Hypercars®, hydrogen, and the automotive transition

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Abstract: Designing and making cars differently – emphasizing ultralight weight, ultralow drag, and integrated design – can reduce required propulsive power by about two-thirds. This can make direct-hydrogen fuel cells and commercially available compressed-hydrogen-gas tanks practical and affordable even at relatively high early prices. Coordinating such vehicles with deployment of fuel cells in buildings permits a rapid transition to a climate-safe hydrogen economy that is profitable at each step starting now. New manufacturing and design methods can also make these radically more efficient vehicles cost-competitive and uncompromised, as illustrated by a 2.38-litre-equivalent-per-100-km midsize sport-utility concept car designed in 2000 by Hypercar, Inc. Major reductions in the required capital, assembly, space, and product cycle time can offer key competitive advantages to early adopters. These changes are increasingly recognized as portents of unprecedented technological and market transitions that can make cars climate-safe and the car and oil industries more benign and profitable.

Keywords: Carbon fibre, composites, design integration, Fiberforge™, fuel cells, fuel economy, fuel efficiency, hydrogen, Hypercar®, lightweighting, mass decompounding, ultralight, whole-system design.

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Biographical notes: Amory Lovins invented the Hypercar concept, cofounded and leads the organization where it was incubated, and chairs its spun-off development firm. Published in 28 books and hundreds of papers, his work has been recognized by the 'Alternative Nobel', Onassis, Nissan, Shingo, and Mitchell Prizes, a MacArthur Fellowship, the Happold Medal, eight honourary doctorates, and the Heinz, Lindbergh, World Technology, and 'Hero for the Planet' Awards.

David Cramer is a member of the team that developed the Hypercar concept at Rocky Mountain Institute and a cofounder of Hypercar, Inc., which is commercializing its key enabling technologies. He holds a BA *magna cum laude* and a BEng with High Honours from Dartmouth College. He has coauthored a book and several professional papers on automotive composites' production costing, manufacturing, and lifecycle, and leads Hypercar, Inc.'s engineering development.

1 Introduction and history

The global automotive industry is arguably the largest and most complex undertaking in industrial history. Its myriad highly evolved production platforms meet with remarkable skill the conflicting demands of price, safety, performance, reliability, emissions, and market appeal. However, in a world where cars multiply twice as fast as people, such escalating concerns as climate protection and energy security are becoming hard to address with vehicles that, despite a century's engineering effort, use only one percent of their fuel energy to move the driver.

Traditionally, automakers and policymakers have presumed that major gains in fuel economy or carbon emissions can come only from government mandate or higher fuel price. In the US, these interventions – favoured respectively by oil and car companies – have attracted titanic lobbying efforts and fought each other to a draw for two decades. Even in the European Union, with its more coherent approach to public needs, policy is buffeted by random and increasingly volatile oil prices and potential supply disruptions. Most developing countries, except perhaps for the People's Republic of China, have subordinated fuel-economy and environmental concerns to their desire to build car industries and buy cars.

Both automakers and policymakers have adopted from economic theory the assumption that any major improvement in fuel economy or carbon emissions must be traded off against size, comfort, performance, cost, or safety – requiring, in turn, government intervention (such as mandate or subsidy) to induce customers to buy the compromised vehicles. The unattractiveness of that presumed compromise underlies US automakers' lobbying and litigation positions, which inadvertently unmarket their own impressive innovations in more efficient, cleaner, but safe and attractive vehicles. In the absence of effective US national policy, disparate state-level policies are emerging, starting in California, and will vex suppliers.

Against this background of increasing inconsistency between public-policy and commercial goals, automaking is exhibiting all the signs of a classic overmature industry: hypercompetition over shrinking niches for convergent products in saturated core markets, global overcapacity and consolidation, cutthroat commodity pricing, modest to negative margins, stagnant basic innovation (until the mid-1990s), and limited attractiveness for recruiting top talent or strategic investment. In short, automaking, like airlines, is a great but challenged industry, ripe for fundamental change. Other industries are examining this opportunity. At the 1999 Paris Auto Show, MIT analyst Prof Daniel Roos warned the assembled CEOs that in the next decade or two, quite a few of them would be put out of business – often by firms they don't now consider their competitors.

Since 1990–91, a small independent development effort has been challenging the conventional approach to automaking, at first from outside and lately from inside the auto industry. It is based on premises that at first seemed implausibly radical, but have withstood a decade's scrutiny and increasingly define the industry's emerging strategy:

- Very large improvements in fuel economy and carbon emissions may be easier and cheaper than small ones, and may be achievable simultaneously without compromising existing goals.

- Such improvements may also bring decisive competitive advantage to early-adopting manufacturers by reducing requirements for capital, assembly, space, parts, and product cycle time.
- This could permit a robust business model based solely on value to customers and advantage to manufacturers – not on fuel price, government policy, or other random variables.
- The resulting vehicles may also facilitate advantageous shifts in fuel infrastructure that meet climate and security goals at costs comparable to or lower than today's and permit a smooth and profitable transition from today's asset base.
- Achieving these ambitious goals requires leadership rather than a regulatory-compliance mindset, and a complete change in how cars are designed and built – a technological and institutional change as striking as those that began to shape today's auto industry nearly a century ago.

In this view, now becoming obvious to many in the industry, technological change will not be smooth and incremental but discontinuous and radical. Astonishing advances in fuel economy and carbon emissions will be less the effects of regulation or fuel price than the emergent byproducts of breakthrough engineering. Rather than requiring governmental inducements to buy costlier or less attractive vehicles, customers will prefer the new versions because they will offer superior attributes at comparable cost. And to achieve this breakthrough, automakers would focus less on lobbying, litigation, and public relations than on engineering.

This article summarizes how these goals can be achieved, progress so far in achieving them, and the prospects of accelerating their realization.

That history began in 1990–91 when physicist Amory Lovins, then research director of an independent nonprofit applied research center, Rocky Mountain Institute, was asked by the US National Research Council to co-keynote a symposium on automotive fuel economy. Engaged for two decades in advanced energy efficiency, he had long wondered how efficient cars could become if optimized as whole systems, starting with radically reduced mass and drag. Stimulated by the NRC invitation and a seed grant from the Nathan Cummings Foundation, he started benchmarking automakers' concept cars. His NAS remarks [1] stimulated GM's head of advanced engineering, Donald Runkle, to invite Lovins in November 1991 to view the firm's then-half-clay *Ultralite* concept car. This sporty 4-seat, 635-kg, carbon-composite, low-drag experiment's fuel economy (3.8 L/100 km average, 2.35 highway, and far better if its two-stroke Orbital engine were changed to a hybrid driveline) confirmed Lovins's intuition of a new design space in which hybrid-electric propulsion could make a platform lighter, simpler, and cheaper, not the opposite, *if* the tractive load were first reduced by severalfold.

From 1991, therefore, he launched RMI's exploration of what came to be called Hypercar® [2] light vehicles: ultralight, ultra-low-drag, hybrid-electric vehicles with highly integrated, simplified, software-rich design. In 1993, after two years' private exploration of the concept with GM and others in the industry, RMI published its preliminary conclusions [3,4], receiving the Nissan Prize at the 1993 ISATA, in order to maximize competition in exploiting the concept by putting it into the public domain so that it could not be patented. This free-software-like approach, plus extensive briefings and consultancies for the industry worldwide, stimulated strong industry interest in hybrid powertrains, much better platform physics, and other innovations, especially in combination.

Through the mid-1990s, RMI's internal Hypercar Center[SM] development programme refined and described the Hypercar concept [5–23]. Its feasibility was confirmed in 1998 by an independent study commissioned from Lotus Engineering (UK) with 17 industrial partners. The industry was meanwhile making its own major commitments to development on these general lines. However, RMI's having put its general concepts in the public domain did not preclude also developing proprietary solutions for implementation.

To support and accelerate the industry's transition by making such solutions more widely available, RMI spun off Hypercar, Inc. in 1999 under Lovins's chairmanship. This private firm develops and licenses key enabling technologies (ultralight autobody manufacturing techniques, whole-platform integration, and system and subsystem technologies) and provides engineering services to help OEMs and major suppliers apply those innovations to their products.

Section 2 of this paper describes some of Hypercar, Inc.'s vehicle engineering innovations and, most importantly, how their integration may be able to achieve fivefold fuel savings – vehicles we will call here '5η' as a generic term – without increasing vehicle cost [24], contrary to the universally assumed theory of diminishing returns to efficiency investments. Section 3 describes a concept car that Hypercar, Inc. developed in 2000 to illustrate the advantages of ultralighting and whole-platform integration. Section 4 summarizes the firm's proprietary advanced-composite autobody manufacturing process. Section 5 explores implications for early adoption of hydrogen fuel cells in vehicles and buildings.

2 Vehicle design principles

2.1 Background

To reduce fuel use and emissions cost-effectively while maintaining market appeal, safety, size, and design flexibility, Hypercar, Inc. starts with whole-vehicle integration based on radical 'lightweighting', drag reduction, and accessory efficiency. This approach is essential to achieve large performance (acceleration, gradability, style, crashworthiness, size, etc.) improvements without adding cost.

The auto industry is increasingly acknowledging the primacy of whole-vehicle design. Efforts to rethink the automobile are now beginning to take hold. For example, General Motors's *AUTOnomy* vehicle architecture, released in early 2002, combines fuel cells and -by-wire technology in an unprecedented 'skateboard' design:

> GM took a radically different approach. Realizing that a fuel cell system could allow for an utterly new shape, the designers tossed out the design requirements of a conventional engine and devised a car from scratch. Once GM walked through that door, a universe of possibilities opened up .... *It turns out that concentrating on the car, instead of just on the fuel cell, makes all the difference. And nobody is more surprised than General Motors* [emphasis added] [25].

2.2 Design principles

Hypercar, Inc. has developed a set of fundamental design principles for any vehicle type:

1. Start from a clean sheet
2. Define clear and complete product requirements
3. Design as a whole system
4. Strongly emphasize platform lightweighting and efficiency.

While conceptually simple, these four principles are powerful and effective in overcoming traditional design barriers and assumptions. Managed well, these four principles also help maintain a development team's focus on meeting the vehicle's targets cost-effectively.

2.2.1 Start from a clean sheet

Incremental product refinement is an important part of engineering. In the auto industry, it has yielded high quality and value, expanding features, and efficient production. However, when seeking major improvements in performance (acceleration, handling, fuel economy, emissions, or any other measure), or such fundamental changes as switching from internal combustion to fuel cells, incrementalism can lead to compromised vehicles, poor sales, or even failure.

For example, putting fuel cells into a current production vehicle requires so much peak power that the powerplant becomes overly expensive, hard to cool and package, and limited in range. Consider, for instance, the cooling issue. Conventional internal combustion engines operate at approximately 110–120°C, and much of the heat escapes in exhaust gas; the rest is handled by the radiator. PEM fuel cells are more efficient, but operate at 80–85°C and disperse much less of their waste heat in exhaust, making the radiator about twice as big and thus adding cost, mass, and aerodynamic drag [26]. These are best avoided by reducing tractive load.

2.2.2 Define clear and complete product requirements

The foundation of clean-sheet design is defining clear product requirements (including cost) in terms of ends, not means, so that ambitious requirements are technology-forcing but technology-neutral. Normal, incremental automotive development assumes an 'incumbent' vehicle and specific desired improvements, so it limits the solution space. Clean-sheet design instead allows anything within the constraints of the product requirements. Like writing a new document from scratch instead of editing an old one, clean-sheet design is both more challenging and more liberating – if the goal is clearly defined. Goal statements must also distinguish between essential and merely desirable.

New goals may introduce new issues. For example, vehicle dynamics is challenging in large but lightweight vehicles because the kerb-to-gross vehicle mass ratio leads to significantly different driving behaviour across the payload range. One way to write product requirements for the chassis system would be to state that the suspension must adapt to changes in payload and mass distributions. A better way would be to set the target as consistent car-like driving behaviour – suitably defined – throughout the payload range of the vehicle. That goal contains no assumptions about vehicle mass or any need for adaptive suspension; it simply states how the vehicle should drive and liberates the engineers to figure out how.

2.2.3 Design the vehicle as a system

Whole-system design goes hand-in-hand with clean-sheet design, but they're different. Clean-sheet design is a starting point, while whole-system design is the method of the journey. Whole-system design focuses the development team on meeting *vehicle*-level targets. Although each team member can be responsible for a system, and each system has its own flexible secondary goals, the primary accountability of each team member is for vehicle-level performance.

Whole-system design also rests on an understanding of how systems and subsystems interact, and highlights interfaces between systems as potential design opportunities. In the 2002 *AUTOnomy* concept car, for example, 'It's adding drive-by-wire that really makes the fuel cell plausible,' stated Larry Burns, GM's Vice President of R&D. Treating vehicle systems as functionally interdependent rather than independent expands engineers' design freedom. Moreover, optimizing the whole vehicle as a system, rather than concurrently optimizing its parts in a dis-integrated way that 'pessimizes' the system, often yields multiple benefits for single expenditures. This in turn can 'tunnel through the cost barrier' by making very large efficiency gains cost less than small or no gains. This has been demonstrated in a wide range of technical systems [24], and appears to be equally true for automotive design. For example, the two-piece Lotus *Elise* composite front subframe carries out up to seven functions, including crash energy absorption, radiator ducting, and headlight support.

Hypercar, Inc.'s Light*SPEED*™ design process, inspired by the development process pioneered by the late Kelly Johnson at the LockheedMartin Skunk Works®, manages the development process through innovative team organization, structure of the development plan, leadership, clear and complete product requirements, and explicit 'rules of engagement'. It was the key to Hypercar, Inc.'s completion of the concept-car design described below in eight months for a few million dollars – far below industry norms.

2.2.4 Emphasize lightweighting and platform efficiency first

Only a small fraction of a vehicle's fuel energy ends up moving the passengers and cargo and powering vehicle systems. Most of the fuel energy ends up as heat through thermodynamic losses, mechanical friction in the driveline, rolling resistance, aerodynamic drag, braking, and electrical system inefficiencies [27,28]. Many studies have concluded that fuel economy is most sensitive to engine and driveline efficiency, and much less sensitive to mass. This belief has underpinned industry emphasis on technologies that improve driveline efficiency, such as fuel cells and hybrids, as offering the greatest leverage to improve fuel economy. Such conclusions are reasonable and appropriate within their incremental engineering context, but are misleading in two respects. First, they don't properly credit mass decompounding, especially in its more dramatic and nonlinear forms; second, they don't count whole-vehicle cost. Taking these into account makes vehicle mass much more important, especially with costlier drivesystems (hybrids and fuel cells). Acceleration, hill climbing, and in some cases towing capability determine the required peak power, and are directly proportional to vehicle mass. Halved mass thus means halved fuel-cell size and cost – even better after mass decompounding.

Despite the supralinear reduction of fuel-cell cost with vehicle mass, nearly all active fuel-cell demonstration programmes (Table 1) have assumed little reduction in platform mass. As a result, many are potentially facing unnecessarily difficult challenges related to packaging, fuel storage, powertrain cooling, and cost.

Mass decompounding – the snowballing of weight savings – is a key to efficient vehicle design. In a 'beneficial mass spiral', a lightweight body requires lighter chassis components and a smaller powertrain, further reducing mass. Several iterations often disclose opportunities not just to make components smaller but to eliminate them. For example, a series hybrid may not need transmission, clutch, flywheel, axles, differentials, driveshaft, universal joints, starter, and alternator. Of course, it will need some new components such as drivemotor(s), power electronics, and electrical storage, so what matters is the *net* change in mass and cost. But whatever the net result, any powertrain will be smaller and cheaper in a lightweight and energy-efficient platform than in a heavy and inefficient one. This can permit the adoption of the most advanced, clean, and efficient powerplants earlier than if they are sized to propel heavy, inefficient platforms.

Platform efficiency also increases by reducing friction from aerodynamic drag, rolling resistance (bearing loss and tyre loss), and energy consumption for heating, ventilation, and air conditioning and for other accessory loads. Like mass, these factors directly affect the peak power required of the powertrain, and should be minimized at the start, *before* sizing the powertrain.

Table 1 Fuel-cell cost and range vs. tractive load, assuming a fuel-cell system cost of US$100/kW (far below near-term cost) and no mass decompounding [50,51]

Vehicle	*Peak stack power (kW)*	*Type ('hybrid' has buffer storage)*	*Fuel-cell system cost (US$) @ US$100/kW*	*Range (km)*
Hypercar *Revolution*	35	Hybrid	3500	531
Jeep *Commander 2*	50	Hybrid	5 000	190
Hyundai *Santa Fe FCV*	75	Fuel cell	7500	402
Honda *FCX-V4*	85	Hybrid	8500	300
Ford *Focus FCV*	85	Hybrid	8500	290
Toyota *FCHV-4*	90	Hybrid	9000	250
GM *HydroGen III*	94	Fuel cell	9400	400
GM *HyWireIII*	94	Fuel cell	9400	129

2.3 Critical enabling technologies

In applying this design methodology, Hypercar, Inc. has identified critical enabling technologies that together can yield major improvements in fuel economy without harming other attributes, including safety and cost. The most important enabling technologies include:

- Advanced-composites-intensive body structure
- Integrated digital vehicle and vehicle dynamics control
- Hybrid-electric propulsion (optionally based on fuel cells).

When designed in from the start, these technologies can yield safe, fuel-efficient, clean, high-performance, and cost-effective vehicles for any market segment, and can give manufacturers the strategic financial advantages of greater flexibility, short lead time, and low capital cost.

2.3.1 Advanced composites

Many materials could be used to reduce vehicle mass. However, for the primary structure – the Body-in-White (BIW) – advanced-composite materials reinforced mainly with carbon fibre offer the greatest potential for mass reduction while maintaining crashworthiness. Advanced composites also greatly simplify manufacturing, offering such strategic benefits as modularity, component integration, low tooling and equipment costs, quick and easy assembly, and potential to eliminate conventional painting.

In today's cars and light trucks, plastic and composite materials are only about 7.5% of total vehicle mass [29], and their applications are generally non-structural. Despite their higher material costs than steel's (Figure 1), plastics and composites have been cost-justified for non- and semi-structural components due to fabrication or assembly cost savings from parts consolidation, cheaper tooling, and lighter weight.

Cost is a key challenge in all of automotive design, and especially for composites. The three most widely cited obstacles to capturing similar benefits by making carbon-composite BIWs are the high cost of the raw materials (~ US\$11–22/kg for standard-modulus carbon fibre vs ~ US\$1.3/kg for steel), the labour intensity of fibre lay-up

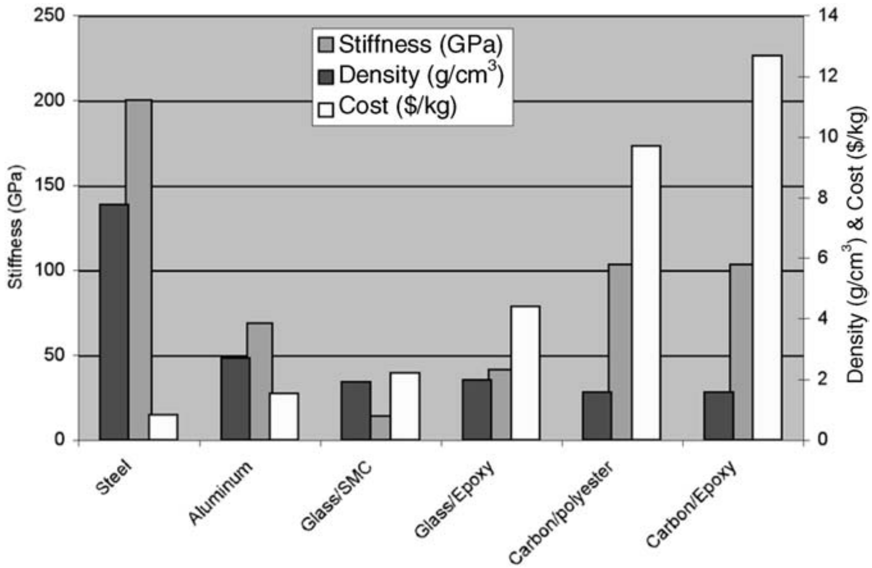

Figure 1 Relative materials properties and costs

and other process steps, and the lack of a viable high-volume process for producing high-performance parts. Nonetheless, new design and manufacturing opportunities can make advanced composites the best choice for replacing steel to save over 60% of BIW mass.

The limiting design criteria in BIWs are stiffness-related, and adequate strength is achieved if the structure meets its stiffness and stability targets. According to Figure 1, the leading alternatives to steel on a cost per unit specific stiffness basis are carbon-fibre composites and aluminium. Despite carbon's materials cost premium over aluminium, 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, Inc.'s concept vehicle, the *Revolution*, described in Section 3, illustrates a promising design/production solution.

2.3.2 Integrated digital control

Migrating vehicle components from discrete, mechanically controlled systems to integrated, digitally controlled systems can yield higher performance and new features. Digital control also yields other benefits including lower weight, higher energy efficiency, safety, reliability, packaging flexibility, assembly improvements, sophisticated powertrain and vehicle dynamics control, aftermarket customization, and the ability to mitigate some of the in-use challenges to alternative-fuel vehicles during initial deployment when fueling infrastructure may be immature.

2.3.3 Hybrid-electric propulsion

Hybrid-electric propulsion (including fuel-cell propulsion) is a key enabling technology for improving fuel economy, for three reasons. First, it removes the constraint that the engine must match the instantaneous power requirements of the driver. Better matching to the engine's efficiency map and slower power ramps yield more efficient, durable, and clean operation. Second, hybridization allows recovery and reuse of part of the otherwise wasted braking energy. Third, engine emissions can be reduced by using electric traction during the most difficult parts of the driving cycle, such as cold start and rapid acceleration.

3 *Revolution* concept car design

3.1 Overview

The *Revolution* fuel-cell concept vehicle was developed by Hypercar, Inc. in 2000 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 (5η) fuel economy and emissions, meet US 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 within five years (Figure 2).

The *Revolution* combines lightweight, aerodynamic, and electrically and thermally efficient design with a hybridized fuel-cell propulsion system to deliver

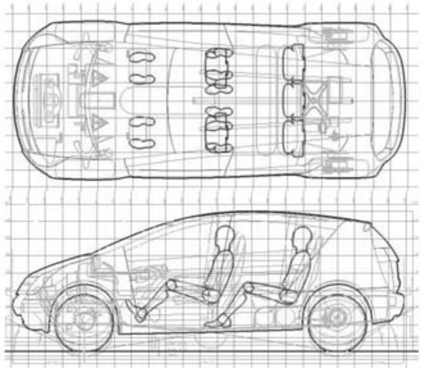

Figure 2 *Revolution* concept car photo and package layout

the following combination of features with 857 kg kerb mass, 2.38 m^2 effective frontal area, 0.26 C_D, and 0.0078 r_0:

- Seats five adults in comfort, with a package similar to the Lexus *RX-300* (6% shorter overall and 10% lower than a 2000 Ford *Explorer* but with slightly greater passenger space)
- 1.95-m^3 cargo space with the rear seats folded flat
- 2.38 L/100 km (99 miles per US gallon) equivalent, using a direct-hydrogen fuel cell, and simulated for realistic US driving behaviour
- 530-km range on 3.4 kg of hydrogen stored in commercially available 345-bar tanks
- Zero tailpipe emissions
- Accelerates 0–100 km/h in 8.3 seconds
- No body damage in impacts up to 10 km/h (crash simulations are described below)
- All-wheel drive with digital traction and vehicle stability control
- Ground clearance adjustable from 13 to 20 cm through a semi-active suspension that adapts to load, speed, location of the vehicle's centre of gravity, and terrain
- Body stiffness and torsional rigidity 50% or more higher than in premium sports sedans
- Designed for a 300 000+ -km service life; composite body not susceptible to rust or fatigue
- Modular electronics and software architecture and customizable user interface
- Potential for the sticker price to be competitive with the Lexus *RX-300*, Mercedes *M320*, and BMW *X5 3.0*, with significantly lower lifecycle cost.

Figure 3 illustrates the main technical features of the *Revolution*, emphasizing those that reduce mass and improve efficiency.

3.2 Lightweight design

Every system within the *Revolution* is significantly lighter than conventional systems (Table 2 and Figure 4) to achieve an overall mass saving of 52%. Techniques used to minimize mass, discussed below, include integration, parts consolidation, and appropriate application of new technology and lightweight materials. No single

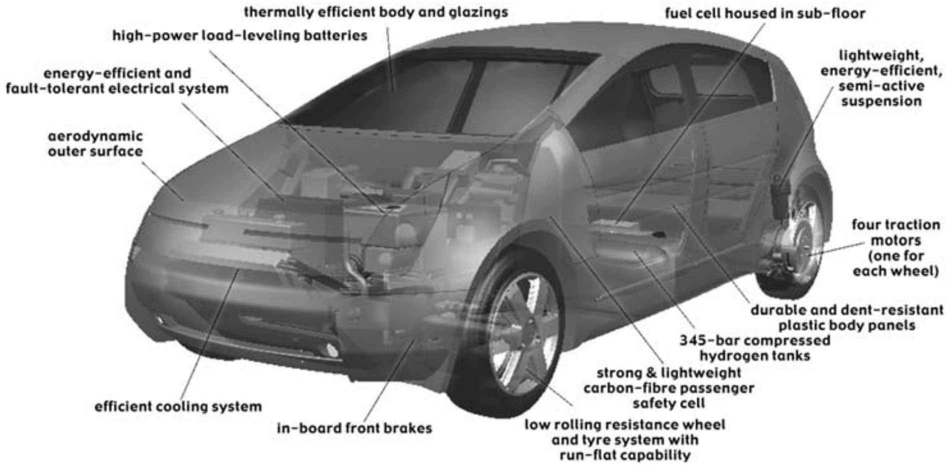

Figure 3 Key design features of the *Revolution*

Table 2 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	1800	856.6	−52%

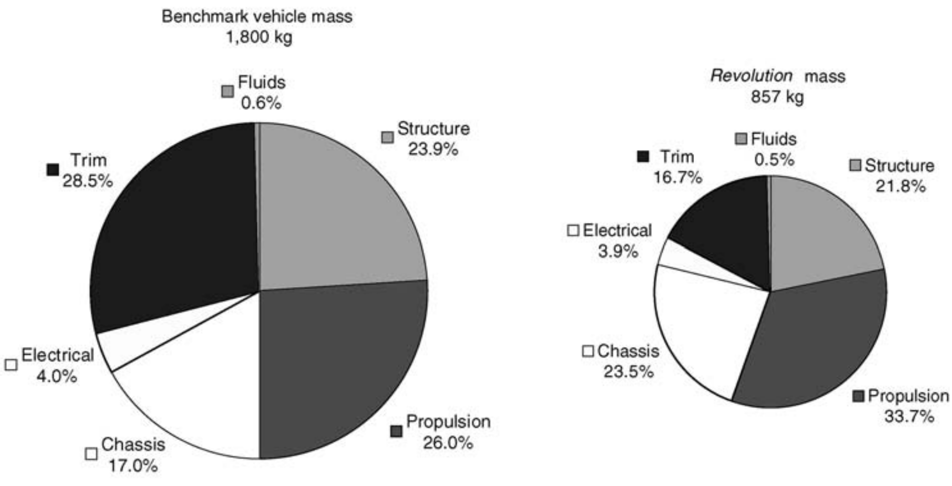

Figure 4 Mass budget and design result

system or materials substitution could have achieved such overall mass savings without strong whole-car design integration.

Many new engineering issues arise with such a lightweight yet large vehicle. While none are showstoppers, many required new solutions that were not obvious and demanded a return to engineering fundamentals. For example, conventional wheel and tyre systems are engineered with the assumption that large means heavy. The low mass, large size, and high payload range relative to vehicle mass put unprecedented demands on the wheel/tyre system. Hypercar, Inc. collaborated with Michelin to design a solution that would meet these novel targets for traction and handling, design appeal, mass, and rolling resistance.

Another challenge in this unusual design space is vehicle dynamics with a gross mass to kerb mass ratio around 1.5 ($\sim$ 1300 kg gross mass/857 kg kerb mass). To maintain consistent and predictable car-like driving behaviour required an adaptive suspension. Most commercially available versions are heavy, energy-hungry, and costly. Hypercar, Inc. collaborated with Advanced Motion Technology, Inc. (Ashton, MD) to design a lightweight semi-active suspension system that could provide variable ride height, load leveling, spring rate, and damping without consuming excessive amounts of energy. Other unique challenges addressed included crosswind stability, crashworthiness, sprung-to-unsprung mass ratio, and acoustics.

3.3 Exterior style and aerodynamics

The *Revolution* concept vehicle is designed as a mid-sized, entry-level luxury sport-utility crossover vehicle (*i.e.*, combining sport-utility with passenger car characteristics). Its design is contemporary and attractive but aerodynamic (Figure 5).

Some of the aerodynamic features include:

- a smooth underbody that tapers up toward the rear to maintain neutral lift
- underbody features that limit flow out of the wheel wells
- tapered roofline and rear 'waistline'
- clean trailing edge
- rounded front corners and A-pillar
- gutter along roofline to trip crosswind airflow
- radiator intake at high-pressure zone on vehicle nose
- wheel arches designed to minimize wheel-induced turbulence
- aerodynamic door handles.

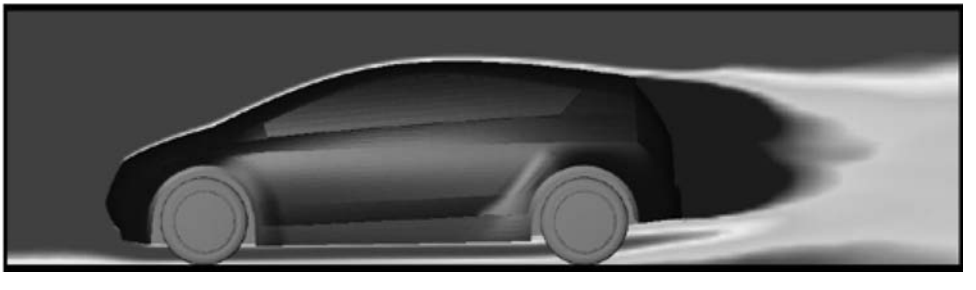

Figure 5 An example of the aerodynamic analysis

In addition to the 'fixed' design features, other systems also contribute to the *Revolution*'s aerodynamic performance. For example, the suspension system lowers ride height during highway driving to minimize frontal area. Also, the suspension and driveline components do not protrude significantly below the floor level; this maintains smooth underbody airflow and minimizes frontal area. Having the rear electric motors in the wheel hubs also eliminates the need for a driveshaft and differential under the vehicle.

3.4 Powertrain

The *Revolution* powertrain design integrates a 35 kW ambient-pressure fuel cell developed by UT Fuel Cells, 35 kW nickel metal hydride (NiMH) buffer batteries, and four electric motors connected to the wheels with single-stage reduction gears. Three 34.5 MPa internally regulated Type IV carbon-fibre tanks store up to 3.4 kg of hydrogen in an internal volume of 137 L (Figure 6). The fuel cell system's near-ambient inlet pressure replaces a costly and energy-intensive air compressor with a simpler and less energy-intensive blower, raising average fuel efficiency and lowering cost.

The commercially available foil-wound NiMH batteries provide extra power when needed and store energy captured by the electric motors during regenerative braking. The $\sim$3 kWh of stored energy is sufficient for several highway-speed passing manoeuvres at gross vehicle mass at grade, and can then gradually taper off available power until the batteries are depleted, leaving only fuel-cell power available for propulsion until the driving cycle permits recharging.

The front two electric motors and brakes are mounted inboard, connected to the

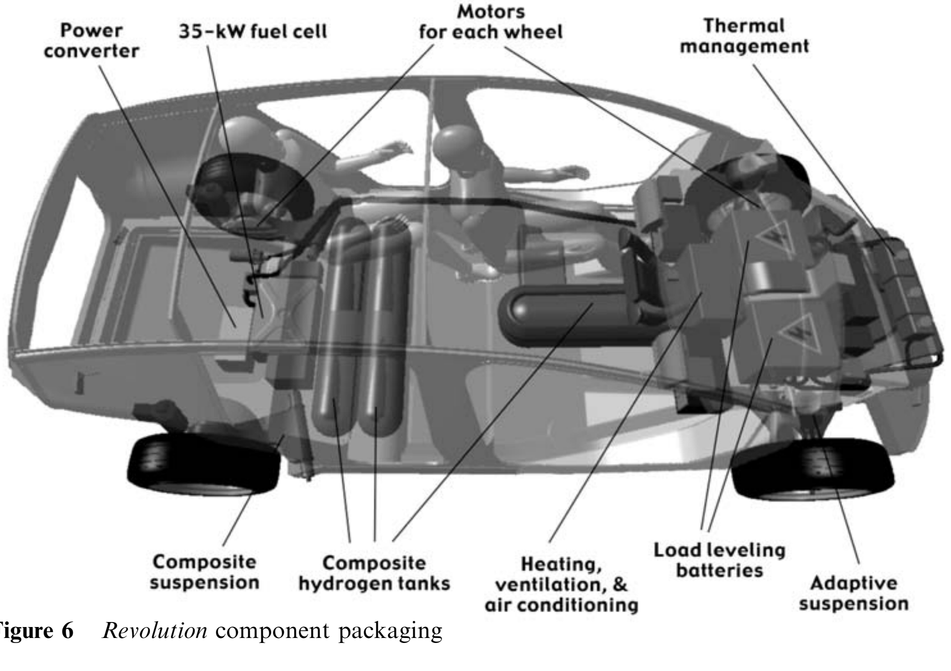

Figure 6 *Revolution* component packaging

wheels via carbon-fibre half shafts. This minimizes the unsprung mass of the front wheels and saves mass via shared housing and hardpoint attachments for the motors and brakes. The front motors are permanent magnet machines, each peak-rated at 21 kW. The rear switched reluctance motors are each 10 peak kW, so they're light enough to mount within the wheel hubs without an unacceptable sprung/unsprung mass ratio. Hubmotors also allow a low floor in the rear, and improve underbody aerodynamics by eliminating driveshaft, differential, and axles. The switched reluctance motors also have low inertia rotors and no electromagnetic loss when freewheeling, improving overall fuel economy especially at high speed. More efficient four-wheel regenerative braking is also possible with this system, further increasing fuel economy.

Proprietary innovations within the *Revolution* manage and distribute power among the drivesystem components. Powertrain electronics are currently expensive, and typical fuel cell systems require extensive power conditioning (using a DC–DC converter) to maintain a consistent voltage, since at full power, the stack voltage drops to approximately 50% of its open circuit voltage. Hypercar, Inc. developed a power electronics control methodology that simplifies power conditioning while optimally allocating powerflows under all conditions. This cuts the size of the fuel cell DC–DC converter by about 84%, reducing system cost, and improves power distribution efficiency, increasing fuel economy.

The normal doubling of radiator size (noted in Section 2.1) for a fuel cell vehicle doesn't handicap the *Revolution* because its tractive load, hence stack size, are reduced more than that by superior platform physics. The *Revolution*'s cooling system efficiently regulates the temperature of each powertrain component without resorting to multiple cooling circuits, which would add weight and cost. The common-rail cooling circuit illustrated in Figure 7 has a branch for each main powertrain component and a small secondary loop for passenger compartment heating. This loop also includes a small hydrogen-burning heater to supply extra startup heat for the passengers when required (though this need is minimized by other aspects of thermal design). The variable-speed coolant pump, larger-diameter common rail circuit, and electrically actuated thermostatic valves ensure sufficient cooling for all components without excessive pumping energy.

The *Revolution*'s fuel economy was modeled using a second-by-second vehicle physics model developed by Forschungsgesellschaft Kraftfahrwesen mbH Aachen ('FKA'), Aachen, Germany. All fuel-economy analyses were based on the US EPA highway and urban driving cycles, but with all speeds increased by 30% to emulate real-world driving conditions. Each driving cycle was run three times in succession to minimize any effect of the initial LLD state of charge on the fuel economy estimate.

In addition to fuel economy, Hypercar, Inc. simulated how well the powertrain would meet such load conditions as start-off at grade at gross vehicle mass, acceleration at both test and gross vehicle mass, and other variations to ensure that the vehicle would perform well in diverse driving conditions.

Illustrating the team's close integration to achieve the whole-vehicle design targets, the powertrain team worked closely with the chassis team to exploit the braking and steering capabilities allowed by all-wheel electric drive to create redundancy in these safety-critical applications. The powertrain, packaging, and chassis teams also worked closely together to distribute the mass of the powertrain

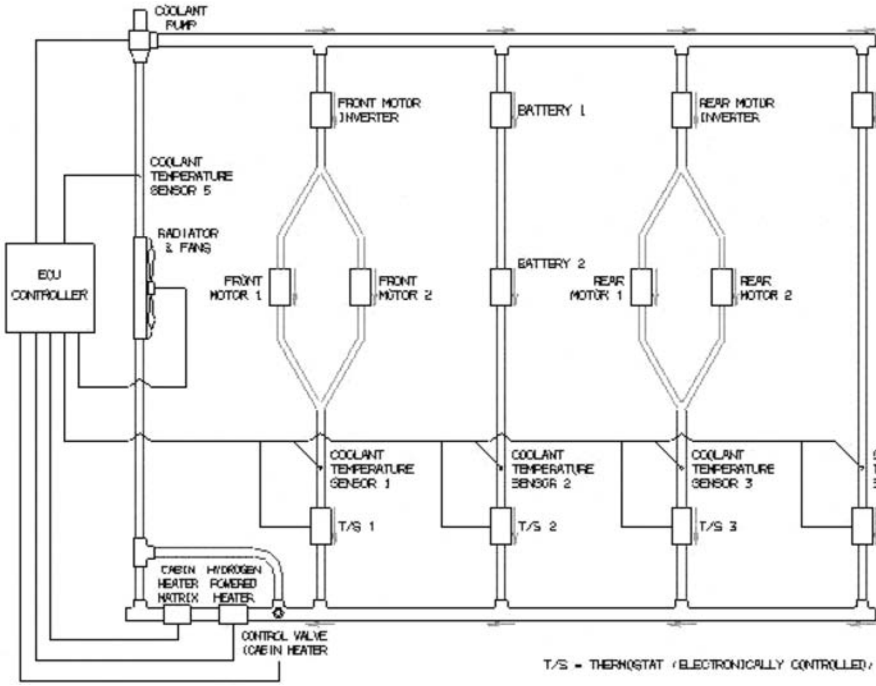

Figure 7 Cooling system schematic

components throughout the vehicle in order to balance the vehicle and keep its centre of gravity low.

3.5 Structure

3.5.1 Aluminium and composite front end

The front end of the *Revolution* body combines aluminium with advanced composites using each to do what it does best (Figure 8). The front bumper beam and upper energy-absorbing rail are made from advanced composite. The rest of the front-end structure is aluminium, with two main roles: to attach all the front-end powertrain and chassis components, and as the primary energy-absorbing member for frontal collisions greater than 24 km/h. Aluminium could do both tasks with low mass, low fabrication cost (simple extrusions and panels joined by welding and bonding), and avoidance of the more complex provision of numerous hardpoints in the composite structure.

3.5.2 Composite safety cell

The overarching challenge to using lightweight materials is cost-effectiveness. Since polymers and carbon fibre cost more per kilogram and per unit stiffness than steel, their structural design and manufacturing methods must provide offsetting cost reductions. Hypercar, Inc.'s design strategy minimized the total amount of material by optimal selection and efficient use; simplified and minimized assembly, tooling, parts handling, inventory, scrap, and processing costs; integrated multipurpose

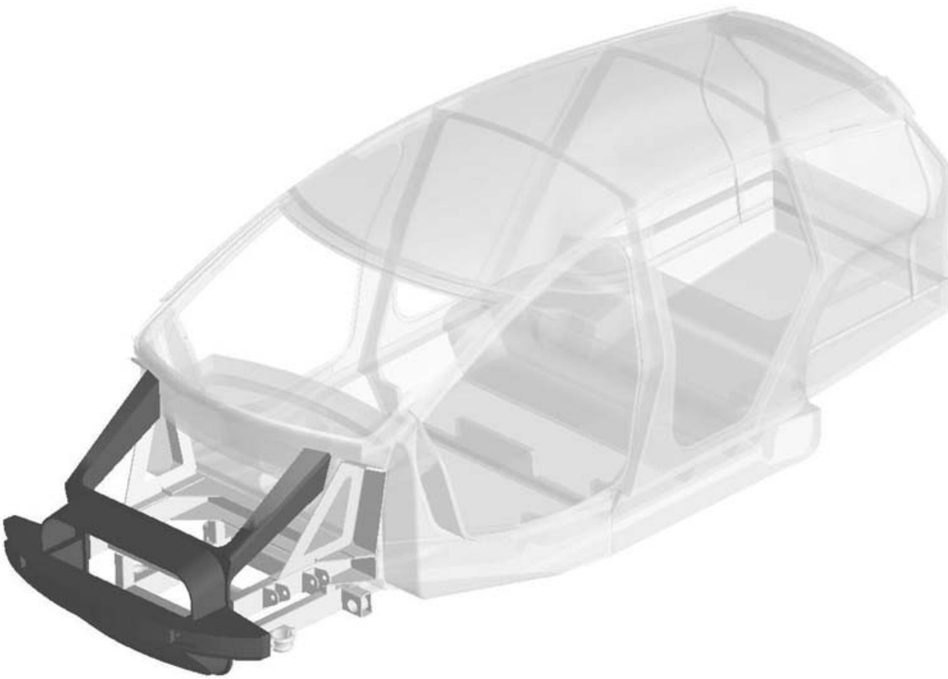

Figure 8 Aluminium and composite front end

functionality into the structure wherever practical; and employed a novel manufacturing system for fabricating the individual parts. Several design features supporting this strategy are described next.

3.6 Design features

3.6.1 Part consolidation

The primary structure is illustrated in Figures 9 and 10. It comprises 14 major parts and 62 total parts – roughly 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 number of parts and joint design simplify assembly, as a relatively small number of parts is held together until the adhesive bond sets up without the need for complex fixtures, and assembly is detoleranced in two dimensions.

3.6.2 Material selection

The materials used in the design of the passenger safety cell are predominantly intermediate-modulus PAN-based carbon fibre and low-viscosity nylon 12 ‘laurolactam’ thermoplastic. To improve processability, long discontinuous fibre (LDF) carbon is used. Compared with continuous fibre, LDF allows greater formability of the part without crimping or buckling because the preform can stretch during

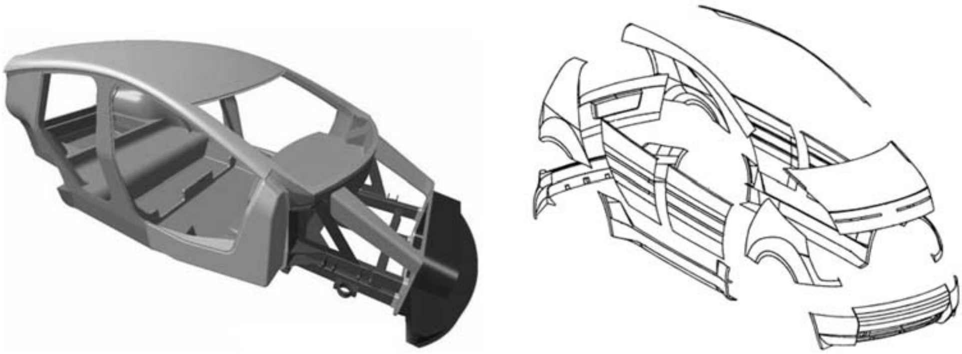

Figure 9 Composite structure, aluminium/composite front subframe, and exterior panels

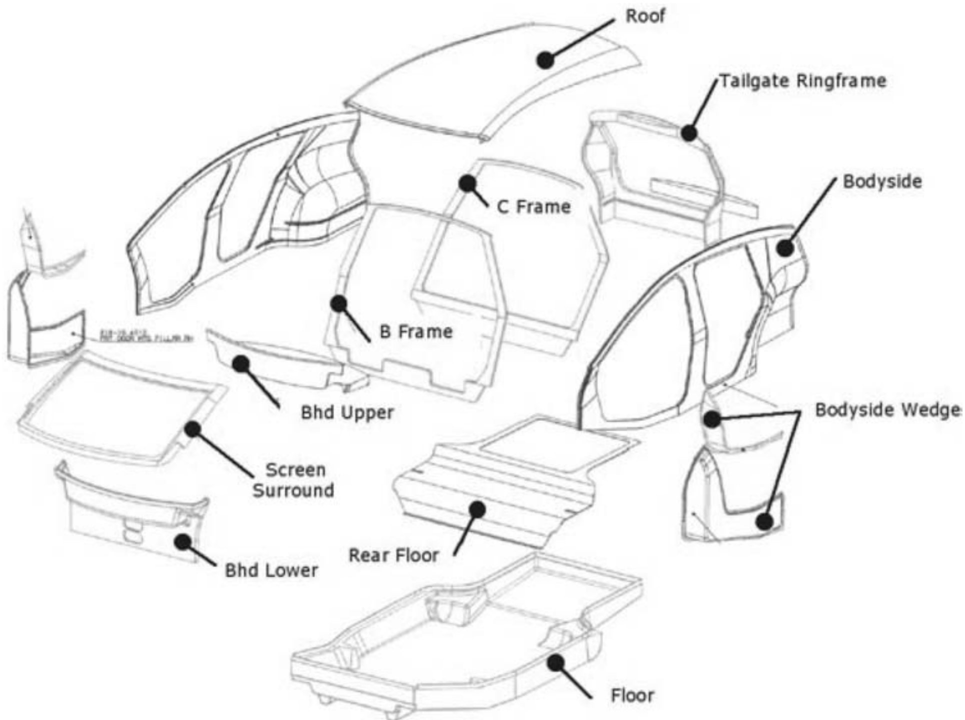

Figure 10 Composite safety cell exploded view

processing. Yet the fibres are long enough to maintain near-continuous-fibre levels of stiffness in the finished part.

3.6.3 Part design

Each part is designed for low-cost fabrication and assembly, achieving a complex structure from simple parts. While some components have complex surface geometry, they are relatively shallow, with few sharp bends or deep draws – minimizing tooling cost, enhancing repeatability, and eliminating the need for labour-intensive pre- and post-process steps.

3.6.4 Structural analysis

Both static structural and dynamic crash analyses were performed on the *Revolution* 'Body-in-Black'™ (BIB). The static analyses indicate a bending stiffness of 14 470 N/mm, a torsional stiffness of 38 490 N•m/deg, first bending mode of 93 Hz, and first torsion mode of 62 Hz – indicating that the structure would be over 50% stiffer than premium sports sedans.

For crash performance, the *Revolution* relies on a combination of the energy absorbing properties of aluminium 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 using industry-standard tools indicate that the *Revolution* would surpass US Federal Motor Vehicle Safety Standards (FMVSS) for a 48-km/h fixed-barrier collision even at speeds up to 56 km/h (Figure 11). The damage from such a front-end collision would be contained within the aluminium front subframe without any damage to the carbon-fibre safety cell, facilitating occupant extrication and repair. Moreover, in a head-on collision with a vehicle up to twice its mass, each traveling up to 48 km/h, the *Revolution* is also designed to meet FMVSS fixed-barrier head-on standards. Thus the *Revolution*'s crash structures would successfully absorb the extra kinetic energy transferred to it due to its lightness relative to its collision partner, and achieve uncompromised passenger safety, while also offering the public-safety advantage of lower mass-aggressiveness toward any vehicles it might hit.

3.7 Occupant environment

The occupant environment typically accounts for 30% of the mass and cost of a new vehicle. Since it is also what users most intimately experience, automakers pay close attention to design for aesthetic appeal, ergonomics, and comfort. The *Revolution* development team was challenged to provide a lightweight interior that would still meet aggressive safety, comfort, acoustic, thermal, and aesthetic requirements. The

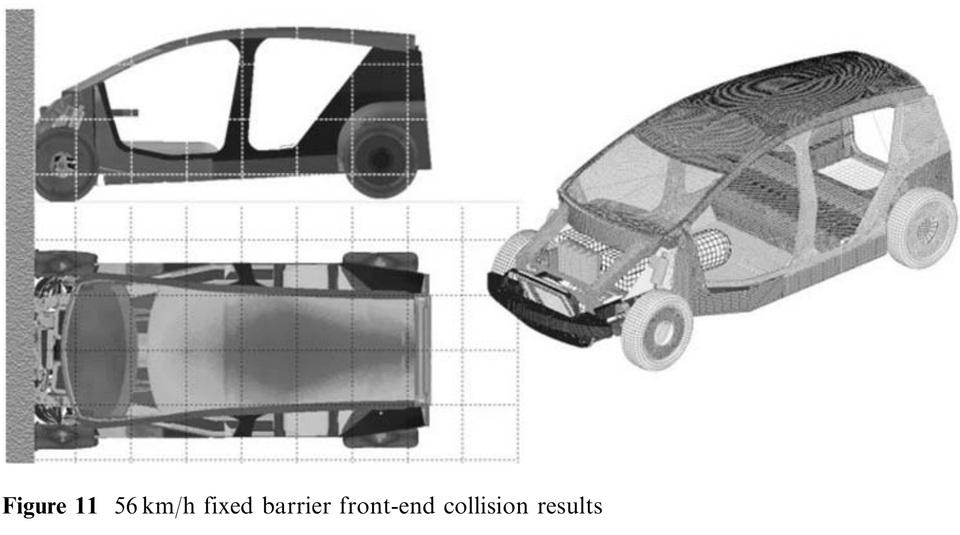

Figure 11 56 km/h fixed barrier front-end collision results

result: much of the inner surface of the carbon-fibre safety cell is exposed to the interior, and energy-absorbing trim is applied only where needed to meet FMVSS requirements (Figure 12). The carbon fibre 'look' is becoming increasingly popular in several automotive and non-automotive markets, so this feature should meet all requirements – light weight, aesthetically appealing, low cost, and safe – though it may not fit the tastes of all market segments.

Other interior safety features integrated into the *Revolution* include front and side airbags, pretensioning seatbelts, and sidestick control of steering, braking, and

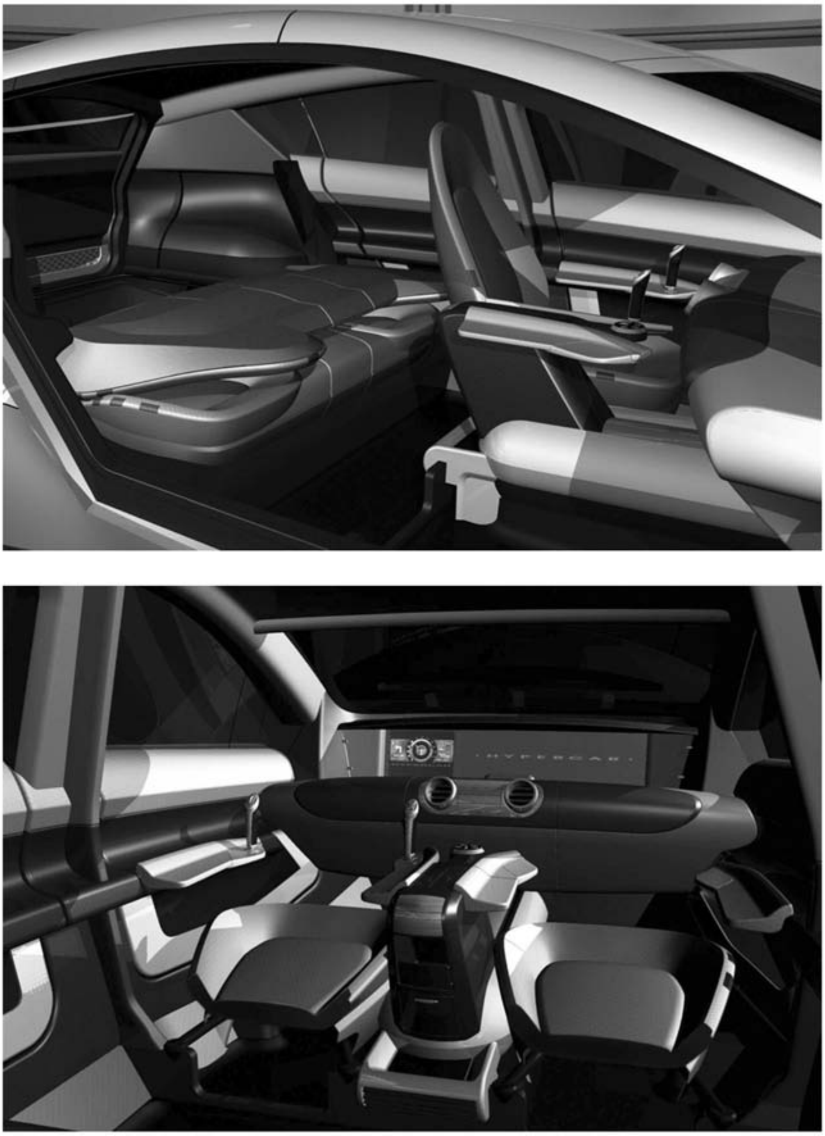

Figure 12 *Revolution* interior drawings

acceleration. While using a sidestick to control automobiles may take some time to gain wide consumer acceptance, its safety benefits are compelling. It gets rid of the steering column and pedals – the leading sources of injury in collisions because they are the first things that the driver hits. Without these obstacles, the seat belt and airbag system have more room to decelerate the driver more gently. This is especially important for short drivers who typically have to pull their seat far forward in order to reach the pedals, putting them dangerously close to the airbag in conventional vehicles. In the *Revolution*, the seat does not adjust forward and back, only vertically, so drivers of all sizes will be the same distance from the airbags, improving its deployment-speed calibration and increasing overall safety. Sidesticks also improve accident avoidance. Studies have shown [30] that after a short familiarization period, sidestick drivers are much better at performing emergency evasive maneuvers than are stick-and-pedal drivers, due to finer motor control in hands than in feet, and greater speed and ease of eye-hand than of eye-hand-foot coordination. Clearly, more work would be required in this area for sidesticks to be feasible, but for the purposes of this concept vehicle, the team could demonstrate sufficient safety benefits to keep them in the final design. DaimlerChrysler, BMW, and Citröen appear to share this view.

Another user interface safety feature is the LCD screen that replaces numerous traditional gauges and displays. Placing the screen at the base of the windshield, centred on the driver's line of sight, allows the driver to change any vehicle settings via a common interface without greatly shifting the driver's viewline or focal distance. The multi-function display and the software-rich design of the vehicle also add such non-safety benefits as the ability to customize the interface and add new software-based services without adding new hardware.

To adjust settings, the driver or passenger would use voice commands or a small pod with four buttons and a jogwheel located in the center console between the front seat occupants (Figure 13). The buttons govern climate control, entertainment, navigation, and general settings, while the jogwheel is used to navigate menus and

Figure 13 Close-up view of control pod

select options. The menu structure is simple and intuitive, with options for user control of distraction level and data privacy.

3.7.1 Climate control

The climate control strategy illustrated in the *Revolution* design is intended to deliver superior passenger comfort using one-fourth or less of the power used in conventional vehicles. This required a systematic approach to insulation, low thermal mass materials, airflow management, and an efficient air conditioning compressor system. The foamcore body, the lower-than-metal thermal mass of the composites, ambient venting, and spectrally selective glazings greatly reduce unwanted infrared gain, helping cooling requirements drop by a factor of roughly 4.5. Power required for cooling is then further reduced by heat-driven desiccant dehumidification and other improvements to the cooling-system and air-handling design.

Similarly, the *Revolution* was designed to ensure quick warmup, controllability, and comfort in very cold climates. The heating system is similar to that of conventional vehicles, but augmented by radiant heaters, a small hydrogen burner for quick initial warmup if needed, and a nearly invisible heater/defroster element embedded in the windshield.

3.8 Chassis

The chassis system combines semi-active independent suspension at each corner of the vehicle, electrically actuated carbon-based disc brakes, modular rear corner drivetrain hardware and suspension, electrically actuated steering, and a high-efficiency run-flat wheel and tyre system. This combination can provide excellent braking, steering, cornering, and maneuverability throughout the vehicle's payload range and in diverse driving conditions.

3.8.1 Suspension

The *Revolution*'s suspension system combines lightweight aluminium and advanced-composite members with four pneumatic/electromagnetic linear-ram suspension struts developed by Advanced Motion Technology, a pneumatically variable transverse link at each axle, and a digital control system linked to other vehicle subsystems (Figure 14). The linear rams comprise a variable air spring and variable electromagnetic damper. The pressure in the air spring can be increased or decreased to change the static strut length under load and to adjust the spring rate. The resistance in the damper can be varied in less than one millisecond, or up to 1000 times per vertical cycle of the strut piston. The overall suspension system takes advantage of the widely and, in the case of damping, rapidly tunable characteristics of these components. Thus the same vehicle can pass terrain that requires high ground clearance, but also ride lower at highway speeds to improve aerodynamics and drop the center of mass.

Each strut is linked transversely (across the vehicle) to counter body roll (Figure 15). The link itself is isolated so that a failure that might compromise anti-roll stiffness would not compromise the pneumatic springs. Hydraulic elements connect the variable pneumatic element at the center of the transverse link to the left and

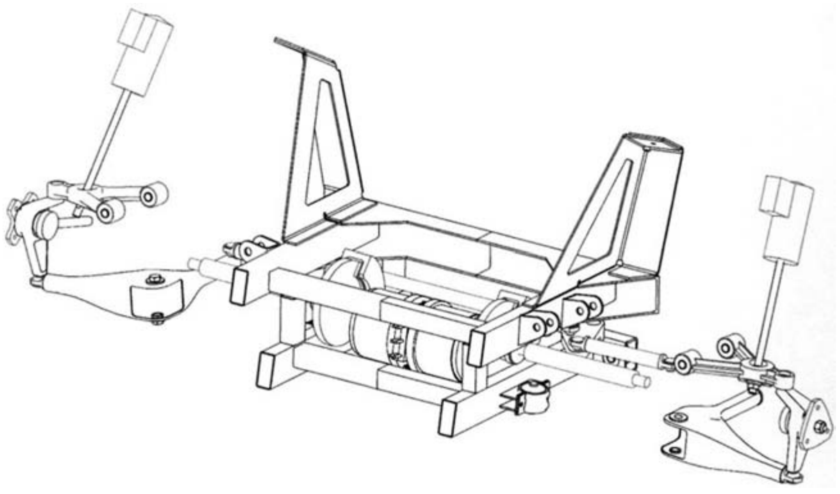

Figure 14a *Revolution* chassis system (front)

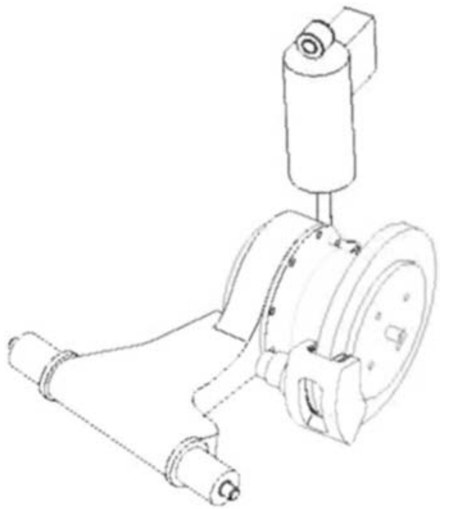

Figure 14b *Revolution* chassis system (rear)

right struts. The stiffness of the transverse link is adjusted by varying the pressure in the isolated pneumatic segment. Oversized diaphragms reduce the pressure required in the variable pneumatic portion of the roll-control link (normally at about 414–828 kPa), minimizing the energy required to tune the anti-roll characteristics. The anti-roll system works in close coordination with the individual electromagnetic struts to control fast transients in body roll and pitch during acceleration, braking, cornering, and aerodynamic inputs. Many technologies can provide semi-active suspension, but the linear rams best fit the *Revolution*'s energy efficiency needs by regenerating modest amounts of power when damping.

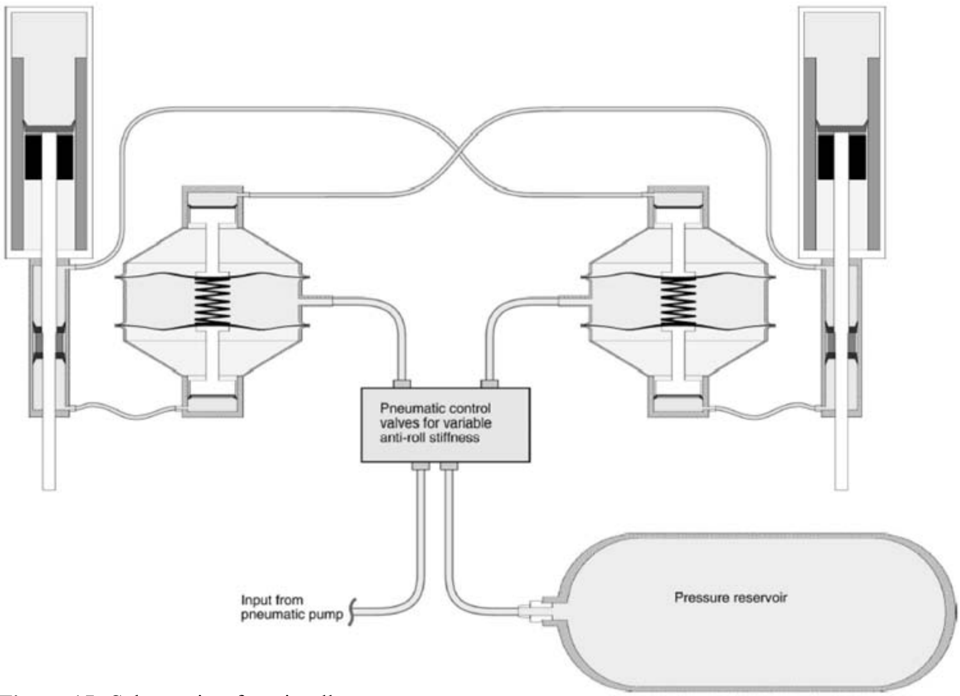

Figure 15 Schematic of anti-roll system

3.8.2 Brakes

The *Revolution*'s brakes combine electrical actuation with carbon/carbon brake pads and rotors to achieve high durability and braking performance at low mass. The front brakes are mounted inboard to reduce unsprung mass. Carbon/carbon brakes' non-linear friction properties depending on moisture and temperature are compensated by the electronic braking control, because the caliper pressure is not physically connected to the driver's brake pedal, so any nonlinearities between caliper pressure and stopping force are automatically corrected. Electrical actuation also eliminates several hydraulic components, which saves weight, potentially improves reliability, and allows very fast actuation of anti-lock braking and stability control. The brake calipers and rotors should last as long as the car.

3.8.3 Steering

The *Revolution*'s steer-by-wire system has no mechanical link between the driver and the steered wheels. Instead, dual electric motors apply steering force to the wheels through low-cost, lightweight bell cranks and tubular composite mechanical links (Figure 16). This design permits continuously adjustable steering dynamics and maintains Ackerman angle over a range of vehicle ride heights, in a modular, energy-efficient, and relatively low cost package.

3.8.4 Wheel and tyre system

Hypercar collaborated closely with Michelin on the design of the wheel and tyre system for the *Revolution*. The PAX® run-flat tyre system reduces rolling resistance

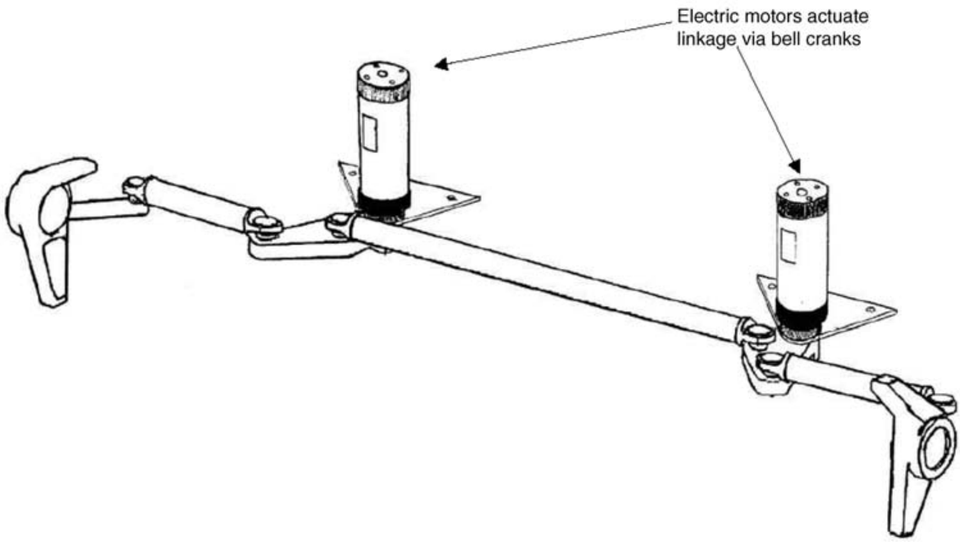

Figure 16 Steer-by-wire system

by 15%, improves safety and security (all four tyres can go flat, yet the vehicle will still be driveable at highway speeds), and improves packaging (no need for a spare). The PAX technology is slightly heavier per corner than conventional wheel/tyre systems, but eliminating the spare tyre reduces total net mass.

3.9 Power distribution, electronics, and control systems

The *Revolution*'s electrical and electronic systems are network- and bus-based, reducing mass, cost, complexity, failure modes, and diagnostic problems compared with traditional dedicated point-to-point signal and power wiring and specialized connectors. The new architecture also permits almost infinite flexibility for customer and aftermarket provider upgrades by adding or changing software. In effect, the *Revolution* is designed not as a car with chips but as a computer with wheels.

3.9.1 Control system architecture and software

The vehicle control system architecture relies on distributed integrated control. 'Intelligent' devices (nodes) perform real-time control of local hardware and communicate via multiplexed communications data links. Nodes are functionally grouped to communicate with a specific host controller and other devices using well-developed controller-area-network (CAN) or time-triggered network protocols. (The latter includes redundant hardware and deterministic signal latencies to ensure accurate and timely control of such safety-critical functions as steering, braking, and airbag deployment.) Each host controller manages the objectives of the devices linked to it. Host controllers of different functional groups are mounted together in a modular racking system and communicate via a high-speed data backplane. This modular, three-level architecture provides local autonomous real-time control, data aggregation, centralized control of component objectives, centralized diagnostics, and high reliability and resilience. The central controller runs additional services and applications related to the operation of the vehicle entertainment systems and data communications. It also provides a seamless graphical user interface to all systems on the vehicle for operation and diagnostics (see *3.7 Occupant Environment*).

This system, developed in collaboration with Sun Microsystems and STMicroelectronics, has many advantages. First, networking allows data to be shared between components and aggregated to create knowledge about the car's behaviour and its local environment and to create new functions in the vehicle. Networking also reduces the weight, cost, failure modes, and complexity of wiring harnesses: for example, a typical vehicle has approximately 25 wires routed to the driver's-side door, while the *Revolution* uses four.

The central controller and user interface and the user communications are all handled by a Java embedded server developed by Sun Microsystems and conforming to the Open Services Gateway Initiative (OSGI) standard. This network-centric approach provides high security, resilience, and reliability. Adding approved hardware devices or certified applets is simple and robust, with automatic installation and upgrading during continuous operation. The *Revolution*'s specific software design contains many useful, innovative, and valuable features.

3.9.2 Power distribution

All non-traction power is delivered via a 42-volt ring-architecture power bus, providing fault-tolerant power throughout the vehicle. Components are connected to the ring main via junction boxes distributed throughout the vehicle, via either a subring (to maintain fault-tolerance to the device) or a simple branch line for non-fault-tolerant devices. The junction boxes are fused so that power can be supplied to the branches from either leg of the ring main. The benefits of this system include low mass, high energy efficiency, fault-tolerance, simplicity, and cost-effectiveness.

3.10 Cost analysis

Given the many new technologies in the *Revolution*, one might wonder how much such a vehicle might cost to produce. Answering this question was one of the main goals of the *Revolution* development programme, which was explicitly designed around cost criteria. The engineering team estimated the vehicle's production cost at a nominal volume of 50 000 units per year, using extensive anonymous supplier price quotations (for 82% of the components), plus some in-house and independent consultants' bottom-up cost modeling for technologies not yet in production. As designed, the vehicle could be sold profitably at standard markups for US$40–45 000 retail. With further development, Hypercar, Inc. estimates that this price could be reduced to approximately US$35 000 – competitive with existing vehicles of similar performance, features, size, and amenity but lacking *Revolution*'s exciting features and quintupled fuel economy.

This cost estimate is directly related to the starting point – the product requirements. Part of Hypercar, Inc.'s reason for designing a vehicle for the entry-level luxury sport utility segment was that its pricepoint would make many of the advanced features affordable. If the product requirements were instead for a small economy car, it would be designed differently to meet those requirements, it may not include all the features of the *Revolution*, and cost reduction requirements could become more stringent.

4 Ultralight autobody manufacturing process

All advanced-composite parts in the *Revolution*'s body structure and suspension system were designed for manufacturing using a patented process under development by Hypercar, Inc. called Fiberforge™. The Fiberforge process starts by making raw materials into a composite 'tailored blank.' Blanks are then turned into final parts by either a liquid infusion moulding or a solid-state thermoplastic stamping process. The tailored blanks are flat laminated sheets made in the rough outline of a part with the orientation and amount of fibres matching loadpaths through the part. Using discontinuous rather than continuous fibres allows these flat sheets to stretch to net shape in either a thermoforming press or a preforming operation.

Fiberforge promises to break through the traditional cost/performance/production-rate tradeoff typical of composites to yield a practical solution that meets automotive requirements at volume. The main process steps are illustrated in Figure 17 and described below.

4.1 Composite blank fabrication

The first step in the Fiberforge process is creating a tailored blank. This process rapidly places semi-consolidated layers of fibre and matrix on a flat conveyor, each layer with a specific fibre orientation. Consolidating the layers through a series of rollers finishes the blanks. This critical first step turns raw material inputs (fibre and polymer matrix) into a form that can be stamped directly (process shown in Figure 17) or preformed for resin infusion processes without additional process steps. The difference between the tailored blank in the case of stamping or resin infusion is the degree of resin impregnation and consolidation.

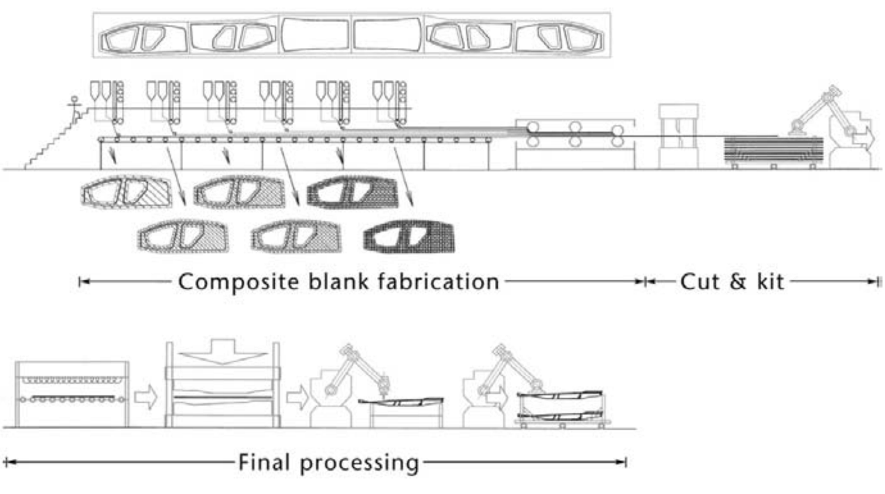

Figure 17 Composite part fabrication (thermoplastic stamping shown)

Key benefits of tailored blanks include:

- **Precise control of fibre alignment, angle, and thickness**. The Fiberforge computer-controlled tailored blanking process can align fibres to match precisely a part's loadpaths and geometry. This best uses the fibres by minimizing the material needed to achieve the required mechanical performance.
- **High fibre volume fraction parts**. In advanced composites, the fibres provide most of the strength and stiffness, while the matrix holds the fibres in place, protects them, and transfers load between them. The higher the volume fraction of fibres in a part, the lower its mass. The Fiberforge process will produce parts with fibre volume fractions from 55% to 65%, depending on the final forming process. This is much higher than traditional automotive composites such as sheet moulding compound (SMC), which typically have fibre loadings of 20–30%.
- **Low scrap**. The tailored blank fabrication process places material only where it is needed in the part, greatly reducing normal scrap rates from edge-trimming and hole-cutting.
- **Flexible production equipment**. Fiberforge equipment can make tailored blanks for any composite part that will fit. Software control allows Fiberforge equipment to create tailored blanks for a variety of parts in series, continuously laying up part-specific blanks to the desired production volume without having to switch tools or forms, and if required, automatically including special plies of different materials, inserts, or structural cores.

4.2 Cut and kit

Tailored blanks are sorted into kits for transfer to the final processing stations. If desired, this step can physically separate blank fabrication from final part manufacturing cells, thus maximizing machine utilization.

4.3 Final processing

The final processing step depends on the specific application. For most of the *Revolution*'s composite parts, the manufacturing process chosen is a resin transfer moulding (RTM) variant using a nylon-12 laurolactam thermoplastic resin. The tailored blanks are preformed, then placed in a mould, 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 if necessary, and racked for transfer to body assembly.

4.4 Body assembly

The body assembly sequence, illustrated in Figure 18, builds up in parallel the front chassis assembly, passenger safety cell, and front bumper subassembly, then mates them together. 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 fast-setting adhesive quickly provides handling strength. The assembly sequence robotically applies adhesive to ensure proper metering and precise placement. After step B6, exterior panels, propulsion, rear suspension, closures (doors, bootlid, and bonnet), and interior elements are assembled to the body.

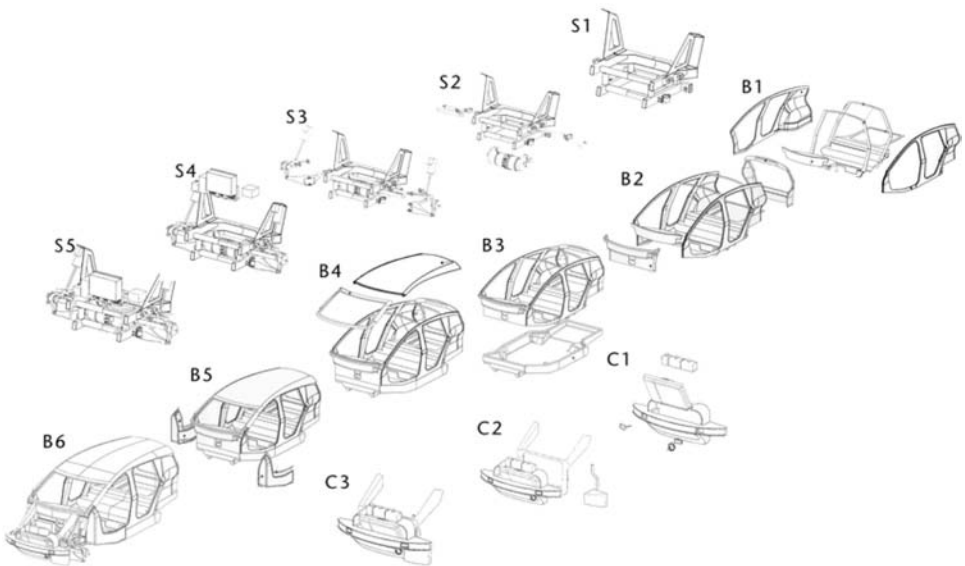

Figure 18 Body assembly sequence

5 Direct-hydrogen fueling and infrastructure

Hypercar, Inc.'s approach to 3–5η vehicles can use any fuel and any powertrain, but that powertrain can be very small. For example, the five-seat carbon *Revolution* concept SUV has essentially the same kerb mass and drag coefficient as the two-seat Honda *Insight* aluminium hybrid car (856 kg, 0.25), although it has a larger frontal area and rolling resistance. The *Insight*'s hybrid-assist powertrain – a 50-kW 1-L VTEC petrol-fueled Otto engine assisted by a 10-kW electric motor – would thus presumably yield respectable performance. Rough estimates suggest that such a combination should achieve in the order of 3.5 L/100 km, severalfold better than today's Otto-engine SUVs. However, integrated ultralight vehicles' most distinctive advantages emerge when they are powered by a direct-hydrogen fuel cell.

Such low-mass, low-drag platforms reduce tractive load by about threefold: the *Revolution* design, for example, is simulated to cruise at 89 km/h on the same power to the wheels (7 kW) that a normal SUV uses on a hot day just to run its air-conditioner. Such low tractive load makes 5η vehicles uniquely ready for direct-hydrogen fuel cells, because their threefold-smaller fuel-cell stack is affordable even at initially high prices (Table 1) – many years sooner than in high-tractive-load platforms – and their threefold-smaller hydrogen tanks are small enough to package well (Figure 6). Eliminating an onboard reformer and fueling the stack with direct hydrogen then maximizes the stack's output rating, lifetime, and fuel and catalyst efficiency, triggering further compounding savings in mass, cost, and complexity.

Hydrogen fueling was once thought to be costly, slow, and difficult to deploy for three reasons:

- The supposed difficulty of onboard storage. This has been solved by commercially available filament-wound carbon-fibre tanks lined with an

aluminized polyester bladder, provided that the vehicle is efficient enough to make the tanks conveniently packageable, as 3–5η designs do. The tanks on the market in 2003 are extremely rugged and safe, have no external high-pressure components, provide normal driving range in efficient platforms, and contain $\sim$8–12 mass percent hydrogen when filled to 345 (US-approved) or 690 (German-approved) bar pressure. Further technical progress will doubtless occur but is not required.
- The presumed hazards of hydrogen gas. These have been technically resolved by more careful study and industry experience. Most experts believe public acceptance is likely once vivid side-by-side safety demonstrations are presented to the public [31]. Hydrogen, like any fuel, is hazardous, but its hazards are quite different from and no more severe than those of petrol or liquefied petroleum gas. Indeed, it can be considered qualitatively safer, due to its buoyancy, diffusivity, and nonluminous flame (which prevents radiant burns at a distance) [32,33]. Commitments by at least eight major automakers to start distributing fuel-cell cars (mainly direct-hydrogen) by 2005, as Honda and Toyota already did (in very small volume and at high prices) in late 2002, bespeak their concurrence.
- The need for new infrastructure to produce and deliver the hydrogen gas. Widely quoted but clearly exaggerated estimates put the US investment need at around US$300 billion. Since such a massive investment would supposedly be needed up front, before hydrogen cars could be sold and begin to yield any revenue to hydrogen producers, this made no business sense.

RMI's 1999 proposal of a novel deployment strategy [22], however, revealed a transitional path that would be profitable at each step, starting now. It would yield early revenue to support subsequent investment, and create many important new value propositions. This strategy, summarized next, has been quietly adopted by major car and energy companies, and is starting to become visible in their announced activities. Since 2001, evidence has emerged that it probably offers important business advantages not only over other ways of building a hydrogen economy, but also over continuing conventional hydrocarbon-based investments such as petrol fueling.

The hydrogen-transition puzzle is unlocked by two keys: hydrogen-ready light vehicles, and integrating their deployment with that of stationary fuel cells in buildings (a problem previously thought unrelated), so that each helps the other happen faster. (That proposition may depend on whether fuel-cell developers first achieve long life, which buildings need, or low cost, which cars need. Many observers would say that durability must come first because low cost will be achieved only by high production volumes whose markets presuppose reasonable durability.)

The first step is installing fuel cells in buildings (which use two-thirds of the electricity in most industrial countries) to provide premium-quality electricity for digital loads, as well as heating and cooling from the fuel cells' and natural-gas reformers' waste heat. (Miniature gas reformers for this purpose are becoming available at $\sim$70–80% efficiency and high reliability; experimental processes look even better; and in some cases where offpeak electricity is cheap, it can be used to electrolyze water instead.)

Meanwhile, hydrogen-ready quintupled-efficiency 5η vehicles would be brought to market, initially for fleets that refuel at a central depot where hydrogen can be produced, then delivered into the cars' high-pressure tanks just like compressed natural gas. Then to enter the general market, such cars could be leased initially to people who work in or near the buildings where fuel cells would have by then been installed. Since the hydrogen appliances to run these fuel cells in the buildings would be sized for peak building loads that would seldom occur, they could usually produce surplus hydrogen that could be compressed, stored, and delivered to the cars parked nearby. Those cars could then deliver premium-quality electricity and valuable ancillary services to the electric grid, at the time and place where they would be most valuable, by serving as plug-in power-plants-on-wheels. This requires investment in more durable stacks, hydrogen delivery to the cars, and electricity delivery from the cars, but those investments are much less than the benefits of greatly increasing asset utilization for both the buildings' hydrogen appliances and the cars' fuel cells (US passenger cars are typically parked $\sim$96% of the time and have a prime-mover asset utilization below 1%). For most electric utilities, such near-the-load generation can be valuable enough [37–40] to repay most or all of the car's ownership cost. Such value propositions as the garage's paying one to park there should attract many market actors. The value of these portable generators will increase further as 'distributed benefits' [41–42] are taken into account. If all US light vehicles were so equipped and used, their generating capacity ($\sim$220 million light vehicles $\times$ 20–45 kW/vehicle) would total $\sim$4–10 TW – $\sim$5–12 $\times$ total US generating capacity (0.86 TW in 2001).

Meanwhile, as hydrogen appliances mass-produced for buildings become cheaper, they could also be installed outside buildings – *e.g.*, at petrol filling stations. This would be a more attractive business than selling petrol, because the proprietor, rather than being under the thumb of refiners and distributors who keep trying capture margins, could independently produce a premium fuel (hydrogen) from two ubiquitous and competitive retail commodities – electricity and natural gas – using the offpeak distribution capacity for each that is already built and paid for. The capital intensity of such a hydrogen refueling infrastructure using miniature natural-gas reformers is probably *less* than the capital intensity of sustaining the existing petrol fueling infrastructure – by $\sim$US$1 trillion worldwide over the next 40 years [43]. Moreover, the hydrogen strategy may even decrease total US consumption of natural gas [44]. More natural gas would be converted to hydrogen to fuel light vehicles, but still more could be saved in power plants displaced by fuel cells (especially the inefficient plants run at or near peak-load periods), in the furnaces and boilers displaced by fuel cells' and reformers' waste heat, and in making hydrogen for refineries to produce petrol [45,47].

As hydrogen, stationary fuel cells, and fuel-cell vehicles become widespread, it will become feasible, and may become cheaper (we don't yet know whether big systems cost less than small ones), to produce hydrogen in bulk and distribute it, much like natural gas today. There are at least two proven, profitable, and climate-safe ways to do this:

- Reform natural gas at the wellhead (now done to make industrial hydrogen from $\sim$6–8% of US natural gas production) and reinject the separated CO_2 into the reservoir (a standard method of enhanced oil recovery, now being tried by Statoil for carbon sequestration in the North Sea). The developer can potentially get paid three times – for hydrogen shipments, enhanced hydrocarbon production (from repressurizing the reservoir), and carbon sequestration. This prospect of exploiting the world's widely distributed two-century natural-gas resource without harming the climate is attracting strong industry interest.

- Electrolyzing water with climate-safe electricity. This wouldn't mean building more nuclear plants because they're grossly uncompetitive, but it would greatly improve the already attractive economics of new renewable resources. Because fuel cells convert fuel into traction 2–3 × more efficiently than Otto engines, even US petrol prices (~ US\$0.33/L, cheaper than bottled water) are equivalent *at the wheels* to hydrogen efficiently made from electricity sold at ~ US\$0.09–0.14/kWh. That is the equivalent of the price that electricity can fetch if, instead of selling electrons as a raw commodity, the proprietor of a dam or a windfarm converts the electrons into a value-added product by attaching a proton to each electron. Thus running, say, a hydroelectric dam in this 'Hydro-Gen' mode can earn ~ 4–8 × more value than just selling electricity. Moreover, modest local storage of hydrogen can turn intermittent renewables, such as wind and solar power, into more valuable firm and dispatchable power.

There are probably more hydrogen options too. Promising renewable methods, including novel hydrogen-producing biofuel systems and direct photolysis, show promise. The BP/Princeton Carbon Mitigation Initiative is finding that coal may be a cheaper long-run source of hydrogen than natural gas: coal contains less hydrogen and is harder to handle, but its much lower price may offset these drawbacks. But we need only one way to produce bulk hydrogen, and we have at least two proven, climate-safe, and profitable ways. More options will just enhance competition. Through a combination of methods enabled by hydrogen-ready light vehicles, the transition from today's fuel mix, whose atoms are nearly one-third carbon and over two-thirds hydrogen, to a future 'low-carbs' diet that is virtually all hydrogen, seems both inevitable and advantageous. And surprisingly, the required hydrogen industry is not much larger than that which already exists. Current global production of industrial hydrogen is about 50 million tonnes per year, a substantial fraction of which (in the US, half) goes to refineries to make light products such as petrol. A hydrogen industry only about half as big again as the existing one, if used to fuel 5η vehicles, could displace the world's entire current petrol consumption [45].

6 Implications for oil and automaking

Natural gas is certainly, and coal may turn out to be, a profitable way to produce bulk hydrogen for hydrogen-ready vehicles. But in the intermediate case – liquid hydrocarbons – the hydrogen seems generally to be worth more without the carbon than with the carbon; *i.e.*, hydrogen plus 'negacarbon' that Kyoto traders will pay one not to emit is typically worth more than hydrocarbon. Liquid hydrocarbons should probably therefore be sent to reformers, not refineries, and some refineries may become merchant hydrogen plants. The oil industry is starting to realize this and to reflect this realization in its strategic planning, although the subject is competitively so important that it is seldom openly discussed.

Even if hydrogen takes over the light-vehicle market, many presume that refineries and upstream oil assets will be protected by perpetual demand for middle distillates, immune to non-petroleum displacement. But this may not be correct. Heavy vehicles may well use biodiesel if they don't convert to fuel cells. Even jet fuel could be displaced over decades: Boeing long ago found bulky-but-lightweight liquid hydrogen an attractive aviation fuel (hence its use in high-performance rockets). Boeing is experimenting with hydrogen fuel cells for aviation auxiliary power and even for propulsion – the storage system already proven in the world's highest-performance solar-powered 'eternal airplane' [46].

The implications of 5η vehicles for the car industry are even more profound, and as with oil, may be painful or beneficial, depending on the acuity of strategic planning and the timeliness of execution. Automakers' and major suppliers' adoption of 5η designs is currently being slowed as much by cultural as by technical and economic constraints. These extraordinarily large, complex, and capable organizations are superbly skilled in metals, much less in advanced composites. They focus on cost per part or per kilogram, not per car. They often treat sunk costs as unamortized assets – basing decisions on accounting, not economics – as if it were better to write off obsolete assets later when they don't have a company than now when they do. They suffer from many institutional rigidities. Their depth of design integration is improving but still suboptimal. Though they contain many excellent engineers awaiting mobilization, it is very hard for OEMs to make leapfrogs ... but very risky not to, because major suppliers and new entrants, not just more adventurous OEMs, could become formidable competitors. Success in vaulting these and other daunting cultural barriers will determine the fate of this industry's incumbent giants, and the prospects for those hoping to supplant them.

A smoother transition could be achieved, sooner, with higher confidence, if national policy encouraged it [47,48]. For example, revenue-neutral 'feebates' (rebates for buying efficient cars, fees for buying inefficient cars, the fees to pay for the rebates) could raise buyers' desire to buy and reduce makers' risk to sell efficient cars. (The California Legislature approved such a law by 7:1 in 1990, and public support there today is at least 3:1.) The rebates could suffice to pay most of the cost of very efficient cars, especially for low-income customers. Adding an 'accelerated-scrappage' provision (rebates for efficient new cars depend on the *difference* in efficiency between the new car bought and the old car scrapped) can also stimulate demand by prematurely retiring the least efficient vehicles, yielding disproportionately rapid benefits for oil savings, climate, prosperity, and security. Moreover, unlike static standards, feebates reward continuous improvement. Such creative, win-win policy instruments can accelerate innovation and encourage needed integration between mobile and stationary uses of fuel cells. Making policy both easier and less necessary is 5η vehicles' end–run around policy gridlock via breakthrough engineering, so customers will ultimately buy such cars for the same reason they now buy digital media instead of vinyl gramophone records – they're simply a superior product that redefines market expectations.

Meanwhile, forces beyond automotive markets are at work. Important military applications and spinoffs, such as the ultralight tactical vehicles vital to meet requirements for deployability, agility, and force sustainment, may speed commercialization. Countries lacking car industries, too, may find strong incentives to build a highly competitive one from scratch using the new, low-capital model. And Royal Dutch/Shell Group's latest planning scenarios [49] envisage a People's Republic of China-led leapfrog to hydrogen and 5η vehicles – a development that now seems to be clearly emerging with encouragement from the paramount leadership of the People's Republic.

To be sure, progress is uneven. The US Department of Energy, which announced an industry collaboration called FreedomCAR in January 2002, is still planning to spend 10–20 years achieving goals comparable to those already met in 2000 (Section 3), while the US National Academy of Sciences in 2001 completed its second study of automotive efficiency that pays no attention to fuel cells and almost none to lightweighting or aerodynamics. But where technical and economic logic are compelling, policy and institutional culture will eventually follow. The increasingly obvious costs and risks of oil dependence [47] and carbon emissions seem bound to accelerate an automotive transition that competitive forces have already made inexorable.

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