ULTRALIGHT-HYBRID VEHICLE DESIGN: OVERCOMING THE BARRIERS TO USING ADVANCED COMPOSITES IN THE AUTOMOTIVE INDUSTRY

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ABSTRACT

Many diverse and important barriers, both real and perceived, inhibit automakers' adoption of advanced composite materials. A strategy to produce an all-advanced-composite body-in-white (BIW) commercially could be the best method to overcome these barriers.

This paper summarizes the ultralight, hybrid-electric "hypercar" concept, emphasizing why mass-optimization is crucial to its design; summarizes potentially applicable high-volume advanced composites technologies; recounts two recent studies of the main barriers to structural composites use in the BIW; explains why a whole-system application—not the conventionally prescribed component-based incrementalism—is probably the best way to conquer these barriers and create new opportunities; and explores in greater detail a key barrier of advanced composites, their manufacturing cost, to show how a whole-system application can circumvent it.

KEY WORDS: Advanced Composites, Ultralight Vehicles, Carbon Fiber

1. INTRODUCTION

Advanced polymeric composites have several advantages—including parts consolidation, high specific strength and energy absorption, styling flexibility, good noise/vibration/harshness (NVH) characteristics, and excellent corrosion resistance—that suit them to automobiles. Furthermore, technological advances in processing and materials appear to make advanced composites suitable for high-volume applications: low-pressure fabrication processes such as resin transfer molding (RTM) could require very low investment costs and, depending on the choice of resin and tooling material, offer fast cycle times, while new versions of resins and fibers promise low cost and high performance.

In addition, recent developments in automotive design drive the need for what is potentially advanced composites' biggest advantage: mass reduction. Ultralight-hybrid vehicle designs, such as Rocky Mountain Institute's "hypercar" concept, necessitate stringent mass-optimization (§2.2), particularly for the body-in-white[1], the automotive term for the unfinished body and its frame or

[1] While composites have been and probably will be used in a variety of applications throughout the vehicle platform, this paper focuses on the BIW for several reasons: it is the largest consistent system of materials in an automobile, it accords

chassis (and, depending on the source, including closures such as the hood, door, and trunk lid). Advanced composite bodies-in-white have the potential to be up to 67% lighter than a conventional steel unibody for equivalent size and safety (1).

However, a quick look at the use of advanced composites in the automotive industry raises an obvious question: If advanced composites are such wonderful materials, why are they not being used? Aside from a few specialty components for niche vehicles, such as one part in the Dodge Viper, and even fewer whole-system applications such GM's 1991 Ultralite concept car, the auto industry has shunned the use of advanced composites (defined as composites with performance superior to glass-fiber-reinforced plastic's[2]). Even regular structural composites, using low-performance reinforcements in quasi-isotropic arrangements, are being applied in lower-than-expected quantities (2).

In response, organizations targeting the automotive industry, such as the Automotive Composites Consortium (ACC), and composite producers, including some in NIST's Advanced Technology Program (ATP), are ambitiously implementing strategies to speed the integration of structural and advanced composites into the automobile. But the ACC's focus on component applications such as a composite pickup truck box (3), like the ATP's funding of manufacturing process improvements without accompanying design changes, indicate a strategy of evolutionary integration. While an evolutionary approach minimizes risk in the short term, it may not be the optimal long-term strategy to overcome the barriers to putting advanced composites into cars.

Just as the combination of an ultralight body with a hybrid driveline provides a "leapfrog" approach to increasing fuel efficiency and decreasing emissions (§2), so the whole-system application of composites to an ultralight monocoque BIW is the best way for the advanced materials and automotive industries to "tunnel through" the barriers to large-scale implementation. To an automaker, a leapfrog approach to composite integration could provide benefits (such as whole-car cost savings, design and production flexibility, and reduced investment requirements) far outweighing the risks and uncertainties of working with unfamiliar materials and technologies. To an advanced materials supplier, a leapfrog approach can prevent the "set up to fail" scenario experienced in many automotive component applications by optimally exploiting the new materials' intrinsic advantages. In addition, a leapfrog approach could potentially expand the advanced materials market by severalfold or more, achieving volumes which could lower their products' costs. Thus an advanced materials push into the BIW should not be simply an issue of material substitution one part at a time: it needs to substitute materials using a whole-platform design that maximizes the materials' benefits while minimizing—and potentially eliminating—many of their costs.

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unique opportunities for fabrication and assembly simplification, and RMI has performed an analysis on its manufacturing and lifecycle cost.

[2] Although glass could play a large role in producing ultralight BIWs, a glass-fiber-reinforced plastic BIW would not be light enough (~25–30% lighter than a conventional steel unibody and about the same as the UltraLight steel auto body) to reap adequate efficiency, performance, and cost advantages as part of a hybrid-drive vehicle. Thus this paper looks at advanced composites, estimated to achieve BIW mass savings of 50–67% (1) in a monocoque design.

2. THE HYPERCAR CONCEPT

The hypercar concept, under development at RMI since 1991, combines an integrated, extremely lightweight and aerodynamically slippery monocoque body and chassis with hybrid-electric drive. This combination can yield high performance, comparable or lower manufacturing cost, and dramatically improved fuel economy and emissions (4,5). Typical 4–5-passenger designs can reduce curb mass by ~2–3-fold, air drag by ~2–3-fold (perhaps even more with special techniques), rolling resistance by ~3–5-fold, fuel consumption by ~5–10-fold, and emissions by roughly two or more orders of magnitude—sufficient to qualify for the California Air Resources Board's proposed "Equivalent Zero Emission Vehicle" standard (5). Moreover, as is explained in this paper, radically simplified design using parts consolidation and molded net-shape body materials could dramatically cut product cycle time, tooling cost, assembly effort, and BIW parts count (5–7).

2.1 Ultralight-Hybrid Synergies Hypercars' apparent ability to meet fuel-economy, environmental, cost, marketability, and manufacturability goals simultaneously and without compromise results from an unusually integrative design process (4,5). Applying established engineering principles in a novel manner and sequence can capture unexpected synergies between the ultralight/ultraslippery platform and its hybrid-electric propulsion, potentially improving fuel economy by manyfold for three main reasons:

- Once the irrecoverable losses to air and road drag are reduced, the only other place the wheel-power is lost is in braking, which is reduced because of the car's lower mass and whose remaining energy is mostly recovered by the hybrid drivesystem.
- The driveline's compounding losses yield compounding *savings* when turned around: each unit of saved road load saves 2–4 units of fuel that would otherwise have to be burned to deliver that energy to the wheels.
- Mass decompounding is bigger with ultralight hybrids than with conventional platforms, because some elements can become much smaller and simpler (such as the onboard generator, called the Auxiliary Power Unit or APU) while others could be eliminated altogether (such as power steering, starter, transmission, clutch, and differentials).

2.2 Motivations for BIW Mass Reduction These synergies were largely overlooked until ~1991 because hybrid-electric drive was considered unavoidably heavy, costly, and complex. This still-wide spread view, however, is an artifact of assuming that mass reductions are motivated by saving fuel cost (or, in cheap-fuel countries like the U.S., complying with equally stagnant fuel-economy standards) and are done *after* hybridizing the driveline, if at all. Both these traditional rationales turn out to be suboptimal.

Traditional mass optimization compares the cost of saving primary mass (classically, ~$2–6 per kg of mass reduction by replacing steel with aluminum) with the present value of the avoided lifecycle gasoline use (in the U.S., ~$2 per saved kg). The modest mass decompounding and the small value of the saved steel are typically neglected, but would hardly change the result. This approach justifies little mass reduction because it assumes expensive incremental substitutions from cheap materials and cheap drivelines. However, if the BIW is instead made primarily of costly materials such as carbon fiber (which can provide the greatest mass savings), and if the driveline uses costly-per-kW electric propulsion, then a completely different optimization drives down curb mass much further. Its main motives are to save materials cost; reduce driveline cost, making super-efficient hybrid drivesystems commercially viable; maximize discontinuous, nonlinear mass decompounding; and shrink the engine map nearly to a point for high efficiency and low emissions (5). In a hypercar, then, the main goal of reducing mass is to save money on making the *car*—a benefit ample to justify advanced composites' relatively high cost per kg (§3, §5). The saved fuel and pollution are mere *byproducts.*

The sequence of mass reduction is as important as its logic. Merely adding hybrid drive to a conventionally heavy steel platform yields unattractive results: heavy hybrids' severe absolute and specific power ratings for the APU and load-leveling device (LLD) inflate mass (which compounds), complexity, and cost until they often exceed the original platform's. But making the platform very light and slippery *before* it is hybridized can immediately create an attractive, doubled-efficiency, fast-cycle car. The APU and LLD can be manyfold smaller, lighter, and cheaper. The series-hybrid engine map collapses nearly to a point. Mass decompounding accelerates as more and more systems and components are downsized or eliminated, further improving packaging efficiency and aerodynamics. Curb mass becomes so small (~420–550 kg for 4–5 passengers) that reduced requirements for costly fibers make BIW production costs attractively low (§7). This fortuitous sequence of consequences turns the vicious circles of heavy hybrids into the virtuous circles of ultralight hybrids (4,5).

For these understandable historical reasons, as well as industry culture (4) and outdated safety assumptions (§5.3), the only hybrids traditionally considered were heavy and relatively high-drag. This made their mass, cost, and complexity compound. Overlooked was the ultralight-and-ultraslippery regime of the hypercar, where hybrids' mass, cost, and complexity instead *de*compound. Thus hypercars necessitate an ultralight BIW; its mass-optimization requires advanced composites (4,6); and hypercars' leapfrog design strategy provides a new driver for converting BIW manufacturing to advanced composites. Strictly speaking, this paper argues that a conversion could be advantageous even without hypercars (§5); they do, however, add a powerful new motive.

3. TECHNOLOGIES FOR VOLUME PRODUCTION

How could polymeric composite BIWs be competitively made in high volume? There is no definitive answer; the slate of potential technologies for fabricating and assembling an advanced-materials-based BIW is large and growing rapidly. The diversity of technological options adds both uncertainty and robustness. Also, while advanced polymeric composites require sophisticated design to take advantage of unique properties such as anisotropy, their high-volume manufacturing and assembly techniques are conceptually simple. The most promising off-the-shelf or near-term technologies for BIW manufacturing are briefly listed next; a fuller survey is in (7).

3.1 Raw Materials Polymeric composites incorporate fibrous reinforcement in a resin matrix. Issues important for raw material selection include cost, compatibility with fabrication technologies, mechanical and environmental performance, and recyclability. For automakers, cost seems to be the biggest concern, as resins can cost 2–4 times and fibers 2–20 times as much as steel per kg.

3.1.1 Resins A number of resins look promising for an automotive BIW: thermosets, such as polyester and vinyl ester, offer relatively low costs (~$2.20/kg compared with steel's ~$0.88/kg) and good processing compatibility, while urethanes and epoxies offer increased mechanical performance for a 1.5–2-fold increase in cost. Thermoplastics such as GE's and Ford's cyclic thermoplastics or DuPont's polyester-based XTC (8) are easier to recycle and can offer fast cycle times and closed-loop recyclability.

3.1.2 Fibers Four main material groups could provide reinforcement in an all-composite BIW: carbon, glass, aramid (Kevlar), and polyethylene (*e.g.*, Dyneema). For many load-bearing applications, carbon is the best performer of the group, with excellent strength and modulus properties, and offers the greatest potential for BIW mass-optimization. However, carbon is currently expensive (see below) and has a catastrophic failure mode. Glass, in particular E-glass, has a low cost, good strength and toughness, and high elongation-to-break which make it attractive as a complement to carbon; but its lower specific properties only offer half the potential mass reduction if used alone. Aramid has excellent fracture-masking properties which also make it a good match with carbon, but is generally difficult to process and is very hydrophilic. Finally, certain polyethylene fibers have very good mechanical properties and a specific gravity less than one, although, perhaps because of their low production volume, they are currently expensive.

3.2 Intermediate Processing Before molding, fibers can be processed into such intermediate forms as tows (or strands in the case of glass), roving, mats, tapes, weaves, braids, and knits. Tows and roving can be cut to produce chopped fiber, while the other forms generally use continuous fiber. Structural composites for aerospace, optimized for high performance, predominately use directed, continuous fiber forms such as prepreg tapes and weaves, while those in automobiles, optimized for low cost, have used randomly placed fibers in chopped forms (such as chopped-strand mat in spray-up forms) or continuous forms such as random-strand mats. Neither the aerospace nor the current automotive approach would be suitable for an all-advanced-composite BIW. A "preform" for a liquid molding process described below would try to strike a balance between performance (largely a function of the length and directional placement of fibers) and cost (a function of labor intensity and capital investment). The conventional tradeoff between performance and cost may be bypassed, however, with innovative technologies such as stitch-bonded complex preforms (§3.5.2).

3.3 Molding In the various molding operations, the intermediate fiber form and resin, combined either previously or directly in the mold, are shaped and hardened into the form of the molding cavity. For an all-composite BIW, liquid composite molding (LCM)—either resin transfer molding (RTM) (including variants such as vacuum-assisted RTM [VARTM] and resin-infusion RTM [RIRTM]) or structural reaction-injection molding (SRIM)—is generally considered to be the most promising process (9). Both RTM and SRIM utilize thermoset resins because of their low viscosity, although cyclic thermoplastics may be adaptable. LCM requires a preform, which can comprise a variety of intermediate fiber forms. The Dodge Viper and Ford Composite Intensive Vehicle (CIV) use random-mat glass preforms. As mentioned above, an advanced-composite BIW would probably use a more complex preform with higher-performance fibers.

Compression molding, normally done with Sheet Molding Compound (SMC), is a high-pressure process with a lower cycle time and generally a better surface finish than LCM, suiting it to BIW applications within the current steel infrastructure (such as Saturn's thermoplastic body panels). However, like glass, a fully compression-molded BIW, due to its weight, may not be able to reap adequate synergies with a hybrid drive, nor have adequate crashworthiness. While some firms, such as HUB Engineering of Burbank, California, have developed compression-molded composite BIW designs, less mature but higher-performance manufacturing technologies such as RTM or SRIM appear to be more applicable to an all-composite BIW.

3.4 Assembly Adhesive bonding is used to assemble thermoset-based composites, while such techniques as vibration welding can be used for thermoplastics. Adhesives like epoxy offer excellent strength, while vibration welding is faster and cheaper (8). Composites can also be mechanically fastened, but with a mass and time penalty. Overall, the assembly processes for composite materials (except perhaps with new snap-together structures developed for advanced aircraft) are slower than welding steel; however, the radical decrease in parts count for an all-composite BIW correspondingly decreases the number of assembly steps. As a result, a clean-sheet assembly process for a composite BIW would require ~10% of the cost of steel-BIW assembly (6).

3.5 Technological Barriers Unlike the overall design strategy for composite BIWs, none of the composite technologies listed above require fundamental advances to permit volume BIW manufacturing. Each needs varying degrees of refinement but seems to face no intractable technological barriers: implementation requires technology optimization and integration rather than invention. Some of the key techno-economic barriers (commonly perceived) are described next.

3.5.1 Carbon-Fiber Cost The cost of carbon fiber is often cited as the most formidable barrier to commercial applications for carbon-fiber composites. For PAN-based carbon fiber, the combination of expensive precursor and low-volume, specialized equipment has led to its high cost (10). However, two enterprising domestic manufacturers, Zoltek and Akzo Nobel, offer low-cost, high-tow (~50k) commodity-grade carbon fiber. Bulk creel prices for their continuous fiber are currently as low as $17.60/kg ($8.00/lb). Central to further decreases in price are cheaper versions of the precursor, which has "no cost controlling differences" from the commodity-grade acrylic fiber that costs ~$3.00/kg (~$1.36/lb) to produce (11). In addition, higher volumes of production are needed to lower unit capital and labor costs. High-volume manufacturing could soon be realized: Zoltek and Akzo plan near-term expansion. Their strategy could overcome the cost barrier for advanced composites with a supply-push of low-cost fiber into the transportation market.

3.5.2 Preforming The difficulty of producing complex preforms at reasonable cost is cited almost as often as carbon-fiber cost as the chief technical barrier to high-volume advanced composites manufacturing. Princeton's Conference on Basic Research Needs for Vehicles of the Future recently gave preforming the highest priority among needed research and innovation (12). Currently, automakers favor quasi-isotropic chopped or continuous mat preforms of glass fiber, which, as was mentioned above, are too weak, isotropic, and hence heavy for a mass-optimized BIW. The anisotropic strategies common in aerospace applications, such as prepreg tapes and hand lay-up with autoclaving, are too slow and costly for cars.

Fortunately, the problem of creating low-cost complex preforms may not be intractable: several innovative technologies could permit the rapid and inexpensive fabrication of complex, net-shape (to avoid scrap) preforms. Fabrics such as COTECH (13) are non-crimp (avoiding the structure-weakening fiber kinks created in braids and weaves), stitch-bonded layers of unidirectional continuous fiber that, according to their manufacturer, can be cheaper than random mat yet perform about as well as unidirectional tape. A stitch-bonding process can inexpensively create complex preforms by combining a quasi-isotropic base of fabric with strategically placed inserts of unidirectional fabric or roving at maximum load points. Alternatively, the CompForm process claims even cheaper and faster complex preforming potential, substituting UV-curable binders for fabric stitches (14)—although this process cannot be used with a carbon-intensive preform. For creating net-shape preforms, fast ultrasonic cutting, using nesting patterns to minimize waste, could be a good complement to stitch-bonding (14). Obviously, complex preforms require heavy front-end engineering to avoid resin flow problems such as racetracking and unexpected fiber movements. Nevertheless, these processes have real-world validity: both UV stitching and ultrasonic cutting were used to create a complex preform for a Buick Riviera bumper beam (14).

3.5.3 LCM Cycle Time The cycle time of advanced composite fabrication is crucial to automotive production: a line making 350,000 vehicles/year needs to produce one car per minute. A typical large SMC part takes around one and a half minutes to mold, while a current RTM part takes around eight minutes (15). Steel, on the other hand, can stamp and weld up to 10 large parts per minute (15). Steel relies on fast serial production lines (up to seven, averaging four, stamping stages per body part); composites on more robust (6), slower parallel ones (a preforming and molding stage). Even though conventional RTM's cycle time is slow relative to steel, it allows larger, more complex parts. Thus, even a 50-fold increase in cycle time can be partially offset by a 10–25 fold reduction in parts count. And because RTM has cheaper tooling and equipment, multiple lines are not necessarily uneconomic (6).

However, multiple lines may not be necessary: several technologies offer dramatic reductions in cycle time. For thermosets, one method is to substitute chemical with E-beam curing, using compatible epoxy tooling and modified resins. Although historically lower performance and more expensive than conventionally cured resins, several high-performance e-beam curable resins have recently been developed that cost only ~$2.20/kg more than conventional resins (16). And while E-beam equipment is currently expensive, several startup companies claim to have developed small, lightweight, and very affordable equipment: one firm claims it can build an equivalent-performing, high-efficiency DC-powered accelerator for 10% of the cost of conventional, low-efficiency radio frequency machines (although only for parts up to 13 mm thick) (17). For thermoplastics, DuPont claims its XTC polyesters can have cycle times under a minute (8). For either of these technologies, assuming no major scaling problems, parallel lines could be avoided altogether and, depending on part consolidation and complexity, could allow far *fewer* units of equipment, each much cheaper than a stamping press.

3.5.4 Surface Quality Because composite monocoques require structural composites with Class A surfaces, a significant barrier is producing components with both high fiber-volume fractions and smooth, porosity-free exteriors. If soft tooling is used to capture strategic advantages or to ensure compatibility with E-beam curing for cycle-time reductions, the challenge of obtaining Class A surfaces becomes more complex and important.

While Class A surfaces could be difficult for structural composites, they are by no means impossible. The stitch-bonded fabric described above for complex preforms wets out easily and has a surprisingly smooth surface, as it is made up of unidirectional layers, so subject to resin consistency and tooling surface quality, it could simply be surface-finished with a Class A mold and painted, saving the investment and operation costs of conventional steel finishing prerequisite to painting exterior BIW parts. An even simpler approach could also avoid painting by applying one of several proprietary (but untested in high-volume production) lay-in-the-mold Class A colorcoat polymer products, or perhaps inject a thermoplastic colorcoat into a Class A mold and then lay in the structural elements behind it using a compatible resin system.

4. BARRIERS TO THE USE OF STRUCTURAL COMPOSITES

The late-1980s projections of composites' automotive growth proved overly optimistic (2). As was mentioned in §1, advanced composites' fabrication, assembly, and performance advantages for the BIW are not reflected in market uptake: even structural glass composites have reached volume production only in relatively minor components. If advanced composites are such advantageous materials and their production techniques rapidly maturing, why are they not more widely pushed by their makers and adopted by automakers? Interviews in the automobile industry (18) and its composite suppliers (2) help explain why, focusing on structural composites—the main function advanced composites would have in a monocoque BIW.

4.1 Barriers in the Automotive Industry Interviewers at the University of Michigan's Transportation Research Institute asked 27 people at Chrysler, Ford, and GM to state, among other things, structural composites' disadvantages and implementation barriers (18). The most cited disadvantage was not any problem with composite materials but rather automakers' inexperience and unfamiliarity, hence discomfort, with using them. Cost, particularly in high-volume applications, was cited nearly as often, reinforced by unmet cost expectations in past trials and by automakers' focus on costs per kg instead of per part or even per car (which is all that customers care about). The third-ranked disadvantage was production concerns, mainly about paintability and compatibility with steel-BIW assembly; fourth came field concerns, chiefly reparability.

Asked about barriers to composites' wide adoption, interviewees noted an astounding 324—12 per person. Instead of open-ended questions about disadvantages, the interviewers offered a precompiled list of barriers. The top ten choices (most frequent first) were recyclability, cost, crashworthiness, ease of design (for composite novices), manufacturing variability, bonding quality, benefit quantification, structural compatibility with steel, supplier capability, and manufacturing compatibility. This diversity bespeaks the issue's cultural as well as technical complexity: clearly there is no one simple answer.

4.2 Barriers in the Structural Composites Industry Researchers at the Environmental Research Institute of Michigan asked 22 automotive composite suppliers for the main impediments to mass-producing structural composites for cars, then classified their responses (2) into six main barriers:

- Automakers' established steel-based infrastructure: automakers' massive steel-based capital investments reinforce their "sunk cost" mentality, while the steel industry's design (such as the American Iron and Steel Institute's (AISI) UltraLight steel autobody (19)) and manufacturing improvements make automakers less inclined to switch.
- Lack of incentives for automakers to adopt unfamiliar technologies such as RTM when fuel economy is their main driver (17), fuel is cheap, and CAFE standards are static.
- Automakers' unpredictable and inconsistent demand for structural composites, precluding long-term R&D expenditures and manufacturing investments.
- Unrealized expectations in structural composite technologies: many of the barriers listed in §3.5, and inefficient translations of innovation from lab to shop floor, restrict the ready choices of mature manufacturing processes.
- Inexperienced composites infrastructure: unreliable cost projections, poor communication among disaggregated suppliers (raw materials makers, molders, and equipment builders), and material and process nonstandardization have discouraged automakers.
- Preemption by a lower-performance structural composite manufacturing technology: SMC's low cycle time, good surface finish, and process maturity suit it to high-volume production runs within the steel infrastructure.

5. OVERCOMING THE BARRIERS

The results of these surveys led one set of interviewers (18) to conclude that since "the adoption of structural composites faces multiple barriers, no one simple quick fix will rapidly accelerate their deployment." Yet despite complex implementation details (§7), there is a relatively simple—if unexpected—conceptual framework to integrate advanced composites into automaking.

The most effective way to overcome the barriers appears to be replacing today's dominant strategy of incremental, part-by-part materials substitution with a whole-system-designed, all-advanced-composite BIW. This "leapfrog" approach integrates a clean-sheet design, high-performance raw materials, existing (even if not yet optimized) manufacturing methods, and a radically simpler and smaller assembly process. It holds promise of bypassing many barriers and of changing automakers' attitude toward advanced composites from a "necessary evil" (if CAFE standards are ultimately tightened) or indefinitely postponable inconvenience (if they're not) into a prompt and lucrative opportunity. Ways to circumvent major barriers (§4) are surveyed next.

5.1 Cost Component-by-component substitution of composites for steel cannot occur until market-determined material prices justify substitution on a single-part basis, either through cheaper manufacturing or through saved gasoline (§2.2), with little if any credit for mass decompounding and even for the saved steel itself. The substituted materials remain costly, however, because only small volumes are being bought. Credit should be, but is not always, taken for the modest reductions in parts count; as a result, thinking in component terms makes it hard or impossible to quantify saved assembly costs. Finally, integration of a composite component within a steel BIW can raise overall assembly costs, especially if the composite parts' cycle times are longer or their dimensions and other properties are more variable. As a result, integration requirements often economically favor compression molding (which displays little anisotropy) over RTM, leading to parts with suboptimal performance for demanding structural applications.

In contrast, clean-sheet whole-platform redesign can yield radical reductions in parts count, size, and complexity: the typical BIW would have only a few parts (somewhat more if each preform and insert is considered a separate "part"), and assembly effort would drop by an order of magnitude (§3.5.3). Buying the special materials in bulk should yield discounts and, through increasing production volumes, cut market prices (§3.5.1). Production volumes could be optimized for convenience and market demand, rather than artificially inflated to meet amortization requirements for steel tools and presses. Production flexibility could be retained not only in volume but also in styling. Finally, savings could accumulate "downstream" from BIW manufacturing through a much smaller and simpler driveline and other components, shorter product cycle times, and greater production flexibility (§5.8).

5.2 Recycling Component-based applications encourage a multiplicity of resins: current automobiles use over twenty (7). Trying to recycle a large number of distinct resins increases dismantling costs, reducing the car's recovery value. The diverse resins are therefore normally not recycled but rather landfilled as automotive shredder residue (ASR), decreasing the overall recycled content of a steel car. Furthermore, these reduced economic rewards to recyclers and manufacturers shrink incentives for further improvement. In contrast, full-BIW composite use, as a single material system, could use a single resin in large quantity and in an easier-to-dismantle format. Recycling potential for advanced composites, given large enough volumes, is favorable to good (7), but even if the whole ultralight car, less the readily removable valuable parts such as electricals, were simply shredded and landfilled, it would weigh less and be less toxic than the ASR from today's cars (7). Finally, even without recycling, the amount of petroleum used as precursors for advanced composites is far smaller than the fuel savings from the ultralight or ultralight-hybrid platform.

5.3 Safety Advanced composites have fundamentally different energy absorption characteristics and failure modes than steel. They fit uncomfortably into the traditional safety-design paradigm, especially when applied by steel-oriented designers who treat advanced composites as "black steel" (or "white steel" for glass composites). Inadequate redesign can yield suspect composite parts, creating an impression of poor safety. However, clean-sheet design of an all-composite BIW can take advantage of these materials' unique properties, including, in proper shapes, specific energy absorption five times that of steel (5). Equivalent safety for an ultralight, using superior materials and design to compensate for light mass, requires a new design approach implementable only at the system level, not in isolated components alone. To explicate the design paradigm for an all-composite BIW, RMI is currently preparing a primer on ultralight composite-based car safety principles and praxis.

5.4 Unfamiliarity The traditional component-based approach creates a niche-material mindset that relegates composites to a minor specialty role—as if designers were asked to put a novel material called "steel" into, say, the alternator in order to become familiar with it. Bodywide application instead forces a design-for-manufacturing (DFM) approach, hence universal familiarity with advanced composites for everyone involved throughout the design and production process. While a

DFM approach is more difficult to implement than the traditional "build-test-fix" operations, the latter would be prohibitively costly over the design lifecycle of a multiple-part, all-composite BIW.

5.5 Designability As mentioned above, composites used only in components have often been treated as "black steel" for carbon-fiber composites. Composite parts are then designed as if the material were traditional and isotropic, leading to composite parts elaborately fabricated into wholly inappropriate metal-like shapes. This adds cost and complexity while sacrificing composites' chief structural benefits. Even when composite elements are redesigned appropriately, such as ACC's proposed front-end structure (3), integrating them into a steel BIW can significantly constrain its design boundaries. In contrast, full-BIW composites necessitate an anisotropic design to achieve adequate safety, stiffness, and mass reduction—all but eliminating the "black steel" design error. Design boundaries become extremely elastic. Finally, before refinements in fabrication technology decrease variability, an all-composite BIW can be designed to allow greater—even though it should normally have smaller—part tolerances. For example, relatively thick layers of strong adhesive can be used to connect components in case of slight variations in their dimensions; while a suboptimal design strategy, it could yield a strong structure with no internal stresses and at reasonable cost, accommodating immature processing technologies in the short-run.

5.6 Compatibility with Current Production Composites used as parts in a conventional BIW are often hard to color-match with metal parts; have different stiffnesses, fatigue characteristics, and coefficients of thermal expansion than metals; and are ill-at-ease in current assembly processes. Designing the entire BIW from composites obviously avoids color and, if a consistent material system is used throughout the BIW, mechanical matching problems. A "clean-sheet" production and assembly process could actually decrease cost and complexity—and even create opportunities downstream such as avoiding painting with lay-in-the-mold color (§3.5.4) and further simplifying assembly by integrating interior structures, such as the dashboard, into the BIW. As an interesting analogue, preliminary "clean sheet" designs for an advanced tactical fighter, optimized for composite manufacturing techniques applicable to cars, increase composites' mass fraction from 28% to 95% while reducing total production cost by about 56% (20).

5.7 Lack of Consistent Demand Component-based composites are subject to many metrics: styling freedom, cost, mass, paintability, assembly, reparability, recyclability, durability, etc. (2)—so many hurdles that in any given instance, risk-averse designers can easily default to steel. If composites are nonetheless selected, specific parts can be specified and outsourced to the lowest bidder in a formulaic way characteristic of any commodity. However, advanced composites are at a pre-commodity stage and require careful partnerships between the automaker and supplier to minimize risk. Accordingly, a leapfrog all-composite BIW would by necessity be treated as an emerging strategic product with correspondingly deep relationships, higher and more predictable demand, and durable order books. Moreover, once the capital infrastructure is designed, the low fixed costs of advanced materials could make variation in order volumes advantageous when compared with either high-volume metals or highly specialized composite components.

5.8 Risk Less widely perceived than the risk of leapfrogging to an all-composite BIW is the inherent and often ruinous risk of the *present* BIW manufacturing infrastructure. Its inherently high fixed costs and low variable costs make profits extremely sensitive to sales volumes, endangering income whenever demand falters. (Shrinking or negative margins then crimp new-model development, R&D, and investment in favor of keeping older models longer.) Furthermore, the high fixed costs impel large production runs, which shrink model variety and focus more risk on the market success of each model. (Hard tooling demands big runs; market fickleness, often small runs. This conflict creates strategic inconsistencies) Long product cycles, too, make new models lag behind dynamic public tastes, further heightening the risk of disastrous ventures. Conventional component-based use of composites, forced into the same paradigm, could carry similar risks.

In contrast, soft-tooled, net-shape advanced-composite monocoques could offer strategic advantages with a precisely opposite risk profile. The tooling could be cheaply fabricated with few parts, inexpensive materials, and only one die set per part. Presses could be inexpensive and low-pressure; assembly, drastically simplified; tolerances, tens of microns or better. The resulting production process could have inherently low fixed costs (§3.5.3) and higher variable costs. The low fixed costs could permit and encourage many small runs of highly differentiated products that diversify the market-risk portfolio. The extremely short tooling cycles and frequent tool replacement or refurbishment could foster continuous improvement and very rapid market-matching evolution. Successes could then be quickly identified and capitalized upon, putting slow-cycle competitors at a significant strategic disadvantage.

6. TUNNELING THROUGH THE COST BARRIER

The cost of advanced composites (§4, 5.1) is one of their most oft-cited disadvantages and implementation barriers. However, IBIS Associates and RMI (6) show that "leapfrog" adoption of advanced composites can yield competitive volume production costs.

Advanced composites have a history of high cost in both aerospace and auto-component substitution (§5.1). However, aerospace applications' costly product development, raw materials, manufacturing, and testing processes differ profoundly from potential automotive high-volume techniques (§3). For example, 72% of the cost of a typical aerospace component is for fabrication (chiefly processes like tape layup and autoclaving), 28% for materials and intermediate process steps like prepregging (9). But for an automotive BIW, only 30% would be for fabrication and intermediate processing, 70% for raw materials (6).

To quantify the costs of the "leapfrog" BIW approach—an all-advanced-composite monocoque—the IBIS/RMI analysis employed IBIS's technical cost model (TCM), a first-order, spreadsheet-based lifecycle-cost model widely considered the industry standard. The TCM assumed the design of the GM Ultralite, a 140-kg (191-kg with closures) prototype carbon-fiber monocoque BIW designed and built in 100 days and hence suboptimized for both mass and manufacturability. The TCM assumed production with high-speed RTM, several tooling and curing scenarios (soft/E-beam, nickel/chemical, and steel/chemical), and slow-cure adhesive bonding for assembly. Ignoring secondary cost savings mentioned in §5.1, the analysis found that *an advanced-composite monocoque BIW could break even in manufacturing cost with a steel unibody at volumes of 100,000 vehicles per year* under a variety of plausible scenarios.

Since the cost at high volume depends mainly on materials, whose largest component is reinforcement, a key variable is carbon-fiber price. In addition, more efficient BIW designs capturing the advantages of advanced composites can achieve good roominess and safety with less fiber, represented by a mass reduction from the baseline, first-cut, and (based on benchmarking) excessively heavy Ultralite design. Figure 1 compares the case-study advanced-composite BIW manufacturing cost against that of a standard steel unibody for changes in carbon-fiber price (Y-axis) and for BIW mass reductions from the Ultralite (X-axis). Each point on the plane represents an all-advanced-composite BIW manufacturing cost, which exceeds that of the steel unibody in the lower-left zone and undercuts it in the upper-right zone.

Three points on the breakeven line explicate how an all-advanced-composite BIW can "tunnel through" the cost barrier. Point "A" corresponds to a vehicle slightly more optimized than the Ultralite and a carbon-fiber price of $11.00/kg ($5.00/lb). Five dollars a pound is an often cited goal for low cost carbon fiber (10,11); manufacturers conservatively estimate the demand needed for $5/lb fiber at 100–120 million lb/y (3–4 times world capacity) (10,11). This volume translates to around 600,000 carbon-fiber BIWs, roughly 7% of the passenger car market (6). Thus if only one out of every fourteen vehicles incorporated advanced-composite BIWs, the attendant lower carbon-fiber price could afford a comfortable margin of design flexibility.

However, $5/lb fiber is not requisite for affordable composite BIW production: points "B" and "C" show that well-designed BIWs allow higher raw material prices. "B" corresponds to Big-Three composite experts' estimate of a mass-optimized carbon-fiber BIW (67% lighter than a conven-

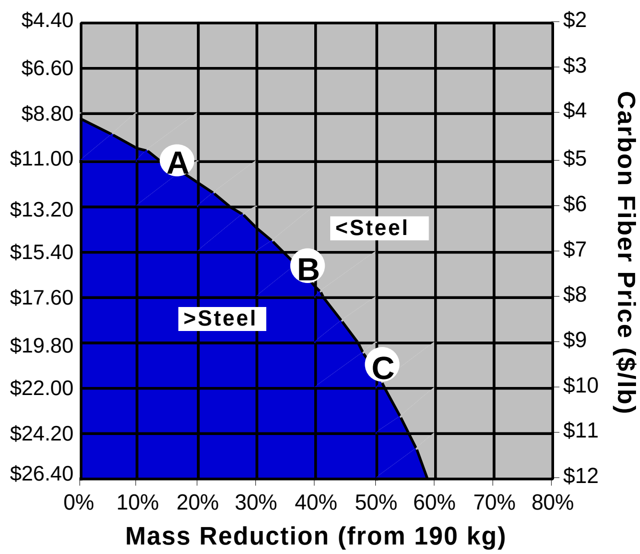

Figure 1. Cost of producing 100,000 all-composite BIWs relative to standard steel unibodies for changes in carbon-fiber price and BIW mass reduction from the baseline design

tional steel unibody)—resulting in an allowable carbon fiber price only ~6% less than current (6). But real-world designs indicate this estimate may be conservative: "C" corresponds to a prototype composite monocoque from Switzerland, the 4-passenger ESORO H301, whose 72-kg BIW is 49% lighter than the baseline Ultralite (21). If made from carbon (it is actually ~75% glass and ~20% aramid), its designers estimate it could be as big and safe as the Ultralite, yet still weigh around the same 72-kg. With this design, an advanced-composite BIW would break even with a carbon-fiber price *higher* than today's and thus could be *cheaper* to manufacture than a similarly-sized conventional steel unibody.[3]

7. CONCLUSIONS

The technology needed for the competitive mass production of automotive BIWs as advanced-composite monocoques is essentially at hand. Optimizing the technology suite requires further development, but as part of normal industrial evolution: the techniques required to progress from adequate to optimal manufacturing are a need—not a significant barrier. The real barrier is automakers' cultural reluctance, for understandable reasons such as their unfamiliarity with advanced composites, to adopt a leapfrog design approach that reveals advanced composites' major advantages in this high-volume application. An incremental strategy may lower short-term risk but could lead to "set-up-to-fail" ventures because of advanced composites' awkward fit into the steel infrastructure.

While understanding the value of whole-system design for advanced composites may be simple, overcoming the cultural inertia of incrementalism will involve a complex, detailed multi-tiered strategy (2, 7,18). Key steps could include, but are not limited to, educating automakers on advanced materials' benefits and design strategies; establishing a common materials, process, and testing database to facilitate standardization and integrate technologies; collaboration among firms in the advanced materials industry, potentially to develop manufacturable, optimized BIW designs such as AISI's ULSAB (19); coordinated, long-term cooperation between the auto and advanced composites industries along the lines of the RTM partnership between Dodge and APX (22) for the Viper; refocusing projects from strategic organizations such as the ACC and ATP from component-specific to whole-BIW designs; and establishing futures markets to stabilize material prices.

Overall, the potential for rapid market emergence of ultralight-hybrid "hypercars" provides a powerful driver for the development of mass-optimized, all-advanced-composite BIWs. Moreover, the potentially decisive competitive manufacturing and marketing advantages of whole-systems design and net-shape, flexible, and fast-cycle manufacturing (§5.8) make the production of ultralight BIWs attractive *without* external drivers—and could even allow them to go full-circle and motivate ultralight-hybrid production. Although adopting a clean-sheet approach to design and materials selection involves an admittedly high level of uncertainty in the short run, those adopting an incremental strategy could be at much greater risk as time passes: failure to lead, let alone quickly emulate, competitors' leapfrogs could be a "bet-your-company" strategy. The wreckage of the mainframe computer industry should have taught everyone the importance of killing one's own products with better new ones before someone else does (as 3M reportedly puts it, "We'd rather eat our *own* lunch, thank you"). Automakers are especially at risk in this case because many of their potential competitors may not yet have appeared on the radar: smart, hungry aerospace engineers in Southern California, Seattle, Switzerland, or Singapore may be the automotive version of the next Apple or Xerox.

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[3] This cost comparison is for direct manufacturing cost. It does not include potential, albeit uncertain, secondary cost savings induced by the BIW such as in-mold finishing and coloring (§3.5.4), integrated non-BIW structures (§5.6), and strategic advantages (§5.8), nor lifecylce cost savings such as increased fuel efficiency (§2).

Yet past innovations such as the GM Ultralite and Impact, the Ford Composite Intensive Vehicle, and the Chrysler Patriot and Viper[4] confirm that with vision and will, a leapfrog design strategy combined with the right technologies can be turned into rapid learning and successful products. America happens to lead (or at least tie) in all the capabilities needed to do this with advanced materials and hypercars. Visionary leaders in the U.S. advanced materials and auto industry are starting to understand the importance of strong and prompt actions to capture that new high ground first. This may well become the central challenge of the late 1990s and beyond for the nation's best materials and process engineers.

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[4] The Impact BIW is an aluminum spaceframe with composite body panels; the Ford CIV BIW, which integrates a RTM structure with SMC body panels and an aluminum front end, has been extensively and successfully crash-tested; the Chrysler Patriot is a performance-optimized race car which combines an ultralight composite monocoque BIW with a series-hybrid drive; and the Viper pioneered a cooperative approach between the automaker and its composite supplier (albeit its design—random-glass body panels on a heavy steel chassis—is not a leapfrog).

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