Hypercars: The Next Industrial Revolution

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ABSTRACT: Strong synergies between ultralight mass, ultralow drag, and hybrid-electric drive can produce attractive designs for superefficient cars (and many other vehicles). A realistic near-term 4–5-passenger "hypercar"—curb mass 585 kg (advanced-polymer-composite monocoque), C_DA 0.36 m^2, r_0 0.0062, fuel-to-shaft η_{av} 0.385, fuel-to-wheels η_{av} 0.29, accessory load 250 W_{av}—can achieve average fuel economy (USEPA 55/45) ~50 km/l, with much room for improvement. Depending on design details, mature ultralight-hybrid hypercars could achieve 60–120 km/l using virtually any fluid fuel, perhaps ultimately ~250 with fuel cells, while being safer, sportier, more comfortable and durable, $10^{1-3}\times$ cleaner, and probably cheaper than today's cars. By using recursive design to maximize mass decompounding, optimizing for manufacturing cost can save far more fuel than traditional optimization for fuel savings. The dozens of technologies required are all demonstrated, but capturing their synergies with radical simplification requires highly integrated whole-system engineering with meticulous attention to detail. Despite the difficulty of this design challenge, market-driven commercialization is proceeding rapidly, with ~$1 billion committed and early entries possible in the late 1990s. The barriers are far more cultural than technical or economic. Implications for a wide range of industries—notably cars, oil, steel, and electricity—could be profound.

1. INTRODUCTION

Automotive designers skillfully meet many conflicting demands. Yet the overarching goals of efficiency, environment, fuel security, and affordability are widely assumed to conflict, because efforts to reconcile them by incremental improvement have been leading into an evolutionary trap of stagnating efficiency with spiraling mass, complexity, and cost. Fundamental, discontinuous, and market-driven design changes could instead meet these key goals simultaneously and without compromise.

1.1. History Since 1991, Rocky Mountain Institute—a 15-year-old, 43-person independent nonprofit resource policy center—has applied to cars its experience from advanced electric end-use efficiency. In many technical systems—buildings, motors, lights, computers, etc.—big electrical savings can often be made cheaper than small savings by achieving multiple benefits from single expenditures. The marginal cost of savings at first rises more and more steeply ("diminishing returns"), but then often "tunnels through the cost barrier" and drops down again, yielding even larger savings at lower cost. RMI hypothesized that the same might be possible in cars. By 1993, this concept had been established and published[1]; by 1995, refined into papers[2–5] advised by hundreds of informants; and by 1996, expanded into a major proprietary study emphasizing manufacturing techniques for high volume and low cost.[6] Evidence is now growing that as hoped, a "leapfrog" raising fuel economy ~4–10× may be easier, cheaper, and strategically more advantageous than an incremental 3× gain (US PNGV, EC 3 l/100 km).

Most big changes in modern cars were driven either by government mandate, subsidy, or taxation motivated by externalities, or by random (Fig. 1) fluctuations in oil price. However, the more fundamental shift to hypercars can instead be driven by customers' desire for superior cars and manufacturers' quest for competitive advantage. Customers will buy hypercars because they're better cars, not because they save fuel—just as people buy compact discs instead of vinyl records. Manufacturers, too, will gain advantage from hypercars' potentially ~3–10× lower product cycle time, tooling and equipment investment, assembly space and effort, and body parts count.

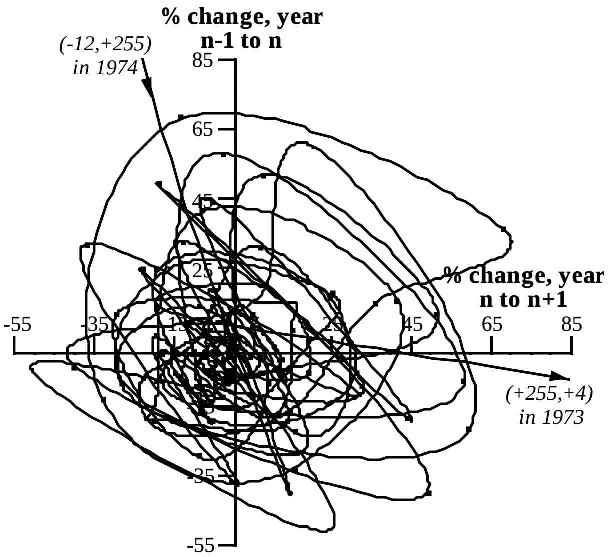

Figure 1 World real oil price movements, 1881–1993 (Worldwatch , BP, and USDOE data)[6]

Since these features offer decisive competitive advantage to early adopters, RMI chose in 1993 not to patent and auction its intellectual property, but rather, like the opensoftware development model, to put most of it prominently into the public domain and maximize competition in exploiting it, *pour encourager les autres.* In late 1993, the concept won the Nissan Prize at ISATA (the main European car-technology conference); in 1994, it was the subject of an ISATA Dedicated Conference, and began attracting considerable attention. By late 1995, RMI was providing compartmentalized and nonexclusive support, strategic and technical, to about a dozen automakers and a dozen intending automakers from other sectors (such as car parts, electronics, aerospace, polymers, and startups, including a number of alliances and virtual companies).

1.2. Status By spring 1996, commitments to ultralight-hybrid development totaled ~$1 billion, recently doubling in less than a year, chiefly in North America and Western Europe but representing every inhabited continent. Though no fully optimized or production-engineered design yet existed, significant progress was being made toward that goal by capable firms, and diverse prototypes had validated the general concept. For example, GM's 1991 sporty 4-seat Ultralite concept car, with curb mass (m_c) 635 kg, C_DA 0.33 m^2, and r_0 0.007, achieved 26.4 km/l without hybrid drive, and has been calculated to achieve ~47–60+ with it. Esoro's 1994 H301 4-seat parallel range-extender hybrid (m_c 670–700 kg, C_DA 0.41 m^2, r_0 0.007) achieved 35 km/l hauling 230 kg of batteries, and would have achieved ~59 km/l if redesigned as a series hybrid with engine η_{av} 0.385. Viking 21, a 1994 2-seat CNG/battery-electric hybrid (m_c 907 kg, C_DA 0.24 m^2) from Western Washington University's Vehicle Research Institute, achieved 86 km/l-equivalent (out of the battery, excluding utility losses) in Los Angeles traffic.

RMI estimates that some early hypercars may reach the market as soon as 1998, and considerably more by 2000. This is far faster than the normal pace of automotive development, but competitive pressures motivate early entry, and parallel development paths could converge rapidly into products. The tooling cycle could shrink from one or two years to months or less (if roughing soft tooling by stereolithography from virtual prototypes), and most components are available in other markets. Encouragingly, GM's Ultralite concept car was made in 100 days by 50 people at a cost of $4–6 million; starting at a similar stage of development, GM's Impact battery-electric concept car was productionized into the EV-1 design in about a year. Hypercars are especially suited to surging from bench to pilot to full production, as Hon da did with the CRX. Although early models couldn't cross the US on one tank, they'd still have enough exciting features to sell well and drive rapid further innovation.

2. PRINCIPLES

After a century's devoted effort by excellent engineers, only ~15–20% of a modern car's fuel energy reaches the wheels, and 95% of that moves the car, not the driver, so only ~1% of fuel energy moves the driver. This is not very gratifying. Its biggest cause is that cars are conventionally made of steel—a splendid material if mass is either unimportant or advantageous, but heavy enough to require for brisk acceleration an engine so big that it uses only ~4% of its power in the city, ~16% on the highway. This mismatch halves an Otto engine's efficiency.

Rather than emphasizing incremental improvements to the driveline, the hypercar designer starts with platform physics, because each unit of saved road load can save in turn ~5–7 units of fuel that need no longer be burned in order to deliver that energy to the wheels. Thus the compounding losses in the driveline, when turned around backwards, become compounding *savings*.

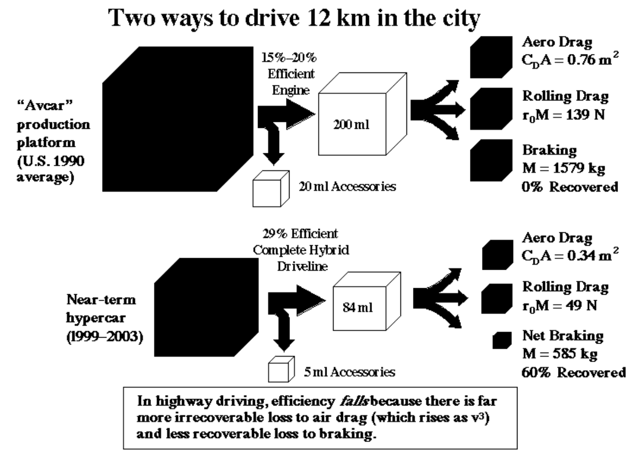

Figure 2 Early hypercars' schematic physical principles

In typical flat-city driving (Fig. 2), road loads split fairly evenly between air resistance, rolling resistance, and braking. Hypercars could have 2–3× lower curb mass, 2–3× (perhaps ultimately up to 6×) lower aerodynamic drag, 3–5× lower rolling resistance, and ~3–10× lower accessory loads than conventional production platforms. As Fig. 2 shows, in a near-term hypercar, irrecoverable losses to air and road drag plummet. Wheelpower is otherwise lost only to braking, which is reduced in proportion to gross mass and largely regenerated by the wheelmotors (70% recovery wheel-to-wheel has been demonstrated at modest speeds). The hybrid decouples engine from wheels, eliminating the 2× part-load penalty of the Otto/mechanical-drivetrain system, so the savings multiplier is no longer ~5–7× but only ~2–3.5×. Nonetheless, even counting potentially worse conditions in high-speed driving (because aero drag rises as the cube of speed and there's less recoverable braking than in the city), the straightforward parameters illustrated yield average economy ~41 km/l.[7]

2.1. Ultralow Drag Hypercars would combine very low drag coefficient C_D with compact packaging for low frontal area A. Several concept cars and GM's productionized EV-1 have achieved on-road C_D 0.19 (*vs.* today's production average ~0.33 and best production sedan 0.255, or Rumpler's 0.28 in 1921). With a longer platform's lesser rear-end discontinuity, Ford's 1980s Probe concept cars got wind-tunnel C_D 0.152 with passive and 0.137 with active rear-end treatment. Some noted aerodynamicists believe ≤0.1, perhaps ~0.08, could be achieved with passive boundary-layer control analogous to the dimples on a golf-ball. Between that idealized but perhaps ultimately feasible goal and the 1996 reality of 0.19 lie many linked opportunities for further improvement without low clearance or excessively pointy profile.[3,7] Thin-profile recumbent solar racecars illustrate how well sidewind response can be controlled, as in the Spirit of Biel III's on-track C_D of 0.10 at 0° yaw angle but just over 0.08 at 20°.

Production cars have $A \leq 2.3$ (US av.) to 1.8 m² (4-seat Honda DX); well-packaged 4-seat concept cars, 1.71 (GM Ultralite) to 1.64 (Renault Vesta II). For full comfort, we assume 1.9 for 4–5 or 2.0 for 6 (3+3) occupants.

Rolling resistance is reduced proportionally to both gross mass and coefficient of rolling resistance r_0. Steel-drum test values of r_0 are 0.0062 for the best mass-produced radial tires, 0.0048 for the lowest made by 1990 (Goodyear), and the low 0.004s for the state of the art. On pavement, with toe-in but not wheel-bearing friction, we assume the EV-1's empirical 0.0062 (Michelin), which might be further reduced without sacrificing safety or handling. Such tires are typically hard and relatively narrow, increasing pressure over the contact patch to help compensate for the car's light mass. The wheelmotors, being precise and ultrastrong digitally controlled servos, could also be designed to provide all-wheel antislip traction and antilock braking superior to those now available.

2.2. Ultralight Mass Today's production platforms have curb mass m_c ~1.47 t (RMI's simulations ad d 136 kg for USEPA test mass). Some 1980s concept cars made of light metal achieved m_c <650 kg (Toyota 5-seat AXV diesel 649 kg, Renault 4-seat Vesta II 475, Peugeot 4-seat ECO 2000 449). But advanced composites can do better, with carbon-fiber composites acknowledged by Ford and GM experts to be capable of up to a 67% body-in-white (BIW) m_c reduction from the 273-kg steel norm without/372 kg with closures—to ~90/123 kg, *vs.* the 5-seat Ultra Light Steel Auto Body's 205/– kg or the 5–6-seat Ford Aluminum-Intensive Vehicle's 148/198 kg.

RMI assumes near-term advanced-composite 4–5-seat BIWs not of 90/123 kg but ~130/150.[3,4] In contrast, the 4-seat Esoro H301's BIW weighed only 72/150 (using lighter-than-original bumper and door designs for comparability)—far below the carbon GM Ultralite's 140/191, even though 75% of the Esoro's fiber was glass, far heavier than carbon fiber.[2] Of carbon-and-aramid BIWs, Viking 23's (1994) weighed 93 kg with closures, while Esoro composites expert Peter Kägi's 1989 2-seat OMEKRON's weighed only *34* kg without closures.[2] Though these examples differ in spaciousness and safety, they confirm carbon fiber's impressive potential for BIW mass reduction. A 115-line-item mass budget benchmarked to empirical component values indicates that a 130/150-kg BIW corresponds to m_c ~521 kg.[3,6] Near-term values for a full-sized 3+3 sedan range upwards to ~700 kg but can be reduced at least to ~600 kg with further refinement.[3,6]

2.3. Hybrid-Electric Drive Hypercars build on the foundation of recent major progress in electric propulsion, offering its advantages without the disadvantages of big batteries. Batteries' deliverable specific energy is so low (~1% that of gasoline) that, as P.D. van der Koogh notes, "Battery cars are cars for carrying mainly batteries—but not very far and not very fast, or else they'd have to carry even more batteries." This nicely captures the mass compounding—snowballing of weight—that limits battery cars, good though they're becoming, to niches rather than to the general-purpose family-vehicle role that dominates at least North American markets.

It is unimportant to this discussion whether hypercars use series or parallel hybrids. Both approaches, and others, may offer advantages in particular market segments.[3,7] Either way, an onboard auxiliary power unit (APU) converts fuel into electricity as needed; the APU can be an internal- or external-combustion engine, fuel cell, miniature gas turbine, or other device. The electricity drives special wheelmotors (conceivably hubmotors, but at least in early models probably mounted inboard to manage sprung/unsprung mass ratios). The motors may be direct-drive or use a single gear, though some designs might benefit from two gear ratios. A load-leveling device (LLD) buffers the APU, temporarily stores recovered braking energy, and augments the APU's power for hill-climbing and acceleration. The LLD can be a high-specific-power battery, ultracapacitor, superflywheel, or combination, typically rated at ~30–50 peak kW but ≤1 kWh (perhaps only ~0.3). High braking-energy recovery efficiency and reducing the APU map nearly to a point require high kW/kg plus excellent design and controls.

2.4. Synergies Ultralight-and-slippery construction alone, as GM's Ultralite proved, improves fuel economy by ~2–2.2×; hybrid drive alone, ~1.3–1.5× (perhaps 1.7× with ultracapacitors). But artfully combining both yields ~4–10× or more, because of synergies between them:[3,6,7]

1. irrecoverable losses are much reduced, and recoverable braking loss is greatly reduced then largely recovered;
2. the driveline's compounding losses yield compounding savings when turned around; and
3. mass decompounds, further reducing both the rolling-resistance and the braking losses as well as the amount and hence the cost of the ultralight materials.

Saving 1 kg of mass directly is customarily assumed to save another ~0.3–0.7 kg indirectly by needing less capacity for structure, engine, braking, suspension, etc. But at the ultralight frontier, the "mass decompounding factor" rises from ~1.5 to much larger values, even approaching 5, because components not only shrink but may disappear. Ultralight platforms need no power steering or power brakes. Hybrids, which (as we'll see) become attractive in ultralights, need no multispeed transmission, clutch, starter, alternator, driveshaft, U-joints, differentials, perhaps axles, probably catalytic converter. Recursive design can make the car simpler, hence lighter and cheaper (Fig. 3, adapted from an Audi concept).[6]

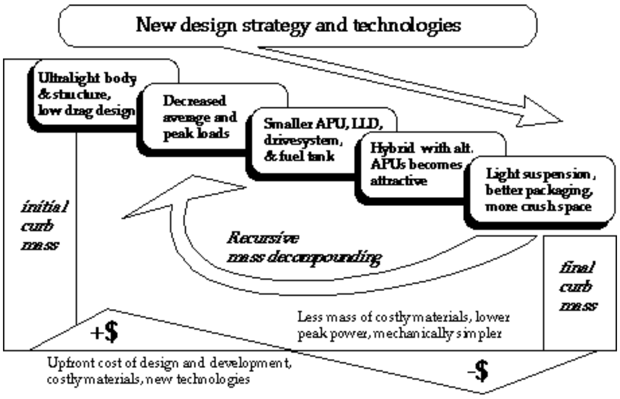

Figure 3 Recursive optimization cuts mass and cost

2.5. Divergences and Challenges The three synergies above weren't well studied until ~1991: hybrids were widely considered unattractively costly and complex, because mass reductions were considered for the wrong reason, in the wrong sequence, and to the wrong extent.

Traditionally, mass was optimized to save fuel cost: each 1-kg mass reduction saved $2 worth of fuel (present-valued over 15 y at a 5%/y real discount rate and at US prices ~$0.33/l, cheaper than bottled water). But substituting aluminum for steel typically cost ~$2–6 per saved kg, and hence was of marginal value. However, making the car not of steel but of costly materials like carbon fiber, and the propulsion system not a cheap internal-combustion engine but an electric system that might initially cost more per kW, completely changes the optimization's goals. One must now minimize the mass of the costly materials; maximize mass decompounding; perhaps adopt soft or shell tooling for capital savings (to offset the costlier material) and faster cycles; reduce the kW ratings, hence the cost and mass, of all the electric propulsion components; and shrink the APU map nearly to a point for best efficiency and least emissions. Mass is then optimized to save money not on fuel but on building the *car*. Paradoxically, this saves far more fuel.

Traditionally, too, automakers hybridized heavy production platforms. Such "tank conversions" required such high kW ratings that the power switches, LLD, and other components weighed and cost too much. Realistic control algorithms required a ≥3× engine map, harming efficiency and emissions. Total mass usually went up, not down. In contrast, starting with an ultralight-and-ultra-low-drag platform and *then* hybridizing it yields striking advantages. The platform's doubled efficiency makes it salable at once, even before it's hybridized, and permits an immediate jump to the strategic advantages of flexible, fast-cycle composites manufacturing (§4.1). Peak power requirements become manageable: the LLD shrinks to <50 kg even with 800 W/kg wound-foil PbA or NiMH batteries. A battery LLD should be very durable because it runs only over a ~35% range of depth-of-discharge. The APU map collapses nearly to a point. The ~4–10× smaller kW ratings cut correspondingly the stringency of driveline components' specific power, energy, and cost requirements. Mass decompounding, hence further kW reductions, accelerate nonlinearly as more components and systems are recursively displaced. Packaging efficiency and aerodynamics improve further. Curb mass, hence the mass of costly fiber, becomes low enough for affordable production. Thus the vicious circles of heavy hybrid design turn into virtuous circles.[6]

Finally, for cultural reasons described in §3.1, and because radical lightweighting was assumed to be unsafe, mass reduction was traditionally considered only to the minor extent permitted by incremental, component-by-component substitution of light for ferrous metals—not the breakthrough potential of advanced composites.

For these three reasons, the only hybrids traditionally considered were heavy, causing their mass, cost, and complexity to compound. Overlooked was the ultralight-and-ultraslippery regime where they *de*compound: the domain of the hypercar. But to enter that realm requires unprecedented whole-system engineering integration and care, and major changes in the culture of automaking. The industry today seldom does leapfrogs; instead, the frog gets smarter but continues to sit in the same pond. Design typically proceeds by slow, incremental change to components, from the engine toward the wheels and emphasizing the driveline. Steel is assumed, so mass accretes. A huge, dis-integrated design group of superb specialists (often narrowly focused, at least in North America and Europe) works like a relay race instead of a team play, losing synergies and yielding baroque complexity.

Hypercars require the frog to leap far into a new pond. Design must be whole-platform, ground-up, and clean-slate, from the occupants outward and from the road loads back upstream, emphasizing fundamental improvements in platform physics. Advanced composites are adopted to eliminate and decompound mass and for strategic reasons (§4.1). A very small, bold, skunkworks-like design team holistically masters details and integratively captures synergies to achieve radical simplicity—obeying Einstein's advice that “Everything should be made as simple as possible, but not simpler.” Good cars are always difficult, but better they be difficult because they’re simple than difficult because they’re complex. One reaches simplicity only through complexity, but this industry has been in the complex phase for decades, and many of its gifted engineers are ripe for something different.

This cultural transformation is a daunting challenge, and it’s not yet clear whether automakers can achieve it. However, if they don’t, they risk being displaced by new entrants with comparable skills but with none of the automakers’ vast physical and human capital trapped in stamping, welding, assembly, and painting. Commercial developments remain extremely fluid, and which firms, or even kinds of firms, will win the race is not yet clear.

2.6. Other Design Considerations Hypercars entail many difficult transitions: from steel to adv anced composites, stamping to molding, hard to soft or shell tools, physical to virtual prototypes, diemaking to stereolithography, welding to integration and adhesives, fast serial production to about equally fast parallel production, mechanicals to electricals, hydraulics to electronics, hardware to software, mass to information, incrementalism to discontinuity, fragmented components to integrated systems, and complexity to simplicity.

The new technical conditions require innovation in areas long thought mature: *e.g.*, efficiency- and emission-optimized *single-point* operation of small (<0.3-l) engines; ultralight wheels, tires, and brakes to minimize unsprung mass; smart active suspensions versatile enough to handle payloads that can approach m_c itself; and novel approaches to safety engineering (§3.3).

Even more interesting is the goal for total car energy, tractive plus accessory, to approach the load of just accessories (lights, climatization, power-steering boost, defrost, entertainment, etc.) in today’s cars. A ~3–10× reduction in accessory loads with the same or better quality does indeed look feasible, based on experience with comparable technical systems in buildings[3,6]; accessory design heretofore has just been an afterthought guided not by real optimization but by wildly inaccurate rules-of-thumb.

3. ADVANCED-COMPOSITE AUTOBODIES

Quite light BIWs could be made with some spaceframe or even perhaps unibody designs, and with light metals rather than with composites; but advanced composites, principally based on intermediate-modulus carbon fiber, seem optimal for both mass and manufacturing.[6] Besides being stronger and stiffer than steel but 4× less dense, carbon fiber has axial heat conductivity approaching copper’s, makes composites with about a third of steel’s coefficient of thermal expansion, and is virtually immune to fatigue and corrosion. A composite BIW of a given stiffness will typically cost and weigh less when dominated by carbon- rather than glass-fiber reinforcement.[4] (Naturally, for safety in extreme crashes, the carbon must be interwoven or overlain with fracture-masking fibers such as aramid, glass, or polyethylene.) A true monocoque, whose shell *is* the structure, will provide the lightest BIW per unit strength or stiffness.[6] The strength of such structures can be experienced by trying to crush an egg in one’s hand, or to eat an Atlantic lobster without tools. But choosing the optimal material and structure are absolutely vital to a successful hypercar. As the old design heuristic reminds us, “All the really important mistakes are made on the first day,” and making the BIW out of metal is usually the most basic such decision. It may work, but not optimally. One can’t make a good hypercar out of steel, for the same reason one can’t make a good airplane out of cast iron: it weighs too much.

3.1. Manufacturing Both design and manufacturing are utterly different with advanced composites than with metal. Despite the prevalent “black steel” mindset, if the composite part looks like the steel part, it may not work and will certainly be grossly suboptimized. Conversely, the approaches being applied to save mass in metal BIWs are roundabout attempts to get them to do awkwardly what composites do naturally, such as providing anisotropic strength matched to the load paths.[6]

Unlike metal BIW-making, where the design of the part, material, and manufacturing process are somewhat linear and sequential, they become intimately interlinked and indistinguishable with advanced composites. The fiber choice, form, and placement, the matrix and core, the manufacturing and recycling methods are part of the entire design-and-manufacturing integration.[6] Quite different, less familiar, and often less mature design techniques are also required. Unfortunately, almost no automakers are yet familiar enough with advanced composites to feel comfortable with them.[5] Their use is hence typically confined to single components whose integration into steel structures creates many needless but well-known problems. However, an all-composite BIW can turn each of those problems into an important new opportunity to make the process and the part work better and cost less.[5,6]

Of the many manufacturing methods available, the family most clearly able to meet hypercars’ volume production requirements at competitive cost and speed with technologies now established (at least individually if not as a complete package) is the combination of special tooling (perhaps coated epoxy) with an ultra-high-speed version of resin transfer molding. RTM can be greatly accelerated, to cycle times ~1–3 minutes, by combining complex preforms, computer-controlled resin injection, online process monitoring, statistical process control, optimized low-pressure mold design, electron-beam curing (using optimized resins that also have lower viscosity, improving injection speed and wet-out), and adhesive bonding.

Each of these steps has lately demonstrated impressive performance in automotive or similar high-volume applications, achieving all automotive requirements, such as Class A finish, high speed, and high consistency. Such methods require maturation, optimization, and integration, but no longer invention: they exist, they work, and they can exhibit very steep learning curves.[5,6]

Proprietary processes developed by at least five firms can also displace painting—the hardest and most polluting part of automaking, accounting for half the cost of a typical assembly plant, ≥25% of the finished cost of a painted steel car part, and over half the total manufacturing process's air pollution—by laying color in the mold, often using a stick-on polymeric product with many advantages, optionally including replaceability.[6]

3.2. Economics Composite cars in volume production would use neither the methods (hand layup and autoclaving) nor the costly, brittle, ultrastrong grade of carbon fiber used in aerospace, but rather high-speed, high-volume methods and intermediate-modulus structural carbon. By early 1996, that fiber's bulk creel price had fallen below $18/kg for 48k tows; under $10/kg (1996 $) is credibly predicted by 2000 as real production displaces a boutique craft industry (low-cost global capacity for such fiber totals only 6 kt/y). The historic 30% fall in real price for each doubling of cumulative carbon -fiber output should long persist.[6]

A mass-optimized carbon-fiber BIW can compete with a steel unibody even with *today's* prices, suboptimized production processes, conservative assumptions, and 100,000 units/y—a common volume for steel cars but neither necessary nor commercially optimal for composite cars. Fig. 4 shows a typical breakeven curve against a steel unibody.[4] Fully burdened production cost is plotted *vs*. carbon-fiber price (vertical axis) and the BIW's degree of lightening by further mass optimization from the GM Ultralite's 140 kg without closures (horizontal axis). Point A shows breakeven with $11/kg carbon if the BIW mass is reduced by only 15%. At Point B, the 67% BIW mass reduction from steel that GM and Ford's top composites experts consider feasible with carbon fiber breaks even at only ~6% below the actual 1996 carbon-fiber price—a margin much smaller than the model's ten conservatisms. Point C shows that a mass reduction equivalent to the Esoro H301's BIW (which would weigh about the same 72 kg if made from carbon and aramid instead of mostly glass and if made as spacious and at least as safe as the Ultralite) *already* beats steel at present prices.[4]

This is because the cost of the special fibers and resins is more than offset by their small quantity and simpler manufacturing. Cars are bought by the car, not by the kg, so a lighter car can cost more per kg. Moreover, only ~15% of the cost of a typical steel car part buys steel; the rest pays for shaping and finishing. But net-shape composites come out of the mold *already* shaped and essentially finished. The mold can be cheap because it is easily made from materials so cheap that their lower durability doesn't matter (but offers the advantage of continuous improvement during refurbishment). Only one tool set is needed per part, not an average of four for progressive hits on a steel part. Only ~10–20 composite parts displace ~200–400 steel parts, and they fit precisely together with ~90% less assembly effort and space. Labor costs may be somewhat more or less depending on process details, but capital investments and other plant costs are *much* lower (tooling was 5–7× less for Renault's L'Espace), dramatically reducing financial risks and barriers to market entry.

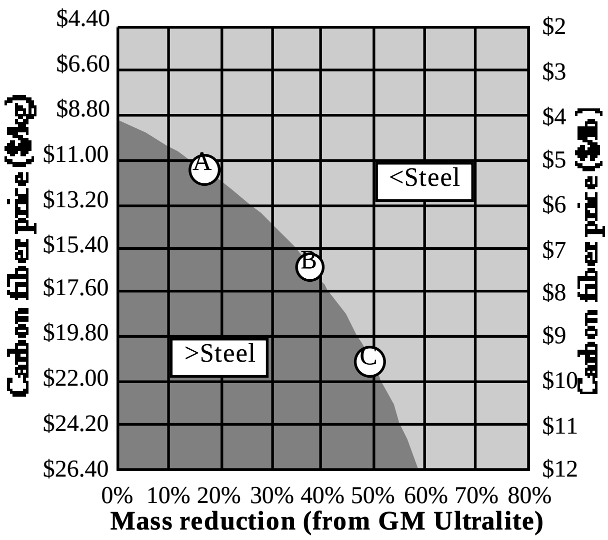

Figure 4 Carbon fiber competes via optimized mass

In general, advanced-composite BIWs' cost and mass advantages should compound as the car proceeds through colorcoating and assembly. Since economies of scale are far weaker for composites than for steel, composites' cost advantages also increase at production runs <100,000/y, which characterize models holding one-fourth of the US market and are in general a key to the flexibility and market success of Japanese automakers.[6]

RMI's findings are consistent with aerospace experience of how system-based design and manufacturing can both cut cost *and* improve performance. For example, the recent manufacturing-optimized design of an advanced tactical fighter aircraft raised its composite mass fraction from 28% to 95% while cutting its projected cost by 56%.[6]

3.3. Crashworthiness Momentum transfer places severe demands on the crashworthiness of an ultralight car colliding with a heavy one. But advanced composites in the right shape can absorb up to 5× as much energy/kg as steel; materials and design are more important to safety than is mere mass; and what it takes to protect people needn't weigh much. Crush cones can absorb >100 kJ/kg and react against a foam-filled composite impact beam, surrounding the passenger cab, that can resist ≥0.5 MN but weigh only ~10–15 kg. Such elements must combine with many others, including progressively stiffer crush structures outside the beam and excellent passenger restraints and cushions.[3,6,7] Metaphorically, the layered approach required might be described as "people, cushioned in foam, surrounded by a Macadamia-nut shell, wrapped in thick bubble-pack." Although detailed designs are not yet complete, early results suggest that safety at least comparable to today's can be achieved with ultralight cars of reasonable size, which would also be less mass-aggressive toward others. Certain features would also make hypercars better able to avoid accidents in the first place, and could greatly speed and ease post-accident extrication.[3,6]

4. STRATEGIC IMPLICATIONS

Hypercars may create the greatest shifts in global industrial structure since microchips, including the following:[6]

4.1. Car Production Steel cars require such extraordinarily costly tooling and equipment that each model is a multi-billion-dollar, bet-your-company investment demanding huge runs to pay back, hence permitting only a few models that can't keep pace with fluid market requirements. In contrast, advanced composites, especially with soft tooling, offer agile production with far lower fixed costs, comparable or perhaps lower total costs, small breakeven sales volumes, diversified model portfolios, rapid product cycles, and ability to track markets. This greatly improves their financial risk profile.[6]

Advanced composites also offer such market advantages as improved fit and finish, more quiet and refined operation, enhanced stylistic and compound-curve flexibility, better reparability, freedom from rust, greater resistance to dents and scratches, and safer, less polluting production.

Yet to capture these advantages, automakers must stop treating their sunk costs as unamortized assets and substituting accounting for economic criteria—as if it were better to write off obsolete capabilities later when they don't have a company than now when they do. They must learn to kill their proudest products with even better new products before someone else does. In the hypercar world, incrementalism is safe only if no competitor leapfrogs faster; but important competitors may still be invisible and unknown. (Since the hypercar is more like a computer with wheels than like a car with chips, some smart, agile systems integrators who have never made a car may outpace the automakers, hiring or allying with car skills as needed: many hypercars may bear badges familiar in a nonautomotive context.) One can feel sorry for one's former competitors only by getting to hypercars first. In a world of *sumo*, early adopters of *aikido* can gain a devastating advantage.

4.2. Car Market Structure Hypercars would shift emphasis from component manufacturing and assembly to downstream, especially major aftermarket customization and upgrading of software (which would flexibly implement many functions now frozen in hardware). Just-in-time, zero-inventory manufacturing-to-order with direct sales and onsite maintenance could further streamline the value chain, yield higher margins at lower retail prices, and shift rents upstream. As with computers, profit will flow mainly to design integrators and to the makers of key enabling technologies, not to assemblers or resellers.

4.3. Materials Polymer composites have largely displaced metal in boats and are taking over aerospace. Cars are next, but have a vast massflow: Americans buy a new one every two seconds. Each hypercar could contain ~92% less iron and steel initially, up to 98% later, and their volume production should make carbon fiber cheap enough to displace most other uses of steel too.[6]

Most other metals, including lead (of which cars use ~70% of US output), aluminum (19%), and zinc (23%), would be used substantially less. Copper use could rise modestly, then fall back. Platinum-group metals could be displaced partly or wholly. Electronics and software would grow strongly. Output of carbon fiber and related materials could ultimately grow by ~10^2×, probably requiring financial or other instruments to stabilize price volatility during the rapid-growth phase, but total polymer content of each car would only about double.[6]

4.4. Materials and Energy Lifecycle Advanced composites are cost-effectively recyclable by at least two demonstrated and several emerging methods. However, reincarnation by upgrading and remanufacturing would indefinitely extend life first. Even just dismantling and shredding a hypercar would yield ~45% less shredder residue than now, and it would be nontoxic. Hypercars would also embody less energy than today's cars: fossil hydrocarbon is ~10× better invested in carbon fiber for cars than burned as automotive fuel. And hypercars would greatly reduce or eliminate most of the 14 fluid and 21 nonfluid massflows required to maintain today's cars.[6]

4.5. Liquid Fuels Hypercars and their heavy-vehicle cousins would ultimately displace about one "nega-OPEC" of oil worldwide. This would presumably depress the oil price, with many consequences, not all pleasant. It would contribute to making most of the oil in the ground no longer worth extracting, as has already happened to most of the coal and uranium, which are now good mainly for holding up the ground. This prospect gives crude-long oil companies an incentive to become crude-short by liquidating reserves and investing the proceeds in hypercars with upside participation, so that they're hedged: if the cars do well, they make less money on oil but more on cars.[6]

4.6. Gaseous Fuels and Fuel Cells Hypercars are fit for gaseous fuels because they use so little that a small, light, cheap tank will give a long range.[6] Even costly hydrogen is attractive because a fuel-cell hybrid converts hydrogen into traction ~3–4× as efficiently as today's cars convert gasoline. Hydrogen, which is easier to make from most renewable sources than is utility-grade electricity, could quickly become the hypercar fuel of choice because hypercars need ~4–10× fewer kW than heavy hybrids, and so can adopt fuel cells much earlier in their development cycle, before they become nearly as small, light, and cheap per kW as they will later. Proton-exchange-membrane fuel cells are ready for this now.[6] But enough PEM fuel cells for even a modest hypercar industry will become cheap enough to beat the operating cost of coal or nuclear power plants, either by installation in buildings (where their waste heat about pays for their methane fuel) or by plugging parked hypercars into the gas and electric grids. Such a ~20-kW "powerplant on wheels" could net-credit its owner about half the cost of finance and depreciation. It doesn't take many people doing this to displace most central power stations, since a full hypercar fleet would have ~5× the capacity of the national grid. Hypercars could thus accelerate by a decade or two the shift to distributed utilities and solar hydrogen, addressing the one-third of CO_2 emissions from transportation *and* the further one-third from power stations.[6]

4.7. Emissions Depending on fuel and APU, hypercars could pollute less than the central stations that now recharge battery cars: *e.g.*, a near-commercial (Stirling Thermal Motors) Stirling engine, burning ordinary gasoline with no catalytic converter, could meet California's "Equivalent Zero-Emission Vehicle" (~0.1×ULEV) standard expected to be adopted in 1996.[3,6,7]

4.8. Health and Safety A properly designed hypercar industry should reduce occupational as well as public hazards, all the way from primary materials supply through manufacturing and ultimate disposal.[6]

4.9. Macroeconomics Depending on the methodology used, hypercars' estimated net effect on employment may range from neutral to favorable. Jobs could migrate and disperse, tending to shift toward smaller scale and more sophisticated occupations. Diverse modes of production could offer comparative advantages for countries in many different stages of industrialization; such "lean-clean-and-green" leapfrog development could have many important spinoff benefits. Aggregate wealth and the quality of work should in general improve.[6]

4.10. Transportation Policy Hypercars cannot solve the problem of too many people driving too many km in too many cars, and could make it worse by making driving more attractive and its marginal cost approach zero. A worldful of ideal hypercars will run out, not of air and oil, but of roads and patience—the constraint *du jour.* Hypercars therefore require, and may buy time for, a parallel effort to foster full and fair competition between all ways of getting about or not needing to, including ways to make markets in "negatrips" and "negacars."[6] Hypercars may also make fundamental transport reforms more difficult by making cars appear more benign. Reform to achieve equity and a desirable urban form and social fabric will depend less on technologies (though many promising ones are emerging) than on the political will to create a society worth driving in. That is a far greater challenge even than hypercars, and surely no less important.

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