
ROCKY MOUNTAIN
INSTITUTE

MAP/Ming Visiting Professorship, Engineering School, Stanford University, 28 March 2007
CEE 173L/273L: Advanced Energy End-Use Efficiency

Public Lectures in Advanced Energy Efficiency:

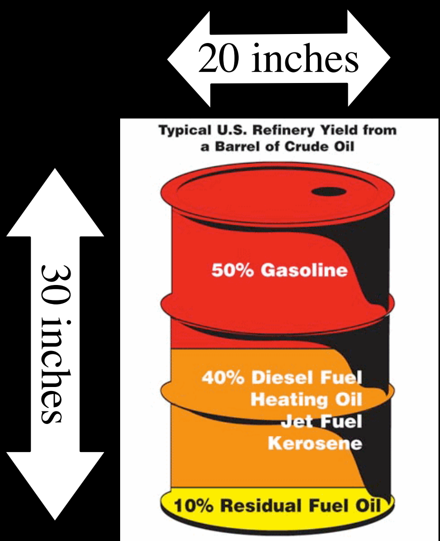
3. Transportation

Amory B. Lovins, SAE
Chairman and Chief Scientist
Rocky Mountain Institute
www.rmi.org

The world consumes a cubic mile of oil per year—85 million barrels per day

[courtesy of CAPT Scott Pugh, USN Ret., RMI Military Principal]

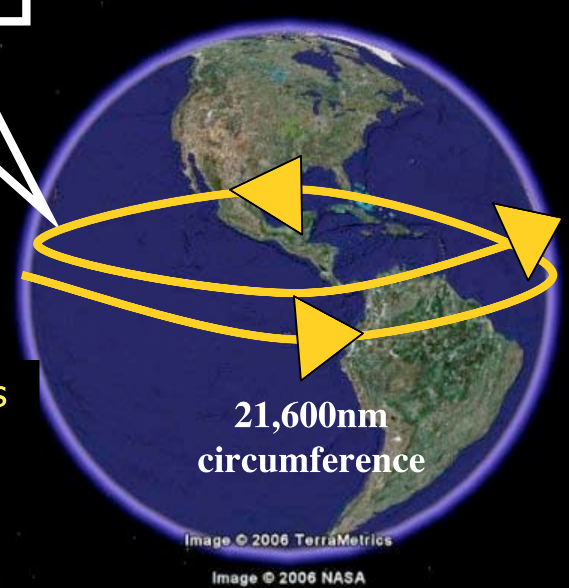
$$\frac{85{,}000{,}000 \times 30 \text{ inches}}{(12 \text{ inches/foot})(6{,}000 \text{ feet/nautical mile})} = 35{,}416 \text{ nautical miles}$$



1 barrel of crude oil = 42 U.S. gallons

20-inch pipeline

$$\frac{35{,}416 \text{ nm}}{24 \text{ hours}} = 1{,}475 \text{ knots} \approx \text{Mach } 2$$

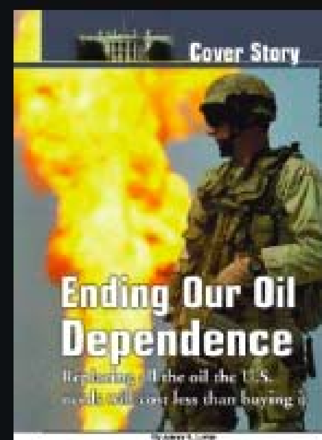


THE WALL STREET JOURNAL.

POLITICS & POLICY

Unlikely Allies Fight U.S. Oil Dependence

Bipartisan Network to Press for Reduced Consumption, Quicker Development of New Fuels



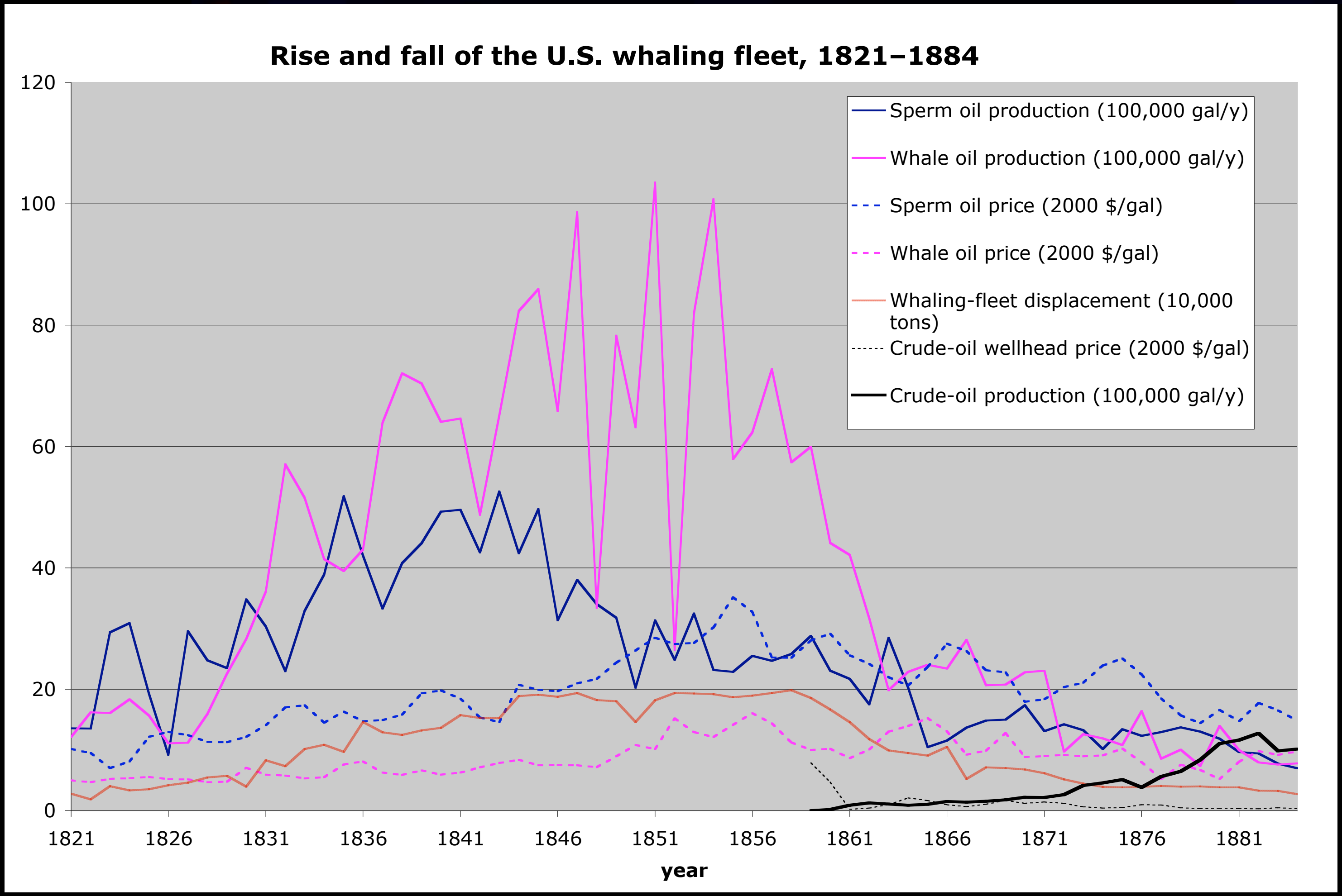
WEEKEND

FINANCIAL TIMES

IEA says world must turn away from oil

■ Agency says governments should act to cut demand

Whalers ran out of customers before they ran out of whales…



…even *before* Drake struck oil in 1859!

Some recent wildcat discoveries

- 8.3 million bbl/d play in the Detroit Formation
- 1.6 million bbl/d play in heavy trucks
- 1.2 million bbl/d play in industrial fuels/feeds
- 1.1 million bbl/d play in buildings
- 0.9 million bbl/d play in aircraft
- 1.6 million bbl/d play in other oil end-uses
- > 5 million bbl/d play in robustly competitive biofuels, chiefly cellulosic ethanol, and in biomaterials and biolubricants
- 12 TCF/y play in electricity and gas end-uses

Shouldn’t we drill the most prospective plays first?

20 Sept 2004 detailed study

Independent, peer-reviewed

Transparent, uncontested

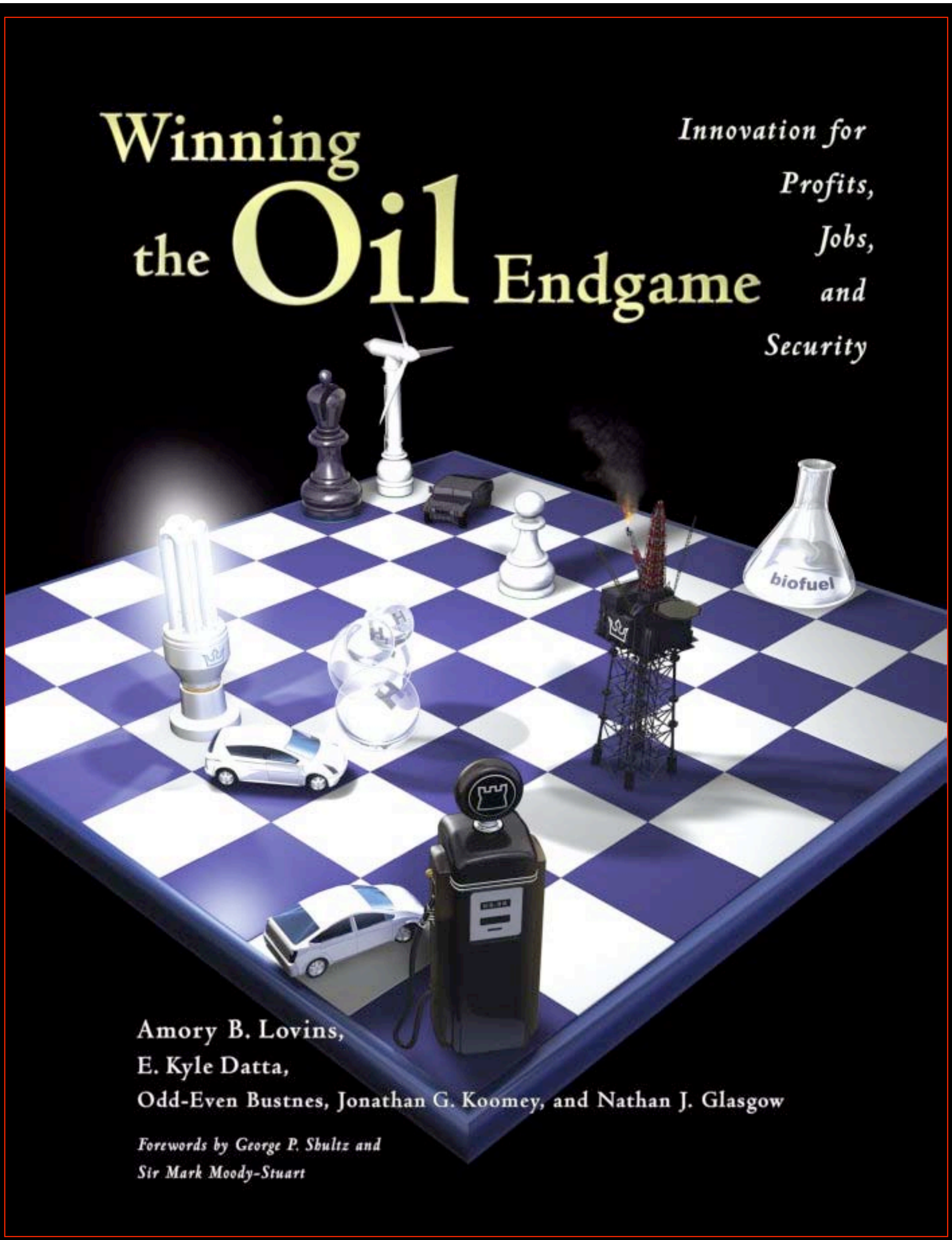
OSD- and ONR-cosponsored

For business & mil. leaders, built around competitive strategy for cars, trucks, planes, fuels, and military

329-page book & complete technical details are free downloads from:

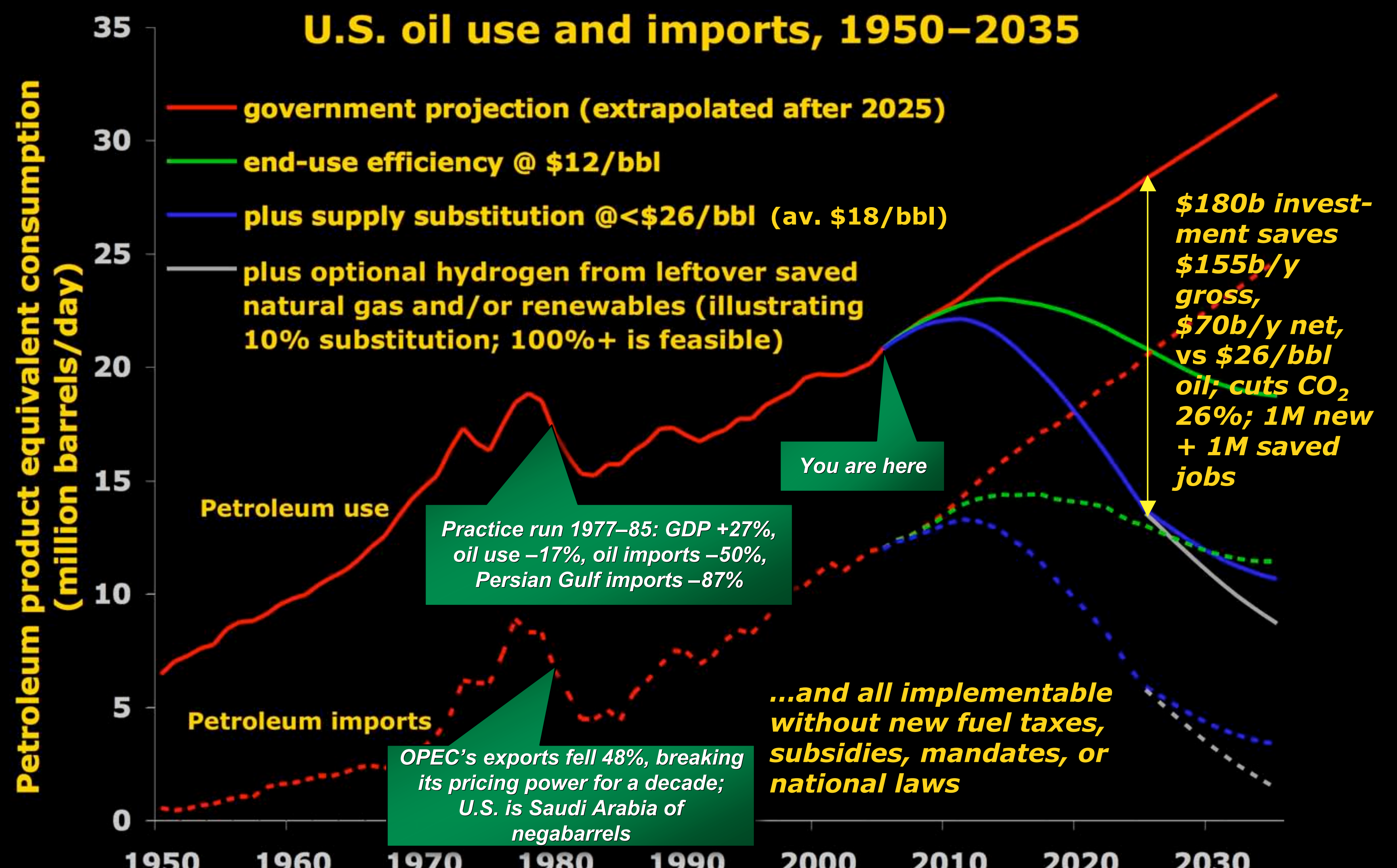
www.oilendgame.com

Over the next few decades, the U.S. can eliminate its use of oil and revitalize its economy, all led by business for profit



This work was cosponsored by OSD and ONR. The views expressed are those of the authors alone, not of the sponsors.

A profitable US transition beyond oil (with best 2004 technologies)



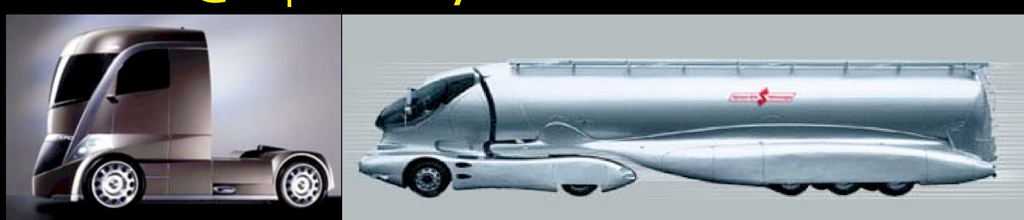
Vehicles use 70% of US oil, but integ-rating low mass & drag with advanced propulsion saves ~2/3 very cheaply

CARS: save 69% at $0.15/L

Surprise: ultralighting is ***free —*** offset by simpler automaking and the 2× smaller powertrain

250 km/h, 2.5 L/100 km

TRUCKS: save 25% free, 65% @ $0.07/L

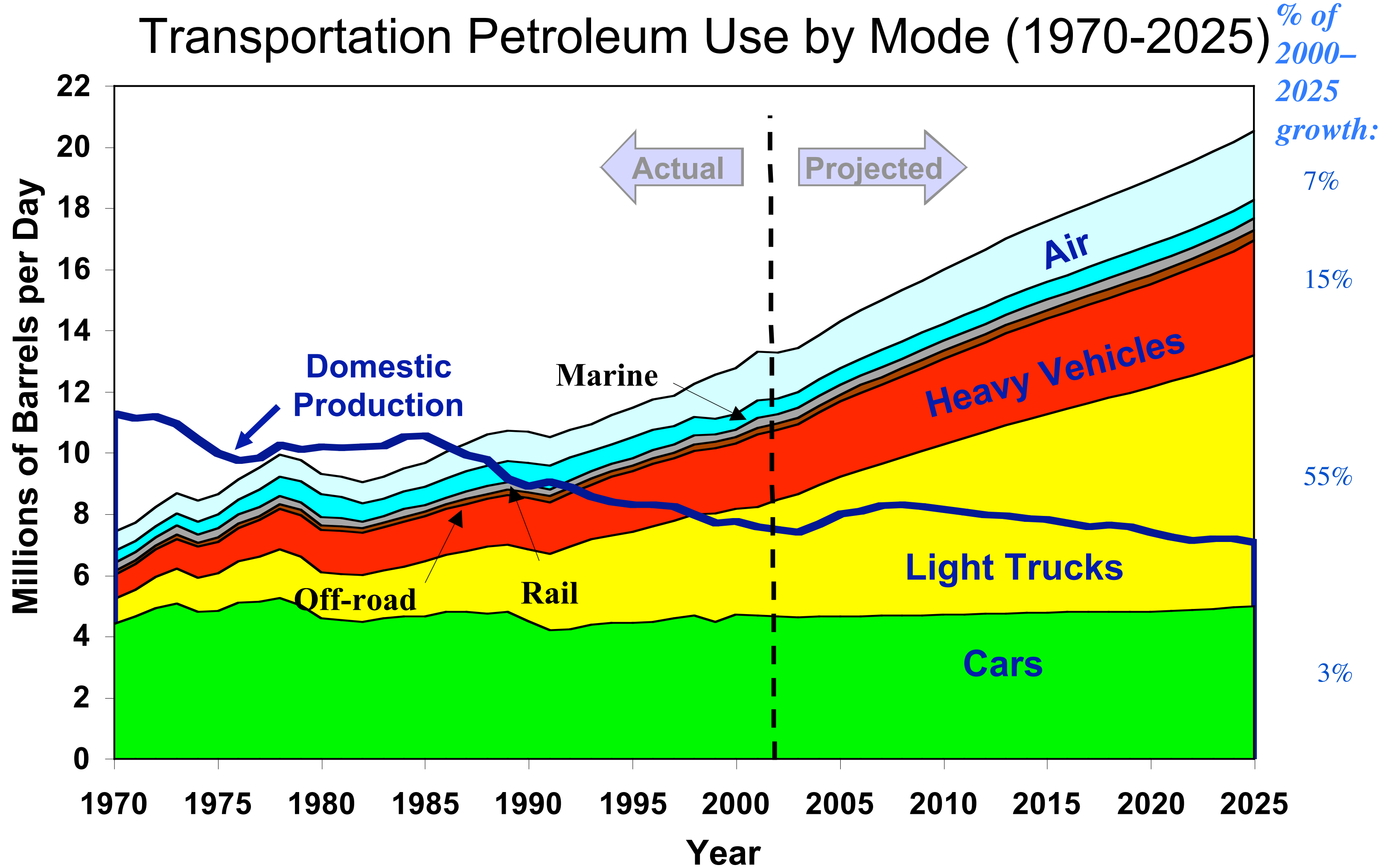


PLANES: save 20% free, 45–65% @ ≤$0.12/L

BLDGS/IND: big, cheap savings; often *lower* capex

Technology is improving faster for efficient end-use than for energy supply

Light and heavy trucks = 70% of projected 2000–25 rise in total U.S. consumption of petroleum products (by volume)



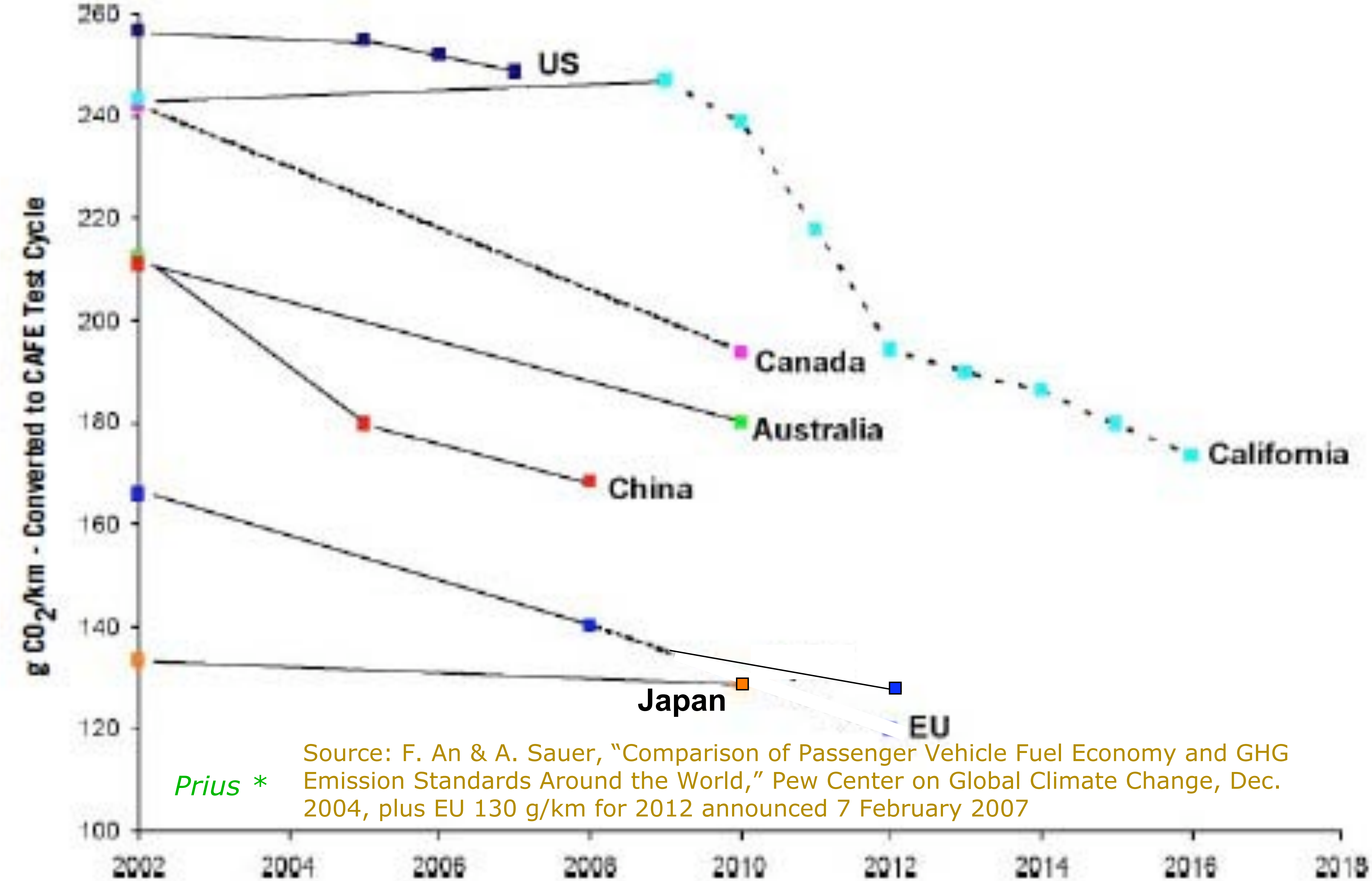
Source: *Transportation Energy Data Book: Edition 23*, DOE/ORNL-6970, October 2003, and *EIA Annual Energy Outlook 2004*, January 2004

Basic automotive physics

Based largely on Marc Ross, U.Mich., "Fuel Efficiency and the Physics of Automobiles," *Contemp. Phys.* **38**(6): 381–394 (1997), which he's updated to 2004

- Powertrain efficiency (tank-to-wheels) ≡
  - engine thermodynamic η (fuel-to-work) × engine mechanical η (work-to-output-torque) × driveline η (engine-to-wheels) ≈ 0.38 [0.45 Diesel] × 0.53 × 0.85 = 0.17 (*vs.* 2004 *Prius* 0.33–0.37)
- Vehicle load = tractive load + accessory loads (~2–3%, often engine-driven with different conversion losses)
- Tractive load in approx. instantaneous kW_{mech} =
  - **Inertia** = $0.5M^*[\Delta v^2/\Delta t]$ ($M^* \approx 1.03M$, $[\Delta v^2/\Delta t]$ in m^2/s^3)
  - + **rolling resistance** = $C_R Mgv$ (M in tonnes, v in m/s)
  - + **aero drag** = $0.5\rho_{air}C_D Av^3/1000$ ($\rho \approx 1.2$ kg/m³, A in m²)
  - + **grade** = $mgv \cdot \sin\theta$ (grade = $\tan\theta$; neglected in next chart)
  - Inertial and grade loads can be negative; 2004 *Prius* hybrid recovers them with average wheel-to-wheel efficiency 0.66
  - 1995 *Taurus* tractive load is only 6.3 kW, equivalent to 1.6 L/100 km or 0.67 US gal/100 mi…but divide by powertrain η!
- Powertrain η can't exceed 1.0, *but tractive load can be reduced almost without limit*

Current and projected new-car efficiency or CO_2 stds. (in US CAFE g CO_2/km-NEDC)



Source: F. An & A. Sauer, "Comparison of Passenger Vehicle Fuel Economy and GHG Emission Standards Around the World," Pew Center on Global Climate Change, Dec. 2004, plus EU 130 g/km for 2012 announced 7 February 2007

Challenging a basic assumption in Detroit and Washington

- Efficiency assumed to be a tradeoff—makes cars small, unsafe, sluggish, costly, ugly,…
- Hence policy intervention needed to induce customers to buy the compromised vehicles

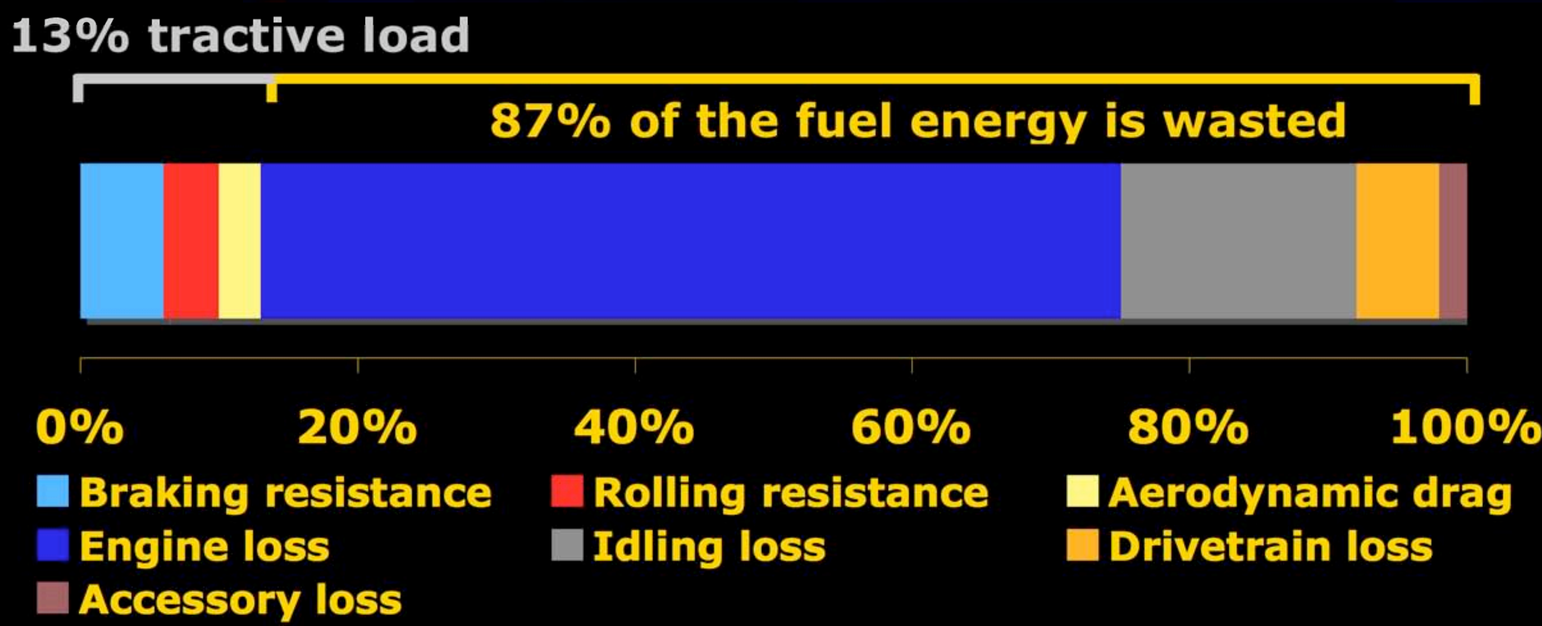
How many people still buy phonograph records…

…or cathode-ray-tube TVs instead of big flat-panel TVs?

◇ An engineering end-run around tax/CAFE gridlock

◇ A robust business model based solely on value to customer and competitive advantage to suppliers

Where does a car's gasoline go?



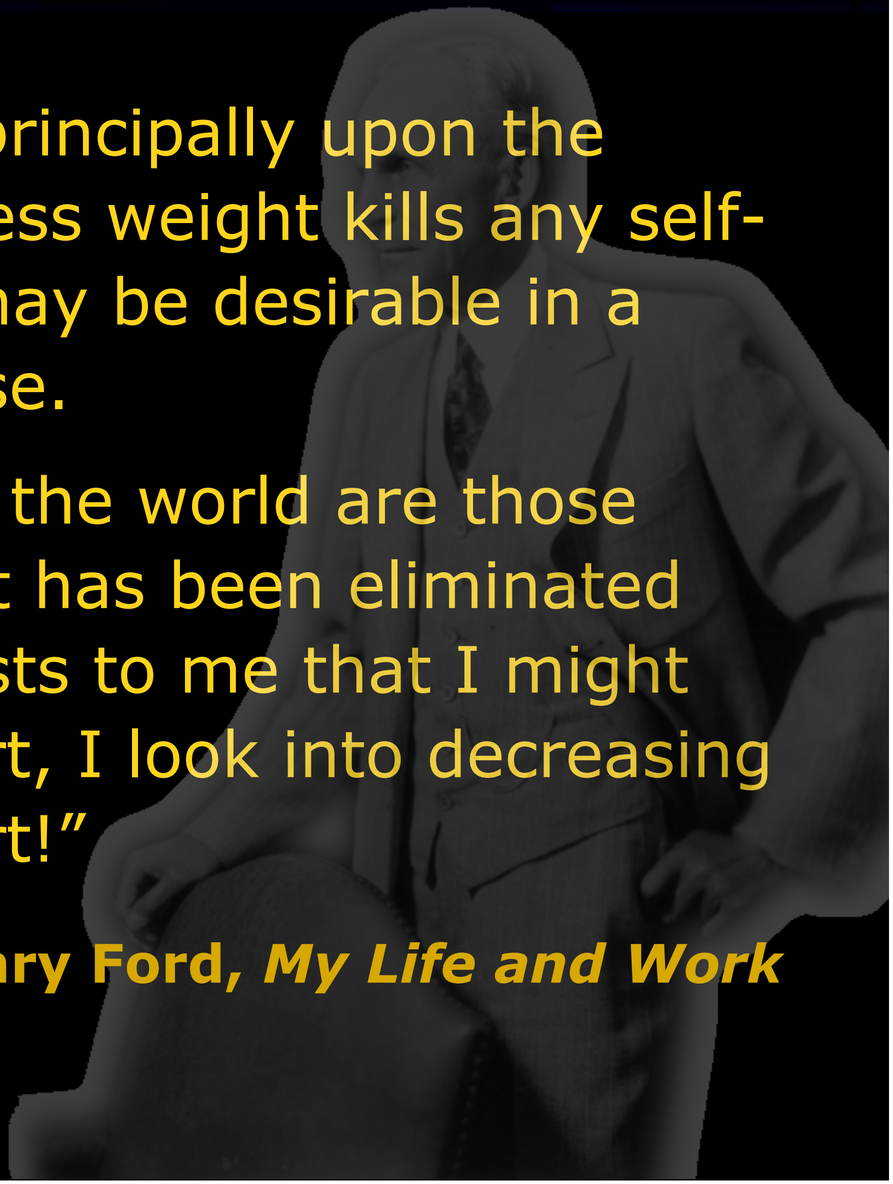
- 6% accelerates the car, 0.3% moves the driver
- Three-fourths of the fuel use is weight-related
- Each unit of energy saved at the wheels saves ~7–8 units of gasoline in the tank (or ~3–4 with a hybrid)
- **So first make the car radically lighter-weight!**

Henry Ford said it best…

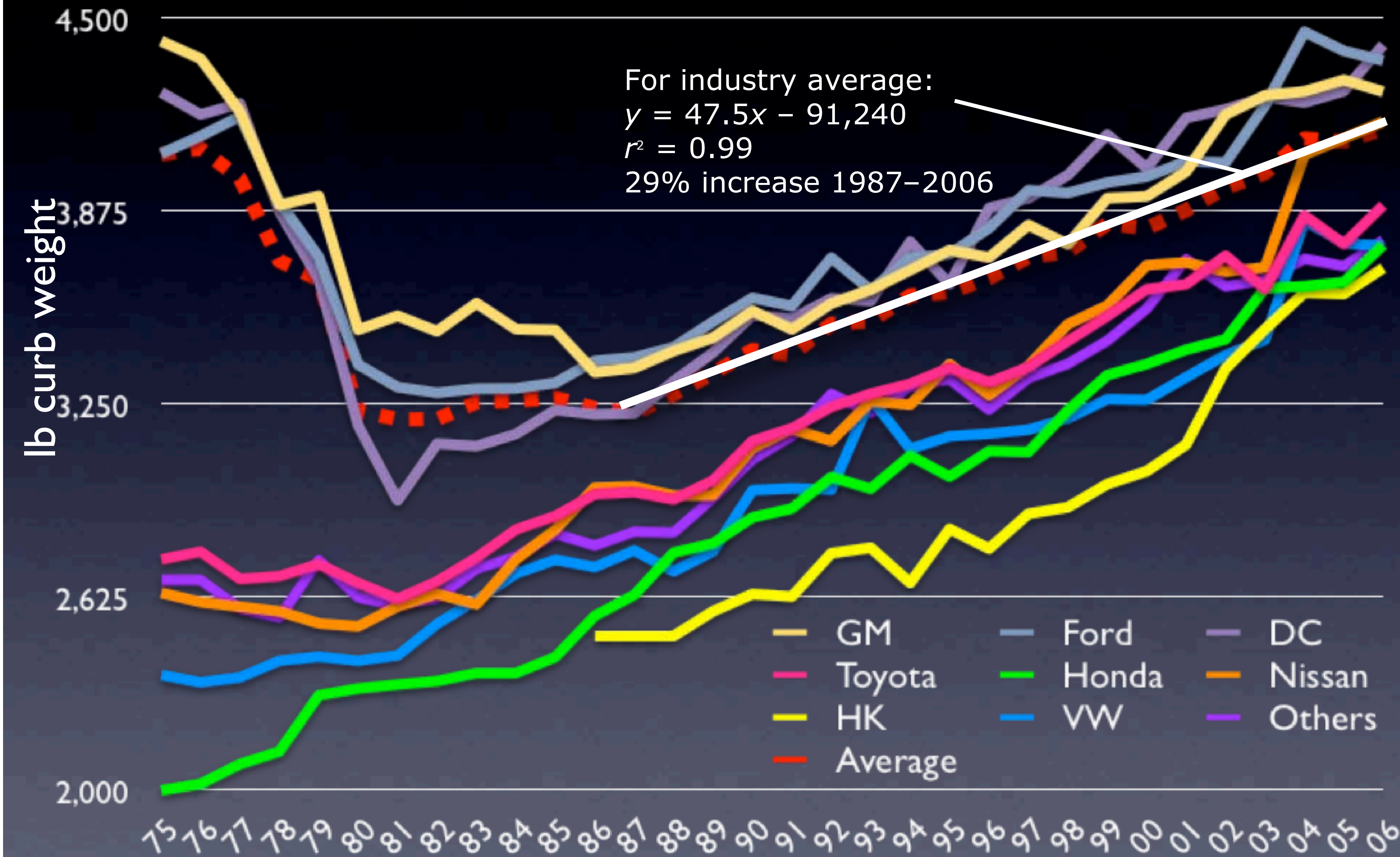
"I had been experimenting principally upon the cutting down of weight. Excess weight kills any self-propelled vehicle….Weight may be desirable in a steam roller but nowhere else.

The most beautiful things in the world are those from which all excess weight has been eliminated ….Whenever any one suggests to me that I might increase weight or add a part, I look into decreasing weight and eliminating a part!"

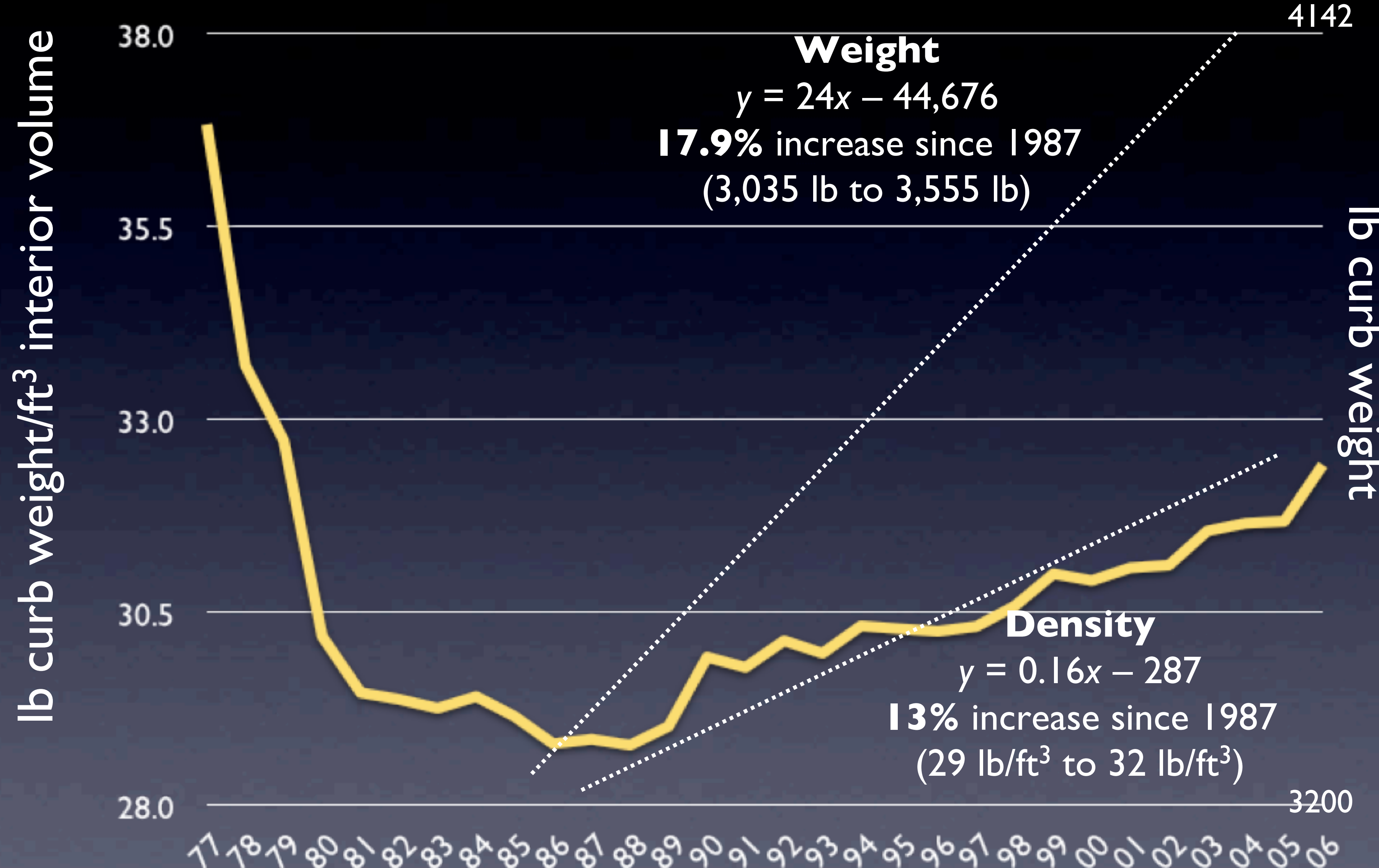
— Henry Ford, *My Life and Work*



Average new U.S. light-duty vehicle now weighs more than 2 short tons



U.S.-sold cars & vans are getting denser, compromising both safety and efficiency



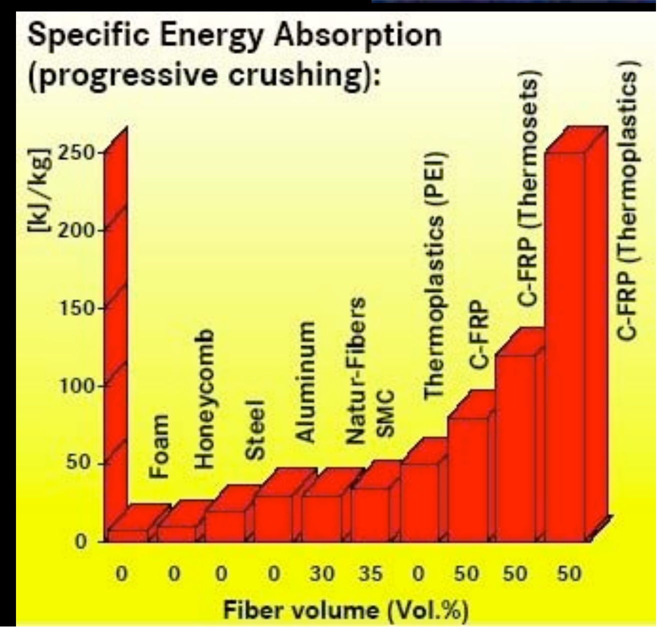
70% of the increase in weight is due to design and materials, 30% to changes in size & mix

Three technology paths: aluminum, light steels, carbon composites (the strongest & lightest)

- *SLR McLaren* suffers immaterial damage in side impact by *Golf*
- 7 kg of woven carbon crush cones (0.4% of car’s mass) can absorb all frontal crash energy at 105 km/h with thermoset (better w/thermoplastic)

Graphics courtesy of DaimlerChrysler AG

- **Carbon-composite crush structures can absorb 6–12× as much energy per kg as steel—and more smoothly**
- **Size is protective, weight hostile; so adding size without weight adds protection and comfort without aggressivity or fuel inefficiency ...saving both oil *and* lives (and $)**



Confirmed by light-composite-car crash experience

Katherine Legge's 290 km/h walk-away ChampCar wall crash on 29 September 2006

Tough stuff (≥250 kJ/kg)

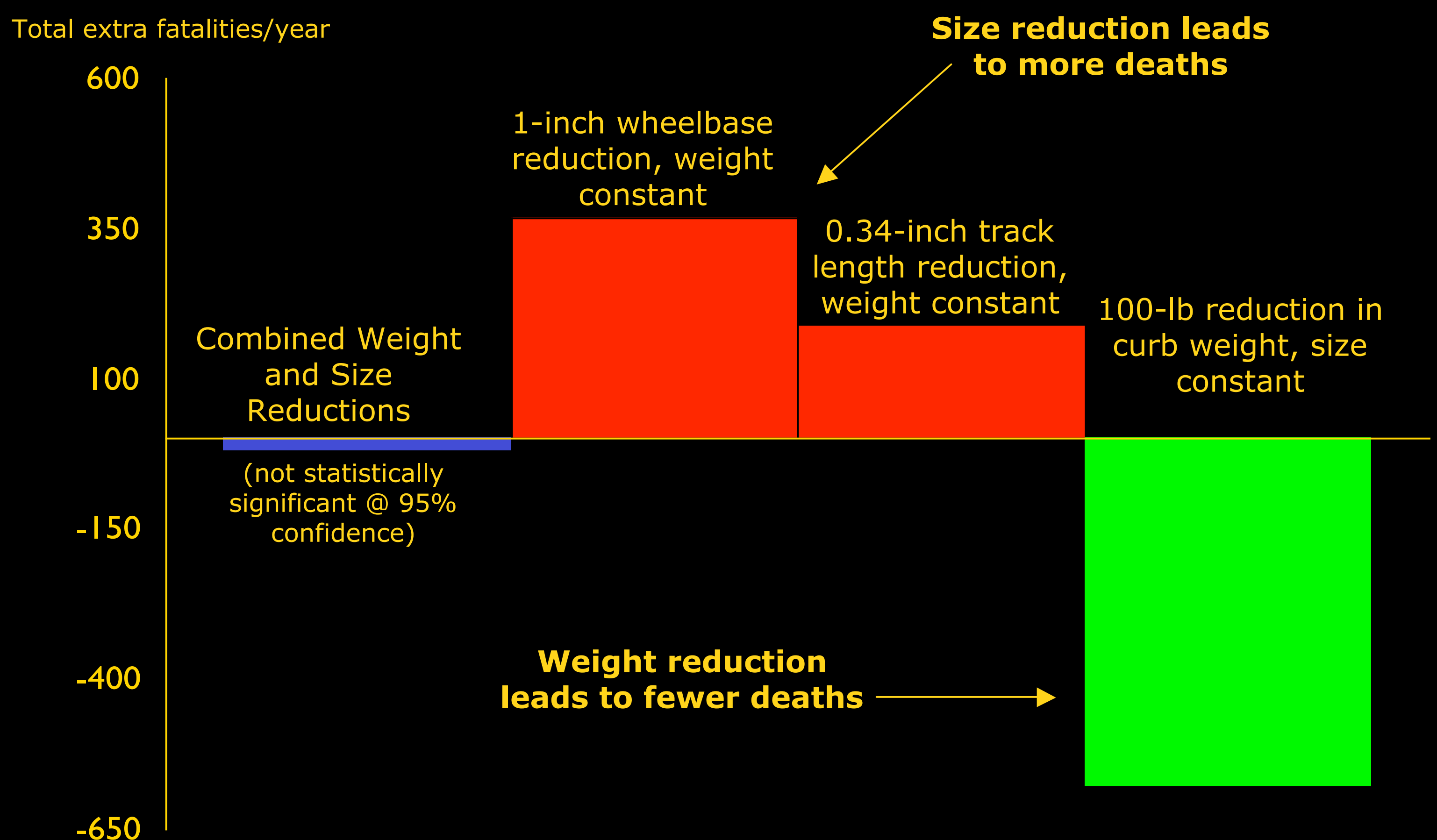
From Tom Friedman's 24 Jun 06 feature *Addicted to Oil* on The Discovery Channel…

Revolution's most highly load-ed and complex body part…

and Tom's futile efforts to damage a 2-mm-thick x 200-mm-diameter thermoplastic carbon-fiber hemispherical shell for a military helmet

The nationwide crash data confirm: *size* confers safety; weight doesn't

When Kahane (NHTSA) found 100 lb lighter would kill 414–1,314 more people, he assumed size and weight were equivalent metrics—but they're not



Therefore make cars bigger but lighter with light-but-strong materials and integrative design

*Results from Van Auken and Zellner (DRI) 2003, **separating size from weight** in NHTSA/Kahane's FARS database*

Effects are due to crashworthiness, crash avoidance, and compatibility. All light vehicles on U.S. roads, and all road users, are included.

Migrating innovation from military aerospace to civilian cars

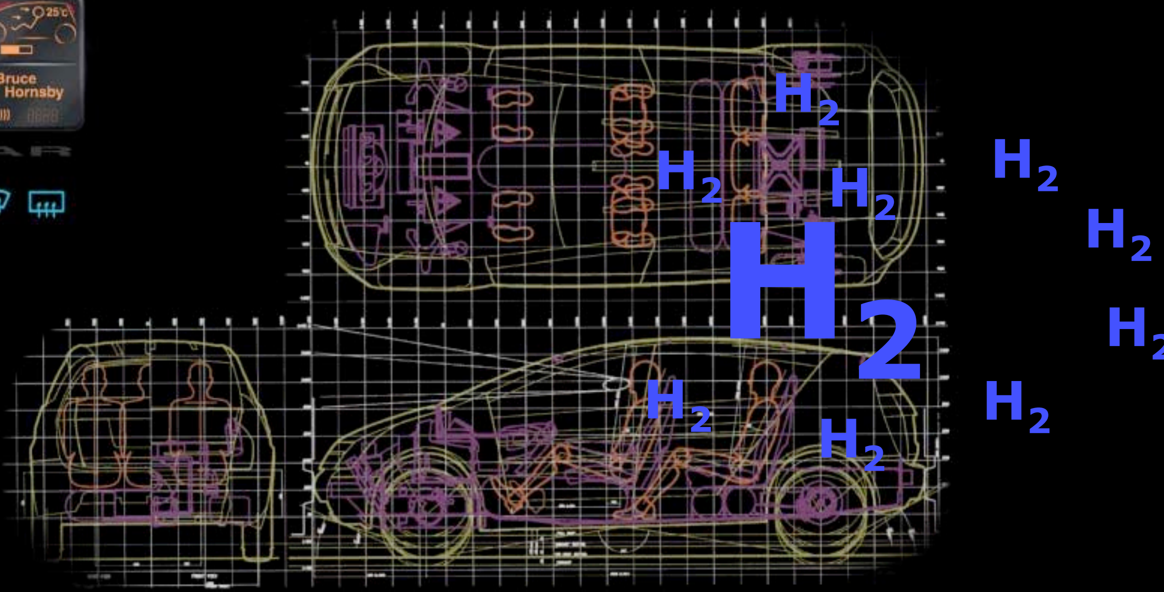
◇ At the Lockheed Martin Skunk Works®, engineer David Taggart led a ’94–96 team* that designed an advanced tactical fighter-plane airframe…

- made 95% of carbon-fiber composites
- 1/3 lighter than its 72%-metal predecessor
- *but 2/3 cheaper*…
- because it was designed for optimal manufacturing from composites, not from metal

*Integrated Technology for Affordability (IATA)

◇ Finding no military customer for something so radical, he left. I soon hired him to lead the 2000 design of a halved-weight SUV (*Intl. J. Veh. Design* **35**(1/2):50–85 [2004])…

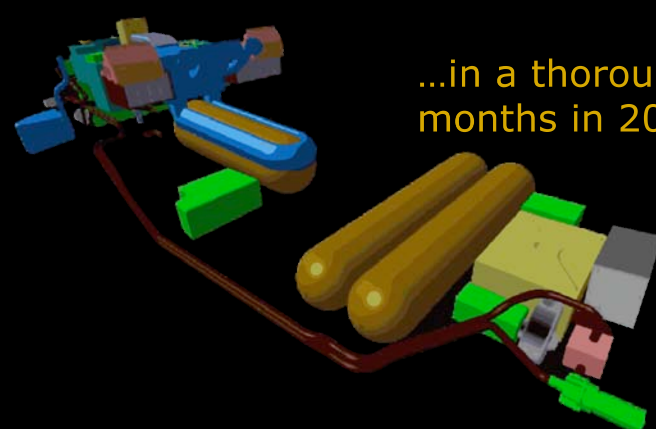
An uncompromised, competitive, 3.6–6.2×-more-efficient midsize SUV



Performance Comparison

Parameter	Units	Hypercar	Lexus RX300	Ford Explorer	GM Triax
		Dual Role SUV / WoW	Crossover Vehicle	Truck Based SUV	Hybrid Electric Lifestyle
					
Acceleration (0-62 Mph)	Sec	8.3	9.0	8.4	13
Acceleration GVW (0-62 Mph)[1]	Sec	11.5	NA	NA	NA
Maximum Speed[2]	Mph	86	112	115	NA
Economy[3] (combined city/hwy)	Mpg	99	20	18	56
Range[4]	Miles	330	320	340	NA
Emissions	US Cal	SULEV	-	-	ULEV
Drag Coefficient	Cd	.26	.36	.43	.27
Aerodynamic cross-section	M^2	2.38	NA	NA	NA
Curb Weight	Kg	857	1832	1873	1330
Payload Capacity	Kg	460	466	408	NA
Cargo Volume	M^3	1.96	2.1	2.3	NA
Start off grade	%	54	NA	NA	NA
Start off grade GVW	%	44	NA	NA	NA
Warranty[5]	years/miles	ULy/200k	4y/50k	3y/36k	NA
Length	mm	4564	4580	4843	4217
Width	mm	1830	1815	1783	1746
Height	mm	1548	1548	1719	1589
Front Track	mm	1580	1565	1493	1516
Rear Track	mm	1560	1550	1488	1500
Wheelbase	mm	2950	2615	2832	2682
Ground Clearance	mm	199[6]	198	170	193
Front overhang	mm	837	930	880	NA
Turning Radius	M	6	6.1	5.8	NA
Tires	Mfg. Spec.	205x460 R18.3[7]	225/70 R16	235/75 R15	175/65 R18

1: Includes 460kg payload, **2:** Constrained by wheel diameter, **3:** Hwy = 84.2 Mpg, City = 115.5, **4:** 132 liter gaseous hydrogen @ 5ksi, **5:** preliminary estimate, **6:** Off-road ride setting, **7:** PAX wheel/tire system



…in a thorough virtual design, done in eight months in 2000, for ~$3 million, by a small team led by Hypercar, Inc. in collaboration with two European Tier Ones…

Midsize 5-seat* Revolution *concept crossover SUV

Ultralight (857 kg = steel –53%) but ultrasafe

0–100 km/h in 8.3 s, 2.06 L/100 km = 114 mpg (H_2)…

or 0–100 in 7.2 s, 3.56 L/100 km

= 67 mpg (gasoline hybrid)

with +$2,511 MSRP (2-y US payback)

68% of the hybrid's fuel saving comes from lightweighting

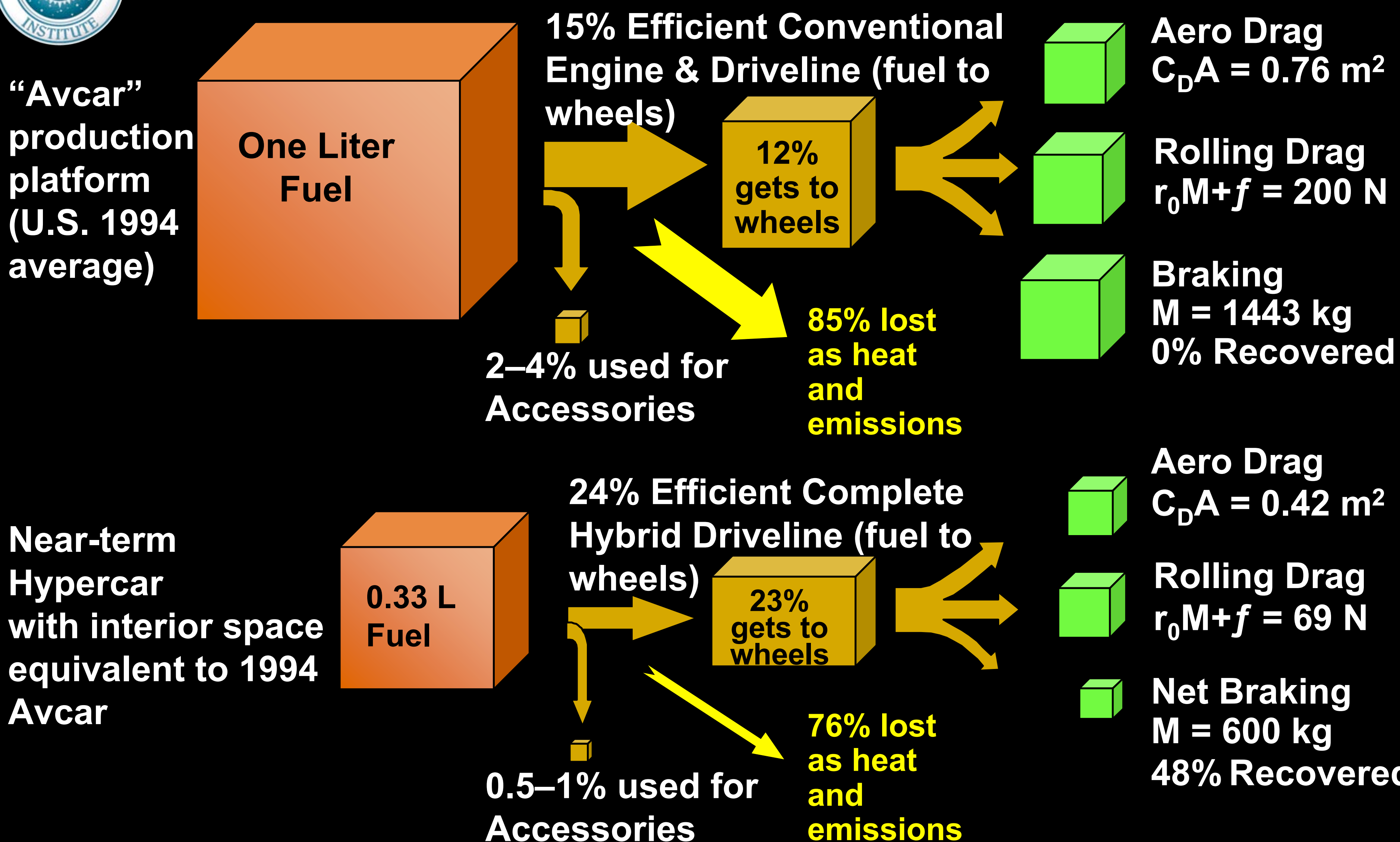
"We'll take two."
— *Automobile* magazine

World Technology Award, 2003

Uncompromised, production-costed, manufactur-able, via strong design innovation & integration

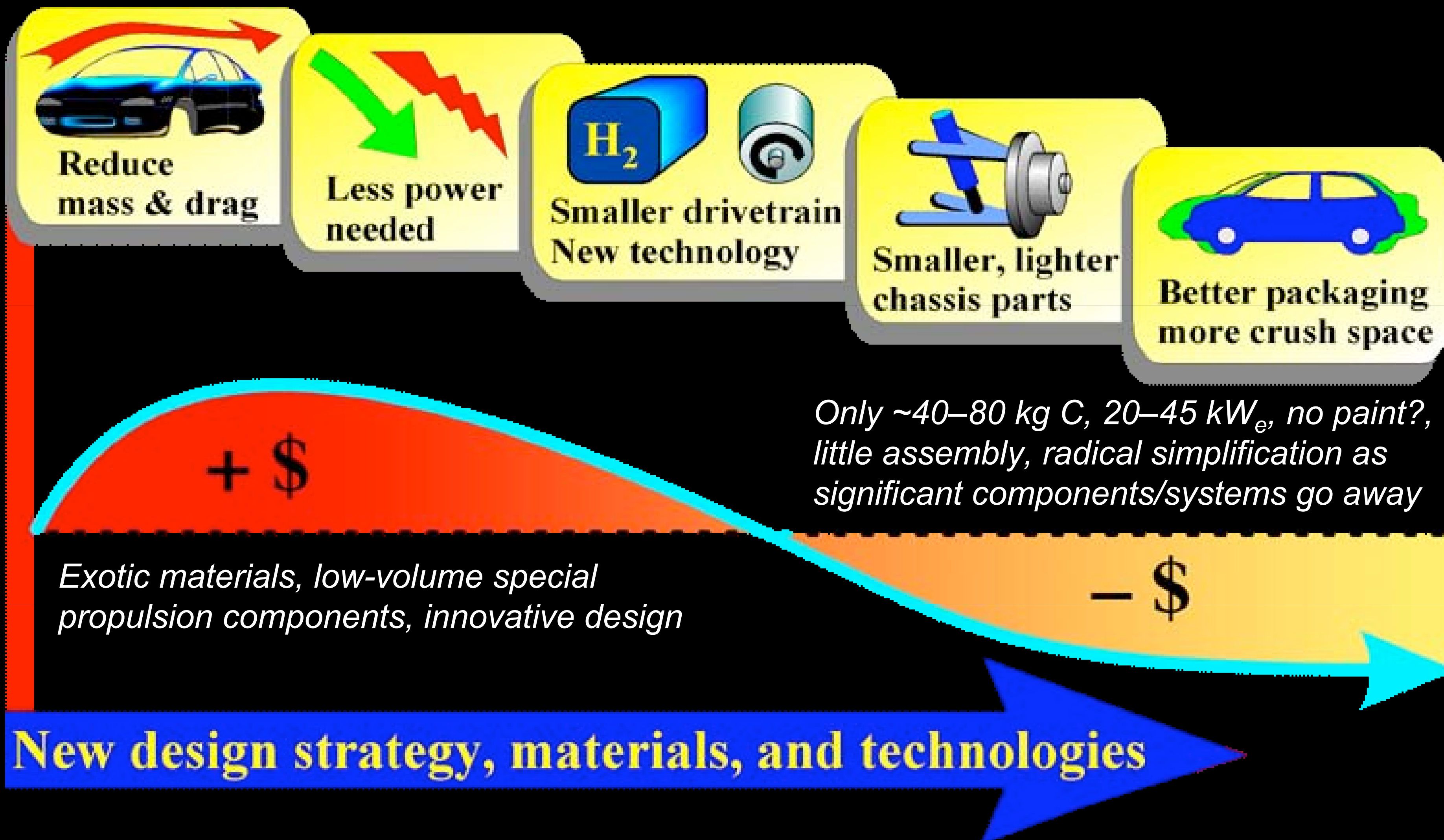

In the United States, like finding a Saudi Arabia under Detroit
In ultimate worldwide full-scale production, a nega-OPEC

Two ways to drive 12 km in the city

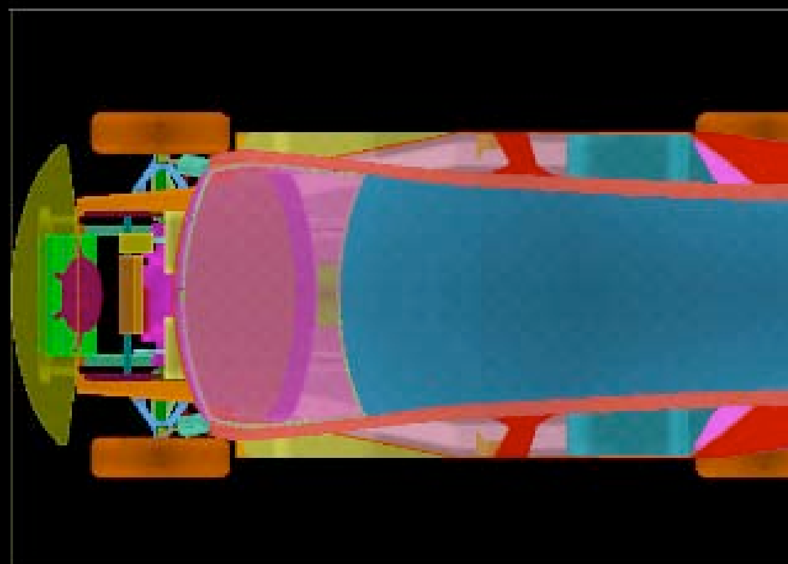


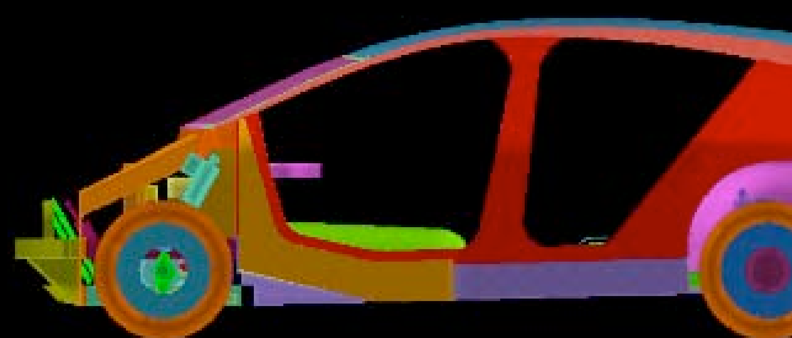
In highway driving, efficiency *falls* because there is far more irrecoverable loss to air drag (which rises as v^3) and less recoverable loss to braking.

Decompounding mass and com–plexity also decompounds cost



857-kg Revolution *crossover SUV simulated frontal barrier crash (2000)*

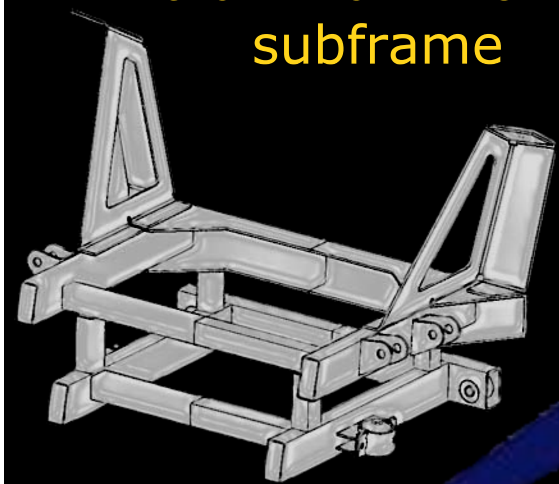




- 56 km/h fixed barrier crash causes no structural damage to passenger compartment; replaceable front end crushes instead
- FMVSS criteria also met in a frontal non-offset collision with a steel SUV twice its weight, each going 48 km/h (combined speed 96 km/h)

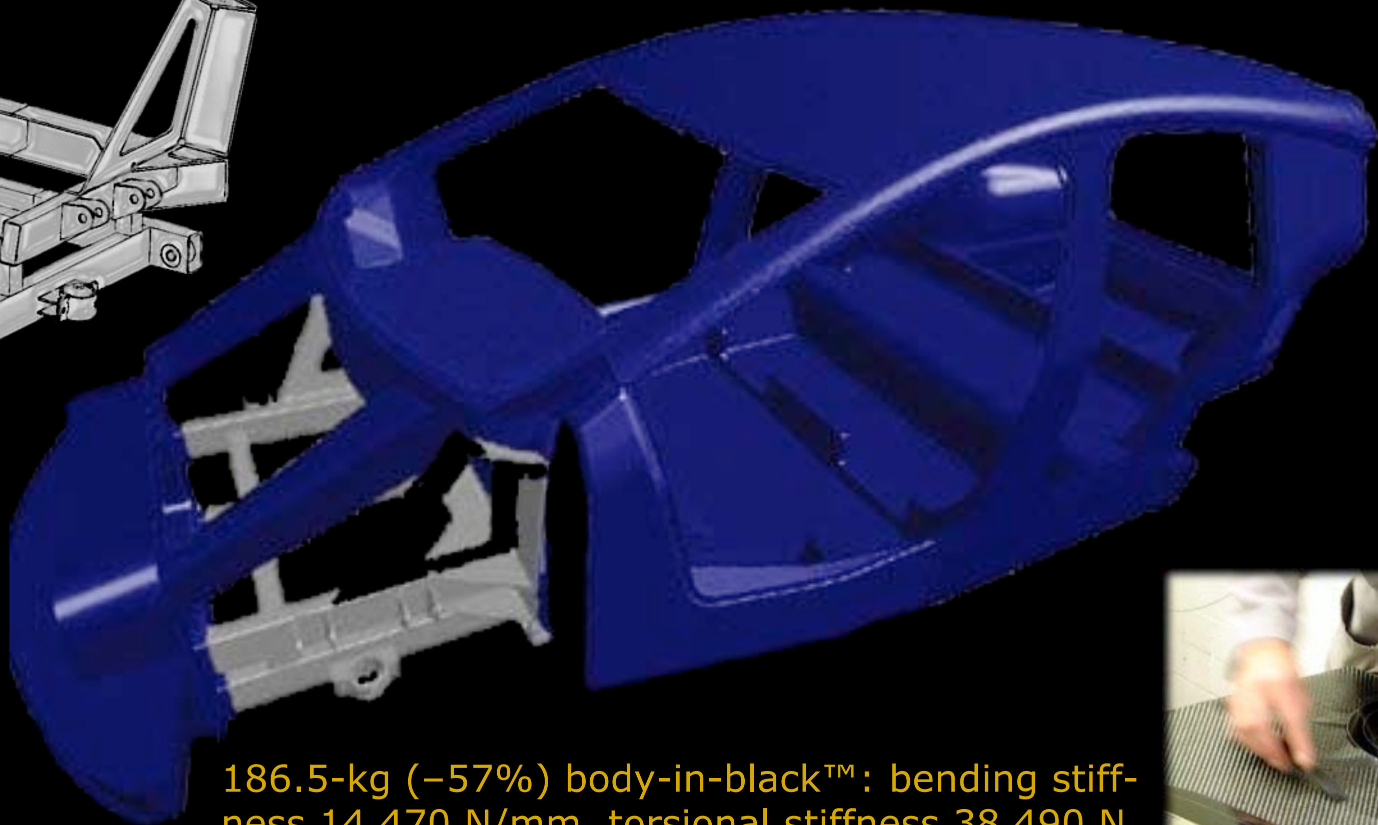
Ultralight autobody materials

aluminum front subframe



Vehicle designed for 320,000-km warranty—no dent or rust, bounces off 10 km/h collision

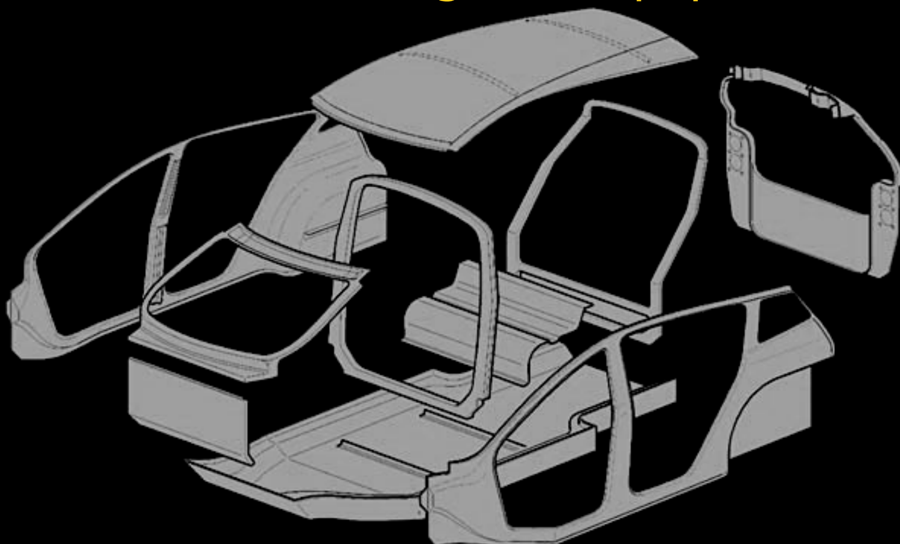
advanced-composite passenger safety cell

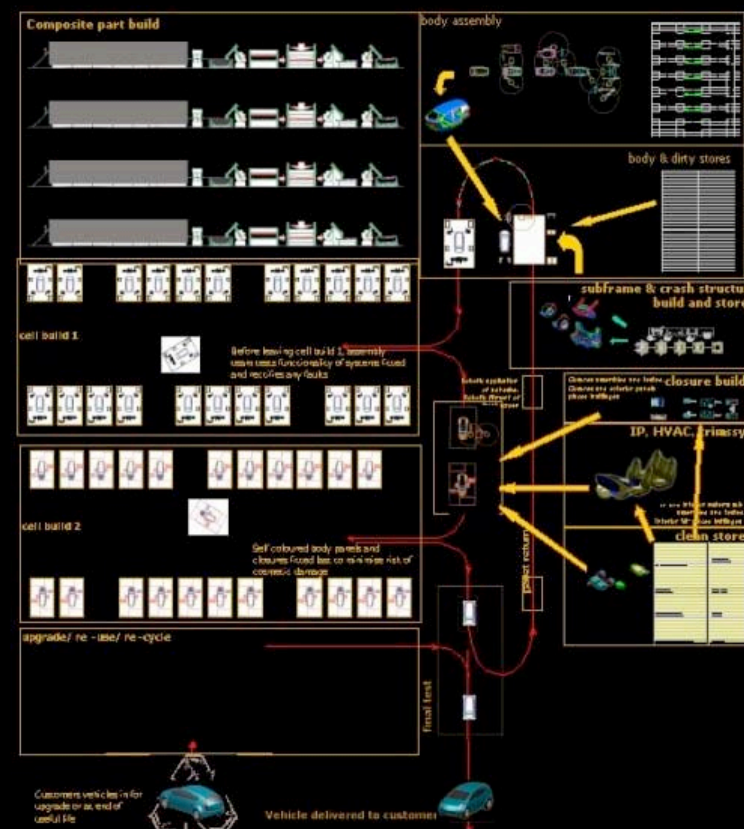


186.5-kg (–57%) body-in-black™: bending stiffness 14,470 N/mm, torsional stiffness 38,490 N •m/°, first bending/torsion mode 93/62 Hz— >50% stiffer than a steel premium sports sedan

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
- 14 low-pressure diesets (not ~10^3)
- Self-fixturing, detoleranced in 2 dim.
- No body shop, optional paint shop
- 2/5 less capital than leanest, 2/3 smaller

Rapid progress with midvolume cost-competitive advanced composites

- BMW: 60 specialists at Landshut, world's biggest RTM press, series production 2000+5…?
  - Already making >1k/y carbon roofs, hoods,…
  - Website strongly praises carbon composites

Concept *Z22* (2000)

- Honda and Toyota: carbon-fiber airplanes

Honda Jet

- Fiberforge®: 1999 RMI spinoff (W. Colo.)
  - Patented digital automated fiber placement process
  - Thermoform to net shape with ≤1-minute cycle time
  - ≥80% of hand-layup aerospace performance @ 20% of cost
  - Mature process at scale beats Al in $/part, steel in $/body at midvolume, and steel in $/*car* at any volume
  - Sample & development customers include OEMs and Tier 1s, *e.g.* JCI *Genus* seat (NAIAS 05)
  - World Techn. Award '03, Davos Tech Pioneer '07

Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures

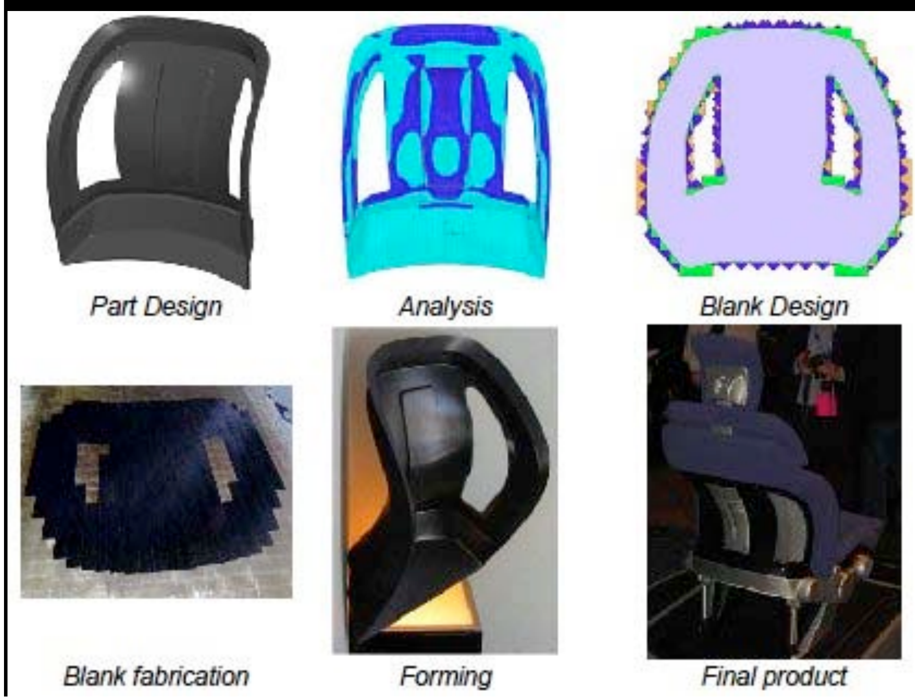
See www.fiberforge.com for technical details and papers

1. Digitally controlled automated fiber placement to create a flat preform (tailored blank™)
   - ◊ Fast (1.35 m/s and rising), precise, CAD-driven
   - ◊ Variable thickness, fiber mix/alignment/location
   - ◊ Ideal for anisotropic parts optimized to load paths

This video is Fiberforge proprietary

Carbon/PEEK 200-mm hemisphere

SOME DIVERSE MATERIALS SYSTEMS & APPLICATIONS



Carbon/nylon-6 seat-back frame (NAIAS '05)

Automated volume mfg. of continuous-fiber-reinforced thermoplastic structures

2. Thermoform on hot die to net shape, cool, trim

High material efficiency, low cost (can start with creel fiber and thermoplastic pellets), very low scrap

And carbon composites don’t rust or fatigue

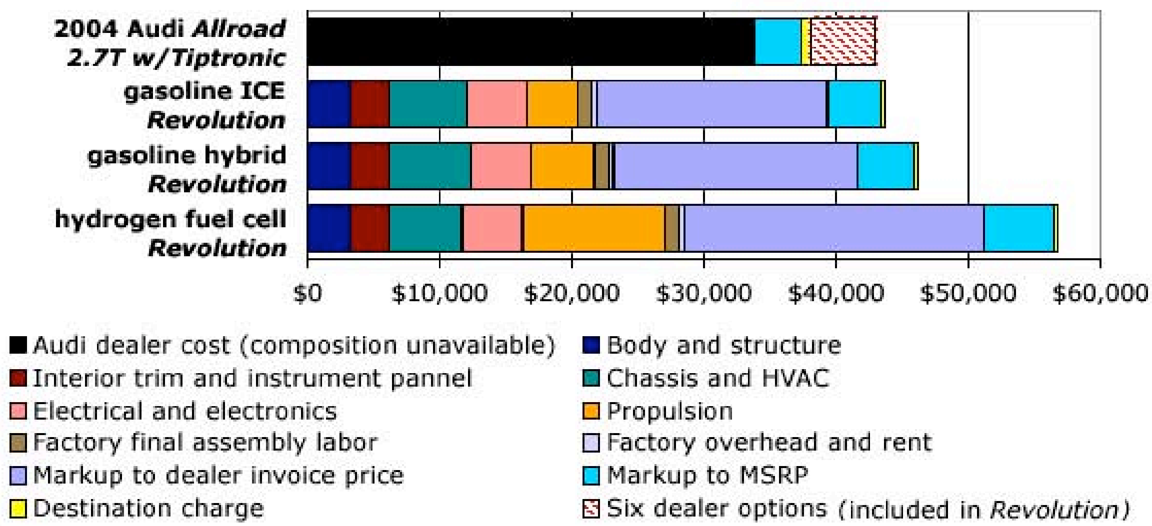
Car design: six *kō-ans* (公案)

- 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—just let the customer demand and get superior design

Result: an automotive *hiyaku* (飛躍, leapfrog)

Light-vehicle analysis based on detailed, production-costed virtual design for midsize SUV

Pretax retail price of selected crossover vehicles (2000 $)



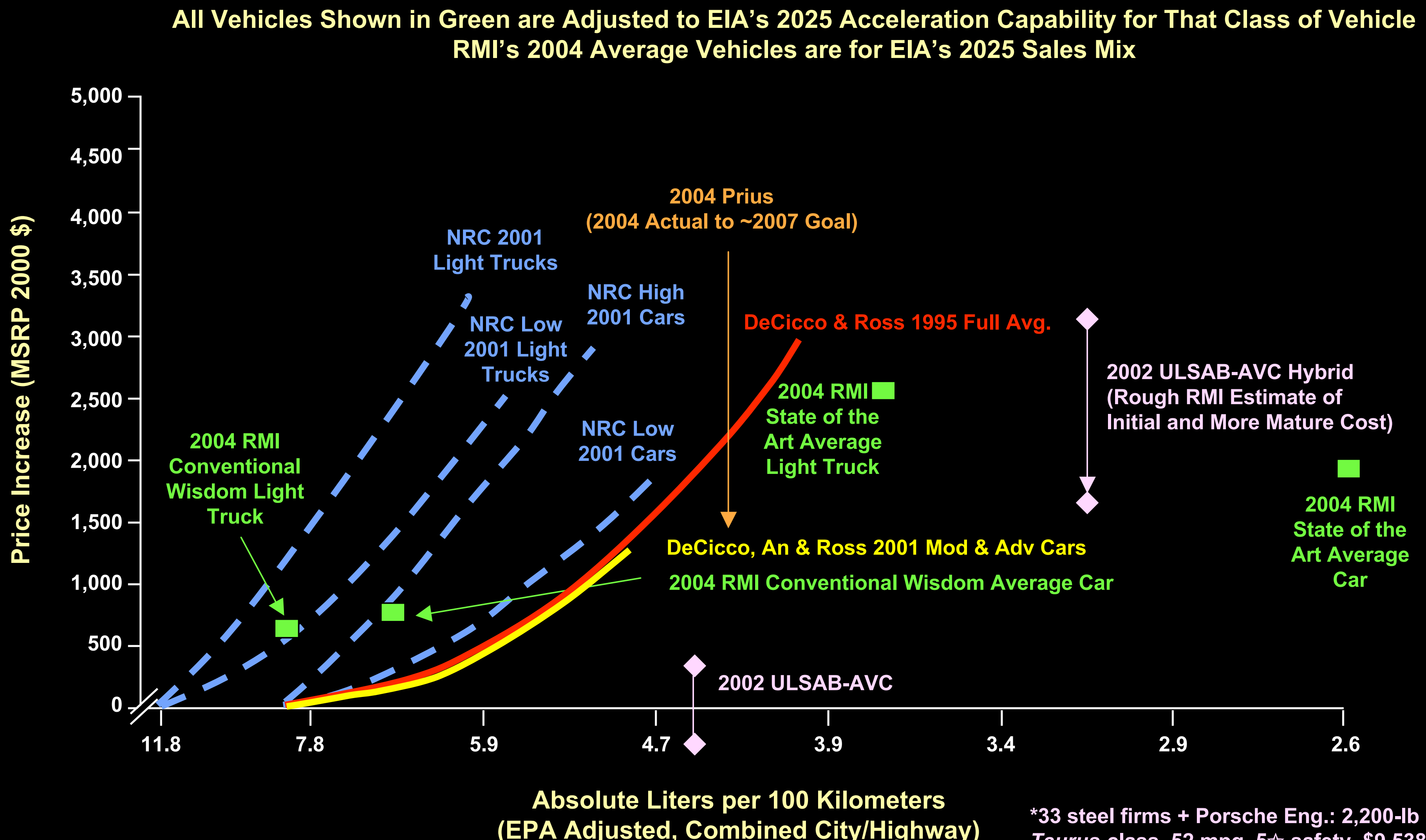
Three AWD *Revolution* variants with EIA 2025 acceleration (0–60 mph in 7.1 s)

	Audi *Allroad* 2.7T	*Revolution* gasoline ICE	*Revolution* gasoline hybrid	*Revolution* hydrogen fuel cell
curb mass (kg)	1,929	878	916	892
EPA adjusted mpg	18.5	44.6	66.0	107.8
Cost of Saved Energy* (2000 $/gal.) relative to:				
Audi *Allroad 2.7T*	0.	0.15	0.56	2.11
previous step	–	0.15	2.36	12.32
pretax price over Audi		1.6%	7.4%	31.9%
mpg increase over Audi		140%	256%	481%
change in annual fuel use @13,874 mi/y (2025 SUV)		–58%	–72%	–83%

*5%/y real discount rate, 14-y life, 0.10/y implicit capital recovery factor

- Crossover concept SUV designed with two Tier I's in 2000; combination of unique public & proprietary data
- Three powertrain variants resimulated by consultants
- Production cost independently analyzed at 499-line-item level of detail, largely by industry bids @ 50,000/y
- Scaled to all light vehicles by well-validated methods

Ultralight-but-safe light vehicles open a new doubled-efficiency design space at no extra cost



*33 steel firms + Porsche Eng.: 2,200-lb *Taurus*-class, 52 mpg, 5☆ safety, $9,538 production cost; BIW –52 kg, –$7

Emerging German innovation: Loremo 2+2 sports car (2009)

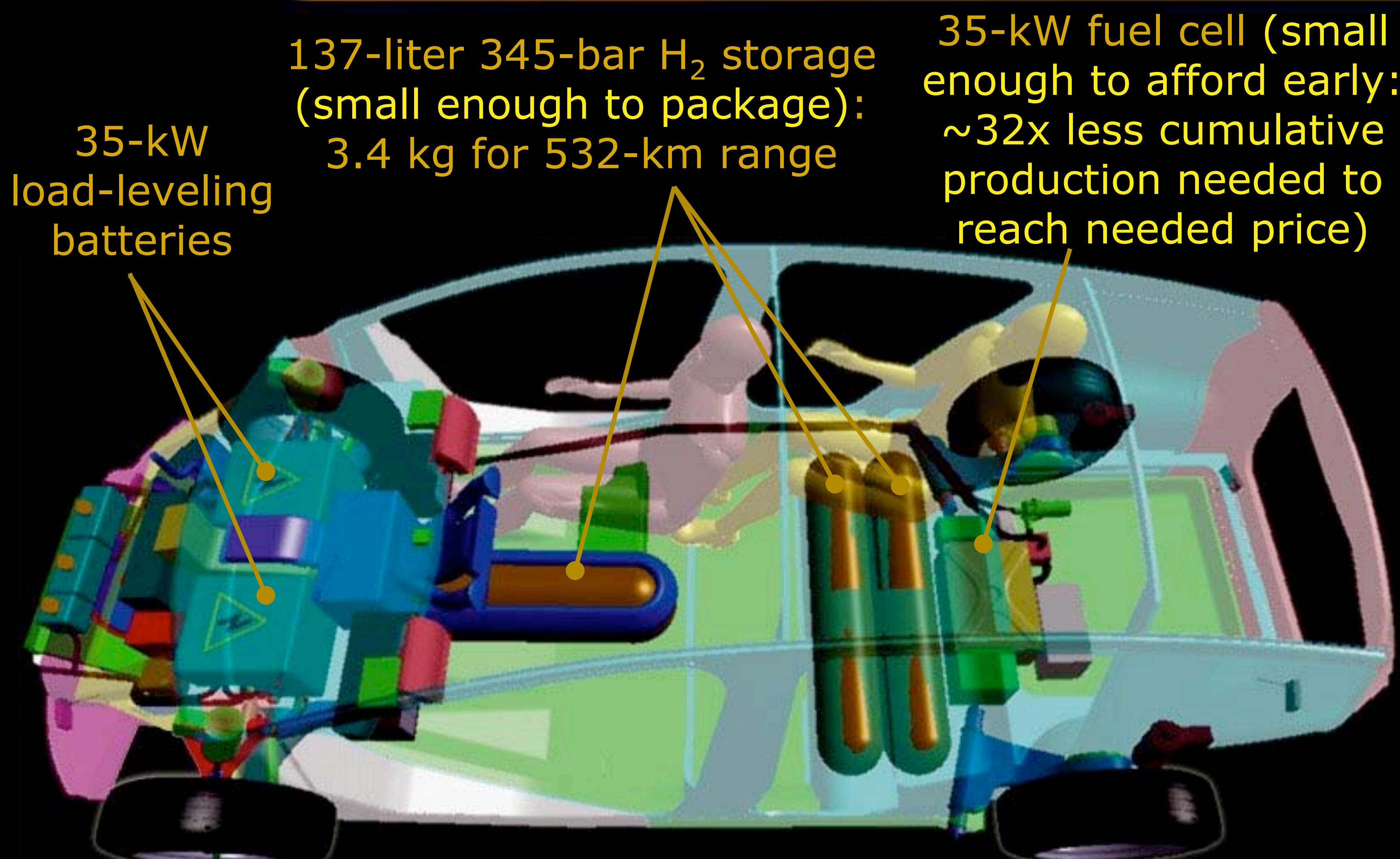
www.loremo.com

- German startup (München 2004)
- Light steel structure (95 kg) with side and center longitudinal beams
- Doorless; rearward rear seats/trunk
- 450 or 470 kg, C_w 0.20, C_wA 0.22 m^2
- Nonhybrid 2- or 3-cylinder turbo-diesel, 15 or 36 kW (20 or 50 hp), 5-speed manual transmission
- LS model: 1.5 L/100 km (157 mpg), 160 km/h, 0–100 km/h in 20 s
- GT model: 2.7 L/100 km (87 mpg), 220 km/h, 0–100 km/h in 9 s
- €10,990 or €14,990 in 2009

Stages of the emerging automotive [r]evolution

- An excellent hybrid, properly driven, doubles efficiency
  - Considerably more if new diesels can meet ratcheting air regs
- Ultralighting (+ better aero and tires) redoubles eff'y.
- Cellulosic-ethanol E85 quadruples oil efficiency again
  - Biofuels can make driving a way to protect, not harm, the climate
- A good plug-in hybrid (such as Toyota is rumored to plan for initial release MY08) redoubles fuel efficiency again, and could be attractive if the power grid buys its electric storage function
  - Precursor of "vehicle-to-grid" fuel-cell play—power plant on wheels
  - So far, these stages can save 97% of the oil/km used today
- Hydrogen fuel cells also compete via cheaper ¢/km and 2–6× less CO_2/km (or zero CO_2 if renewable)

857-kg curb mass (÷2), low drag, load ÷3, so 89 km/h on same power as normal a/c, so ready now for direct hydrogen fuel cells



Identical logic for HEVs, PHEVs, BEVs

Lightweighting cuts powertrain costs and enables advanced powertrains early

Example: fuel-cell vehicles with equivalent performance; same story for hybrids

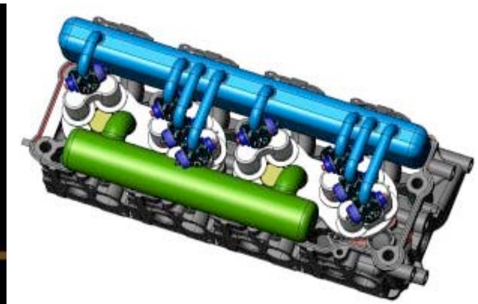


Vehicle	Power (kW)	Type	Cost @ $100/kW	Range (km)
Hypercar *Revolution*	**35**	**hybrid**	**$3,500**	**531**
Jeep *Commander 2*	50	hybrid	**$ 5,000**	190
Hyundai *Santa Fe FCV*	75	fuel cell	**$ 7,500**	402
Honda *FCX-V4*	85	fuel cell	**$ 8,500**	298
Ford *Focus FCV*	85	hybrid	**$ 8,500**	322
Toyota *FCHV-4*	90	hybrid	**$ 9,000**	249
GM *HydroGen III*	94	fuel cell	**$ 9,400**	402
GM Hy-Wire	94	fuel cell	**$ 9,400**	129


Platform physics is more important than powertrain—and is vital to its economics

- Cars can run clean IC engines on gasoline or NG ($\equiv 1\eta$)
- Better ones using hydrogen in IC engines ($\leq 1.5\ \eta$)
- Still better ones using H_2 in IC-engine hybrids ($\sim 2.5\eta$)
  - Ford "Model U" concept car…but tanks >4× bigger (niche market)
- Better still: ultralight autobodies, low $C_D A$ & r_0 ($\geq 3\eta$)
- Power those platforms with IC-engine hybrids ($3.5–4\eta$)
  - Hypercar 5-seat carbon *Revolution* has the same m_c & C_D as 2-seat aluminum Honda *Insight*…*Insight*-engine hybrid version 3.6L/100km
- Best: put fuel cells in such superefficient bodies ($5–6\eta$)
- **The aim isn't *just* saving fuel and pollution**
  - Also strategic goals in automaking, plug-in power-plants-on-wheels, off-oil, primary fuel flexibility, accelerated transition to renewables,…
- **H_2 needs 5η vehicles far more than vice versa**
- **5η vehicles make robust the business case for providing the H_2 that their fuel cells would need**

An example of emerging powertrain breakthroughs

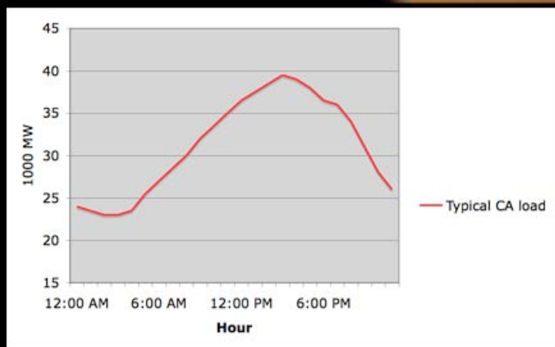


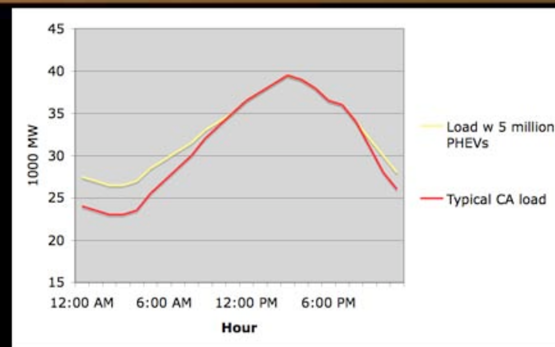
- Fast, small, light, cheap, proven, mature electronic valves permit extremely precise fuel and air injection under real-time closed-loop control
- This in turn permits unusual event sequences and combustion cycles in camless engines
- Those are expected to yield ~55–60% efficiency from any fuel (on the fly), with >50% higher torque, >30% smaller size, >10% lower cost, and extremely low emissions needing no cleanup
- The first such prototype “digital engine” ran 30 January 2007 in a test cell at Sturman Industries near Colorado Springs, Colorado; rapid progress (www.sturmanindustries.com)

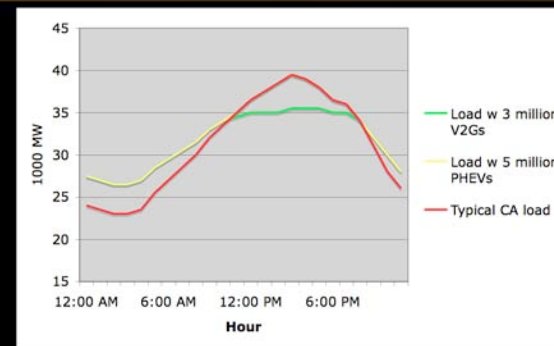
And what about plug-in hybrids?

- Better platform physics are the key to making PHEVs efficient and affordable
- PHEVs can further improve powertrain efficiency and, depending on fuel and power sources, emit comparable or less CO_2 per km driven
- PHEVs can charge with cheap offpeak electricity and sell valuable storage at peak hours back to the grid, paying for the batteries (which the utility may finance or own)
- PHEVs add offpeak storage to the grid, expand-ing markets for variable renewables (windpower)
- This needs a "smart garage"

Smart vehicle-to-grid (V2G) interface could be important







The grid could recharge PHEVs with previously spilled night windpower, then lop daytime peak

- Cars are parked ~96% of the time
- PHEV batteries or FCEV fuel cells in a superefficient U.S. light-vehicle fleet have ~6–12× total U.S. electric generating capacity, so even modest V2G displaces all coal/nuclear plants
- First ~2 million US drivers selling that capacity back to utility where/when most valuable could earn back entire car cost
- V2G Hypercar®-class vehicles could ultimately solve up to ~2/3 of the world's CO_2 problem
- Utilities love G2V: offpeak el. sales, ratebasing grid expansion, el.→transp. GHG shift, battery finance, hi-tech customer bundle

Today's cars: the highest expression of the Iron Age

- Extraordinary technical and commercial achievement, $1T/y industry
- The most complex mass-produced artifact in human history
- Produced every 2 seconds in the U.S. alone
- Costs less per kg than a McDonald's quarter-pound hamburger
- Meets demanding and often conflicting requirements with great skill
- But many reasons for rapid and fundamental change now emerging
  - convergent products and shrinking niches
  - in saturated core markets
  - at cutthroat commodity prices
  - with stagnant basic innovation
  - and growing global overcapacity
  - forcing increasing consolidation
  - yet thin profits limit investment & recruitment…
  - thus a great industry but a bad business
- Time for something completely different!

Does the frog leap?

- Incremental, component-level design, from engine toward wheels, emphasizing driveline gains
- Assume steel, gain mass
- Dis-integrated, specialist
- Huge design group (10^3)
- Relay race
- Lose most synergies
- Institutionalized timidity
- Baroque complexity
- Complex, hence difficult

- Whole-car, clean-sheet design, wheels-back, emphasizing platform physics *first*
- Ultralight, maximize mass decompounding
- Integrative, holistic
- Tiny design group (10^1)
- Team play
- Capture all synergies
- Skunk Works® boldness
- Radical simplicity*
- Simple, hence difficult

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

Is Detroit ready for transformation by such disruptive technologies?

- Tremendous engineering talent…if unleashed
- Weak balance sheets, slow innovation, many cultural and structural rigidities
- Tend to treat sunk costs as unamortized assets
  - Must base strategic choices on economics, not accounting
  - Must also consider cost per *car*, not per part or per kg
- Incoherence persists: lobbying and litigation strategy tends to stomp on internal innovation
  - GM's *EV-1*, 2001 anti-CAFE, now Pavley (California CO_2 law)
- But cultural obstacles are starting to weaken under the assault of Schumpeterian "creative destruction"
  - Better to embrace disruptive technology early than be forced into it late and grudgingly

Can Detroit use efficiency as a transformative strategy?

- Boeing’s crisis in 1997 was like Detroit’s today
  - Wrenching changes instituted at BCA, including TPS (*e.g.*, moving assembly); manufacturing and costs brought back under control
  - But what about growth? What was in the pipeline after *777*?
- In 2003, Airbus for the first time outproduced Boeing
  - “This is really a pivotal moment…could be the beginning of the end for Boeing's storied airplane business,” said Richard L. Aboulafia, a Teal Group aerospace analyst, in 2003
- Boeing’s bold, efficiency-led 2004 response: *787 Dreamliner*
  - ≥20% more efficient than comparable modern aircraft, *same price*
  - 80% advanced composite by volume, 50% by mass →
    - Bigger windows, higher-pressure cabin

  - 3-day final assembly (*737* takes 11 days)
  - 513 orders (490 firm + 23 pending), 314 additional options
  - Sold out until 2013—fastest order takeoff of any airliner in history
  - Now rolling out *787*’s radical advances to *all* models (Yellowstone)
- Airbus: Ultra-jumbo *A380*, 2 years late, ~€5b over budget
  - Response? Efficient, composite *A350*—probably too late

Key straws in the shifting winds of Detroit

- 2004: RMI suggests OEMs imitate Boeing
  2006: Alan Mulally, leader of Boeing Commercial Airplanes, becomes CEO of Ford
  - "[He] said the automaker would require a full transformation …of the product line and…of the business"—not the typical Detroit turnaround. —*New York Times*, 24 Oct 2006, p. 1
- OEMs' increasing openness to basic mfg. change
- UAW and dealers now pushing innovation as the best hope of saving the OEMs
- Emerging prospects of leapfrogs by China, India, and even new market entrants
- Competition, at a fundamental level and at a pace last seen in the 1920s, will change OEMs' managers or their minds, whichever comes first

Heavy trucks: save 25% free, 65% @ 25¢/gallon

Better aero & tires, better engines etc., less weight

PACCAR high-eff. concept truck

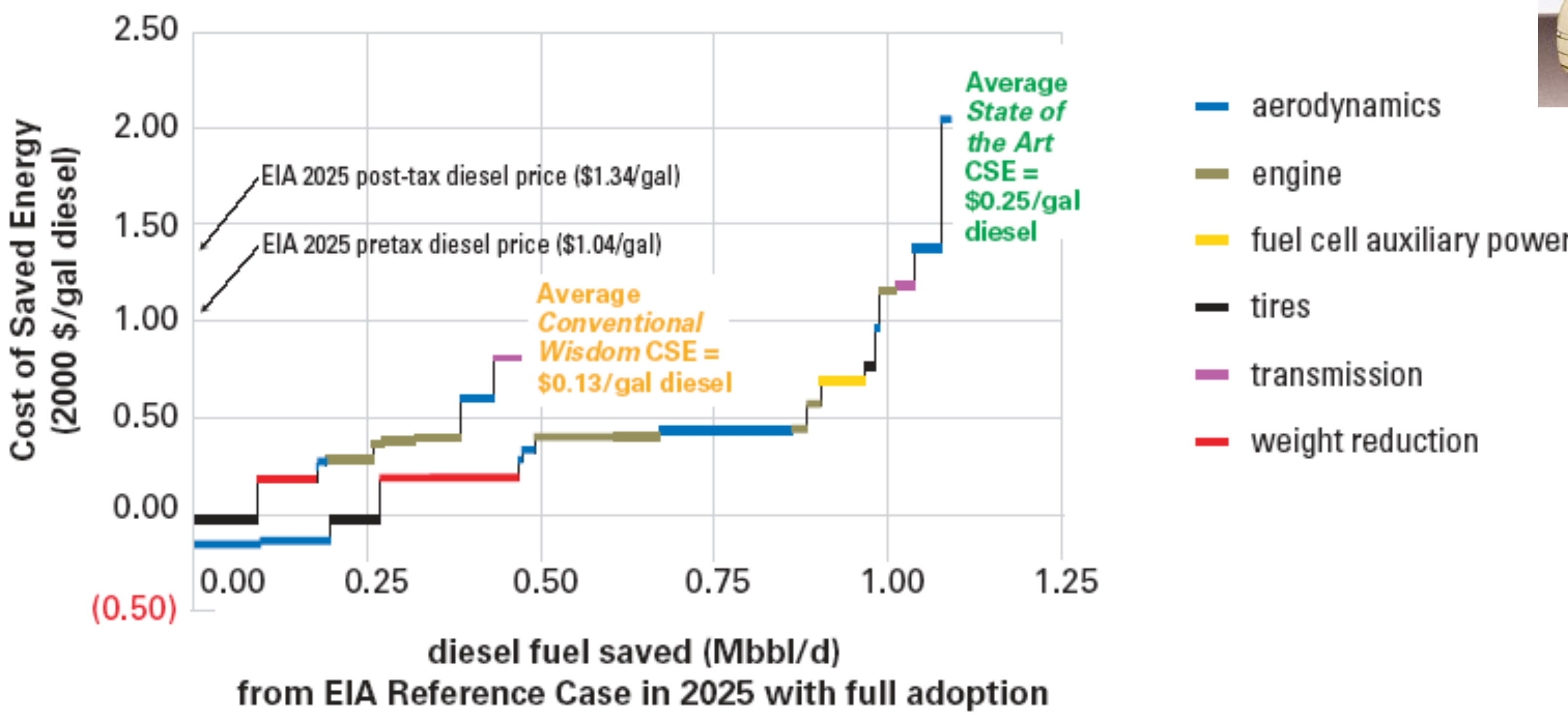
Colani/Spitzer tanker (Europe), reportedly 11.25 mpg

Two recent concept trucks

6.2 to 11.8 mpg with 60% IRR by improving aero drag, tires, engines, mass, driveline, acces. loads & APU; then ~16 mpg via operational improvements; being built 2005

Big haulers' margins double from 3% to 6–7%…so create demand pull —currently underway, led by major customers

Heavy trucks use 12% of all U.S. oil in 2025; 2004 technologies could save 65% of that use at 25¢/gal diesel



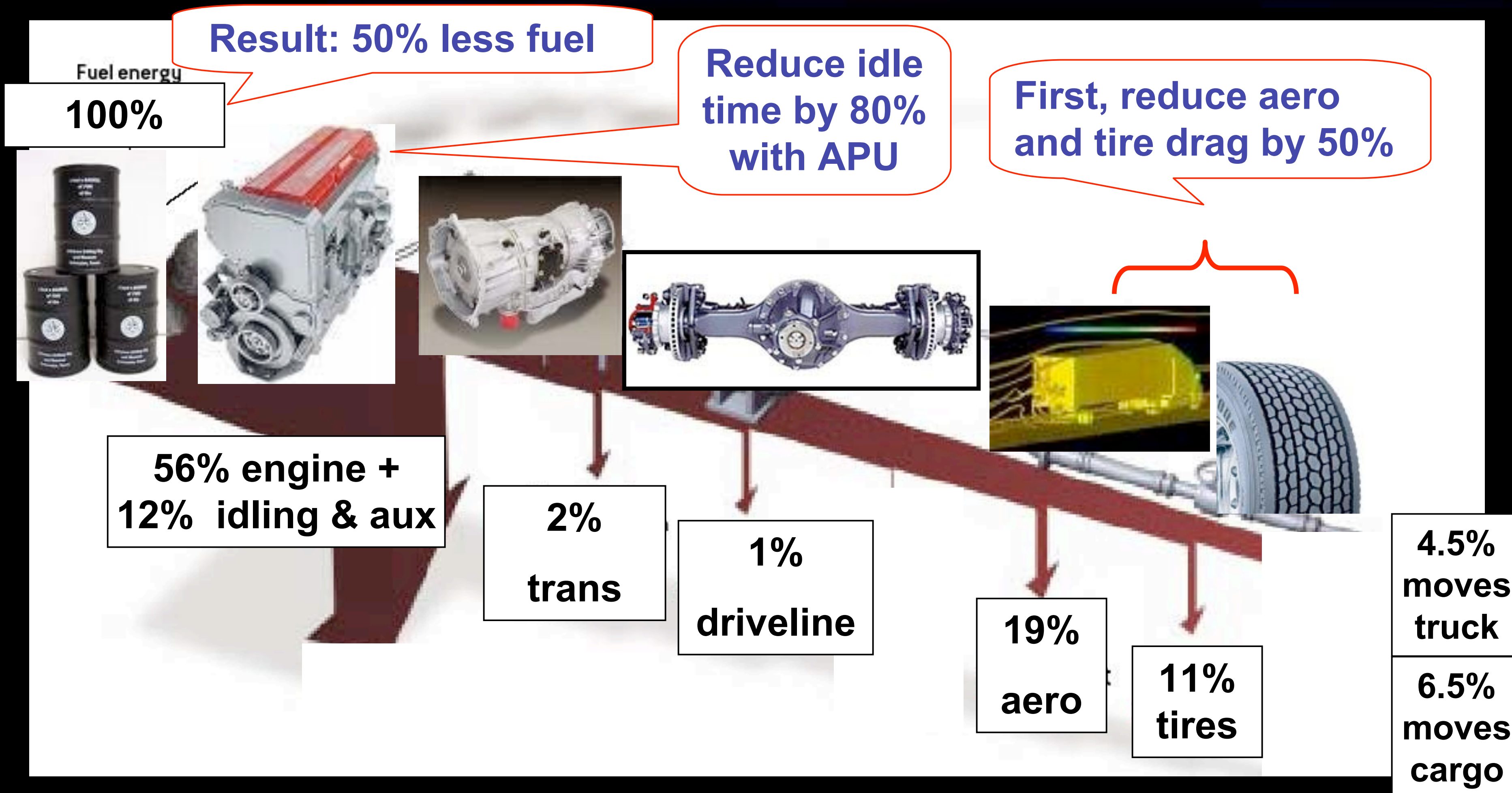
End: 11.8 mpg, then ~16-equivalent w/further improve-ments (we've since found ≥1.5 mpg more, excluding potential in basic logistics, de-materializa-tion, relocal-ization, lon-gevity, etc.)

Start: 6.2 mpg

RMI analysis in Tech. Annex 6, www.oilendgame.com. Main sources: MIT, ANL, industry tests

Losses and savings multiply

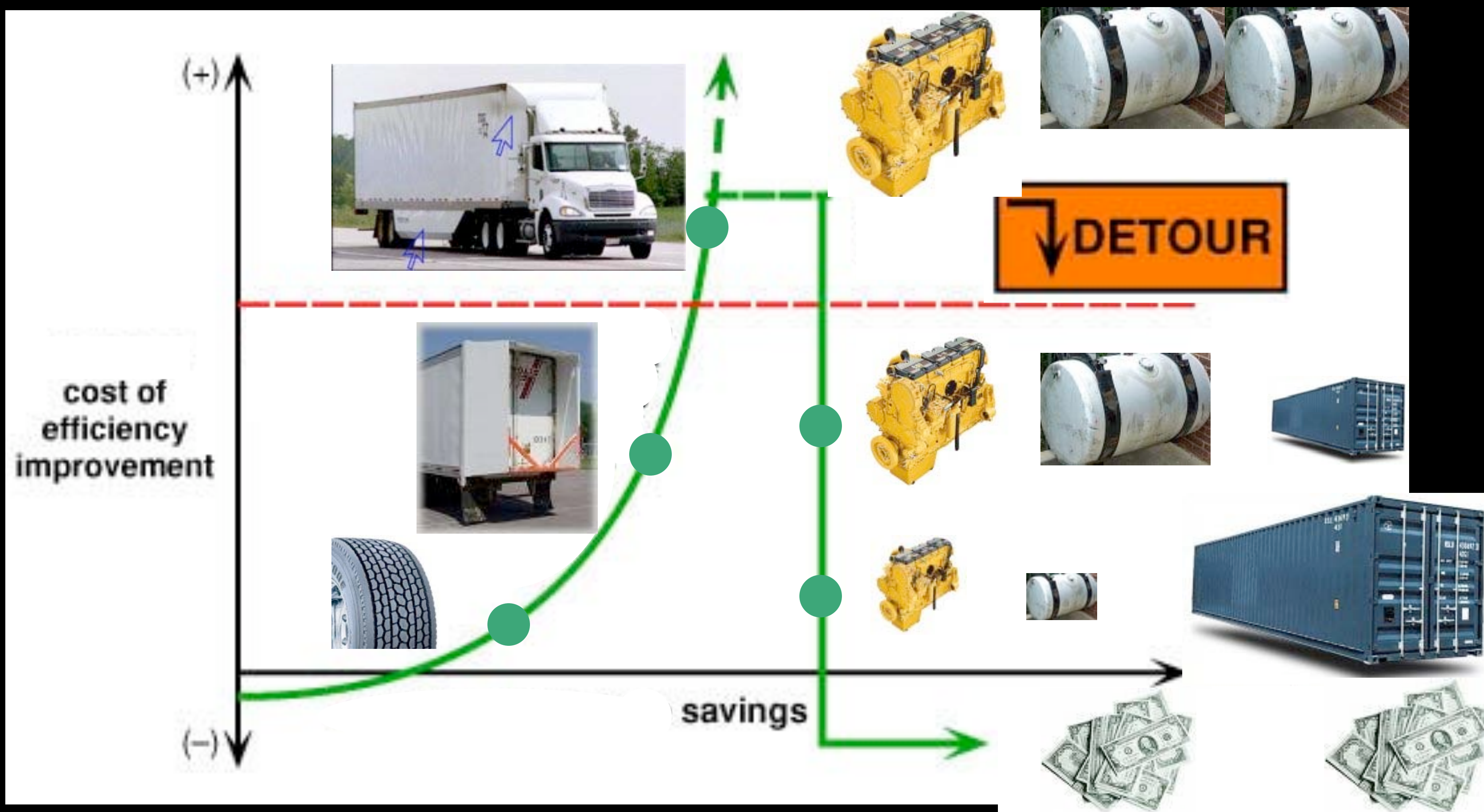
Savings *downstream* make upstream equipment smaller and cheaper



Each unit of avoided energy flow or friction in the pipe saves *ten* units of fuel at the power plant

This and following slide courtesy of M. Ogburn, RMI

New design mentality: “tunnel through the cost barrier”

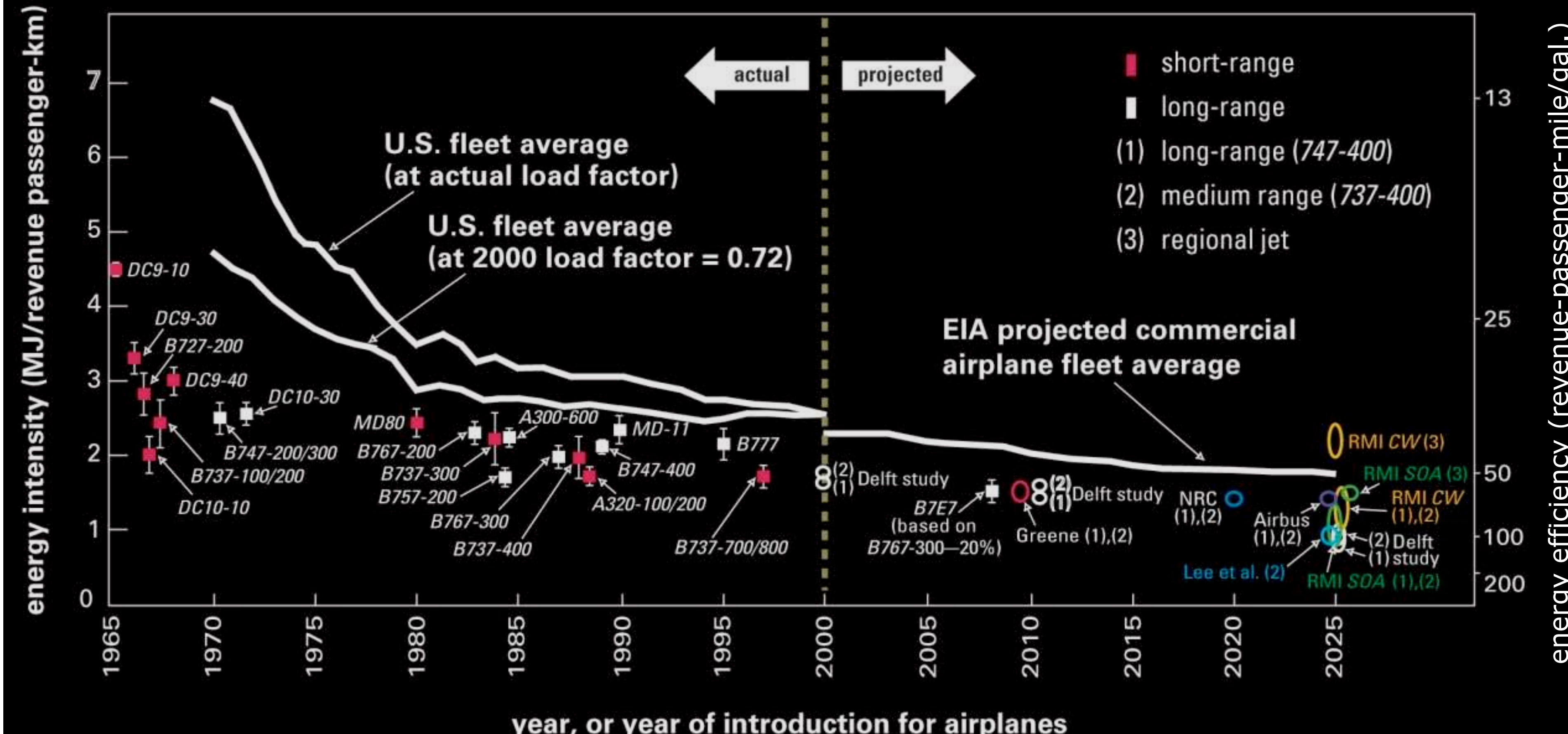


1. Multiple benefits from single expenditures
2. Piggyback on retrofits


Boeing 787 interior

Airplanes: industry agrees fleet can get 2–3× more efficient


NASA image of Blended-Wing-Body



- Keys: advanced composites, new engines, aerodynamics
- Could save 45% of EIA 2025 fuel @ av. 46¢/gal Jet-A without Blended-Wing-Body (BWB); ~65% with BWB at comparable or lower cost
- Then another ~2× profitable potential from LH_2-fuel-cell-electric-prop cryoplanes

Conservatisms include *no*…

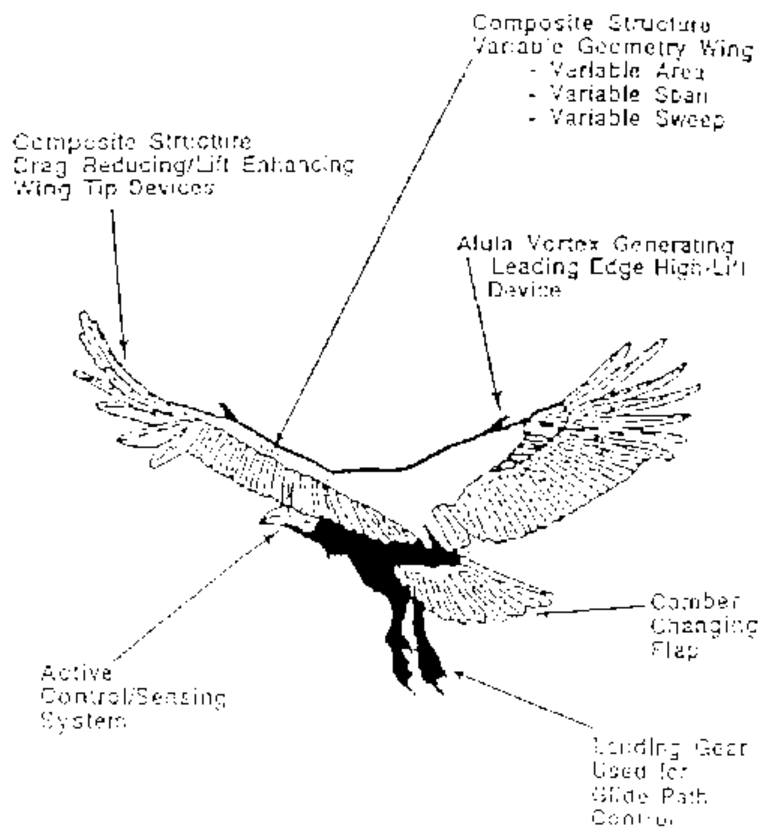
- Adaptive engines (ADVENT,…)
- Highly integrated adaptive structures, *e.g.*, morphing aircraft forms and flight surfaces
- Powered wheels, inductive runway integration
- Advanced electric end-use efficiency
- Efficient high-speed propeller propulsion
- Pneumatic blowing, plasma boundary-layer,…
- Full accounting for system benefits of integrating BWB, adaptive engines, and other advanced tech
- Leaner force structures (~5–10x fewer aircraft?) possible with new capabilities, especially BWB
- LH_2 cryoplanes

Ultramodern aeronautical technology embodied in a gliding bird

A California Condor (*Gymnogyps californianus*)

Important Aeronautical Technology Incorporated In Birds

- Mission Adaptive Wing
- Active Controls/ Control Configured Vehicles
- Composite structures
- Damage Tolerant Structures
- Fully integrated System Design
- Advanced Manufacturing Techniques



Courtesy of Dr. Paul MacCready, founder and Chairman, AeroVironment, Inc.

After kerosene (>2025), cryoplanes (liquid H_2 fuel) with zero carbon?

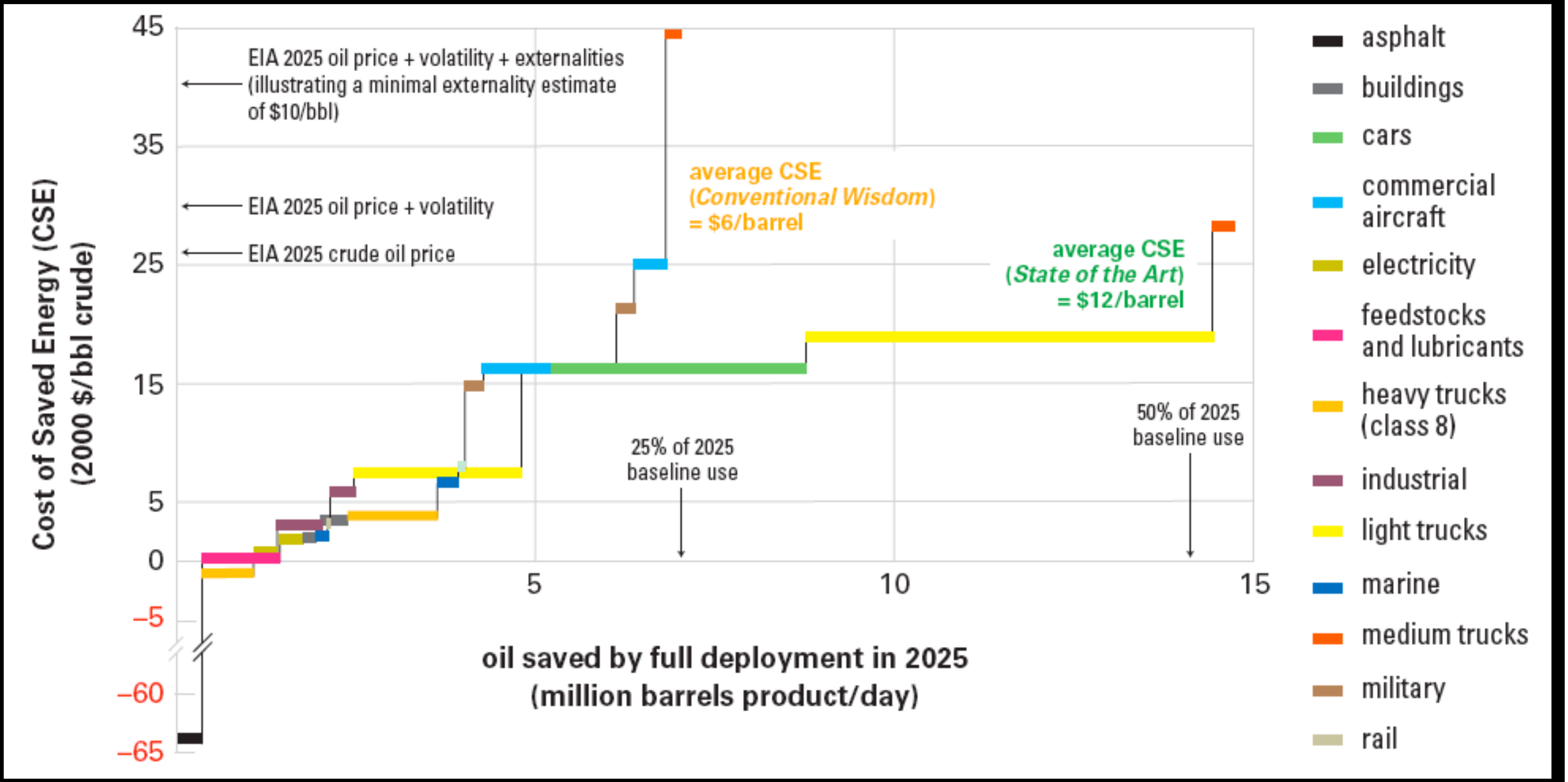
(*not* assumed in RMI's efficiency analysis)

- LH_2 is 4× bulkier but 2.8× lighter than Jet A—and clearly safer*
- Designed & tested: Airbus, Boeing, Tupolev *(TU-154* '88*)*, USAF
- Typical (*767*-class) Boeing study w/mass decompounding
  - Bad: empty weight (OEW) +8%, drag +11% (because bulkier)
  - Good: *takeoff* weight (MTOW) –24%, Initial Cruise Altitude Capability +13%, better climb characteristics, less engine maintenance burden
  - Net: ~4–5% better energy efficiency tank-to-flight based on airframe performance alone, or ~10–15% with H_2-optimized engines
  - Liquefaction 300→20K @ modern 4–5 kWh/kg (12–15% of LHV) roughly cancels airplane's efficiency gain; well-to-tank eff. is comparable to oil's
- –NO_x, 0 smoke/particulates/CO/HC/onboard CO_2; H_2O vapor?†
- Fuel cells are emerging for APUs—but maybe for propulsion too
  - P.M. Peeters (following NASA's Chris Snyder) thinks lightweight fuel cells & superconducting-motor unducted fans could *double* efficiency *vs.* LH_2 turbofan planes: his 415-seat conceptual design (7000 km, 0.75 LF) uses 55% less fuel than *747-400*; his 145-seater (1000 km, 0.70 LF) uses 68% less fuel than *737-400* (and at Mach 0.65, block time increases only 10%; might be *faster* if hubless, point-to-point, GPS-free-flight, ultralight, lower aero drag)
  - Thus ~20% long-haul and ~50% short-haul savings *beyond* RMI's analysis

*NASA-Glenn CR-165525 & CR-165526

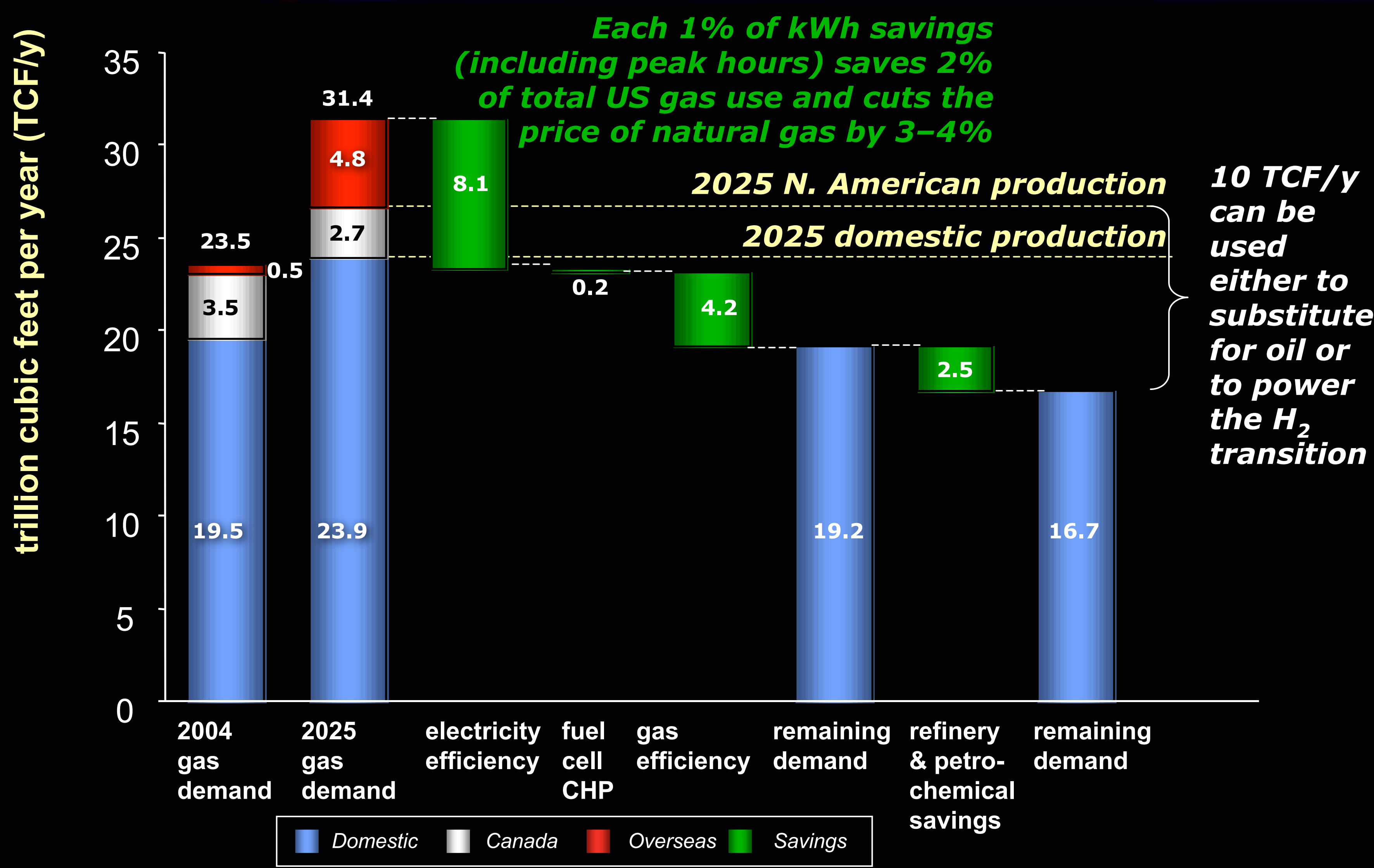
†Gauss *et al.* 2003, *J Geophys Res* **108**(D10):4304, say climate impact is ~15x smaller than avoided CO_2 (kerosene *vs* climate-safe hydrogen in a huge subsonic fleet), but do discourage stratospheric and polar flight

It pays to be bold: saving half the oil for $12/bbl is better than saving a fourth at $6/bbl — else alt. supplies cost too much

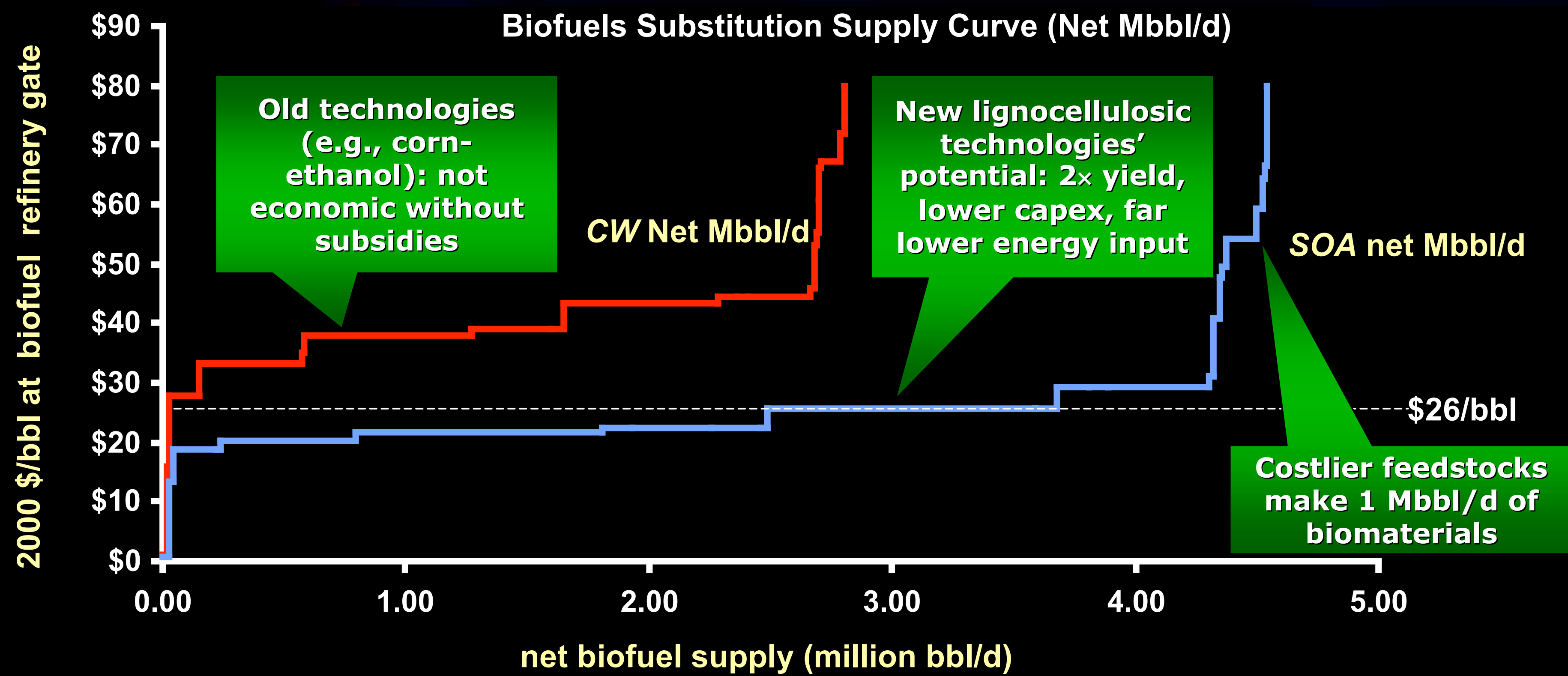


Hypothetically **assuming full deployment in 2025 (actually we realize half the savings by then); these curves assume *no further invention* in 2005–25**

>12 TCF/y (340 billion m³/y) of US natural gas could be saved by efficiency, at an average cost ~$0.9/GJ (~1/8th current price)

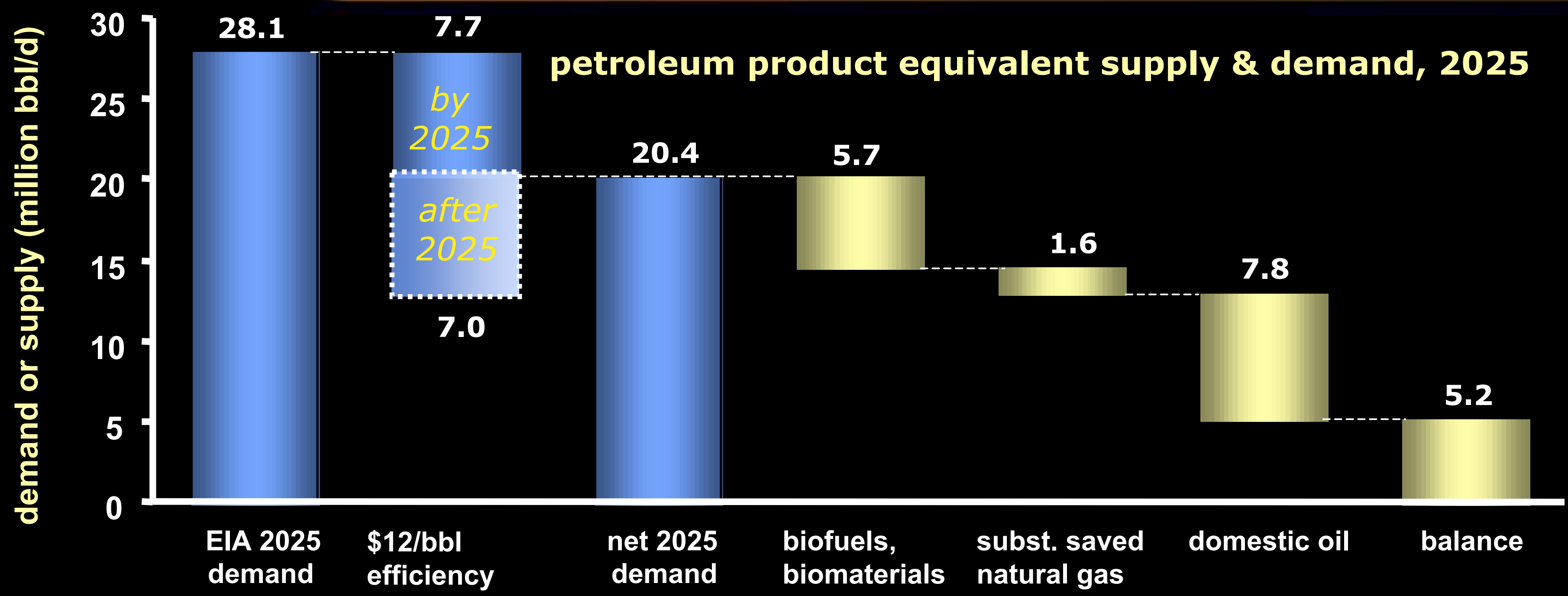


New biofuel technologies could provide 3.7 Mbbl/d cheaper than oil—without subsidies or crop/land/water problems



- Brazil has replaced 26% of gasoline with sugar-cane ethanol, competitive without subsidy (the startup subsidy has been recovered ~50× over)
- Sweden is going off oil by 2020 via cellulosic ethanol; also anticipates H_2
- Europe in 2003 made 17× as much biodiesel as US: oil companies distribute >50%; shifts farmers from subsidy to revenue

2025 demand-supply integration

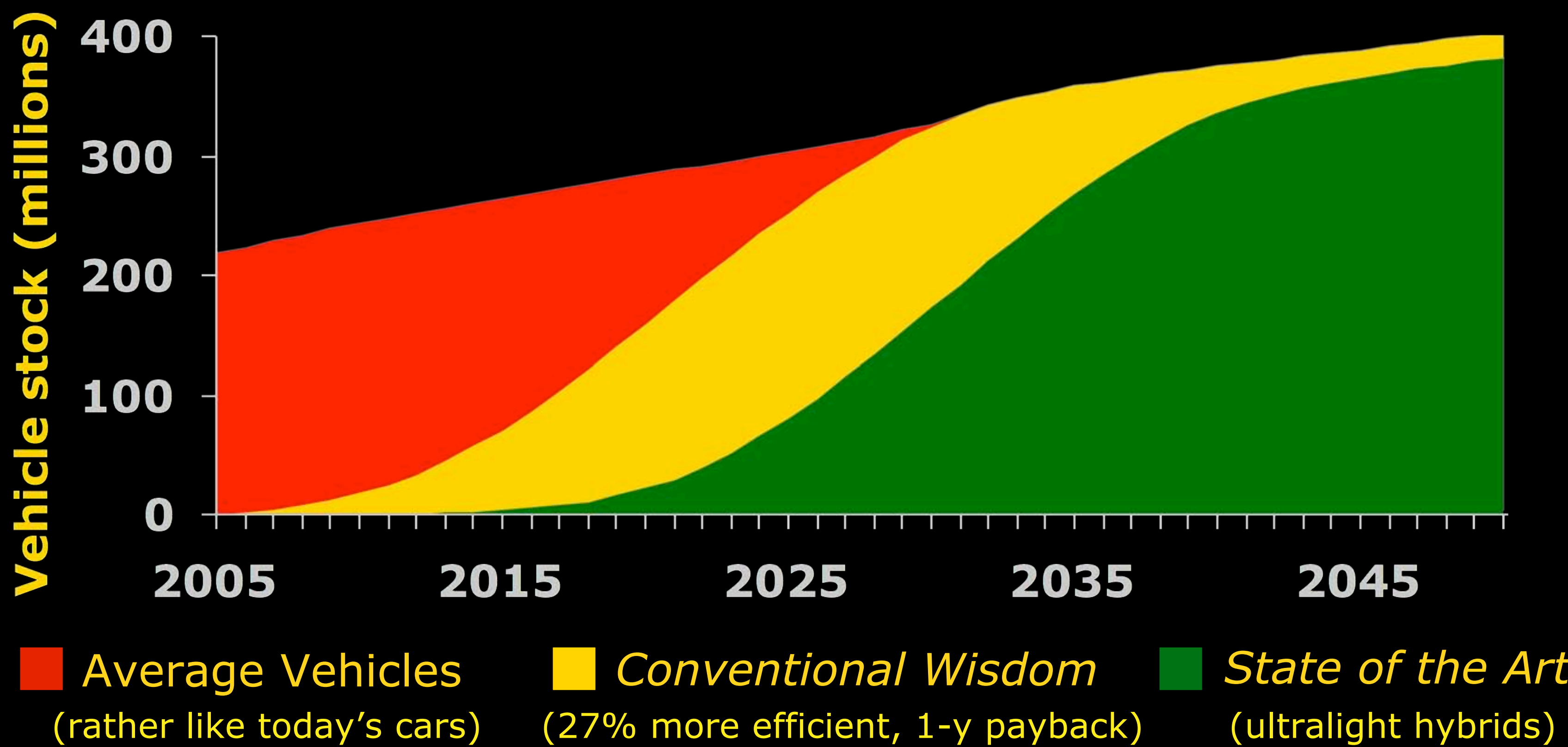


Great flexibility of ways and timing to *eliminate* oil in next few decades

- **Buy more efficiency (it's costing only half as much as the oil it replaces)**
- **Efficiency is only half captured by 2025—7 Mbbl/d still in process**
- **"Balance" can import crude oil/product (can be all N. Amer.) or biofuels**
- **Or saved U.S. natural gas @ $0.9/million BTU can fill the "balance"…or**
- **H_2 from saved U.S. natural gas can displace "balance" *plus* domestic oil**
- **Not counting other options, *e.g*. Dakotas windpower—50 MT/y H_2 source**

Mobilization: Accelerating Change

4.5 Mbbl/d saved, $391 billion in retail fuel savings



90–100% *State of the Art* vehicles by 2040

Big, fast changes have happened

- U.S. automakers switched in **6 years** from 85% open wood bodies to 70% closed steel bodies—and in **6 months** from making four million light vehicles per year to making the tanks and planes that won World War II
- Boeing transformed its planes in **4 years**, 2004–08
- GM's small team took *EV1* from launch to street in **3 years**
- Major technological diffusions take **12–15 years** for 10%→90% stock adoption, but policy can speed takeoff by 3 years
- In 1977–85, U.S. cut oil intensity 5.2%/y—equivalent, at a given GDP, to a Gulf every 2.5 years
  - Biggest contribution: U.S.-made new cars gained 7.4 mpg in 6 y (47%, 4.9%/y)—96% from smarter design, only 4% from smaller size
- If every light vehicle on the road in 2025 were as efficient as the best 2004 cars & SUVs, they'd save twice as much oil as the U.S. now imports from the Persian Gulf

Military energy efficiency: "endurance" as the emerging fifth strategic vector

- After speed, stealth, precision, networking…
- DoD is increasingly handicapped by half-century-old pattern of using & getting energy, designed for massive steel forces "floating to victory on a sea of oil"
  - 6/7ths of fuel that defeated Axis came from Texas; today, war-fighting is 16× more oil-intensive, and Texas is a net importer of oil
- Today's warfighting needs just the opposite—unprecedented agility, mobility, maneuver, range, persistence, reliability, autonomy, low cost—via inherently far greater "endurance"
- Fat fuel-logistics tail now a magnet for insurgents, a serious military liability, and a huge financial burden
- DoD needs less/little/no reliance on long, brittle supply chains… and ≥3–4× lower platform fuel consumption, which is feasible
- Yet DoD has assumed fuel logistics to be free and invulnerable
- Major strategic shift to efficiency now emerging

Dramatic gains in combat effectiveness *and* energy efficiency are available in almost all military uses, *e.g.*:

(scaled-down wind-tunnel model)

BWB quiet aircraft: range & payload × ~2, sorties ÷ 5–10, fuel ÷ 5–9 (Σ 2–4)

SensorCraft (C⁴ISR): 50-h loiter, sorties ÷ 18, fuel ÷ >30, cost ÷ 2

VAATE engines: loiter × 2, fuel – 25–40%, far less maintenance, often lower capital cost

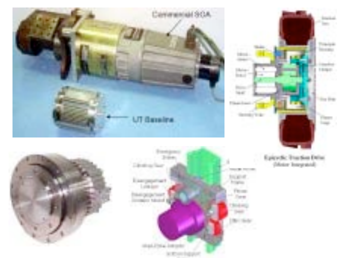
Optimum Speed Tilt Rotor (OSTR): range × 5–6, speed × 3, quiet, fuel ÷ 5–6

Re-engine *M1* with modern diesel, range × ≥2, fuel ÷ 3–4

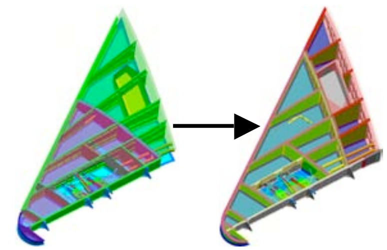
More lethal, highly IED-resistant, stable *HMMVV* replacement, weight ÷ 3, fuel ÷ >3

Hotel-load retrofits could save ~40–50% of onboard electricity (thus saving ~1/6 of the Navy's non-aviation fuel)

FOB uses 95% of gen-set fuel to cool desert; could be ~0 with same or better comfort

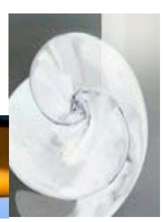


Actuators: performance × 10, fault tolerance × 4, size & mass ÷ 3–10



25% lighter, 30% cheaper advanced composite structures; aircraft can have ~95% fewer parts, weigh ≥1/3 less, cost less

Advanced propulsors can save much noise and fuel



Rugged, 2.5-W PC, $150, solar + back-up crank

A zero-net-energy building (it's been done in –44˚ to 46˚C at lower cost)

160-Gflops supercomputer, ultrareliable with no cooling at 31˚C, lifecycle cost ÷ 3–4

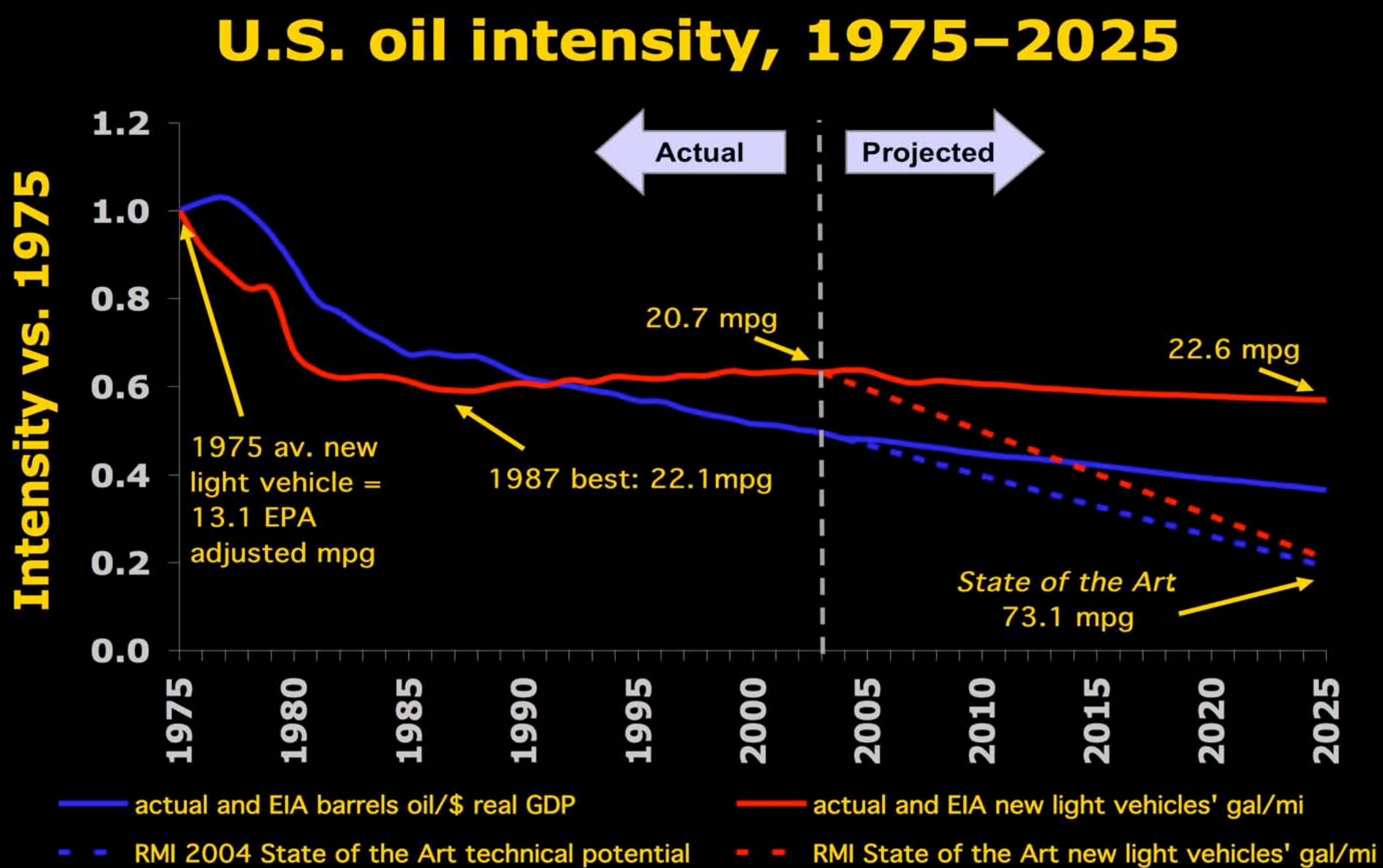
What if DoD investment in advanced light materials could transform the U.S. economy as profoundly as Internet, GPS, and chips?

- Advanced materials & propulsion systems can find a Saudi Arabia (>9 Mbbl/d) of saved oil under Detroit & Seattle…
- …and help DoD transform its forces, strengthen warfighting capability, and cut fuel cost by billions of $/y and logistics cost by tens of billions of $/y
- The U.S. could cut oil use by 50% by 2025, imports by 75%
- The key DoD action needed is S&T investment in advanced materials, especially high-volume/low-cost manufacturing

The prize

- A nega-Gulf every 7 y
- Vastly less world dependence on oil and conflict over oil
- A competitive Big 3
- Cheaper oil; more balanced U.S. trade, global development, and diplomacy
- More capable and confident warfighting
- Less need for it
- A safer world

Even 100% (not ~55%) implementation by 2025 would occur at reasonable speed



Implementation is underway via "institutional acupuncture"

- RMI's 3-year, $4-million effort is leading & consolidating shifts
- Need to shift strategy & investment in six sectors
  - Aviation: Boeing did it (*787 Dreamliner*)…and beat Airbus
  - Heavy trucks: Wal-Mart led it (with other buyers being added)
  - Military: emerging as the federal leader in getting U.S. off oil
  - Fuels: strong investor interest and industrial activity
  - Finance: rapidly growing interest/realignment will drive others
- Cars and light trucks: slowest, hardest, but now changing
  - Alan Mulally's move from Boeing to Ford with transformational intent
  - UAW and dealers not blocking but eager for fundamental innovation
  - Schumpeterian "creative destruction" is causing top executives to be far more open to previously unthinkable change
  - Emerging prospects of leapfrogs by China, India, ?new market entrants
  - Competition, at a fundamental level and at a pace last seen in the 1920s, will change automakers' managers or their minds, whichever comes first—watch this space!

There have been some skeptics….

Getting off oil, you say?

Now they’re more interested

Innovative public vehicles too
(though our analysis assumes none)

- Novel *ultralight rail* (www.cybertran.com) w/system cost ~$2.5M/km or $15k/seat; in testing at Alameda Naval Air Station

CyberTran test vehicle, ~$100k, 12m L, 2m H & W, 6–20 seats w/122-cm pitch, 4 doors on each side, 149 kW, 3.4 T empty, 4.54 T loaded, 30–240$^+$ km/h, styled to taste; guideway for two lanes can be retrofitted over a typical road median, yielding 1.3–2.1× more seats/system mile than a saturated 4-lane road; *cf.* ULTra, www.atsitd.co.uk, and Austrans, www.austrans.com/index.php

- Curitiba (Brazil) "surface subway" bus system

  - 3/4 of commuting in Houston-sized city, beats cars
- T.U. Delft highway "Superbus" for 2008 Olympics
  - "Triple stretch limo," 0.1 MJ/p-km (<TGV, <maglev) @ 250 km/h, 2.5m W × 50m L, 2 m high at cruise, C_D 0.18, 6 T GWV (n=25)

The solution is not just technical: transportation is a means, not an end

- The aim is to get *access* to where we want to be
  - Be there already (sensible land-use)
  - Virtual mobility (move only electrons)
  - Physical mobility (move protoplasm…but how?)
    - Walking
    - Personal vehicle (bicycle, scooter, motorcycle, car,…)
    - Shared personal vehicle or public vehicle
- How far does public policy let trips and negatrips compete fairly—not just transport modes?
- What if we stopped mandating/subsidizing sprawl?
- What if drivers got what they paid for *and* paid for what they got? if all modes, & negatrips, competed?
- All key Qs…but focus here is on *vehicle technology*
  - Whole-*system* efficiency potential is far larger (~10x)
  - Even better styling flexibility; if it's not efficient, it's not beautiful

Peeling layer upon endless layer of the tears-free efficiency onion…

- *Beyond Hypercars® (4–6×)*: transport demand mgt; mode-switching (Curitiba/Bogatá/Lima bus, Cyber-tran™, hybrid bikes…); vehicle-sharing (Stattauto, ZIPcar,…); mobility-/access-based business models (mobility.ch…); don't mandate/subsidize sprawl…: 10×
- *Beyond efficient aircraft (2–5×):* big operational gains at airport & system levels; point-to-point in smaller aircraft (hubless w/gate & slot competition); air taxis; mobility-/access-based models; virtual mobility…: 10×
- *Beyond efficient trucks (2–3×):* trains, logistics,…: 10×
- This is what we can now clearly see as practical and profitable—but innovation will probably continue

Time to reinvent the wheels…

“Sometimes one must do what is necessary.”

— Churchill

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