Hypercars: The Next Industrial Revolution

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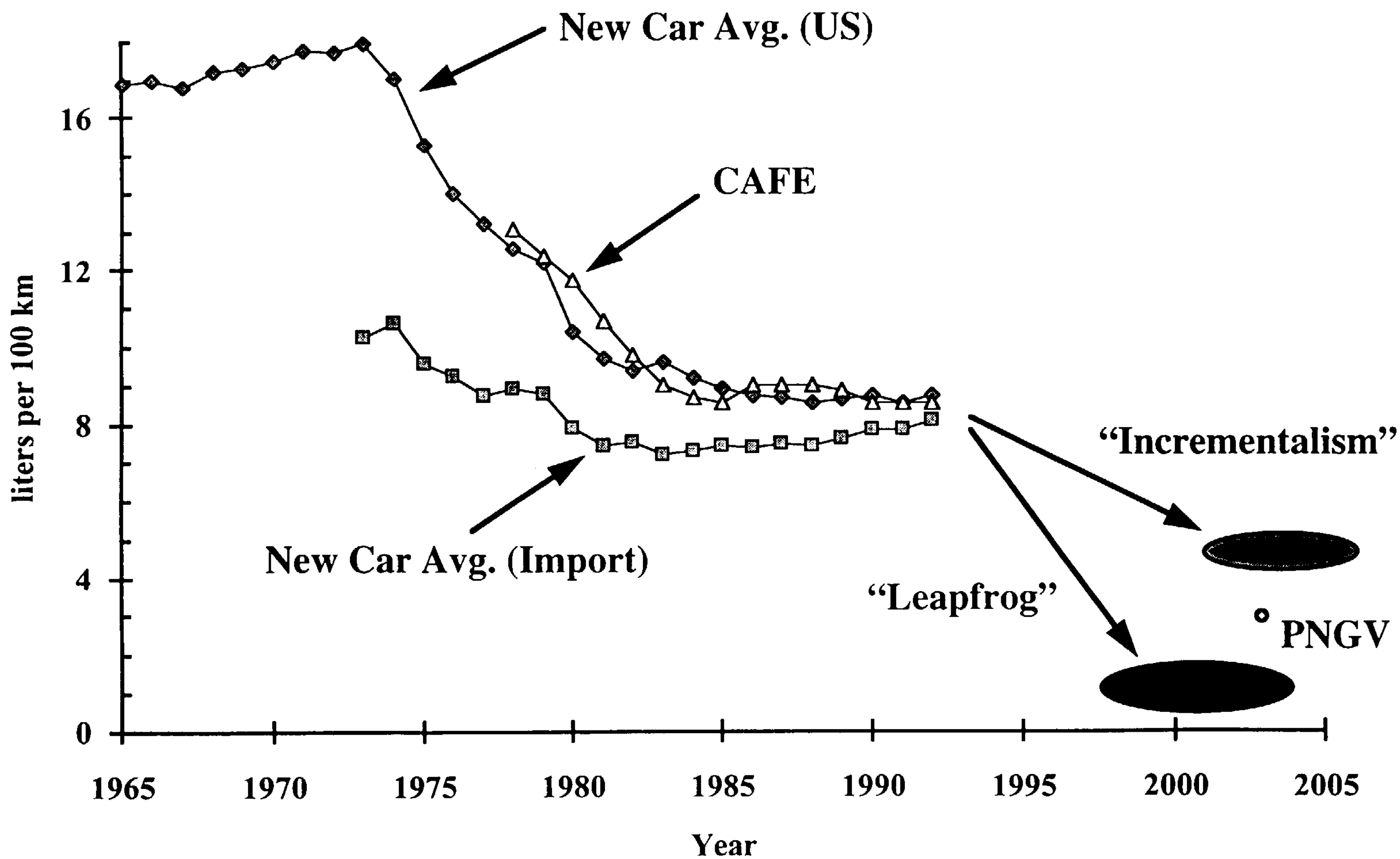
Extensively refereed and documented technical papers and nontechnical versions are available from the Center.

- Introduction
- Technical strategy
- Characteristics
- Implementation

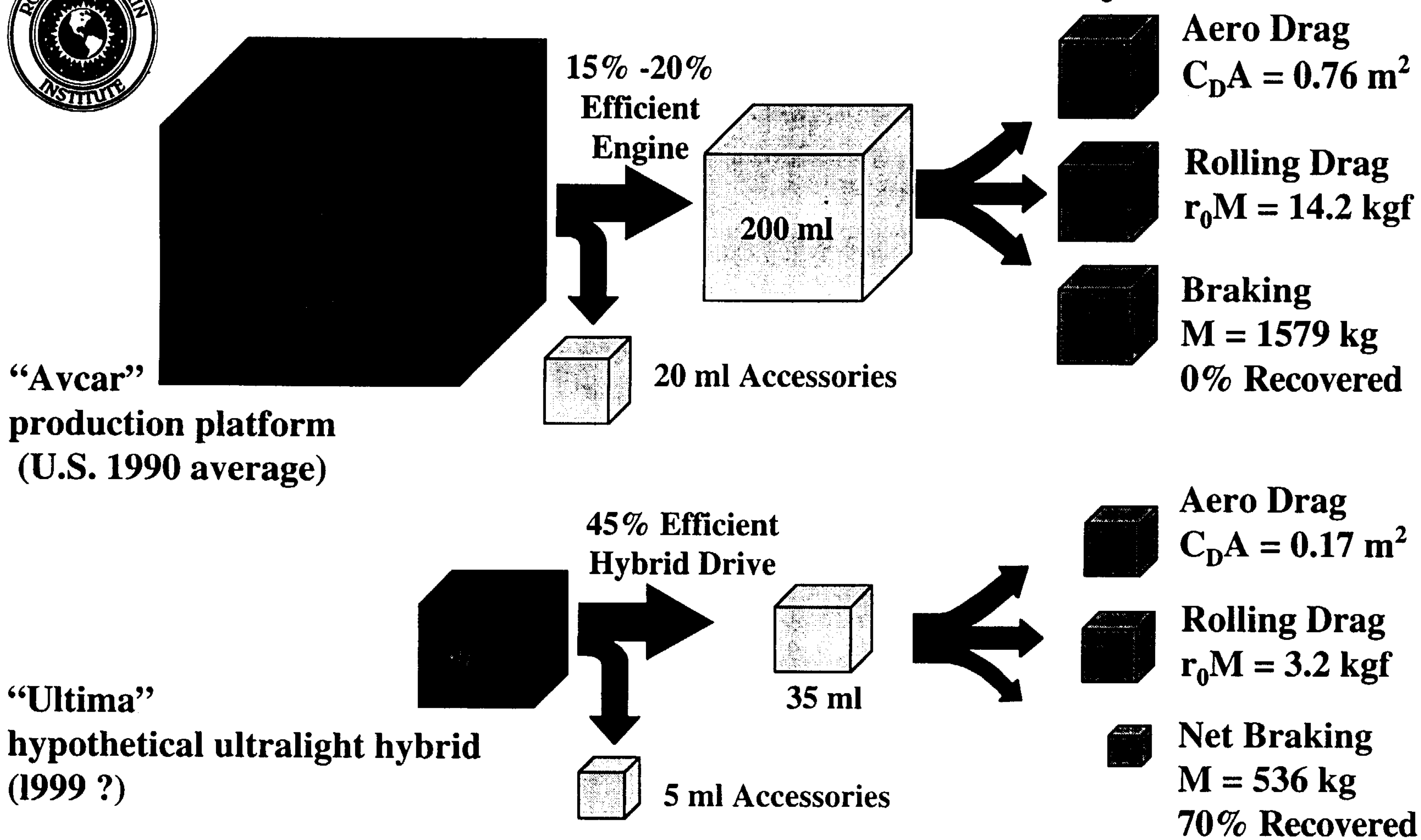
What are hypercars?

- not incremental but ‘leapfrog’
- an artful fusion of the best existing technologies
  - ultralight / slippery (improves efficiency ~2–2½×)
  - hybrid-electric (improves efficiency ~1.3–1.5×)
  - high-level system integration, meticulous attention to detail
- superior characteristics: for a family car,
  - ≤0,6–1,6 litre/100 km (~150–≥400 mi/USgal) composite ratings
  - ≥100 times cleaner; probably cleaner than battery-electrics
  - great fuel flexibility, convenient for liquids and gases
  - safer, sportier, more comfortable/quiet/durable/beautiful
  - probably cheaper
- completely different in technology, manufacturing, and sales
- profound implications—perhaps the biggest change in industrial structure since the microchip
- important cultural and market barriers need attention
- can buy time, but can’t solve the transport problem

Trend Is Not Destiny ?



Two ways to drive 12 km in the city



In highway driving, efficiency *falls* because there is far more irrecoverable loss to air drag (which rises as v^3) and less recoverable loss to braking.

ET 8/94, TCM 2/95

Reducing drag coefficient, C_D

1970: norm ~0,5–0,6
1992: U.S. average 0,33, best sedan 0,29, best productionized 2-seat 0,18
1992: best worldwide production platform (Adam Opel) 0,255
1921: Rumpler 7-seat Tropfenwagen (midengine prototype) 0,28
1985: Ford Probe V concept car 0,137 (<F-15's C_D!)
1987: Renault Vesta II 4-seat concept car 0,186
1991: GM Ultralite 4-seat concept car 0,192
1990s: likely practical limit w/ passive boundary-layer control ~0,08–0,10

Reducing frontal area, A (m^2)

1992: average U.S. 4/5-seat production platform ~2,3; 2-seat Honda DX 1,8
1987: Renault Vesta II 4-seat concept car 1,64
1991: GM 4-seat Ultralite concept car 1,71

So today's typical 0,33 × 2,3 m^2 C_DA = <u>0,76</u> m^2; GM's Ultralite, <u>0,33</u> m^2; the best parameters separately shown for 4-seaters, 0,137 × 1,64 = <u>0,22</u> m^2 (30% of today's); and edge-of-envelope, ~0,08 × 1,5 m^2 = <u>0,12</u> m^2 (16% of today's). We assume C_DA = <u>0,27</u> near-term, <u>0,17</u> later, <u>~0,13</u> edge-of-envelope.

Reducing the mass, M, of 4-seat cars

Mass compounds by ~1,5× in heavy cars, ~5× in ultralights.

Typical 1990 U.S. production platforms had curb mass ~1 443 kg.
However, mainly light-metal concept cars built in ~1983–87 included:

VW	**5-seat**	**Auto 2000**	**779 kg**
Volvo	**4-seat**	**LCP 2000**	**707 kg**
Toyota	**5-seat**	**AXV Diesel**	**649 kg**
Renault	**4-seat**	**Vesta II**	**475 kg**
Peugeot	**4-seat**	**ECO 2000**	**449 kg**

The unoptimized 1991 4-seat GM Ultralite weighed 635 kg; the 1994 4-seat ESORO H301 hybrid, ~670 kg including 230 kg batteries; the 1989/90 2-seat Kägi OMEKRON electric, 490 kg including 260 kg batteries. Detailed I.95 mass budgets for a 5-seat series hybrid yield ~400–500 kg. Thus <500 kg curb mass is practical now, 400 in ~1998. (USEPA test mass is 136 kg more.)

Reducing tyre rolling resistance, r_0

Modern radials' r_0≈0,007–0,010; best mass-produced, ~0,0062; best made by 1990 with good handling (by Goodyear), 0,0048; 1993 state-of-the-art, even less. We assume 0,006–0,007 including parasitic mechanical losses.

Hybrid-electric drives

- The wheels are driven wholly or mostly electrically by up to 4 ?hub-integrated switched reluctance motors (a British technology that is inherently smaller, lighter, cheaper, stronger, faster, quieter, and more efficient, rugged, fault-tolerant, and controllable than asynchronous or permanent-magnet motors). Braking is electronic and regenerative.
- Electricity is made onboard as needed in a tiny IC or EC engine, gas turbine, thermophotovoltaics, or fuel cell, *e.g.* an Otto (probably Orbital-derivative 2-stroke) $\eta = 0{,}3$ engine or $\eta = 0{,}5$ semiadiabatic Diesel.
- A few batteries (or a C-fibre superflywheel or ultracapacitor) store braking energy for hill-climbing and acceleration—*not* for range, since lead-acid batteries have ~1% as much energy per kg as fuel. Only ~0.5 kWh is needed; 2.5 kWh & 40 kW of hybrid-optimized NiMH weigh ~50 kg.
- Later, ideally a modular fuel cell (?monolithic solid-oxide, self-reforming and reversible, thereby eliminating the buffer storage too).
- Dramatically lower accessory loads and parasitic mechanical drag.
- Extremely light but crashworthy (advanced polymer composites); max. payload/mass; designed like an airplane, not a tank; 'fly-by-light/power-by-wire', smart active suspension, and powerful integrative software.

Advantages of hybrid-electric drive

- Using fuel for range cuts driveline mass ~4× below battery cars'.
- Mass savings compound faster than with other drivelines.
- Engine ~10 kW: sized *not* for peak acceleration but for ~1–3 kW cruising load + engine's ~4–8 kW share of gradeability + <1 kW accessories.
- Engine runs at a point (series) or over a small range (parallel), not over a big map, *doubling* typical Otto-engine efficiency. (A typical U.S. car's engine, to accelerate 0–97 km/h in 11 s, is oversized ~6× highway, 24× city.)
- Engine never idles—it shuts off when enough energy has been stored.
- Regenerative braking recovers ~70+% of braking energy (demonstrated w/permanent-magnet motors, higher with switched reluctance, highest with nonbattery buffer too; requires excellent software and electronics).
- Efficiency and emissions *improve* with traffic congestion, because regenerative braking makes them better in city than in highway driving.

Strongly synergistic w/ultralight: lower irrecoverable losses (air and road drag) leave more energy recoverable from braking; mass decompounding is bigger with both ultralights *and* hybrids, and biggest with both together.

Key parameters and USEPA composite fuel efficiencies of selected 4-seat existing and hypothetical cars (modelled per Rohde & Schilke)

C_DA, m^2	M, kg	r_0	E_{acc}	C_DAM	engine η	driveln η	regen η	l/100 km	mi/gal
production cars: typical U.S. 1990									
0,76	1 443	0,009	≡1,0	1 095	~0,30	~0,60	0	**8,00**	**29,4**
demonstrated concept car: GM Ultralite 1991 (1,5-l 83-kW 2-stroke engine)									
0,33	635	0,007	<1,0	208	unpubl	unpubl	0	3,79	62
hypothetical synthetic-polymer-dominated ultralight hybrids:									
'Conservativa' worst-case illustration (uncontroversial parameters)									
0,40	700	0,008	0,80	280	0,35	0,75	0,60	**2,44**	**97**
'Gaia' near-term design ('optimized Ultralite', standard petrol engine)									
0,27	580	0,007	0,50	154	0,30	0,90	0,70	**1,61**	**146**
'Ultima' advanced design ('state-of-the-shelf'—very light, good Diesel)									
0,17	400	0,006	0,30	68	0,50	0,90	0,70	**0,63**	**376**
'Imagina' (aero++, fuel cell or best Diesel, C-flywheel/ultracapacitor)									
0,13	*400	0,005	*0,25	52	*0,56	0,96	*0,88	***0,38**	***614**

Still not edge-of-envelope, because these parameters can be further improved with demonstrated 1994 technologies. Engine efficiency is peak ($BSFC_{min}$)—~280 g/kW$_{mech}$h is η_{max} = 0,30; driveline efficiency is engine-output-shaft-to-wheels; regenerative braking efficiency is wheel-to-wheel, including storage in/out η and square of driveline η.

Sensitivity tests confirm wide flexibility

1. Hybridizing the 635-kg Ultralite yields ~1,2–2,1 l/100 km.

- **With η = 0,30 engine, 0,9 driveline, 0,7 regeneration, 2,07 l/100 km = 114 mi/gal; with η = 0,50 engine, 1,24 l/100 km = 190 mi/gal.**

2. Performance remains impressive even with 300-kg payloads.

• Conservativa + 300 kg	2,70 l/100 km	87 mi/gal
• Gaia + 300 kg	1,82 l/100 km	129 mi/gal
• Ultima + 300 kg	0,74 l/100 km	318 mi/gal
• Imagina + 300 kg	0,45 l/100 km	523 mi/gal

3. Ultima-class performance can come by many reasonable routes.

- **With η = 0,50 powerplant (good small Diesel) and M = 635 kg = GM Ultralite, Ultima yields 0,79 l/100 km = 298 mi/gal.**
- **At Ultima's original 536-kg test mass, η = 0,30 powerplant (ordinary petrol engine) yields 1,04 l/100 km = 225 mi/gal.**
- **Thus neither 400-kg curb mass nor η = 0,50 powerplant is essential.**
- **Thus the ~0,6–1,6 l/100 km performance domain leaves both technological flexibility and an appropriately wide safety margin.**

Conclusion: ~10× efficiency gains now feasible

- A 4-passenger ultralight hybrid can be an order of magnitude more efficient than today's production platforms if it combines the best demonstrated levels of powerplant and regeneration efficiency, mass, and rolling resistance, plus
  - *either* proper credit for the efficiency of a modern switched reluctance driveline (a well-demonstrated technology)
  - *or* C_DA one-fifth below the best demonstrated big-car levels.
- Gaia uses conservative accessory loads and engine, driveline, and regeneration efficiencies.
- The high levels of efficiency claimed, therefore, appear quite robust under aggressive but realistic assumptions.
- However, the *best* combinations of parameters for each segment require extensive analysis, experiment, and test-marketing.

1991 concept car illustrates ultralight strategy

General Motors conceived in IV.91, road-tested in XII.91, and showed in I.92 a 4-seat concept car, called the Ultralite, that:

- took 50 people, $4–6M (~8 h of GM's N. Amer. losses), & 100 d to make
- 635-kg curb mass including 4 airbags, 56% below typical
- 6-piece, 191-kg (unoptimized) carbon-fibre/epoxy composite body
- roomy inside (Chevrolet Corsica), tiny outside (Mazda Miata)
- top speed 218 km/h, accelerates 0–100 km/h in 8 s (like Mustang)
- $C_D = 0{,}192$, $A = 1{,}71$ m^2, so C_DA only 43% of the U.S. norm
- twice as efficient as the average new U.S. car: 5,22 l/100 km city, 2,90 highway, 3,85 composite (62 mi/USgal)
- cruises at 81 km/h and 2,35 l/100 km on 3,2 wheel kW (Audi 100–71%)
- Lisbon to Moscow or New York to Los Angeles on ~110 l of petrol
- *not* hybridized: rather, a conventional 1,5-l, 2-stroke, 3-cylinder IC engine (in-line direct-injection stratified-charge, 83 kW, 79 kg) in removable rear 'pod' with conventional Saturn automatic 4-speed transaxle
- should be very crashworthy and meet ULEV emission standard
- not yet optimized (mass, engine,...) nor engineered for production

Ultralights can be affordable

Carbon fibre in X.94 cost ~$18/kg, 20× more than steel; 12× is expected XII.95. But what matters is cost per *car*, not per kg:

- Carbon fibre is stiffer and stronger than steel but 3/4 lighter, so 2–3× fewer kg are needed. In many uses, other and cheaper fibres are as good or better (glass, aramid,... offer better elongation and toughness).
- Of the cost of a typical steel car part, only ~15% buys steel; the other 85% pays for its shaping and finishing. But 'net-shape' composites emerge from the mould virtually ready-to-use, in complex, sleek forms.
- Composites' mouldability into large, complex units can cut parts count by ~100×: the basic body can have not ~300–400 but only ~2–6 parts.
- Those few light, easily handled parts can fit precisely together (tolerance down to a few μm) with ~90% less assembly labour and space.
- Coated-epoxy moulding dies cost ~50–90% less per copy than steel dies: fewer parts, fewer dies per part, and cheaper materials and fabrication.
- Composite colour-moulding could eliminate painting—the hardest and dirtiest automaking step, often half of steel body parts' total cost.
- Collectively, these advantages offset (or more) higher fibre cost/kg.

Manufacturing and sales would be transformed

- Ultralights are not just another kind of car but a whole new culture—as different as fax is from telex or computers from typewriters.
- Tooling for a steel car takes a thousand engineers about two years. But epoxy tooling's short life and very quick fabrication supports fast cycles, short time-to-market, continuous improvement, small production runs, and strong product differentiation—a striking strategic advantage.
- Production time is probably less per car: moulding is slow and parallel, not fast and serial, but composites need far less assembly and rework.
- Personal-computer analogy: as cutting-edge design integration turns into standard recipes, clonemakers can undertake local assembly using commodity elements from Intel, Seagate, Microsoft,.... Will hypercars' powerplants, motors, storage devices,... be so very different?
- As with PCs, production with the cheap tooling could be small and local.
- Just-in-time, zero-inventory manufacturing-to-order could greatly reduce today's ~50+% markup, so even if hypercars cost more to *produce* (unlikely), they could still be profitably *delivered* at a lower price.
- Their radical simplification and exceptional inherent reliability may also permit onsite maintenance, just as with mail-order PCs today.

Ultralight can be ultrasafe

Design and materials are far more important than mass. The structures and restraints that protect people weigh little. Also:

- short stops, fast acceleration, nimble handling, superb traction/braking
- ultrastrong energy-absorbing materials (oriented-C-fibre monocoque,...)
- special composite structures developed for aerospace (buckling members, breakaway elements, filament-wound cruciform members, impact-belt circumferential hollow beams, cones,...) absorb ~3× more energy/kg than metal: *e.g.*, three <400-g C-fibre conical shells can smoothly absorb the entire crash energy of a 600-kg car hitting a barrier at 40 km/h.
- less sophisticated composite cars have crash-tested very convincingly
- Indy 500 composite-car drivers limp away from 370 km/h crashes
- strong, bouncy car body can be designed to be launched not mashed
- design and materials prevent intrusion into passenger compartment
- much easier/faster/safer post-accident extrication than from steel
- mass decoupled from size, so wide track, long wheelbase and ridedown
- better visibility, quieter (hence less driver fatigue)
- mechanically more reliable, graceful failure, preventive diagnostics

Ultralight hybrids can be ~100× cleaner

Four effects multiply to make hypercars ~10^{2-3}× less polluting:

- ~10–25× less engine displacement (~10-kW engine sized to tiny average load) slashes all emissions (though not linearly for NO_x)
- for a given platform, operating the engine in a smaller map—with idle-off, regenerative braking, and no 'command enrichment'—cuts small engines' emissions per litre by a lot (~6×?)
- further reductions, plausibly ≥2×, if engine is emission-optimized, especially for near-single-point operation (series hybrid)
- cleaner fuels are convenient (CH_4, H_2,...), saving another ~2–∞×

These nearly independent effects multiply: 10–25 × 6 × 2 × 2 = ~240–600× (much better w/special fuels or with fuel cells): good ultralight hybrids are cleaner *in* Los Angeles than battery-electrics! Therefore 'zero'- (elsewhere-) emission rules should and probably will be revised to allow cleaner hybrids ('virtual ZEVs').

Cultural barriers in the car industry

- changing a diemaking, steel-stamping culture into a moulded-net-shape-materials/electronics/software culture is extremely challenging
- hypercar is more like a computer with wheels than like a car with chips
- systems integrators with rapid learning, no fear of new materials and products, and agile production may do better than automakers
- automakers are imprisoned by sunk costs treated as unamortized assets, as if it were better to write off obsolete capabilities later when they don't have a company than now when they do
- need net-shape presumption with fallback to metal, not the reverse
- determine best ways to manufacture with net-shape materials, then design car to exploit them, not the reverse
- redesign every part from scratch with zero-based mass budget: composites are *not* 'black steel'; if the part looks the same, it won't work
- *must kill your product with better new ones before someone else does*
- incrementalism is a bet-your-company choice (hope none of your competitors is faster); but leapfrogging on a risk-managed trajectory, first to ultralights and then to ultralight hybrids, lets you feel sorry for your former competitors—*if and only if you do it first*

Institutional barriers in the marketplace

- world-market oil will probably keep getting cheaper for decades even without hypercars, much more so with them (1 nega-OPEC)
- high petrol taxes cut driving moderately but car l/100 km little
- fortunately, astronomical fuel taxes are not the only option:
  - standards made U.S. new cars as efficient as Europe's and Japan's (or more so) despite fuel prices ~2–5× lower, and can be further improved
  - but standards can be gamed and are static (no incentive to do better)
  - 'feebates' look more dynamic: when you buy a new car,
    - you pay a fee or get a rebate (which, how big depends on efficiency)
    - each year, the fees pay for the rebates (revenue-neutral)
    - the rebate for buying an efficient car can depend on the *difference* in efficiency between the new car you buy and the old car you scrap
    - 'accelerated scrappage' rapidly improves fleet efficiency & emissions
- start thinking now, urgently, about huge structural & job shifts
- the car market is being transformed anyway; hypercars will accelerate this; a hardship or a lucrative opportunity?

Tank conversions *vs.* motorized butterflies

If you hybridize a heavy production platform in the hope of lightening it later...

- severe specific power requirements, big power switches
- big, heavy, short-lived, expensive buffer storage
- mass compounding drives total mass not down but up
- realistic control algorithm implies >3× engine map, low η
- complexity, mass, and cost often exceed Avcar's

But if instead you start with an IC-engine composite ultralight platform and *then* hybridize it...

- attractive, doubled-efficiency platform is saleable at once
- immediate switch from physical to virtual prototyping and from tool-steel dies to CAD/stereolith/epoxy molding dies
- order-of-magnitude lower product cycle times, assembly labor & space, and tooling costs—prompt, decisive lead
- peak power requirements become manageable (~60 kW)
- buffer storage *needs* only ~0.5 kWh; mass falls to ~50 kg (NiMH), then ~10–20 kg (C-fiber flywheel, ultracapacitor)
- battery buffers last, running at ~20% depth-of-discharge*
- series-hybrid engine map collapses to a point (or nearly so)
- insensitive to cost, W-h/kg, & W/kg of powerplants & fuels
- mass decompounding accelerates with radical simplification as more and more systems and components disappear
- packaging efficiency and aerodynamics improve further
- ~400–500-kg curb mass becomes feasible for family sedans
- platform production cost starts to look very attractive

*w/2.5 kW-h @ hybrid-optimized 50 W-h/kg NiMH

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We also need negakilometres and negacars

- Hypercars can't solve the basic problem of too much driving by too many people in too many cars, and may well make it worse.
- Even with 1-l/100-km, clean, recyclable, renewably fueled cars, a milliard Chinese or 8 million Los Angelenos driving them still wouldn't work: we wouldn't run out of oil or air, but we'd surely run out of roads and patience. Avoiding the constraint *du jour* requires not just better cars but also less automobility:
  - end-use/least-cost strategy (the end-use is *access* not mobility)
  - full and fair competition between all modes of access
  - economic *glasnost*—prices that tell the truth
  - transport *perestroika*—not centrally planned socialism for cars and free markets for all others, but a truly level playing-field
  - innovative policy instruments: *e.g.*, congestion pricing, parking feebates, commuting-efficient mortgages, advanced land-use planning, pay-at-the-pump car insurance, and making 'nega-km' markets (how much is it worth paying people to stay off the roads? probably a lot...)
  - is this trip necessary? what kind of life and community do we want?

Conclusions about hypercars

- attack platform physics, not driveline; radical simplification
- ~5–20× efficiency gains are feasible by many available methods, though some near-commercial technologies are needed to reach the top end
- smaller but still major improvements in vans, heavy lorries,...
- further technical developments (best ways to configure, propel, manufacture, recycle, test, mend,...) are a need but not a barrier
- hypercars offer superior safety, emissions,..., probably affordability
- people will ultimately buy them because they're better, not to save fuel
- highly compatible with abundant/renewable liquid and gaseous fuels
- not clear who will do it best—unique market entry/exit opportunities
- leapfrog strategy is a competitive and public-policy imperative
  - do it first before it's done to you
  - potential for major economic disruption if bungled or ignored
- exhilaration and terror are both appropriate reactions; we can choose
- strong case for thoughtful policy intervention to smooth the transition
- requires strong parallel emphasis on comprehensive transport reform
- one of the greatest adventures in industrial history: ready or not, here it comes!

Advanced Ultralight Hybrids:
Necessity and Practicality of a Leapfrog

Remarks to the Vice President's Automotive Technology Symposium #3
Structural Materials Challenges for the Next Generation Vehicle

U.S. Department of Commerce, Washington, D.C.
22–23 February 1995

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Popular, semitechnical, and technical backup publications are available. Please request publications list.

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Whatever exists is possible: examples of fuel economy

parameter→	C_D	A	M_{curb}	r_0	$E_{acces.}$ index	η_{engine}	$\eta_{driveline}$	η_{regen}	l/100 km	mi/gal
units→ *platform*↓	–	m^2	kg	–	1990 Avcar ≡ 1.0	fuel to output shaft	output shaft to wheels	wheel to wheel	EPA rating, 55/45 city/hwy., M_{curb} + 136 kg	
Tested concept cars										
GM Ultralite 1991	0.19	1.71	635	0.007	?	?	?	0	3.79	62
ESORO H301 1994	0.23[a]	1.8	670[b]	0.007	?	?	?	?	~2.83[c], ~1.68[d]	~83[c], ~140[d]
Calculated variants *(RMI approximation using Rohde & Schilke parametric model, SAE P-91)*										
Ultralite with hybrid	0.19	1.71	681[e]	0.007	0.50	0.30	0.90	0.60	1.97	119
H301 with series hybrid	0.23	1.8	457[bf]	0.007	0.50	0.30	0.90	0.60	1.87	126

a) Street measurement updated I.95; wind-tunnel is 0.19. **b)** After removing excess resin estimated by builder at ~30 kg, but including 230 kg of batteries in range-extender parallel design for 120-km combustion-free range (data updated I.95). **c)** *If* all electricity were made onboard @ η = 0.30, the Swiss urban/highway mix would be 2.83 l/100 km = 83 mpg. **d)** Calculated from (6 kWh grid electricity + 1 l gasoline)/100 km for typical Swiss city/highway mix, using conventional 8.78 (Bosch) kWh/l delivered- (not primary-)energy equivalence. Measured performance: hybrid-mode 2.94 l/100 km @ EU 90 km/h; electric-mode 10 kWh_{DC}/100 km urban, 7.44 in typical Swiss urban/highway mix. **e)** Relatively heavy design with no body optimization or mass decompounding; 50-kg NiMH buffer. **f)** *If* fuel were converted onboard to electricity @ η = 0.30. Mass = 670 kg[b] incl. 16-kW engine – 230 kg batteries + 50 kg buffer batteries + 16 kg generator/controller – 49 kg mass decompounding @ 30%.

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Does the fat pupa shed weight 1 mg at a time—or crawl out, spread its wings, and fly away?

Builder	Seats	Materials	Body-in-white mass (kg) with closures... excluded	Body-in-white mass (kg) with closures... included	Curb mass (kg)
Avcar, ~1994	4–5	Steel	~275	~372	~1,470
Advanced unibody est.	4–5	Steel	~195–220	—	~1,363–1,388[a]
Ford AIV Taurus	4–5	Al, etc.	148	198	1,269[a]
IBIS Assocs. est., 1994	4–5	E-glass, etc.	236	—	1,218
PNGV target, 1994	4–5	Carbon, etc.	138	186 (–50%)	882 (–40%)
GM Ultralite, 1991	4	Carbon, etc.	~140	191	635
RMI costing est., I.1995	4–5	Carbon, etc.	125–133	150	~530
ESORO H301, 1994 (I.95 upd)	4	75% glass, 5% C, 20% Aramid	72	120[b]	~500[c]
RMI bench-mark, I.1995	4–5	Carbon, etc.	—	100 or 140[d]	482 near-, 410 midterm
WWU VRI Viking 23, 1994	2+[e]	Carbon, a little Aramid	—	93	864 incl. 314 batts.
Kägi OMEKRON, 1989–90	2	Carbon/Aramid	34	—	490 incl. 260 batts.

a) Assuming no component optimization or mass decompounding. **b)** Excluding ~30 kg excess mass in bumpers and double-hinged doors, as estimated by builder, but including 2 bumpers and 4 composite seats. **c)** If redesigned from a 670-kg[b] range-extender parallel hybrid with 230 kg of batteries to a series hybrid with 50 kg of batteries, assuming no electrical improvements or mass decompounding (though both would be available). d) Includes 29 kg special safety structures, 8 kg hardpoint mounting inserts, and 3 kg elastomeric bumper skins. **e)** A series hybrid not needing this design's batteries, 0.9-l IC engine, CNG tank, etc. could instead use the same structural mass budget to carry 4+ people.

SOURCE: *Hypercars: Materials and Policy Implications*, The Hypercar Center, RMI, 1995

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Are composite bodies affordable?

In I.1995, RMI approximated body-in-white production costs by combining IBIS Associates' steel-unibody (and some composite-monocoque) input data with a relatively heavy RMI mass budget and with representative production costs provided by a leading composite-structures manufacturer

- **for a thoroughly analyzed, proven production process**
- **to make a major (~30-kg) composite-monocoque part**
- **with moderate complexity and no Class A surfaces**
- **assuming tooling is discarded every 30k units**
- **with *no* capital economies of scaling up to 200 k units/y**
- **with semiautomation that could be substantially increased (RMI assumed 0–25% further reductions in labor cost).**

RMI assumed composites with 70% (vol.) fiber, ranging

- **from one-half to zero E-glass, the rest carbon**
- **from all-epoxy to all-urethane or equiv. resins ($1–2/lb)**
- **at carbon creel prices from $6.6/kg (Akzo-Nobel quotation for next tranche) to $12/kg (expected end-1995, *vs.* ~$15/kg X.94), though a hypercar industry's volume implies <$2/kg**
- **for an open-aperture BIW mass of 125–133 kg,**
- **with *assembly* costs 10-20% those of a steel unibody (because the entire BIW is integrated into just a few parts).**

These assumptions yielded BIW costs of $1,100–2,080 (1994 $), with midcase $1,440—*vs.* $1,500 for the high-volume IBIS steel-unibody BIW. Carbon's labor intensity was 2× higher, its capital intensity 5× lower. Carbon's cost advantage increases for *finished* auto bodies, since lay-in-the-mold color is cheaper than painting. Further research in spring 1995 will greatly refine this preliminary analysis. PS/2E c:\work\hcbtwecs.doc WfW6.0 ABL 17.II.95

SOURCE: *Hypercars: Materials and Policy Implications*, The Hypercar Center, RMI, 1995

What makes hypercars safe

Principles

- Design and materials are more important than mass.
- Less mass makes the car less dangerous to others.
- Crash-protection structures and materials weigh little.

Implementation

Precrash avoidance

- nimbler handling, shorter stops, more stable dynamics
- wide stance, long wheelbase, reduced risk of hydroplaning
- all-time all-wheel antiskid braking and antislip traction
- better visibility, less noise, greater driver alertness

Crash energy management & trauma reduction

- Crush-cone array absorbing >100 kJ/kg
- Impact beam around passengers (>0.5 MN, 10–15 kg)
- Crush structures and ridedown distance (lots of room—car's size decoupled from mass, tiny driveline components)
- Pretensioning seatbelts, force limiters at anchor points, strong but resilient seats, ample head support
- Frontal and side-impact airbags for all, foam bolsters
- Collapsing steering column, breakaway pedals, etc.
- Shell fracture management (no intruding edges)

Postcrash recovery

- automatic 911 call on airbag deployment
- master electric shutoff, virtually leakproof fuel tank
- far easier access to / egress from passenger compartment
- much faster and safer extrication, by design

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Designing an elegantly frugal car that performs

Frog gets smarter but doesn't leap	*Leapfrog! New pond!*
Component-by-component	Whole platform
Incremental changes to tradition	Zero-based, ground-up, clean-slate
Design from engine toward wheels, emphasizing driveline refinement	Design starts with occupants and road loads, emphasizing platform physics
Assume steel	Assume advanced composites*
Accrete mass	Eliminate and decompound mass
Largely ignore synergies	Design to capture synergies
Dis-integrate and specialize	Re-integrate; master details holistically
Huge design group, relay race	Small design group, team play
Institutionalized timidity	Skunkworks-style boldness
Baroque complexity	Radical simplicity**
Complex, therefore difficult	Simple, therefore difficult

"...[A]dvanced composite material development is outside our core technology, so we do not have manpower or facilities assigned to that development area."

—Senior official, major U.S. automaker, October 1994

***"Everything should be made as simple as possible, but not simpler."* —Einstein

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Selected Publications

RMI's latest hypercar (formerly called supercar) publications include (please add 20% shipping in N. America):

- *"Reinventing the Wheels": January 1995 *Atlantic Monthly* feature nontechnically explaining the basic concepts and implications (#T94-29, 10 pp., $5)—recommended as the best place for most readers to start
- *"Hypercars: Answers To Frequently Asked Questions," Jan. 1995 (#T95-1, 6 pp., $3), supplements #T94-29
- *"Hypercars and Today's Cars: An Illustrated Comparison," Feb. 1995 (#T95-6, 2 pp., $1.50)
- "The Hypercar Packet," T95-1 & -6 plus energy diagram and several popular articles (#T95-16, 16 pp., $5)
- "Hypercars: The Next Industrial Revolution": semitech. general storyboard, SI units (#T95-19, 20 pp., $10)
- "Policy Implications of Supercars": semitechnical August 1993 storyboard (#T93-21, 8 pp., $4)
- "'Zero Emission' Vehicles Aren't": Letter in *The Electricity Journal*, June 1993 (#U93-17, 2 pp., $1.50)
- "Electrotechnologies": Followup to U93-17, *Electricity Journal*, January 1994 (#U94-10, 1 p., $1.50)
- "Advanced Ultralight Hybrids: Necessity and Practicality of a Leapfrog," technical graphics from address to Vice President's PNGV symposium on structural materials, 22 February 1995, SI units (#T95-18, 10 pp., $4)
- Front matter of *Hypercars: Materials and Policy Implications*, 31 Jan. 1995 (#T95-17, 15 pp., $8)
- *Hypercars: Materials and Policy Implications*, proprietary technical analysis, August 1995, ~300 pp, $10,000. to the industry (discounts available to qualifying nonprofit organizations); includes #T95-27, -34, -35
- "Vehicle Design Strategies to Meet and Exceed PNGV Goals," technical parametric design analysis, SAE 951906, June 1995 (#T95-27, 43 pp., $10)
- "Address to 1993 Asilomar Conf. on Strategies for Sustainable Transportation" (#T95-30, 11 pp., $6)
- "Hypercar: A Threat to the Oil Industry?," *Oil & Gas J.* reprint w/background, August 1995 (#T95-32, 6 pp., $3)
- "Amory Lovins: Moving Toward a New System," semitechnical interview from Scott Cronk's Society of Automotive Engineers (SAE) book *Building the E-motive Industry* (#T95-33, 7 p., $4)
- "Supercars: Advanced Ultralight Hybrid Vehicles," *Wiley Encyclopedia of Energy Technology and the Environment* reprint, basic annotated semitechnical primer, SI units, January/June 1995 (#T95-34, 32 pp., $12)
- "Costing the Ultralite in Volume Production: Are Composite Bodies-in-White Affordable?," SAE technical paper in press, August 1995 (#T95-35, 14 pp., $10)

In addition, during 1995:

- The Hypercar Center will publish a semitechnical introduction to hypercar safety;
- *The Washington Post Magazine* is expected to print an article on reducing travel demand (#T95-7, ~3 pp., ~$2);
- substantial broadcasting and other publications will continue, and a popular book is under consideration.

All new publications are announced in RMI's free *Newsletter*, and many are* or will soon be posted to the Institute's Internet homepages (above). If you are also interested in how RMI's work on hypercars evolved, you may want to read:

- "Advanced Light-Vehicle Concepts": RMI's first effort to assemble the general concept, as lecture notes for a National Academy of Sciences hearing—ideas mostly there but not yet fully synthesized (#T91-20, 15 pp., $7)
- "Supercars: The Coming Light-Vehicle Revolution": the first thorough technical synthesisis of the hypercar concept, from the June 1993 ECEEE symposium in Rungstedgård, Denmark (#T93-10, 34 pp., $8)

Rocky Mountain Institute, founded in 1982, is an independent, nonprofit, nonpartisan resource policy center. Its ~40 staff foster the efficient and sustainable use of resources as a path to global security. RMI has earned a reputation for finding new solutions to old problems, or, better still, avoiding them altogether. The Institute works mainly on energy, water and agriculture, and transportation efficiency "green" real-estate development, local economic development, global security, and their interconnections. RMI is best known for having laid most of the conceptual and technical foundations of the $5-billion-a-year "negawatt" (saved-electricity) industry and invented end-useleast-cost resource analysis.

Amory B. Lovins, 47, cofounded and directs research at RMI and at its Hypercar Center. A consultant experimental physicist educated at Harvard and Oxford, he has received an Oxford MA (by virtue of being a don), six honorary doctorates, a MacArthur Fellowship, and the Nissan, Mitchell, "Alternative Nobel," and Onassis Prizes. He has held a variety of visiting academic chairs; briefed nine heads of state; published 22 books and several hundred papers; lectured and broadcast extensively; served on the Department of Energy's senior advisory board; and consulted for scores of utilities, industries, and governments worldwide, mainly on advanced electric efficiency and more recently on new automotive concepts. *The Wall Street Journal*'s Centennial Issue named him among 28 people in the world most likely to change the course of business in the 1990s.

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