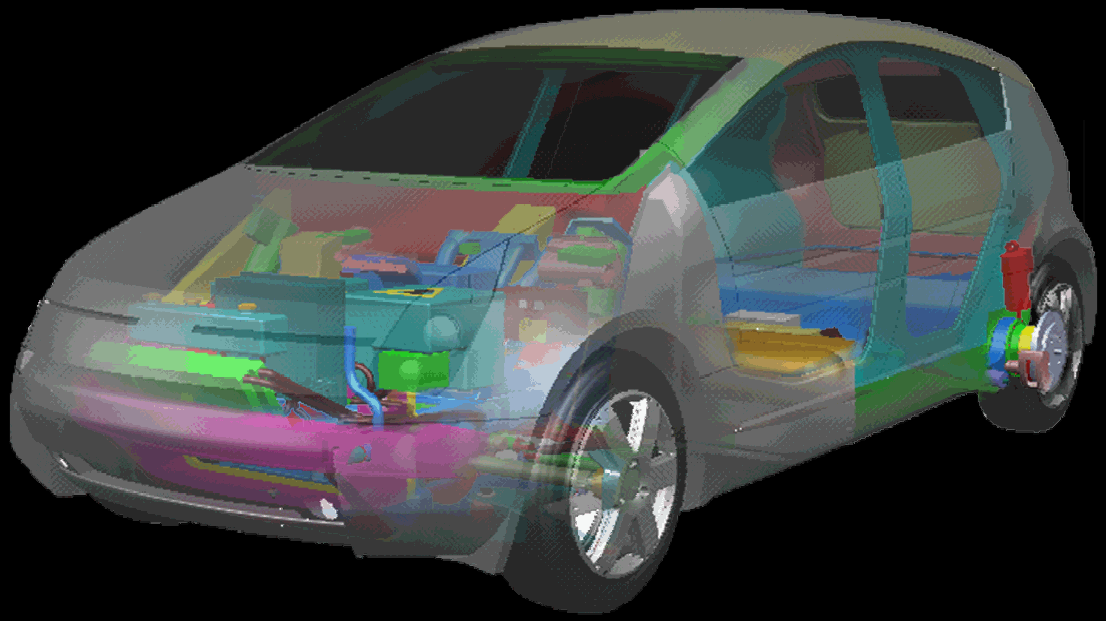
CNO's Naval-Industry R&D Partnership Conference 2003

Ronald Reagan Building, Washington, DC, 5 August 2003

How to Make 'em *Really* Better, Faster, Cheaper: Hypercar® as a Model for Integrative Design Process

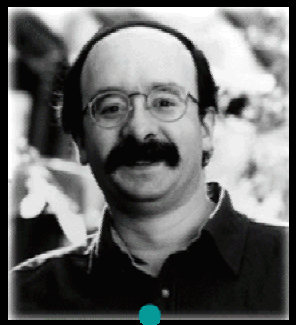


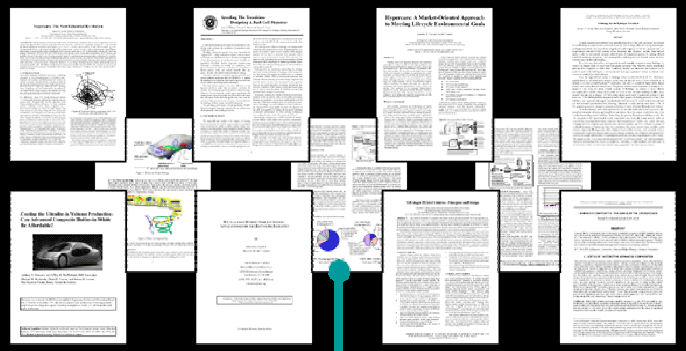
Amory B. Lovins, Chairman of the Board, Hypercar, Inc.
and CEO, Rocky Mountain Institute
www.rmi.org, www.hypercar.com, ablovins@rmi.org

Hypercar, Inc.: 12 years of **vision**

1999 Nissan Prize

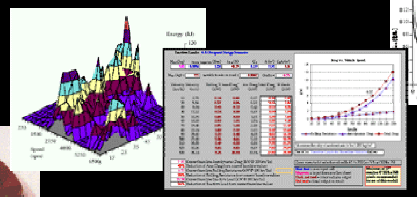
1999 & 2003 World Technology Awards

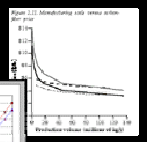


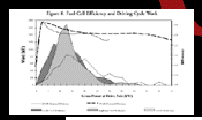


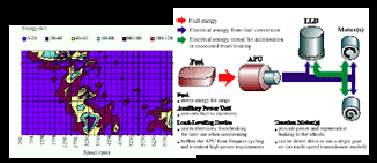
1990 — 1995 — 2000

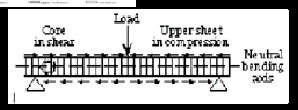
Rocky Mountain Institute → Hypercar Center → Hypercar, Inc.



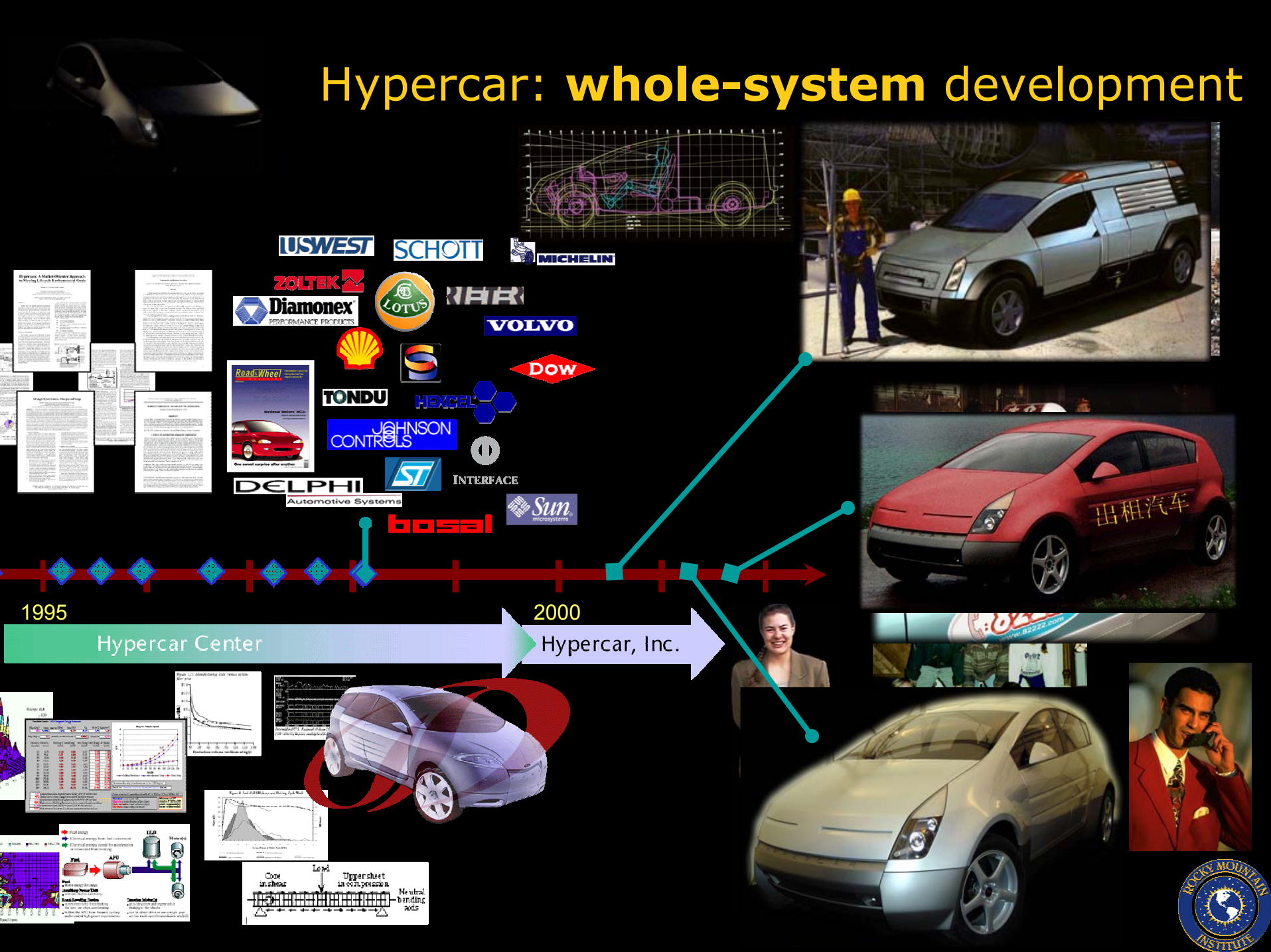








Hypercar: **whole-system** development



Hypercar® concept: brief history

- Invented 1990–91, previewed ’91 (NAS), explored w/GM,…, published ’93 (ECEEE, ISATA, SAE,…)
- Incubated at RMI’s Hypercar Center ($3M — 2/3 grants, 1/3 earned) 1991–99, many profl. publns.
- Published concept extensively ’93–99; ~$10b stimulated ’93–00 by nonexclusive consultancies
- Independent feasibility study by Lotus Engineering (UK) 1998 with 17 industrial partners
- Spun off Hypercar, Inc. 1999 as IP firm to support industry’s transition; raised $9M of private equity
- Concept car designed 2000 with TWR Engineering (UK) and other US and European consultants
- Discussing joint development/licensing w/OEMs
- Currently validating AVACS™ mfg. process

Hypercar, Inc.: supporting the industry's transition

- Mission: be the premier provider of lightweight, efficient solutions that enable automakers to pro-duce sustainable vehicles profitably for everyone
- Reducing weight, at competitive cost, without com-promising other attributes, is a key enabling techno-logy for improving nearly all performance factors
- Independent technology development and engineer-ing services firm with distinctive competence in advanced composite structures and manufacturing
- Not an automaker; powertrain- and fuel-neutral
- Patent-pending "Body-in-black"™ solution promises meeting all requirements competitively at volume
- An internal development illustrates the potential

Show car and a complete virtual design, production-costed and manufacturable

So what about a HyperVee — a *really* lean green machine?

Can Hypercar, Inc.-like thinking yield a transformational ultralight expeditionary tactical land vehicle — *e.g.*, for Special Forces and Marines?

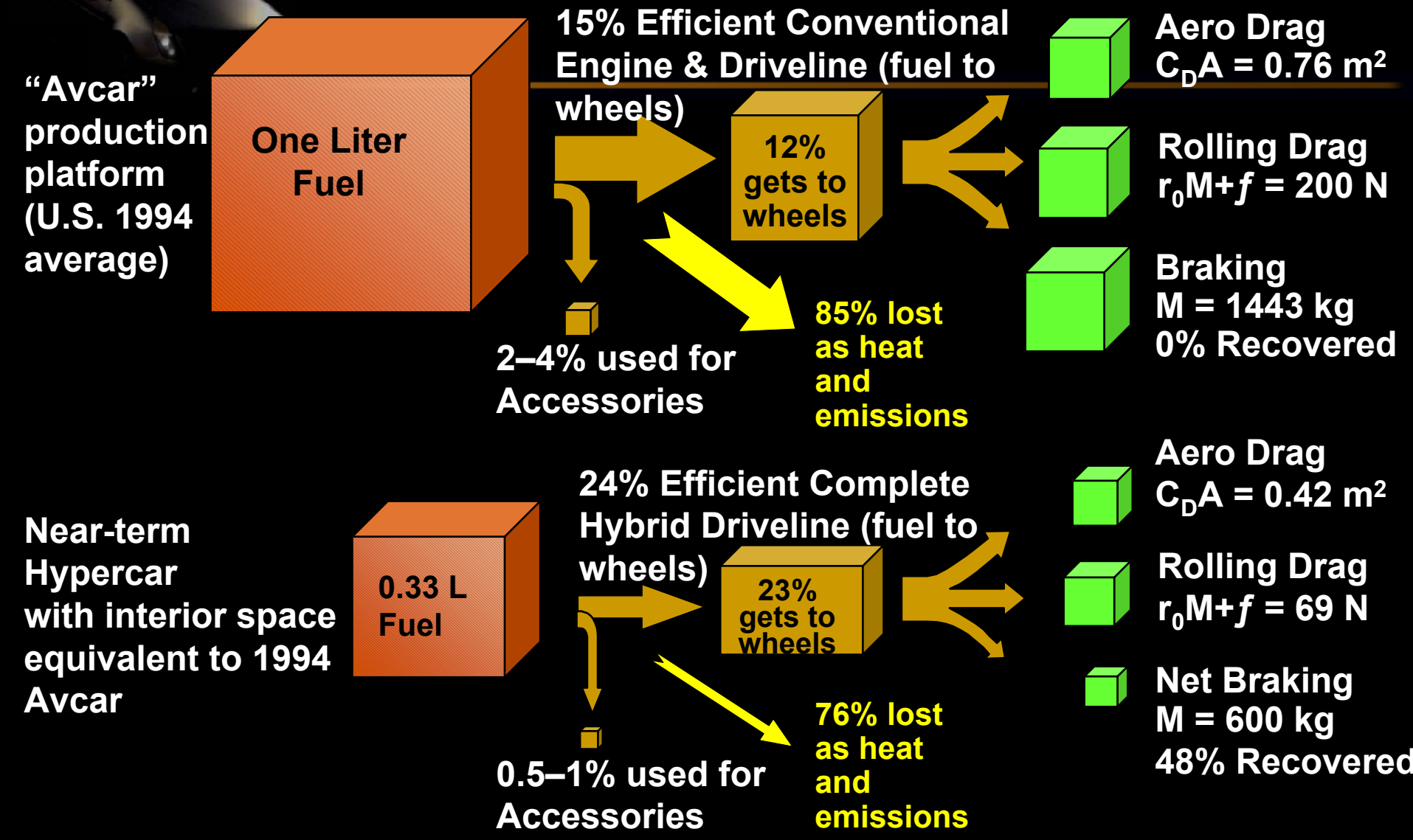
Tactical design considerations for a HyperVee

- For the mission set, what characteristics (airdrop-pability, amphibious capability, radar stealth,…) are most important and most compatible/synergistic?
- Some basic advantages, such as near-zero signa-tures, agility, low sustainment, and low profile, are inherently built-in at no extra weight or cost
- So is small-arms protection; could Velcro on more armor for *e.g.* RPGs (ceramics, light active armor)
- Could be an ultralight but rugged "utility vehicle": standard platform + plug-and-play mission modules
- Could change operations for other platforms, *e.g.* by providing power to serve as APU for idling tanks
- Seek most generic/complementary attribute set

Civilian Hypercar® design: six kô-an (公案)

- Big fuel savings cost less than small fuel savings.
- To leap forward, think backwards.
- By not saving fuel, more fuel is saved.
- To make cars inexpensive, use costly materials.
- To make cars safer, make them much lighter.
- To get the cleanest and most efficient cars, don’t mandate them.

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.

Designing backwards

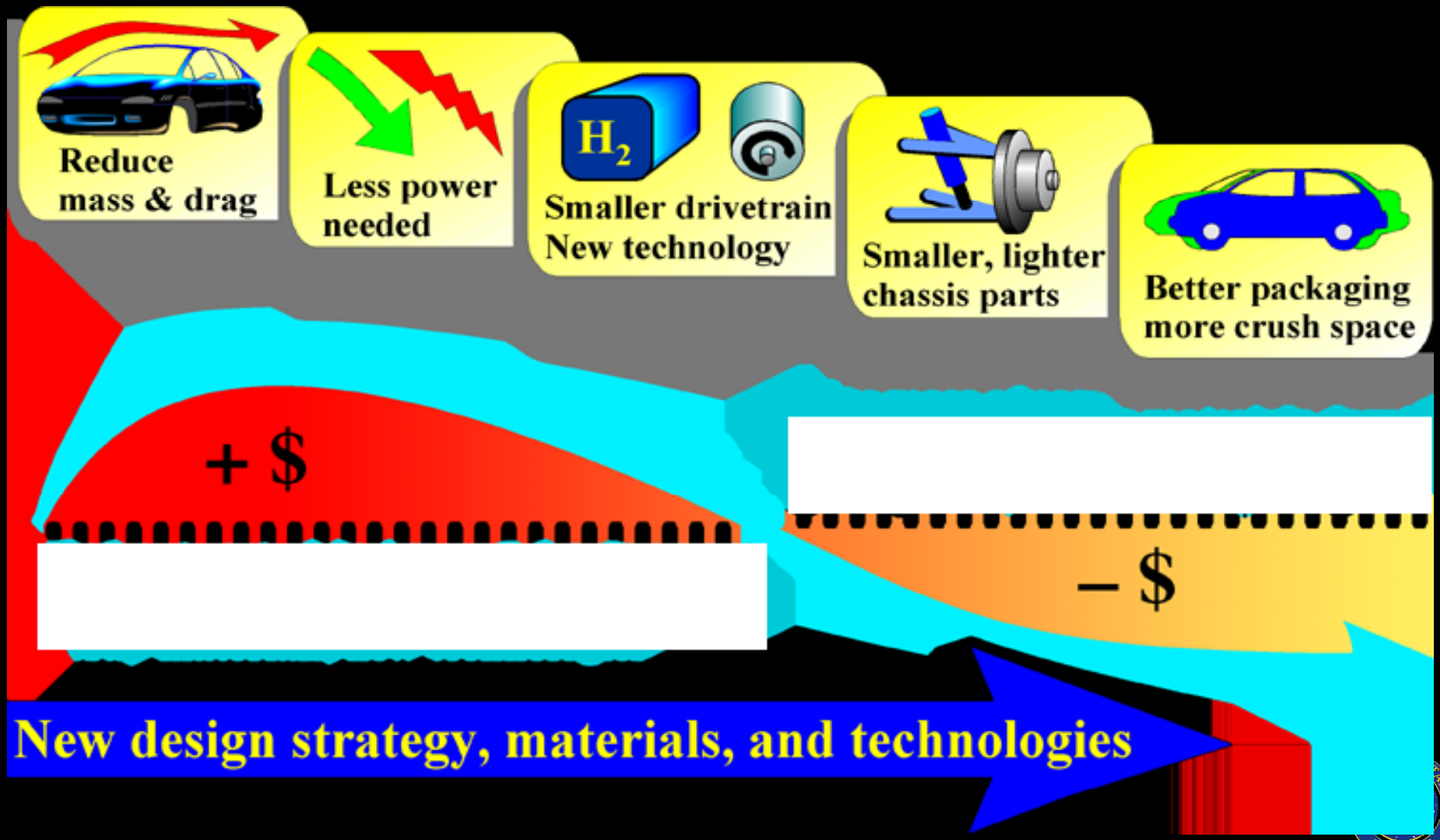
- Conventional design: from fuel to wheels
- ~7 units of fuel are used to deliver 1 unit of energy to the wheels ("compounding losses")
- Since ~85% of the fuel energy is lost in the engine, en route to the wheels, and in accessories, focus on incremental reductions in those losses

- Hypercar® design: from wheels back to fuel
- Radically cut the car's mass and drag *first*
- Each unit of energy saved at the wheels saves ~7 units of fuel up front ("compounding savings")
- This makes tripled efficiency straightforward with a conventional engine-driven hybrid, ≥5× with fuel cells

Saving >80% of fuel…incidentally

- Conventional design: save fuel as specific goal
- Trade off and compro-mise other design goals (size, cost, perform-ance, perhaps safety)
- Rely on government intervention—efficiency standards, gasoline taxes, subsidies, mandates—to induce people to buy those less attractive cars
- Hypercar design: make the car *superior*, yet compar-ably priced, so people will want to buy it (like buying digital media instead of vinyl phonograph records)
- This also happens to save even more fuel
- Ultralight, ultra-low-drag triggers a long series of "virtuous circles"; then hybrid drive can make the car lighter, simpler, cheaper
- Mass savings snowball… nonlinearly

Decompounding mass and com–plexity also decompounds cost



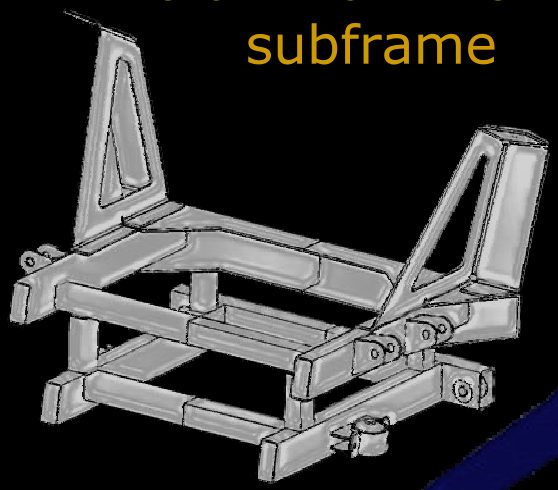
Affordable cars via costly materials

- Conventional design: stamped/welded steel
- Cheap material/kg, but costly to manufacture
- Two years to design & make ~1,000 steel dies
- High capital intensity, breakeven volume, and financial risk per model
- Long product cycle time increases risk
- Uninviting risk/reward profile

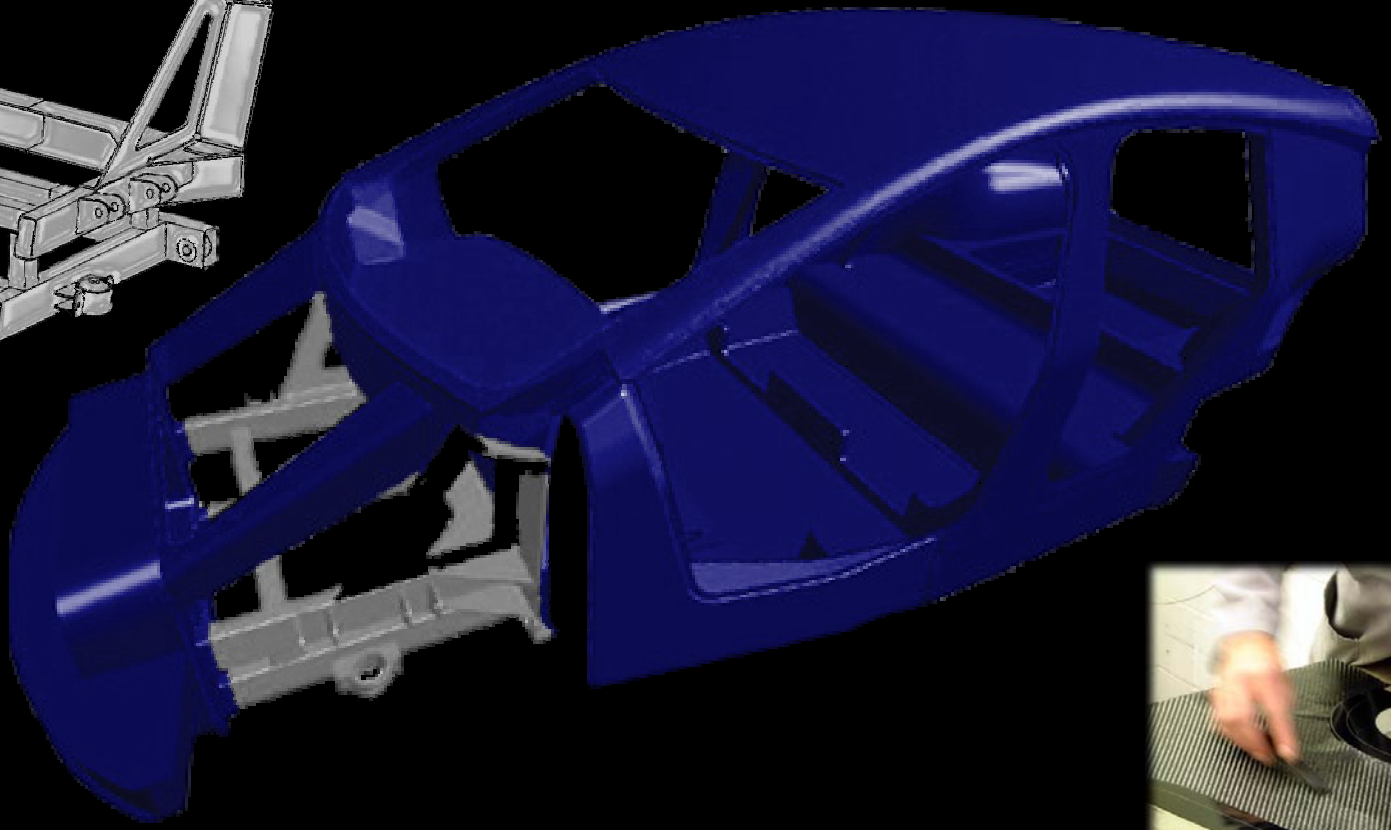
- Hypercar design: molded/ glued advanced composites
- Costly material/kg, but we all buy cars by the car, not by the kg; offset by mfg.
- <20 dies, can be soft tooling
- Self-fixturing assembly
- Many-fold less capital, assembly, parts, ?time
- Small propulsion system
- Very low breakeven volume and risk per model
- Not sumo but aikido

Ultralight autobody materials

aluminum front subframe

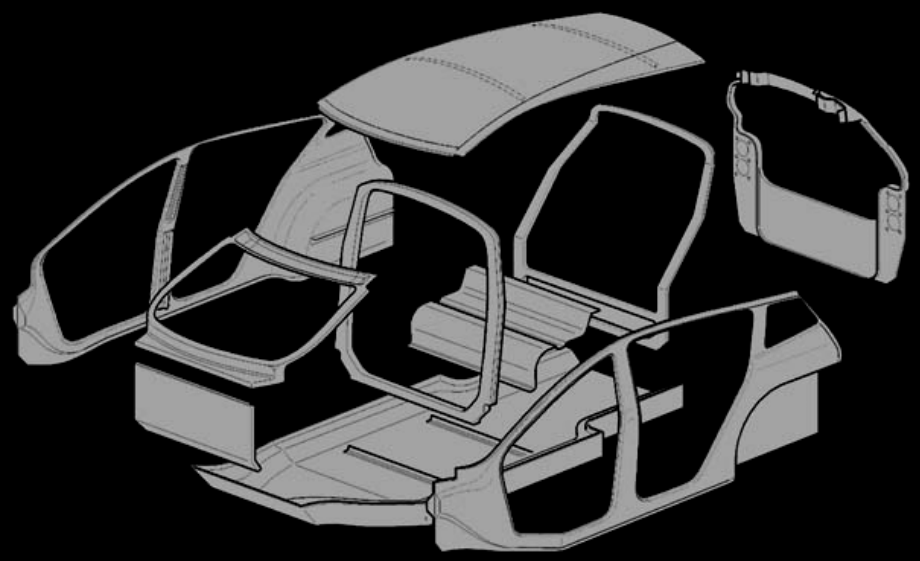


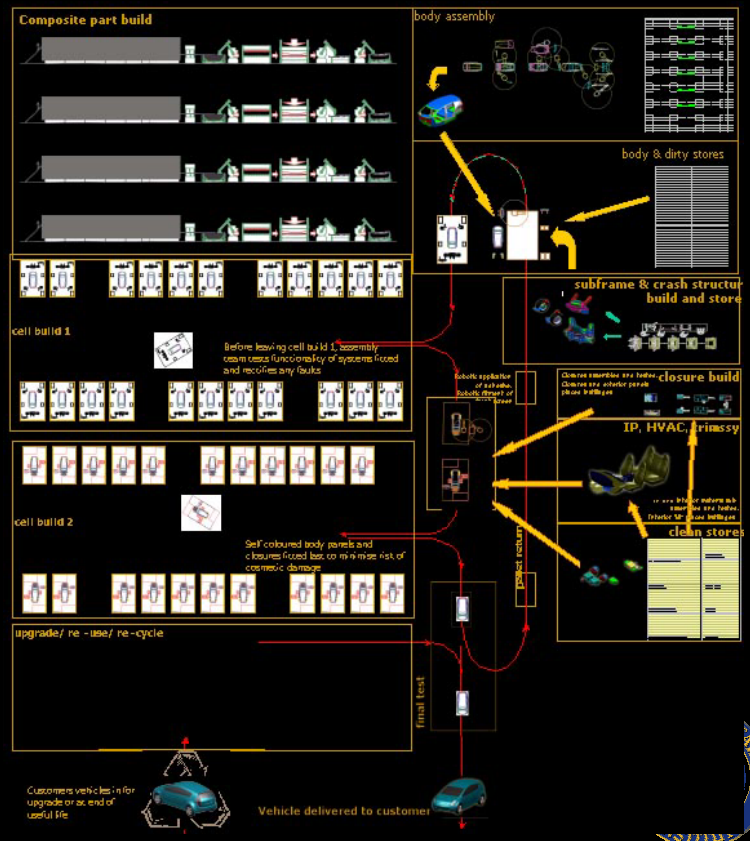
advanced-composite passenger safety cell



Radically simplified manufacturing

- Mass customization
  - *Revolution* designed for 50k/year production volume
  - Integration, modular design, and low-cost assembly
  - Low tooling and equipment cost

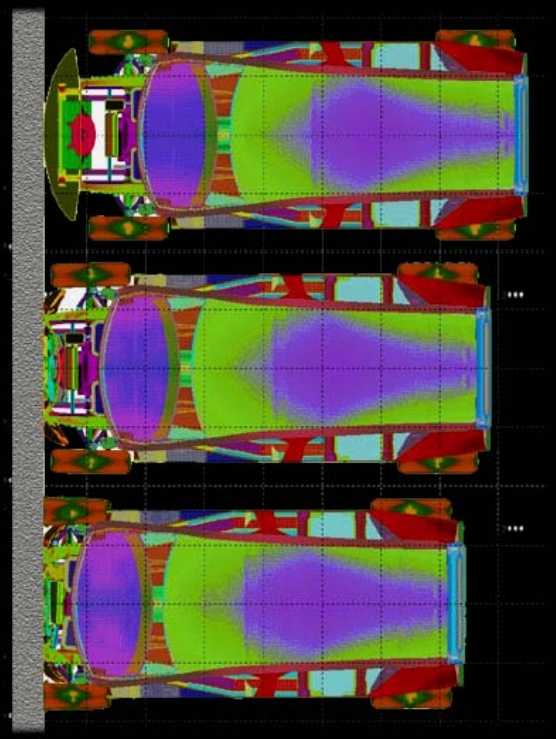


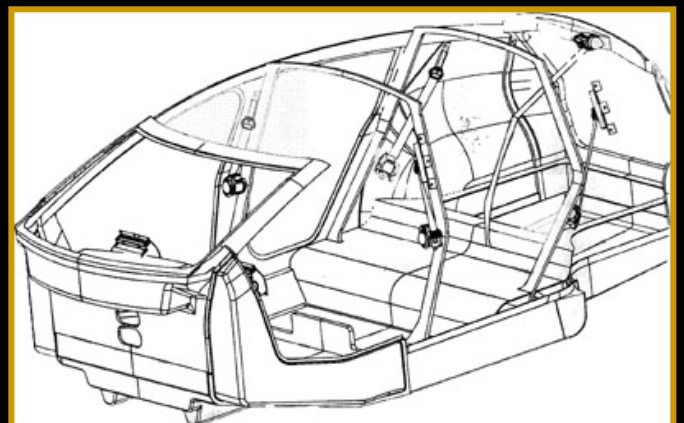


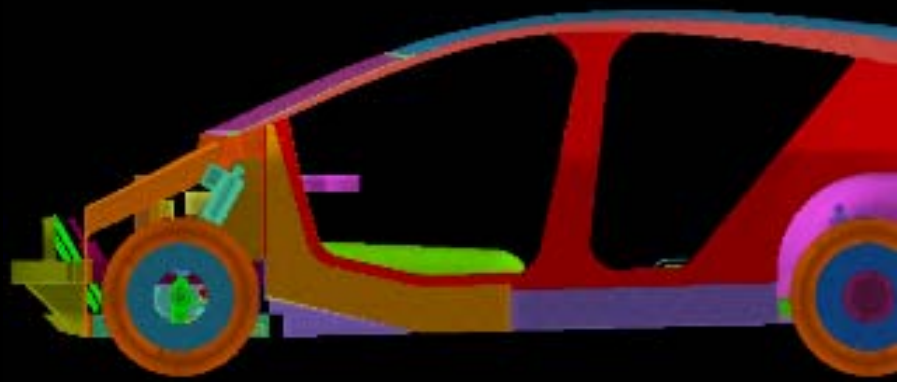
14 major structural parts, no hoists
No body shop, optional paint shop

Ultralight for crashworthiness

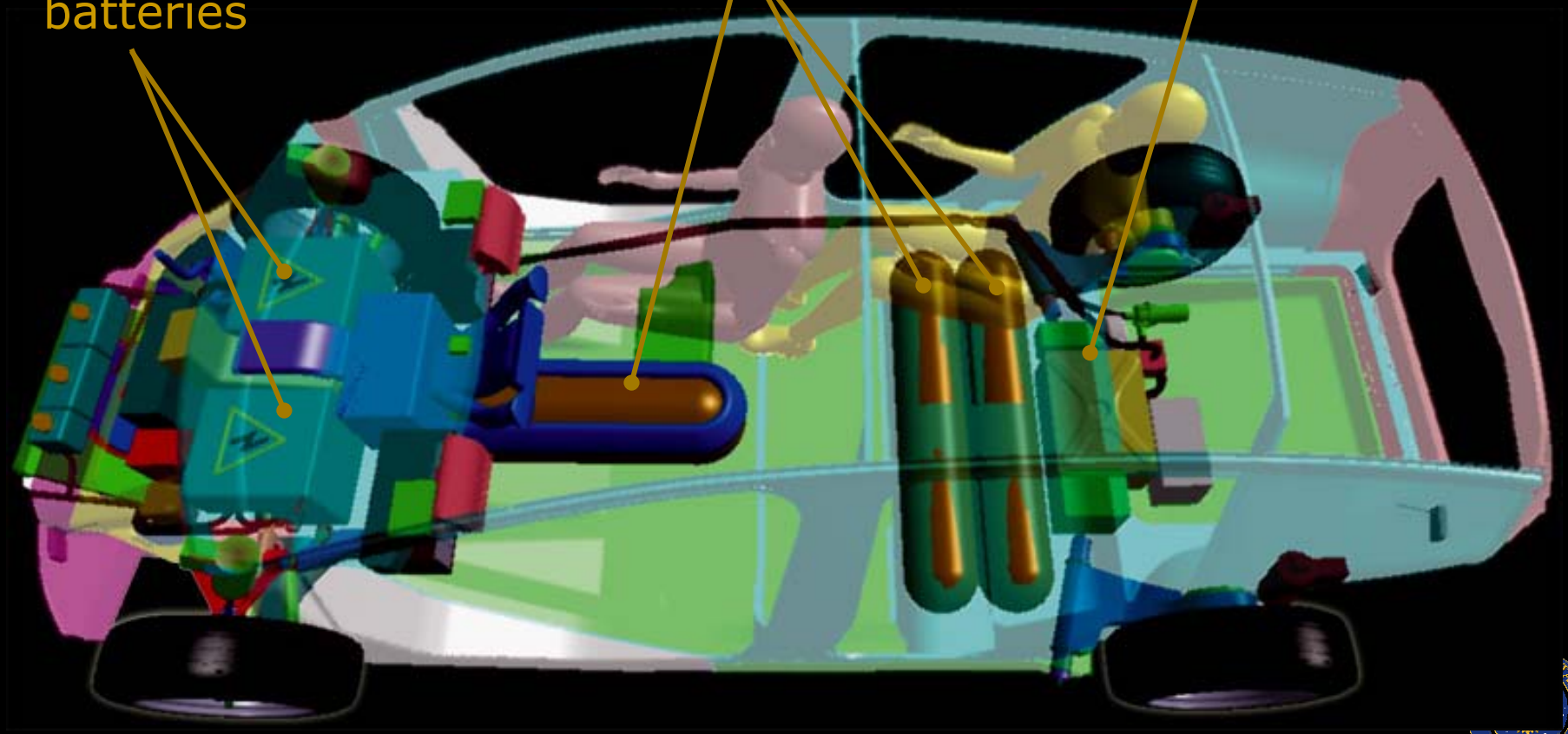
- Carbon composites can absorb 5× as much crash energy per kg as steel (110 kJ/kg), and can do so far more smoothly
- Holistic safety design
- 10 km/h crash: no damage to autobody
- 56 km/h: no damage to passenger cell
- Head-on collision with a vehicle twice its mass, each going 48 km/h, still protects occupants from serious injury







89 km/h on same power as normal a/c, so well suited to direct-hydrogen fuel cells—enabling a rapid, profitable H_2 transition



efficiency **pays**

Vehicle	Fuel-cell power (kW)	Type	Relative output	$ cost premium *	Range (km)
Hypercar *Revolution*	35	hybrid	100%	**N.A.**	530
Toyota *FCHV-4*	90	hybrid	257%	**+ $ 5,500**	250
Ford *Focus FCV*	85	hybrid	243%	**+ $ 5,000**	320
GM *HydroGen III*	94	FC	269%	**+ $ 5,900**	400
Hyundai *Santa Fe FCV*	75	FC	214%	**+ $ 4,000**	400
Honda *FCX-V4*	78	FC	223%	**+ $ 4,300**	300
Jeep *Commander 2*	140	hybrid	400%	**+ $ 10,500**	150

* Department of Energy $100/kW target for 2004, *excluding* other fuel-system & traction components, mass decompounding,…

Rapid, profitable **H_2 transition**
(RMI, NHA paper, April 1999, www.rmi.org)

- Put fuel cells first in buildings for co-/trigen + UPS
  - Fuel with natural-gas reformers (or off-peak electrolyzers)
  - Big market — buildings use 2/3 of U.S. electricity
- Meanwhile introduce H_2-ready Hypercars
  - Fleets (return nightly to the depot for refueling)
  - General market: start with customers who work in or near the buildings that by then have fuel cells
    - Use buildings' hydrogen appliances for refueling
      - Sized for peak building loads that seldom occur
    - Sell kWh and ancillary services to grid when parked
      - Marginal investment in H_2 compression/fueling, grid connection, & more durable fuel-cell stack is modest
    - Earn back much/most of cost of car ownership
      - U.S. full-fleet potential ~5–10 TW, ~6–12× grid cap.

Rapid, profitable H_2 transition (2)

- Meanwhile, hydrogen appliances get cheaper, so put them outside buildings too
  - At filling stations — a much better business than gasoline
    - Use two ubiquitous, competitive retail commodities — CH_4 and el. — and play them off against each other
    - Use just the offpeak distribution capacity for gas and electricity that is already built and paid for
    - Mainly reformers: electrolyzers are favored only at high volume, small unit scale, and cheap offpeak kWh
    - ~10^3 units @ US$6/MBTU gas beat $0.9/gal in $/mi
  - Scaleable, modular, big economies of mass-production
  - As both hydrogen and direct-hydrogen fuel-cell vehicles become widespread, bulk production and central distribu-tion of hydrogen becomes practical and may be justified

Rapid, profitable H_2 transition (3)

- ≥2 proven, cost-effective, climate-safe methods
  - Reform natural gas at the wellhead and reinject the CO_2
    - Reforming (~8% of U.S. gas now) & reinjection are mature
    - Potentially three profit streams: H_2, $+CH_x$, $-C$
    - Strong industry interest (BP, Shell, Statoil), 200-y resource
  - Electrolyze with climate-safe electricity
    - Greatly improves ecs. of renewable electricity, bec. H_2-to-wheels is ~2–3× more efficient than gasoline-to-wheels
      - Even U.S. gasoline ($1.25/gallon) is equivalent at the wheels to $0.09–0.14/kWh electricity with a proton attached to each electron — so run dams in "Hydro-Gen" mode, shipping compressed hydrogen instead of kWh (a value-added product instead of the electron commodity)
      - H_2 storage makes wind/PV power firm and dispatchable
- Probably more: coal, oil, various renewables,...

Hydrogen-ready cars + integrated with buildings = hydrogen transition

- No technological breakthroughs required *(e.g.*, onboard reformers) — just durable and cheaper fuel cells
- Can market fuel-cell cars as soon as durable fuel cells become available, and can do so profitably many years earlier than inefficient vehicles would allow
- Meanwhile, engine or engine-hybrid Hypercar vehicles would impress (*e.g.*, ~3–3.5 L/100 km for a midsize SUV)
- No need for new liquid-fuel infrastructure (methanol, ultrapure gasoline,…) nor for liquid hydrogen
- Integrating mobile and stationary deployment makes the transition profitable at each step (>10%/y real return)
- It doesn't matter whether durable stacks come first (favoring buildings) or cheap stacks (favoring cars); whichever comes first accelerates both markets

More profitable for hydrocarbon owners too? Just try this quiz…

- (H – C) > (H + C)?
- Is the hydrogen worth more without the carbon than with the carbon?
- Is hydrogen plus negacarbon (which someone may pay you *not* to put into the air) worth more than hydrocarbon — even if carbon is worth zero?
- Is a hydrocarbon worth more feeding a refinery or a reformer?
- Should refineries become merchant H_2 plants?

(Left as an exercise for the reader. Then run, do not walk, to the hydrogen economy.)

More hydrogen surprises

- GM thinks U.S. use of natural gas would be *lower* with a miniature-gas-reformer H_2 transition, because gas used to make H_2 would be more than offset by gas saved in power plants, in boilers and furnaces, and in making H_2 for gasoline
- Sandy Thomas (www.h2gen.com) argues that global capital investment in a gas-based H_2 hydrogen fueling infrastructure over the next 40 y would be ~$1 trillion *less* than for gasoline
  - Upstream investments in gas are only ~2/3 as capital-intensive as those in oil, paying for H_2 reforming/delivery with a surplus of ~$600 per fuel-cell car served
  - Converting a filling station to make H_2 costs ~10% as much as building the station, or ~$2^1/_2$% as much as building it and its upstream fuel supply; converting 10–20% costs ~$2–4b
  - Deutsche Shell could convert all German stations in ~2 y

Good economics too

- Ford, Accenture, and many others have found that hydrogen made at filling stations or in buildings from natural gas, even at higher long-run prices (say, $6/MBTU), would compete handily with $1.30/gallon gasoline
- In round numbers, fuel cost would drop from 5¢/mile to ~3¢/mile
- The car could cost the same to buy as today's cars around (probably) the end of this decade, but would also offer many valuable advantages, plus the plug-in-power-plant option
- Carbon sequestration — centralized or not — would have a very minor effect on cost per mile

Much of the needed hydrogen is already being made for other uses

- Today's 50 MT/y H_2 (~37–45% used by refineries) — *if* it all directly fueled 5η* light vehicles instead — could displace two-thirds of all U.S. gasoline (or all by ~2010 at recent 6%/y H_2 growth)

  *Hypercar®-class platform physics mean nominally "3η" if Otto, "4η" hybrid or Diesel, "5η" (at least) if fuel-cell

- If fueling 5η light and 2η heavy vehicles, 50 MT/y H_2 could displace all U.S. highway-vehicle fuel
- U.S. refineries use ~7 MT/y H_2 — enough, if so used, to displace 1/4 of U.S. gasoline (2× Gulf share) or 1/7 of U.S. highway-vehicle fuel
- 50 MT/y H_2 could be made by ND+SD windpower
  - Byproduct O_2 could gasify biomass or coal into more H_2 or el.

Hydrogen safety

- All fuels are hazardous, but…
- Hydrogen is comparably or less so, but different
  - Buoyant (8× CH_4), diffusive (4× CH_4, 12× gasoline)
  - Clear flame can't sear you at a distance; no smoke
  - Hard to make explode; can't explode in free air; burns first
  - 4× gasoline-fume concentration required to burn; 22× less explosive power
  - Rises, doesn't puddle
  - *Hindenburg* myth (1937) — *nobody* was killed by hydrogen fire
  - Completely unrelated to hydrogen bombs

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Demonstrating hydrogen *vs.* gasoline safety

Worst-case test of deliberate H_2 leakage (left: 1.54 kg = entire tank volume in ~100 s, 185 MJ) *vs.* a small leak of gasoline (right: 1.6-mm hole, 2.37 L = 0.63 USgal, 74 MJ). The H_2 flame is visible because of sodium in particulates naturally present in the air. This test assumed a leak at the tank's Pressure Relief Device (yielding the fastest possible loss) *and* failure of the standard H_2 sensor, pressure-drop, and flow-comparator shutoff devices. A H_2 leak *under* a fuel-cell vehicle designed to standard protocols would require failure of those 3 safety devices and of the fuel line. The H_2 and gasoline tests were done *in the same car.* M.R. Swain, "Fuel Leak Simulation," www.eren.doe.gov, 2002.

3 s: Ignition. H_2 @ 28 L/min, gasoline @ 0.68 L/min

60 s: H_2 flow subsiding; max 47˚C on rear window, 19.4˚C on tray behind rear seat. Zooming in on gasoline car…

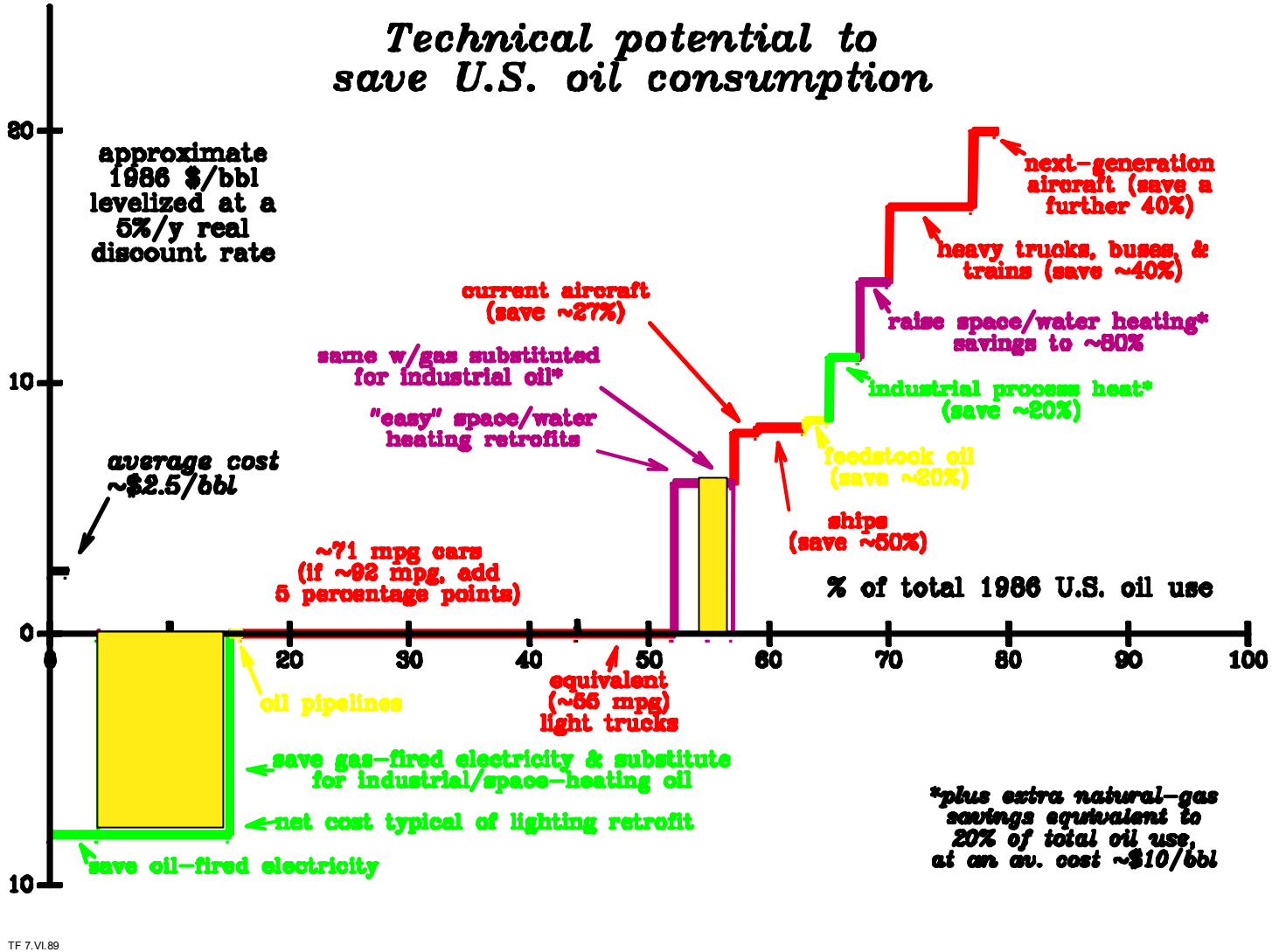
90 s: H_2 plume nearly stopped.

140 s: Gasoline-car interior alight. Tires later burst.

Hydrogen logistics

- Generally safer than liquid hydrocarbon fuels
  - Ultrastrong carbon tank is extremely resistant to battle damage; cushioned H_2-filled tanks could readily be airdropped & plugged in
  - ~14× less mass of fuel onboard per unit range
- Feasible (though awkward) to deliver in bulk
- Typically easier to produce in-theater at any scale
  - From any hydrocarbon or carbohydrate with a portable reformer
  - Or from water + electricity from any source, even idling tank/truck
  - Extensive off-the-shelf hardware is available, more on the way
- Double logistics advantage — fuel and drinking water
- Worth re-examining the single-fuel doctrine
- Or solid-oxide fuel cells: burn hydrocarbons directly

A 1987–88 RMI Analysis for Shell Found a Retrofit Potential to Save ~80% of U.S. Oil at Average Levelized Cost ~US$2½/bbl…



…but now every step is known to be bigger and cheaper!

Contingency: off-oil mobilization

- 2003 RMI analysis/synthesis is now underway on a rapid, full, profitable U.S. off-oil roadmap
- The RMI exercise, with OSD/ONR funding, will:
  - update RMI's 1987–88 supply curve for oil end-use efficiency (but will show two variants)
  - include aggressive supply-side transition (H_2, biofuels, gas)
  - analyze how much of the unbought overhang of oil substitu-tions can be elicited by traditional plus ~15–20 new policy instruments (those not using price, tax de/regulation)
- Expected to be more profitable for the country and probably also for hydrocarbon companies
- Ripe for industry to consider, both as contingency and as business opportunity

The oil endgame is starting

- Many oil majors wonder whether to say so; the chairs of four already did (plus those of three big automakers)
- The China-led hydrogen/Hypercar leapfrog in Shell's 10/01 "Spirit of the Coming Age" scenario is clearly now underway, with strong support from the highest levels
- Oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices
- Don Huberts, Geoffrey Ballard, Sheikh Yamani: "The Stone Age did not end because the world ran out of stones, and the Oil Age will not end because the world runs out of oil"
- Like uranium already and coal increasingly, oil will become not worth extracting — good mainly for holding up the ground — because other ways to do the same tasks are better and cheaper

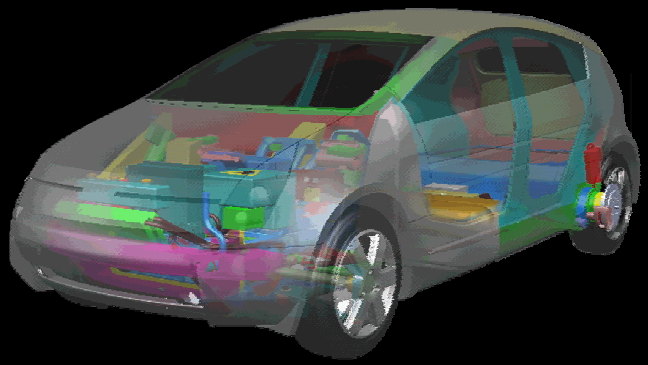
It's time — and integrative engineering can lead the way

"People and nations behave wisely —
once they have exhausted all other alternatives."
— Churchill

"Sometimes one must do what is necessary."
— Churchill

"We are the people we have been waiting for."
— Hopi Elders

www.rmi.org



www.hypercar.com

About the author: A consultant experimental physicist educated at Harvard and Oxford, Mr. Lovins has received an Oxford MA (by virtue of being a don), eight honorary doctorates, a MacArthur Fellowship, the Heinz, Lindbergh, World Technology, and Heroes for the Planet Awards, the Happold Medal of the UK Construction Industries Council, and the Nissan, Shingo, Mitchell, "Alternative Nobel," and Onassis Prizes; held visiting academic chairs; briefed 16 heads of state; published 28 books and several hundred papers; and consulted for scores of industries and governments worldwide, including oil majors since 1973, automakers since 1991, DOE, and DoD. *The Wall Street Journal*'s Centennial Issue named him among 39 people in the world most likely to change the course of business in the 1990s, and *Car* magazine, the 22nd most powerful person in the global automotive industry. His work focuses on whole-system engineering; on transforming the car, energy, chemi-cal, semiconductor, real-estate, and other sectors toward advanced resource productivity, and on integrating resource efficiency into the emerging "natural capitalism."

About Rocky Mountain Institute (www.rmi.org): This independent, nonpartisan, market-oriented, technophilic, entrepreneurial, nonprofit organization was cofounded in 1982 by Hunter Lovins and CEO Amory Lovins. RMI fosters the efficient and restorative use of natural and human capital to create a secure, prosperous, and life-sustaining world. The Institute's ~50 staff develop and apply innovative solutions in business practice, energy, transportation, climate, water, agriculture, community economic development, security, and environmentally responsive real-estate development. RMI's ~$6-million annual budget comes roughly half each from programmatic enterprise earnings (mainly private-sector consultancy) and from foundation grants and donations. Its work is summarized in the business book *Natural Capitalism* (w/Paul Hawken; 9/99, www.natcap.org).

About Hypercar, Inc. (www.hypercar.com): In August 1999, Rocky Mountain Institute transferred its internally incubated technical activities on Hypercar vehicles to this partly-owned second-stage for-profit technology development firm, its fourth spinoff. Funded by private investors, Hypercar, Inc. pursues business opportunities related to the Hypercar concept developed at RMI since 1991. Mr. Lovins chairs Hypercar's Board and holds minor equity options in the firm.