycle and indirect costs. The hypercar BIW is given no credit in lifecycle cost for reducing or eliminating any fluids or replacement parts other than fuel. However, an actual hypercar, depending on its APU and load-leveling-device (LLD) technologies, should eliminate 6–8 of a modern steel production platform's 14 consumable nonfuel fluids and 12–13 of its 21 routinely replaced mechanical or electrical elements (Lovins *et al.* 1996). The rest, other than wiper fluid, should show reductions. In all, the postmanufacturing materials throughput to run and maintain the car should decrease by an order of magnitude below today's conventional cars—hardly a trivial benefit to the owner and to the environment. However, even if it were included in our analysis, the hypercar driveline assumed in the model even for the steel car—an impractical combination because the baseline steel BIW weighs too much—would largely vitiate this advantage.

In addition, the model takes no CAFE credit (avoided penalty) for improved fuel economy—a factor that could *by itself*, at the original IBIS assumption of $50/(car*mpg) (Dieffenbach & Mascarin 1993), pay for roughly a third the manufacturing cost of the baseline Ultralite compared to the "unrealistic efficiency" steel unibody (103 mpg), or could pay for *two* Ultralite BIWs given the original steel-BIW efficiency assumptions (33 mpg). Furthermore, the model takes no secondary (BIW) materials savings credit—which, at the original IBIS assumption of $1.00/kg and our 75% compounding factor, would reduce the composite BIW cost by $86. Finally, the model assumes no ZEV or other emissions credits, even though simulations show that a well designed hypercar, even with a gasoline-burning engine, should come very close to meeting the California Air Resources Board's recently proposed VZEV targets (Moore & Lovins 1995, Lovins *et al.* 1996).

Finally, the model assumes a 10%/y real discount rate. Discounting tends to understate the benefits of environmentally sensitive technologies, whose advantages are realized over many years. Although consumer discounting is an observable economic phenomenon in the short term, many question its application to goods with long-term societal benefits (Pearce *et al.* 1989). However, the model bypasses social lifecycle costs and quantifies only individual (user) costs—ignoring many benefits of hypercars such as reduced material flows. Still, for quantifiable user costs, the discount rate significantly reduces the composite BIW's potential lifecycle savings. For example, every dollar saved during the last year of the car's lifecycle translates to only 28 cents in the model.

9. System boundary. This analysis deals only with BIW cost. The retail price of the *entire car* is quite another matter:

- Painting or equivalent finishing could add less cost to the hypercar BIW than to the steel BIW if, as proponents of proprietary lay-in-the-mold color-coat technologies claim, their process can eliminate the paintshop, which can cost $100–250 million to build.
- The hypercar's interior trim, seats, etc. may also be substantially cheaper because of partial integration into the composite BIW, with for example, some of the basic seat structure built-in.
- The hypercar's driveline, wheel/suspension assemblies, and other components may also cost less than those of the steel car because of low peak loads, design synergies, and radically simplified design: *e.g.*, a hypercar has only a ~20-kW engine and needs no multi-speed transmission, clutch, driveshaft, U-joints, axles, differentials, or starter, while such remaining components as HVAC, engine cooling, and mechanical brakes can be dramatically downsized. Thus the same design integration that accelerates mass decompounding by downsizing or eliminating components (Moore & Lovins 1995) saves *costs* correspondingly. How far such savings are superseded by the costs of new or special components (LLD, wheel motors and controllers, etc.) requires further analysis.
- As noted in the *Introduction*, the Hypercar could better lend itself to streamlined marketing structures that could greatly reduce markups from production cost to retail price (Lovins *et al*. 1996).

Thus the hypercar BIW's cost-competitiveness with the steel-unibody BIW is neither a necessary nor a sufficient condition for the retail hypercar to undercut the price of the steel one; but it is certainly important and helpful, since most automakers' main reason for rejecting hypercars is the supposed unaffordability of advanced composites in the BIW. One would on the contrary suspect that if the composite BIW is broadly comparable in manufacturing cost to the steel BIW, then the ultralight hypercar may well be competitive in total cost as well, and still more so in retail price.

10. Strategic benefits. The composite BIW tooling and production agility and its small-run flexibility, especially with soft tooling and rapid curing/joining, should create economic value that may swamp the cost and markup differences assessed here. Just the potential major reduction in product cycle time, possibly with soft tooling roughed with fast-prototyping techniques infeasible for hard tooling, could by itself offer a decisive competitive advantage (Romm 1991).

Conclusions

Using assumptions consistent with currently proposed manufacturing methods, and assuming a 100k unit/y production volume, a carbon-fiber-composite monocoque body-in-white suitable for an ultralight-hybrid hypercar should have a lower manufacturing cost than a standard steel unibody at carbon-fiber prices of about $11/kg ($5/lb) (or more at lower production volumes) and with a ~15% reduction in the mass of the base-case BIW. Such a competitive carbon-fiber price is estimated by a major maker of this material to result from demand equivalent to making on the order of 0.6-0.9 million carbon-fiber cars per year—an order of magnitude smaller than the U.S. market for passenger cars. If the carbon-fiber body-in-white is mass-optimized, with safety and spaciousness broadly comparable to the IBIS steel BIW, then the breakeven carbon-fiber price approaches $16.50/kg ($7.50/lb), a figure only ~6% less than the late-1994/early-1995 bulk purchase price.

Under all conditions analyzed—even at $8/lb and without mass optimization—the carbon-fiber BIW has a lower *lifecycle* cost than the steel unibody at production volumes below 75,000 units per year. This is a volume significant enough to merit production by a major automaker and to yield major reductions in carbon-fiber price, but small enough to offer some of the strategic and marketing advantages of boutique manufacturing. Moreover, the base-case materials cost, using commodity-grade yet structurally sound carbon fiber at early-1995 market price, is 87% below the $13,000 of the 1991 handmade GM Ultralite concept car—a figure widely cited as evidence that composite BIWs cannot compete with steel. This encouraging cost reduction in just four years results from innovations in lower-cost fibers and in ways to mass-produce composite autobodies. However, the resulting composite materials cost, still five times that of a steel unibody, is ripe (as our analysis of both carbon-fiber price and optimal BIW mass indicates) for further reduction.

Significant to the motor-vehicle and car-body industry, which lost 40% of its jobs between 1977 and 1992 (Lovins *et al.* 1996), the composite BIW's insensitivity to labor in both manufacturing and lifecycle costs offers greater flexibility in the choice of production method and smaller incentives for increased automation or for moving production offshore.

The model strengthens an interesting conclusion reached by Moore & Lovins (1995): once the BIW and the car become relatively light by adopting a composite monocoque, further mass reductions are only weakly motivated by fuel economy. Rather, the main reasons for saving even more mass are to reduce the peak power and hence the cost, mass, and complexity of the driveline; to shrink the APU map; and (as evidenced in the model) to save on the mass of costly fibers required.

Taken as a whole, this analysis suggests that concerns about the economic viability of carbon-fiber (or similarly costly) advanced composites as the basic material for high-volume ultralight BIW production may be misplaced. Although such concerns seem plausible because carbon fiber costs manyfold more per pound than steel, fuller production-cost analysis shows that carbon's higher cost per pound can be offset, or more, by other savings in BIW manufacturing, especially in tooling and equipment cost. In essence, the body-in-white may have several times as many dollars' worth of materials, yet still cost less than the steel unibody because of reduced capital, assembly, and other costs. Composite BIWs' lower investment requirements also imply lower barriers to market entry. Further research extending the comparison beyond the body-in-white to include painting, the rest of the car (*e.g.*, drivesystem, chassis, interior, etc.), marketing and strategic issues, and fuller lifecycle costing may reach similar conclusions.

Are the Advanced Materials and Auto Industries Ready for Action?

With a few visionary exceptions, most advanced materials and processing companies, long nurtured by military and aerospace R&D and procurement budgets, seem hesitant to make an aggressive transition from low-volume/high-cost to high-volume/low-cost production. To this industry, high-volume applications mean such products as golf-club shafts (which contain a few ounces of carbon fiber each) and bike frames (a few pounds). For the automobile, current applications include components such as compression-molded bumpers and filament-wound driveshafts or compressed-natural-gas tanks. Few firms are yet ambitious enough to seek whole-*system* applications such as automobile bodies-in-white. Their hesitance comes from the scars left by past overestimates of demand and by close acquaintance with the more metals-friendly

elements of the car industry. For example, the carbon-fiber industry grew 15% annually during the 1970s and 1980s, rising to 50% in 1990 on the assumption of high military and aerospace demand. The next year, with a changed political environment and the cancellation of many programs, firms were selling the overproduced fiber *at cost*; moreover, some prominent firms, such as BASF and Courtaulds, left the industry altogether (DeLong 1994). In 1995, CIBA Composites merged with Hexcel as the latter emerged from Chapter 11. The resulting risk aversion of the advanced composites industry suits it to classic demand-pull behavior.

In the transportation sector, the market pull will have to come from the automakers. Yet a significant switch from steel to composites will require them to learn more about and gain confidence in an unfamiliar material. This will take time, but time is of the essence. The growth potential and profitability for advanced materials, especially carbon fiber, are high, but wasted time could mean lost profits, market share, and competitiveness. This analysis shows that with good, efficient designs, composite monocoques may likely be cost-competitive with steel at a relatively high carbon-fiber price. However, the monocoques could be cost *winners* with lower carbon prices which, with economies of scale, should occur once ultralights are produced at high volumes. Overall, the advanced composites industry and the automakers share a kind of prisoner's dilemma: joint action rewards both industries, while action by either alone is risky. It does not matter who takes the first leap, but it is vital to leap together and promptly.

Future Tasks

This analysis illuminates composite BIWs' costs, but uses relatively suboptimized BIW design and manufacturing processes. It compares GM's 100-day first-cut Ultralite BIW from a $4–6-million concept-car project, neither optimized nor engineered for production, with productionized steel unibody designs refined over decades at enormous cost. An obvious next step is to repeat the analysis with better optimized composite BIW designs and production processes. A useful extension would examine larger body styles, such as the 3+3 PNGV car, and heavier vehicles such as sport/utility vehicles and pickup trucks. Postproduction costs also need fuller analysis, taking fuller account of ultralight platforms' very different driveline technological choices, optimization, and performance.

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