Supercars
The Coming Light-Vehicle Revolution

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Note to U.S. readers: The final version of this paper will be publicly released in Denmark on 1 June 1993, and reprints will be available from Rocky Mountain Institute. At ECEEE's request, we have used metric units (usually supplemented by U.S. units), 1989 European Currency Units alongside 1989 US$, European numerical conventions (comma as separator, space to demark thousands, "milliard" for 10^9), and mostly British spelling and vocabulary. Final formatting--fonts, title centering, etc.--will be done for the *Proceedings* by the editors and is not shown in this version. The graphics will be produced at higher quality. Similar papers will probably be presented at the Asilomar ACEEE transportation summer study in August 1993, at the Aachen (FRG) cars conference in September 1993, and possibly elsewhere. A popular version, "Reinventing the Wheels," is also in preparation for *The Atlantic Monthly*.

Supercars: The Coming Light-Vehicle Revolution

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1. SYNOPSIS

Ultralight hybrid-electric family cars could achieve <1,6 litres per 100 km (composite) now, probably 0,8-1,0 ultimately, with superior safety, amenity, performance, and apparently price. Industrial implications are profound.

2. ABSTRACT

Ultralight 4-passenger cars with modern hybrid-electric drives could achieve <1,6 litres per 100 km (>150 mi/US gal composite) with demonstrated technologies such as switched reluctance motors, conventional buffer batteries, and compact petrol engines. Consumption <1,0, probably 0,8, l/100 km (~240-300 mi/US gal) is probably achievable with advanced technologies expected to be demonstrated shortly, such as monolithic solid-oxide fuel cells, carbon-fibre flywheels, and small adiabatic diesels. Far from sacrificing other attributes for efficiency, ultralight hybrids could be *more* safe, peppy, clean, durable, reliable, quiet, comfortable, and beautiful than existing cars, yet be priced about the same or less.

The key improvements required--chiefly aerodynamic drag and mass 56-57% below present U.S. production cars--have been demonstrated, and further ~2-3x reductions in drag-mass product appear feasible. Net-shape materials, chiefly polymer composites, could do this while cutting production costs through materials savings, hundredfold fewer parts, tenfold less assembly labour and space, and halved tooling costs. Epoxy dies, lay-in-the-mould colour, and other innovations permit extremely short product cycles, just-in-time local manufacturing with direct delivery (hence the same retail price even if production cost were considerably higher), and onsite maintenance. This would fundamentally change how cars are made and sold. It could be the biggest change in industrial structure since the microchip.

Such "supercars" face serious cultural obstacles in the car industry and institutional barriers in the marketplace. Supercars' immense societal value merits policy intervention to help speed and smooth this challenging transition, making it less a hardship than a lucrative opportunity. Supercars could also buy time to implement, but cannot replace, fundamental transportation and land-use reforms.

3. THE FALLACY OF INCREMENTALISM

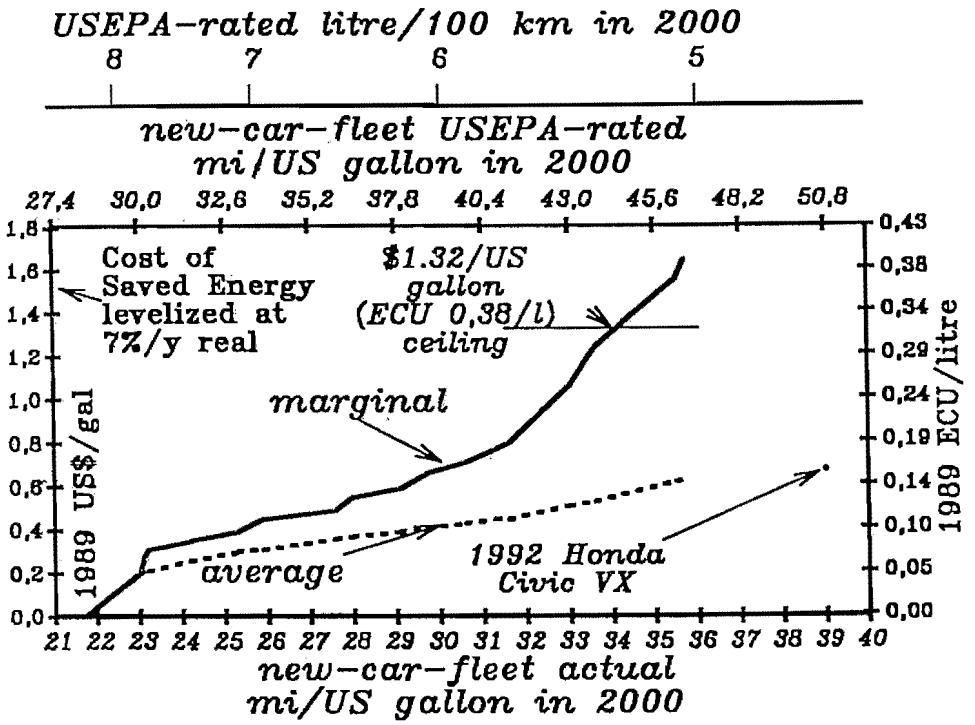
Troubled car industries now weaken many national economies, while inefficient light vehicles and their ever-increasing use are major causes of oil dependence, air pollution, noise, climatic threats, and other important social costs. These problems demand transportation and land-use innovations, combined with cleaner, more efficient vehicles (Johnson 1992). Yet the conventional wisdom framing the U.S. car-efficiency debate is that the doubling of new-car efficiency during 1973-86 virtually depleted the "low-hanging fruit"--opportunities for fuel economy consistent with affordability, safety, and performance.

We shall argue that, on the contrary, the next doubling will be easier than the first was, because it will come from very different sources: not from incremental refinement of today's cars but from replacing them altogether with a different and functionally superior concept of car design, manufacture, and sales (Lovins 1991). We shall attempt to describe an auto-industry transformation that seems technologically plausible and commercially attractive in the 1990s and beyond, initially for niche and later for general markets, suggesting also analogues in other kinds of vehicles. The implications of this transformation are not all welcome, but the issue seems less whether it will happen than who will do it first and best, and whether it will be done thoughtfully.

New U.S.-made cars halved their fuel intensity during 1973-86, from ~17,8 to a European-like 8,7 l/100 km; ~4% of the savings came from making the cars smaller inside, ~96% from making them lighter and better

(Patterson 1987).[1] Although that gradual decoupling of mass from size reached a temporary plateau using conventional materials, many other refinements are far from saturated. Further incremental improvements therefore yield a supply curve (Figure 1) extended 24% from the U.S. Department of Energy's (Difiglio *et al.* 1989) by adding two further measures, idle-off and aggressive transmission management (Ledbetter and Ross 1990). The curve shows cumulative gains in new-car fuel economy[2], and their empirical marginal costs[3], from fully deploying a limited list[4] of 17 well-quantified technologies already used in mass-produced platforms, without changing the size, ride, or acceleration of average U.S. 1987 cars. Most of the measures are conventional, *e.g.*, front-wheel drive, four valves per cylinder, overhead cams, and five-speed overdrive transmissions.

Figure 1. Supply curve for incremental improvements in the composite efficiency of average new 1987 U.S. cars as implemented in the year 2000 (Ledbetter and Ross 1990), plus, as an empirical check, the 1992 Honda Civic VX (Koomey et al. 1992)



Ledbetter and Ross (1990) found that this approach can cut 1987-base fuel intensity in 2000 by ~35%, to 6,99 actual (5,36 rated) l/100 km. That would just counterbalance projected U.S. growth in vehicle-km travelled by 2010 (Kelly and Williams 1992). Each saved litre would cost, on average, ECU 0,15 ($0,14)--less than half today's U.S. petrol price.[5] At about half that cost, savings ~72% as large are also achievable in U.S. new light trucks. Such cost-effectiveness is probably conservative, as illustrated by improvements in one subcompact platform: the 1992 Honda VX's 56%-improved fuel economy[6] (4,62 l/100 km, 51 mi/gal) increased its retail price by ~ECU 717 ($650), or ECU 0,20 per saved litre ($0,69/gal)[7], less than the average-cost supply curve in Figure 1 would predict, and far below the marginal cost curve, which is the more appropriate comparison.

A similar, more limited analysis (Duleep 1991), considered authoritative by an official assessment (OTA 1991), explicitly ignores emerging technologies. These, however, are "reasonably certain" over the next 10-15 years, so conservative official findings "should *not* be taken to mean the technological limit of what is possible with the current state of the art" (NRC 1992): a similar assessment 10-15 years ago would surely have omitted many important advances found in today's cars.

Indeed, in the mid-1980s, over a dozen concept cars combined excellent but fairly conventional components in conventional ways to *demonstrate* doubled or tripled fuel economy (1,7-3,5 l/100 km, 67-138 mi/gal), often with 4-5 passenger capacity and apparently respectable--in a few cases, superior--safety, emissions, and performance (Bleviss 1988).[8] At least two versions would reportedly cost about the same to mass-produce as present cars.

The short-term approach (NRC 1992) is valuable for understanding the potential and limitations of incremental improvements to stamped-steel, direct-mechanical-drive, internal-combustion, petrol-driven cars, but it says nothing whatever about what other designs can do. Attractive though incremental improvements can be, focusing on them diverts attention from a basic challenge to the auto industry: fundamentally redesigning cars and the car business can save much more fuel still, probably cost less, and redefine which firms prosper.

Conventional cars, like other technologies, have entered their era of greatest refinement just as they may have become obsolete. Imagine that a seventh of the GNP in, say, the United States were devoted to manufacturing typewriters. The Big Three typewriter manufacturers have gradually moved from manual to electric to typeball models. Now they are making delicate little refinements somewhere between a Selectric 16 and a Selectric 17. Their typewriters are excellent and even profitable. People buy over ten million of them every year. The only trouble is that the competition is working on subnotebook computers.

That, we suggest, is where the global auto industry is today--painstakingly refining designs that may soon be swept away, perhaps with terrifying speed, by the integration of very different technologies already in or entering the market, notably in advanced materials, software, motors, microelectronics, power electronics, electric storage devices, and computer-aided design and manufacturing. This paper attempts to sketch the outlines of that potential transformation.

4. THE ULTRALIGHT STRATEGY

The incremental approach to improvements saves so little fuel because it focuses disproportionately on fine points of engine and transmission design while comparatively neglecting the basic strategy of making the car very light and aerodynamically very slippery.[9] This strategy rests on the basic physics of cars: in urban driving on a level road, drivewheel energy--typically only ~15-20% of fuel input energy[10]--is devoted about one-third to heating their brakes when they stop, one-third to heating the air they push aside, and one-third to heating the tyres and road (MacCready 1991). On the highway, air resistance, proportional to the square of speed, accounts for ~60-70% of tractive energy needs. The keys to automotive fuel economy, therefore, are braking and downhill-coasting energy recovery, aerodynamic drag, tyre rolling resistance, and mass. Benefits from improving any one of these are limited, but benefits from improving all of them together are striking, and they often reinforce each other.

The basic parameters, however, are not equally important: for current U.S. cars, fuel economy is about equally sensitive to reductions in drag and in rolling resistance, but is nearly three times that sensitive to reductions in mass (OTA 1991). Major changes in any of these variables quickly lead to unfamiliar territory (Rohde and Schilke 1980) where standard coefficients and approximations break down (Sovran and Bohn 1981): higher fuel economy typically makes aerodynamic drag considerably more important and mass somewhat less, and drag starts to outweigh rolling resistance at lower speeds. External factors matter too: drag becomes less important as traffic congestion turns highway driving into stop/go urban-style driving (Maples 1992). And all the variables interact: mass, for example, becomes less fuel-using with low rolling resistance and regenerative braking, while narrower, harder tyres (which achieve the former benefit) can help lighter cars to push through puddles.

In efficient cars, too, previously unimportant terms such as regenerative braking and accessory loads become dominant. Air and road drag become so small that not just one-third but most of urban-driving tractive energy goes to braking and hence becomes available for recovery. Accessory loads are normally modelled as ~9-10% of present fuel consumption, but such accessories would use half the fuel in a quintupled-efficiency car; fortunately, they too are candidates for dramatic savings.

Aerodynamic drag is proportional to the product of drag coefficient, C_D, times effective frontal area, A (cross-sectional area as seen from the front). Both terms can be markedly improved, and have been in part. In 1975, when many estate wagons had C_D = 0,6, a distinguished group of physicists concluded that "about 0,3-0,5 is probably near the minimum for a practical automobile, although even lower values are possible in principle" (APS 1975). Now principle has become practice. New U.S. cars' drag coefficient averaged 0,48 in 1979, 0,37 in 1987, and ~0,33 in 1992. Today's sleekest platforms in mass production are ~0,26 (among U.S. sedans, 0,29). Volvo's new ECC concept car is 0,23, and the production-engineered version of GM's electric Impact platform

tests at 0,18 (A.B. Jordan, personal communication, 31 March 1993). Yet Volkswagen has measured 0,18 for the 1921 Rumpler Tropfenwagen seven-seater midengined car (R. Cumberford, personal communications, 22 February 1992 and 14 March 1993). Since the mid-1980s, many 4-passenger concept cars have achieved <0,2--*e.g.*, 0,19 for GM's Ultralite, 0,186 for Renault's VESTA II, and 0,137 for Ford's 1985 Probe V, which was more slippery than an F-15 jet. Some LeMans racecars would achieve ~0,1 if not compromised to increase downforce for traction.

The most important step in achieving drag coefficients <0,2 is simply making the bottom of the car as smooth as the top. Low C_D is actually easier to obtain in a large than a small car because there is more room to avoid rear-end discontinuities. Contrary to a common belief, the influence of the ground plane ranges from neutral to favourable with good design (Lissaman 1988), which must provide adequate ground clearance. Even the GM/AeroVironment Sunraycer solar car's 0,125 wind-tunnel C_D could have been cut by one-fifth with better wheel-well treatment and other refinements (P. MacCready, personal communications, 1991). Ultimate practical limits appear to lie around 0,1, perhaps somewhat less, using advanced surfaces for passive boundary-layer control. As with aircraft, where dozens of small surface refinements can add as much as 180 km/h of airspeed, such low drag requires unusual care. As mass declines, greater care is also required in designing crosswind response (Hibbs 1988), both for stable handling and to avoid the need for parking tiedowns.

The other aerodynamic drag factor, frontal area, is also reducible by better packaging and styling. More compact powertrain components[11] permit steeply downsloping (heavily raked) bonnets, which in turn permit more visibility with less glass and hence less mass. The ~2,3-m^2 frontal area typical of new U.S. cars is easily reducible to ~1,9 with no sacrifice of interior roominess; it is, for example, 2,01 in the somewhat boxy 5-passenger Volvo ECC and 1,80 in the 1991 Honda Civic DX. Among four-seater concept cars, GM's Ultralite achieved 1,71, and Renault's VESTA II, 1,64. Two-seaters even with conventional propulsion can yield reasonable comfort with only 1,3 m^2 (M. Seal, personal communication, 22 February 1992). Frontal area can be cut further by all-interior (*e.g.*, optical or TV) rear-view mirrors and by compact powertrains (see §6 below).

Rolling resistance, r_0--the dimensionless per-tyre ratio of road drag to vertical load--is surprisingly poorly understood and measured, and most tyremakers consider r_0 data confidential. This nonrecoverable loss typically totals ~0,007-0,01 for modern radial tyres--half the ~0,02 of 1970-vintage bias-ply tyres (Bleviss 1988)--and one major automaker reports 0,0062 for good mass-produced tyres fully compliant with all U.S. regulations. For a given road surface, tyre temperature, pressure, torque, and speed, r_0 depends on energy losses in tyre and tread deformation and hence on arcane design details and low-hysteresis materials (Kyle 1988). Considerable progress has been made, though generalizations are difficult because tyre and vehicle must be designed together. Improved polymers are an obvious starting-point: *e.g.*, Venezuelan tests in 1981 suggested a ~15-30% r_0 reduction and halved tread abrasion from an Austrian liquid-injection-moulded aramid/polyurethane tyre produced for Soviet offroad vehicles (Bleviss 1988). In 1990, Goodyear announced it had cut r_0 in its G-22 4,4-bar concept tyres for GM's Impact electric concept car to only 0,0048, conventionally rated at 81 km/h (50 mi/h), with "excellent traction and highway performance" (Goodyear 1990). This value has since been further reduced (Bill Egan, personal communication, 30 March 1993). Comparable developments are underway in Europe and Japan. New concepts also show promise, including variable-camber double-tyre and variable-pressure (like Russian truck) configurations and several unusual cross-section designs. Paul MacCready reports (personal communications, 1991) that the Sunraycer's bicycle-tyre 0,0037 could readily have been cut by one-fifth, but car tyres have different requirements: ride, dry and wet traction, and durability, especially in a light car lightly loaded, cannot be sacrificed in favour of too-small r_0. The present car-tyre art is thus ~0,005-0,006, with advanced concepts approaching ~0,004--a fifth the value of two decades ago.

New U.S. production cars' curb weight, M, averaged 1 443 kg in 1990; a light one like a Toyota Tercel LE sedan weighs 946 kg. Yet numerous production and prototype platforms weigh far less: for example (Bleviss 1988), VW's 5-passenger Auto 2000 (779 kg), Peugeot's 5-passenger 205XL (767 kg), Volvo's 4-passenger LCP 2000 (707 kg), VW's 4-passenger E80 diesel (699 kg), British Leyland's 4-passenger ECV-3 (664 kg), Toyota's 5-passenger AXV diesel (649 kg), Renault's 4-passenger VESTA II (475 kg), and Peugeot's 4-passenger ECO 2000 (449 kg).[12]

Typically these designs made extensive use of conventional lightweight materials. However, the usual approach, favoured *e.g.* by Ford--substituting aluminium for steel--reduces weight, increases cost by ~ECU 2-7 (~$2-6) per kg saved, offers superplastic moulding potential, and often modestly increases fabrication difficulty; in all, it

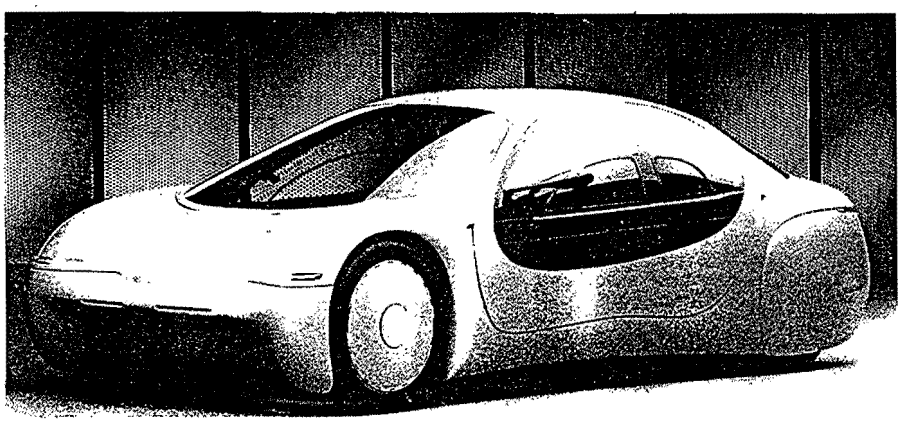
is a useful near-term material option but not an optimal strategic approach. Substituting instead advanced polymer composites[13] and other net-shape materials such as engineering plastics[14] can achieve far greater reductions in mass and drag, while transforming the carmaking process and marketing structure in a way that fundamentally reduces cost--"tunneling through" the cost barrier to conventional mass reduction.

5. BEYOND THE IRON AGE: NET-SHAPE MATERIALS

A typical steel part's cost is only ~15% for steel; the other 85% is for shaping and finishing that raw material (Seiss 1991). Steel is so ubiquitous, and the success of highly evolved steel-car manufacture--one of the most remarkable engineering and managerial achievements in human history--makes its very high design, tooling, fabrication, and finishing costs so familiar, that we overlook how they outweigh its cheapness. An electrocoating plant costs a quarter-milliard dollars; a paint shop, a half-milliard dollars; complete tooling for one car model, upwards of one milliard (10^9) dollars. Making a steel car requires thousands of engineers to spend a year designing and a year building a football-field-full of million-dollar steel dies that are used as long as possible (ideally decades), then thrown away. That inflexible, costly tooling in turn means huge production runs, high risks of stranded investments, and long amortization times, time-to-market, and product cycles that crimp flexibility and innovation. Thus today's most "modern" cars are really the cutting edge of old technology. Yet new, nonmetallic materials are not just a substitute for steel, as they have been used so far[15]; they can transform the nature of cars, manufacturing, and marketing. And in the process, they also support the ultralight strategy.

A striking example of this transformative potential is the Ultralite concept car that ~50 General Motors technologists built in 100 days in 1991 (Keebler 1991, Sherman 1992, Gromer 1992). It cost ~$4-6 million, or ~8 hours' worth of GM's 1991-92 North American losses. This sporty, 4-adult, 4-airbag car (Figure 2) achieves C_D = 0,192, A = 1,71 m^2, M = 635 kg, and highway-speed rolling resistance r_0 ~0,007 at 4,4 bar tyre pressure. These parameters yield a rated 3,79 l/100 km (62 mi/gal), comprising 5,22 l/100 km (45 mi/gal) city and 2,90 (81 mi/gal) highway.[16] Cruising at 2,35 l/100 km at 81 km/h (100 mi/gal at 50 mi/h) requires only 3,2 kW (4,3 hp) of power to the wheels--71% less than an Audi 100 needs. Efficient, wheels-at-the-corners packaging gives the Ultralite the interior spaciousness of a Chevrolet Corsica that is twice as heavy and half as efficient--but within the outside volume of a Mazda Miata.[17] The 79-kg rear engine[18] in a removable "pod" achieves a 218-km/h (135 mi/h) top speed and accelerates 0-97 km/h in 7,8 seconds.[19] For a quick design, not yet optimized[20] nor engineered for production, these are impressive achievements.

Figure 2. General Motors' 1991 Ultralite concept car (photo courtesy of GM)



Of the car's >100 significant innovations, the most important was its 6-piece, 191-kg, ~ECU 13 280- (~$12 000)-materials-cost monocoque body. Foam was sandwiched between two layers of composite made by applying epoxy resin over carbon-fibre cloth, interwoven with roving (continuous-strand carbon-fibre rope) at stress points. The body was fabricated by the maker of the *Voyager* aircraft that his brother then flew round the world on one tank of fuel.[21] The trade and financial press, however, while admiring the Ultralite's body, complained that the miraculously strong black threads of carbon fibre, only 7 m (0.018") in diameter, cost ~ECU 20-99 ($18-90) per kg[22], two orders of magnitude more than sheet steel at ~ECU 0,61-0,88 ($0,55-0,80) per kg. But those critics forgot that what matters is not cost per kg but cost per *car*. Consider:

- Carbon fibre is stiffer and stronger than steel per unit cross-section, but a quarter as dense; it has 2-4x the stiffness but two-thirds the density of aluminium. Fibre typically occupies ~30-50% of total composite volume in current car practice, ~60-65% in optimal components[23] (G.M. Wood, personal communication, 26 March 1993). Thus about one-third to one-half as much mass of carbon is needed as of steel, considering that the fibres can be placed and aligned to match the stress field and interwoven to distribute loads (Gromer 1992), just as a cabinetmaker orients wood grain to stress. The art of composite design is optimal fibre placement to match a controlled load path, so as to capture the material's strengths and compensate for its weaknesses.
- For many applications, just as serviceable composites can be made from glass fibre as from carbon fibre. Glass is tougher, heavier[24], more elongating for energy absorption, and ~2-6x cheaper for equivalent strength or stiffness. A composite production car would use a judicious mix of E- and S-glass, carbon, aramid, etc., as Consulier has done in ~100 Federally certified monocoque vehicles sold since 1988.[25]
- The ~85% (*i.e.*, of order ECU 4-6/kg) of steel parts' total cost that is due to shaping and finishing is largely[26] avoided: composites emerge from the mould relatively ready-to-use, in complex, sleek, and beautiful shapes unattainable with metal, and with tolerances down to a few tens of micrometres (or a few micrometres in aerospace practice).[27]
- More importantly, composites' mouldability in large, complex units can cut the parts count, in principle by ~100x. The body-in-white (basic open-aperture body without trim, chassis, or powertrain) can have not 300-400+ but only 2-6 parts that can snap precisely together, slashing the costs of design, paperwork, tooling, transportation, and inventory.[28]
- Required assembly space and labour drop by ~10x. Although joining is slower than robotized welding, far less of it is needed (Amendola 1990).
- Components and assemblies, and the powertrain elements needed to propel them, become much lighter, hence easier for fewer people to handle with less equipment in a more flexible assembly setup.
- Painting--the costliest, hardest, and most polluting step in carmaking, accounting for nearly 90% of some major automakers' mass of hazardous and toxic releases--can now be eliminated by lay-in-the-mould colour that yields a more durable and attractive finish.
- The coated epoxy dies cost ~40-50% as much per product copy as do tool-steel dies--by some estimates far less--for several reasons. Epoxy wears out faster but is very cheap to make or recondition. Moulding composites needs only one die per product, not a stepped series for successive strikes.[29] And it is far cheaper to have one large, complex die for an integrated composite assembly than the hundreds or thousands of dies needed for equivalent separate steel parts.
- The epoxy dies' shorter life and short development time are another key advantage. Opportunities for improvement at the time of tooling replacement or refurbishment are more frequent. New dies can then be made within days under computer control (even roughed directly by stereolithography) and very quickly amortized. They thus support the small design teams, reduced economies of scale, very short product cycles, and continuous improvement that market nimbleness demands. This is a fundamental and, in the car business, a revolutionary strategic advantage (Romm 1991): as "a further incentive to adapt the supply of cars rapidly to the evolution of demand,...the flexibility introduced in the automobile industry by the technology of synthetic materials has powerful analogies with the flexibility introduced by...electronics technology" (Amendola 1990).
- The finished materials are extremely durable--composites don't dent, rust, etc.--and could last for enough decades to be heirlooms, then, with careful design, be recycled.[30] Major failures rarely occur in accidents and are usually repairable--by boatmakers if not sheetmetal-workers.[31]
- Net-shape materials can often be advantageously used in the frame (if any) and other components, not just in the body. Indeed, composite-skin, foam-core materials permit monocoque construction with no frame: like an egg, the body *is* the structure. Monocoques' remarkable flexural and torsional stiffness[32] simplifies many aspects of design and permits softer springing, improving ride and handling.

These and other, even more profound, implications for safety will be considered in §8, and for manufacturing and marketing in §9. For the moment, we need only note that the features just listed can collectively make up for even expensive (carbon-fibre) composites' apparent cost disadvantage per kg, or more. Many examples confirm that savings on tooling and assembly labour can make seemingly costly moulded materials *cheaper* than steel.[33] This saving can pay for better powertrains, controls, aerodynamics, etc. within a similar total budget.

The most pessimistic of the experts we consulted estimate mass-production cost of ultralight carbon-fibre cars at one to two times that of steel cars today. The most detailed assessments, however, suggest breakeven at carbon-fibre costs widely expected to prevail by 2000 if not before.[34] Moreover, carbon is only about half the total mass of carbon-fibre composites, and there are many other kinds of far cheaper fibre that can make excellent ultralight cars.

Mainly for the latter reason, most composites-manufacturing experts, including some at major automakers, are convinced that in a "greenfield" (start-from-scratch) comparison, composite cars even at present costs *always* undercut the mass-produced cost of steel cars. Indeed, some practitioners believe that lower tooling cost permits advanced composites to beat steel cars' cost today at production rates <30 000 units per year[35], while other sources (Amendola 1990) have found the breakeven volume for synthetics had recently doubled, in only a couple of years, to ~50 - 60 000 units/y--a level "slightly more...than Jaguar's or Porsche's output." Either of these case-specific levels is ample for exploiting important "boutique" markets--niches large enough to yield attractive production economies and to start moving down the learning curve toward lower costs and larger markets. Moreover, market segmentation and differentiation, hence more and faster-changing models coupled with slower-growing aggregate demand, entail "a clear-cut trend towards a decrease in the average production scale. In the long run, this factor could be a powerful force stimulating the diffusion of synthetic materials into the automobile industry" (Amendola 1990).[36]

The resulting revolution of car design, production, and operation--as profound as the electronics-driven transformation was in the 1970s--has just begun. The challenge to metal might come surprisingly quickly. U.S. passenger cars' bodies switched from 85% wood in 1920 to over 70% steel only six years later (Abernathy 1978), making possible the modern assembly line. Mainly in the 1960s, composites rapidly displaced wood and metal in boatbuilding, as they are now doing in aerospace niche markets. Today, the switch to moulded synthetic materials could support "a major breakthrough in the technological development of the automobile industry" (Amendola 1990), making it at long last an agile, short-cycle competitor (Romm 1991).

6. HYBRID-ELECTRIC DRIVES

Net-shape ultralight car platforms, then, can probably cost about the same as steel platforms or less. But adding a further step can make them still cheaper and radically simpler: hybrid-electric powertrains.[37] A really successful hybrid car cannot be made out of steel, for the same reason that a successful airplane cannot be made out of cast iron (R. Cumberford, personal communication, 23 February 1992). But net-shape ultralight materials and hybrid drives are strongly synergistic, because hybrids' design and performance depend critically on mass, drag, and rolling resistance, and because mass savings compound more quickly with hybrids than with conventional powertrains.

Pure-electric, externally recharged cars work poorly when scaled up to carry 4-5 passengers rather than one, because the battery mass, like any other vehicle mass, compounds: too much energy and power are needed to haul the heavy batteries, requiring heavier batteries to store that extra energy, etc. In all, each unit of added battery mass increases total vehicle mass by a factor conventionally assumed to be ~1,5 in heavy cars and often ~5 in ultralights (M. Seal, personal communication, 22 February 1992).[38] Electric hybrids, however, scale well to both large and small sizes *of ultralights*. With ultralight construction, the car's size has little to do with its body's mass: going from two to four passengers adds <100 kg (*id.*), not counting suspension and powertrain. And with low drag and regenerative braking, the energy needed to propel larger vehicles' greater mass is largely recovered, although heavier equipment is needed to accelerate that higher mass.

In the simplest (series-hybrid) concept, the wheels are always driven electrically, but the electricity is made on-board as needed by a low-power[39] Otto, diesel, or gas-turbine engine or a fuel cell. This has four key advantages over direct mechanical drive (Rohde and Schilke 1980):

- The engine is sized to the average load, not the peak load, because a small buffer store between the engine-driven generator and the traction motor(s) stores energy for hill-climbing and acceleration.
- The engine drives a generator, not the wheels, so it runs only at its optimal condition. Just this collapsing of the engine performance map to a point *doubles* an Otto engine's practical average efficiency, and permits simultaneous optimization for emissions too.
- The engine never idles; when not running at its "sweet spot," it turns off. Idle-off in a non-hybrid VW Golf saves 21% of fuel in the European urban test cycle (Barske 1991). This is broadly consistent with the USEPA urban cycle, where the car idles 18% of the time (Sovran and Bohn 1981). Savings are slightly smaller if, for the driver's peace of mind, idle-off is automatically overridden whenever the turn indicator reports the driver is waiting to turn across traffic.
- Regenerative braking (recovering most of the braking energy into the buffer store) improves conventional platforms' fuel economy by a further one-fourth; in the USEPA urban cycle, 23% of the time is spent braking. In principle, with no constraints on safety or driveability, regenerative braking "could recover as much as 70% of [available] kinetic energy in an urban cycle" (DOE 1992), and ~70% recovery has in fact been measured both in an electric car (M. Seal, personal communication, 22 February 1992) and in a hydraulic-accumulator urban bus (Vint 1987).[40] The fine torque/speed control permitted by a new type of motor (see below) may well make it practical to achieve such values consistently, and can certainly achieve perfectly smooth progressive braking. Regenerative braking should also "allow the friction brakes to last the life of the vehicle" (Martin 1992).

Together, these features permit the fuel-tank/engine/generator to be inherently smaller, lighter, cheaper, and longer-lived than the ~300-400 kg of batteries they typically displace in a pure-electric car; and those mass savings then compound. Severalfold lighter, though costlier, batteries of more exotic kinds are becoming available, but the hybrid's chemical fuel will still win, because it has ~100x the energy density of lead-acid batteries. It thus permits longer range with lower total mass, cost, and refueling inconvenience.

There is also a large spectrum, or rather matrix, of more complex hybrid designs[41], varying in amount of storage, whether they accept any recharging energy (mains or photovoltaic), and whether the wheels are ever driven mechanically. Conventional parallel hybrids meant as range extenders are seldom optimal. However, some parallel hybrids may offer modest advantages over series hybrids by accelerating electrically to cruise speed, then cruising under mechanical engine drive with engine speed varying only ~15% and torque threefold--a small performance map. Such parallel designs typically use rear-wheels mechanical drive and front-wheels electric drive (the former with overrunning clutches for reversing). They recover somewhat less braking energy than a series hybrid, but can have more graceful failure, since there are two potentially independent power sources; are more complex; and may weigh more. They can achieve zero tailpipe emissions in the city, where they run all-electrically, and ultralow emissions under engine or dual power on the highway.[42]

Whatever the design, today's hybrids typically reduce fuel intensity by ~10-15% on the highway, ~50% in city driving, and ~35% composite (Barske 1991, Delsey 1992). Driving a 100-km ECE test cycle in an experimental VW Golf diesel hybrid, for example, uses 2,5 litres of diesel fuel plus 16,3 kWh of electricity (Streicher 1992), equivalent in end-use energy terms to ~4,1 l diesel/100 km. Volvo's ECC parallel hybrid saves ~38% highway and ~49% city.[43] (The advantage is so large in city driving partly because electric motors have much higher torque ratios at low speeds than do internal-combustion engines.) Even paper designs with higher drag than the Ultralite and 2,5 times as heavy confirm that hybrid drive can cut composite-rated fuel use by up to 60% via regenerative braking plus optimized engine sizing and loading (but not corrected for any mass compounding). However, hybridizing lighter, lower-drag, lower-rolling-resistance vehicles will save even more, because a larger share of tractive energy will go into braking, from which it is potentially recoverable (Rohde and Schilke 1980). The degree of this gain, which both determines and depends upon drivesystem mass, may be the biggest single uncertainty in supercars' ultimate performance limits.

Many designers add unnecessarily bulky, heavy, costly, inflexible, and hot-running electric drives to conventionally heavy platforms. Some designers, notably in the solar-car community and in Switzerland, understood early

the importance of low mass for electric and hybrid cars, but may still be complicating their task by choosing asynchronous (induction) or DC motors that often require gears.

Electric/hybrid vehicle designers differ on the ideal traction motor, and impressive progress has enabled both asynchronous and DC motors to achieve the goals set out in §7. Yet especially in the U.S., most experts, while familiar with those achievements, have overlooked (DOE 1992, Martin 1992) the potential advantages of modern switched reluctance drives.[44] Recent advances, summarized here for completeness, have reduced decade-old problems to myths (noise, torque ripple, cost, etc.) and indeed made switched reluctance drives unusually attractive. A recent review (Lovins and Howe 1992) suggests that for fundamental reasons, properly designed switched reluctance drives can outperform all other types, including electronically commutated permanent-magnet motors, in size, mass, efficiency, versatility, reliability, ruggedness, fault-tolerance, and cost. Switched reluctance drives' main advantages (Lawrenson 1992, Blake and Lawrenson 1992) include:

- Speed is limited only by rotor bursting strength, with 100 000 rev/min readily achieved--far more than gearless cars need.
- Starting and low-speed torque are uniquely high--typically 4-6+ times higher than for a same-frame asynchronous motor--making the motor typically 1-2 frame sizes smaller.
- Throughout the very wide speed and torque ranges and in all four quadrants (forward and backward, motoring and generating), the speed/torque curve is entirely under real-time software control; any desired asymmetry can be achieved, including different motoring and braking characteristics.
- Extraordinary overload capabilities (often sufficient to absorb all braking energy from ultralights) are disproportionately further enhanced by any cooling of the shell, since virtually all heat dissipation is in the stator.
- DC-input-to-shaft efficiency is much higher than for asynchronous or DC systems: *e.g.*, 93% for a 2,6-kW drivesystem built with an amount and quality of copper and iron typical of *standard*- (not premium-) efficiency asynchronous motors, *vs.* 89-90% for the highly optimized ~1,5-3 kW Sunraycer PM drive.
- Exceptional efficiency is also maintained over a far larger operating map.
- Fault-tolerant advantages include "limp-home" if even one pole pair remains energized, whereas asynchronous motors don't run if any pole pair fails.
- The rotor's high strength and small moment permit an angular response of 10^3-10^5 rad/s^2 and control bandwidth of 10^2-10^3 Hz, rivalling the costliest spindle drives or industrial servos.
- Whole-system mass-production cost is typically ~15-40% below that of same-torque variable-speed asynchronous systems, and usually below that of *constant*-speed asynchronous motors.

These remarkably strong, light servomotors can, but need not, be integrated into each wheel hub, eliminating all gears and saving net weight.[45] Depending on failure-mode analysis and the ability of the buffer store to accept high inrush currents, it may be possible to eliminate mechanical brakes. At least in principle, differential wheel-speed, integrated with electronic suspension to lean into turns, may also permit an ultralight car with hard, narrow tyres to steer without angling the front wheels. Switched reluctance drives' only disadvantage is that they are an order of magnitude harder to design than traditional types: excellent design demands a level of system (especially software) integration and numerical simulation that only a few dozen people have mastered.[46]

7. INTEGRATED DESIGN OF ULTRALIGHT HYBRIDS

Redesigning an ultralight-*and*-hybrid car from scratch, using aerospace systems concepts, could yield an elegantly frugal and unusually attractive vehicle (Lovins 1991). A 4-passenger family-car version would start with low mass (<700 kg now, <500 kg soon, perhaps ~400 kg ultimately), and could achieve high crashworthiness with special materials and design (§8). Like an aircraft, it would be designed for high payload/curb-weight ratio, perhaps above the Peugeot 205XL's 0,56; would use switched reluctance actuators, of which Ford cruise controls now use ~4 000 units a day; and would control them by fibre optics ("fly-by-light/power-by-wire"). It would combine a drag coefficient of <0,2 now and ~0,1 later with smart active suspension and advanced tyres.[47] Its hybrid drive would initially use a small internal-combustion engine, on the order of 10-15 kW--probably an advanced stratified-charge[48] engine, high-pressure-injection diesel[49], Elsbett engine[50], or small gas turbine[51]--directly driving a switched reluctance generator. Buffer storage would be provided initially by a few kWh of improved conventional batteries, such as nickel/metal-hydride, lithium, or sodium-sulphur, driving 2-4 switched

reluctance motors (possibly hub-integrated). This design--at least if a series hybrid--eliminates the transmission, driveshaft, universal joints, differential, perhaps axles, and possibly brakes.

Meanwhile, accessory loads would be rigorously reduced, starting with the air conditioner that in a typical U.S. car is now sized to cool an Atlanta house (Lovins 1991). Glazings, which gain ~70% of the unwanted heat, would be very lightweight but spectrally and perhaps angularly selective--perhaps later variable-selectivity. The shell would be light-coloured[52] and perhaps have high infrared emissivity, the roof might be vented like a tropical LandRover's, and any sunroof would be passively gain-controlled.[53] A photovoltaic vent fan and compact body superinsulation would further cut cooling loads.[54] Any remaining cooling would be done by alternative means (Houghton *et al.* 1992): absorption and/or desiccant devices driven by engine waste heat, or a staged indirect evaporative chiller, or a very efficient (probably scroll-compressor) heat pump, or an Ericsson heat pump (Stickney 1992), probably with heat-pipe evaporator bypass, economizer, and fuzzy-logic controls. Heating would be by passive heat pipe; all ventilation and comfort delivery, by low-face-velocity coils and high-efficiency fans (*id.*). This approach--thermal gain avoidance plus superefficient space-conditioning--would simultaneously cut mass, drag (via reduced engine-compartment bulk), engine loads and sizing, engine performance map range, total cost, emissions, maintenance, CFCs, and discomfort (Lovins 1991).

Moreover, a single high-intensity-discharge light source, such as those recently introduced by Philips, Hella, and GE, could provide all exterior and cabin lights via fibre optics and light pipes. Electric loads and mass would be minimized everywhere, from electroluminescent panel lights (used in GM's Ultralite) to speaker supermagnets (used in Ford's Taurus), and from CMOS chips to shaft-integrated switched reluctance fans and pumps. Entertainment systems would be as light and power-frugal as the best consumer battery portables.

All the powertrain friction reductions available, down to the last bearing and advanced lubricant, would be systematically exploited--though scarcely any mechanical powertrain would be left, and power steering and brakes would be as unnecessary as they are in the Ultralite. The frustrating ~20-25% nonrecoverable loss now typically added to tyre rolling resistance to account for losses in wheel bearings, brake drag, etc., thus raising effective total r_0 to nearly 0,008, would be cut by using regenerative electronic braking and lightweight drum brakes, fewer wheel-related bearings and gears, and special, smaller-capacity bearings.

The car's drag-mass product[55] is a rough qualitative indicator of tractive loads. In our baseline near-term supercar, which we might call the "Gaia", it would fall from the Ultralite's 0,19 of the 1990 U.S. new-car mean by a further one-fourth, to ~0,14 of the 1990 norm. It could achieve this, for example, with a mass of 580 kg (9% below the Ultralite, or 13% above the 1987 Renault VESTA II), a frontal area of 1,9 m^2 (11% above the Ultralite), and a drag coefficient of 0,14 (matching Ford's 1985 Probe V). Good r_0 = 0,007 tyres, very low accessory loads, efficient driveline, and regenerative braking would be added too, and a modern hybrid drive powered by a 30%-efficient petrol engine.[56] Standard parametric analysis suggests that this sevenfold reduction in drag-mass product from the 1990 U.S. new-car mean[57] would correspond to a ~5x gain in fuel economy. Thus a car spacious enough for four adults with luggage could achieve 1,6 l/100 km (150 mi/gal).[58] Of course, capturing even part of this goal would be richly rewarding; but capturing all of it seems well within reach of technologies already individually proven and only awaiting proper integration.

The next generation of technologies that should emerge from the laboratory during the mid-1990s shows strong promise of an even more surprising technological edge-of-envelope early in the next decade. Three look particularly important: advanced kinds of fuel cells (which convert hydrogen directly into electricity and water)[59], "electromechanical batteries" using composite superflywheels[60], and possibly ultracapacitors.[61] With plausible further progress, an early-next-century hybrid car might, for example, have under the bonnet a grapefruit-sized fuel cell wrapped in a <40-litre[62] envelope and user-selected to the proper modular size, which could even be temporarily modified for special applications; a melon-sized package of power electronics, also modular (plug in an extra "slice" for higher performance); an orange-sized computer; perhaps an optional breadbox-sized space-conditioning package; and virtually nothing else; so why have a bonnet? There could be two boots for extra storage and crush space (§8).

The radical further simplification resulting from the reversible fuel cell would be the biggest step towards cutting M to ~400 kg. Together with C_DA ~0,17 m^2--*e.g.*, C_D ~0,10 and A ~1,7 m^2 or some equivalent combination--C_DAM would fall to ~6% of the 1990 U.S. new-car mean. With extremely low accessory loads and

excellent tyres, driveline, and regenerative braking, such a hypothetical design, which we might call the "Ultima," would correspond to a 10x gain over today's fuel economy--to 0,8 l/100 km (300 mi/gal).[63]

These nominal parameters compare thus with two empirical sets:

Table 1. Key parameters and composite fuel efficiencies of selected existing and hypothetical 4-passenger cars

					C_DAM		composite rating		
platform	C_D	A, m^2	M, kg	r_0	m^{2}kg	index	l/100 km	mi/gal	fuel index
production cars									
typical U.S. 1990	0,33	2,3	1 443	~0,008?	1 095	1,00	8,0	29,4	1,0
demonstrated concept car									
GM Ultralite 1991	0,192	1,71	635	0,007	208	0,19	3,79	62	0,5
hypothetical ultralight hybrid cars based on net-shape materials									
"Gaia" near-term design	0,14	1,9	580	0,007	154	0,14	~1,6	~150	0,2
"Ultima" advanced design	0,10	1,7	400	0,006	68	0,06	~0,8	~300	0,1

where C_D = drag coefficient, A = frontal area, M = curb mass, r_0 = tyre rolling resistance coefficient

Efficiencies at least as good as the Ultima's can be calculated with small adiabatic diesels, already shown to match or exceed the assumed 50% fuel-cell efficiency (P.B. Hertz, personal communication, 31 March 1993), so success with the fuel cell is not essential. Indeed, *any* 50%-efficient power source in the Ultima's low-drag hybrid platform would yield 0,80 l/100 km (294 mi/gal) even if M were increased to 636 kg, *the same as the Ultralite*, so the Ultima's ambitious 400-kg mass target is not essential either (thanks to 70%-efficient regenerative braking).[64] That is, a 4-passenger hybrid could be ~10x as efficient as today's production cars if it combined demonstrated power-plant and regeneration efficiency, mass, and rolling resistance with excellent driveline efficiency and with aerodynamic drag only one-fifth below the best demonstrated levels (VESTA II for A and Probe V for C_D). (Such good aerodynamics do not seem necessary either, because switched reluctance hybrid systems should improve on the assumed driveline and regeneration efficiencies.) Conversely, the Ultima hybrid's 400-kg curb weight would still yield 1,04 l/100 km (226 mi/gal) even if powered by a standard 30%-efficient petrol engine. Thus the <0,8-1,0 l/100 km range (in round numbers, ~240->300 mi/gal) claimed for the Ultima leaves both technological flexibility and a substantial safety margin--appropriate in view of the many uncertainties.

Nor does this exhaust the technical potential. Long-term limits, as noted earlier, might be around C_DA 0,15 m^2, so a 400-kg 4-passenger car might eventually achieve C_DAM only ~5% that of today's production platforms. Making less conservative, but not unreasonable, assumptions about driveline and regeneration efficiency with mature superflywheel and fuel-cell or adiabatic-diesel technology then leads to composite fuel intensity <0,6 l/100 km. By then, of course, fuel-saving returns will have diminished severely, so such innovations would need other motives.

At such low mass, as with 57-kg ultralight aircraft that weigh less than the pilot, payload becomes a large fraction of curb weight. Test weight *including payload* therefore becomes critical: a 0,4 l/100 km family car would have to leave the family behind.[65] The performance envelope must provide adequate gradeability at the design payload. But today's lamentably low load factors average only ~1,2-1,3 adults in central Europe and ~1,1 in North America, not 4+, so on-the-road fuel economy will typically be better than at full payload.

A family car using advanced fuel cells or flywheels could cross the lower 48 United States on one small tank of fuel (~30-50 l of petrol or equivalent). The small mass of fuel required for a long range would in turn permit the use of compressed natural gas or other relatively clean and abundant fuels without undue tank mass and volume penalty. Alternatively, hydrogen fueling could become attractive, since so little fuel is burnt that its cost and that of its storage arrangements become more tractable. If liquid biofuels were used, the small amounts re-

quired for such a fleet could be sustainably derived from farm and forestry wastes without requiring special crops or fossil hydrocarbons (Lovins *et al.* 1984). And onboard energy storage of 5 kWh (*e.g.*, 100 kg of nickel/metal-hydride batteries) would enable shell-mounted photovoltaics to power a typical Southern California commuting cycle just from the energy captured each day from outdoor parking[66], without ever starting the engine or plugging into a recharger. Even in less favourable climates, a solar boost can greatly improve an ultralight hybrid's fuel economy.

An early priority should be assessing the transferability of these concepts to vans and light trucks (Bleviss and Walzer 1990). This is urgent in the United States, whose light trucks are not only a fifth less efficient than cars but are also driven farther for much longer. In model year 1987, despite their 31% market share, they therefore accounted for ~48% of new light vehicles' projected lifetime fuel consumption (Patterson 1987a). Yet polymer-composite utility vehicles and even buses look very encouraging.[67] With such lightweight bodies, valuable added height costs very little weight--nor stability, since it does not materially raise the centre of gravity.

Some analogues are also evident for heavy lorries--traditionally, inefficient vehicles with efficient diesel engines. The most fuel-efficient experimental Kenworth or Navistar 36-T (80 000-lb) lorries reportedly test at best values approaching ~25 l/100 km (~9,5 mi/gal), which for a 909-kg (2 000-lb) car would mass-scale to only ~1,2 l/100 km (~200 mi/gal) (K.G. Duleep, personal communications, 12 July 1991 and 29 March 1993). A privately designed composite 18-wheel "bullet truck" with C_D ~0,2 and nearly doubled normal intercity fuel economy is also in model testing (Weaver 1992).

8. SAFETY, PERFORMANCE, AND AESTHETICS

A common generic objection to fuel-efficient cars is their alleged crash risk. But this confuses fuel economy, mass, size, and design.

Fuel economy and light weight need not compromise safety. There is no correlation, far less a causal relationship, between present cars' crash-test performance and their mass, nor between their fuel economy and their on-the-road death rate.[68] That is chiefly because occupant protection systems are lightweight, and because vehicles' design and materials are vastly more important than their mass. It may also be partly because light cars can avoid more accidents by stopping sooner and handling more nimbly.[69]

Existence proofs suggest that the general lessons invited from gross correlations between light cars and higher death rates are misleading. Americans can now buy a 4,2 l/100 km (56 mi/gal) car with a lower death rate than a 10,2 l/100 km (23 mi/gal) car; cars with identical efficiencies but over tenfold-different death rates; and cars at any mass that differ in crashworthiness by more than tenfold. Such comparisons reveal some unusually dangerous cars now on the road at various levels of mass and fuel economy, but they make no case that fuel economy does or must conflict with superior safety.[70] Rather, their high scatter emphasizes the importance of design differences.

Theoretically, collisions between two cars identical except in mass tend to damage the lighter car more. (Practically, this is often incorrect because other, unequal factors such as design dominate. The National Highway Traffic Safety Administration sought to show the danger of light cars in recent light/heavy crash tests; the light cars reportedly came off better until stronger heavy cars and flimsier light cars were substituted.) This idealized theory leads some to propose that you should drive a heavier car--thus reducing such collisions' risk to yourself while raising others' risk correspondingly.[71] But the right answer is to make *all* cars[72] safe whatever their weight, without putting all the adjustment burden on light cars. Heavier vehicles should be made less aggressive (Käser 1992)--softer, less angular, more absorptive, with bigger ridedown distances--and the road fleet's mass distribution should be further narrowed, *e.g.* by incentives for replacing inefficient with efficient cars (§11). Heavy lorries with slightly relaxed length limits could even be equipped with a highly energy-absorbing structure on the front to help protect any car they might hit (M. Seal, personal communication, 24 March 1993).

Better control of destructive driver behaviour such as drunkenness is often crucial: behaviour may be up to a thousandfold more risk-determining than the car itself (L. Evans, personal communication, 1992), and only about a twentieth of crashes do not involve driver factors (Evans 1991). But as to the car, modern designs and

materials can do far better than Henry Ford had in mind when, in 1926, he said that "A heavy man cannot run as well as a trim man. You do not need weight for strength" (S. Abouzar, personal communication, 3 July 1991).

GM's Ultralite confirms that mass per unit volume can be cut by more than half below the "steel plateau" level. This decoupling permits fuel-efficient cars to remain ultralight while combining roomy interiors with ample crush length, which appears to improve crash performance somewhat. Yet better materials and design can also substitute for crush length.

Composites and other ultrastrong net-shape materials--many stronger than the familiarly durable but lower-grade carbon-fibre fishing rods, skis, etc.--would dominate in a supercar. They would bounce without damage in minor fender-bender collisions: most deformations of carbon-fibre composite panels simply pop out again with little or no damage. Under severe loads, composite structures fail very differently than metal, so "totally different design concepts have to be applied", and understanding of failure modes is not yet mature. However, even under compressive loading--often considered composites' weak point[73]--"Composite structural elements...show high and in many cases better energy absorption performance than comparable metal structures" (Kindervater 1991).[74] Extensive aerospace experience is available from designing all-composite structures and aircraft (like the Stealth bomber and fighter) to withstand bird and stone strikes, landing stress, etc.

Light metals would also be used where appropriate, such as in sections of crushable light-metal foam or honeycomb for energy management in a serious crash. These materials, available for two decades (APS 1975), have a nearly perfect square-wave response--they squash flat, absorbing enormous energy, before transmitting crash accelerations--making them an ideal substitute for ridedown length.

Other crash-energy-managing design options include buckling members, down-deflecting heavy driveline components, filament-wound or sheet-and-keel[75] cruciforms, and "impact belt" beams.[76] Composite prototype and small-production cars and vans with proprietary crash structures have in fact yielded some of the best crash-test results ever recorded by a major automaker; some were probably driveable after a 56-km/h barrier crash (P.H. Magnuson and major-automaker experts, personal communications, March 1993; Grosse 1992).

An ultralight car using ultrastrong materials, modern airbag restraint systems, and crash-energy-managing design can weigh less than half as much as today's platforms--as the Ultralite does--yet be far safer than any car now sold. That is why racedrivers are rarely killed nowadays when composite cars hit walls at >350 km/h: as tens of millions of Americans saw on their 1992 TV news, the composite car flies to bits, failing at "trigger" sections specifically designed to initiate such breakaway and absorbing extensive crash energy through controlled failure modes, but the "survival capsule" remains intact and the driver generally limps away with perhaps a broken foot. To be sure, ordinary drivers would lack the racedriver's helmet, fitted foam restraints, spaceframe, etc., but even in a head-on collision their lower speeds would imply one-fourth the racedrivers' crash energy, and even if they were more seriously injured, that would be a great improvement on their fate in today's cars.[77]

The main potential safety disadvantages[78] of the ultralight hybrids described in §§6-7 are that

- with their low drag and low or absent engine noise, pedestrians may not hear them coming unless a noisemaker is added that somehow warns without being objectionable, and
- obstacles such as small trees, crash barriers, and lampposts, against which a heavy car can dissipate energy by breaking or deforming them, may instead stop a light car or make it bounce off, increasing deceleration and perhaps bounceback acceleration forces on passengers.[79]

But beyond their general crashworthiness described above, such "supercars" also offer important safety features:

- The 2- or (with series hybrids) 4-wheel switched reluctance drives offer full-time antilock braking and antiskid traction, but with far greater balance, response speed, and effectiveness than today's methods.
- Supercars' light weight means faster starts and stops; their stiff shell, quicker and more precise handling.
- Carbon-fibre designs can be so stiff and bouncy that an ultralight car, if broadsided by a heavy lorry, could go flying--like kicking an empty coffee-can. The very unfavourable momentum transfer would go not into mashing the ultralight car but into launching it. Yet occupants restrained by belts, bags, and headrests and protected from intrusion into their protection space might well survive unless accelerated by

more than the often survivable ~40-60 *g* range--in which case they'd be dead anyway in any car today, light or heavy, steel or composite.

- In the rare accidents so severe as to crush the composite shell (usually in hammer-and-anvil fashion), the occupants would be far less likely to be injured than by intruding torn metal edges in a steel car; with any potentially intruding carbon-fibre shards overlain by or interwoven into fracture-masking aramid or polyethylene cloth, the crushed composite sections can become relatively innocuous.
- Victims' extrication would be much faster (a crucial element of critical medical care--most victims not dead on the spot can be saved if brought to hospital within an hour): the doors are likelier to function, the composite shell can provide easier access[80], cutting it with a rotary wheel is quick and makes no sparks to ignite fuel vapours, and breakaway energy-absorbing main components would no longer impede access to the passenger compartment.
- Ultralights' decoupling of mass from volume makes it straightforward to maintain a wide track and long wheelbase for rollover resistance.
- Hydroplaning risk should not rise and may fall, because the car weighs less but has narrower tyres.
- The small powertrain volume and raked bonnet are consistent with improved visibility and, as Dr Michael Seal suggests, with headlamps behind the bottom of the windscreen (so they are cleaned by the same wipers). The HID headlamps are also exceptionally powerful and can cause road markers and certain textiles to fluoresce.
- With careful design, composites', especially foamcore composites', excellent attenuation of noise and vibration could yield an extremely quiet ride--important because road noise is no longer masked by engine noise.[81] This plus the virtually complete absence of wind noise should make driving less fatiguing, potentially boosting driver alertness.
- The whole car is so simple, reliable, corrosion-resistant, fault-tolerant, and failsafe-designable that dangerous mechanical failures are far less likely.

For all these reasons, the design approach described here could yield substantially improved safety. Supercars could also offer ample comfort, unprecedented durability and ease of repair, exceptional quietness (sound-deadening materials, no wind noise, no squeaks), beautiful finish and styling while retaining significant stylistic flexibility, impeccable fit and weatherproofness, high performance (light weight means faster acceleration), unmatched reliability, and--as we shall see next--probably low cost.

One caveat is in order, however. Especially in the litigious United States, innovation is deterred by the threat that makers of new and hence initially "unproven" technologies may have to pay damage claims even for accidents in which they are blameless. Some experts fear that such potential liability might add exposure up to several thousand ECU or $ per car-year, especially for manufacturers large enough to invite lawsuits but not large enough to defeat them. Absent tort reform, removing this important barrier to market entry may require some government indemnity or coinsurance to makers of supercars meeting a national safety standard, at least until actuarial experience has field-validated their theoretical ability to match or exceed the safety of today's cars.[82]

9. NEW INDUSTRY STRUCTURES, ECONOMICS, AND JOBS

Ultralight hybrids are not just another kind of car. The industrial and market structure they imply is as different as computers are from typewriters, fax machines from telexes, and radio from the Pony Express. Supercars imply wrenching changes that may come far more quickly than our ability to manage them. If ignored or treated as a threat rather than seized as an opportunity, these changes are potentially catastrophic for millions of individuals and tens of thousands of companies. The prospect of supercars can therefore be either devastating or exhilarating. To understand this choice, we must explore how a supercar industry would differ from today's auto industry in production, sales, and design.

The optimal scale of production may be profoundly different than steel cars' tooling and painting investments dictate. It could even be a several-hundred-person franchise operation analogous to a regional soft-drink bottling plant. Today's cars are rapidly built from a myriad shipped-in parts on single, extremely costly assembly lines where delay incurs intolerable costs. In contrast, supercar production's layup/moulding/curing operations are slower but fewer than stamping, machining, and welding operations, so total production time per car could be shorter. Moreover, cheap tooling permits supercar fabrication to run on many parallel lines, reducing holdups, and if done onsite those lines would occupy most of the space, with little needed for final assembly.

Shipments and inventories of parts would be limited because there are relatively few parts[83]: in-plant skill, not systemwide logistics, would be the key to profitable manufacturing.

The supercar art will be not in assembly, or mainly in components, but in design integration (to which we shall return later). Before this was understood about personal computers, they were misperceived to be "rocket science," a natural monopoly of giant firms like IBM. Then some Texas Instruments engineers set up Compaq, which combined the same Intel chipsets, Seagate drives, and so on--arguably more innovatively. And then firms like Austin and Dell piggybacked on those assemblers' research to substitute their own, bare-bones, low-overhead assembly and marketing operations. As soon as the public learnt that mail-order "clone" PCs worked about as well and cost half as much, the original makers' market shares plummeted; Compaq learnt the new rules and now competes head-to-head with the clonemakers, but IBM's PC lesson was more painful. Now powerful but no-name microcomputers are assembled from the same standardized parts in thousands of basement-scale businesses, an electronic version of piecework home handicrafts, and cutting-edge designs gradually become standard recipes.

The ability to make or buy the basic physical components of supercars is already potentially widespread: composite parts, switched reluctance drives, controllers, and similar elements require great skill to design well but much less skill and little capital to assemble adequately. Specializing their design and greatly expanding their production is a challenging but normal manufacturing task, just like expanding the recently infant microchip, disk-drive, and software industries as demand grew. Supercars might therefore become surprisingly like PCs if the integration skills also diffused. Supercars might ultimately become in their turn a virtual mail-order commodity, subject to centralized design testing (like FCC testing for computers' electromagnetic interference) and then made widely to those certified designs. The masters of the essential software and hardware components--the analogues of Microsoft and Intel--might be the big winners, not the final products' assemblers and sellers.

Informed by the computer example, rapidly collapsing the levels of the market would be a daring, high-risk, but perhaps high-payoff strategy. Just the way Japanese agents sell prefabricated-to-order houses today, a supercar-maker could sell cars through CD-ROM demonstrations and test drives provided by a salesperson who visits your home. You choose the options you want; they instantly go by modem to the factory; it makes the car to order; a few days later, it's delivered to you. It is unlikely to fail (far fewer total parts and moving parts, fewer connections and fasteners, more fault-tolerant electronics, cooler running, etc.). But if it does fail, someone from a service company will come fix it; nearly all of its few parts are small, light, readily hand-carried, and easily installed. Today, even some photocopiers automatically diagnose themselves and summon technicians by modem; perhaps some handy supercar owners too, guided by the car's powerful self-diagnostics or remote expert evaluation by modem hookup, might choose to plug in replacement modules automatically express-shipped to their door. If all this makes sense today for a $1 500 computer, why not for a $15 000 car?

Such direct marketing could transform the economics of supercars. Today, the suggested retail price of a typical U.S. car has been marked up by perhaps three-fourths from its bare, no-profit marginal variable cost of production, or by one-half including intended profits, warranty costs, and plant costs. Designs are frozen many years in advance, and the mix of features, colours, etc. is chosen months in advance. Even if demand forecasts turn out wrong, as they often do in today's fickle markets, the undesired products have already been built, so they must be carried and then rebated or discounted until they sell. This adds a severe burden to the already formidable cost of marketing, inventory, selling, and transactions: in the United States, one-fourth more people work for auto dealers than for auto manufacturers. But conversely, just-in-time final assembly-to-order and zero-inventory direct sales[84] would presumably enable a supercar to sell for the same retail price as now even if it cost considerably more to produce, which few composites experts believe it would.

If supercar entrepreneurs were as radical structurally as technologically, they might slash dealer support and eliminate prebuilt inventory, directly costing nearly a million American jobs (many already at risk from the trend toward one-price, no-haggle selling). Their production costs would then be comparable to or lower than for today's platforms and their selling costs would be minimal, so retail car prices well below today's would still support improved gross margins. For those who made the change early, the car business could be enormously profitable--until, as with PCs, competition brought a flood of new market entrants, margins became thin again, and consolidation began. By then, too, some of today's automakers could be out of business--the typewriter- and sliderule-makers of the '90s. Product differentiation and minor support services would become the battleground. Buyers, like buyers of personal computers today, could choose various tradeoffs: spend more on com-

posites, less on rust and dents; more on user-friendly diagnostics and plug-in fixits, less on shop repairs; more on safety options, less on hospital bills; more on the car, less on the dealer markup. Even though little of today's markup ends up in the dealer's pocket, reallocating some or all of it offers opportunities for all of a much smaller number of parties to the transaction to be better off.

But what about those whom a streamlined supercar industry may not need? The car industry and associated businesses employ one in seven American workers, use 40% of the machine tools and 12% of the steel, use 20% of the aluminium, glass, and semiconductors, and represent 10% of all consumer spending (Runkle 1992). Supercars appear to involve up to two orders of magnitude less parts-fabrication work and one order of magnitude less total assembly work than steel cars, though still significant finishwork. Design teams would probably be very small--tens, not thousands--in order to be fast and completely integrated. To be sure, large new industries would spring up, such as composites fabrication to the extent it were not robotized[85], advanced motors and electronics, software, etc., but those jobs may go to other people in other places. Petrochemicals would gain; steel would lose. Computer-aided mouldmaking and filament-winding equipment would gain; lathes and milling machines would lose. Startup firms would supplant aging giants. Parts firms and body shops would need new skills but find greatly diminished scope. Auto dealers might become as rare as public stables.

No one has yet begun to assess winners, losers, and relatively graceful transitional patterns for the potentially rapid and traumatic shifts in employment implied by this new type of manufacturing, marketing, and maintenance--a bigger challenge to industrial renewal and retraining policies than any nation has yet faced. But as §10 will suggest, this challenge may be unavoidable, because a country or a company that ducks it may face competitors who feel no such inhibition. It is presumably better to have a traumatized and diminished auto industry with great new market prospects than to have none. And it is better to have a vibrant, short-cycle, adaptive, keenly innovative, and resilient auto industry than a lumbering, capital-intensive, vulnerable one.

This is also an international issue--a potentially major problem for a country that unwittingly lets others destroy its traditional car industry, and a potentially major opportunity for a country that gets there first. Which countries make, have, and use how many cars could shift rapidly. A very senior Mexican official recently remarked that he wants to make supercars in Mexico, not only to create a durably competitive car industry, but also to solve domestic air and oil problems. The same thought may occur to other developing countries rich in talented low-wage people, increasingly including world-class engineers and software writers, but poor in oil.

With tooling costs low and design barriers high, the business will flow to integrative talent, not to capital; but with assembly labour reduced, there could be less incentive than now to move assembly offshore. Nonetheless, supercar jobs, like electronics assembly today, could become a fought-over global commodity much faster than jobs making steel cars, with their huge tooling investments. Automakers wishing to expand into developing countries may find a welcome only for supercar plants, not for traditional plants. Negative technology transfer is also a risk: if steel cars rapidly became obsolete but their tooling were not scrapped, it could enter a secondary market and be sold cheaply to developing and ex-Socialist countries (as East German tooling recently was to the Baltic republics), locking them into economic inferiority and resource waste for even longer.

Then there is the matter of where the car centres of the world--the Detroits, Cowleys, and Wolfsburgs--could get the milliards of dollars required to retool to make supercars, if they were culturally able to do so. Unfortunately, the automakers with the most capital for new ventures, such as Toyota, are the best at steel-stamping and hence have the least incentive to change. For other, hungrier firms, however, novel sources of retooling investment might arise. As one example, direct project financing by major oil companies could help both sides. After all, the lower 48 United States contain the equivalent of a five-million-barrel-per-day (0,3-TW) oilfield, bigger than the biggest in Saudi Arabia, that is nonpolluting, uninterruptible, and nondepleting. It's the accelerated-scrappage-of-gas-guzzlers oilfield. Today, oil companies go to the ends of the earth to drill for very costly oil that may not even be there. It would be embarrassing to drill more milliard-dollar dry holes while someone *else* found all that cheap "oil" under Detroit. Just as oil majors now hedge upstream/downstream, oil/gas, etc., they could hedge between barrels and "negabarrels": they could project-finance supercar retooling with upside participation via equity conversion or royalty, so that if the supercar business proved a great success, they'd make less money on oil but more on cars. Preliminary discussions with some cash-rich oil majors have established interest in this investment concept, although it remains to be seen whether Big Oil and Big Cars can put aside their private antipathy for each other for long enough to collaborate to mutual advantage.

10. INDUSTRIAL TRANSFORMATION AND CULTURAL CHANGE

Reinventing the automobile is far from the consciousness of most (but not all) of today's automakers. They struggle daily and nightly for next quarter's dividends; the prospect of scrapping their tooling and their mindsets and starting over is another problem they feel they just don't need. The world of supercars is not only frightening; for many it is so alien as to be hard to conceive at all.

Big automakers start, as Dr Lee Schipper has remarked, with two nearly fatal disadvantages: they're big, and they're automakers. They are dedicated, extraordinarily capable, and often socially aware organizations, but too often their form, style, and speed of learning match the ponderous technologies, vast production runs, and long product cycles inherent in steel cars. Their "productivity improvements have been balanced by a continuous decrease in...innovative capability" as ever more highly integrated production processes make innovation more difficult, solidifying a "fluid" industry into a "specific state" (Amendola 1990, Abernathy and Utterback 1978). Automakers have a diemaking and steel-stamping culture, not a composite-moulding, electronics, and software culture.[86] They are prisoners of enormous sunk costs which they treat as unamortized assets, substituting accounting for economic principles; hence they go to heroic lengths to adapt four-cylinder engine-block capacity rather than retool. This mindset (Abernathy 1978) is a critical obstacle to the transition toward supercars: new ways cannot diffuse without displacing old ones that resist with distinctive vigour (Amendola 1990).

Many automakers act as if they would rather take writeoffs of their obsolete capabilities later when they don't have a company than now when they do: as if they preferred comfortable obsolescence, even unto bankruptcy, over uncomfortable basic change to ensure long-term profitability. Their strategy appears, at least from the outside, to be to milk old skills and tools for decades, watch costs creep up and market shares down, postpone any basic innovation until after all concerned have retired--and hope none of their competitors is faster.

A different strategy, favoured by a growing number of internal policy entrepreneurs but as yet scarcely on top management's radar, would enhance automakers' survival prospects: welcome and capitalize on innovative public-policy instruments that condition the market for supercars (§11); immediately switch to ultralights using net-shape materials in integrated assemblies; and then, in one more giant leapfrog, move quickly to electric hybrid drives, first with engines and then with fuel cells, managing risk at each step with more conventional fallback positions to cover any temporary technological gaps. If our logic is correct, the first firm that intelligently and aggressively pursues this strategy should be able to feel sorry for its former competitors.

Who will that firm be? It might be an automaker or an aerospace company. It might also be the next Apple or Xerox--a group of smart, hungry systems engineers in a garage in southern California, eastern Massachusetts, or northern Italy: perhaps even innovators from within the car business, but unburdened by its sunk costs and traditional attitudes. The most apt competitors might be high-technology systems integrators, because supercars are much more a software than a hardware problem; they are much more like a computer with wheels than like a car with chips. And those competitors might well be American, because that nation leads in the combination of key technical capabilities needed--systems integration, software, advanced materials, and micro- and power electronics--and often in entrepreneurial speed and vision.

The chemical industry may also be a key player. Although the auto industry is woefully undersupplied with people as good at synthetic materials as classical automakers are at steel, some firms are starting to appreciate that moulded materials "allow simplification of both cars and productive processes and a more frequent change in the range of models supplied" (Amendola 1990)--factors often more important than raw cost per part. All the large chemical companies already have "automotive centres" in the Detroit area, and there are analogous European programmes. Through this technological fusion, "a new area of research and production, linking the chemical and the automobile industries, is quietly developing," increasing chemical firms' downstream integration while pushing automakers, at least temporarily, toward backwards vertical integration (*id.*).

If the auto industry is to adapt to and grasp the ultralight-hybrid opportunity rather than be run over by others' faster adoption of it, it will need to change its habits:

- It will need to learn in weeks to months, not years to decades. (This speed is what sorts out winning from losing computer companies: some reports suggest they make 90% of their profit in the first six months

of a product's lifecycle.) Kelly Johnson's old skunkworks at Lockheed originated certain innovative aircraft from scratch in four *months*. With today's tools, making an innovative car should be faster.

- To achieve this, it will have to keep its workgroups lithe, its headcounts small, and its bureaucracy suppressed, so as to uplift and liberate its many brilliant individuals.
- It will have to establish a presumption in favour of net-shape and near-net-shape materials in integrated assemblies, defaulting to metal only where necessary--rather than switching from metal to mouldable materials only incrementally as an occasional "frill."
- It will have to redesign components, assemblies, and systems from scratch, using a zero-based mass budget, to exploit the new materials' capabilities: composites are *not* "black steel." A component that looks the same in composite as it did in metal is grossly misdesigned.[87]
- It will need to determine the best ways to manufacture with net-shape materials, *then* design cars that best exploit those methods--rather than, as now, designing cars first, like abstract art, and then figuring out the least unsatisfactory way to make them within the constraints of traditional metalforming art.
- It will need to learn that how hard each part is to make and apply is at least as important as how many parts there are.
- It will have to treat temporary uncertainties over the best approaches to recycling composites, field repairs, and certain design and manufacturing techniques as normal problems to be overcome expeditiously, not as reasons to shun net-shape materials: the Big Three U.S. automakers are learning only slowly about a possible switch to advanced composites because they have only a few dozen people exploring it.
- It must involve its workers and suppliers early in thinking through the transition in all its dimensions, from labour flexibility and retraining to occupational health: waste minimization, recyclability, closed loops, and nontoxic materials will be important when manufacturing with large volumes of composites.
- It will have to pursue ultralight hybrids whether it believes they are the next car or only a niche car. It can assume a small market--easily tested through rental companies--but must stay ready to surge production quickly if the market explodes (as with the Honda CRX, which entered the market almost from bench-scale production). Such flexibility, well clad in transitional risk management, exploits a potential profit opportunity, but unwillingness to try it is a You-Bet-Your-Company decision. In marketing as in invention, chance favours the prepared mind.
- It will have to put more effort into leapfrogging straight to ultralights and then to ultralight hybrids, reaching its objective in only two main retoolings, and less effort into small but very costly marginal refinements in existing platforms with tiny marginal returns. (Of course, each of the two big jumps will include many small improvements, moving from established interim technologies to better ones as they mature, but the nature of the new tooling makes cycle times far shorter than for steel cars.)
- It will have to have to learn that even if a tactical goal is to improve today's platforms, the strategic goal is to make them obsolete as quickly as possible before competitors do. As *The Wall Street Journal* remarked, surveying the wreckage of the mainframe computer industry (Zachary and Yoder 1993),

> ...[S]low reaction stemmed partly from a reluctance to undermine sales of cash-cow large machines. "You have to face up to the question of destroying your product with new products," says John Morgridge, chief executive of Cisco, which makes networking hardware. "If you don't do it, someone else will."

Today, automakers seem far from appreciating this imperative. But one way or another, we believe they will learn it--some to their pain, others to their profit. They must choose to be Control Data or Apple, Bull or Dell.

11. MARKET CONDITIONING AND PUBLIC POLICY

There are compelling public reasons to make cars more efficient, whether incrementally or radically. The benefits in oil displacement, energy security, international stability, avoided military costs[88], balance of trade[89], climatic stabilization, clean air, health and safety, noise, and quality of urban life can hardly be overstated. Cars' externalities approach $\$10^{12}$/y in the U.S. alone (MacKenzie *et al.* 1992, Ketcham and Komanoff 1992), many times internal costs (Johnson 1992), and could be perhaps halved by supercars, saving several hundred billion dollars a year in pollution, accident, land, noise, vibration, congestion, pavement, military, and climatic-change costs (C. Komanoff, personal communication, 8 March 1993). Indeed, as part of a strategy of industrial regeneration, supercars could form the centrepiece of a powerful reintegration of the economic, energy, environmental, and military elements of security (Romm and Lovins 1992).

We believe people will buy supercars *not* mainly because they save fuel but rather because they should be superior cars in all other respects--cars alongside which today's most sophisticated steel models might even seem a bit primitive and antiquarian. Yet however ultimately inevitable these competitive factors may make the transition to supercars, it may if unguided produce two kinds of failures. It may be both unnecessarily disruptive, shattering industrial regions and jobs, and unnecessarily slow and unpredictable in capturing the strategic benefits of saving oil. Further, many automakers convinced that fuel economy must be antithetical to other marketing factors may resist supercars for too long and thereby consign themselves and their workers to commercial oblivion. To achieve a relatively smooth transition rapidly and with high confidence may require public-policy interventions in which industrial, oil, security, and environmental imperatives converge: interventions to give automakers strong incentives to pursue the "leapfrog strategy" boldly (§10), and to overcome their customers' well-known market barriers to buying fuel-efficient cars.

Thanks to ever-cheaper oil and improving fuel economy, the real 1989-$ cost of fueling a new American car for 40 km was about $4 in 1929, $3 in 1949, $2 in 1969, and $1 in 1989 (MacCready 1991). Moreover, both the futures market (which predicts, and can be used to lock in, oil prices) and careful examination of technological revolutions in both supply and demand strongly suggest that real oil prices will trend downwards for at least the next couple of decades. Although oil prices will doubtless spike occasionally as war or peace breaks out in the Middle East, one cannot count on costly oil to sell fuel-frugal cars. On the contrary, the two are mutually inconsistent: as the 1986 oil-price crash proved, efficient cars *prevent* high oil prices.

What about high fuel taxes? International comparisons show that motor-fuel prices modestly affect km/y driven but are only tenuously related to new-car fuel economy (Schipper *et al.* 1992). Even in Europe and Japan, with petrol taxed to ~2-4x U.S. prices, new cars are little more efficient than in the U.S. (*id.*). This is because of dilution by fixed costs, high consumer discount rates (especially if first-ownership is customarily short), company car ownership, unusual tax policies, and other distortions that shield drivers from their normal costs (Dolan *et al.* 1993). Though these factors' relative importance varies by country and over time, collectively they cause a pervasive market failure. After all, the incremental analysis in §3 found that buying a new car whose fuel economy is markedly higher than the best new-fleet average in Europe--even severalfold higher according to the best mid-1980s prototypes--would be far cheaper than buying cheap American petrol today. Yet most of those improvements were not brought to market because manufacturers shunned the retooling risk in fear of uncertain market response. OECD on-road fleet-average intensities stayed roughly flat through the 1980s, ranging from nearly 8 (Denmark) to nearly 11 (Japan) l/100 km.

The small fuel-price elasticity of new-car efficiency means theoretically that extremely high fuel prices would be needed to bring supercars to market. But supercars' social value can be signalled and their early production encouraged by other means. For example, the United States' Corporate Average Fuel Economy standards apparently achieved most or all of the U.S. doubling of new-car fuel economy (Greene 1989): new cars ended up approximately as efficient as European and Japanese models--perhaps even more so when normalized for size, performance, and accessories. This was despite U.S. petrol prices so low that fuel is only one-eighth the total cost of driving, so the fuel's price signal is diluted 7:1 by the other costs of owning and running a car.

CAFE can certainly be improved in many details (OTA 1991, NRC 1992). However, performance standards, though a helpful backstop, are not easy to administer, invite gaming, and are technologically static; there is no incentive to do better. A more promising approach would add revenue-neutral "feebates"[90] (Lovins 1991a). When you buy a new car, you pay a fee or get a rebate; which and how big depends on how fuel-efficient the car is (and perhaps also how clean and/or safe it is); and the fees pay for the rebates. Better still, the rebate for a fuel-efficient new car can be based on its *difference* in fuel economy compared to the old car that is scrapped--thereby getting efficient, clean cars on the road and inefficient, dirty cars off the road faster. (Malfunctioning or ill-maintained "superemitters" are often of 1970s vintage; ~10% of the U.S. car fleet produces half its air pollution.) Such "accelerated-scrappage feebates" would open large new markets for the auto industry, foster competition, and reward rapid and continuous innovation with market share, potentially without limit.[91]

Many variations on these themes are being considered, including feebates decoupled from separate scrappage rewards, volume-normalization to avoid incentives for downsizing, and rebates paid directly to manufacturers rather than to buyers so as to compound price reductions by reducing markups. Rebates on superefficient cars could be big enough to push the effective retail price below that of a used car, boosting margins, and could even exceed factory prices (Kempton 1991). The ~10^{12}/y estimate of U.S. car-related externalities would support

marginal feebate slopes on the order of hundreds of dollars per mi/gal (on the order of ECU 10^3 per l/100 km), though much less could prove sufficient. Weak feebates have been legislated in Maryland and Ontario, and a more comprehensive one ("Drive+") was approved by an extraordinary 7:1 margin in the California legislature in 1989, though subsequently vetoed. It seems bound to spread to state if not Federal agendas in the next year or two. Feebates could command wide consensus and break the political logjam that has long trapped the U.S. in a sterile debate over higher petrol taxes *vs.* stricter CAFE standards, as though those were the only two policy options and small, slow, incremental improvements were the only technical options.[92] Outside North America, governments more used to specific direction of major industries may enjoy even wider policy options.

A successful shift to supercars, however, will not solve the fundamental problem of too much driving by too many people in too many cars (Sperling *et al.* 1992), and could worsen it if supercars proved so attractive that even more people would want to buy and drive them. If 1-litre-per-100-km, roomy, clean, safe, renewably fueled cars were on the road today, one milliard Chinese or eight million Los Angelenos or Londoners driving them--or today's global car fleet driven ever greater km per year--still wouldn't work; instead of running out of air or oil, we'd run out of roads and patience.[93] Avoiding the constraint *du jour* requires far more than extremely fuel-efficient vehicles: they are an essential time-buying step, but no panacea.

Sustainable transportation requires designing communities around people, not cars, and rethinking land-use so we needn't travel so much to get the access we want. This in turn requires an end-use/least-cost access strategy and decision process to foster competition between all modes of access, including those that displace the need for mobility. It needs creative public-policy instruments[94] that introduce market mechanisms to a transportation system still crippled by lopsided subsidies, car dominance, and top-down central planning. Such policy innovations can join with supercars, and their analogues in other modes, to foster global competitiveness and meet ambitious oil-displacement, air, noise, urban-quality, CO_2, equity, and development goals.

None of these changes will be easy--only easier than not making them. They will take decades, because "the machine that changed the world" (Womack 1990) has a more formidable momentum than perhaps any other major human achievement. Yet recent industrial history, notably in computing and telecommunications, suggests that the switch to supercars could be far faster than basic shifts in where people live, work, shop, and recreate. The speed and size of this change could be deeply disruptive--and could bring enormous benefits. As with any technological revolution, disruption is inevitable; we can only choose whether to make it hurt or help us. If the technical and market logic outlined here is anywhere near right, we are all about to embark on one of the greatest adventures of our species' industrial history. Ready or not, here it comes.

12. ACKNOWLEDGMENTS

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13. ENDNOTES

[1] During 1978-87 on average, interior volume decreased by <1%, but volume per unit curb weight rose 16% from better packaging, power per unit engine displacement rose 36%, and acceleration increased 6% (Ross 1989). During 1976-85, weight reduction was the most important (~36%) of the identified causes of improved fuel economy, but during 1985-89, weight increased slightly and ~58% of fuel-

economy gains vanished into ever-faster acceleration (Westbrook 1990). Fuel economy is roughly proportional to the square root of acceleration time, both because of increased idling losses with higher-displacement engines (Ross 1989) and because of severe maximum-to-average power mismatch that makes powerful engines "expensive even when it is not being used" (APS 1975). A typical ~1 364-kg (~3 000-lb) U.S. car's ~90-kW (~120-hp) engine, sized for ~11-s acceleration from 0 to 97 km/h, is oversized about sixfold in cruising and 24-fold in city driving, so it usually operates at severely depressed efficiency (C. Gray, personal communication, 1992). Such overpowered but heavily marketed cars have top speeds that average 206 km/h, twice the maximum U.S. legal limit. In principle, just better matching of engine power to average load could double or triple fuel efficiency (*id.*).

[2] Unless otherwise noted, we express fuel economy in terms of USEPA-rated composite mi/gal and intensity in the corresponding l/100 km, which equals 235,2/(mi/gal). This composite is rated 55% on the urban and 45% on the highway test cycles, both designed in 1975. By the early 1980s, average well-maintained petrol cars' on-the-road fuel economy was typically ~10% lower than rated for city, ~22% for highway, and ~15% for composite driving. By 1990 the composite discrepancy remained ~15,2% for the car fleet but had widened to ~24,5% for light trucks, with an approximate doubling expected by 2010 (Maples 1992). The USEPA petrol-powered urban fuel-economy rating is approximately equivalent to the European urban-cycle test (or the Japanese 10-mode test) times 1,12; the highway rating, to the European 90 km/h test (or the Japanese 60 km/h test) times 0,87 (Bleviss 1988). We also generally use calendar year as a surrogate for model year. We adopt here the normal but odd convention of the distance travelled, rather than the product of distance times the passengers or payload carried--like the energy-per-*seat*-km metric used in analyzing surface mass transit or air travel.

[3] Expressed as levelized Cost of Saved Energy, equal to $Ci/S[1-(1+i)^{-n}]$, where C = capital cost, i = annual real interest rate expressed as a decimal (here, 0,07), S = annual fuel savings, and n = lifetime in years. Thus Cost of Saved Energy is capital cost divided by the discounted stream of fuel savings over the car's lifetime. If C includes an appropriate financing charge, CSE can be compared directly with the levelized price of delivered motor fuel.

[4] Omitted measures include reducing or eliminating brake drag, using switched reluctance generators that also replace the heavy starter motor (and eliminate high-speed alternator magnetic loss), and replacing v-belts with synchronous belts.

[5] All dollars in this paper are 1989 US$ (= 1,1024 1989 ECU), gallons are U.S. gallons (= 3,785 l), and miles are U.S. statute miles (1,609 km).

[6] The 1992 Honda Civic VX 4-passenger hatchback had 56% higher km/l than its previous-year base model, the 1991 DX. The 1992 VX was also substantially bigger (2,18 *vs.* 2,06 interior m³, 4,07 *vs.* 3,99 m long), with 17 l more volume for passengers and cargo combined, and delivered 10% more peak torque, yet weighed less (950 kg curb weight with driver airbag, *vs.* 979 kg with none) (Koomey *et al.* 1992). The 1992 VX was also 16% more efficient than NRC's (1992) "lower-confidence" estimate of what is technically feasible for a subcompact car *in 2006*.

[7] This analysis of Manufacturer's Suggested Retail Price ("sticker price") is normalized for identical cosmetic and safety features (Koomey *et al.* 1992).

[8] A few of these concept cars had peculiar features not shared by others and hence not essential to such good efficiency. Their collective performance is consistent with that of a later prototype, General Motors' heavy but sleek and sporty 2-passenger Impact. It was all-electric, but if it converted petrol to wheelpower one-third as efficiently as it converted electricity (9,3 kW_eh/100 km), it would use only 2,94 l/100 km (80 mi/gal). Correcting to a half-as-heavy powertrain would make this ~2,53 l/100 km (93 mpg), but correcting for likely aerodynamic changes would lower it again to ~2,64 l/100 km (89 mpg) (P. MacCready and A. Brooks, personal communications, 1991). However, with a fairly efficient two-stroke petrol engine and three-speed manual transmission sized for sports-car performance (0-97 km/h in ~6,5 s), its efficiency would degrade to ~3,5 l/100 km (~68 mi/gal). Conversely, a separate calculation by K.H. Hellman (1992) assumes a much lighter powertrain converting methanol to wheelpower with 23% efficiency, and estimates <1,04 l/100 km (>225 mi/gasoline gal) if performance is normalized to the Impact's 121-km/h (75-mi/h) cruising speed rather than to its short acceleration time (0-97 km/h in 8 s): such a car (0-97 km/h in ~32 s, ~682 kg, ~13 kW) would probably not be marketable, but the calculation remains instructive.

[9] However, one survey of 95 U.S. car-parts *suppliers* (as opposed to manufacturers), with combined annual revenues of $30 milliard, found that they strongly favoured weight reduction as the key, and felt they would "have no problem with a 45 percent improvement" in mandated new-fleet-average fuel economy by 2000 (Chappell 1989)—although of course they would not bear all the retooling burden.

[10] Ross (1989) shows this as 12% because he counts the 30% Second Law penalty from the irreversibility of combustion. In his reckoning, of the remaining 70% of fuel energy usefully released in the combustion process, 33% goes to the cooling system and exhaust, 12% to friction, 4% to accessories, 9% to torque conversion and transmission, and 12% to the drivewheels.

[11] For example, ~15% of the total gain in fuel economy from using a modern two-stroke instead of a four-stroke engine is from reduced drag, nearly 40% from reduced mass, and the rest--slightly under half--from direct reductions in engine specific fuel consumption (K. Schlunke, address to NRC Irvine hearing [see (Lovins 1991)], 8 July 1991). Thus the claimed indirect fuel-economy benefits of the compact powerplant can nearly double the direct ones.

[12] Light weight is common in sports/racing cars--the 1957 2-seater aluminium/steel Lotus Super Seven (later the Caterham 7, still available in kit form) weighs ~600 kg--but is less common in 4-passenger platforms. Several composites experts have confirmed the feasibility of a ~450-kg U.S. family car. This is not a new idea. In 1980, the Battelle Memorial Institute (Columbus, Ohio) designed, but never built, a 545-kg "Pertran" vehicle simulated, with regenerative braking, to achieve composite ratings of 2,76-2,94 l/100 km (80-85 mi/gal) with a petrol or 2,3-2,3 l/100 km (100-105 mi/gal) with a diesel engine (Bleviss 1988).

[13] Not to be confused with "composite" (55% Urban / 45% Highway) U.S. fuel-economy ratings.

[14] *E.g.*, polyamides, polycarbonates, polyacetals, thermoplastic polyesters, and polyphenylene oxide. In U.S. cars, such materials were 4,1% of conventional polymer mass in 1970 and 16% in 1985, and are forecast to rise to 26% in 1995 (Amendola 1990).

[15] The average 1992 U.S. car contains ~110 kg of composites and plastics--7,7% by mass, or perhaps ~20-30% by volume, with the auto industry using ~5% of all plastics produced; but the increasing mass fraction, up from 5,8% in 1980, understates market capture because the synthetics weigh less than the metals they replace (Amendola 1990). Composites have long been used for such heavy-duty components as leafsprings and GMC Truck driveshafts, saving respectively 60% and 80% in weight (DOE 1993). The German Aerospace Research Establishment in Stuttgart has made a complete composite powertrain with gudgeon pins, piston rod, crankshaft, and Cardan shaft (C.-J. Winter, personal communication, 4 March 1993). But the substitution has often been piecemeal and unsystematic, and the design often improperly imitative of the original steel part--like the early plastic radio and TV cabinets that were shaped and patterned to look like wood boxes, before designers discovered ergonomic forms. Where it is done right, as in many plastic and composite bumpers, not just weight but also C_D benefit.

[16] For the lighter (475-kg) Renault VESTA II, the corresponding figures were 2,72 l/100 km (86 mi/gal) composite, 3,67 (64) city, and ~2,06 (~114) highway. The two vehicles have identical C_D, but the VESTA II's 1,63-m² frontal area (5% less than the Ultralite's), 160-kg lower curb weight, and slower acceleration (its top speed is correspondingly 36% lower) permit it to use a 20-kW (27-hp) engine--the same size as the Pertran's and only one-fourth as powerful as the Ultralite's. This reduced underloading yields two-fifths higher fuel economy. Of course, compared with the many mid-1980s concept cars (Bleviss 1988), the Ultralite's composite fuel economy is not unusual; it is essentially that of VW's IRVW safety test car delivered to the U.S. Department of Transportation 15 years earlier.

[17] The Ultralite's 279-cm wheelbase (66% of overall length) equals that of a Lexus LS-400 or (nearly) of a Buick Park Avenue.

[18] The 1,50-l, 83-kW (111-hp), 3-cylinder-in-line, 2-stroke, direct-injection, stratified-charge, all-roller-bearing engine drives an ordinary 4-speed rear-drive transaxle slightly adapted from a Saturn production model.

[19] Such acceleration is characteristic of *e.g.* the Mustang GT, which has one-fourth the Ultralite's composite fuel efficiency. The Ultralite's efficiency would be even higher without this sports-car performance. For example, Pininfarina's 1993 2-passenger, thermoplastic-over-spaceframe Ethos II coupe (*Autoweek* 1993) weighs more (730 kg), though its identical 0,19 C_D and 10% smaller frontal area (A = 1,53 m²) yield a 12% lower aerodynamic drag. Its Orbital engine, only half as big and powerful as the Ultralite's, yields a two-thirds longer acceleration time and an 8% lower top speed. Yet this reduced performance, close to the U.S. average, improves engine optimization enough to yield 2,76 l/100 km at 120 km/h (85 mi/gal at 74 mi/h), improving to 2,10 l/100 km at 60 km/h (112 mi/gal at 37 mi/h); the 90 km/h cruise rating is 12% more efficient than the Ultralite's.

[20] As a senior designer remarked, "There are a lot of areas we could make a lot lighter" (Coates 1992). This is true even of the shell, since its biaxial carbon-fibre cloth is probably stronger than necessary in some directions. The engine was also not highly optimized.

[21] Burt Rutan of Scaled Composites, Inc., Mojave, California.

[22] This range goes from a low figure for sporting-goods-quality carbon to a high one for carbon typically used for cars. Representative 1993 U.S. creel prices for the latter are around $26/kg, *vs.* $2/kg for E-glass and ~$11/kg for S-glass with ~20% higher performance; simple biaxial cloth costs ~$44/kg for carbon, ~$31/kg for S-glass, and ~$8/kg for E-glass. (Cloth can also be woven with anisotropic properties and multiple materials.) However, about half as much carbon as E-glass fibre is needed for equivalent strength and stiffness (but not elongation or toughness) in many applications, so the effective cost difference is not ~13x but only ~6x. (This is because carbon

fibres are not only stronger and far stiffer but also smaller, with 2-3x the surface area of glass, and hence absorb more energy in being separated from the resin matrix.) GM's Pyrograf process should cut carbon cost to ~$4-5/kg; it does not yet yield fibres suitable in length for structural applications, but may evolve in this direction.

[23] Since the rest is a somewhat less dense and considerably less strong epoxy or similar resin, the cross-section of a whole composite (not pure carbon fibre) exceeds that of equivalently strong steel, but its mass is roughly two-thirds lower.

[24] Hollow glass fibre offers significant potential for weight reduction, though not to levels equivalent to solid carbon fibre.

[25] Consulier Automotive (2391 Old Dixie Highway, Riviera Beach, Florida 33404, 407/842-2492, FAX 845-3237), founded in 1985, produces road-certified monocoque composite sportscars and some vans--apparently the only such full-composite road vehicles in production. Its 2-passenger GTP Sportscar base model has C_D = 0,28 (sacrificed for downforce to enhance roadholding at the 226 km/h or 140 mi/h design speed), A = 1,7 m², and M = 794 kg without air conditioner or such accessories as power locks and power windows; the monocoque body/chassis weighs 125 kg when removed from the mould. With a 2,2-l, ~150-kW engine, it reportedly outraces any showroom car, yet achieves 7,8 l/100 km (30 mi/gal) composite. Current prices start at $52,5k complete or $27,5 kit. Other models include an experimental 1 080-kg, ~160-kW-engined version that accelerates 0-97 km/h in 3,5 s, and a 4-passenger paper design expected to survive a 65-km/h (40 mi/h) crash. Unfortunately, the number of costly vehicles required for crash-testing inhibits both market entry and model improvements by such small firms. The tradeoffs between carbon and other fibres are complex; switching from E-glass to carbon for the monocoque shell of a GTP made for Energy Partners, for example, saved ~45 kg at an extra materials cost of ~$1k; and carbon is prestigious and marketable, but justifying carbon on fuel-saving grounds alone requires large mass compounding factors. Carbon is typically preferred in firewalls, pillars, and similar structural elements, for lightness in large panels such as roofs and floors, and sometimes for stiffness to protect the passenger compartment (given intrusion protection), while glass is most often used for elongation and toughness in front and rear crush zones.

[26] The term "net-shape" does not mean no handwork is required to make the mould and prepare the materials to be moulded; to achieve an exemplary product, squeegeeing, handling of bleeder cloth and waste resin, etc. can add significant handwork. Laying up the fibres for imbedding in the resin involves complex manual or robotic work in some cases, but in others simply uses prewoven cloth or other mass-produced forms. Substantial advances in manufacturing automation are both desirable and possible.

[27] One noted automaker, in contrast, has employed large men with rubber sledges to beat steel roof pillars into position so the roof will fit on.

[28] Volvo's 1985 assessment of its Mg-intensive LCP 2000 concept car found essentially unchanged mass-production cost just from streamlined assembly alone, *without* assuming net-shape materials or their other advantages.

[29] Similarly, a reaction injection moulded synthetic fender may cost the same as a steel fender but have a 78% lower tooling cost (Amendola 1978; Busch, Field, and Clarck 1978). Actual polyphenylene-oxide-for-steel substitution in Cadillacs cut tooling cost by an estimated 74% (DOE 1993).

[30] Some have suggested that for this very reason, supercars should be not sold but leased, so that after perhaps ~5-10 years, as in Japan and Sweden today, they must be scrapped: otherwise their durability will block the introduction of even more advanced models, as durable DC-3s did with later aircraft. Even without such a procedure, the U.S. may follow the European trend of requiring the automaker to take ownership of old cars anyhow in order to recycle them. For that purpose, composites can be pyrolysed, or shredded into short-fibre reinforcement for engineering materials, but it is better to disassemble them chemically (*e.g.*, by methanolysis) to recover reusable molecules and structures, not just energy. Broadly speaking, optimal depolymerization of the resin should yield intact fibres usually cleanable to original condition, plus repurifiable monomer. These products' value plus avoided costs of solid-waste disposal appear to justify the operation (R.S. Stein, personal communication, 23 March 1993; G.M. Wood, personal communication, 26 March 1993), but the best ways to conserve energy and large molecules require considerable further research and should not be discouraged by ill-considered regulation. Such research is "a need but not a barrier" (G.M. Wood, *id.*).

[31] Consulier and many other composite racecar builders have demonstrated this. Some issues remain, however, about inspectability for hidden damage and its potential effect on later performance. Composite aircraft wings are routinely repaired to nearly original strength after bird or stone strikes, but such thorough inspection and repair may be difficult for cars. Imbedded conductive or optical fibres may prove useful diagnostic tools.

[32] For example, the stiffness of the 794-kg Consulier coupe even with no glass is within 2-5% that of a glazed Mercedes 450-class sedan with ~2,7x its mass (P.H. Magnuson, personal communications, March 1993).

[33] *E.g.*, a 5,9-kg steel tricycle with 126 parts was redesigned to a 1,4-kg, 26-part plastic version at one-fourth the cost, and a mainly brass toilet float/valve assembly, from 556 to 88 g, 14 parts to one, and $3,68 to $0,58 (Seiss 1991). A windscreen wiper arm was reengineered from 49 parts to one at lower total cost even though it was made of ~ECU 34/kg (~$14/lb) carbon fibre (A. Green, personal communication, 23 February 1992). Similarly, Chrysler found that composites could cut a steel car's subassembly count by ~75% (saving much assembly labour), plant cost by ~60%, and tooling cost by 50%, and its body-in-white parts count by 98-99% (*Automotive News* 1986). ACEEE's consultant has found similar values.

[34] However, such costs could fluctuate widely during the early phases of developing large-scale synthetics markets in automaking: a single niche platform could easily use the entire available carbon-fibre production capacity.

[35] Pininfarina's Ethos II aluminium/thermoplastic concept car (*supra*) is expected to support 10 000-unit production "at a [~1993] cost of less than $20 000 each" (*Autoweek* 1993).

[36] Amendola (1990) cites the example of the Fiat Tipo's 12,5-kg hatchback, produced in-plant every 94 s from two glued synthetic shells on two automatic moulding lines, each containing two 2 300-T presses. The synthetic material makes short production runs economical and permits rapid changes. Consulier notes that low-pressure injection moulding would be particularly attractive for its composites, and is seeking to adapt to recyclable polycarbonate car mouldings a large machine developed to mould F-16 canopies.

[37] The U.S. Department of Energy defines hybrids as depending "partially upon externally generated electricity for propulsion energy," but here we mean *internally* generated electricity, generated onboard from a fuel and perhaps by photovoltaics. We therefore adopt Rohde and Schilke's (1980) definition—a vehicle "in which the power is obtained from two or more sources which have been connected or hybridized"—and by "hybrid-electric" we mean at least one of those sources is electricity made onboard. This need not exclude all external recharging, but our analysis assumes no such recharging and suggests it may not be widely desirable.

[38] The mass compounding factor varies widely among components and positions (*e.g.*, seats *vs.* calipers). In many aircraft, it is 10+, even 20+ for loads far from the centre of gravity: according to a possibly apocryphal but plausible story, saving 0,23 kg of stick-grip weight in a Douglas Skyhawk may have saved ~5,5 kg of airframe (R. Cumberford, personal communication, 22 February 1992).

[39] This need not mean physically small. Automakers have overemphasized compact engines to fit high shaftpower into small spaces. But low-drag ultralights require little shaftpower. The engine can then be less power-dense, simpler, lower-stress, cheaper, and more reliable—just like an aircraft engine, optimized for mass rather than for size (M. Seal, personal communication, 22 February 1992).

[40] Ordinarily, slow braking recovers less energy than fast braking because there is more time for deceleration to be done partly by air and tyre drag, which are irrecoverable. The lower the drag, however, the less this distinction matters.

[41] Besides the usual series and parallel variants (*infra*), a "universal" design combines engine and motor output in a planetary gear drive (Streicher 1992).

[42] Policy organs like the California Air Resources Board should consider amending their mandatory "zero"-emission sales levels—actually "elsewhere-emission vehicles" (Schipper 1992) whose electricity is made outside the local airshed—to permit this mode. That would greatly facilitate the deployment of hybrids superior to pure-electric cars in all respects, probably including total emissions. Other public policies meant to promote electric cars should also be reexamined to ensure they do not discriminate against hybrids.

[43] Compared with its base model, the automatic-transmission Volvo 850, which weighs 134 kg less: the ECC's 200-kg saving from using aluminium is more than outweighed by batteries and other powertrain components. The ECC is rated at 5,2 l/100 km highway, 6,0 city; the 850, at 8,4 and 11,8. Naturally, the ECC would use even less fuel if it didn't weigh 1 580 kg.

[44] These electronically commutated brushless DC machines have a different number of rotor and stator poles, both salient. The rotor is laminated iron, with no bars, windings, or magnets; it spins around to align itself with the rotating stator field synthesized by power electronics under digital control referred to real-time shaft-position sensing. The rotor has low inertia and high strength and runs virtually cold. Fail-safe, soft-start, variable-speed power electronics, driven by sophisticated software and firmware on hybrid power chips, provide optimized stator excitation, with even greater flexibility than a doubly-excited DC machine. With possibly only one switch per winding, enhanced torque/ampere, and greatly constrained fault modes, the electronics are cheap, simple, and unusually robust. Noise and torque ripple can be lower than with an asynchronous motor (virtually undetectable torque ripple of 0,05% has been measured at low speeds). Form factor is extremely flexible, and the output shaft can be integrated into the application. Sizes can be mW to MW; current designs span five orders of magnitude in speed and eight in torque (Lawrenson 1992).

[45] Ente per le Nuove Tecnologie l'Energia e l'Ambiente (ENEA), in Rome, is pursuing a hybrid with hub-mounted switched reluctance drives, powered initially by a diesel and later by fuel cells (U. Colombo, personal communication, 15 March 1993)—essentially the approach suggested in §7. Tokyo R&D has already used four-wheel hub-integrated permanent-magnet motors, albeit sharing one controller, in its 4-passenger, Prelude-sized NAV (Next Generation Advanced Electric Vehicle), which weighed 1 203 kg including 436 kg of lead-acid batteries. Many experimental car developers use Unique Mobility's hub-mountable permanent-magnet motors (Golden, Colorado). Axial-airgap PM motors designed by Oak Ridge National Laboratory (J.V. Coyner, personal communication, 26 March 1993) appear to offer suitable geometry and very high specific power at high speeds (but probably not at low speeds). However, suspension engineers dislike hub-mounting: they note that coupling separate motors to the wheels reduces unsprung weight, aiding suspension design.

[46] Most are at Switched Reluctance Drives Ltd, Springfield House, Hyde Terrace, Leeds LS2 9LN, U.K., 44 532 + 443-844, FAX + 423 179.

[47] Suspension must be especially smart to ensure adequate control, especially in cornering on rough or slippery surfaces, while passenger load varies from light to nearly the ultralight car's own mass. Although a lighter car can grip better in hard cornering, as if it had wider tyres—"Lopping a thousand pounds off a car chassis does extraordinary things to handling, finesse, acceleration, and economy, regardless of how it is accomplished" (McCosh 1993)—alternative tyre profiles (§4) may also be desirable; hard, narrow tyres are not the only option. The Ultralite's tyres, for example, cut normal rolling resistance by ~67-72% with special tread materials and design. Though inflated to 4,4 bar, they soften the ride with a modified rounded-sidewall profile. They are also self-sealing to avoid the weight of a spare tyre and jack by coping with ~75% of punctures. This feature degrades rolling resistance from r_0 = 0,0048 to ~0,0052, which might go a bit higher to ensure good handling with our lighter platform (Bill Egan, personal communication, 30 March 1993).

[48] This could well be a modern two-stroke direct-injection stratified-charge engine like the Orbital and its derivatives. By late 1992, with properly optimized software, these offered ~5-10% fuel-economy gains over even the best four-valve-per-cylinder four-stroke stratified-charge engines—or ~15% counting indirect effects on weight and drag (Ken Johnsen, personal communication, 16 December 1992). Manufacturers' data with low-octane petrol suggest minimum brake specific fuel economy around 250 g/kWh, or 34% thermal efficiency, at 1,2 l and quite similar values down to ~0,15 l. But even at displacements of only 0,125 l, about the minimum range for a ultralight hybrid, conventional four-stroke production motorcycle engines can produce 80 kW/l at ~10 000 rev/min, and racing versions, ~192 kW/l at ~20 000 rev/min (Yagi *et al.* 1991). Such small engines might weigh only on the order of 10 kg.

[49] An Audi 100 with a new 2,46-l, 5-cylinder Audi turbo diesel engine meeting EC emissions Standard 88/436/EEC, with injection pressures up to 0,9 kbar, has achieved 7,2 l/100 km on the EEC urban cycle, 4,2 (S6) at 90 km/h (Bauder and Stock 1990). Its optimal-point specific fuel consumption was only 198 g/kW$_{mech}$h, with more than one-third of the engine map <250 g/kWh. This corresponds at the optimal loadpoint to 43% engine efficiency (fuel input to shaft output), *vs.* ~32-36% for good spark-ignition Otto engines. A 43% efficiency had previously been obtained only in large truck engines. Of course, variable-geometry turbocharging, adiabatic design, membrane oxygen enrichment, and other advances could yield still further gains if seriously pursued. For example, adiabatic (low-heat-rejection) turbocompounded multicylinder diesels which recover exhaust energy with a turbine are estimated 48% efficient (336 kW) with a ~40% mass and size reduction; low-friction versions using "such components as gas bearings, 'ringless' pistons, low friction 'dry' ceramic bearings and solid lubricants" were suspected in 1983 to yield 54% efficiency (Bryzik and Kamo 1983); most analysts believe various approaches to advanced diesels will ultimately exceed 50% efficiency; and Cummins Engine (Columbus, Indiana) is reportedly operating a small, one-cylinder laboratory version of the ceramic adiabatic diesel at ~56% (P.B. Hertz, personal communication, 31 March 1993).

[50] This improved and multifuel-capable direct-injection diesel engine is reportedly quieter, cooler (no radiator), cleaner (though strict particulate and NO_x standards would leave some uncertainties to be resolved), and more efficient over a wider range than conventional diesels (36% peak, but an impressive 30% above 10-15% of full load), but has about the same mass-production cost as today's engines. A 1,4-l, 66-kW Elsbett engine in an Audi 100 achieved 3,3 l/100 km (77 mi/gal) in the European 90-km/h test, 21% below the fuel intensity of the Audi turbo diesel reported in the previous footnote (Mellde *et al.* 1989).

[51] Volvo's 1993 ECC concept car uses the 41-kW, 90 000 rev/min Volvo/ABB/Vattenfall gas turbine. Alternatives include the smaller gas turbine in Renault's series-hybrid Véhicule Electrique Routier and a reported 6-cm Kyocera turbine, and perhaps highly efficient thermal-radiation-to-photovoltaic converters with no moving parts.

[52] In 1991, 21-24% of new cars sold in the U.S. were white—the most popular colour, surpassing the runner-up by roughly twofold except in the compact and sports category, where red captured 19%.

[53] *E.g.*, with Cloud Gel (SunTek, Albuquerque, New Mexico), which turns brilliantly reflective white at a preset temperature, then resumes its translucency when it recools.

[54] *E.g.*, compact vacuum insulation (~0,56 W/m²K per 2,5 mm). Metal foam or honeycomb layers used primarily for energy management in a crash could also be made highly insulating and sound-attenuating with low-emissivity coatings and noble-gas fill.

[55] Many parametric analyses use the C_DA/M quotient to predict whether a given design will perform better in city or highway driving, since drag is important to fuel efficiency at high speeds and mass more so at low speeds. However, this quotient is not an efficiency figure of merit, since it increases with smaller mass and stays constant if both mass and drag change in equal proportions. The C_DAM product better indicates potential efficiency because it decreases in proportion to savings in either drag or mass. It cannot, however, directly predict fuel consumption; both drag and mass, plus many other parameters including regenerative braking efficiency, are needed for precise predictions in a given driving cycle (Rohde and Schilke 1980).

[56] Our assumed 280 g/kW_{mech}h (0,46 lb/hp-h) is typical of today's excellent off-the-shelf ~10-20 kW petrol engines: such 30% efficiency including powertrain (Remenda, Hertz, and Krause 1988) and ~33% for just the engine (P.B. Hertz, personal communication, 31 March 1993) has been observed with a 70-cm³, 4-kW 1984 Honda motorscooter engine, so newer and larger designs can do even better (*id.*)

[57] For model year 1990, C_DAM was ~1 095 m²kg, because C_D = 0,33, A = 2,3 m², and M = 1 443 kg.

[58] The parametric approximation of Rohde and Schilke (1980) yields 1,43 l/100 km (164 mi/gal) urban, 1,72 (137) highway, and 1,56 (151) composite. Adding 300 kg of payload degrades composite efficiency to 2,1 l/100 km (112 mi/gal). We assume the parameters shown in Table 1 below, driveline efficiency 0,9, regeneration efficiency 0,7 including storage losses, accessory load 15% of tractive energy (which differs only 8% in the two test modes), and minimum brake-specific fuel consumption of 280 g/kWh. The efficiency assumptions appear reasonable for a thoughtfully designed switched reluctance system, but in practice would depend on details of configuration, components, control algorithms, and test cycles.

[59] Mature monolithic solid-oxide fuel cells (as distinct from ~0,1 kW/l tubular bundles) will ultimately yield perhaps ~1,4 kW_e/kg—over twice the power density of an Ultralite engine with generator—and ~2,8 kW_e/l (10 kW_e from a 15-cm cube). The technology is not yet so mature: a recent design for unmounted 10-kW_e packaged *systems* (Allied-Signal 1993) yielded only 0,36 kW_e/kg and 0,53 kW_e/l (from the core alone, 0,48 kW_e/kg and 1,04 kW_e/l), but can doubtless be improved. The superinsulated cells run red-hot at ~1 000°C, are ~50-60% efficient (more at part-load), and might cost ~ECU 190-290 (~$175-260) per kW_e. They are self-reforming, can accept a wide range of fuels, and are reversible (Erdle *et al.* 1990), eliminating the buffer store. Successful tests of small multicell stacks have already shown an impressive cell power density of 0,41 gross or 0,34 net W_e/cm², and should expand to the kW_e range during 1993-94. Ceramic heat-exchanger experience confirms that with proper engineering, even such large ceramic stacks can cold-start to full power in one minute or less, via a fueled heater, without cracking or fatigue (Gorik Hossepian, personal communications, 2 February and 25 March 1993).

A different, nearer-term, more mature, but less power-dense and versatile type of fuel cell, the proton exchange membrane (PEM) design, has about half the cell power density (~0,24 kW_e/kg), but needs bulky, costly, and energy-consuming reformer, pump, humidifier, cooling, and compressor auxiliaries expected to depress the total to 0,04-0,07 kW_e/kg (Swan and Appleby 1992)—*vs.* a typical car engine's 0,2-0,4 kW_{mech}/kg or the Ultralite engine's 1,05 kW_{mech}/kg. However, a 20-kW_e, 60-cell PEM stack using gaseous hydrogen fuel is reportedly expected to achieve 0,09 kW/kg in April 1993 at ~46-47% efficiency, rising to >50% at one-fourth load (S. Misiaseck, Energy Partners, personal communication, 23 March 1993). Its developer, Energy Partners (1501 Northpoint Pkwy, Suite 102, W Palm Beach, Florida 33407, USA, 407/688-0500, FAX -9610), modified a Consulier (*q.v. supra*) 2-passenger GTP Sportscar platform. The ~227-kg 20-kW fuel cell (expanded from a recently tested 7-kW, 25-cell PEM stack built for the Royal Australian Navy), a 36-kg Uniq motor/controller, and a ~272-kg, 20-kW_p, 9-kWh lead-acid battery bank to boost acceleration together raise curb weight from 795 to ~1 182 kg, including a 68-kg carbon-fibre body, although the batteries would be removed as soon as fuel-cell progress permits. Total system efficiency from fuel-in-tank to wheels is expected to be ~38-39%, roughly three times that of typical U.S. production cars, implying composite fuel consumption on the order of ~2,9-3,9 l/100 km (~60-80 mi/gal) with the heavy batteries in place.

Recent developments, including a ~40x reduction in platinum catalyst density (so that only ~$40/car more would be paid for fuel-cell Pt than is already being paid for catalytic-converter Pt), suggest that PEM systems' mass-produced marginal *cost* could approximate that of the conventional engine and powertrain elements displaced (Kelly and Williams 1992).

[60] Superflywheels spin wound carbon-fibre composite rotors on magnetic bearings in a 10^{-5} Torr vacuum. A Lawrence Livermore National Laboratory design (Comfort *et al.* 1992; R.F. Post, personal communications, 29 January and 26 March 1993) would spin 8-cm-radius concentric cylinders at 144 000 rev/min, while an Oak Ridge National Laboratory design (D.U. O'Kain and J.V. Coyner, personal communication, 26 March 1993) would spin bigger hoop rims with 70-72% carbon-fibre volume fraction at ~46 000 rev/min. Both designs

would transfer power through a generator/motor using powerful permanent magnets and low-loss electronics, returning almost all (LLNL expects 96%) of the electrical energy input. Either design would not run down for months. Superflywheels should be essentially immune to aging and to degradation with charge/discharge cycling (carbon fibre can run without fatigue at 70-75% of ultimate yield strength), as long-lived as the car, economically competitive (all materials or components are similar to others already in other commercial uses), and readily gimballed or soft-mounted. Safely confining composite-rotor failure appears to require containment slightly more massive than the rotor; fortunately, though catastrophic failure is dramatic, the rotor turns to small, sootlike particles rather than to shrapnel.

Building on a billion dollars' worth of gas-centrifuge-related composites experience, ORNL demonstrated in 1985 a specific energy of 244 Wh per kg of rotor rim mass at 1 405 m/s ultimate speed (at which the web failed first, not the rim), using ordinary IM7 carbon fibre with an ultimate strength of ~4,8 GPa or 0,7 million lb/in^2. A reasonable operating speed for this material would be ~1 225 to 1 270 m/s. Conservatively assuming 1 200 m/s, ORNL confidently expects packaged, whole-system, ready-to-gimball "can weight" equivalent to ~55-65 Wh/kg. Such a hybrid-car device storing 4,2 kWh (3,0 kWh available at an easily increased 45-kW full-power rating) would weigh ~65-75 kg, probably cost <$3k, occupy ~51 l, and fit in the spare-tyre well. LLNL proposes smaller modules (~15 l, ~26 kg, ~1 kWh, ~37 Wh/system kg). Thus flywheel specific energy can at least equal and perhaps double the best lead-acid batteries' ~35 Wh/kg, while offering many operational advantages. More importantly, either superflywheel design can handle peak power loads ~20-100x larger than batteries of comparable capacity (high kW capacity is easily achieved by adding modest amounts of copper), making regenerative braking simpler and more efficient.

Further progress is likely. Specific energy, for example, depends linearly on fibre strength. LLNL has analyzed a higher-performance (T-1000 class) carbon fibre for which ORNL has achieved ~6,55 GPa (0,95 million lb/in^2) strand tensile strength. ORNL considers this material not yet cost-effective or mature for applications, but when it is, it may yield specific energy approaching 100 Wh per system kg. Progress continues: very small experimental quantities of ~10,3-GPa (~1,5 million lb/in^2) carbon fibre are expected to become available from Japan in late 1993 at ~10^2x current IM7 prices. The theoretical limit is severalfold higher. Some experts believe "buckytubes" (a tubular form of buckminsterfullerene) may offer a breakthrough for making stronger and cheaper carbon fibres.

[61] The miniaturized, multifarad-range ultracapacitor, being developed chiefly in the U.S., Japan, and Russia, is currently very costly, but might not remain so. Affordable units might become the peak-power buffer store of choice, as they have no moving parts, are very compact, and can handle extremely high currents, such as regenerative braking from panic stops. Both ultracapacitors and fuel cells for hybrid cars are specifically targeted by President Clinton's 22 February 1993 "clean car" initiative.

[62] The 1993 Allied-Signal preliminary design has a 154-l envelope.

[63] The parametric analysis uses the variables shown in Table 1 and the method described above for the "Gaia," but accessory loads are renormalized to 16% of tractive energy to equal Gaia's. Minimum brake-specific fuel consumption is also reduced by 39% to 170 g/kWh, or 50% thermal efficiency, as a surrogate for an advanced fuel cell or a small adiabatic diesel, though either may well be more efficient than that, and we have not increased driveline efficiency to account for the fuel cell's elimination of the generator. On these straightforward assumptions, the method of Rohde and Schilke (1980) yields 0,56 l/100 km (416 mi/gal) urban, 0,66 (355) highway, and 0,61 (386) composite. Our 0,8 l/100 km nominal value thus appears conservative.

[64] Just hybridizing the Ultralite itself with 0,3 engine efficiency, 0,9 drivetrain, and 0,7 regeneration, if accessory loads are 10% of tractive energy, yields 1,72 l/100 km (137 mi/gal); at 50% engine or fuel-cell efficiency, 1,05 l/100 km (224 mi/gal).

[65] Adding a 300-kg payload to the 400-kg Ultima degrades its composite efficiency to 0,85 l/100 km (276 mi/gal), but that of the long-term-limits variant is still 0,6 l/100 km.

[66] Weekday driving is ~0,1 of daylight hours, and monocrystalline silicon cells on a typical supercar can collect ~0,8 kW_e in typical daylight. In Sweden, the average car is parked 96% of its life (Nyman 1992). As Paul MacCready points out (personal communication, 4 March 1993), this is precisely why superefficient but otherwise similar cars cannot cost much more than today's cars: airliners carry paying passengers most of the time, so they justify costly fuel-saving improvements that bring no other benefits. In contrast, most private cars don't produce revenue and mainly sit idle, so most owners aren't motivated to pay much to save fuel without getting other valuable benefits.

[67] Halved-weight (1 045-kg), low-load-floor, full-standup-height monocoque composite vans with up to 682 kg (3/4 t) payload and 7,8 m^3 of cargo space, being built by Consulier (*q.v. supra*) for Federal Express, are already achieving ~53-57% reductions in composite fuel intensity, to 7,8 l/100 km or 30 mi/gal (*Success* 1992). Consulier's composite ~1 089-kg Urban Delivery Vehicle, with up to twice that payload, weighs less fully loaded than a comparable steel van does empty. The same firm's 23-passenger bus design cuts curb weight by more than half, to only 1,8-2,0 T (P.H. Magnuson, personal communication, 22 March 1993), while a larger composite bus design, by

halving weight, saves 30% of fuel use, reduces engine size, and permits single rather than dual rear tyres (DOE 1993). In pickup trucks, larger payloads and open beds would reduce potential fuel savings, but the usually cited necessity for rear-wheel drive for load-hauling in a light truck is not a disadvantage (OTA 1991), because it is consistent with rear- or four-wheel-drive hybrids, and their dual drive would be especially helpful in hauling heavy loads uphill.

[68] Historic data must be interpreted with care. Until 1985, the U.S. accident population was only ~15% restrained by belts and airbags, rising to ~50% in 1990 (D. Friedman, personal communications, March 1993). Although admirably extensive analyses of mass *vs.* safety have been performed (*e.g.*, Evans 1991), the higher crash death rates observed in the *average* of today's light cars (but certainly not in all models) are for a fleet all built with broadly similar methods and materials, and hence cannot be used to predict the safety of the completely new kinds of cars proposed here.

[69] Such effects are almost impossible to measure because, for example, larger cars (which tend to be heavier with currently dominant designs) tend to drive more miles, carry more people, and be driven in less urban settings (hence at higher speeds) and in riskier ways, while smaller cars tend to have younger drivers who are more crash-prone but survive better (Evans 1991, pp. 75-76).

[70] A car-design variable strongly correlated with risk is acceleration—a fact unmentioned since Detroit intensified its marketing of muscle cars.

[71] As Evans (1991) states, "When a crash occurs, other factors being equal[:] The lighter the vehicle, the less risk to other road users. The heavier the vehicle, the less risk to its occupants." The opposite should therefore also be true.

[72] And light trucks and sports utility vehicles. In the United States these were exempted from safety requirements, and their crash-test performance shows it.

[73] This varies with composition: the ratio of strength in tension to that in compression is approximately 1 for most carbon fibre, 3-4 for aramid, and up to 10 for high-performance polyethylene. Among many proofs of the right composites' suitability for compressional loads, a carbon/epoxy unmanned minisubmarine exhibited no fibre breakage at pressures equivalent to 7 km depth (G.M. Wood and D.A. Waters, personal communication, 26 March 1993).

[74] For example (Kindervater 1991), in "fracture dominated crushing modes of carbon or hybrid [carbon-aramid] composite tubes[,] specific energies over 100 kJ/kg [with nearly 100% crush force efficiency A_E, *i.e.*, nearly ideal plastic energy absorption] could be obtained compared to 60 kJ/kg...in the best aluminium configurations." Specific energy absorption equal to that of aluminium tubes, at comparable or somewhat lower A_E, can also be obtained from sinewave-beam composite assemblies. For such reasons, composites are predicted within the next ten years to be used "for up to 80 percent of the structural weight of a helicopter." To be sure, "Pure carbon fibre reinforced laminates under compression loading can have extremely high energy absorption capability but disintegrate completely into small laminate fragments," but "Hybridization with tougher fibres such as Kevlar or high performance polyethylene [stacked or in intraply weaves]...provides post crash structural integrity" with lower stiffness but also perhaps lower weight, since polyethylenes like Dyneema SK60 have specific gravity below unity.

[75] Such a cruciform using hybrid composites to resist longitudinal crushing (of, say, an aircraft subfloor supported by cruciform pillars) absorbs ~3.25x the kJ/kg of an aluminium cruciform (Kindervater 1991); comparable U.S. automakers' findings are ~4.

[76] Käser (1992), of the Institute for Lightweight Structures at the Swiss Federal Institute of Technology (Zürich), shows that a foam- or honeycomb-filled, nearly rectangular beam wrapped around a light car (500-600 kg curb weight, 2,5-2,8 m overall length) can decelerate ~250-kN mean impacts at ~48 mean *g* without intrusion. "Higher impact forces and decelerations can be obtained with small modifications without significant increase of weight."

[77] Given such an ultrasafe family car, you could in principle make it even a little safer in two-car collisions (albeit less able to maneuver to avoid them, and more hazardous to other cars) by using more mass, including more of those same safety-producing materials. But you may not want to, because the marginal cost would be relatively high, the marginal benefit relatively low, and the performance penalty from mass compounding possibly substantial. However, the better the regenerative braking, the smaller the mass penalty—hybrids scale up well—so some extra mass yielding potentially large increments of safety could be accommodated if desired. Our conclusions therefore do not depend on extrapolating our qualitative safety conclusions to the extremely lightweight frontiers of the 400-kg Ultima.

[78] Minor ones might also exist, such as post-crash high-voltage conduction by uninsulated carbon fibres.

[79] Such artificial barriers can be redesigned, but must still withstand natural forces.

[80] The Ultralite's clamshell doors, for example, open up the entire side of the car at once, giving simultaneous full access to both the front and rear of the whole passenger compartment. Yet the thin carbon-fibre door, light enough to be lifted by a small child, is so strong that it provides adequate side impact resistance with no B-pillar.

[81] Active noise cancellation works much better for engine noise than for road noise, but a tyre tread has been proposed whose halves make out-of-phase sounds that tend to cancel at some frequencies (P. MacCready, personal communication, 4 March 1993). Interior quietness need not require much weight: some modern aircraft, for example, selectively filter out annoying frequency ranges with "tuned" inhomogeneous layers of polyimide foam.

[82] AeroVironment (Monrovia, California) is coordinating a systematic exploration of the many public policy issues raised by integrating a new kind of vehicle, the electric "SubCar," into innovative transportation systems. Like anything different, including supercars, the SubCar raises a host of issues from emissions to liability and insurance. For example, Consulier's 2,59-meter-long, 5,9 l/100 km [40 mi/gal] "Ram-Chop" urban commuter-vanlet design, seating four abreast ahead of a >1,4-m^3 over-engine cargo area, is so short that two can be parked end-to-end or side-by-side in one U.S. parking space, like Fiat's even shorter (2,1-m) 3-passenger Downtown (*Autoweek* 1993); but would that be legal?

[83] This is true of body and structural elements, driveline, and the maddeningly complex little items that add so much assembly time. For example, trim would be avoided or moulded in, seats very simple (perhaps evolved from the Ultralite's suspended mesh on tubular composite frames), most wiring avoided or displaced by fibre optics, etc.

[84] This system has already been in place in Japan for a generation (J. Womack, personal communication, 18 March 1993). Sears, for that matter, sold a $395 "motor buggy"—then a novel product—through its mail-order catalogue in 1910.

[85] Perhaps like filament-winding and -weaving of carbon-carbon rocket nozzles using textile equipment. A Drexel University team has even reportedly filament-wound an entire car body, but by hand.

[86] Some are diversifying, as in GM's Hughes electronics and EDS software activities, but the cultural integration has not been easy. The diffusion of synthetic materials technologies into automaking has been discontinuous, slow, and incremental (Amendola 1990).

[87] Conversely, for example, changing the section of a beam from an I (steel) to a plate-and-box (composite), with the same total cross-section, can boost its strength, but not stiffness, by three orders of magnitude (A. Green, personal communication, 23 February 1992).

[88] The United States spends in peacetime nearly $50 milliard per year on specific military forces whose primary mission is intervention in the Persian Gulf—equivalent to paying ~ECU 808/T (~$100 per barrel) of Gulf oil, five times the world oil price.

[89] For example, cars and car parts account for the equivalent of three-fourths of the U.S. trade deficit with Japan.

[90] The term is due to A.H. Rosenfeld, and the concept appears to have been developed by R.H. Garwin in the early 1970s, a few years before Rosenfeld and Lovins.

[91] One might suppose that scrapping the least efficient cars first would disproportionately harm the poor. However, at least in the U.S., more frugal early-1980s cars have now trickled down to the poor, whose cars are on average *more* efficient than the newer, often overpowered models driven by the rich (D. Gordon, personal communication, 12 February 1993).

[92] The Maryland statute, unlike the California "Drive+" scheme, was unfortunately framed in terms of fuel economy rather than CO_2 per km, and hence fell afoul of Federal preëmption. The Ontario scheme, approved by all the diverse interest groups, was not revenue-neutral but explicitly meant to raise revenue (it imposed a fuel-economy tax ranging from +C$7 000 to -C$100). Our remarks about the awkward U.S. politics of petrol taxes do not imply that motor fuel should not be priced at its full social cost; rather, that while helpful, especially with car-km travelled, this would be a weak and slow signal to buy efficient cars. It is important both to make cars efficient *and* to reduce driving (Johnson 1992); the two could be linked by reinvesting petrol taxes in developing supercars and retooling to make them.

[93] In most of the world's cities, cars now dominate the public realm, and social interactions are often reduced, in Andres Duany's phrase, to "aggressive competition over squares of asphalt." Automobility has indeed eroded community and submerged civilized purpose: as Johnson (1992) quotes T.S. Eliot, "A thousand policemen directing the traffic / Cannot tell you why you come or where you go."

[94] *E.g.*, congestion pricing of roads and parking, parking feebates, commuting-efficient mortgages, advanced land-use planning (Weissman and Corbett 1992, Newman *et al.* 1992), internalization of social costs (MacKenzie *et al.* 1992), pay-at-the-pump car insurance (El-Gasseir 1990, Tobias 1993), and making "negamile markets" that maximize competition between all modes of mobility (and ways to get access without mobility, such as telecommuting or being there already). How much is it worth paying people to stay off the roads so we needn't build and mend them so much? Probably a lot. We should make markets to find out.

14. REFERENCES

Abernathy, W.S. 1978: *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*, Johns Hopkins (Baltimore, Maryland).

Abernathy, W.S. and J.M. Utterback 1978: "Patterns of Industrial Innovation," *Technology Review*, June-July.

Allied-Signal Aerospace Company 1993: Data on 10- and 50-kW_e MSOFC system designs (AiResearch Los Angeles Division, 2525 W 190th St, PO Box 2960, Torrance, California 90509-2960).

Amendola, G. 1990: "The diffusion of synthetic materials in the automobile industry: Toward a major breakthrough?," *Research Policy* 19(6):485-500.

American Physical Society 1975: *Efficient Use of Energy*, American Institute of Physics Conference Proceedings No. 25, AIP (New York).

Automotive News 1986: "Chrysler Genesis Project Studies Composite Vehicles," p. 36, 5 May.

Autoweek 1992: "Pininfarina Ethos II" and "Fiat Downtown," 22 March, p. 15.

Barske, H. 1991: "Rationelle Verwendung von Kraftstoff: Autos mit 3 Liter Benzinverbrauch, eine Utopie?," at 13.1-14 in B. Löffler, ed., *Procs. 6th Ann. Conf., Environment and Renewable Energy II--Objectives 1991 to 2000*, Basel.

Bauder, R. and Stock, D. 1990: "The New Audi 5-Cylinder Turbo Diesel Engine: The First Passenger Car Diesel Engine with Second Generation Direct Injection," SAE Paper 900648.

Blake, R.J. and P.J. Lawrenson 1992: "New Applications of Very Large and Small Switched Reluctance Drives," 4.4.1, *Procs. Power Conversion and Intelligent Motion*, Nüremberg, April.

Bleviss, D.L. 1988: *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s*, Quorum Books (Westport, Connecticut).

Bleviss, D.L. and P. Walzer 1990: "Energy for Motor Vehicles," *Sci. Amer.*, pp. 102-109, September.

Bryzik, W. and R. Kamo 1983: "TACOM/Cummins Adiabatic Engine Program," SAE Paper 830314.

Busch, J.V., F.R. Field, and J.P. Clarck 1978: "Economics of Automobile Body Panels," MIT Materials Systems Laboratory paper at ATA-CNR Seminar *Innovation in Materials for the Transportation Industry*, Torino, 4-6 November.

Chappell, L. 1989: "Suppliers say U.S. car fleet can get 41 mpg in 10 years," *Automotive News*, 21 August, p. 10.

Coates, D. 1992: "GM's Ultralite Concept Car," *Industrial Design*, October, pp. 78-81.

Comfort, W.J., S.E. Bumpas, T.A. Edmunds, A.R. Hall, A.D. Lamont, H.K. McCue, and E. Zywicz 1992: "Feasibility Assessment of Electromechanical Batteries for Electric Vehicles," UCRL-ID-109422, May, Lawrence Livermore National Laboratory, Livermore, California.

Delsey, J. 1992: "Environmental comparison of electric, hybrid and advanced heat engine vehicles," *Procs. Urban Electric Vehicle Conf. (25 May)*, OECD/NUTEK/IEA, Stockholm.

Difiglio, C., K.G. Duleep, and D.L. Greene 1989: "Cost Effectiveness of Future Fuel Economy Improvements," *En. J.* 2(1):65-83; see also Energy and Environmental Analysis, *Developments in the Fuel Economy of Light-Duty Highway Vehicles*, August 1988 report to Office of Technology Assessment.

DOE 1992: Notes of the Hybrid Planning Workshop (Dearborn, 22-23 September), U.S. Department of Energy (Washington DC).

DOE 1993: *Lightweight Materials for Transportation: Program Plan*, Office of Transportation Materials, U.S. Department of Energy (Washington DC), April, §C.7.1, §C.8.2, §C.9.

Dolan, K., B.E. and B.G. Andersson, H. Nishimake, L. Schipper, R. Steiner, and W. Tax 1993: *Fiscal Policies Affecting Automobiles in W. Europe, Japan, and the United States*, LBL draft report originally prepared as an appendix to (Schipper *et al.* 1992).

Duleep, K.G. 1991: *Potential to Increase Fuel Economy to 2001*, Energy & Environmental Analysis, Inc. (1655 N. Ft. Myer Drive, Arlington, Virginia 22209).

El-Gasseir, M.M, 1990: "The Potential Benefits and Workability of Pay-As-You-Drive Automobile Insurance," 8 June testimony to California Energy Commission (Sacramento), Docket #89-CR-90.

Erdle, E., W. Dönitz, R. Schamm, and A. Koch 1990: "Reversibility and Polarization Behaviour of High Temperature Solid Oxide Electrochemical Cells," World Hydrogen Energy Conf. 1990, from Dornier GmbH (PO Box 1420, D-7990 Friedrichshafen 1).

Evans, L. 1991: *Traffic Safety and the Driver*, Van Nostrand Reinhold (New York).

Goodyear 1990: News Release #19295-490, April, from Corporate Headquarters (Akron, Ohio 44316-0001).

Greene, D. 1989: "CAFE or Price?: An Analysis of the Effects of Federal Fuel Economy Regulations and Gasoline Prices on New Car MPG, 1978-89," Oak Ridge National Laboratory/USDOE Office of Policy, Planning and Analysis draft, 10 May.

Gromer, C. 1992: "Ultracar," *Popular Science*, April, pp. 33-35 & 125.

Grosse, B. 1992: "2-28-92 Consulier GTP Barrier Impact Test," nonproprietary excerpts provided by Consulier Automotive.

Hellman, K.H. 1992: "Passenger Car Fuel Economy--Beyond 2010," unpublished typescript, USEPA, 313/668-4246.

Hibbs, B. 1988: "Sunraycer Aerodynamic Environment," Lecture 2-2, in *GM Sunraycer Case History*, M-101, Society of Automotive Engineers (SAE) (Warrendale, Pennsylvania).

Houghton, D.J., R.C. Bishop, A.B. Lovins, B.L. Stickney, J.J. Newcomb, M. Shepard, and B.J. Davids 1992: *The State of the Art: Space Cooling and Air Handling*, E SOURCE (formerly COMPETITEK) (see Lovins and Howe 1992).

Johnson, E.W. 1992: "Taming the Car *and* Its User: Should We Do Both?," *Bull. Amer. Acad. Arts & Scis.* 46(2):13-29.

Käser, R. 1992: "Safety potential of urban electric vehicles in collisions," *Procs. Urban Electric Vehicle Conf. (25 May)*, OECD/NUTEK/IEA, Stockholm.

Keebler, J. 1991: "GM builds 100-mpg 'Ultralite' car," *Automotive News*, 31 December, pp. 1 & 31.

Kelly, H. and R.H. Williams 1992: "Fuel Cells and the Future of the US Automobile," 7 December review draft, U.S. Congress, Office of Technology Assessment (Washington DC).

Kempton, W. 1991: "Automobile Efficiency and Behavior: Lessons from Utility Energy Efficiency," 31 July, Center for Energy and Environmental Studies, Princeton University (Princeton, New Jersey).

Ketcham, B. and C. Komanoff 1992: "Win-Win Transportation, A No-Losers Approach to Financing Transport in New York City and the Region," Transportation Alternatives (New York).

Kindervater, C. 1991: "Composite Structural Crash Resistance," Institute for Structures and Design, Deutsche Forschungsanstalt für Luft- und Raumfahrt (Stuttgart), presented at 3-5 June 1991 DLR Crash User Seminar.

Koomey, J.G., D.E. Schechter and D. Gordon 1992, "Cost-Effectiveness of Fuel Economy Improvements in 1992 Honda Civic Hatchbacks," LBL-32683, Lawrence Berkeley Laboratory (Berkeley, California 94720).

Kyle, C.R. 1988: "The Sunraycer: Wheels, Tires and Brakes," Lecture 2-3, in *GM Sunraycer Case History*, M-101, Society of Automotive Engineers (SAE) (Warrendale, Pennsylvania).

Lawrenson, P.J. 1992: "A Brief Status Review of Switched Reluctance Drives," *Eur. Power Electronics and Drives Assn. J.*, September, pp. 71-79.

Ledbetter, M. and M. Ross 1990, "Supply Curves of Conserved Energy for Automobiles," *Procs. 25th Intersoc. Energy Conversion Engineering Conf.* (Reno, Nevada, 12-17 August), American Institute of Chemical Engineers (New York).

Lissaman, P.B.S. 1988: "Concepts in the Aerodynamic Drag of Road Vehicles," Lecture 2-1 at pp. 22-23, *GM Sunraycer Case History*, M-101, Society of Automotive Engineers (SAE) (Warrendale, Pennsylvania).

Lovins, A.B. 1991: "Advanced Light Vehicle Concepts," briefing notes for the Committee on Fuel Economy of Automobiles and Light Trucks, Energy Engineering Board, U.S. National Research Council (Irvine, California, 9 July, updated 3 August), Rocky Mountain Institute, Publication #91-20.

Lovins, A.B. 1991a: "Feebates," 6 July memo, Rocky Mountain Institute, Publication #91-21.

Lovins, A.B. and W. Howe 1992: "Switched Reluctance Motor Systems Poised for Rapid Growth," Tech Update TU-92-4, E SOURCE (1050 Walnut, Suite 205, Boulder, Colorado 80302-5140, USA).

Lovins, A.B., L.H. Lovins, and M. Bender 1984: "Energy and Agriculture," at 68-86 in W. Jackson, W. Berry, and B. Colman, eds., *Meeting the Expectations of the Land*, North Point (San Francisco).

MacCready, P.B. 1991: "Further Than You Might Think" and "Electric and Hybrid Vehicles," Conference on Transportation and Global Climate Changes and Long-Term Options (Asilomar, California), 26 August.

MacKenzie, J.J., R.C. Dower, and D.D.T. Chen 1992: *The Going Rate: What It Really Costs to Drive*, World Resources Institute (Washington DC).

Maples, J.D. 1992: "The Light Duty Vehicle MPG Gap: Its Size Today and Potential Impacts in the Future," 1 December draft, University of Tennessee Transportation Center.

Martin, R.A. 1992: "Selection Criteria for EV Propulsion Motors," *Procs. Solar/Electric Vehicle '92* (Boston), Northeast Sustainable Energy Association, October, summarized in "The Six Most Important EV Motor Requirements," *Electric Vehicle Progress*, 1 December, p. 3.

McCosh, D. 1993: "The Promise of Aluminum: The 50-mpg Sedan," *Popular Science*, February, pp. 76-81.

Mellde, R.W., I.M. Maasing, and T.B. Johansson 1989: "Advanced Automobile Engines for Fuel Economy, Low Emissions, and Multifuel Capability," *Annual Review of Energy* 14:425-444.

National Research Council 1992: *Automotive Fuel Economy: How Far Should We Go?*, National Academy Press (Washington DC).

Newman, P. and J. Kenworthy with L. Robinson 1992: *Winning Back the Cities*, Pluto Press Australia Ltd (Leichhardt, NSW).

Nyman, H. 1992: "Transport of people and goods in metropolitan areas," *Procs. Urban Electric Vehicle Conf. (26 May)*, OECD/NUTEK/IEA, Stockholm.

Office of Technology Assessment 1991: *Improving Automobile Fuel Economy: New Standards, New Approaches*, OTA-E-504, U.S. Congress (Washington DC).

Patterson, P. 1987: "Periodic Transportation Energy Report 1," DOE CE-15, U.S. Department of Energy (Washington DC), 202/586-9118, 16 November.

Patterson, P. 1987a: "Periodic Transportation Energy Report 2," *id.*, 23 December.

Remendra, B.A.P., P.B. Hertz, and E.A. Krause 1988: "Comparison, Selection and Modelling of Small Powerplants for the Nexus Vehicle," SAE Paper 880270.

Rohde, S.M. and N.A. Schilke 1980: "The Fuel Economy Potential of Heat Engine/Flywheel Hybrid Automobiles," *Supplement to Procs. 1980 Flywheel Technology Symposium* (DOE/ASME/LLL), CONF-801022-Supp (Scottsdale,Arizona), October, and SAE Special Publication P-91, 1981; see also N.A. Schilke, A.O. DeHart, L.O. Hewko, C.C. Matthews, D.J. Pozniak, and S.M. Rohde, "The design of an engine-flywheel hybrid drive system for a passenger car," SAE Paper 841306, 1984.

Romm, J. 1991: "Why America Beat Iraq But Loses to Japan," Rocky Mountain Institute Publication #S91-39, summarized in "The gospel according to Sun Tzu," *Forbes*, 9 December, pp. 154-162, both Rocky Mountain Institute Publications #S91-39.

Romm, J. and A.B. Lovins 1992: "Fueling a Competitive Economy," *Foreign Affairs* 71(5):46-62 (Winter 1992/93); unabridged version "Making Security Profitable," available from Rocky Mountain Institute.

Ross, M. 1989: "Energy and Transportation in the United States," *Annual Review of Energy* 14:131-171.

Runkle, D. 1992: Address to National Laboratories Conference (Warren, Michigan), 22 January.

Schipper, L. 1992: "Electric Vehicles in a Broader Context: Too Early or Too Late?," *Procs. Urban Electric Vehicle Conf. (27 May)*, OECD/NUTEK/IEA, Stockholm.

Schipper, L., R. Steiner, M.J. Figueroa, and K. Dolan 1992: "Fuel Prices, Automobile Fuel Economy, and Fuel Use for Land Travel: Preliminary Findings from an International Comparison," LBL-32699, Lawrence Berkeley Laboratory.

Seiss, R. 1991: presentation to NRC Irvine hearing (see Lovins 1991) on behalf of Dow Chemical Co., 8 July.

Sherman, D. 1992: "Using Carbon Fibers to Conserve Hydrocarbons: GM Ultralite," *Motor Trend*, February, pp. 74-76.

Sovran, G. and M.S. Bohn, "Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules," SAE Paper 810184; see also G. Sovran, "Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Cycle, SAE Paper 830304, and the summary in OTA 1991, App. A.

Sperling, D., L. Schipper and M. DeLuchi, "Is There An Electric Vehicle Future?," *Procs. Urban Electric Vehicle Conf. (27 May)*, OECD/NUTEK/IEA, Stockholm.

Stickney, B. 1992: "Super Efficient Refrigeration Systems," Tech Update TU-92-3, E SOURCE (1050 Walnut, Suite 205, Boulder, Colorado 80302-5140).

Streicher, W. 1992: "Energy demand, emissions and waste management of EVs, hybrids and small conventional cars," *Procs. Urban Electric Vehicle Conf. (25 May)*, OECD/NUTEK/IEA, Stockholm.

Success 1992: "Building the Dream," *Success*, November 1992, p. 10.

Swan, D.H. and A.J. Appleby 1992: "Fuel Cells and Other Long Range Technology Options for Electric Vehicles[:] Knowledge Gaps and Development Priorities," *Procs. Urban Electric Vehicle Conf. (26 May)*, OECD/NUTEK/IEA, Stockholm.

Tobias, A. 1993: *Auto Insurance Alert! Why the System Stinks, How to Fix It, and What to Do in the Meantime*, Simon & Schuster (New York).

Vint, M.K. 1987: "Design and Construction of a Fuel Efficient Braking System," SAE Paper 871233.

Weaver, L. 1992: Video and analyses provided 11 May (14 Home Place, Topsham, Maine 04086).

Weissman, S. and J. Corbett 1992: *Land Use Strategies for More Livable Places*, Local Government Commission (909 12th St., Suite 201, Sacramento, California 95814).

Westbrook, F.W. 1991: *Allocation of New Car Fuel Economy Improvements, 1976-1989*, Camden Corp. report to Oak Ridge National Laboratory.

Womack, J. 1990: *The Machine That Changed the World*, Macmillan/Rawson, and 1991 paperback edition, HarperPerennial (New York).

Yagi, S., K. Fujiwara, N. Kuroki, and Y. Maeda 1991: "Estimate of Total Engine Loss and Engine Output in Four Stroke S.I. Engines," SAE Paper 910347.

Zachary, G.P. and S.K. Yoder, "Order From Chaos," *Wall St. J.*, 27 January 1993, p. A1.

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Rocky Mountain Institute is an eleven-year-old, independent, nonprofit resource policy center. Its mission is to foster the efficient and sustainable use of resources as a path to global security. Its ~37 full-time and ~20 part-time staff pursue research and outreach in energy, transportation, environmentally responsive real-estate development, water, agriculture, local economic development, global security, and their interconnections. Half of the Institute's ~$1.8 million annual revenue comes from programmatic enterprise, chiefly RMI's E SOURCE subsidiary (Boulder, Colorado)--the premier information source on advanced techniques for electric end-use efficiency, serving several hundred utilities, industries, governments, and other organizations worldwide. The Institute's remaining revenue comes from foundation grants and from tax-deductible donations by individuals and corporations. A list of technical and popular publications is free upon request.

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L. HUNTER LOVINS, ESQ., is Rocky Mountain Institute's President and Executive Director. She holds BAs from Pitzer College in Political Science and in Sociology, a JD from Loyola University School of Law (Los Angeles) with the Alumni Award for Outstanding Service to the School, and an honorary LHD from the University of Maine. She helped establish and for six years was Assistant Director of the California Conservation Project ("Tree People"), an innovative urban forestry group. Mrs. Lovins has coauthored six books and many papers. She was 1982 Henry R. Luce Visiting Professor at Dartmouth College, and was co-Principal Investigator of studies for the Defense Civil Preparedness Agency and the German Federal Environmental Agency. With her husband and colleague Amory, she is a frequent consultant to governments and the private sector. The Lovinses shared a 1982 Mitchell Prize for their essay on reallocating utility capital and a 1983 Right Livelihood Award (often called the "alternative Nobel Prize").

ABOUT THIS EDITION:

This paper was circulated in review draft during February-March 1993 to more than 80 U.S. and international experts both in and outside the auto industry. Detailed comments received from more than 30 of these peer reviewers and ECEEE's four referees were taken carefully into account, and nearly all incorporated, in this revision. Scores of minor corrections and edits greatly improved the paper, and the reasonableness of its key assumptions and resulting efficiency projections was widely confirmed. Those projections were also greatly elaborated through the courtesy of a major automaker, which kindly provided a parametric spreadsheet.

The resulting efficiency figures were close to but more favorable than those previously obtained by manual calculation, so the parametric modelling supported an expanded analysis and somewhat stronger conclusions in this edition's §7, reflected also in §§1-2. Significant revision and expansion also occurred in the Abstract (§2) and in the discussion of tires (§4), composite materials (§5), and safety (§8). The previous overabbreviated discussion of transportation policy in the former §12 was condensed into a few paragraphs at the end of §11 at the Editor's request.