Advanced Ultralight Hybrids: Necessity and Practicality of a Leapfrog

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Structural Materials Challenges for the Next Generation Vehicle

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

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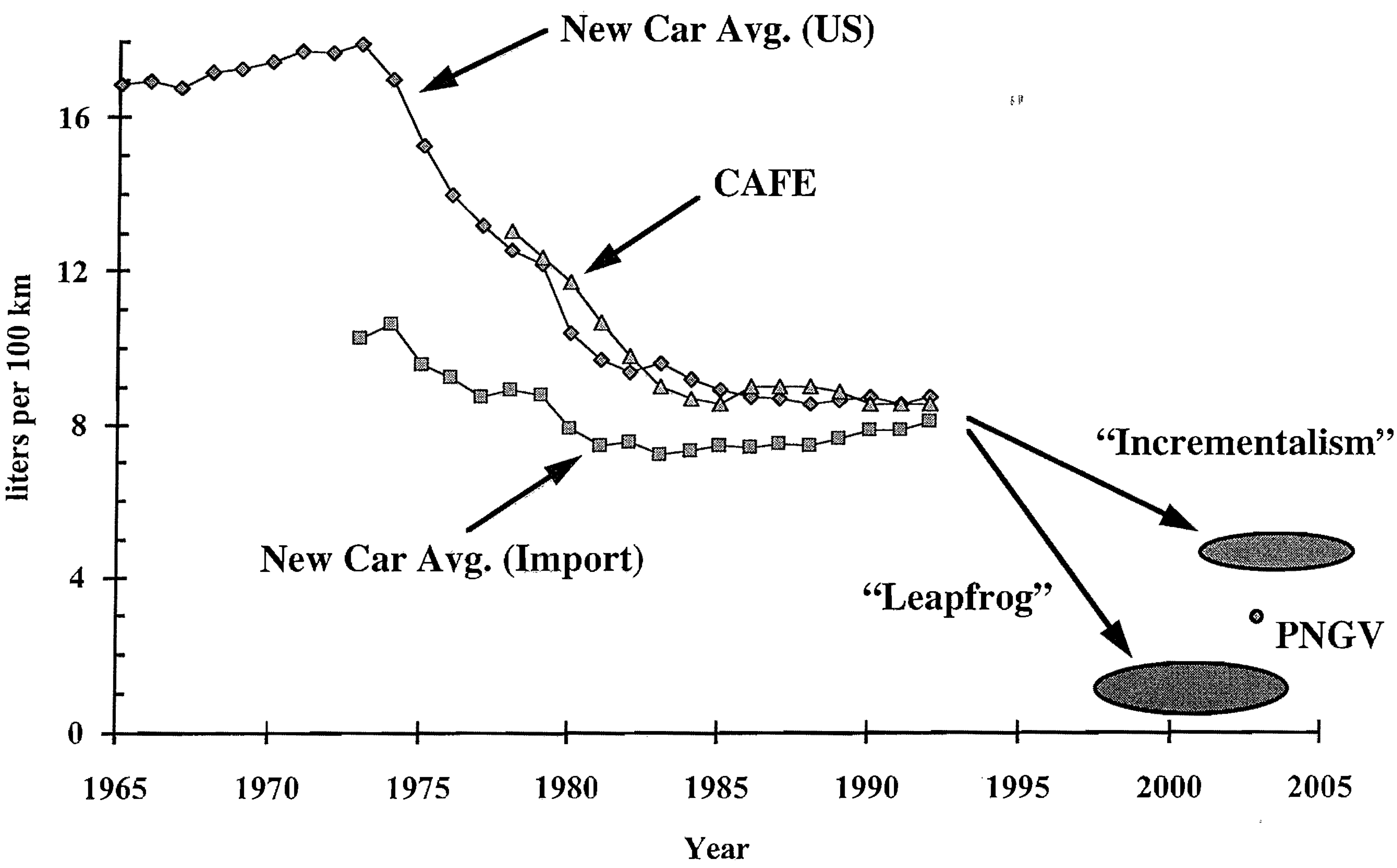
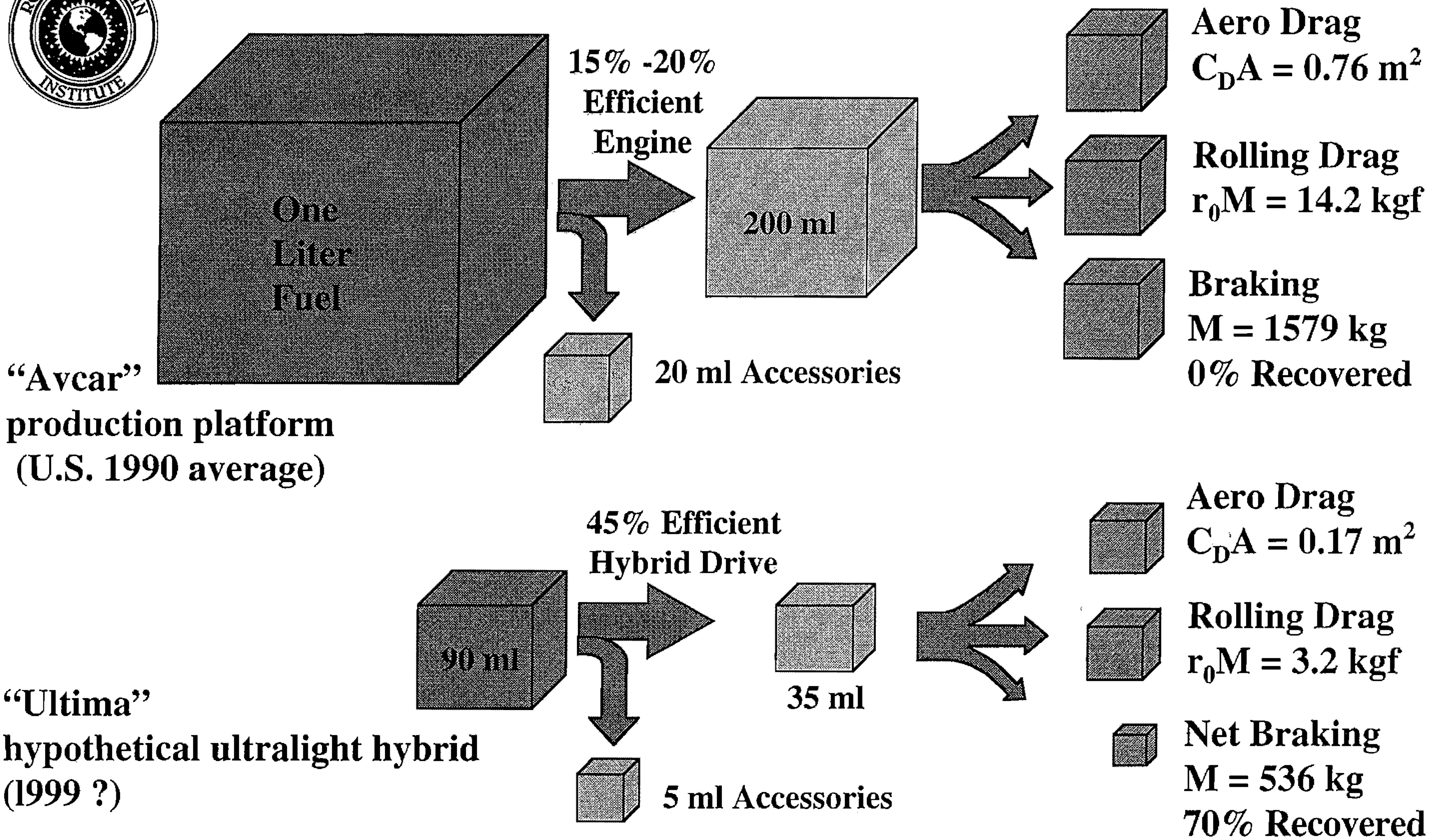
Trend Is Not Destiny ?



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.

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

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 Ultra-lite 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%.

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...		Curb mass (kg)
			excluded	included	
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.

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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

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-use/least-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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