ULTRALIGHT-HYBRID VEHICLE DESIGN: IMPLICATIONS FOR THE RECYCLING INDUSTRY

BY

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The materials revolution revisited

In 1920, almost nine out of every ten US autobodies had open passenger compartments and were made mostly of wood. In 1926, only *three* out of ten had this design; the rest had shifted to closed passenger compartments and were made mostly of steel [1]. Within a six-year period, steel had gone from a bit player to the dominant automotive material. And during the same period, battery-electric and steam-powered drivesystems finally gave way to ones based on internal-combustion-engines.

Rarely has a technological change been so dramatic—and enduring. Seventy years later, almost every car on the road has a platform combining a steel unibody (an integrated body-chassis construction introduced by Citroën in 1934 [2]) with an internal-combustion-engine drivesystem. Naturally, automotive retirement and recycling practices have evolved to fit this platform. As steel is prone to degradation over time, and complex ICE drivesystems are generally hard to replace, automakers design cars with little potential for remanufacturing to extend their life. And when a car's life is over, the salvageable parts are removed and then the remainder is shredded—a process optimized for recovering the ferrous metal content.

Current retirement and recycling practices may become obsolete as a result of a potentially large shift in automotive materials and drivesystems—one of similar proportion to what took place in the 1920s. Ironically, the advanced composite materials that could induce this shift are based on the same principle as wood. Wood is a composite material that combines stiff and strong cellulose fibers in a tough lignin matrix. Advanced composites too combine stiff and strong fibers—usually carbon or aramid, sometimes with glass—in a matrix, either thermoset or thermoplastic. Unlike wood, advanced composites can be severalfold stronger and stiffer than steel per unit mass. Because of their superior specific properties, they could potentially make cars not only ultralight but also ultrarigid and ultrasafe.

Traditionally, advanced composites have been expensive, limiting their use to low-volume applications. Consequently, their role in the automotive world has been limited to racing, where performance, not cost, matters most. A few hundred Formula 1 monocoques hardly present a reason to change steel-based automotive retirement and recycling processes. But recent findings that advanced composites can offer economic and performance advantages for regular, everyday family cars could quickly change and expand the materials' use—and lead to a fleet of clean, highly-recyclable, and fuel-efficient hypercars in the process.

What is a hypercar?

The hypercar design concept combines an ultralight, ultra-aerodynamic autobody with a hybrid-electric drivesystem. This combination would allow dramatic improvements in fuel-efficiency and emissions. Computer models predict that near-term hypercars of the same size and performance of today's typical 4–5 passenger family cars would get three times better fuel economy [3]. In the long run, this factor could surpass five, even approaching ten. Emissions, depending on the powerplant, or APU, would drop between one and three orders of magnitude, enough to qualify as an "equivalent" zero emission vehicle (EZEV) under the California Air Resources Board (CARB)'s proposed standards [4]. In addition, as explored in this paper, hypercars' recyclability should be equivalent or better, while their potential longevity truly should make them "durable" goods.

In all, hypercars' fuel efficiency, low emissions, recyclability, and durability should make them very friendly to the environment. However, environmental friendliness is currently not a feature that consumers particularly look for when purchasing a car. Consumers value affordability, safety, durability, performance, and convenience much more. If a vehicle can not meet these consumer desires as well as be profitable for its manufacturer, it will not succeed in the marketplace. Simply put, market acceptance is paramount. As a result, hypercars principally strive to be more attractive than conventional cars to consumers, on consumers' own terms, and just as profitable to make. Advanced composites are integral to achieving these goals.

Why advanced composites?

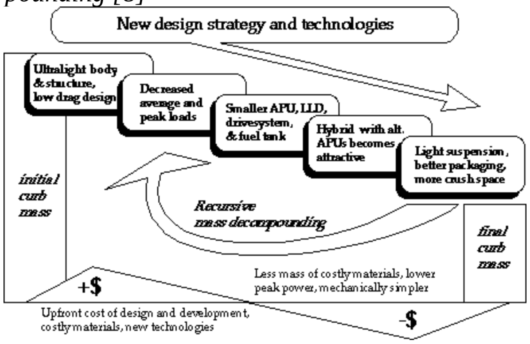
The incorporation of advanced composites can make vehicles more attractive to consumers in several ways [4]. 1) Advanced composites’ high stiffness should give a typical family car noise, vibration, and harshness (NVH) characteristics unmatched by today’s finest luxury cars. 2) Their corrosion and fatigue resistance could make cars extremely durable and immune to rust. 3) Depending on how they are fabricated, advanced composites could offer cars a wide range of styling opportunities and a near seamless fit. 4) Advanced composites’ low tooling costs (*see below*) and quick fabrication could give cars unprecedented design flexibility, enabling frequent model changes and improvements. And 5) when designed properly, advanced composites can provide excellent crashworthiness. They have several properties, including their stroke efficiency and specific energy absorption, that are ideally suited for safety applications. In fact, several automakers are exploring the possibility of putting advanced composites in their *steel* cars to make them safer [5].

But what makes advanced composites the most attractive is their potential for mass reduction. Reducing a vehicle’s mass makes it peppier and/or more fuel-efficient to drive (particularly so with a hybrid drivesystem [3]), nimbler to handle, and easier to stop. Advanced composites’ superior mechanical properties allow them to largely decouple size from mass—enabling cars to be big, safe, *and* ultralight. Experts from various US and European manufacturers estimate an all-advanced-composite autobody could be 50–67% lighter than a typical similarly sized steel unibody. For comparison, advanced steel autobody designs, such as the UltraLight Steel Auto Body (ULSAB), are around 25–30% lighter [6], and aluminum ones, 40–55%. The Coupé (Figure 1), a large, 5 passenger EV designed and built by the Swiss firm Horlacher (Möhlin), demonstrates composites’ potential. Its all-*glass*-composite autobody is 47% lighter than a comparable steel unibody, and its designers estimate an advanced-composite version (*i.e.*, using carbon and aramid reinforcement) could be ~60% lighter.

Figure 1: The Coupé [7]

The benefits of shedding a couple of hundred-kg from the autobody are modest until the effects on the rest of the car are considered. Reducing the mass of the autobody has enormously positive “downstream” effects on other automotive systems. First, the lighter autobody decreases the power needed to propel and accelerate the car, allowing the drivesystem—conventional or hybrid—to be smaller for equivalent performance. The smaller drivesystem as a result lowers the mass of the car even more, reducing the load on the suspension. And the smaller suspension, with the lighter drivesystem, can reduce the loads on the autobody, reducing its mass further, and so on until the mass reduction is met with diminishing returns. The main result is a “virtuous” circle of recursive mass decompounding shown in Figure 2. Ultimately, the ultralight, advanced-composite autobody may induce a less-obvious, yet extremely important benefit from reducing overall vehicle mass—reducing vehicle *cost*, hence increasing their potential for profitability. A smaller drivesystem, producing fewer kW of average and peak power, is cheaper: *e.g.*, a 4-cylinder engine costs less than a V-8. For hybrids, the savings are more dramatic as the costs of

Figure 2: The “virtuous” circle of mass decompounding [8]



power-storage devices like batteries and powerplants like PEM fuel cells generally vary linearly with their power output. In addition, several automotive components can be eliminated when the vehicle is light, further reducing the cost: power steering, for instance, was eliminated for GM's all-advanced-composite-autobodied prototype vehicle, the Ultralite, without compromising its handling.

Advanced-composite economics

But what about the cost of the advanced-composite autobody itself? As mentioned, advanced composites are expensive materials. In fact, *low-cost* advanced composites are fifteen times as expensive per *kg* as sheet steel. But what matters is the cost per *autobody*, not per kg. In other words, materials costs matter, but so do manufacturing costs.

While steel is a cheap material, its manufacturing equipment is quite the opposite: a large stamping press costs roughly $25 million, and a typical steel die can cost $1 million. As a typical steel unibody has ~300 parts, and each part can require up to 7 successive stamping hits, it is not uncommon for just the *tooling* for a new autobody to exceed $1 billion. On the other hand, advanced-composite autobodies can have 1–2 orders of magnitude fewer parts (*e.g.*, GM's Ultralite had eight) and require only one tool—and one low-pressure press—per part. Fewer parts also mean simpler assembly, with corresponding reductions in factory space and equipment.

Thus, the overall investment costs for the tooling and equipment of advanced-composite autobodies should be dramatically less than that for steel unibodies. Coupled with likely reductions in the cost of assembly, the low investment costs for advanced-composite autobody manufacturing can partially or wholly offset the difference in material costs for vehicles with production volumes estimated as high as 125,000 units a year—representing the production volume of about a quarter of the light-vehicle models on the market and rising [9, 10]. Thus advanced-composite autobodies have the potential to make a car attractive for consumers (*i.e.*, big, rigid, safe, and durable) *and* profitable, not only by offering low investment and assembly costs but also by reducing the cost of other automotive systems.

Furthermore, an advanced-composite autobody makes a hybrid drivesystem more economically feasible, which in turn can further improve the vehicle's fuel economy and emissions—particularly important in light of potential EZEV and ULEV regulations—without sacrificing performance. Hybrids provide other benefits such as more flexible packaging, enabling more crush space for enhanced safety, and the potential for increased simplicity: *e.g.*, a PEM fuel cell/ultracapacitor series-hybrid drivesystem could have very few mechanical—and even fewer *moving*—parts, eliminating components like clutches, transmissions, driveshafts, differentials, axle joints, etc. [4].

The net result of their attractiveness and potential profitability is that ultralight vehicles, most likely coupled with a hybrid drivesystem, could soon hit the market. While it is impossible to predict if and when, how many, and from whom, the safe money is not on the "business as usual" approach of incremental platform refinement. Given the competitive environment for selling cars and hypercars' potential market advantages, the platform "leap" to ultralight hybrids will likely be rapid and discontinuous—potentially equaling the rate of automotive change in the 1920s. In anticipation, over 25 firms, ranging from major automakers to want-to-be "virtual" ones, have consulted with the Hypercar Center and have invested significant capital—estimated to be $1 billion and growing—into the research and development of technologies relevant to ultralight hybrids. Whether hypercars come or not, their potential is real, and recyclers and polymer interests should be prepared.

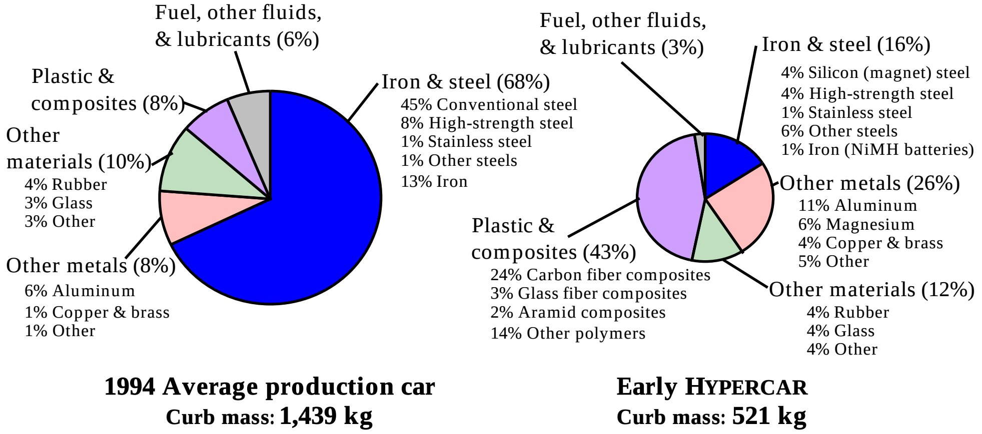
RECYCLING THE HYPERCAR

Five factors will affect the recyclability of a hypercar: 1) its materials; 2) the foresight in its design, 3) the durability and upgradeability of its construction, 4) the technological options for its disposal and recycling, and 5) markets for its recycled materials.

Materials

The change that will most significantly affect the hypercar's recyclability, as well as have the greatest impact on the automobile recycling industry, is its materials. As explained above, the hypercar's autobody likely would be made from advanced composites instead of steel. But other components would also see a shift to a variety of lightweight materials including aluminum, magnesium, high-strength steel, and even advanced composites themselves. Figure 3 illustrates both the overall mass difference between an illustrative early hypercar and an average production car and their radically different materials composition. The calculations underlying these mass numbers can be found in [4].

Figure 3: Mass composition of typical 4–5-passenger platforms



The mass of nonferrous metals would increase slightly for hypercars due to the electrical drivesystem, while the amount of steel would drop by 80% to less than 100 kg. Almost all of this steel would be found in the hybrid driveline, ball bearings and races, suspension, and specific hardpoints—virtually none in the autobody. As the current recycling infrastructure relies primarily on revenue generated from extracting ferrous metal from the recycled hulk, a hypercar's autobody would not be profitably recycled without new recycling methods. However, advanced composite materials are expensive and thus provide a strong economic incentive for developing a viable recycling method.

One potentially decisive benefit of using advanced composites in the hypercar's autobody is the potential to use the same resin type—or resins compatible with the same recycling method—for both the autobody *and* much of the interior. Most of the current dismantling effort required to manually separate large interior components such as the dashboard and instrument panel would then disappear and the downstream materials recovery would be simplified. One even could imagine scenarios where the dismantling effort might even shift to removing the handful of *metal* suspension and steering components that might complicate recycling on a predominantly polymer-based vehicle.

A variety of both thermoplastic and thermoset resins could be used as the matrix in the hypercar's advanced-composite autobody and for other polymer-based components. Yet specific resins are not discussed here because the choice depends on many design criteria that are outside the scope of this paper. Many assume thermoplastics to be more recyclable because, in theory, they can be simply melted and reconsolidated into new parts. However, their high sensitivity to contaminants and high viscosity could limit their applicability to recycling advanced composites and other heterogeneous materials [11]. Therefore, this paper focuses on more advanced processes that could be used to recycle both thermoplastics and thermosets.

Clean-sheet design

When building a car from the ground up, as is the case with a hypercar, many new opportunities arise. One is that new design concepts and approaches can be better implemented, such as designing to ease disassembly and maximize recyclability. Adding new criteria, such as recyclability, to the design process can also add complexity, but it can be implemented more effectively and at a lower cost when done on a system-wide, not "add-on" basis. This is simply because system-wide changes in design criteria require changes in the whole car in order to be most effectively implemented. For example, recent attempts to decrease the mass of steel autobodies, such as the ULSAB, have focused on a whole-platform redesign instead of a part-by-part substitution, with considerably more success [6]. Retrofitting an existing product can result in added complexity, hence cost, and a suboptimal implementation of the new design criteria.

Hypercar design teams would have the flexibility to explore fundamental improvements in making the car more recyclable. 1) Modular design could allow easy removal and upgradeability for the powertrain and other components (*e.g.*, the GM Ultralite had a rear-mounted "pod" to easily switch powerplants and transmissions). 2) Single-resin-system parts and a dramatic reductions in overall parts count, as discussed, could significantly decrease dismantling effort. And 3) clean-sheet "reversible" joining methods, such as adhesively-bonded joints that would be quickly undone with a laser, UV light, or electron-beam radiation, could speed disassembly when necessary.

Life/durability

New cars are increasingly reliable and durable, enough so that it has become common to see cars with 100,000 or more mile warranties advertised. Hypercars could potentially accelerate this trend. The hypercar's advanced composite autobody would last longer because composites don't rust, barely fatigue, and can better handle small impacts without damage. In addition, if a hybrid-electric drive is used, its components, generally mechanically simple, are expected to outlast those of conventional drivesystems. Also, the mechanical systems that are typically the first to wear out—such as the clutch, transmission, and alternator—would be either nonexistent or considerably simplified.

The durability of hypercar's body and drivesystem could lead to retirement options besides disposal and recycling. One could be the growth of an industry that refurbishes and upgrades old hypercars for resale in different market segments, either overseas or within the U.S.. Another could be the emergence of ”upgradeable” cars as technological progress inevitably leads to better-performing components. If industry-wide standards for interoperability are set, components of the drivesystem and their software control could be highly customized and continually improved, allowing hypercar owners to essentially keep their car up to date without replacing it—like upgrading your computer's 486 processor to a Pentium.

If durable hypercars come to market and stay in use longer than conventional vehicles, and if refurbishment or upgradeability becomes popular, the recycling industry would be profoundly affected. In the mature U.S. market where the total number of vehicles in use is growing only slowly (~1–2% per year) and the turnover of the fleet is constant or slightly declining [12], improved durability would permanently slow fleet turnover and reduce both new car purchases and the number of cars retired from use each year.

Other forces, however, could counteract the effect of durability on fleet turnover. One example is the possible accelerated rate of change of car technology that would render vehicles technically obsolete far earlier than when they physically wear out—like deciding to dispose of your 486 and buy a whole new Pentium Pro system, complete with 17″ monitor and 64-bit bus. Unless it is feasible and attractive to upgrade old models, they could be sent to the dismantler for "early retirement." But even if fleet turnover does slow down, the potential recoverable value of hypercars' autobody materials, as discussed below, could increase recyclers' profit per car and offset any losses due to decreased throughput.

Key advanced composite recycling technologies

Current recycling options

No matter how long it lasts, a hypercar will eventually reach the end of its useful life and end up at a dismantler. Once the salvageable parts have been removed, the unsalvageable portion will have to be either recycled or discarded. How would it fare in the recycling system as we know it?

Currently, the U.S. automobile recycling system is driven by market economics—most of the vehicle can be reused or recycled at a profit [13]. Government regulations play only a small role in the process because it is economic to salvage parts for resale or remanufacture and then to recover the leftover metallic content. The success of this recycling system—94% of the vehicles retired each year are processed, and 75% of the mass of each vehicle is recycled—depends mostly on strong and robust end markets for the recycled materials and components [12,13]. Automotive materials and components without end markets and thus incentives for recovery—the 25% of the vehicle *not* currently recycled—are landfilled as automotive shredder residue (ASR), or "fluff." Thus, to avoid mostly being landfilled as ASR, hypercars need to be profitable to recycle.

Under the current automotive recycling system, this would probably not be the case. After removing a hypercar's salvageable drivesystem components, wheels, and various electronic systems, only a small amount of metal in the steering system and suspension might be recovered during shredding. The rest, including most of the advanced-composite autobody and polymer interior, would end up as ASR. Although the mass of ASR from a hypercar—due to its ultralight materials and design—likely would be *less* than for today's average car, it would not generate any profit for the shredder nor be environmentally beneficial. For hypercars, recyclers would have to be employ new technologies in order to recover value from what would otherwise end up as fluff.

Since most of the material left after dismantling a hypercar would be polymers and advanced composites—and much of the value would be in the advanced composites' fibers—the new recycling technologies must center around these materials. Today, advanced composites are most often recycled by grinding them for use as filler in new parts. While this method is relatively simple and inexpensive, it leaves much potential value unrecovered since it retains none of the resin's or fiber's valuable properties.

To maximize the resale value of the recycled products, advanced-composite recycling technologies must recover the materials as close as possible to their original form: polymers should be turned into easily repolymerizable products, and fibers should retain their mechanical properties and be in continuous form. In these forms, the recycled resin and fiber might be "closed loop," or reused in new hypercars for the same applications—unlike recycled automotive steel, which ends up in lower-grade products due to its impurities. However, while considerable effort has been put into recovering resins in their most valuable form, little research has been conducted on continuous fiber recovery. Instead, most fiber recovery efforts have focused on recovering the fibers in short form (less than 3 cm) because the materials' handling methods are much less complex. So even though the short fibers could not be used as substitutes in continuous-fiber applications, they could still retain much of their economic value when used for less structurally demanding purposes [14].

For recovery of these high-value products, two advanced-composite recycling strategies, solvolysis and low-temperature catalytic pyrolysis, show great near-term promise. Both processes could recover the resin matrix and reinforcing fibers from retired advanced composites, allowing their resale in potentially lucrative end markets. Though neither process currently is used commercially to recycle advanced composites, they both have been industrialized for recycling other materials: separated, unreinforced plastics for solvolysis and tires for low-temperature catalytic pyrolysis. Given the potential expansion of advanced composites' use, their industrialization for these materials may not be far behind.

Solvolysis

Solvolysis is used to break down a variety of polymers at elevated temperature and pressure and with an appropriate solvent: *e.g.*, methanol, alcohol, or glycols. The end products of the process are valuable monomers and polyols that can be directly repolymerized. Solvolysis has proven successful on a small scale for recycling pure, unmixed manufacturing scrap and some post-consumer plastics [11]. Research is being done to allow the process to handle certain mixed plastic streams and to be more tolerant of contaminants. Despite some success in unmixed plastic recycling, solvolysis has never been used to recycle advanced composites. It could prove to be effective for recycling composites in the future, but research in this direction (*e.g.*, on solvent/fiber compatibility) is essential.

Pyrolysis

Standard pyrolysis breaks down polymers at very high temperatures in the absence of oxygen. Due to the extreme, high-temperature environment, it can convert mixed polymer waste streams into low-value "pyro-oil" (a mix of petrochemicals whose exact composition depends on the feedstocks), ash, and heat. While technically feasible, standard pyrolysis would not be desirable for recycling scrapped advanced-composite autobodies, again because the fibers could not be recovered. However, a handful of innovative processes based on pyrolysis have shown great promise by reducing the operating temperatures so that the fibers are not destroyed.

One low-temperature pyrolysis process, employing a catalyst to trigger pyrolytic degradation at temperatures below 200 °C, is under development by Adherent Technologies, Inc. (Albuquerque, NM). This recycling effort, although currently operating on a small scale, is of particular interest because its developers are focusing their research on advanced composites—not just unreinforced polymers. In this process, the resin is removed in a gaseous state and then condensed or potentially distilled in a separate chamber, leaving the fibers, with some non-polymer residue such as pigment and filler, intact.

Recent tests hint at the promise of low-temperature pyrolysis for recovering fibers—albeit in chopped form—near to their original properties. Chopped fibers recovered from woven carbon fiber/epoxy composite scrap exhibited a 9% loss in tensile strength from their virgin state. As weaving fibers typically causes 5–10% loss in their mechanical properties, little, or even *no* damage was done to the fibers in this test. Examination of the recycled fibers' surface characteristics revealed no evidence of damage and only a small amount of residual resin [15].

While Adherent has tailored its pyrolytic process to recover fibers, others, primarily the National Renewable Energy Laboratory (Golden, CO), have focused on recovering higher-value polymer precursors. Their approach is to understand the conditions that produce valuable monomers and chemical feedstocks during pyrolytic decomposition so that process parameters can be controlled to maximize their yield. Simple analyses indicate that this process would be economic for a variety of polymer feedstocks [14]. While their work currently focuses only on mixed plastics, the approach could be applied to advanced composite recycling as well.

Markets for recycled material

Processes such as low-temperature pyrolysis demonstrate the technical feasibility of advanced composite recycling, but markets for the recycled material are essential in order to justify implementing the technologies. While such markets are difficult to predict in the uncertain future, current trends suggest the economics will be favorable.

For resins, processes such as NREL's pyrolysis currently could return recycled material to the polymer fabricators at a cost competitive with virgin feedstocks—encouraging evidence that the polymers in a hypercar could be economically recycled [14]. For fibers, although current efforts focus on recovering them in non-continuous forms, the market for chopped and milled versions is strong. For instance, demand for chopped and milled carbon fiber for thermoplastic molding compounds exceeds 625,000 kg/y and is growing at over 10% annually [16]. Fibers recycled through the low-temperature pyrolysis process could potentially be sufficient for this market and others, but at a fraction of the current price. Preliminary cost estimates made by Adherent Technologies indicate that chopped recycled carbon fiber could be profitably supplied at less than a *fifth* of the current virgin price [17].

Of course, a few factors could devalue the materials recycled from hypercars. For instance, the prices of virgin materials are "moving targets," which, if lowered, could make the recycled materials not cost-effective to recover. For example, many are predicting dramatic reductions in carbon-fiber price [9, 18, 19, 20]. Also, products designed with recyclability *not* in mind, such as composite autobodies with combinations of fibers that aren't easily separable, could make materials recovery very difficult, thus less economic. Furthermore, the profitability of dismantling could be affected by rapid technological progress, causing demand for components from older cars to plummet. However, these forces could affect the viability of any automobile recycling system, not just one built around hypercars.

CONCLUSION

The automobile industry is on the threshold of potentially dramatic change in its materials use and platform design. Ultralight-hybrid hypercars, using advanced composites for the autobody, may be more attractive to the consumer, just as profitable to the producer, and much more friendly to the environment than conventional cars. Whether hypercars enter the automotive market as depicted here or in some other form, the technologies embodied in the concept will likely influence how cars are made within the near future. Thus, the automobile recycling industry should be prepared for these changes, even if the first "true" hypercars are not scrapped, due to their durability, for decades to come.

With careful clean-sheet design and the industrialization of recycling technologies similar to those described here, hypercars may even *increase* the recyclability of cars in the future. Hypercars' reduced power requirements could make the drivesystem smaller and simpler, enabling components to be modular for easy removal and upgrading. Its use of a small set of recycling-compatable resins could allow components like the interior, now largely landfilled as fluff, to be recycled along with the advanced-composite autobody. And in the long term, recycling technologies optimized for continuous fiber removal could allow "closed loop" recycling. Therefore, the materials that are now an impediment could actually be the key to increasing automotive recyclability.

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