UNCOMMON KNOWLEDGE:
AUTOMOTIVE PLATFORM SHARING'S POTENTIAL IMPACT ON ADVANCED TECHNOLOGIES

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ABSTRACT

Automakers are embracing with vigor the strategy of dedicated platform sharing, which portions common design, engineering, and production efforts over a number of outwardly distinct models. Platform sharing mixes lower-volume "differentiating" technologies to increase market attractiveness with higher-volume "standardized" technologies to lower overall costs. "Disruptive" advanced technologies like polymer composites and the Hypercar™ concept, ill-suited to conventional, mass-production automaking, may fit very well within the new rules of platforms.

Key Words: Automotive Platform Sharing, Hypercar, Advanced Composites

1. PLATFORM SHARING

1.1 The Trend Almost a decade after Saturn's launch by General Motors as an autonomous, customer-focused enterprise offering "a different kind of company…a different kind of car," the automaker recently introduced a second line of "different" car models. At first glance, these midsized cars may be noteworthy for their continuation of the Saturn theme of dent-resistant polymer body panels and their bold plans to capture market share from foreign automakers. Potentially more interesting, however, is how these cars were brought to market. While Saturn's original smaller cars were developed and manufactured independently from GM as truly unique products, its latest cars are modeled on an existing GM product (the Opel Vectra), contain key components (engines and transmissions) employed by other GM divisions, and are assembled in an ex-Chevrolet factory (1,2).

Why did GM change the way Saturn makes cars? According to *Business Week*, "The harsh realities of global auto consolidation are prevailing over the plucky individualism that made Saturn a maverick. GM no longer can afford to let Saturn design, engineer, and manufacture unique vehicles from scratch…Saturn vehicles must now share underpinnings and many components with GM brands." (3) Trying to avoid the perception of being "just another car division of General Motors," (3) Saturn is relying on unique customer service and a handful of easily identifiable technologies (*e.g.*, polymer body panels) to differentiate itself from its GM brethren. With this strategy, Saturn still offers a "different kind of car," while the differences—real, not perceived—are arguably skin deep.[1]

Saturn's fate is not unique. The newest car from once independent Jaguar shares much of its mechanicals with other Ford divisions (4). The latest Saab shares the same Opel platform as the midsized Saturns (5). In fact, almost every global automaker is adopting this development strategy, commonly called "dedi-

[1] A skeptic would look at the larger Saturn as a modified Opel Vectra with polymer skins and different powertrain options. But Saturn personnel strongly argue that its car is indeed distinct from the Vectra. As evidence, Saturn engineers presented to *Car and Driver* a small box full of all the parts common to the two cars—only around 100, and those mostly fasteners (1). However, Saturn admits the V-6 engine design comes directly from Opel, and "members of the development team freely concede that they pretty much lifted the Opel's brakes and suspension design intact" (1). It seems that the Saturn, while containing distinct parts, is indeed heavily based on the Vectra's design; an analogy is a house based on an existing blueprint but having a slightly modified floor plan, different appliance options, and distinctive materials.

cated platform sharing." Dedicated platform sharing, or platform sharing for short, is the amalgamation of disparate car models into a common vehicular architecture, which is then modified to produce distinct models, often for different brands.[2] Platform sharing allows automakers to spread their "common knowledge" of design, engineering, and production across numerous products. This practice is not new—automakers have been sharing platforms across their brands for decades—but the aggressive implementation of it is. GM, for example, is consolidating models from 5 different brands into its upcoming midsized Epsilon platform (6). Ford is reducing its worldwide platforms from 32 to 16 while increasing model derivatives by 50% (7). Volkswagen is in the process of reducing its platform count from 16 to 4 (8). Fiat, most dramatically, is planning to produce 3 million vehicles a year on just three platforms (9).

Platform sharing has many motivations (§1.4), but, as *Business Week* alludes to, the primary one is economics. With world automotive production overcapacity hovering around 30% (10), platform sharing promises to eliminate redundancies, both in development costs and the number of platforms offered in the marketplace. The potential to reduce the latter redundancy, in fact, is a chief rationale for recent auto company mergers: the recent Renault/Nissan tie-up will consolidate Nissan's 25 platforms and Renault's 8 into a total of 10 (11).[3]

1.2 The Basics Platform sharing encompasses a range of tactics. At one end of the spectrum, car models based on the same platform are "badge engineered," a practice long employed by U.S. automakers in which virtually identical cars are sold across different nameplates.[4] At the other end, automakers can produce very distinctive vehicles off the same platform that share few visual and dynamical traits. Volkswagen employs this strategy to dramatic ends, with its distinctive VW New Beetle, Jetta, and Golf, Audi A3 and TT, and two other European models sharing a common architecture and 65% of the same components (8). Few in the public realize the high-end, "halo car" $35,000 TT is heavily related to the post-modern, mass-market $17,000 New Beetle. That's the point: the automaker can spread expensive design, engineering, and manufacturing costs across 1.5 million vehicles (8), while customers feel they're getting unique products.

Platform sharing saves design and engineering costs by spreading out development expenses over several models. For instance, Ford employs a common vehicular structure and suspension geometry for its "DEW" platform, comprising the Lincoln LS and Jaguar S-Type (12). By reducing the repetition of basic engineering work, Ford not only saved development resources but also performed more design optimization, improving the cars' performance (12). In addition, platform sharing saves manufacturing costs by creating standardized modules (*e.g.*, chassis and suspension in Ford's case) that are produced at very high volumes. The high volumes provide economies of scale, as tooling and equipment are amortized over greater production runs, materials prices decrease with bulk purchasing, and labor becomes more productive as it more rapidly ascends the "learning curve." Renault, for one, has recently realized cost benefits

[2] Platform sharing does not have to be "dedicated." Instead of proactively consolidating models into a common architecture, automakers can create product variants from an existing car model not originally designed to serve as a platform. "Unplanned" platform sharing, however, is becoming less popular as automakers try to capture the benefits of designing platforms to accommodate multiple models up front (§1.4). While many of the arguments in this paper apply to unplanned platform sharing, they are tailored to dedicated platform sharing, which seems to be increasingly the industry's modus operandi.

[3] In fact, analysts commenting in the *Financial Times' Automotive World* predict consolidation will drive even more mergers in the future: "…in the next millennium, five or six mega-players will dominate the field, (each) producing between 5–12m vehicles a year" (10).

[4] For instance, DaimlerChrysler's "JA" platform offers three models: the Plymouth Breeze, Dodge Stratus, and Chrysler Cirrus. All cars share the same body, chassis (with similar dimensions), suspension, and powertrain design; the differences between the models are largely in fascias, trim, and options. Among a few other distinctions, the "entry-level" Plymouth offers only a 4-cylinder and cloth seats; the "sporty" Dodge gets alloy wheels and a bigger engine; the "luxurious" Chrysler gets fancier trim (*e.g.,* leather and sunroof). However, from a modest distance away, only a person well versed in these products would be able to tell them apart.

from platform sharing, saving $330 million in development and tooling by consolidating its family of large cars into one platform (8).

When done well, platforms not only reduce costs but also increase value.[5] Highly tailorable platforms, like Volkswagen's, can provide model variants with unique characteristics. Automakers create these characteristics by modifying the platform's standardized, high-volume hardware (*e.g.*, engineers used uniquely-tuned spring rates, dampers, and roll bars for the suspensions of the Jaguar and Lincoln [12]), and adding key, lower-volume differentiating technologies (§1.3). The resulting differentiated models, in general, are more valuable in the marketplace. For one thing, differentiated cars have features better matched to their target customers. Utility-minded U.S. consumers, for example, have shown a willingness to pay significantly more for sport-utility themed variants (*e.g.*, the Subaru Outback and Honda CR-V cost ~$5,000 more than their mainstream counterparts, the Subaru Legacy and Honda Civic [13]). Also, differentiated products off the same platform can create the perception of exclusivity or superiority, generally reinforced through branding. GMC Sierras, marketed to "the 1% who ask more from a truck," fetch a higher price than equivalently equipped, virtually identical Chevrolet Silverados (13).

1.3 The Technologies From a design perspective, successful platform sharing boils down to carefully mixing and modifying technologies. On one hand, standardized components, generally "invisible" to the customer, make the car affordable. On the other, the differentiating modifications and components—those that the customer can directly see, feel, and hear—increase the car's value. Specifically, conventional technologies and their modifications can fall into three groups:

- *Standardized technologies* include electronics and wiring layout; steering; suspension; braking systems; some interior pieces (*e.g.*, HVAC, airbags, interior lighting); underlying body and structural components; and often powertrain elements (engine, transmission, differential, and axles).[6]
- *Differentiating modifications* of the standardized technologies typically involve suspension and steering tunings (softer/harder bushings, anti-roll bars, spring rates, and dampers; steering ratio and power-assist profile); engine design and control-system tweaks (*e.g.*, low-end torque *vs.* high-end power); transmission-gearing changes; and structural alterations (*e.g.*, wheelbase and track adjustments, closure additions, seating height).[7]
- *Differentiating technologies* comprise non- or semi-structural body elements (trim, headlights, taillights, bumper fascias, sheet metal, closures—mainly hoods—and glazings); some interior pieces (*e.g.*, trim, seats, dash); and under-hood packaging layout and presentation, including cosmetic engine parts such as embossed valve-train covers.

In this context, platform sharing is remarkably similar to the architecture of the personal computer. The PC's base of standardized technologies, invisible to the user (CPU, hard drive, motherboard, RAM, video

[5] This value is relative to volume-produced cars offering little or no distinction. In other words, a 500,000 vehicle/y platform with four distinct variants arguably has more overall market value than a single vehicle of the same production run, all other factors (*e.g.*, build quality, safety, size, amenity) being equal.

[6] Powertrains don't fit neatly into the standardized-technology category. On many platforms individual models are offered with several engine and transmission choices, making those components "differentiating" from an individual model perspective. But as these technologies are often shared across platforms and carried over during platform redesigns, this paper categorizes powertrains as standardized technologies in that they are produced in high volumes.

[7] Honda and Fiat have recently taken body and structure modifications to a new level (14,8). Honda, with its "flexible common platform," developed three dimensionally distinct versions of its latest Accord. For previous Accord platforms, Honda biased the body design for the North American market, which prefers bigger cars to other global markets. For its latest body design, Honda used front and rear chassis subframes with adjustable brackets, enabling varying track widths—once prohibitive as it required extensive structural modifications. As a result, the Japan could get a long, narrow Accord; Europe a shorter, wider version; and the U.S., a long, wide variant. Fiat, on the other hand, has moved from sheet-steel-based unibodies to the more flexible, steel-tube based spaceframe structures. Spaceframes cost much less to tool and fabricate and better allow for changes in body dimensions. Fiat predicts unprecedented production flexibility from its switch to spaceframes, lowering breakeven volumes from hundreds of thousands of vehicles per year to 40–60 thousand (15).

and sound card, and operating system), has led to rapid and seemingly perpetual cost savings. Conversely, the PC's differentiating technologies (physical design, user interface, application software, and accessories) have created premium-inducing value—as evidenced by Apple Computer's iMac, whose revolutionary physical design has spurred sales over cheaper, less elegant PCs. With the computer industry's fast product cycles, rapid innovation, and constantly decreasing price/performance ratio (*i.e.*, "Moore's Law")—which have often translated into high market valuations on Wall Street—it is not surprising that automakers seem to be hastily adopting the PC-like strategy of platform sharing.

1.4 The Benefits In addition to minimizing development costs, manufacturing economies of scale, and maximizing product value, well-executed platform sharing can offer several other benefits to automakers:

- *Reduced component counts:* Sharing enabled VW to trim its number of door locks from 122 to 28 and of starter motors from 46 to 10 (8). Decreasing the number of separate components simplifies inventory and tracking and encourages supplier consolidation, providing a friendlier environment for Toyota Production System-inspired "lean-manufacturing" techniques.
- *Superior innovation and quality:* Eliminating the need to engineer separately hundreds of parts allows development resources to be concentrated on fewer technologies, fostering innovation and quality improvements in the smaller set of technologies (8).
- *Global standardization:* Flexible platform strategies like Honda's (footnote 7) allow dissimilar models to be produced according to individual countries' tastes while standardizing production facilities and streamlining both logistics and management.
- *Greater product variety:* Although platform sharing consolidates disparate models, it can ultimately foster a greater number of distinct products. Automakers can develop new products off platforms faster, cheaper, and with lower risk than if developed independently, because they can piggyback on existing development work and components already in production. By basing its new PT Cruiser on the existing Neon platform, DaimlerChrysler is bringing its radically designed car to market for "a fraction of the $700 million spent on the Neon" (16).

1.5 The Downside Despite its benefits, platform sharing is not a panacea for improving automakers' technical and financial performance. This strategy must be executed carefully, lest automakers run into potentially costly and unwieldy problems:

- *Product dilution:* A platform, depending on the standardized technologies, can be stretched too thin if it forms the basis of too many disparate models. BMW points out that VW's Jetta (§1.2) can't compete with its own independently developed models because the Jetta is based on a platform serving several other cars. According to a spokesman, "VW wants to position the (Jetta) as a…competitor, but there's not enough rear seat comfort because the wheelbase is too short" (8). In addition, platforms that span across models of different stature run the risk of cheapening high-end products or adding unnecessary cost to lower-end ones. The most infamous example was GM producing a widely criticized Cadillac variant (the Cimmeron) off its economy small-car platform in the 1980s. BMW rebukes platform sharing on this account: "…we would not [share] platforms because we think…that the customer will notice" (8).
- *Incompatibility:* A platform's differentiating technologies must be carefully designed to integrate with the standardized technologies. Otherwise, automakers will have to perform modifications to make the two types of technologies compatible. These compatibility adjustments are not differentiating modifications (§1.3), and they provide no value of their own to the end product. For example, in adapting the steel-skinned Vectra into its own midsized cars, Saturn engineers had to modify the Vectra's structure extensively to accept polymer panels (2). This costly modification did little by itself to differentiate the product (*i.e.*, both products have essentially the same dimensions and structural performance); it was needed just to accommodate the differentiating technology.
- *Risk concentration:* While automakers may experience lower risk in bringing out model variants off a dedicated platform, they may experience greater overall risk if the underlying platform

they've developed and tooled for proves fallible. A defect in a standardized technology design multiplies the risk across numerous models, making recalls and redesigns potentially very expensive—as in GM's recent recall of 1.1 million vehicles for a common brake-safety defect, and its offer of free repairs for 2.4 million more (17). Also, consumer tastes can change rapidly (*e.g.*, from cars to SUVs), making a platform's physical dimensions or functional characteristics possibly ill-matched to the market. Technologies, too, can change, particularly vehicular electronics, and a platform may not be compatible with the upgrades. And potentially, regulations, public concerns, or an oil shock could make a platform technologically ill-suited to meet increasing efficiency demands.

Ford learned the downside of platform sharing the costly way with its first midsize consolidated platform, which spawned the European-market Mondeo, U.S.-focused Contour and Mystique, and trans-Atlantic Cougar. The much publicized platform development program had numerous delays and cost overruns, and totaled more than $6 billion (18). The resulting products (with the exception of the recently introduced, lower-volume Cougar) sold below expectations in key markets, as the model variants' designs—unlike the Accord's (footnote 7)—were not tailored well to their intended customers (18). Ford's experience (which it has markedly improved upon, not only for its aforementioned DEW platform but also its upcoming small and midsized ones) shows that poorly executed platforms can be "one size fits none."

Such pitfalls offer lessons to automakers moving down the platform-sharing path. First, automakers should ensure from the start that each platform's differentiating technologies are compatible with standardized ones. Second, they should create an architecture that can incorporate new, rapidly developing technologies. And third, they should maximize the flexibility of their platform's standardized technologies; this flexibility will enable them to create model variants of distinct size, functionality, and character that can keep pace with fast-moving market demands. With these lessons in mind, the Hypercar™ concept, described next, may prove a desirable design strategy for dedicated platforms.

2. HYPERCARS

2.1 Disruptive Technological Change The recent history of technological change follows a familiar cycle. First comes an idea for a "disruptive" technology, a term coined by Harvard Business School professor Clayton Christensen (19)—a fundamental innovation promising breakthrough performance compared with established, incrementally advancing technologies. A band of "early adopting" people and organizations flocks to the new concept and begins to flesh it out—first on paper, next in the laboratory. Then an entity demonstrates a crude prototype of the concept, building excitement and a wider network of advocates. Development capital begins to flow to the innovation, and soon a first product appears in the marketplace. This early product may not perform as well as established ones—and it initially doesn't sell very well—but its makers rapidly advance it as they ascend the "learning curve." Eventually, the new technology improves to the point where it competes with, and eventually makes obsolete, its once established competitor. As the incumbent, it begins to lapse back into merely incremental change, until the next innovation arrives, and so on.

The length of this cycle varies widely: for software, it may be months; computer hardware, years; automobiles, nearly a century. In the 1920s, cars arguably underwent their last fundamental change, shifting from open wooden structures to closed steel (20) and from a relatively equal mix of electric, steam, and internal-combustion (ICE) engines to ICEs as standard. Since then, automobiles have advanced considerably—cars now have laser-welded unibody structures and ICEs with fully electronic ignition and controls—but their underlying set of technologies remains essentially the same.

In 1991, Rocky Mountain Institute (RMI) first articulated its Hypercar concept, a new vehicle design relevant to both cars and light trucks and proposing discontinuous leaps in materials, propulsion, electronics, and technology integration. By definition a disruptive technology, the concept propounds a shift from metal to composite structures; mechanical to electrical drivesystems; hardware- to software-dominated electronics;[8] and complex and fragmentary to highly integrated componentry and design. The resulting shifts, if pursued to their full potential and artfully integrated, foretell breakthroughs for consumers, manufacturers, and society (21,22,23). For consumers, Hypercars are capable of offering improved safety, comfort, and driving dynamics (*i.e.*, ride and handling), with features better matched to their wants. Hypercars could lower manufacturers' development time, tooling costs, and assembly effort. And Hypercars, with potential fuel efficiencies and emissions (*i.e.*, CO_2, CO, HC, and NO_x) reductions many times better than equivalent conventional cars', could dramatically help the environment.[9]

2.2 Design Strategy The Hypercar design strategy, visually represented in Figure 1 and described in detail in (22,23), follows a two-part design heuristic. First, automakers should employ advanced materials (E in Figure 1) and low-load design to make the vehicle very lightweight, aerodynamic (A), electrically efficient (B), and low in rolling resistance (I). Next, they should add hybrid-electric propulsion—which combines a small engine or other power source (C and H),[10] electricity buffer storage (G), and electric motors (D) to provide the best combination of performance, efficiency, and emissions—and advanced electronic control (F).

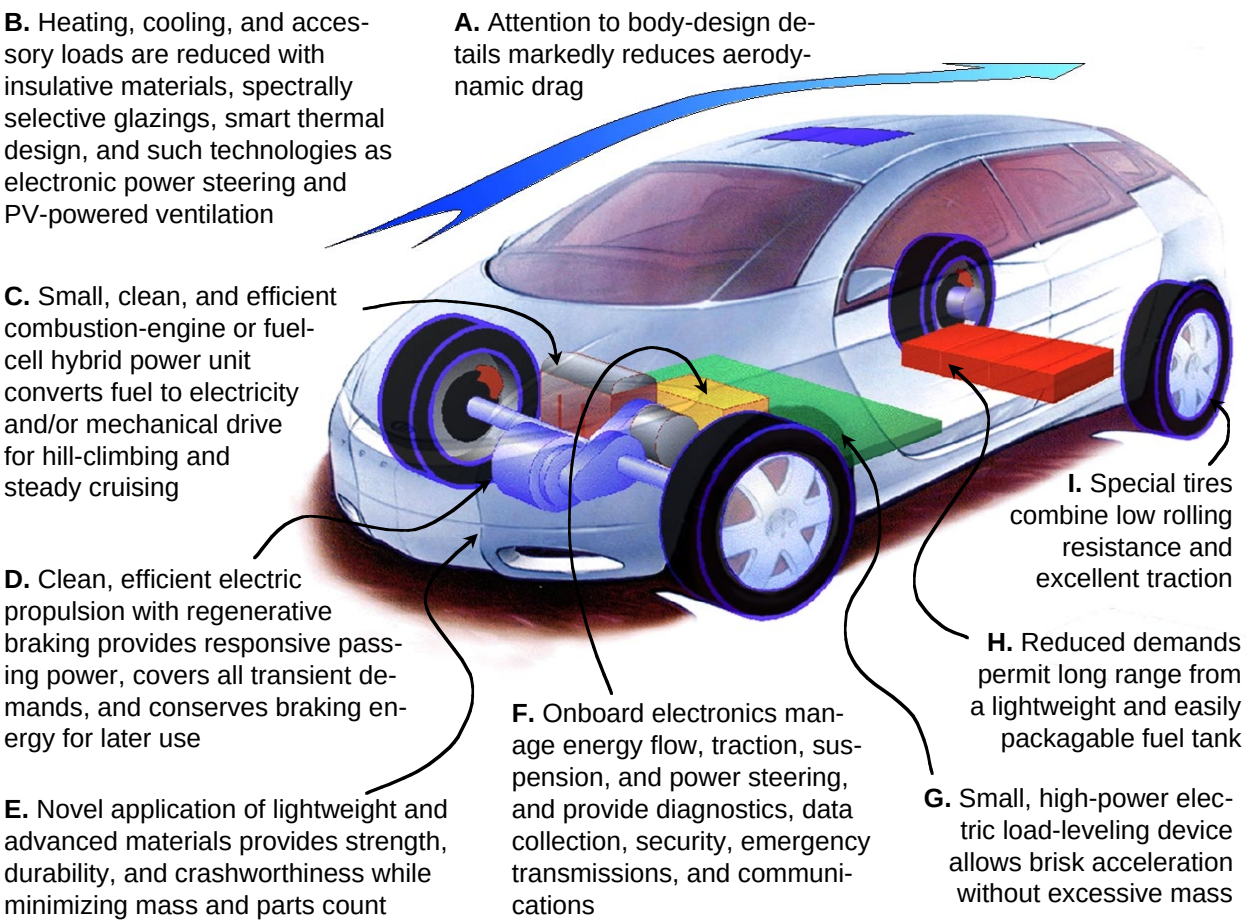
Starting with an ultralight and low-drag body and structure lowers the vehicle's overall tractive load, minimizing the power needed to propel it. As a result, the car can perform well with a smaller drivesystem, enabling the costly-per-kW hybrid and its associated advanced electronics to become economically attractive. Further, the smaller hybrid drivesystem initiates a process of "mass and cost decompounding" as it requires less structure to support it, making the structure itself lighter, cheaper (as fewer kg of costly materials are used), and—due to the hybrid's packaging flexibility—potentially safer (21). Fuel-cell power units directly using compressed hydrogen gas rather than onboard liquid-fuel reforming also become feasible because the tank becomes small enough to be appropriately packaged (24).

[8] *E.g.*, a shift from a system of individual hardwired controllers for functions like anti-lock braking and engine control to a distributed controller-area network with software control of sensors and actuators.

[9] Because of Hypercars' high fuel efficiency and low emissions, many people continue to perceive them foremost as "eco-cars" whose success will be more tied to the price of oil or government regulation than the realization of their technological potential. In fact, Hypercars' benefits to both consumers and manufacturers are likely to be the key drivers determining their market adoption. In this regard, Hypercars are more like LCD flat-panel computer monitors than, say, energy-efficient compact fluorescent lightbulbs. While the latter are bought chiefly because of their energy savings, people buy flat-panel screens for their low-profile packaging and superior image quality. The fact that LCD monitors use 95% less energy than equivalent CRT monitors is a bonus that most people don't consider in their purchase.

[10] In a "series" hybrid, the engine, also called a hybrid power unit (HPU), generates electricity to power electric motors that drive the wheels. In a "parallel" hybrid the HPU both directly drives the wheels and produces electricity to power electric motors. Depending on the parallel hybrid's control strategy, the electric motors are used selectively to assist in acceleration and braking. The hybrid architecture, particularly in series, allows for many HPU options, from petroleum-fueled ICEs to natural-gas turbines to hydrogen-powered fuel cells. See (22) for more information.

Figure 1. Hypercar Design Strategy and Anatomy



2.3 Recent Developments Based on an important metric—events by major and emerging players in the automotive industry—Hypercars appear to be moving rapidly from disruptive concept to the marketplace. As summarized in Table 1, eight years after RMI proposed its concept, Hypercar-related activities are significantly accelerating.[11] After initial (and reasonable) skepticism, automakers have publicly given support to the concept; committed significant development resources to advanced materials, drivesystems, and electronics, and displayed impressive prototypes. New players—including a spinoff from RMI called Hypercar, Inc.—are emerging to capitalize on this period of technological change. And, most significantly, in December 1999, a mass-producible, lightweight, aerodynamic, hybrid-electric vehicle, the Honda Insight, is coming to the U.S. market—arguably the first product to qualify as an early Hypercar.[12]

[11] It is difficult to determine objectively to what degree RMI was a driver, based on its extensive consulting and outreach to industry, or merely a predictor of these changes.
[12] The second, the Huatong Paradigm, is expected to come to the Chinese market in early 2000 (Table 1).

Table 1. A Timeline of Hypercar-Related Developments (25)

Date	Organization	Development
7/91	RMI	RMI proposes composite, hybrid-electric Hypercar (then "supercar") concept at a National Academy of Sciences hearing. Industry, at the time, widely considers Hypercars implausible. RMI begins aggressive outreach and consulting to promote its concept.
12/91	GM	GM shows the halved-weight-and-drag, doubled-efficiency carbon-fiber-composite Ultralite concept car.
9/93	U.S. Government	Government announces partnership (called PNGV) with big-three U.S. automakers to produce 80-mpg "supercar" sedans by 2004.
11/96	GM	GM announces to public it is developing radically more efficient cars with halved weight and drag and hybrid-electric drive.
4/97	Daimler-Benz	Daimler-Benz invests U.S.$350M in Ballard to put hydrogen fuel cells in cars, pledging 100,000 cars/y by 2005.
12/97	Toyota	Toyota launches its ~66-mpg "Prius" hybrid in Japan for ~$16k, announces U.S. launch for 2000, and predicts hybrids will capture 1/3 world market share by 2005.
1/98	Big Three	GM shows 3 hybrid versions of its EV1 electric vehicle, claiming production readiness by 2001. Ford shows ultralight, ~63-mpg P2000 rumored to be in dealerships by 2000. Chrysler shows two composite concept cars, including a 70-mpg hybrid.
8/98	Huatong Motors and ADC	Huatong Motors (China), in collaboration with Texas-based Automotive Design and Composites (ADC), announces near-term production of a 60-mpg composite-bodied hybrid-electric, the "Paradigm," at up to 30,000 cars/y.
10/98	VW	VW announces early-2000s production of a ~120-mpg, carbon-fiber composite subcompact.
1/99	Ford	Ford announces it has designed a fuel-cell sport-utility and has built a Taurus-performance fuel-cell sedan.
1/99	DaimlerChrysler	Newly formed DaimlerChrysler shows two hybrid vehicles, including a large, carbon-fiber-bodied, fuel-cell-hybrid Jeep SUV.
3/99	Mitsubishi	Mitsubishi announces it will have a hybrid-electric vehicle available by the end of 2000, at half the cost of a Toyota Prius.
3/99	BMW	BMW claims it will first to put fuel-cell cars on the market, with the hydrogen-powered fuel cells powering these cars' electrical systems.
4/99	Swatch	Swatch discusses potential hybrid car production in three years with an unnamed U.S. automaker.
4/99	GM and Toyota	GM and Toyota launch a 5-year collaboration on fuel cells, electric drive, and hybrids. Joint production of advanced vehicles rumored at NUMMI facility in California for early 2000s.
5/99	Toyota	Toyota announces it will soon unveil a hybrid minivan and SUV.
5/99	Lotus	Lotus (England) announces a light composite U.S. threat to Porsche's Boxster, and in 2000 will make for GM a version of its light composite Elise.
5/99	Formosa Plastics	Formosa Plastics commits $2 billion to make 500,000/y polymer-body electric cars, including a hybrid.
5/99	ECD, EV Global Motors, UQM	Energy Conversion Devices (ECD), Lee Iacoca's EV Global Motors Co., and Unique Mobility (UQM) announce a joint venture to manufacture and sell composite-bodied hybrid-electric and fuel-cell vehicles for world markets.
6/99	Toyota	Toyota says it will bring a fuel-cell car to market by 2003, one year before DaimlerChrysler.
6/99	Huatong and ADC	ADC announces first quarter 2000 production of the Paradigm, with a plant capacity of 60,000 units a year, and a manufacturing cost of $6500 at half plant capacity.
7/99	Honda	Honda announces the U.S. launch of its "Insight" aluminum-and-composite-bodied, aerodynamic, hybrid-electric, 70-mpg 2-seater for December 1999—arguably the first production vehicle applying the basics of the Hypercar concept.

While the Insight is small and relatively expensive,[13] and only pushes the technological envelope modestly (it uses structural composites and electrical drivepower in limited roles), its design applies the basics of the Hypercar concept. Fully realized Hypercars are more an extrapolation of than a discontinuous leap from Honda's product. In fact, focusing on the Insight's weaknesses could be making the same mistake steel producers made when they initially dismissed the disruptive technology of mini-mill steel (19).[14] If enlightened automakers—both established and emerging—continue their progress in applying the concept, in particular stepping up their automotive-composites development (§3), Hypercars will move into more automotive markets. Ultimately, as discussed in section 4, the Hypercar's conceptual fit with platform sharing could make it a dominant technology architecture—until, of course, the next fundamental innovation supplants it. In the automotive world, that could mean a long tenure.

3. COMPOSITES

3.1 Why Composites? While an average U.S. vehicle is three-quarters steel, iron, and aluminum, and less than ten percent polymer and composite by mass, a Hypercar could be only one-third metallic and more like one-half polymer, composite, and advanced composite (21).[15] Why do Hypercars adopt such a dramatic shift in materials—particularly considering advanced composites' nominal use in the automotive industry? While metals are advancing rapidly in areas important to Hypercars, like mass reduction and tooling cost (particularly with spaceframes),[16] advanced polymer composites offer a superior combination of benefits for structural applications like the autobody and chassis (*i.e.*, suspension, axles, tie rods, etc.). In particular, composite materials stand out when considering four areas critical to Hypercars' breakthrough potential: mass reduction, crashworthiness, product quality, and manufacturing agility. Importantly, composites' performance in any of these areas alone do not justify their use—it is their potential in all of the areas together which makes them attractive. And while "in theory, theory and practice are the same, but in practice, they're not," early real-world evidence of composites' attractiveness is seen in manufacturable composite-bodied vehicles like Solectria's Sunrise, DaimlerChrysler's CCV, Ford's CIV, Horlacher's Coupé, McLaren's F1, and Huatong's Paradigm as well as cars with significant composite components, like the Lotus Elise.

[13] While at $19,500 it is remarkably cheaper than other advanced vehicles like the $35,000 EV1, it is still far more expensive than other vehicles in its class, like the Honda Civic hatchback or the Toyota Echo.

[14] Established steel producers first dismissed mini-mill products as low-grade materials only applicable to bottom-of-the-market applications like rebar, not high-quality, highly profitable products like sheet steel. However, mini-mill steel offered the potential for breakthrough advantages (radically lower capital and labor costs), and it was not long before it improved in quality and captured higher-value applications like structural steel. Now, mini-mill steel is poised to enter the sheet-steel market, and possibly become the incumbent technology. From this perspective, Honda's Insight could very well be the Hypercar's rebar equivalent.

[15] Composites combine two distinct materials to create a new material with superior properties than its parts'. Polymer composites combine a tough, light polymer matrix (*e.g.*, epoxy, polyester, vinyl ester) with strong and stiff reinforcing fibers (*e.g.*, glass, carbon, aramid). "Advanced" polymer composites—those discussed in this paper and often referred to as simply "composites"—have properties greater than moderately loaded, 100% random E-glass-reinforced composites.

[16] For example, both aluminum and steel are making strides in lightweight automotive structures. Ford's aluminum-intensive P2000 midsized-car autobody with closures (doors, hood, decklid) is 54% lighter than the comparable 1997 Taurus's (26). The steel industry, as an update to its Ultra Light Steel Auto Body program (ULSAB) (26), has created an Advanced Vehicle Concept project (ULSAB-AVC) to create lightweight whole-vehicle (*i.e.*, not just body and chassis) designs, including one targeted for the 80-mpg, ~900-kg PNGV initiative (27, Table 1). For tooling and equipment investment, Fiat's steel spaceframe manufacturing technology is enabling very low breakeven volumes (footnote 7). Also, the Norwegian company Hydro Raufoss Automotive is producing aluminum-extruded chassises for the Lotus Elise at 3,000 units a year (soon to be expanded up to 10,000 with General Motors buying rights to the chassis) profitably, because of its low tooling costs of a "few thousand £" per die (15).

3.1.1 Mass Reduction Reducing a car's mass improves its performance (*i.e.*, acceleration, handling, and fuel economy), cuts its emissions (as less fuel is combusted and acceleration transients are less severe), and can lower the cost of drivesystem and chassis components.[17] While mass reduction benefits any car, it is critical for Hypercars' economic feasibility (*i.e.*, "cost decompounding" in §2.2). Because of their high specific strength and stiffness, advanced polymer composites have a greater potential for reducing the mass of automotive structures than metals. Experts from Ford and GM have estimated that advanced composite structures can be up to two-thirds lighter than equivalently sized conventional steel ones (28,29). Recently, MTC, Inc. confirmed this with a predominantly composite, non-manufacturable autobody prototype that weighs 68% less than a similarly sized steel autobody (30).

However, current manufacturing processes constrain composites' mass savings to the realm of light metals: manufacturable composite autobody designs like the Sunrise (31), Paradigm (32), and CCV (33) all save roughly half the mass of comparable steel structures, similar to Ford's aluminum P2000 (footnote 16). Although not clearly superior to metals, composites' real-world 50% mass reduction is enough to trigger Hypercars' gains in efficiency, performance, and cost decompounding. And while not strictly necessary, future advances in manufacturing technologies may realize the remainder of composites' mass-saving potential.

3.1.2 Crashworthiness Lightweight cars, facing a fleet of heavier vehicles, have greatly expanded and more challenging crash-safety requirements. They must be soft enough to crush smoothly against a fixed barrier (*e.g.*, guardrail, tree, wall) under the load of their own reduced mass, yet also be able to absorb extreme forces in high-speed collisions with much heavier vehicles while maintaining their occupant survival space. In this regard, composites' tailorable crush behavior and high specific stiffness are highly valuable. Composites can be designed to crush predictably and progressively to absorb collisions with a fixed barrier—the standard type of collision government and industry groups use to measure a car's crashworthiness. In such tests, dedicated, very lightweight, front composite-crush structures in the Elise and McLaren F1 absorbed almost all the energy in the fixed-barrier collisions (34). In addition, a 1984 Ford Escort with a retrofitted composite front end and no airbags scored higher in government crash tests than both a production and an aluminum-intensive 1995 Taurus (34).

But likely of more concern to potential lightweight car buyers than hitting a fixed barrier is the prospect of colliding with a heavy SUV or truck. In this scenario, composites may be the best lightweight material choice. Composites' high specific stiffness can be used to maintain occupant survival space in severe collisions or rollovers without large, vision-impairing "A" pillar cross-sections. The Ford Composite-Intensive-Vehicle (CIV) performed so well in its roof-crush test that it exceeded the bolted-down measuring equipment's maximum load capacity, actually pulling it from the floor (35). The added stiffness that composites can provide to the survival space also provides an improved reaction member for unusually high crash forces. Composites' high specific energy absorption—up to ~5 and ~3 times the best steel and aluminum structures, respectively (36)—and efficient use of available crush space, approaching twice that of metals,[18] can then be more fully utilized in the crushable sections of the car. To this end, AD&C estimates its Paradigm absorbs 80% more crash energy than a comparable steel chassis (32). Further, composites' mass reduction, as noted, enables hybrid drive, which has more flexible packaging requirements and could enable the car to have more available crush distance.[19] All in all, composites provide engineers

[17] The same can, of course, be said for reduced aerodynamic drag, rolling resistance, and accessory loads (22).

[18] The improved efficiency in use of available crush space is a function of composites' potential microfracturing behavior that can provide near constant (*i.e.*, flat) crash-force transmission to the passenger compartment, as compared to the force spikes produced by fold propagation in the crushing of metal structures. This fracturing behavior, in combination with their high specific energy absorption, means that composite structures of reduced size and mass can be designed to absorb far more energy than if they were made from metals.

[19] The large and essentially uncrushable engine and transmission in a conventional car—due to its mechanical coupling to the wheels and limited ability to be divided—restricts the available crush distance in the front of the vehicle.

with a design space that can make lightweight cars unusually safe, not just in crash tests but also in the reality of the modern road.

3.1.3 Product Quality Composites' inherent properties translate very well into the product attributes customers prefer in cars and trucks, with one notable, but not intractable, initial exception (surface quality).[20] Four composite properties in particular lead to desirable vehicular characteristics:

- *Stiffness*: Composites' stiffness can result in less tradeoff between comfort *vs*. handling.[21] The "first-mode" body stiffness of the Ford CIV was 35 Hz (35), and the GM Ultralite (Table 1), 45 Hz (37), both better than those of typical luxury cars.
- *Insulation*: Composites' sound, vibrational damping, and thermal properties—most dramatic with core-in-the-middle "sandwich" structures—can lead to improved acoustics, NVH, and interior climate that improve comfort and reduce driver fatigue. Because of its inherent dampening properties, the Paradigm's composite suspension has no rubber bushings or dampers (38). The Sunrise, in part due to its composite body, maintains a comfortable 20–25°C interior temperature for ambient temperatures ranging from –10 to +35°C, despite a downscaled HVAC system (39).
- *Moldability*: Composites' moldability allows for complex, large parts and dramatic component consolidation: while steel body structures have hundreds of parts, the CIV body has six composite pieces (35), the CCV body has only four composite parts (33), and the entire Sunrise chassis is a single, 112-ft^2 piece (40). Aside from manufacturing benefits (§3.1.4), part consolidation reduces cut lines and seams and permits large, one-piece underbodies, improving aerodynamics. In addition, composites' moldability increases styling flexibility, evidenced by most current cars' use of composites for complex-shaped fascia and exterior trim. The 1998 Mustang hood, for example, had to be made in composites because it had too deep a draw to be feasible with metals (32).
- *Impact and corrosion resistance*: Composites can be resistant to minor dings, dents, and fatigue, and don't rust. Saturn (§1.1) has leveraged this benefit into marketing success.

3.1.4 Manufacturing Composites' moldability can provide numerous manufacturing advantages. Parts consolidation minimizes tooling and parts count and their associated investment, inventory, tracking, and assembly effort and space. DaimlerChrysler estimates its CCV, largely due to its composite body, would require a sixth the assembly space, a third the assembly effort, and a third the investment of a comparable steel-bodied car (33). Consolidation can expand beyond body structures: the Lotus Elise's 7.5-kg front-end composite structure combines mountings for the headlamps, radiator, "clamshell" one-piece body front end, sealed ductwork for the radiator and HVAC intake, and the capability of absorbing most of the energy from a 30-mph fixed-barrier crash—eliminating dozens of parts, tools, and assembly operations. (41) Composites also require less pressure to form into shape, lowering the per-unit cost of tooling and equipment. The Paradigm's entire body and chassis tooling cost is on the order of only $100,000 (38). Additional manufacturing benefits from composites' moldability can include shortened product cycle time (*i.e*., less tooling to fabricate, fewer jigs and fixtures, fewer manufacturing and assembly stations to set up, etc.), increased potential for design flexibility (*i.e.,* rapid tooling changes), and the potential elimination of costly and time-consuming paint processes—in-mold coloring, aside from helping with the Class "A" issue (footnote 20), could obviate the typical ~$350M several-hour-cycle-time paint shop (33).

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[20] Depending on the materials (*i.e.*, resin and fiber loading) and manufacturing process, certain composites can have a tough time providing shiny, metal-like Class "A" finishes. Class "A" is attainable in non- or semi-structural composite parts, as sheet molding compound (SMC) exterior panels are used on dozens of vehicles such as the high-end Lincoln Navigator. But smooth, shiny surfaces are more of a challenge for structural parts. A variety of in-mold color technologies, as well as improved molding techniques, hold promise to improve structural composites' finish. Alternatively, composite cars can be designed to obviate the need to structural Class "A" parts (*e.g*., a composite spaceframe with hang-on panels).

[21] Improved handling is not only of value to enthusiasts but also improves driver control in panic situations and dynamic-stability control by vehicle systems. Greater rigidity allows more accurate sensor inputs for vehicle attitude and a better reaction member for damper-, brake-, and drive-torque-based corrections.

3.2 Composite Affordability Composites' potential benefits will be for naught unless the materials can be economically manufactured. RMI has long argued (37) that economic production is possible, particularly at low- and mid-volumes (up to 100k/y). Intuitively, economic production is hard to envisage, as advanced composites' per-kg cost can be severalfold greater than aluminum's, and an order of magnitude greater than steel's. While material costs have decreased rapidly—Cape Composites is offering unidirectional carbon prepreg at under $8/lb, and Zoltek plans to offer carbon fiber at $5/lb or possibly less (34)—they are only part of the cost picture.

When accounting for "upstream" costs beyond raw materials like manufacturing, well-designed composite structures should be able to overcome current and future materials cost disadvantages. First, lightweight structures, particularly in mass-optimized Hypercar designs, minimize the use of costly materials. A halved-mass structure can afford a two-fold higher materials cost. Second, composites can substantially reduce capital investment (§3.1.4), thus minimizing a structure's amortized tooling and equipment costs—which can be several hundred dollars per car for even the highest-volume steel platforms (37). Third, composites' part consolidation greatly minimizes assembly effort and its associated costs—typically constituting more than one-third of a structure's unfinished cost (37). Fourth, composites' potential elimination of the paint shop further decreases investment and amortized costs (§3.1.4). Fifth, composites' lightweighting creates cost-decompounding benefits, particularly for Hypercars and their relatively costly-per-kW hybrid drive components (§2.2). Finally, composites consolidation potential can reduce design, engineering, and manufacturing costs by integrating multiple functions into single components—from the Lotus front-end example (§3.1.4), to suspension parts,[22] to potential consolidations of the body, instrument panel structure, and interior bits.[23] To wit, IBIS Associates' cost modeling (37) indicates that "upstream" cost savings should be able to offset composites' materials costs when compared to high-volume steel structures. More importantly, the Paradigm's anticipated $6,500 manufacturing cost per composite, hybrid-drive car could be the first real-world example to realize these savings (38, Table 1).

4. COMPOSITES, HYPERCARS, AND PLATFORM SHARING

4.1 Uncommon Knowledge As summarized in the last two sections, the Hypercar design strategy and advanced composites may provide a host of potential benefits for automobiles. Hypercars' synergy of lightweight construction, hybrid-electric drive, and advanced electronics diminish the traditional tradeoffs between performance *vs.* efficiency, ride *vs.* handling, and affordability *vs.* amenity. Advanced composites offer the potential of enhanced safety, durability, comfort, and structural stiffness.

However, conventional wisdom is that these technologies are ill-suited to the requirements of modern automaking, and more applicable to low-volume, boutique products than mainstream vehicles. The primary reason is that Hypercars and composites don't fit comfortably into the industry's traditional mass-production model. Volume production requires that technologies be produced cheaply and at a fast rate, traditionally about one unit per minute to keep pace with the final assembly line. A recent article in the *Detroit Free Press* (43) commenting on the future of composites reflects this opinion:

> Vehicles probably will not be made entirely of plastic any time soon. Key structural and mechanical parts need to be extremely strong—which means they would need to be made of composites like carbon-fiber. But composites take too long to make, and time equals cost in the world of manufacturing…the technology is there, but the expense is too high.

[22] A design for a one-piece composite lower suspension arm on the Paradigm replaces two conventional lower-control arms, inboard pivots, coil springs, shocks and an anti-sway bar—and can be manufactured for just $25 (38).
[23] Delphi Automotive, for example, demonstrated dramatic functional consolidation with a one-piece composite cockpit module that integrates components of the HVAC, instrument-panel, electrical, steering, safety, and infotainment systems (42).

What this excerpt fails to consider is the potential impact of dedicated platform sharing—a trend that could change the industry's rules. Platforms unite the once-separate worlds of high-volume production and niche manufacturing. With platforms, standardized technologies (§1.3) still need to adhere to the rigors of volume production to realize economies of scale, but differentiating technologies—employed for their market and risk benefits—don't.

4.2 Hypercars and Platforms Hypercars, like conventional cars, have a mix of standardized technologies and differentiating technologies and modifications. However, the breakdown of its mix is different:

- *Standardized technologies* in Hypercars are the drivesystem—the hybrid power unit, load-leveling device, and electric motors; electronic hardware (controllers, sensors, and actuators); and some chassis (*e.g.*, suspension) and interior components.
- *Differentiating modifications* comprise the packaging and sizing of drivesystem;[24] suspension and chassis adjustments; and software control of motor performance,[25] active suspension settings, and the character of traction control, anti-lock braking, coast/regeneration mix, etc.
- *Differentiating technologies* include the structure and body; interior parts affecting function, look, and feel; and modular electrical and electronic features that could be made plug-and-play via flexible, multiplexed electronics and software-dominated architecture.

Thus Hypercars have a mix of technologies—standardized technologies that lower overall product costs and modifications that increase product distinction—that could be compatible with most automakers' emerging, platform-based business models. But Hypercars may be more than just compatible with platform strategies. Hypercars may be *desirable* for them. Composites, for example, not only have favorable low-volume economics but also less obvious attributes potentially advantageous to platforms. Also, Hypercars' standardized technologies may have the potential to be applied more broadly and their differentiations more easily achieved, both bringing economic advantages. Finally, the Hypercar strategy may be effective in dealing with the potential platform-sharing pitfalls identified in section 1.6.

4.2.1 Low Breakeven Volumes Steel, the dominant automotive structural material, fits very nicely into mass production environments: it has fast shaping and assembly operations (albeit many of them) and a low ratio of variable to fixed costs. As a result, new structural materials are commonly expected to fit steel's volume-friendly mold. But platforms challenge this assumption. As key automotive differentiating features are size, ergonomics, styling, and functionality, automotive structures may be better suited as differentiating technologies rather than standardized technologies with modifications.[26] In this regard, composites' attractive low-volume economics and adequate operational cycle times could increase model variants' distinctiveness, hence market attractiveness.

Fiat, with ambitious plans to share platforms and create highly differentiated models (§1.1, footnote 7), publicly stated that its ideal breakeven volume per distinct model could be around 50,000 cars/y (8).[27] Composite processes can meet this volume. Assuming 250 working days a year, two 8-hour shifts, and an average 20% downtime, a manufacturing cell would require a cycle time of a little less than 4 minutes—or 8 minutes with a parallel line (which appears feasible given composites' low capital costs). Ford

[24] With certain hybrids, automakers could add or subtract drivesystem power by adding or subtracting modules within components (*e.g.*, cells or cell strings for FCs and batteries, power switches for controllers).

[25] For example, well-designed switched-reluctance motors permit real-time software control of torque/speed relationships with a degree of flexibility unavailable with ICEs and other mechanical componentry.

[26] While their overall design could vary significantly from model to model, "differentiated" composite automotive structures may share engineering work for certain elements—*e.g.*, structural members like firewalls, suspension sub-frames, cross-car beams, and rocker panels—that do not directly affect a model's distinctiveness.

[27] A Fiat senior vice-president stated in *Financial Times' Auto World* that "(Fiat) would break even at 250,000 units a year, the same as currently, but we will do it with more products in the future, so that the risk involved…is lower. Maybe we would have five models in the family, but still break even at 250,000" (8).

demonstrated a 7-minute cycle time for its resin-transfer-molded processed CIV (35); DaimlerChrysler demonstrated a 3-minute cycle time for its injection-molded CCV (33); and DuPont predicted a 90-second cycle time for its compression-molded composite spaceframe design (44). While mainstream automaker developments, like the Automotive Composite Consortium's P4 liquid molding process (45), are pushing to lower composites' cycle time to a mass-production level, platforms make such efforts luxuries: even without them, composite manufacturing appears to be sufficient for platform-sharing strategies.

4.2.2 Other Benefits of Composites Advanced composites, aside from their lower breakeven volumes, could bring less obvious benefits to dedicated platforms. Specifically, in the four areas discussed in section 3.1, composites could bring strong platform-specific advantages:

- *Mass reduction:* Composites' lightweighting creates a larger design space for tailoring the efficiency and performance of different models to market-segment requirements. Lightweighting also makes hybrids, and their platform benefits (§4.2.4), feasible and attractive through the decompounding of mass and cost.
- *Safety*: Since advanced composites can largely decouple mass from size, the variance in mass between differently sized models off a common platform can shrink. As a result, potential crash loads across different models could converge, reducing the need for costly structural reengineering (*e.g.*, stiffening of the front end for a heavier car to handle greater kinetic energy) and its associated crash test/revise/retest cycles. Also, because composites tend to fail locally, models can be designed to incorporate expendable and easily replaced dedicated crush structures to absorb crash energy (well above and beyond the usual bumper beam for 5-mph impacts), enabling further levels of safety standardization for platforms.
- *Product quality*: Composites' inherent stiffness, damping, and durability could allow platforms to span more markets, as composites' baseline properties (ride, comfort, handling) would enable low- and high-end cars to share platforms. The torsional stiffness of composite structures can turn the normally narrow tradeoff of ride *vs.* handling into a wide range of market options.
- *Manufacturing*: Composites' reduced count of tools, jigs, and fixtures could increase the flexibility of assembly operations, simplifying the process of assembling model variants on the same line. In addition, reduced product cycle times achieved by quicker tooling fabrication could allow automakers to spin-off platform variants faster to keep pace with shifting market tastes.

4.2.3 Greater Standardization Like advanced composites, the Hypercar design strategy could bring advantages to platforms. A Hypercar's standardized technologies—chiefly its hybrid drivesystem and electronics[28]—may have a greater capacity for standardization than its conventional automotive equivalents. Standardization decreases the number of distinct components that needs to be designed and engineered and increases the efficiency of capital investment, lowering overall costs (§1.2).

Engines and transmissions are currently standardized, but often they have to be heavily modified for individual models. These modified drivesystems, due to their mechanical limitations, frequently don't furnish the level of differentiation model variants require; this becomes particularly evident with SUVs that share an engine but require more torque than cars built on the same platform (*e.g.*, the CR-V and Civic). To overcome this shortcoming, automakers can share powertrains across different platforms (making them, as noted in footnote 6, ostensibly differentiating technologies). However, these shared drivesystems create packaging and integration challenges for automakers, as platforms then have to be compatible with several unique drivesystem architectures.

[28] As noted in footnote 8, Hypercars' electronics would shift from hardwired, dedicated controllers to a software-based, flexible controller-area network, enabling standardization of controllers, sensors, and actuators.

Hybrids—particularly ultralight hybrids—may offer standard configurations within platforms that can require fewer modifications to create high levels of differentiation. Hybrids unbundle the functions of power production and torque, which are tightly coupled in conventional drivesystems. The HPU provides continuous power generation; the load-leveling device (LLD) provides peak power; and the electric motors deliver power and torque to the wheels. Moreover, lightweight vehicle architectures have reduced peak power and torque requirements, so that the drivesystem performance requirements for vehicles of different sizes tend to converge. As a result, a Hypercar-based platform could adopt standard drivesystem components—like a HPU, LLD, and front-drive electric motors—and offer distinct peak power and torque availability for model variants by changing the control software, adding LLD and power-electronics modules, and adding electric motors at the rear wheels (which would also add all-wheel drive). Hybrids may as well enable better uniformity across platforms. Hybrids' packaging flexibility and unbundling of power and torque create the potential for commodity-like components to serve multiple platforms, even from different automakers—one possible reason why Ford and DaimlerChrysler are jointly developing fuel cell HPUs with Ballard Power.

4.2.4 Easier Differentiation Model differentiation can be expensive: Saturn spent $700M to engineer and $550M to tool its variant of the Opel platform (46). For this reason, Hypercars may be attractive in that their technology mix is, by nature, differentiating (*i.e.,* composite structure) or more readily modifiable (*i.e.,* drivesystem, suspension, and electronics). First, composites' moldability, potential for standardized safety engineering (§4.2.2), and low-volume economics, coupled with hybrids' packaging flexibility, enable model variants with highly distinctive size, style, and functionality—possibly much greater than steel unibodies, and equivalent or better to metal spaceframes. Second, hybrids' unbundling of drivesystem functions could provide greater levels of performance differentiation as well as more flexibility in the selection of componentry—*e.g.*, low-emission fuel cells, turbines, and Stirling engines are better suited to provide continuous power than variable power and torque. Finally, Hypercars' hybrid-electric drivesystem, suspension, and "infotainment" systems will be highly integrated and software controlled, enabling changes in code to accomplish many functional modifications that transcend individual systems.[29]

4.2.5 Avoiding Platform Pitfalls As Ford learned the hard way with its Mondeo, platform sharing with conventional technologies carries several potential risks. The Hypercar design strategy may help abate these perils when considering the three platform-sharing "lessons" identified in section 1.6:

- *Ensure the compatibility of standardized and differentiating elements*: By shifting to composites, Hypercars eliminate potentially costly compatibility issues (*e.g.*, differences in surface finishes, dimensional tolerances, etc.) between underlying metal structures and the composites and plastics that—in conventional cars' fascia and closures—often differentiate them (47); also, much of Hypercars' differentiation will be done through software, which will transcend typical hardware-based (chiefly packaging and joining) compatibility problems.
- *Be able to incorporate new, rapidly developing technologies*: the Hypercar design strategy is a big umbrella that can accept many types of technologies (22). Its hybrid drive can accommodate several distinct types of engines, LLDs, and motors. Its structure can incorporate a variety of polymers, fibers, and manufacturing methods (21), and arguably could incorporate light metals. Finally, its CAN-based electronics should be plug-and-play, incorporating new technologies as they come to market, and its software control upgradeable as developers create new, improved control algorithms.
- *Maximize the flexibility of a platform's standardized technologies*: Hypercars' structures as differentiating technologies are by definition flexible, especially when compared to conventional cars' less flexible standardized metal structures; its drivesystem, through unbundling power and torque and software control, can give model variants highly differentiated driving characteristics.

[29] *E.g.*, a driver may want the car to handle more "comfortably" while she's on a cell phone, in which the infotainment system would signal a change in handling characteristics governed by the power controller, electric motors, and active suspension.

4.3 Implications Composites and Hypercars—inapplicable to traditional mass-production practices—are likely compatible with, and desirable to, the increasingly popular strategy of platform sharing. Platforms, hence, could provide a new logic in how advanced technologies and architectures are adopted in future. For close to a century, only incremental or "sustaining" (19) automotive advances have been possible because innovations have had to pass through a high-volume filter. Now, new leapfrog or "disruptive" technologies may pass muster if they offer sufficient market and risk benefits, enabling them to classify as differentiating technologies. Also, new automotive design strategies could thrive if they create an attractive economic picture to automakers—lowering costs through standardization while increasing value through differentiation.

As noted, automotive platform sharing conceptually shares much in common with the design and manufacture of personal computers (§1.6). Composites and Hypercars could heighten this similarity. Hypercars like PCs employ standard, yet highly modular, "internals" (*e.g.*, drivesystem and electronics) and differentiate through stylish and functional synthetic molded exteriors, flexible packaging, well-executed system integration, and "look and feel" controlling software. The implications of making a car's architecture more like a PC—while limited in number, as cars have to transport humans while PCs just electrons—could be powerful. Standard "internals" could lead to formal agreements like the PC's ISA bus standard or defacto ones like that for IRDA. Hybrids are particularly friendly to standards as they can unbundle conventionally connected drivesystem requirements (§4.2.3), can be mechanically simpler (*e.g.*, a fuel cell compared with an ICE, or an electric motor contrasted with a transmission), and likely reduce the number of competitive factors affecting selection.[30] Ultralight hybrids are even friendlier, as they converge the varying drivesystem requirements of differently sized models. Building on the trend of increasing supplier outsourcing (*e.g.*, Delphi, once captive to GM, plans to sell 50% of its parts to other automakers by 2002 [48)]), standards could enable suppliers to manufacture common components that require only minor modification to fit in various automakers' platforms. Moving from automaker-specific to open standards could increase the commodification of many automotive technologies, intensifying competition, likely decreasing cost and boosting innovation on a component level.

Ultimately, if advanced technologies and architectures are adopted, platform sharing could change the nature of competition in the whole industry. Automakers, like PC makers, could compete less on specific technologies and more on cutting edge products (*e.g.*, the iMac), superior systems integration (*e.g.*, Sony's ultrathin form-factor laptops), and market responsiveness (*e.g.*, Dell's rapid product cycles). Competition, of course, would be fiercer (and provide ample opportunities for new players), but the attendant benefits consumers are witnessing in computers—rapid leaps in performance with decreases in costs—may come with it.

[30] For example, HPUs could compete on six areas—price, mass, efficiency, reliability, form factor, and power—compared with mechanically-driven ICEs that compete on at least nine areas (the first five above plus torque, speed, emissions, and compatibility w/ proprietary standards).

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REFERENCES

1. T. Swan, "Saturn L-Series Sedan," Car and Driver, 45, (2), pp. 86–89 (August 1999).
2. M. Arnholt, "Saturn Grows Up," Ward's Auto World, 35, (7), pp. 43–45 (July 1999).
3. W. Zellner, "A Different Kind of Saturn," Business Week, pp. 28-29 (5 July 1999).
4. J. Lorio, "LS Versus S-Type," Automobile, 14, (5), p.67 (August 1999).
5. D. Davis, "Saab 9-5," Automobile, 12, (7), pp. 94–96 (October 1997).
6. T. Murphy, "Co-Design Modularity" Ward's Auto World, 35, (6), p. 29 (June 1999).
7. S. Birch, "Building the Puma," Automotive Engineering**,** 106 (5), pp. 107–109 (May 1998).
8. R. Bremner, "Common Knowledge," FT Automotive World, pp. 42–46 (June 1999).
9. D. Kurylko and L. Ciferri, "Fiat's Three-Platform Strategy Will Help Maker Reduce Costs," Automotive News, p. 60 (19 July 1999).
10. A. Eggleston, et. al., "Comment: Consolidation," FT Automotive World, p. 16 (June 1999).
11. W. Diem, "The Renault-Nissan Deal," Ward's Auto World, 35, (5), pp. 59–60 (May 1999).
12. T. Lewin, "Jaguar's Bid for the Middle," FT Automotive World, pp. 46–49 (April 1999).
13. Price data from www.autobytel.com.
14. J. Yamaguchi, "Honda Euro Accord," Automotive Engineering**,** 106 (12), pp. 14–17 (December 1998).
15. J. Crosse, "Experts in Aluminum Have Key to Low-Volume Car Lines," FT World Automotive Manufacturing, (14), p. 12 (June 1999).
16. F. Markus, "2001 Chrysler PT Cruiser," Car and Driver, 45, (1), pp. 44–49 (July 1999).
17. A. Mathews & J. Ball, " GM Offers to Repair 3.5 Million Vehicles," Wall St. J., pp. A2 & A6 (22 July 1999).
18. M. Walton, Car, W.W. Norton, New York, p. 263, 1997.
19. C. Christensen, Innovator's Dilemma, HBS Press, Boston, 1997.
20. G. Amendola, "The diffusion of synthetic materials in the automobile industry: Towards a major breakthrough?" Research Policy 19 (6), pp. 485–500, (December 1990).
21. A. Lovins, et. al., Hypercars: Materials, Manufacturing, and Policy Implications, Rocky Mountain Institute Publication T96–7, Snowmass, CO, 1996.
22. T. Moore, "Ultralight Hybrid Vehicles: Principles and Design," Proceedings of the 13th International Electric Vehicle Symposium (EVS–13), 13 (2), pp. 8–15, Osaka, Japan (1996).
23. A. Lovins, "Hypercars: The Next Industrial Revolution," Proceedings of the 13th International Electric Vehicle Symposium (EVS–13), 13 (2), pp. 113–120, Osaka, Japan (1996).
24. B. Williams, T. Moore, and A. Lovins, "Speeding the Transition: Designing a Fuel-Cell Hypercar," *Proceedings. 8th Annual U.S. Hydrogen Meeting*, National Hydrogen Association, pp. 171-207 Alexandria VA (11–13 March 1997).
25. A. Lovins, "Putting Central Power Plants Out of Business," presentation to the Aspen Institute Energy Forum, Aspen, Colorado, 7 July 1998 (updated 17 July 1999). Most developments in the table can be found in CALSTART's News Notes, www.calstart.org.
26. Ford press release, 5 Jan 1998. The P2000's body-in-white and closures weigh 182kg compared to a 1997 Taurus's 397kg.
27. A. Kochan, "'Car of the Future' Focuses on Steel," FT World Automotive Manufacturing, (14), pp. 15–17 (June 1999).
28. N.A. Gjostein, "Technology Needs Beyond PNGV," Basic Needs for Vehicles of the Future, New Orleans, Louisiana (5 January 1995).
29. E. Eusebi, "Composite Intensive Vehicles—Past, Present, and Future," PNGV Symposium on Structural Materials Challenges, U.S. Department of Commerce, Washington, DC (22-23 February 1995).
30. "Light is Right! Supplier Demonstrates Weight Savings of 68% Over Typical Body Structure," USCAR Mileposts, p. 7, (Fall 1998).
31. Jeff Fisher, Solectria Corporation, (personal communications), Wilmington, MA, October 1996.
32. V. McConnell, "Future Cars Take Shape with Composites," Reinforced Plastics, 43 (5), pp. 44–48 (May 1999).
33. A. Jacob, "Chrysler Rethinks the Composite Car," Reinforced Plastics, 41 (11), pp. 44–48 (December 1997).

34. M. Brylawski and A. Lovins, "Advanced Composites: The Car is at the Crossroads," SAMPE International Symposium, 43 (2), pp. 1135–1148 (1998).
35. R. Carpenter, "Design of Structural Composites in a Lightweight Body Structure," Proceedings of the Advanced Composites Conference and Exposition, 11, pp. 75–86, Detroit, MI (November 1995).
36. C. Kindervater, "Crash Resistance and Strength of High Performance Composite Light Vehicle Substructures," Procs. Dedicated Conf. on Supercars, ISATA (Int. Symp. on Adv. Transp. Appl.), pp. 741–751, Aachen, Germany, (1994).
37. A. Mascarin, et. al., "Costing the Ultralite in Volume Production: Can Advanced Composite Bodies-In-White Be Affordable, Procs. International Body Engineering Conference, pp. 56–70, Detroit, MI (November 1995).
38. G. Kobe, "China's Paradigm Shift," Automotive Industries, pp. 82–83, (June 1999).
39. Solectria Sunrise brochure, Solectria Corporation, 68 Industrial Way, Wilmington, MA 01887 USA.
40. "EV Boasts Largest One-Piece Composite Chassis in U.S.," Composites Technology, p. 9 (July/August 1998).
41. K.J. Sears, "Lightweight Technologies of Lotus Elise," Proceedings of the 6th European Congress on Lightweight and Small Cars, Cernobbio, Italy (2-4 July 1997).
42. Delphi Automotive press release, 1 March 1999.
43. C. W. Craig "Cars of the Future to Look Familiar," Detroit Free Press, (April 29, 1999).
44. J. Fisher and J. Dieffenbach, "Recent Developments in Thermoplastic Composites for Body Panels and Structures," Procs. International Body Engineering Conference, pp.9–17, Detroit, MI (November 1995).
45. "USCAR'S Composite Consortium to Unveil Breakthrough Manufacturing Process," USCAR press release, 24 September 1998.
46. Ward's Wrapup, Ward's Auto World, 35, (6), p. 29 (June 1999).
47. M. Brylawski and A. Lovins, "Ultralight-Hybrid Vehicle Design: Overcoming the Barriers to Using Advanced Composites in the Automotive Industry," SAMPE International Symposium, 41 (1996).
48. R. Golding, "Severing the Umbilical Cords," FT Automotive World, pp. 26–27 (April 1999).