Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure

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Abstract

Reducing vehicle weight is critical to improving fuel economy and addressing range, performance, size, and cost challenges associated with fuel-cell and hybrid propulsion systems. This paper describes the design, fabrication, and assembly approach used for the carbon-fiber composite body structure in Hypercar, Inc.'s *Revolution* concept vehicle. The *Revolution*'s 187-kg body structure is 57% lighter than a conventional steel body structure of the same size, while providing superior crash protection, improved stiffness, and favorable thermal and acoustic properties. The design balances several competing requirements, including surface finish, reparability, crash performance, weight, packaging constraints, and cost. A large part of the *Revolution*'s body structure is an advanced-composite passenger safety cell. Its design permits a novel high-volume manufacturing process under development by Hypercar. Applied together, the design and production method result in a lightweight, affordable advanced-composite body structure consistent with competitive vehicle cost at production volumes of 50,000 vehicles per year or greater. This paper describes the design and production method of the composite body, explains how the body is integrated with the rest of the vehicle, and analyzes the benefit of lightweighting on overall fuel-cell vehicle cost.

1. Introduction

The strategic, business, and social need for fuel-efficient and clean vehicles is evident worldwide. In developing countries where there is accelerating growth and sales of automobiles, policymakers have an opportunity to direct this growth toward clean and efficient vehicles. In industrialized countries, consumers and policymakers are beginning to demand or require high environmental performance without compromising safety, amenity, driving performance, or cost. Globally, the transportation sector's seemingly insatiable thirst for petroleum compromises national security by creating strong dependencies on unstable regions. The United States, for instance, imports 53% of its petroleum and Europe imports 76%, making them heavily dependent on petroleum exported from the politically volatile Middle East. The same dynamic is emerging in developing countries. China, for instance, currently imports 30% of its petroleum, but with vehicle sales growing 10% per year, by 2010 this figure is expected to climb to 50%. Thus, China is rapidly heading the same direction as North America and Europe by becoming heavily dependent on unstable regions of the world for a key input to its economy [1].

Recognizing this need, the global auto industry has made advances in developing cleaner engines, improving driveline efficiency, and lightweighting. The industry increasingly uses high-strength steel, aluminum, magnesium, plastics, and composites, all to varying degrees, to achieve modest weight savings. But much more technical progress is required in order to improve fuel economy significantly and reduce emissions fleet-wide. Currently, automakers are focusing development on hybrid-electric and fuel-cell drivesystems. Additional changes will be required to the entire vehicle platform to make these advanced drivesystems cost-competitive with conventional drivesystems in the near- and mid-term.

A key enabling technology is advanced composites. Advanced composites are defined here as engineering polymers reinforced with a high-performance, man-made fiber such as carbon. Widespread industry adoption of these materials has been limited by three fundamental limitations: (1) lack of experience and knowledge in how to design with advanced composites, (2) high cost of the raw materials, and (3) no affordable process for producing advanced-composite parts in high volume to automotive production standards. Since its inception, Hypercar has been pioneering the design and high-volume manufacturing process development of advanced composites for automobile structures. To date, the results of this work indicate that when used in concert with other lightweight materials, volume production of advanced-composite body structures can be economically advantageous while outperforming other materials in weight savings, strength, stiffness, and occupant crash protection.

1.1 Importance of lightweighting

> "Fat men cannot run as fast as thin men, but we build most of our vehicles as though dead-weight fat increased speed…. I cannot imagine where the delusion that weight means strength came from…." —Henry Ford

For HEVs and fuel-cell vehicles to be accepted by the mass market (without drastic changes in fuel price or regulations), they must achieve performance levels similar to conventional vehicles for a comparable purchase price. Though they are excellent vehicles, current HEV offerings all carry a $7,000–9,000 price premium, added bulk and weight, and various performance and feature compromises, thus making them niche vehicles. Some of the price premium is due to low volume production, but the added complexity and componentry associated with hybrid drivesystems will continue to make them more costly for the foreseeable future, even in high volume. Fuel-cell vehicles face an even greater cost hurdle. Today, fuel-cell systems cost several thousands per kilowatt to produce. Even at the U.S. Department of Energy 2004 cost target for automotive fuel cells of $100/kW (dropping to $35/kW for 2008) [2], fuel cells will be hard pressed to compete with conventional cars on a cost-performance or system power density basis without first working to reduce the peak power required of the drivesystem.

Reducing mass is the highest-leverage means of reducing peak power available to vehicle designers. During steady-state driving, which is most of the time, vehicles require only a small fraction of their maximum power output to sustain their speed. Peak power is needed during hard acceleration and in other high-load driving conditions (such as for towing or during passing maneuvers at gross vehicle mass up a steep incline). The power required to achieve a given level of acceleration is determined to the first order (*i.e.*, not taking into account such other factors as aerodynamic drag, rolling resistance, and motor efficiency) by the vehicle's rate of change of kinetic energy:

$$P_{acc} = \frac{m}{2} \bullet \frac{\left(v_1^2 - v_0^2\right)}{t} \qquad (1)$$

where m = mass of the vehicle and its occupants, v_1 is the final velocity, v_0 is the starting velocity, and t is the time elapsed to reach v_1 from v_0. It is clear from this equation that halving the mass of the vehicle will also halve the peak power required. In climbing a grade, mass is also a primary determinant of power because potential energy also scales with mass:

$$P_{hill} = m \bullet g \bullet v \bullet \sin(\theta) \qquad (2)$$

where g is the acceleration of gravity and θ is the angle of the incline. Moreover, rolling resistance is also proportional to mass.

Thus, in HEVs and fuel-cell concept cars where cost-per-peak-kilowatt is significantly higher than for conventional vehicles, reducing mass is among the highest leverage factors for improving affordability. Considered from another perspective, without lightweighting, environmental vehicles will inherently be either more costly or lower performing, or worst of all, both! Through mass-efficient design and careful application of lightweight materials, vehicles of any size can be made more than 50% lighter, compensating in whole or in part for the higher cost of the HEV or fuel-cell drivesystem.

1.2 Carbon-fiber composites

Many lightweight materials can be used to reduce vehicle weight. For the vehicle's primary structure—its Body-in-White (BIW)—advanced composite materials using primarily carbon fiber offer the greatest potential for mass reduction while also maintaining crashworthiness and unlocking new strategic benefits for the manufacturer such as component integration, modularity, lower capital and assembly costs, and potential to eliminate conventional painting and its corresponding environmental and capital cost.

While plastic and composite materials are used in automobiles today, they constitute only approximately 7.5% of total vehicle mass [3] and the applications are generally not for the primary vehicle structure. Composite materials forms are typically chosen for ease of processing and moderate lightweighting. For instance, glass-reinforced sheet molding compound (SMC) is the most popular composite material system, used in many composite applications in vehicles. SMC's popularity arises from its ability to be stamped into shape, its much lower capital costs relative to steel, and its lower density. Together, these attributes result in overall cost and weight savings. However, due to the random orientation of the fibers, low fiber volume fraction, and low-performance fibers used, the structural performance and degree of lightweighting offered by SMC and many of its current rival material systems are only moderate, thus lowering their potential to replace steel in vehicle structures.

Advanced composites, such as carbon-reinforced polymers, represent the most logical replacement for steel in vehicle structures where significant weight reduction (greater than 60% compared with steel) is desired. The two most widely cited obstacles to the use of carbon composites in automotive structures are the high cost of the raw materials (~\$11–22/kg vs. ~\$1.3/kg for steel) and the high labor required to produce advanced composite parts.

Cost is a key challenge in all of automotive design, especially for composites. Yet historically, despite their higher materials costs relative to steel (Figure 1), plastics and composites have been justified on a cost basis for non- or semi-structural components due to fabrication or assembly cost savings achieved typically via parts consolidation, less expensive tooling, and direct and indirect cost savings resulting from lighter weight. A similar case can be made for using advanced composites in the vehicle's primary structure. In a car body, the main design criteria are stiffness-related, as the body typically has adequate strength if it meets its stiffness and stability targets. Thus, the best alternatives to steel from a cost per unit specific stiffness perspective are carbon-fiber composites and aluminum (Figure 1). Although its cost per specific stiffness is higher than aluminum's, other factors such as overall weight savings potential, cost savings due to parts consolidation, functional integration, and lower tooling and equipment costs make carbon composites potentially cost-competitive in many applications on a per-vehicle basis. Hypercar's *Revolution* concept vehicle, described below, demonstrates this promising design/production solution that addresses the challenges of using carbon composites while also exploiting its other benefits.

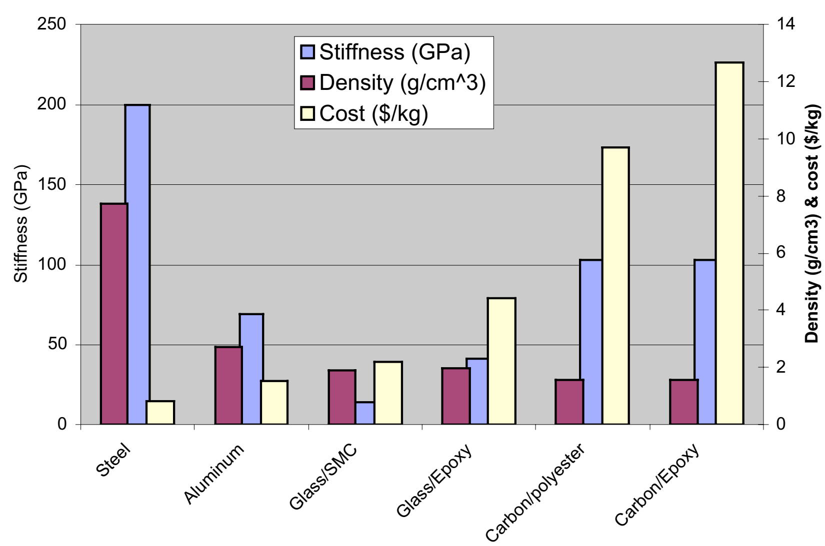

Figure 1: Relative materials properties & costs

2. *Revolution* Fuel-Cell Vehicle

The *Revolution* fuel-cell concept vehicle was developed internally by Hypercar to demonstrate the technical feasibility and societal, consumer, and competitive benefits of holistic vehicle design focused on efficiency and lightweighting. It was designed to have breakthrough fuel economy and emissions, meet U.S. and European Motor Vehicle Safety Standards, and meet a rigorous and complete set of product requirements for a sporty five-passenger SUV crossover vehicle market segment with technologies that could be in volume production at competitive cost within five years (Figure 2).

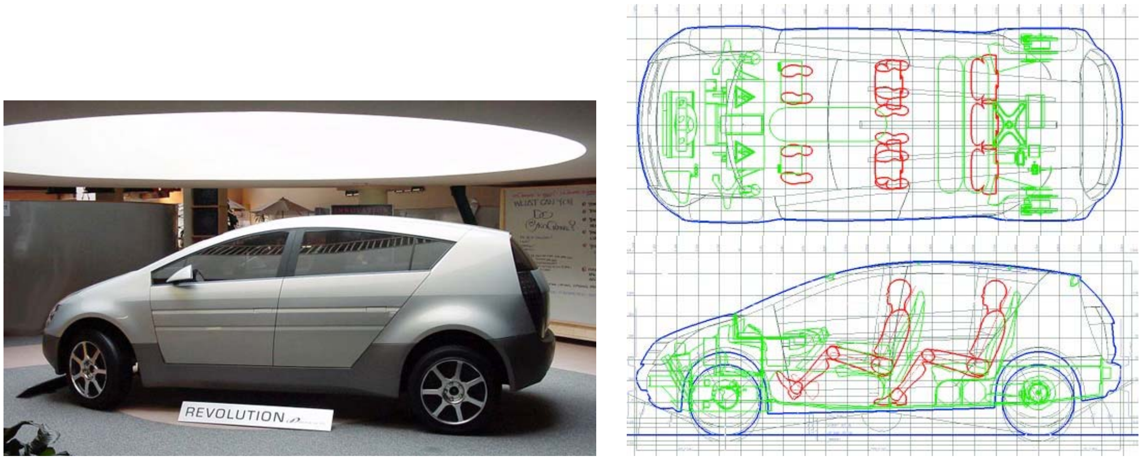

Figure 2: Photo of full-scale model of *Revolution* and package layout drawings

The *Revolution* combines lightweight, aerodynamic, and electrically and thermally efficient design with a hybridized fuel-cell propulsion system to deliver an unprecedented combination of features:

- Seats five adults with a package similar to the Lexus RX-300
- 1.95-m^3 cargo space with the rear seats folded flat
- 2.38 L/100 km (42 km/L, 99 mpg) using compressed 345-bar gaseous hydrogen fuel
- 530-km range on 3.4 kg of hydrogen
- Zero tailpipe emissions
- Accelerates 0–100 km/h in 8.3 seconds
- No damage in impacts up to 10 km/h
- All-wheel drive with digital traction and vehicle stability control
- Ground clearance adjustable from 13–20 cm through a semi-active suspension that adapts to load, speed, location of the vehicle's center of gravity, and terrain
- Body stiffness and torsional rigidity 50% higher than premium sports sedans
- Designed for a 300,000+-km service life
- Modular electronics and software architecture and customizable user interface
- Potential for the sticker price to be competitive with the Lexus RX300, Mercedes M320, and the BMW X5 3.0, with significantly lower lifecycle cost

How is this achieved? Through careful whole-system design that integrates several advanced technologies at once in synergistic ways. An overview of some of the technologies in the *Revolution* can be found in Figure 3 and background information is available in [4, 5, 6, 7].

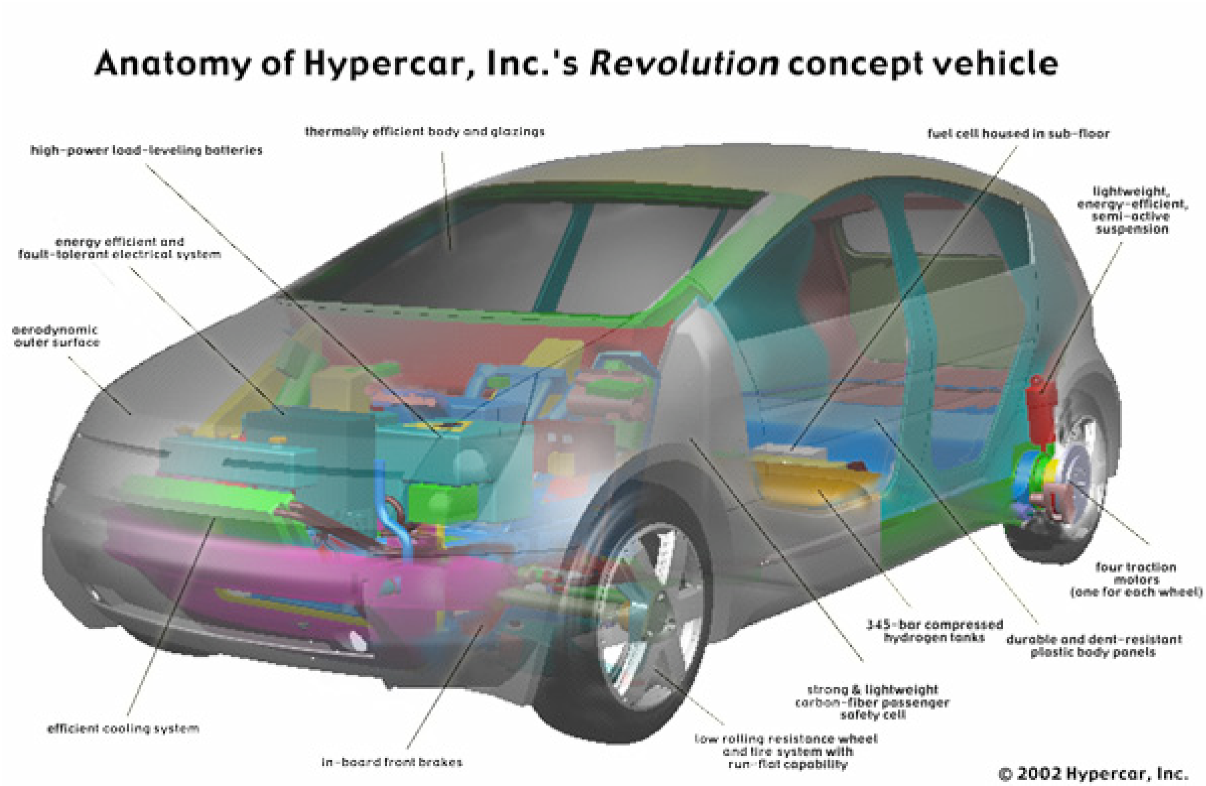

Figure 3: Technologies within the *Revolution*

2.1 Lightweight design

Every system in the *Revolution* is significantly lighter than conventional systems (Table 1 and Figure 4). Different techniques were used for each system to achieve such weight savings. The body structure achieved nearly 60% mass reduction versus steel by using a combination of carbon-fiber composites, aluminum, and unreinforced thermoplastic. Carbon-fiber composites were used in the passenger safety cell and in dedicated composite energy absorbing members. Aluminum was used primarily in a front-end sub-frame, and unreinforced composite panels form the vehicle's skin (Figure 5). The aluminum subframe and plastic skin are made with standard production techniques and will thus not be discussed in detail here.

Table 1: Mass comparison of *Revolution* with a conventional benchmark vehicle

System	**Benchmark mass (kg)**	***Revolution* mass (kg)**	**Difference (%)**
Structure	430	186.5	-57 %
Propulsion	468	288.3	-38 %
Chassis	306	201.2	-34 %
Electrical	72	33.4	-54 %
Trim	513	143.2	-72 %
Fluids	11	4.1	-63 %
Total	**1,800**	**856.6**	**-52 %**

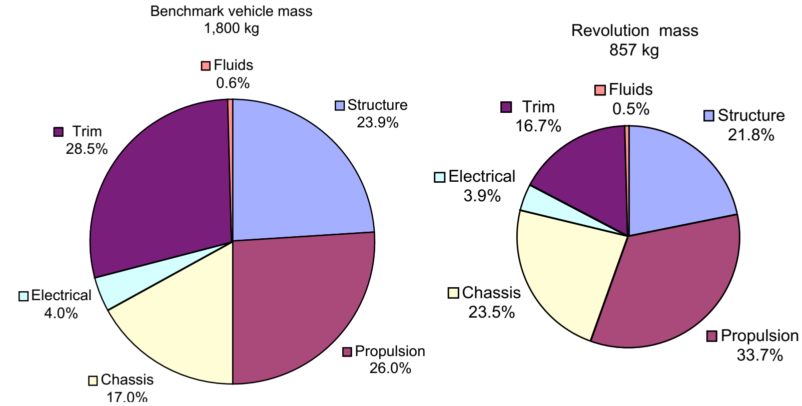

Figure 4: Mass pie charts

3. Composite Safety Cell Structural Design

The overarching challenge to using lightweight materials is cost-effectiveness. As carbon fiber composites cost significantly more per kilogram and per unit stiffness than steel, cost savings must be found in the structural design and manufacturing methods in order to make composites economically feasible. The design strategy that Hypercar employed was four-tiered: minimizing the total amount of material (and its corollary: ensuring most effective use of the material used) through concentrated, highly effective use whenever used; simplifying assembly, tooling, parts handling, inventory, and processing costs through design; integrating as much functionality into the structure as was practical; and employing a novel manufacturing system for the fabrication of the individual parts. Several features of the design that support this strategy are described below.

3.1 Design features

3.1.1 Part consolidation

The primary structure is illustrated in Figures 5 and 6. It is composed of fourteen major parts and 62 total parts—65% and 77% fewer parts than in the equivalent portion of a conventional stamped steel BIW, respectively. Each major part in the composite safety cell is joined using a patent-pending blade and clevis fully bonded joining technique that is strong, robust, and self-fixturing. Together, the small number of parts and the joint design simplify assembly, as just a few parts must be held together until the adhesive bond sets up, without the need for complex fixtures.

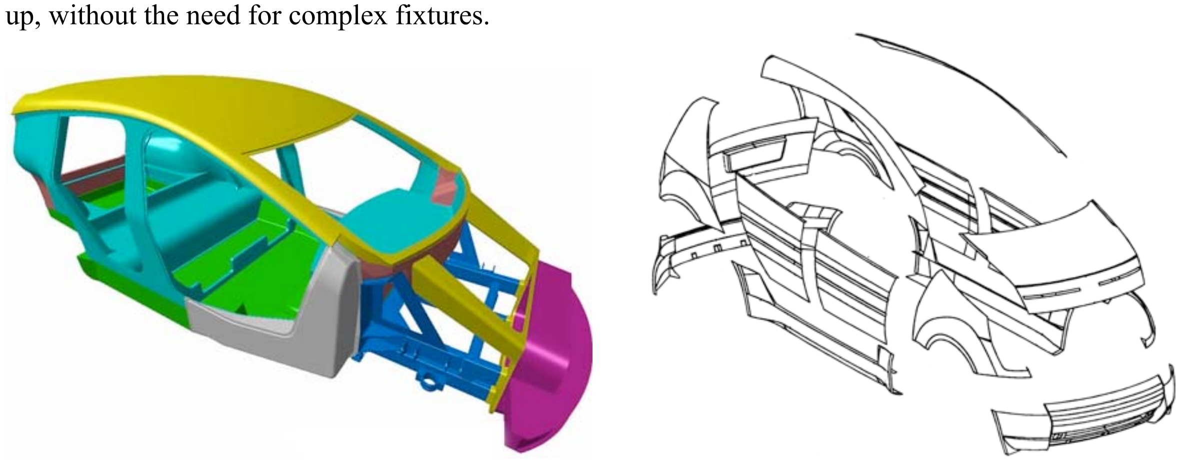

Figure 5: Composite structure, aluminum/composite front sub-frame, and exterior panels

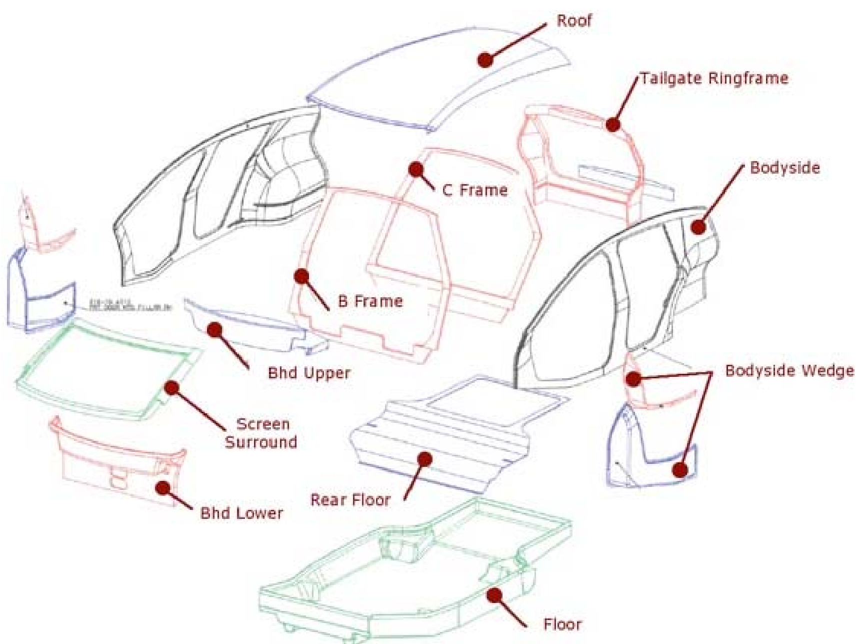

Figure 6: Composite safety cell exploded view

3.1.2 Material selection

The materials used in the design of the passenger safety cell are predominantly intermediate modulus PAN-based carbon fiber and low-viscosity nylon 12 laurolactam thermoplastic.

To improve processability, long discontinuous fiber (LDF) carbon is used. Compared with continuous fiber, LDF allows greater formability of the part without crimping or buckling because the preform can stretch during processing. Yet the fibers are long enough to maintain near-continuous-fiber levels of stiffness in the final part.

3.1.3 Part design

Each part is designed for low-cost fabrication and assembly. All parts exploit global complexity rather than including local complexity. For instance, while the components have complex surface geometry, the components are relatively shallow with few sharp bends or deep draws, minimizing tooling cost, enhancing repeatability, and eliminating the need for labor-intensive pre- and post-process steps. Even though the geometry of each individual part is relatively simple, the parts combine to form a complete structure with all of the necessary complexity and geometry.

3.2 Structural analysis

Both static structural and dynamic crash analyses were performed on the *Revolution*. The static analyses indicate a bending stiffness of 14,470 N/mm and a torsional stiffness of 38,490 N•m/deg—both figures greater than 50 % stiffer than premium sports sedans.

In terms of crash performance, the *Revolution* relies on a combination of the energy absorbing properties of aluminum and the strength of carbon composites to achieve levels of safety comparable to—and in many crash scenarios, exceeding—those of heavier vehicles. For instance, in front-end collisions, computer analyses indicate that the *Revolution* would surpass U.S. Federal Motor Vehicle Safety Standards (FMVSS) for a 48-km/h fixed-barrier collision even at speeds up to 56 km/h. Additionally, the damage from a front-end collision up to 56 km/h would be contained within the aluminum front sub-frame without any damage to the carbon-fiber safety cell, facilitating occupant extrication after a crash and simplifying repair. In a head-on collision with a vehicle up to twice its mass, each traveling up to 48 km/h, the *Revolution* is designed to meet FMVSS 48-km/h fixed-barrier head-on standards. Thus, the *Revolution*'s crash structures would successfully absorb the extra kinetic energy transferred to it during a head-on collision due to its lightness relative to its collision partner without compromising passenger safety.

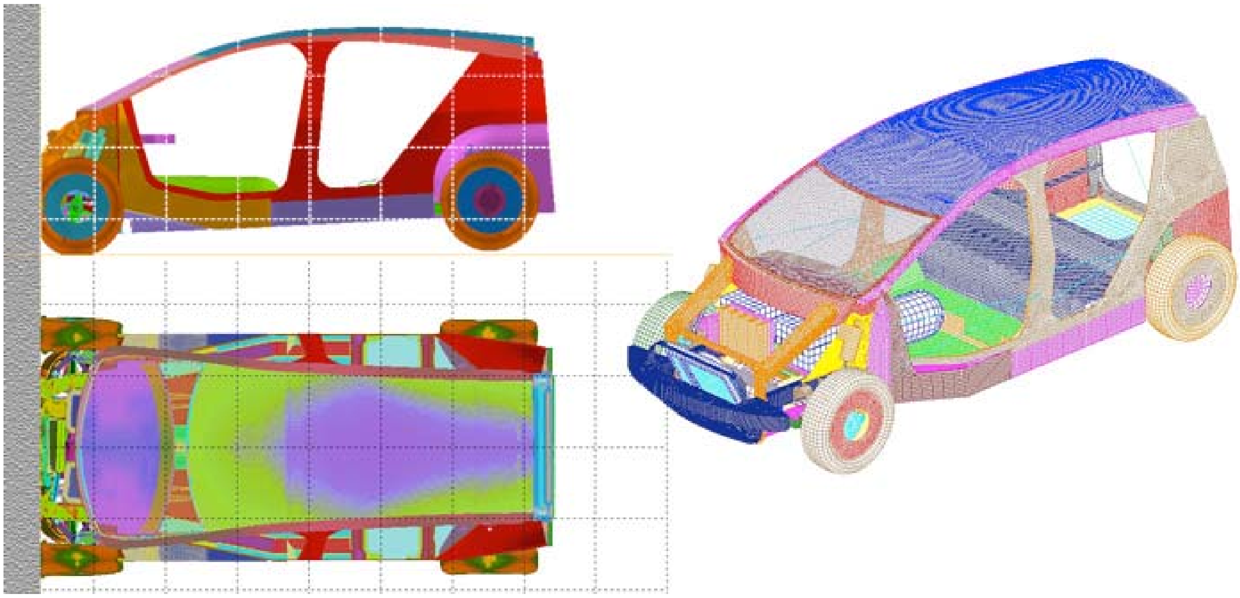

Figure 7: 56-km/h fixed barrier front-end collision results

4. Part Fabrication Method

The parts are designed for manufacture using a patent-pending process under development by Hypercar called Advanced Volume Automotive Composite Solution (AVACS). The AVACS process begins by creating a composite "tailored blank" from raw material inputs. These blanks are then used in either a liquid infusion molding or a solid-state thermoplastic stamping process to create the final part. The tailored blanks are flat sheets made in the rough outline of each part with the fibers oriented as desired and in the appropriate thickness for the part. Because the fiber form is LDF, these flat sheets can be stamped to final shape or preformed for use in an infusion process. The prime benefit of the AVACS process is that it breaks through the traditional cost-performance-production-rate tradeoff typical of composites to yield a practical solution that meets automotive requirements. The main process steps are illustrated in Figure 8 and described below.

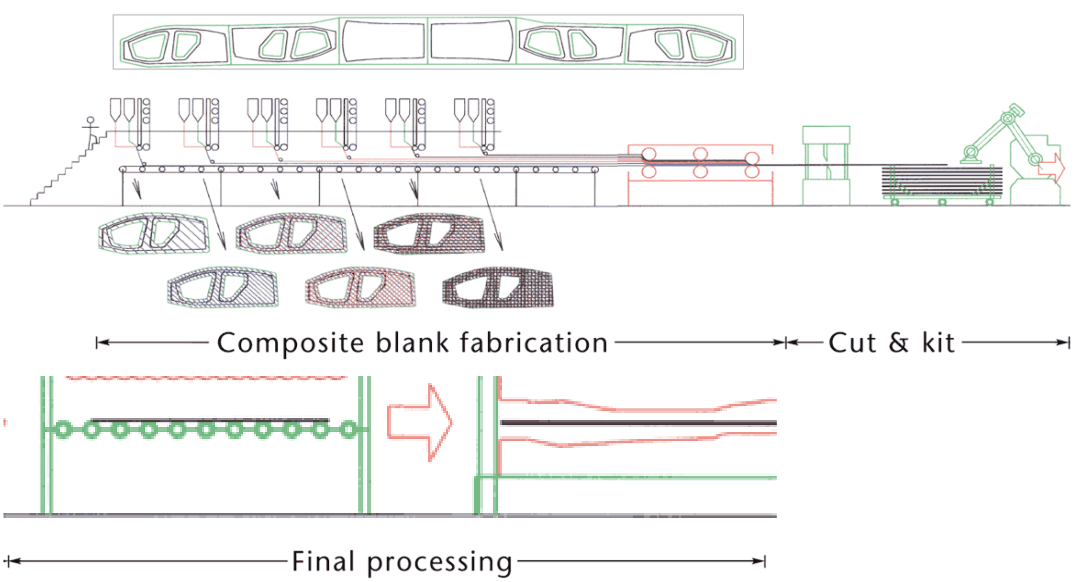

Figure 8: Composite part fabrication (thermoplastic stamping shown)

4.1.1 Composite blank fabrication

The first step in the AVACS process is creating a tailored blank for each composite part. This process places semi-consolidated layers of fiber and matrix on a flat conveyor, each layer with a specific fiber orientation. Consolidating the layers through a series of rollers finishes the blanks. This critical first step turns raw-material inputs (fiber and polymer matrix) into a form that can be stamped directly (process shown in Figure 8) or preformed for resin infusion processes without additional processing steps. The difference between the tailored blank in the case of stamping or resin infusion is simply the degree of resin impregnation and consolidation.

Key benefits of tailored blanks include:

Precise control of fiber alignment, angle, and thickness. Using computer control, the AVACS tailored blanking process can place highly aligned fibers that precisely match the load paths and geometry required for the part. This makes best use of the fibers, minimizing the material required to achieve the desired part performance.

High fiber volume fraction parts. Since the fibers provide the bulk of the strength in composites and stiffness of the part, the higher volume fraction of fibers, the lighter the part. The AVACS process will produce parts with fiber volume fractions from 55 % to 65 % depending on the final forming process—much higher than typical SMC composites.

Low scrap. The tailored blank fabrication process places material only where it is needed in the part, thus avoiding the need to cut out large holes or do extensive trimming.

Flexible production equipment. AVACS equipment can make tailored blanks for any composite part that fits the equipment. Software control allows the equipment to make a variety of parts in series, continuously laying up part-specific blanks to the desired production volume without having to switch tools or forms. It is also easy to include special plies of different materials (such as insulation) or structural cores.

4.2 Cut and kit

Once produced, the tailored blanks are sorted into kits for transfer to the final processing stations. This step allows for the blank fabrication to be physically separated from the final part manufacturing cells, if desired, thus enabling high machine utilization.

4.3 Final processing

The final processing step is determined by the specific application. The manufacturing process chosen for most of the *Revolution*'s composite parts is a resin transfer molding (RTM) variant using a nylon-12 "laurolactam" thermoplastic resin. In this step, the tailored blanks are preformed then placed in a mold along with any inserts and foam cores. The tool is then closed and resin is injected. Finally, the tool is cooled and the part is removed, trimmed to final shape, and racked for transfer to body assembly.

5. Body Assembly

The body assembly sequence, illustrated in Figure 9, involves building up the front chassis assembly, passenger safety cell, and front bumper subassembly in parallel and then mating them together as the last step. The joint design and part breakout allow the safety cell to be built progressively with minimal jigs and fixtures, since the joints self-align the parts and the quick-loc adhesive system quickly provides handling strength. The assembly sequence uses robotic application of adhesive to ensure proper metering and high application precision. After step B6, exterior panels, propulsion, rear suspension, closures (doors, trunklid, and hood), and interior elements are assembled to the body.

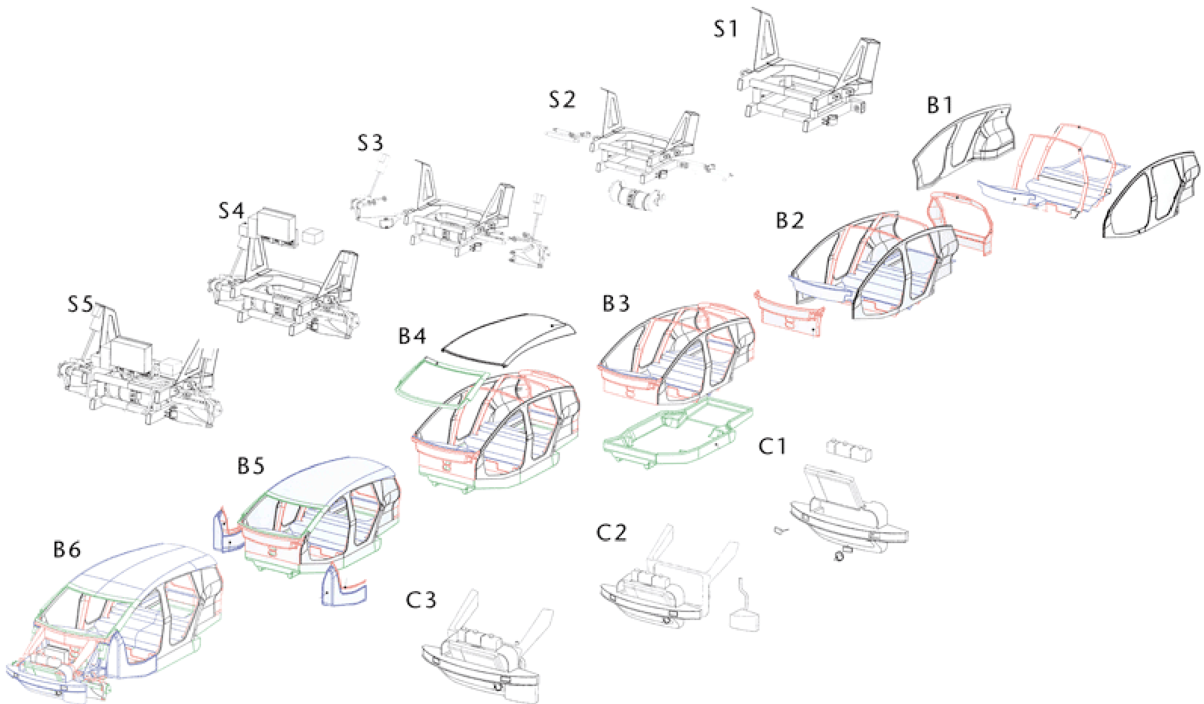

Figure 9: Body assembly sequence

6. Cost Analysis

At the design target of 50,000 vehicles-per-year production, the preliminary cost of a total finished body (*i.e.*, not body-in-white) with closures is $4,087 (in 2000$, Figure 10). Additional unit cost reduction is expected with increased volume. Further, work is underway to assess the cost-volume relationship of the AVACS process and to refine the process to reduce underlying costs.

Model inputs	**Value**	**Units**
Materials		
Carbon fiber	13.2	$/kg
Nylon 12 resin	8.8	$/kg
Foam core	9.9	$/kg
Inserts	2.2	$/kg
Production		
Model years	5	y
Production volume	50,000	/y
Capital amortization rate	10%	/y
Labor rate	52	$/h
Management rate	100	$/h
Materials scrap	15	%
Tooling cost includes jigs & fixtures		

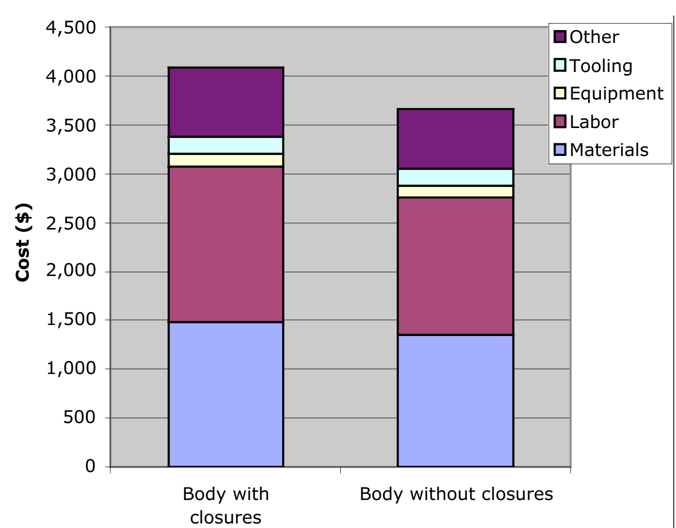

Figure 10: Cost elements and assumptions for the finished body cost for the *Revolution*

The model includes all costs associated with sustained production at the target production volume. Thus, it includes fully burdened direct labor and engineering, management, quality control, and tooling rework labor to maintain production, although it does not amortize process or equipment development costs. The costs of all procured parts, which include all non-structural body panels and the aluminum front sub-frame, were estimated by leading tier-one suppliers and are categorized as "other" in the cost model. The rest of the costs were estimated by defining a macro-cell for each part that contains each required manufacturing step and its process parameters.

Direct cost comparisons with a conventional steel BIW are difficult since many functions and features that must be added to the BIW costs are already integrated into the *Revolution*'s body structure that are not included in steel body structure costs. These features also reduce the cost of other vehicle systems, thus yielding a competitive vehicle cost even if the body costs more than a steel one. Some of the features integrated into the *Revolution*'s body structure include:

- in-mold coloring of the exterior panels, which eliminates conventional painting
- integral acoustic and thermal insulation, which reduces the cost and mass of add-on damping materials
- integral suspension mounting features, which reduce the cost and mass of the suspension subsystem
- composite structure used as the cosmetic interior surface for many areas of the passenger compartment, eliminating some cosmetic trim
- integrated cooling lines and electrical conduits

Additionally, the induced direct and indirect cost savings due to lightweighting on the propulsion and chassis systems further strengthen the overall benefits of the *Revolution*'s lightweight body structure. For example, Table 2 compares the total cost of the *Revolution* with several other fuel-cell concept cars' and shows how lightweighting and efficiency can more than halve the peak power required of the fuel cell, and hence its cost (even at $100/kW, which is far below near-term whole-system cost).

Table 2: Fuel-cell system cost and range comparison

Vehicle	**Peak power (kW)**	**Type**	**Cost @ $100/kW**	**Range (km)**
Hypercar *Revolution*	35	hybrid	**$3,500**	531
Hyundai *Santa Fe FCV*	75	fuel cell	**$ 7,500**	402
Honda *FCX-V4*	78	fuel cell	**$ 7,800**	298
Ford *Focus FCV*	85	hybrid	**$ 8,500**	322
Toyota *FCHV-4*	90	hybrid	**$ 9,000**	249
GM *HydroGen III*	94	fuel cell	**$ 9,400**	402
Jeep *Commander 2*	140	hybrid	**$ 14,000**	150

Sources: [2] and [8]

7. Conclusion

The *Revolution*'s composite-intensive body design combines nearly 60% lighter weight with high structural performance and cost competitiveness at 50,000/y production volume. The benefits to vehicle manufacturers are strong, especially in the context of hybrid and fuel-cell vehicle development where power is supplied at a premium price. And due to the separation of the functions of structure and external skin, the economics of producing vehicle variants with the same geometric structure becomes more favorable. Hypercar is currently developing further the vehicle design and AVACS manufacturing system, conducting a series of hardware and process test and validation prototypes in order to validate the viability and compelling benefits of the design and manufacturing process methodology.

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