

ADVANCED COMPOSITES: THE CAR IS AT THE CROSSROADS

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ABSTRACT

A recent flurry of announcements from major automakers suggests a rapidly maturing seriousness about putting advanced technologies (hybrid drivesystems, fuel cells, aluminum bodies, etc.) into near-term vehicles. For the advanced composites industry, the window of major automotive opportunity seems to have arrived, only to find the industry unready to grasp it. The best way to protect existing markets and create major new ones is to emulate not the metals industries' *products*, but their coherent and aggressive creation of automaking *solutions*.

KEY WORDS: Applications: Automotive, Business/Market Strategy, Advanced Composites

1. STATUS OF AUTOMOTIVE ADVANCED COMPOSITES

After decades confined to narrow niches, advanced polymer composites—those with properties superior to random-E-glass-reinforced polymers—are at a crossroads. Behind are the prodigal costs associated with military aerospace applications and the meager volumes per unit with sporting goods. Ahead lie opportunities in such high-volume and high-value-added markets as commercial aerospace, construction, energy storage, and mass transportation. However, organizations with an interest in advanced composites—polymer firms and trade groups, fiber suppliers, fabricators, etc.—seeking to grasp these opportunities face a tough struggle. In each market, advanced composites face numerous technical and cultural challenges as well as fierce competition. In particular, the automotive industry, because of recent evidence of a technological renaissance, provides perhaps the most lucrative opportunity. But success in capturing this market seems doubtful without prompt, industrywide action requiring changes in attitudes and priorities. When two prominent MIT materials scientists can claim—albeit in a contentious article (1)—that advanced-composite vehicles are a “chimera...because we cannot mass-produce an affordable, ultralightweight polymer-based vehicle body,” “glass fiber polymeric composites are price competitive with aluminum and steel only when used in small quantities,” and “carbon-fiber composites are prohibitively expensive,” there is much work to do.

1.1 History While their promise has been touted for decades (*e.g.*, the 1979 carbon-fiber composite Ford LTD prototype), advanced composites remain a curiosity in the automotive industry¹, used in only a few productionized cars such as the all-carbon-fiber McLaren F1, whose total production volume is ~100 units. In all, the current annual automotive use (by mass) of advanced composites trails steel by roughly *six* orders of magnitude.

¹ Lower-performance commodity polymers and polymer composites (*e.g.*, SMC, random-glass RTM), on the other hand, are widely used in the industry—they make up ~7.5% of the mass of a typical vehicle (2), making them by mass the second most-used material group behind iron and steel. However, as this paper will argue, the use of polymers and commodity composites in advanced-vehicle platforms may depend on the success of *advanced* composites. Copyright ©1998 by Rocky Mountain Institute. All rights reserved. Conference pre-print for the 43rd International Society for the Advancement of Material and Process Engineering (SAMPE) Symposium and Exhibition, 31 May–4 June 1998. HYPERCAR is a trademark, and HYPERCAR CENTER a service mark, of Rocky Mountain Institute.

As Rocky Mountain Institute (RMI) argued in a previous SAMPE paper (3), this is because advanced composites—or for that matter commodity polymer composites—don't fit well into conventional metals-based platforms nor the production methods and mindsets that create them. The incompatibilities of advanced composites with commodity metals include different design (*e.g.*, isotropy and homogeneity), manufacture (processability, dimensional control, cycle times, temperature tolerance, and assembly methods), and performance (coefficients of thermal expansion, electrical conductivities, and surface finish). Not surprisingly, inserting composites into a steel car raises numerous, often costly, and sometimes intractable compatibility issues.² When these are addressed, the composite material must ordinarily conform to the constraints of the surrounding steel structure, not vice versa, shrinking composites' design space and benefits. Add the belief that materials cost per kilogram (kg) is what matters—even though nobody but a scrap dealer buys cars by the kg—and you get technical and cultural conditions in which the benefits of incrementally adding advanced composites into metal autobodies rarely exceed their costs.

1.2 The Need for Whole-System Applications To succeed in the metals-dominated automotive market, advanced composites must be applied as a whole system such as a complete autobody and chassis assemblage (3). Moving from incremental part-by-part substitutions to extensive, whole-platform “clean-sheet” applications shifts the challenges from making composites compatible with metals to solving system-wide issues (*e.g.*, cost per autobody or car, crashworthiness, overall surface quality). Automakers and suppliers can then focus their effort not making composites act like metals, but exploiting composites' unique benefits to make superior products.

2. NEW OPPORTUNITIES IN THE AUTOMOTIVE INDUSTRY

2.1 An Explosion in Technological Diversity Until recently, the automotive industry seemed unwilling to adopt new body materials extensively. Whole-systems “leapfrog” arguments (3) were theoretically correct, but lacked compelling force in the technologically conservative automotive environment so long as competition did not require new thinking. After all, the underlying nature of automotive technologies has remained fundamentally unchanged throughout this century. Gasoline-fueled, internal-combustion-engined powerplants have dominated drivesystems since they beat out steam- and electric-powered drivesystems eight decades ago. Carbon steel has been the most widely used material in autobodies and chassis since it overtook wood in the late 1920s. The dominance of these technologies indicates a static tendency that if continued would make the widespread adoption of fundamentally different technologies, like advanced-composite materials, slow and difficult.

However, as numerous examples in other industries (*e.g.*, computer mainframes, typewriters, propeller aircraft) have shown, trend is not destiny. Spurred on by the force of competition and the perceived threat of regulation, automakers are exploring a host of advanced technologies for a new generation of vehicles producible in volume within the next decade. These vehicles' powerplant options include advanced internal- and external-combustion (Stirling-cycle) engines, microturbines, and even hydrogen-powered fuel cells, powering hybrid-electric drivelines (typically with electric or electric-plus-mechanical-drive traction) buffered by high-power batteries, ultracapacitors, or superflywheels. A host of alternative materials, including advanced polymer composites, could make these vehicles' chassis and body dramatically lighter, triggering design synergies that decrease the hybrid drivelines' mass, complexity, and cost.

² Eight major compatibility issues are described in (3). For instance, polymers and composites used in steel autobodies (*e.g.*, body panels) often have to withstand a high-temperature (~175°C) E-coat and paint process; resins thus have to be formulated at added cost and complexity for this one-time extreme environment. Also, composite parts which can not be “whacked into shape” often require special, costly assembly techniques to attach them to metal structures with greater dimensional variabilities.

2.2 Examples Recent activities by the world’s largest automakers hint at an explosion of technological and vehicle-platform diversity. In late 1996, GM brought its EV1 battery-electric vehicle to the U.S. market—the first volume-produced electric vehicle since the turn of the century. Though constrained in cost and driving range by its heavy lead-acid-battery-powered drivesystem, the EV1 has an aluminum/composite autobody with a little over half the mass of an equivalent steel unibody and a drag coefficient ~40% less than a typical production car. A year later, Toyota brought the first mass-produced hybrid-electric vehicle, the 66-city-mpg “Prius,” to the Japanese market. Pricing it competitively with conventional sedans, Toyota is reportedly willing to sell up to 2,000 Priuses a month (4) at up to 60% below their production cost to establish global leadership in advanced-drivetrain vehicles.³ Not to be outdone by Toyota’s effort (which netted two coveted Japanese car-of-the-year awards), several other non-U.S. automakers joined the advanced-drivesystem bandwagon, including Honda with a near-production 70-mpg hybrid, hybrid concept cars from Nissan, Subaru, Mazda, Volvo, and Audi, and 80-mpg nonhybrid but lightened Audi and VW platforms planned for volume production in 1998–99.⁴

In January 1998, GM unveiled three 60–80-mpg four-passenger hybrid-electric concept-car variants of its EV1 platform, including a fuel-cell model, and predicted commercial production by 2001, or by 2004 “if not sooner” for the fuel-cell version (6). Ford showed its aerodynamic, aluminum-bodied 60+-mpg P2000 midsize sedan, expected to be in dealerships by 2000, soon followed by hybrid-drive and fuel-cell⁵ variants (8). Chrysler unveiled the Intrepid ESX2 prototype, an aluminum/composite, direct-injection-diesel-powered hybrid car projected to cost \$45,000 less per unit than the firm’s previous hybrid (9).

2.3 The Hypercar Concept The rapidity of automakers’ adoption of advanced technologies gratified but did not surprise Rocky Mountain Institute (RMI), which since 1991 had suggested that the automotive industry is ripe for fundamental innovation. In mid-1991, the Big Three automakers claimed that fuel economy couldn’t improve more than 10% without making the car unmarketable (10). RMI, however, argued that carefully integrating advanced technologies could make cars better in all respects, probably including cost. The hypercar concept appears to have influenced automakers’ current flirtation with advanced technologies: RMI since 1991 (and its Hypercar Center since 1994) has advised several dozen current and potential automakers, heightened customer expectations, and fomented vibrant market competition.⁶

The hypercar concept integrates an ultralight, ultra-low-drag vehicle platform (Figure 1a) with a hybrid-electric drivesystem (Figure 1b).⁷ This combination, applicable to both cars and light

³ In fact, Toyota seems to view hybrids as much more than niche vehicles: its CEO predicted in late 1997 that hybrid-electrics will get a one-third world market share by 2005 (5).

⁴ Paradoxically, these hybrid-drive innovations have preceded, whereas in technical logic they should have followed, fundamental improvements in platform physics, starting with far lower mass.

⁵ In April 1997, Daimler-Benz invested over US\$325 million in Ballard Power Systems, Inc. (7), the leader in proton-exchange membrane (PEM) fuel cells, with a pledge to produce 100,000 fuel-cell vehicles per year by 2005. This prompted Toyota in October 1997 to promise fuel-cell vehicle volume production even earlier (8). In December 1997, Ford invested US\$420 million in Ballard (7).

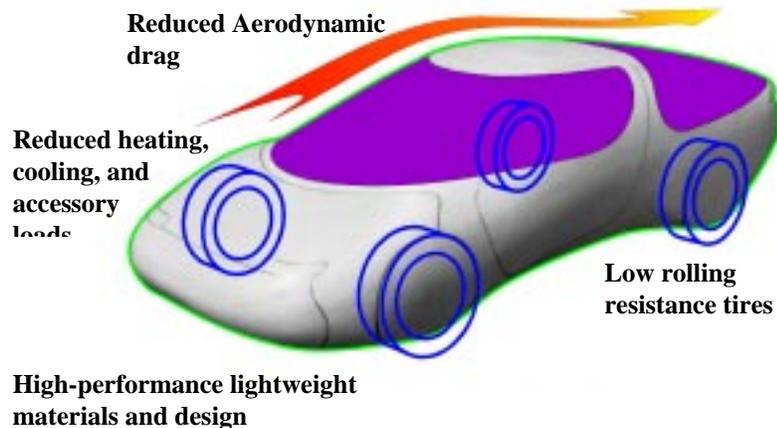
⁶ Like a freeware developer (*e.g.*, the Unix family, or Netscape’s strategy to give away its web browser and code), RMI from the start gave away its hypercar intellectual property instead of patenting it, in order to maximize competition in exploiting it. Network-economic models, through a process of “increasing returns,” postulate that the value of an idea or artifact increases with the number of users (11). Thus by giving away its hypercar concept, RMI has increased its value through expanding the network of hypercar advocates and potential adopters.

⁷ For a fuller treatment of hypercars, see (12,13). Ultralight implies a mass reduction 2–3-fold from a baseline vehicle (*e.g.*, ~500–700 kg for a 5-passenger Taurus-class car with baseline mass ~1420 kg). Low-drag denotes both reducing aerodynamic drag—a function of the coefficient of drag (C_D) and the frontal area—by 1.75–2.3-fold (*e.g.*, $C_D = 0.2$ – 0.15 from a Taurus baseline of 0.33, together with ~0.13 m² lower frontal area) and rolling resistance—a

trucks, facilitates dramatic improvements in fuel efficiency and emissions while maintaining or exceeding conventional vehicles' safety, amenity, performance, and probably affordability (12). Computer models indicate that these ultralight, low-drag, hybrid-drive hypercars should improve fuel efficiency 3–4-fold with near-production-ready technologies and 4–5-fold with a PEM fuel-cell powerplant and further refinements while sustaining or improving all other qualities. Ultimately, fuel efficiencies up to ~200 mpg for a 4-seat car should become feasible. Emissions (*i.e.*, CO, HC, and NO_x) should be 1/10th those of ultra-low-emission vehicle (ULEV) standards, in the range of proposed equivalent-zero-emission vehicle (EZEV) standards, even burning ordinary gasoline with no catalytic converter (12).

Due to their fuel efficiency, low emissions, and lifecycle benefits (13) hypercars should certainly be “green.” But their prospect for widespread adoption may depend less on environmental regulation (*e.g.*, climate-protecting, CAFE, and EZEV regulations) than on two powerful market forces: customers want superior products, and manufacturers desire competitive advantage. In short, hypercars have to be both useful and fun to drive, and fast, low-risk, and inexpensive to build.

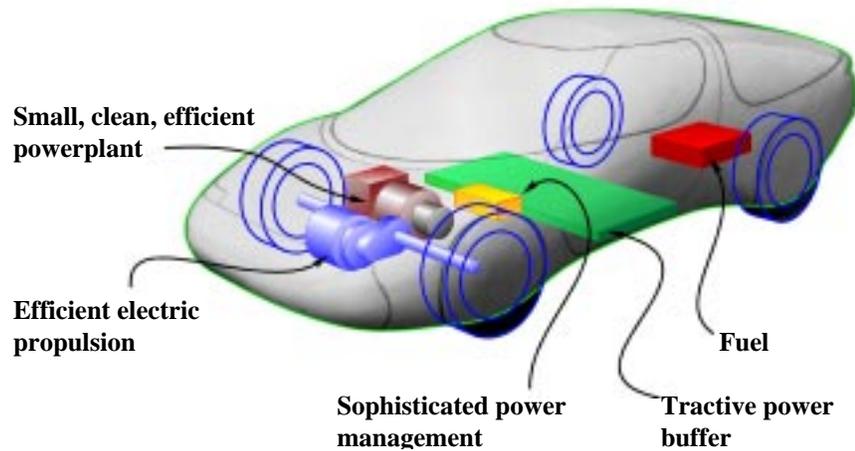
Hypercars promise both advantages by virtue of using fundamentally different materials and design and manufacturing methods, particularly in the autobody and chassis (13). For instance, ultralight materials make cars accelerate and handle better for a given drivetrain; offer important safety features that offset their mass disadvantage against heavy steel cars; can improve durability and recyclability; and offer radically more compact, affordable, flexible, and agile manufacturing processes.



High-performance lightweight materials and design

a. Start with an ultralight, low-drag platform...

function of vehicle mass and the coefficient of rolling resistance (r_0)—2.5–5-fold (*e.g.*, “ultralight” mass reduction and $r_0 = 0.0065$ – 0.0045 compared to ~ 0.01). In addition, hypercars accessory load (HVAC, lighting, etc.) should be reduced by at least 2–4-fold (*e.g.*, 500–250 W from a Taurus baseline of ~ 1000 W).



b....then add clean, efficient hybrid-electric propulsion

Figure 1. Hypercar Design Strategy

2.4 Cost Decompounding Reducing the mass of a vehicle, particularly the autobody⁸, through lightweight materials helps other systems. Less tractive load provides the same or better performance with a smaller hybrid drivesystem. That makes the car even lighter, reducing suspension and chassis loads. The lighter suspension, chassis, and drivesystem can reduce loads on the autobody, reducing its mass further. This cycle continues through recursive mass decompounding (Figure 2) until stalled by diminishing returns.

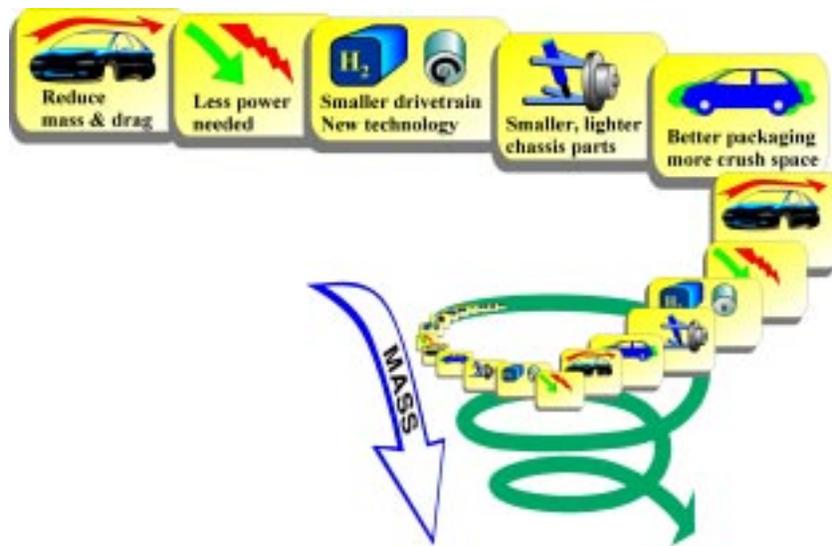


Figure 2. Mass Decompounding

For ultralight hybrids, mass decompounding can also lead to a hidden benefit that unlocks the aforementioned economic paradox: *cost* decompounding (Figure 3). An ultralight platform's

⁸ The structure of a car, including all body structures, frames, and panels but no bumpers, seats, wheels, trim, and drivesystem, steering, or suspension elements. The autobody, which is typically a quarter of the curb mass of a vehicle, largely determines its safety, structural integrity, aerodynamics, look, feel, handling, and comfort.

smaller drivesystem produces fewer kilowatts of average and peak power, which can decrease costs for components like fuel cells more or less linearly.⁹ Several automotive mechanical and electrical components can also be eliminated, further reducing the cost (*e.g.*, GM’s 1991 carbon-fiber composite Ultralite needed no power steering). Finally, recursive mass decomposing optimizes the autobody to its lowest possible mass, minimizing materials costs. In principle, the extra cost of advanced materials and drivesystem technologies can thus be roughly offset by savings from their careful integration, elegantly frugal use of materials, and, ultimately, economies in fabrication, painting, and assembly (15). The choice of materials is thus no afterthought but a vital precondition of commercial success—costlier ultralight materials can be the key to a competitively priced *car*.

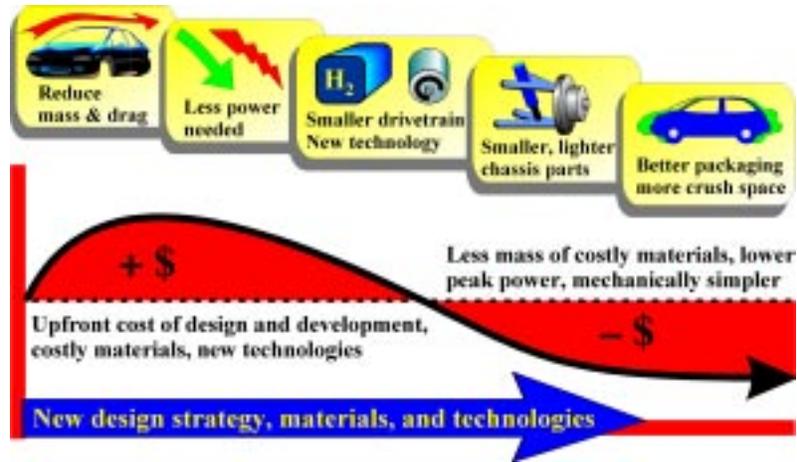


Figure 3. Cost Decomposing

Several candidate materials, including aluminum, polymer composites, and possibly high-strength steel could meet hypercars’ low-end mass-reduction requirements (13). But in theory and practice, advanced polymer composites show the greatest potential for the mass reduction as well as other benefits (*e.g.*, safety, manufacturing agility, low manufacturing financial risk) necessary for hypercars’ and other advanced platforms’ market success (13). For example:

- While advanced steel offers at best 25–35% autobody mass reduction and aluminum 40–55%, GM’s and Ford’s composites experts have estimated a 50–67% reduction using automotive advanced composites (16,17) whose specific strength and stiffness—assuming low-cost (*e.g.*, 50k-tow carbon fiber), well-designed materials—are 2–6 times higher than the metals (13). This maximizes mass and cost decomposing.
- The Advanced Composites Consortium built a Ford Escort glass-composite front end using a manufacturable design 25% lighter than the original steel assembly but constrained to the same packaging. With *no* airbags, it passed all government crash tests, yielding superior performance in all but one category to the original all-steel production vehicle (18). Head Injury Criterion scores were 31% below a 1995 steel Taurus design’s with airbags (or 35% below an aluminum version’s) (19). Imagine what it could have done with clean-sheet packaging

⁹ For example, RMI computer models indicate that the Ford P2000’s (\$3.4) 40% lower curb mass than a Taurus—not an “ultralight” mass reduction, but impressive—reduces the drivesystem power requirements 37 kW (from the Taurus’ 105kW) for equivalent gradability and acceleration. Both cars were modeled with the same aerodynamic drag, tires, and hybrid drivesystem components to isolate mass-reduction benefits. In this example, assuming a volume-produced PEM fuel-cell stack cost of \$50/kW (14) and a load-leveling device (LLD, *e.g.*, high-power battery) cost of \$30/kW, and power savings of 13kW for the fuel-cell stack and 24kW for the LLD, lightweighting would cut ~\$1,300 off the drivesystem’s cost, not counting potential savings on electric traction motors, controllers, etc.

and high-performance materials: perhaps like McLaren's carbon-fiber F1 sports car, which drove away from a 30-mph fixed-barrier crash test. The only thing seriously damaged was a CD-changer mounted in the front end; the total deflection of the steering column was just one-eighth of an inch (20).

- The composite body panels of Renault's L'Éspace van had a 5–7-fold lower tooling cost than an equivalent steel design (21).

3. THE LIGHTWEIGHT-MATERIALS COMPETITION

What, then, is the advanced-composites industry doing to capture the new opportunities of advanced-vehicle platforms? Very little when compared to steel and aluminum. The intense competition for the advanced-vehicle market, with many attributes of classic tribal behavior¹⁰, has only two serious players, both metals.

3.1 Steel Steel is the dominant automotive material, accounting for 55% the mass of an average 1997 family vehicle (2), because it's inexpensive per kg, strong and stiff, and relatively predictable and manufacturable. Steel enjoys the benefits of incumbency, such as familiarity and extensive manufacturing infrastructure. However, steel is heavy, capital-intensive, and slow to tool—tooling for an all-new body and chassis can exceed \$1 billion—making it less desirable for advanced-vehicle platforms and risk-averse, lower-volume, or agile manufacturers. The steel industry, whose sales are ~17% automotive (2), could have taken a reactionary approach and discouraged the development of advanced vehicles; instead, it embraced them, undertaking a bold collaborative effort to position steel as a viable lightweight material.

In 1995, 32 (now 35) steel companies hired Porsche Engineering to execute the \$22-million UltraLight Steel Autobody (ULSAB) project (23). ULSAB's goal was to design, tool, and assemble a fully-validated high-strength steel 5-passenger autobody, creating a model that is about 25% lighter, 569% torsionally stiffer, and reportedly safer and \$150 cheaper than conventional steel unibodies (23). The project realized early that these objectives were unattainable through incremental refinements; breakthroughs would only occur with a whole-systems focus. Thus to overcome steel's intrinsic high density while meeting ULSAB's objectives, Porsche took a "clean-sheet" approach and employed holistic design techniques. Relatively costly ferrous materials (90% of the ULSAB design employs high- or ultra-high-strength steel) combine with fledgling processing technologies (*e.g.*, tailored blanks, hydroforming, and sandwich construction) into a whole that the steel industry argues to be practical, despite some potential difficulties such as acoustics and packaging, specific to the particular design adopted. Thus the steel industry in many ways is taking the "whole-systems" approach requisite for composites' success, dramatically rethinking how steel structures are designed and manufactured to overcome their implementation barriers.

3.2 Aluminum Aluminum currently ranks third behind steel and polymers in automotive use (2). But the Aluminum Association's explicit vision is "to drive a significant increase in the use of aluminum in automobiles and light trucks worldwide, including the adoption of aluminum structures." (24) To realize that vision, the aluminum industry has partnered with automakers on two fronts: incorporating aluminum parts in existing steel-dominated platforms, and pursuing all- or mostly-aluminum platforms.

¹⁰ According to *The Wall Street Journal* (22), "once-cordial steel and aluminum executives barely talk when they run into each other at the airport. Steel-industry leaders plant pro-steel questions at auto conferences to sway the debate...badmouthing—in public and in private—is becoming commonplace." A steel-industry executive best characterized the competitive behavior as "a real donnybrook."

On the first front, aluminum has for decades aggressively pursued chassis, body closure, and under-the-hood applications. Relentless pursuit of material substitution opportunities is paying off. Almost every automaker has developed aluminum-block engines; each U.S. automaker mass-produces aluminum hoods (*e.g.*, Chrysler Concorde, Ford F-Series Pickups, GM G-cars); and many are increasing aluminum in suspension components and driveshafts (25). These add up to nearly a doubled use of automotive aluminum since 1978 (2). Complementing this incremental substitution is a broader, more ambitious focus—pursuing high-volume aluminum-intensive vehicles—backed by serious resources. Partnering with the aluminum industry, automakers have made numerous aluminum-structured concept vehicles (*e.g.*, Chrysler Neon Lite and Intrepid ESX, Ford Taurus AIV, Synergy 2010, and P2000 [\$3.4]) and low-volume production cars (*e.g.*, GM EV1, Plymouth Prowler, Acura NSX) to work out cost and safety issues, create new forming, bonding, coating, and other key technologies to solve automakers’ basic manufacturing problems, and get automakers familiar and comfortable with the material (25). Most prominent is the long-term collaboration between Alcoa and Audi that resulted in the mid-volume, aluminum-spaceframe and -closures A8, which achieved 40% lower mass and one-third fewer parts than other luxury vehicles (25). Aluminum firms seem to sense that the opportunities in high-volume next-generation platforms are still greater and will demand even more aggressive pursuit to capture: in the fall of 1996, Alcoa’s chairman pledged \$1 billion to any automaker willing to partner to produce a high-volume aluminum vehicle (25).

3.3 Advanced Composites Because advanced composites are heterogeneous materials, with dozens of resin systems, fibers, and processing methods, there are few if any fully integrated companies analogous to Alcoa, or broad trade groups like AISI. Polymer firms’ disparate interests, and their different markets such as durables *vs.* packaging, complicate or prevent a coherent industrywide strategy. Nonetheless, polymer firms, fiber producers, and fabricators all have a vital interest in the success of automotive advanced composites¹¹, whose benefits flow from whole-system applications (3), requiring industrywide integration and collaboration (§4).

So far, individual polymer firms and specialty trade groups have pursued and refined only incremental applications on existing platforms. A few, like GE Plastics’ collaboration with Delphi, are developing innovative substitutions—the collaboration produced an all-thermoplastic door frame module that reduced the mass, cost, assembly time, and parts count (from 61 to 1) compared to the previous steel structure (26). But most polymer firms are competing with one another for *existing* uses, such as interior and trim components, rather than with steel and aluminum for major new applications. Specific sectors, like SMC, are also having success targeting incremental applications—new body applications like hoods for the 1998 Lincoln Continental and Navigator and parts like Ford’s fuel-tank heat shields have increased overall SMC volume 50% since 1993 (27). However, efforts to target broad structural uses have been largely absent; with one possible exception¹², no organization has announced developing a polymer- and com-

¹¹ It is unclear whether commercializable autobodies and chassis can be made exclusively from low-performance polymer composites. Hence future successes for these firms may depend on increasing the performance of their products through integrating them into higher-performance advanced composites. See next footnote.

¹² Namely, Chrysler’s modest 1997 subcompact “China concept vehicle” (now called “Composite Concept Vehicle” [CCV]). Aiming to “fill the niche between motorcycles and current entry-level vehicles (28),” the CCV is roomier than a Neon but half the mass, gets 50 mpg with conventional propulsion, costs 15% less to build, requires fivefold less tooling cost and sevenfold less factory space, and meets all of Chrysler’s profitability criteria (28). Its glass-reinforced PET matrix has relatively low performance, but its injection molding manufacturing process—which uses 160-ton molds the size of railroad boxcars and high-pressure, 9,000-ton injection equipment—has relatively high cost, at least compared to other composite manufacturing methods (13). No doubt the CCV’s 1998 Spyder sports-car manifestation could be made crashworthy (the CCV is not) with a sufficient fiber fraction or stronger fibers, but it is not at all clear that these concept cars’ technical and commercial merits will match their boldness. RMI’s analyses suggest that higher-performance materials, and manufacturing methods that similarly consolidate parts and allow lay-in-the-mold color but permit much faster and cheaper tooling and equipment, could bring to a broad range of

posite-intensive vehicle platform. DuPont's XTC-S thermoplastic-spaceframe program, arguably the closest attempt to date (29), was canceled in 1997. An "ultralight composite autobody" or an aggressive push akin to Alcoa's are conspicuously absent. Though one such effort is being privately organized, most polymer and composites firms seem to lack the strategic vision to identify its success with their own and the internal focus to take advantage of its opportunities.

3.4 Consequences Advanced composites firms can choose to remain on their "business as usual" course, tacitly ignoring advanced-vehicle platforms and big new markets, or can match aluminum and steel and pursue them aggressively. The former strategy may seem the most comfortable and least distracting, has increased volumes and made automakers more familiar with the materials in ever more applications, and has had just enough successes to be seductive. But success may prove temporary¹³, and is wearing thin: polymers and composites' automotive growth flattened out in the 1990s (2) and has been outpaced twofold by aluminum and threefold by high-strength steel since the mid-1970s. Ultimately, business-as-usual could be the riskiest strategy—not only for potentially large new composites applications but also for *existing* markets. A case in point is the P2000, an advanced-vehicle platform and drivesystem testbed recently unveiled by Ford (30). Ford's explicit lightweighting goals for the exploratory project—a senior manager claimed they "analyzed every part to find mass reduction, while still considering a part's impact on vehicle strength, stiffness, and wear" (30)—would seem to make this a perfect partnering opportunity for the advanced composites industry. However, out of the 100 suppliers contributing to the project, no polymer or composites firms played a significant role, while three aluminum suppliers contributed significantly. It should be no surprise that aluminum is the dominant material in the P2000, accounting for 37% of its mass (30). The P2000 hardly employs any advanced composites, using more titanium (5 kg) than carbon fiber (4 kg). What should most alarm the composites industry is that the P2000 uses a *lower mass* of polymers and composites than a 1997 Taurus (30).

Steel-focused advanced-vehicle efforts, including ULSAB, are also bypassing composites. Lotus Engineering, a pioneer of automotive composites, investigated the potential for producing a volume-production-feasible ~67-mpg 4-seater by 2005 (31)—and chose steel as the major material in the vehicle body structure. Polymers were relegated to bumpers and fenders. Other composites-relevant applications were given to light metals: the chassis, wheels, and body closures went to aluminum, while the seat frames and steering column went to magnesium.

Thus the P2000, as well as efforts like Lotus's, provides a sobering lesson for firms that have an interest in advanced composites: by not pursuing extensive, structural, whole-system, high-performance applications of their products, they put *all* automotive applications at risk. As steel and aluminum court whole-system applications for next-generation vehicles, composites and polymer applications could be squeezed in a P2000-like metal vice (Figure 4), competing for shares of a shrinking vehicle-mass pie, if the composites industry persists in business-as-usual complacency.

platforms (*e.g.*, family cars, sport utilities) important technical, marketing, and strategic advantages unavailable to the CCV/Spyder approach. Embedding the body manufacturing method in a more comprehensive whole-vehicle concept like the hypercar reinforces this comparison.

¹³ There is always the danger that composite parts—like the SMC body panels on GM's APV minivans—can default back to steel. Other materials, like aluminum, are pursuing the same substitution opportunities as composites (in addition to their whole-vehicle efforts) with increasing vigor and success (§3.2). And as current car designs are optimized for metals, the unfavorable design space sets limits on composites' opportunities for substitution (3).

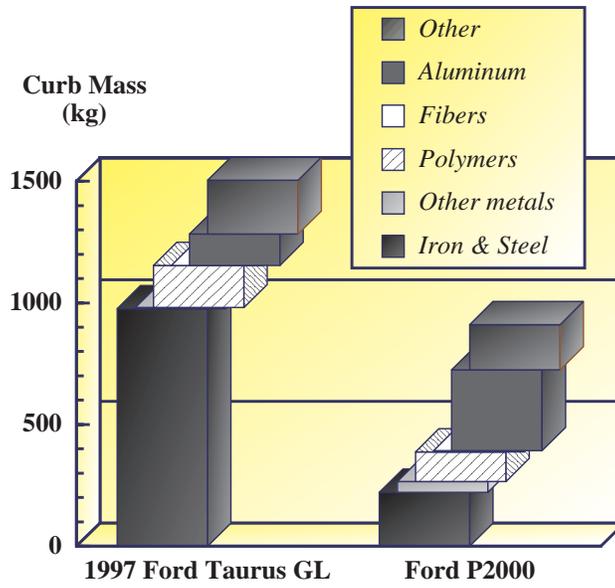


Figure 4. A Metal Vice: The Materials Breakdown of the P2000

4. TEN STRATEGIC ACTIONS

Advanced composites' success in automotive markets requires that the composites industry adopt a quite different strategic posture that mimics not metals (trying to make its materials act like theirs) but the metals *industries*. Composites firms would do well to heed seven lessons:

4.1 Build a Car Create an ultralight, newsworthy, high-quality, polymer-based, advanced-composite-dominated car that is at least as powerful a model of structural applications as ULSAB and P2000. Whether it aims at a public premarket demonstration (ULSAB), precommercial exploration (P2000), or low-volume production (Audi A8), the project must demonstrate superior mass reduction, safety, commercial agility, and manufacturing feasibility (low-cost and capable of meeting all automaker requirements). An important, first-step demonstration could cost on the order of \$10–100 million—about two to three orders of magnitude smaller than the annual revenues of firms with an interest in advanced composites. There is clearly a demand for this type of project: 83% of 235 Big-Three engineers surveyed agree that “the plastics industry should sponsor a pre-production vehicle to show the viability of plastics and composites in automotive applications (32).”

4.2 Take a Whole-Systems Approach Like ULSAB, first optimize the whole-vehicle as a system, then tackle the barriers to implementing that system vision; otherwise, focusing first on parts in isolation will pessimize the system. Focusing on the inherent advantages and challenges of advanced composites, without being distracted by their incompatibilities with metal-dominated structures, could steer attention away from qualities necessary in metal manufacturing and toward qualities that match composites' unique capabilities: not cycle time but cheap tooling and equipment, agility, volume flexibility, and parts quality; not cheaper kg of materials but cheaper *cars* through mass optimization and simpler manufacturing; not paintshop compatibility but ability to eliminate the paintshop through lay-in-the-mold color (3,13).

4.3 Integrate Like ULSAB, focus on *integrating* the best existing technologies, not inventing wholly new ones. ULSAB showed how costly materials and unfamiliar manufacturing methods could be cost-effectively combined. Rapid molding techniques and low-cost, high-performance materials, artfully combining the best proven elements, offer similar potential with advanced polymer composites (3,13,14).

4.4 Partner with Automakers Like the aluminum industry's partnering efforts on manufacturing, or ULSAB's educational focus on integrated design, collaborate with major automakers to change their perceptions and practice. The barriers to competitive advanced-composite autobodies are less technical (3,13) or economic (14) than cultural: “metal mindset,” “black steel,” incrementalism¹⁴, treating sunk cost as unamortized assets, focusing on parts rather than cars, etc. (3,13). RMI's proprietary scenario-planning analysis of the transition to advanced composites suggests that automakers' corporate strategy and composites mentality are critical to success—far more so than manufacturing breakthroughs or even regulatory pull, helpful though

¹⁴ Psychologically imprisoned by existing assets, automakers err on the conservative side—especially compared to the electronics and software industries—when changing their products. The industry's capital intensity creates risk aversion and makes most products minor refinements of existing technologies. Automakers also tend to adopt new technologies slowly, fitting them within existing product lines and often limiting their potential. On the contrary, new technologies thrive in wholly new platforms. For example, if you were a microprocessor developer in the 1970s, would you rather put your product into an established electric typewriter that incorporated it only as an “add-on” feature, or into a fledgling personal computer that was wholly designed around your product? As noted in (3), a similar logic applies to putting advanced composites into a steel autobody versus, say, an all-advanced-composite monocoque autobody.

both could be. Collaboration also leverages the composites industry's limited resources with automakers' enormously larger ones (\$17 billion a year in U.S. R&D, apparently excluding suppliers (2)), almost none of which now go to advanced composites. Having possibly only a few dozen people knowledgeable in this area, and, until a couple of years ago, none with significant carbon-fiber manufacturing experience, automakers have insufficient "critical mass" of composites knowledge, hence little understanding of the benefits of learning more. Meshing automakers' R&D budgets with composites firms' knowledge seems a natural fit, and can be motivated by the other strategies suggested here.

4.5 Collaborate Organize and collaborate as the steel industry has in ULSAB. Superior technology cannot win without organization and leadership. Set aside parochial differences; play to strengths; compensate for weaknesses; recognize that in this highly diverse industry, no single firm or segment has everything that is needed. Government bailouts cannot be expected: the Partnership for a New Generation of Vehicles (PNGV) has practically eliminated polymer composites, its early favorite, from its 2004 target vehicles, partly because of the composites industry's weak response. The concept of partnerships is not foreign to the composites industry (*e.g.*, Bayer/GE Plastics polycarbonate glazings, DSM/BASF structural resins, UTC/Dow RTM), but broad partnerships around whole-systems strategic goals are. The obvious vehicle for such consortia is trade groups such as the American Plastics Council, Society of the Plastics Industry, and APME in Europe, or an alliance of such groups: they are meant to look after the industry's long-term interests, transcending short-term constraints and interfirm rivalries. They have plenty of talent, but need to rise to the occasion: one such industry group's indecision recently delayed by at least a year an initiative to address many of the needs suggested here.

4.6 Be Ambitious Like the aluminum industry, make no little plans. Even if composites firms can't offer Alcoa's billion-dollar carrot, more need ambitions and bold goals as impressive as, say, Zoltek's \$5-a-pound carbon by 2000 (33). Those who don't feel ready to lead should at least be willing to follow the industry's dedicated visionaries.

4.7 Act Now As ULSAB showed, act now or forever hold your lost opportunities. ULSAB was partly a response to the PNGV threat to cut steel out of next-generation autobodies because it weighed too much. The steel industry mobilized, to good effect. Now the composites industry could be on the way to losing the lightweighting race to aluminum—which would then create yet another huge set of unamortized assets, delaying consideration of the polymer alternative for decades more.

Yet while emulating these lessons of the metals industries' successes, the advanced-composites industry also needs to blaze a new trail in three respects:

4.8 Foster Up-and-Coming Automakers Emerging automakers, domestic and foreign, may provide a uniquely potent pathway for commercialization. A variety of high-technology firms (electronics, software, car-parts, aerospace), singly or combined, have most of the skills needed to make ultralight advanced-platform vehicles. Car-parts makers, for example, have essentially all of the automakers' capabilities but few of their inhibitions. Allying with an agile Tier-1 design-engineering firm would equip, say, a giant electronics firm with the few skills it lacked, like homologation, crashworthiness, and vehicle dynamics. The capital requirements for many of the advanced automotive technologies are relatively low, just like those of advanced composites. Many of the new automotive players' skills, assets, and momenta strongly favor these alternatives, especially in designs emphasizing electric traction, fuel cells, and sophisticated electronics/software architectures. Thus a plausible scenario could see wholly new real or "virtual" automakers, unencumbered by old automotive assets and habits, entering the market early next

century, under familiar or new badges and using a variety of novel distribution channels including Internet sales.¹⁵

4.9 Seek Synergies with Advanced Drivesystem and Component Developers Ultralight advanced-composite platforms fit ideally with hybrid-electric propulsion, each reinforcing the other's advantages through mass and cost decompounding (footnote 9), packaging, heat-sinking, and other design synergies. Moreover, they enjoy specific technical links. Ultralight traction motors may require composite shells and shafts. Ultralight, spectrally selective polymer glazings can greatly improve the energy efficiency of passenger comfort control, provided through polymer-based waste-heat-driven HVAC systems. Cost-effective low-temperature fuel cells are highly likely to be glued together from sophisticated roll-to-roll polymer components; ultracapacitors' success depends on carbon chemistry; superflywheels depend on high-performance carbon fiber. Such energy-related applications' success in automotive markets could be in turn the key to opening up other very large composites markets in buildings and distributed electric power systems.

4.10 Rewrite the Rules of Competition Focus on showing how composites can create wholly new and winning designs: don't just compete on traditionally narrow criteria, but rewrite the rules of competition (34). Composites permit unrivaled feature and function integration. For example, the Lotus Elise's 7.5-kg front-end composite structure simultaneously provides structural integrity (mountings for optional headlamps, radiator, and "clamshell" one-piece front body), sealed ductwork for the radiator and the HVAC intake, and a crush structure so effective that it absorbs the entire energy of a 30-mph fixed-barrier crash, leaving the aluminum chassis undamaged (35). Such multiple benefits from single expenditures exemplify the automotive industry's next design frontier.

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