

Hypercars: A Market-Oriented Approach to Meeting Lifecycle Environmental Goals

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ABSTRACT

Growing social and regulatory pressures are compelling automakers to make cars with not only higher quality but also lower lifecycle environmental impacts. Examples include rules and incentives for clean manufacturing, low-emission vehicles, and recycling. Yet focusing on any single issue or stage of the car's lifecycle in isolation can easily turn into a zero-sum game: any improvement in one area can worsen other issues or stages, or even render the car unmarketable or unprofitable. This paper describes a system-level approach to car design that could minimize lifecycle environmental impacts without sacrificing the features that make cars attractive to consumers, such as price, performance, safety, comfort, and styling. This approach is the ultralight, hybrid-electric "hypercar" concept developed at Rocky Mountain Institute's Hypercar Center since 1991. The paper details how a car optimized to meet market and regulatory requirements can also have a minimal lifecycle environmental impact.

WHAT IS A HYPERCAR?

New materials, processes, and technologies are rapidly evolving that promise to change automotive design in the near future. Potentially even more important to future automobiles is a rapidly emerging worldwide effort to rethink the automotive design process to focus on whole-system optimization within a new design space. System optimization is important because today's automotive design is increasingly being constrained (e.g., by consumer and regulatory demands for reduced emissions and energy consumption, low cost, and improved safety). Meeting these constraints with today's disintegrated, component-based design approach has become difficult; mass, cost, and complexity are all tending to increase. More flexibility is available, however, in a design space centered around a very lightweight and low-drag platform propelled by an efficient hybrid-electric drivesystem. A recursive process to minimize vehicle mass—mass decompounding—downsizes all drivesystem and mass-dependent components in concert so as to capture the synergies among them. At the end of this design process, each component is optimally sized for the entire vehicle.

This "hypercar" design concept combines an ultralight and ultralow-drag platform with a hybrid-electric drivesystem. Skillfully combining these features would create a desirable product that not only would perform well, but also would improve fuel efficiency and emissions while creating other important lifecycle benefits. Computer modeling performed at The Hypercar Center predicts that near-term (say, end-of-the-decade) hypercars of the same size and performance as today's typical 4–5-passenger family cars could get three times better fuel economy [1], subject to further major improvements thereafter. Figure 1 illustrates how the synergies between

- 63% lower mass,
- 55% lower aerodynamic drag,
- 65% lower rolling resistance,
- 300% more efficient accessories (lighting, HVAC, audio system, etc.),
- 60%-efficient regenerative braking (*i.e.*, braking energy recovered), and
- 29%-efficient hybrid drive

could improve a typical 1990 production platform's fuel economy during level in-city driving. Depending on the powerplant employed, emissions could also decrease substantially—enough to qualify as an Equivalent Zero Emission Vehicle (EZEV) under the California Air Resources Board (CARB)'s proposed standards [1].

Figure 1. Two ways to drive 12 km in the city.

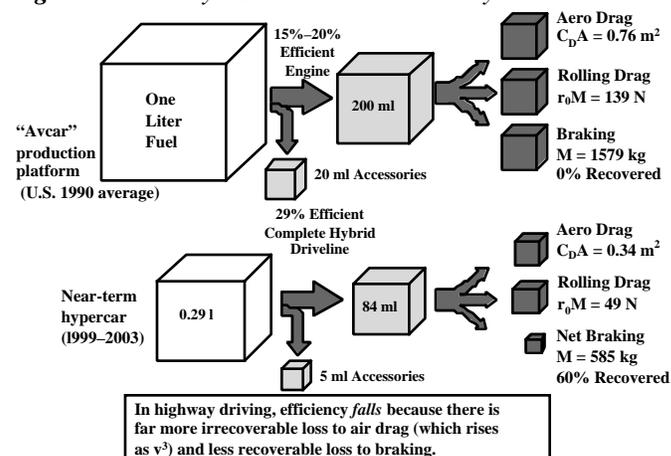
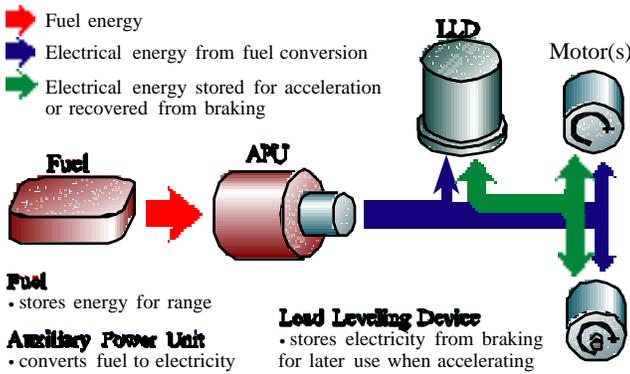


Figure 2. Components of a series hybrid-electric drivesystem.



HYBRID-ELECTRIC DRIVE – In order to improve packaging, fuel economy, and emissions, the hypercar would use a hybrid-electric drivesystem. Both electricity (under our assumptions, generated onboard and recovered from electronic braking rather than recharged from the utility grid) and fuel (liquid or gaseous) provide traction via three main components: an auxiliary power unit (APU), a load-leveling device (LLD), and an electric motor or motors. These components can be configured in series, parallel, or various combinations. In the series configuration, illustrated in Figure 2, the APU generates electricity to power the electric motors and charges the LLD. In parallel configuration, the APU can provide mechanical power directly to the wheels (typically at high tractive loads) in addition to generating electricity. The choice of configuration [1] is outside the scope of this paper and unimportant to its conclusions.

The hybrid drivesystem’s components and fuels can accommodate many options with varying environmental impacts. For instance, the APU could be a small Diesel engine, a small spark-ignition engine, a Stirling engine, or even a fuel cell—each able to use different types of fuel. The LLD could be a flywheel, an ultracapacitor, or any of a variety of high-power-density batteries. Some potential impacts of specific component technology choices are discussed later.

ADVANCED COMPOSITES – In addition to hybrid-electric drivesystems, hypercars would employ composites that embed reinforcing fibers (*e.g.*, carbon, aramid, high-strength glass, Dyneema) in a polymeric matrix. Such “advanced” composites (stronger or stiffer than standard glass-fiber-reinforced versions) have many characteristics that make them attractive for autobody use: durability; outstanding fatigue and corrosion resistance; highly tailorable material properties; generally low coefficients of thermal expansion; good attenuation of noise, vibration and harshness; and precise formability into complex shapes. With careful design, advanced composites could lighten the vehicle more than is possible with steel or aluminum. Materials experts from various automakers estimate that an all-advanced-composite autobody could be 50–67% lighter than a current similarly-sized steel autobody [2,3], as compared with a 40–55% mass reduction for an aluminum autobody and a 25–30% mass reduction for an optimized steel autobody [4].

A handful of existing composite vehicles illustrate composites’ potential for lightweighting. One 1996 example is the 5-passenger Coupé (Figure 3) luxury battery-electric vehicle

developed by Horlacher AG (Möhlin, Switzerland) for low-volume production by Electric Car Company Ltd. (Thailand). Its all-glass-composite autobody weighs 47% less than a comparable steel autobody—60% less, its designers estimate, if made with carbon and aramid instead of glass.

Lightweighting the vehicle improves acceleration, handling, braking, and many other characteristics. For instance, the Lotus Elise’s lightweight body structure (an aluminum spaceframe with a composite skin) is credited as a main cause of its nimble handling and brisk acceleration. Moreover, lightweighting the autobody is a necessary first step in the process of whole-car mass reduction depicted in Figure 4. An ultralight body and structure decreases the propulsion power requirements, permitting a smaller drivesystem without sacrificing performance and making feasible new drivesystem options. The light body and small drivesystem then reduce the suspension, braking, and steering loads, hence the mass required for chassis components. The smaller drivesystem also expands packaging flexibility, which allows more under-the-hood space to be used for crash-energy management. This lightweighting process can then be repeated with a more refined autobody design based upon the lightweight components. Recursive mass decomposing helps to keep platform costs competitive with today’s vehicles by reducing the power and energy ratings of the propulsion components (also reduced by lower aerodynamic and rolling resistance), the mechanical complexity of the driveline, and the mass of costly lightweight materials. Frugal use of those materials then combines with their simpler, less capital-intensive manufacturing and assembly to help overcome their cost-per-kilogram premium over steel [6,7,8]. Safety need not be compromised, even in collisions with heavier vehicles, because advanced composites have extremely high specific energy absorption and crush-force efficiency [1,9] and because the compact, more flexibly packagable hybrid drivesystem leaves more room for dedicated crush structures.

Automakers have strong financial incentives to make hypercars, irrespective of their lifecycle environmental concerns. Composite manufacturing processes are far (for Renault’s L’Espace, 5–7 times [10]) less capital-intensive than steel or aluminum ones, and the tooling cycle can be much faster [6]. These characteristics could greatly reduce financial risks and breakeven production volumes per model, permitting more agile response to changing consumer desires and engineering advances. Barriers to market entry by new competitors would also decrease [*id.*].

Figure 3. Electric Car Company’s Coupé [5]



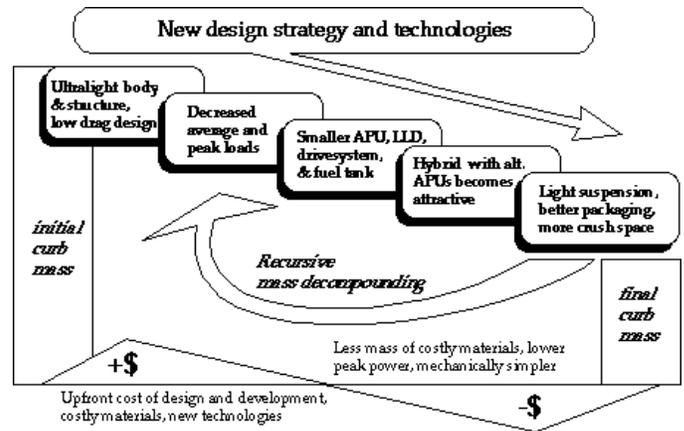
Hypercars could thus meet or exceed regulatory requirements for safety, fuel economy, and emissions *and* consumer demands for performance and affordability. Instead of being merely a fuel-efficient or low-emission car with poor performance, capacity, comfort, safety, or range, hypercars could essentially make CAFE irrelevant: they would be severalfold more efficient than the 8.55 L/100 km standard car *and* attractive to consumers. And while CAFE requires only fuel efficiency, systems-based hypercar design could lower *lifecycle* impacts below those of conventional vehicles.

LIFECYCLE CONSIDERATIONS

Whether consumer attitudes will continue shifting towards more environmentally benign products is both important and unknown. The ‘green’ consumer, who considers lifecycle impacts a high priority, may emerge as a strong force (e.g., many young people with keener environmental awareness are starting to buy cars). This trend, coupled with recent moves towards corporate sustainability (e.g., GM’s signing the CERES principles [18]), may intensify, moving lifecycle issues up on the corporate priority list. Many manufacturers are also paying attention to product stewardship, especially those wishing to sell cars globally (chiefly in Europe, with its spreading requirements to increase recycling and to take back products at the end of their life). To avoid future liability, then, it behooves manufacturers to close their material cycles by turning waste streams into usable products, recycling them internally, and eliminating waste.

Despite these indications that lifecycle issues may become more important, they currently play only a marginal role in car design. Most of today’s consumers value affordability, safety, durability, performance, and convenience over fuel economy, emissions, and recyclability. Worse, automakers, using traditional design concepts, see the latter attributes as in conflict with the former, and hence fear that emphasizing the latter could hurt sales and profits. Market acceptance is therefore paramount: hypercars must be *more* attractive to consumers than conventional cars.

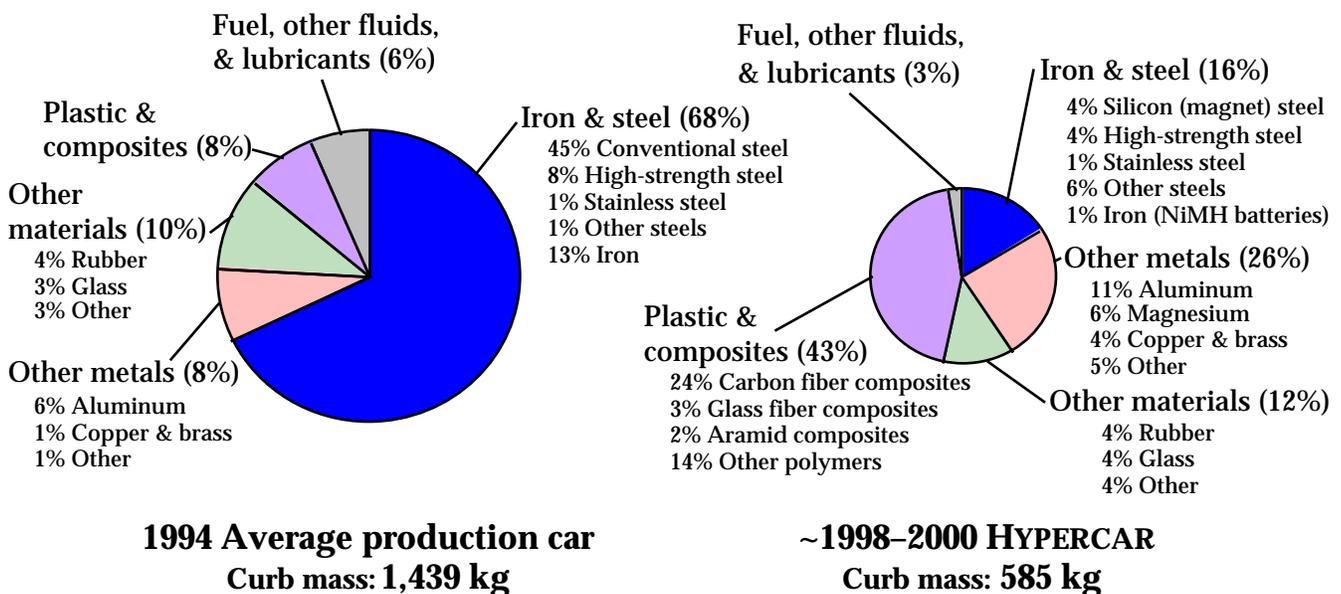
Figure 4. Hypercar design strategy: the cycle of mass decomposing [11].



Manufacturers that try to address both lifecycle and market issues with an incremental design approach get caught up in tradeoffs and details. For example, the relative recycling merits of steel vs. aluminum depend strongly on the application. In contrast, the systems-based design philosophy necessary to make ultralight hybrids work would *also* reduce some of those vehicles’ largest lifecycle environmental impacts, because their lightweighting and relative simplicity automatically reduce their up-front and lifetime needs for materials and energy. A systems-based hypercar design could thus achieve both market and lifecycle environmental goals simultaneously and without compromise, conferring advantage whether or not lifecycle performance becomes important in the market or the political sphere.

MATERIALS USED IN HYPERCARS – Researchers at The Hypercar Center have developed an illustrative mass budget for a near-term, 4–5-passenger hypercar [6], based on 110-line-item benchmarking to components that exist. Figure 5 compares this budget with that of a typical 1994 U.S. production car [12]. The proportions of different materials would change dramatically: metals would contribute 42% of the hy-

Figure 5. Materials breakdown (area proportional to mass).



percar's mass (down from 76% for the 1994 average car), plastic and composites would contribute 43% (up from 8% for the 1994 average car), and ferrous metals' absolute mass per car would fall by 90% while polymers—mainly advanced composites—roughly doubled. The implications of the possible changes in materials on lifecycle energy usage could be profound.

A lifecycle energy analysis in the 1970s showed that making a typical automobile from virgin materials used about as much energy as each year's driving: *i.e.*, the ratio of embodied energy to total lifecycle energy, assuming a 12-year product life, was $\sim 1/13$. A 1995 assessment by Ford's Scientific Research Laboratories [13] found little change: the embodied materials and manufacturing energy was equivalent to 1.2 years' driving (or 1.4 years counting the "energy overhead" of gasoline production). Thus during 20-odd years, while fuel economy doubled and more energy-intensive light metals were more widely adopted, improved industrial efficiency and recycling roughly compensated. Would that still occur with a hypercar, using even less mass of very different materials?

The energy needed to produce a hypercar depends on materials and process choices that are enormously diverse; some are still being commercialized. However, there is good qualitative evidence that hypercars would embody *less* energy in their materials than contemporary metal-dominated cars. As shown in Figure 5, a typical near-term hypercar would weigh about one-third as much as the steel car it would replace. Yet the embodied energy of its materials would certainly not be threefold higher per kg: typically cited values are 77–121 MJ/kg for most polymers (carbon fiber is not exceptional in this regard), 342 for aluminum, and 64–129 for steel [14]. These figures don't account for fabrication or recycling; the former can be quite energy-intensive for metals and the latter for plastics, as discussed below. And of course the ultralight materials yield operational fuel savings at least an order of magnitude larger than their embodied energy [6]: hydrocarbons would be far better invested in cars' polymeric composites than burned in their engines, even if the composites were used only once and never recycled or recovered.

MANUFACTURING OF HYPERCARS – Though the hypercar's largest lifecycle benefit would be its reduced fuel consumption and in-use emissions, large benefits could accrue in manufacturing too. Early, relatively crude manufacturing methods might show only marginal environmental benefit, but more mature advanced-composite autobody manufacturing holds promise of major reductions in energy used, scrap generated, and pollution created.

An early advanced-composite autobody manufacturing process could consume slightly less manufacturing energy than conventional vehicle manufacturing—one-third less according to analyses performed by Frank Stodolsky at Argonne National Laboratory's Center for Transportation Research [15]. That probably understates composite cars' advantage, because: (a) though made of composites, ANL's modeled vehicle would weigh ~ 250 kg more than a near-term hypercar [1], requiring more energy to inject, cure, and transport this extra mass throughout the manufacturing process; and (b) all platforms were assumed to require the same assembly energy, although a composite hypercar would actually have an order

of magnitude fewer parts than a metal one, reducing assembly effort by ~ 80 – 90% [6].

Besides using less energy, the composite manufacturing methods proposed for hypercars and optimized for their costlier-per-kg materials could largely eliminate manufacturing scrap, improving both the environment and the bottom line. Stamped steel parts typically generate ~ 30 – 40% scrap [16]. Although this scrap steel is recycled into new products, its anticorrosion zinc coating complicates recycling because hazardous zinc dust forms when the scrap steel is remelted [17]. In contrast, composites' near-net-shape preforming techniques could reduce scrap to a few percent.

Manufacturing a hypercar might increase or decrease pollution depending on choices of materials and technologies. Adopting relatively clean resins and curing methods could make autobody manufacture and final assembly cleaner than today's. For instance, today's most polluting manufacturing facility is the paint shop: General Motors ascribes more than 43% of its total toxic releases and transfers to painting and coating operations [18]. But advanced composites offer unique opportunities to eliminate the paintshop. Several proprietary in-mold color technologies could allow the composite parts to emerge from the mold with Class A finish. This could probably be justified by avoided capital costs alone, since the paintshop can account for half the cost of the whole assembly plant.

However, hypercars are not guaranteed to be cleaner to manufacture. Not only could the manufacturer choose dirtier materials and manufacturing methods based on cost and lack of regulatory pressure, but shifting to new kinds of components could simply change one kind of embodied pollution into another. For instance, the hypercar's drivesystem is mechanically simplified by replacing mechanical with electrical systems. Fabricating today's engines and multi-speed transmissions creates pollution from foundry and machine shop slag, contaminated sand, and used machining fluid and solvents [19]. In contrast, the hybrid-electric drivesystem could require some machining and foundry operations *and* the manufacture of far more power electronics devices—traditionally a highly polluting process. The net effect of such shifts merits further study and appropriate incentives.

IN-USE IMPACT – Although in-use operation of an automobile is arguably responsible for the largest portion of its lifecycle environmental impact, few incentives exist for manufacturers to reduce its impact below regulatory or market requirements. However, uncertainties in future regulatory action, consumer preferences, and the price and availability of fuel make it worthwhile to explore hypercars' opportunities for reducing in-use energy, emissions, and materials.

Energy use – Today's cars use about nine times as much energy to run as to make [13], so improving fuel economy is the single most effective way to save lifecycle energy. Computer modeling, using empirical component performance maps, indicates that a near-term 4–5-passenger hypercar could average ~ 2.58 L/100 km [1]. (The second-by-second Idaho National Engineering Laboratory model used, SIMPLEV [20], correlates well with test data [21] but predicts slightly worse fuel economy than CarSim—a proprietary hybrid-car simulator developed at AeroVironment for GM [22].) Thus its total in-use energy consumption would be approximately 30% that

of today's average U.S. car, falling from 704 GJ [15] to 218 GJ, and if both had the same embodied energy, the hypercar's lifecycle energy consumption would be ~67% lower.

Emissions – Today's automobiles emit a variety of air pollutants and pollutant precursors, such as oxides of carbon and of nitrogen, volatile organic compounds (VOCs), and particulate matter. These products of combustion are often hazardous to living things. VOCs and oxides of nitrogen react together, in the presence of sunlight, to form photochemical smog, which is mostly ozone—a secondary pollutant now pervasive and problematic in many cities and even in rural areas [23]. Hypercars' effects on each pollutant depend strongly on choices of drivesystems, fuels, and operating conditions, but some qualitative conclusions are already clear.

A hypercar's CO₂ emissions would be reduced in rough proportion to its fuel saving—more with renewable fuel, which would become cheaper per kilometer as fuel economy improved. However, this same reduced marginal cost of driving could also encourage more driving, offsetting some of the saving in fuel and CO₂ (though economists would presumably consider the increased driving an improvement in welfare, at least in terms of internal cost alone).

Hypercars' diverse and rapidly evolving powerplant options make it hard to compare their non-CO₂ emissions with those of today's more mature production platforms, which are themselves full of complex tradeoffs. For example, with spark-ignition (SI) engines of a given design, higher efficiency will typically raise NO_x emissions while lowering HC and CO emissions. (At mean-brake-torque timing, engine-out NO_x emissions peak; however, retarded timing and recirculated exhaust gas are often used to lower the peak combustion temperature, which drives the kinetics of NO formation [24].) Surprisingly, in today's SI-engine automobiles, smaller engines are not necessarily cleaner than larger engines, for two main reasons: (a) smaller engines are more often found in economy vehicles that typically have less robust emissions control technology and consequently have higher malfunction rates [25]; and (b) smaller engines in an oversized drivetrain are forced to run at high load more frequently, and typically spend more time in enrichment—which increases power and protects the catalyst from overheating, but worsens emissions. An SI engine chosen for the auxiliary power unit (APU) of a hybrid drivesystem could be not only appropriately sized, but also engineered to minimize both cold-start *and* off-cycle emissions: its catalyst could be preheated by the LLD or by new heat-storage techniques, and it could operate only near its optimal efficiency and emissions points.

Further near-term emission reductions are available from a nearly commercial Stirling engine [26]. Emissions modeling of a hypercar using this engine, ordinary gasoline, and no catalytic converter—5 passengers, 585-kg curb mass, 0 to 97 km/h in 8.5 s—indicate that it could meet California Air Resources Board's "Equivalent Zero-Emission Vehicle" (0.1 × ULEV) standard expected to be adopted shortly [1,6,27].

In-use materials flows – Routine maintenance of today's cars requires diverse massflows that deplete, pollute, and consume energy and money. Hypercars could reduce and in some cases eliminate these materials flows.

Major non-gasoline automotive fluid flows include oil (from engines, transmissions, differentials, power steering units, etc.), antifreeze, and brake fluid. Out of the 2.7 billion liters of waste oil in the US, nearly 40% is released to landfills, sewers, and storm drains [28]. Nearly half of all U.S. transportation oil is disposed of in an environmentally damaging manner, such as incineration and spraying on dirt roads for dust control [29]. Used engine and transmission oil contains heavy metals, and engine oil contains benzene, a known carcinogen. Near-term hypercars with mechanical APUs would require only a modest fraction of today's average oil requirement (since the powerplant would be far smaller). Similar reductions could be anticipated for antifreeze, power steering fluid, and gear lubricants. Later models could use fuel cells that require no oil or other non-fuel fluids except air.

The massflow of parts (*e.g.*, oil and air filters, hoses, belts, clutch disks, spark plugs, and brake, suspension, steering, and driveline components) would also generally be reduced through mass reduction, elimination, or less demanding operation that extends part life (*e.g.*, in braking systems with lighter vehicles and regenerative braking). Collectively, these effects would be rather large.

Hypercars could also create new materials flows, depending on the specific design. For instance, the power electronics or drivemotor(s), although engineered for the life of the vehicle and for remanufacturability, could fail and need replacement. Also, to the extent that high-specific-power batteries were used as LLDs, they could create flows of possibly hazardous materials. However, given the rapid rate of development of flywheels and ultracapacitors, batteries would probably not be used extensively, and if they were, relatively innocuous types are becoming available; and the batteries would be an order of magnitude smaller and much longer-lived than those in battery-powered electric cars.

LIFE EXTENSION AND RECYCLING – Life extension/durability – New cars are increasingly reliable and durable—some have 150,000-km or longer warranties—and hypercars could be even more so. An advanced-composite autobody should last longer because composites don't corrode, scarcely fatigue, need few or no fasteners, and can withstand small impacts without damage. In addition, the hypercar's hybrid-electric drive components are expected to outlast more mechanically complex drivesystems and to offer simpler modular replacement and remanufacturing.

The hypercar's durability could profoundly affect both the environment and the auto industry. First, increasing the car's durability in the relatively mature U.S. automotive market should slow the rate of fleet turnover, potentially slowing domestic new-car sales. This would benefit the environment by gradually reducing the rates both of extracting raw materials and of later dispersing some of them into the environment. However, countervailing forces seem likely: (a) Automakers might prefer to lease their vehicles so that they could more closely control fleet turnover. (b) Changing tastes in styling could lead to cars with shorter lifetimes. (c) Fast-moving car technology might render vehicles technically obsolete far before they wear out. These conflicting trends between the body's durability and the market's desire for change could, for example, foster a major new industry that refurbishes and upgrades old hypercars for resale in different market segments,

either overseas or within the United States. A single autobody, much like an airframe, could see many incarnations in different markets with reconditioned or upgraded software, hardware, colorcoat, and interior. If the industry sets standards for interoperability, drivesystem elements could be highly customized and continually improved, allowing hypercar owners to keep their car up to date without replacement.

Recycling the hypercar – With a collection rate over 90% and a materials recovery close to 75%, North America's current market-driven automobile recycling system is by most standards very successful. Even so, efforts are currently underway to find ways to recycle much of the remaining 25% of the car (which includes virtually all the polymer content) that currently ends up in landfills. European regulatory initiatives aim to raise the recycled fraction to 85% by 2002 and to 95% by 2015 [30]. Efforts by the U.S. automakers through the Vehicle Recycling Partnership have largely centered around (a) using recycle as filler in certain components, (b) developing effective dismantling strategies, and (c) designing for disassembly. How might hypercars fare given these trends?

At first glance the hypercar's high polymer content and low ferrous-metal content seems to inhibit recycling, since virtually the entire hypercar would end up in a landfill if it was sent to an auto recycler with today's equipment and practices. Surprisingly, though, making the entire car from polymers could actually be the key route to economically recycling virtually the *entire* car. Because most of the polymers would be of more valuable kinds, each of the present barriers to recycling plastics (dismantling effort, recycling infrastructure, polymer composite recycling technology, and markets for the recycled material) could be overcome with careful planning and design for recyclability.

For example, dismantling effort could be dramatically reduced by adopting a small slate of polymers for the interior, components, and body. If this set of polymers is compatible with a single recycling process, fewer parts would need removal before the hulk could be sent to the polymer recycler. Thorough labeling and design for disassembly would also improve dismantling efficiency. Hypercars' clean-sheet design would permit such system-wide changes.

Even though today's infrastructure is built around recovering the metallic content of cars, the collection and dismantling portions of the infrastructure could remain largely intact. Steel shredding operations would see less use, but their operators would have plenty of time to pay for their existing capital equipment (whose payback is usually on the order of 3–5 years [31]) and gradually shift to other activities—either to nonautomotive steel markets (85% of total U.S. steel use) or to new polymer recycling operations. Since new vehicles are used on average for more than a decade before they reach the dismantler's yard, and hypercars' durability might keep them in service much longer, the steel shredding industry would have plenty of time to adapt to the new automotive materials.

Current recycling options – Two advanced-composite recycling strategies, solvolysis and low-temperature catalytic pyrolysis, show great near-term promise to recover high-value products from scrapped hypercars. Both processes could recover the resin matrix (or simpler but reusable molecules) and the reinforcing fibers, which are often worth an order of mag-

nitude more per kilogram. Though neither process is yet used commercially to recycle advanced composites, both have been industrialized for recycling other materials: separated, unreinforced plastics for solvolysis and used tires for low-temperature catalytic pyrolysis. Given hypercars' potential two-order-of-magnitude expansion of markets for advanced composites, timely maturation of these apparently cost-effective processes can be expected.

Solvolysis is used to break down a variety of polymers at elevated temperature and pressure 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, although technically it should be possible. Further research in this direction (*e.g.*, on solvent/fiber compatibility) is essential.

Standard pyrolysis breaks down polymers at very high temperatures in the absence of oxygen. This extreme environment 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 because the valuable fibers could not be recovered. However, several innovative lower-temperature processes based on pyrolysis have shown great promise for this use.

One low-temperature pyrolysis process, using a catalyst to trigger pyrolysis below 200°C, is under development by Adherent Technologies, Inc. (Albuquerque, NM) [34]. Though currently operating on a small scale, this emerging process is focused on advanced composites, not just unreinforced polymers. 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—with nearly their original properties. Chopped fibers recovered from woven carbon fiber/epoxy composite scrap exhibited a 9% loss in tensile strength from their virgin state. Since weaving these fibers typically causes 5–10% loss in their mechanical properties, the recycling process thus caused little or no net damage. Examination of the recycled fibers' surface characteristics revealed no evidence of damage and only a small amount of residual resin [32]. This is not surprising, since carbon fiber is *made* by pyrolyzing polyacrylonitrile at temperatures above 800°C.

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 those products' yield. Simple analyses indicate that this process would be economic for a variety of polymer feedstocks [14]. While NREL's work

currently focuses only on mixed plastics, the approach might also apply to advanced composite recycling.

Markets for recycled material – Processes such as low-temperature catalytic pyrolysis demonstrate the technical feasibility of advanced composite recycling, but markets for recycled materials are essential for implementation. While details of the emergence of such markets are hard to predict, current trends suggest the economics will be favorable.

Processes like NREL's pyrolysis currently could return recycled resins or resin precursors 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, the market for chopped and milled versions is strong. For instance, each year the U.S. demand for chopped and milled carbon fiber for thermoplastic molding compounds exceeds 625,000 kg and grows by more than 10% [33]. Fibers recycled by low-temperature pyrolysis could potentially be sufficient for this market and others, but at a fraction of the current market value: preliminary cost estimates made by Adherent Technologies indicate that its recycling process could profitably yield chopped recycled carbon fiber at less than a fifth of its current virgin price [34].

Of course, materials recycled from hypercars could be devalued by other factors. For instance, the prices of virgin materials are moving targets which, if lowered, could make the recycled materials no longer cost-effective to recover, and many analysts are predicting dramatic reductions in carbon-fiber price [35,36,37]. Products not designed for recyclability, such as composite autobodies with hard-to-separate combinations of fibers, could make materials recovery very difficult and less economically feasible. Furthermore, the profitability of dismantling could shift with rapid technological progress, changing the demand for and value of components both from older cars and from hypercars, which would contain high-value components such as the easily removable LLD. However, these changing conditions could affect the viability of any automobile recycling system, not just one optimized for hypercars.

Overall, the hypercar's impact on recyclability, hence on lifecycle environmental impact, looks positive. But successful recycling would still rely, at least as much as it does now, on intelligent vehicle design, commercialization of promising recycling technologies, and markets for the recycled material.

CONCLUSIONS

A whole-system approach to automotive design can ensure that diverse and seemingly inconsistent environmental goals are met concurrently and without compromising marketability. The hypercar concept could greatly reduce lifecycle environmental impact while enhancing market acceptance and value. Lifecycle performance could be profitably improved whether or not customers demand it. Automakers thus gain a new opportunity to compete with superior products that also happen to be environmentally sound throughout their manufacturing, use, and ultimate disposition.

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