Advanced Light Vehicle Concepts

Briefing Notes for the Committee on Fuel Economy
of Automobiles and Light Trucks

Energy Engineering Board
Commission on Engineering and Technical Systems
U.S. National Research Council

Workshop on "An Evaluation of the Potential
and Prospects for Improving the Fuel Economy
of New Automobiles and Light Trucks in the
United States," 8-12 July 1991

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by Amory B. Lovins
Director of Research
Rocky Mountain Institute
1739 Snowmass Creek Road
Snowmass CO 81654-9199
303/927-3851, FAX -4178

Abstract: *Bigger, cheaper fuel savings can come from more and better technologies, capturing synergisms, "tunneling through the cost barrier" with lightweight integrated assemblies that save parts and labor, and basic redesign using radically simplifying aerospace systems concepts. Technological leaps are important for oil-saving, environment, affordability, and the car industry's competitiveness.*

Introduction

I'm grateful for your invitation to explore new ways to extend the art and science of carmaking. Twenty-odd years' worldwide work on energy efficiency have convinced me that:

- major gains in car efficiency will be generally easier and cheaper to achieve in the future than they were in the past, because big new technical opportunities are emerging faster than old ones are being used up;
- doing this right can support rather than conflict with simultaneous improvements in emissions, CFC use, and safety; and
- the formidable engineering talents represented in this workshop can produce affordable, peppy, safe, comfortable family cars that clobber 60 rated composite mpg, approach 100 mpg, and promise significant further progress.

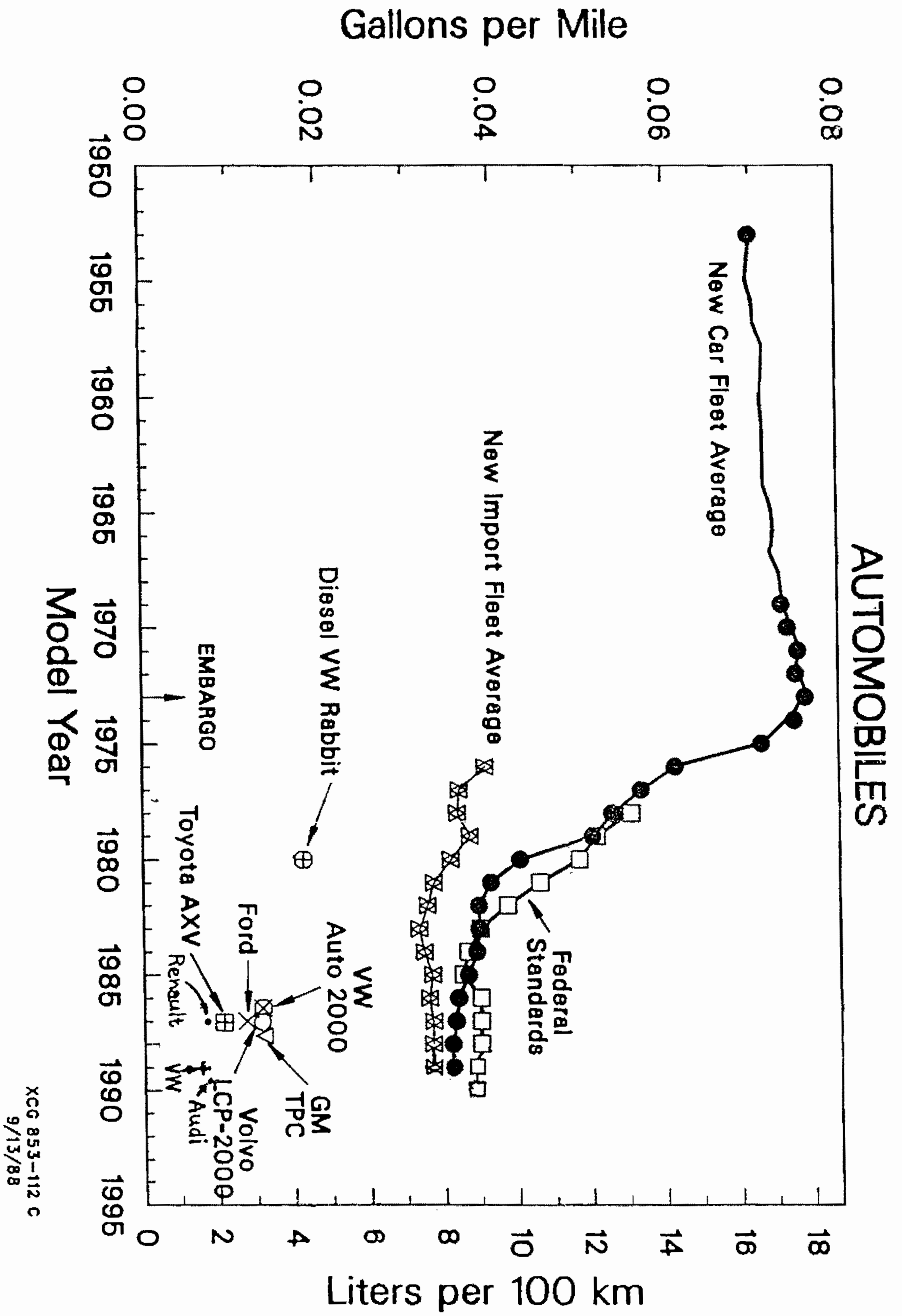
Whatever exists is possible. My sporty, 1,834-lb two-seater averages 60 actual mpg (it's EPA-rated 49/52/*50.4*, but I live at 7100' with 27% less air, hence less drag, and almost no city driving). More importantly, Debbie Bleviss will describe some of the dozen-odd prototype cars already tested, often over five years ago, in the composite ~67-120+ mpg range. Each of these prototypes has unique peculiarities, but collectively they show that peppy, crashworthy cars can be built that carry up to five people at ~100+ mpg and at standards of amenity acceptable to many people in the most advanced industrial countries. For reasons I'll describe, at least two of those prototypes should cost approximately nothing extra to mass-produce. I'll discuss how we can do that well -- and then, with different designs, better -- with considerable flexibility in interior volume and performance.

These remarks are about technology, not policy. However, it is just as important to condition a market as to make cars to sell in it. Along with copies of all my overhead slides, I'll hand out a short memo on a market-oriented way to get clean, efficient cars on the road and dirty, inefficient cars off the road while greatly benefitting the auto industry.

The halving of new-car fuel intensity since 1973 *[see time-series overhead]* is an impressive technical achievement, especially while improving safety and emissions and maintaining comfort. (Phil Patterson found that only 4% of that doubled efficiency came from making cars smaller; the rest came from making them smarter.) But today, many analysts say that all the low-hanging fruit has already been picked -- that we are nearly out of ways to make far more efficient cars that Americans would want, and could afford, to buy and drive.

I've heard that before. It's what many designers of buildings and industrial processes say about saving electricity. But while it may have been right five or ten years ago, it's wrong today. New technologies (most of the best less than a year old) and new ways to combine them can now save twice as much electricity as was possible five years ago, and at only a third the real cost. That's a sixfold gain in cost-effective potential in five years, and nearly 30-fold in ten years. This "negawatt revolution" even appears to be accelerating through interactive advances in diverse technologies. Perhaps the most important source of progress is a better understanding of how best to combine the best ingredients into integrated packages so as to take advantage of their cost-saving and performance-enhancing synergisms.

So I ask you for the next few minutes to indulge me in the hypothesis that something like this is now ripe to occur in light-vehicle efficiency too: that the auto industry today has a remarkable opportunity to capture design synergisms that can help to leapfrog over the levels and costs of achievement normally considered.


Gallons per Mile
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AUTOMOBILES
New Car Fleet Average
New Import Fleet Average
Diesel VW Rabbit
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Federal Standards
VW Auto 2000
Ford
Toyota AXV
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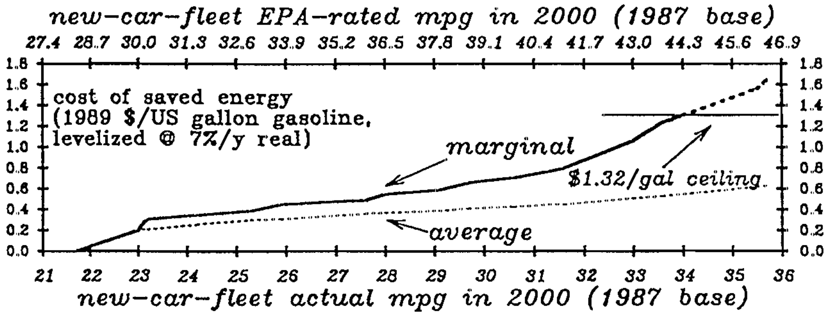
MAKING AFFORDABLE, SUPER-EFFICIENT LIGHT VEHICLES

Conventional, incremental extensions of carmaking art typically have supply curves rather like this:



The savings with marginal cost cheaper than gasoline correspond to saving 2.1 quadrillion BTU/y in 2000 and 4.9 quads/y in 2010.

SOURCE: Difiglio et al. *[DOE] + idle-off and aggressive transmission management (Ledbetter & Ross 1990)*

The 17 available, cost-effective measures shown can maintain average 1987 new-car size, ride, and acceleration with ~35% fewer gal/mi: ~33.6 actual (~43.8 rated) mpg at ~53¢/gallon average internal cost. Similar light-truck savings ~72% as big would cost half as much. But we can do better: e.g., if GM's Impact used gasoline ~33% as efficiently as it uses electricity, its 0.15 $\mathrm{kW_{e\text{-}in}}$-h/mi would be 80 mpg (or ~93 mpg counting the half-as-heavy powertrain).

How can we drive the supply curve down toward the lower right, saving more fuel at lower cost (subject to boundary conditions of amenity, safety, emissions, and performance)?

1. **Substitute optimizations for crude conservatisms.**
2. **Add omitted technologies.**
3. **Count omitted synergisms.**
4. **"Tunnel through the cost barrier" with new materials that reduce parts count and assembly labor.**
5. **Redesign more simply with aerospace systems concepts.**

1. Substitute engineering optimizations for crudely conservative assumptions.

For example, the supply curve shown for 2000 assumed:

- drag coefficient 0.3 (= Ford Sable etc., <0.37 1987 av.); but much better -- even 0.2 or less -- is achievable: Peugeot 405 0.29, Toyota AXV 0.26, GM Impact 0.19, Renault Vesta II prototype 0.186, Ford Probe V prototype 0.137.
- unchanged curb weight ~2,800 lb, far above some 4- and 4/5-passenger designs (VW Auto 2000 ~1,700 lb, Peugeot 205XL 1,687 lb, VW E80 diesel 1,540 lb, BL ECV-3 1,460 lb, Toyota AXV diesel 1,430 lb, Renault Vesta II 1,043 lb, Peugeot ECO2000 990 lb). Indeed, Flemings et al. (MIT Materials Science) told OTA in 1980 that a U.S. car fleet averaging 2,000 lb and ~50 mpg could be achieved by materials substitution alone. (Each 200 lb reduction improves composite fuel economy by ~5%.)

2. Add omitted technologies. Three examples:

- Eliminate brake drag with better retractors.
- Replace remaining V-belts with nonstretch synchronous belts. This saves ~5-15+% of power transmitted, with strongly negative net cost because it saves maintenance, and permits lighter shafts and lower-friction bearings.
- Use a closely-coupled switched reluctance motor as the generator and starter-motor -- eliminating the starter-motor, solenoid, etc. and their weight and maintenance, improving C_D, and offering a slight power boost and regenerative braking. (VW/Bosch's Hybriddrive already replaces the flywheel, starter-motor, and alternator.)

A digression on switched-reluctance motors

Over 300 person-y and $40M (1991 $) of effort since the late 1960s have made Switched Reluctance Drives Ltd (Leeds, U.K.) the world leader in motors that generally outperform induction, DC, synchronous, and servomotors in size, weight, versatility, reliability, ruggedness, and cost. This requires exceptionally integrated understanding of motor design, micro- and power electronics, and especially software.

These electronically commutated motors have a different number of rotor and stator poles, both salient. The rotor is laminated iron (no magnets, bars, or windings), has low inertia and high strength, and runs "cold." Fail-safe, soft-start, variable-speed power electronics, driven by sophisticated software and firmware on hybrid power chips, provide optimized stator excitation. With possibly only one switch in series with each winding, the electronic components are cheap, simple, and very robust. Noise is less than with an inverter-fed induction motor. Shape is extremely flexible -- short/fat, long/thin, etc. Sizes can be mW to MW, with up to 270-400 hp now commercial. Speed is limited only by rotor strength.

Throughout the speed range of 0-30,000+ rpm and in all four quadrants, the torque/speed curve is under full real-time software control, performance can be symmetrical, and torque and braking strength can be arbitrarily shaped. Starting torque is up to 500+% of rating at startup and 250% at low speed, where torque ripple can be <0.05%. SRDs have continuously rated low-speed (20-30 rpm) torque ~1.8->4x higher than same-frame induction motors.

Efficiency is very high over almost the whole speed/torque range, and can be automatically optimized: ~0.93 @ 3½ hp has been obtained from designs like standard-, <ins>not</ins> high-efficiency, induction motors, leaving several percentage points to go. Even at very high torques and low speeds, temperature rises are modest, and heat, being all in the stator, is readily extracted from the motor case, so peak and continuous ratings can be nearly identical. Application-specific densities per active stator volume can include e.g.:

- 0.036 hp/in^3 (1.66 kW/l) and 0.13 ft-lb/in^3 (10.6 Nm/l) for a TEFC 1,500-rpm 132-frame industrial model,
- 0.056 hp/in^3 (2.55 kW/l) and 0.20 ft-lb/in^3 (16.2 Nm/l) for a through-ventilated variant,
- 1.15 hp/in^3 (52.3 kW/l) and 0.12 ft-lb/in^3 (10.0 Nm/l) for an oil-cooled 50,000-rpm aerospace version.

High torque/inertia ratios permit e.g. a fist-sized 1-kW model to toggle in <50 ms between +3,000 and -3,000 rpm. The rotor can be shaft-integrated with e.g. a fan or impeller.

The simplicity of the circuit and its small switch sizes (due to more torque/A) make the electronics smaller and cheaper than for induction and DC drives. The design is highly fault-tolerant; operation continues despite most faults, and fault cutout/detection/management are easily automated.

SRDs are normally 1-2 frame sizes smaller than standard-efficiency ASD-controlled induction motors with the same torque, are 4-20 percentage points more efficient (without using high-efficiency motor materials), and on a like-for-like basis have whole-system cost ~15-40% lower: e.g., \$10-14/kW in the ½-kW range at ~10^5/y production in 1991.

3. Count omitted synergisms.

Synergisms let single expenditures yield multiple benefits.

First an example from the more efficient use of electricity:

Most analyses of electric drivepower systems count only two technologies (high-efficiency induction motors and adjustable-speed drives), which save ~23% of motor-system energy at average cost >2¢/kW-h. However, an RMI systems analysis found in 1989, and EPRI concurs, that adding 33 more improvements to the motors, electric supplies, controls, and mechanical drivetrains at least doubles the savings -- to ~50%, or ~160 GW nationwide, or ~$50/car -- and cuts the cost by >4x, to 0.5¢/kW-h (16-month payback @ 5¢/kW-h). This is because you pay for only 7 of the 35 measures -- the other 28 are free byproducts -- and because technology, lifetime, and sizing interact helpfully. (Adding improvements in and beyond the driven machines downstream would make potential savings even bigger and cheaper.) But achieving such big, cheap savings <u>requires whole-system engineering with meticulous attention to detail</u>.

In the electric-efficiency context, this requires small design teams. (Might this mean that a skunkworks-like approach to car design, akin to present Japanese practice, might do better than thousand-engineer efforts?) It also requires treating obsolete investments -- both economically and psychologically -- as sunk costs, not unamortized assets (<u>cf.</u> automakers' investment in sheet-metal capacity), so that innovations aren't unfairly blocked from market entry.

Consider potential synergisms in the typical family-car air conditioner: big enough for a Sunbelt house, heavy, costly, high-maintenance, full of CFCs, and a drain on engine power. Its often 5+ hp input fights the ~2-6+ kW_t peak cooling load in a 140-200+°F-interior-surface car that's sat in the sun all day. Glazings can cause >70% of that peak load. Internal solar gain-avoidance options include:

- light-colored paint and upholstery (can save ~37 F°)
- PV-powered thermostatic vent fan (saves 20+ F°)
- spectrally selective glass (saves 20+ F°), esp. w/angular selectivity (near-commercial) synergistic with C_D
- variable-selectivity glass (experimental, MBB et al.)
- high-efficiency/power-managed internal lights, fans, and accessories, and thin shell/?firewall superinsulation, to cut all heat gains to the passenger compartment

After gain avoidance, alternative cooling options include

- absorption chiller (from engine heat w/?heat pipe)
- high-efficiency scroll compressor optimized by fuzzy-logic fast controls, heat-pipe evap'r bypass, economizer
- dessicant dehumidifier (regenerable by engine heat) to stretch comfort envelope and handle peak latent load
- heat pump (Impact heats/cools w/1-kW_e, timer-driven)
- perhaps an indirect-evap option for dry climates

Any combination of such options is synergistic: it will

- make the air-conditioner lighter, smaller, less necessary
- reduce peak-load engine sizing, weight, cost, emissions
- narrow the engine's required operating envelope
- reduce/eliminate CFC use and cut maintenance needs
- probably compact the under-hood layout, ?lowering C_D
- possibly or probably reduce total net cost

4. "Tunnel through the cost barrier"

Early evidence is emerging that superefficient cars (~70-120+ mpg) can cost substantially <u>less</u> than otherwise equivalent highly efficient cars (~40-60 mpg), or about the same as ~30-mpg cars, mainly via integrated assemblies.

Extensive use of composites and plastics to achieve ~1,000-1,400 lb curb weight allows large, complex assemblies to be molded as a unit and snapped together. Not having to make and assemble many small parts, and needing fewer, cheaper dies, can pay for the fancier material with money left over to buy lower C_D (also easier with the molding), smarter chips, etc. -- making total marginal cost ~0 and improving safety, fit/finish, styling, and longevity. This is consistent with:

- **Chrysler's finding that composites could cut a steel car's subassembly count by 75% (saving much assembly labor), plant cost by ~60%, and tooling cost by 50%, and its body-in-white parts count from ~300-400 to 5-7;**
- **similar 1991 findings by a consultant to ACEEE; and**
- **Volvo's LCP-2000 economic analysis (plus unpublished similar analyses for a Peugeot prototype).**

Lightweight integrated assemblies are a key to favorable economics in the "incremental" cars illustrated by the dozen-odd 2/4-, 4- and 4/5-passenger prototypes getting ~67-120+ mpg. It's not rocket science -- nothing speculative or exotic.

However, we can go much further by redesigning the vehicle using aerospace systems concepts. The resulting concept car illustrates the conservatism of today's prototypes.

Elements of an elegantly frugal concept car

- Extremely light and crashworthy -- crushable light-metal foam, composites, plastics, Mg, ?Ti,....; design for payload:curb-weight ratio (Peugeot 205XL: 0.56), like aircraft
- C_D <0.1 w/advanced tires, smart active suspensions, "fly-by-light/power-by-wire" SRD actuators; >20-y life?
- Series hybrid drive w/multifueled, idle-off, small engine sized to average, not peak, load, with a tiny operating envelope & SR generator/starter; ?~3-kbar direct-injection diesel, ceramics, 2-stroke, membrane O_2 enrichment,...
- Small battery/capacitor buffer or 51-73 W-h/lb flywheel
- Four hub-integrated switched-reluctance motors at zero marginal weight, with regenerative superantilock braking
- No transmission, driveshaft, differential, or axles
- ?No conventional brakes, except for backup or panic stops
- ASAP, replace engine/generator w/advanced, preferably monolithic solid-oxide, modular fuel cell: ~0.5 hp/lb, ~0.062 hp/in^3, self-reforming, reversible (no batteries)
- Angularly selective, variable-selectivity, perhaps variable-opacity glazings, light colors, ?Cloud Gel sunroof
- PV vent fan (& ?charger), lightweight body superinsulation (e.g., compact vacuum insulation @ R-5 to -10 per 0.1", + low-E/Ar/honeycombing of lightweight body materials)
- Absorption/dessicant or similar chiller, heat-pipe heater, quiet high-efficiency SR fans, fuzzy-logic comfort controls
- Miniature ?sodium (?central/fiber) lamp(s), EL panel
- Care in every detail: SR pumps, interior sideviews, NdFeB speakers, CMOS chips, advanced bearings/lubricants,...
- W/best thin solid/high-P tires + SRD, ?need steering?

Conclusions

The 67-120+ mpg performance of the dozen-odd prototypes already tested -- some peppier and safer than today's cars -- is technically conservative <u>because it does not draw upon any of these 18+ advanced elements</u>. Thus efficiency 2-3x that being debated already exists <u>without</u> using many of today's best technologies, most already available and the rest rapidly emerging. Using <u>any</u> of them would make the prototypes even better and thus reinforce my robust conclusion that safe, peppy family cars are feasible at ~70-100+ mpg.

Today's car efficiency isn't like a 300-pound man who's lost 150 lb and can't lose much more; it's like a 600-lb man who reduced to 450 lb before gaining much of the modern knowledge of nutrition and exercise that can get him down to 150. And now that he can get out of his chair and start moving around, the next 300 lb will be easier than the first 150!

As they scrutinize this thesis, the automakers will, I hope, not pick nits but join in capturing its spirit of innovation -- and not worry that any acknowledgement of potential invites rigid command-and-control regulation, for there is a rich potential to devise <u>market</u> incentives that reward efficiency.

Automakers have extraordinary technical skills. I have worked with other, similarly skillful companies that have greatly stretched, in only a few years, the envelope of what they thought possible. I am confident that given sound incentives, and in a nonadversarial context of collaborative problem-solving, resourceful automakers can do the same.

How Low Can We Go?

Taking drag x mass (AC_DM) as a rough index of kinetic loads and hence of ultimate efficiency potential, and holding 1990 average frontal area (~2.1 m^2) constant as an approximate surrogate for size:

CAR TYPE	CURB WT. (LB)	C_D	INDEX OF AC_DM
1990 domestic av.	3,180	0.33	**1.00**
(EPA 24/36/29.4 mpg)			
straightforward gains	2,000	0.26	**0.50**
("incremental ad-hocracy")	Escort diesel 2,100 1980 Flemings ~2,000	best 1990 prod'n; = Toyota AXV	
mid-1980s prototypes	1,450	0.20	**0.28**
	Toyota AXV 1,430; midsize Pertran est. ~1,200-1,500	Renault Vesta 2 0.186; [1990] Impact 0.19; Peugeot VERA+ 0.22	
1991 edge-of-envelope?	1,050	0.14	**0.14**
	Renault Vesta 2 but bigger	Ford Probe V 0.137	
1990s technical limit?	875	0.06-0.08	**~0.06**
	ultralight/safe (crushable light-metal foam,...)	Sunraycer 0.125	

Better driveline/accessories efficiency, and effective regenerative braking in modern series hybrids, offer scope for capturing broadly comparable gains in fuel economy.

Summary of evolutionary strategy

1. Avoid regulatory mandates; innovation is too hard.
2. Nibble away at modest, conventional, incremental improvements (~1-2%/y), milk present tooling as long as possible, wink at obsolescence, and watch cars become steadily costlier.
3. In perhaps a decade, when competition absolutely requires it, retool to "tunnel through the cost barrier" with light integrated assemblies, using the money saved on parts count and assembly labor to buy other measures.
4. Well into the next century, maybe redesign from scratch using aerospace systems concepts and radical simplification, but for now, put that on the back burner.
5. Hope none of your competitors is faster.

Summary of revolutionary strategy

1. Embrace, promote, and capitalize on market-oriented rewards for maximizing efficiency early, e.g., revenue-neutral feebates with accelerated scrappage.
2. Since technologies for the "vanilla" incremental improvement (step 2 above) are already available and generally commercial, take production models promptly through the lightweight/lower-cost "tunnel" (step 3 above) while moving as quickly as possible to radical redesign (step 4 above), condensing the timescale and number of retoolings ultimately required.
3. Feel sorry for your former competitors.

Contextual thoughts on superefficiency

- U.S. automakers' survival requires technological leaps. A "leapfrog strategy," bypassing costly incremental improvements to a fundamentally obsolescent design, can be globally competitive and meet ambitious oil-displacement/ smog/CO_2 goals. If you can't afford to do it right the first time, how come you can afford to do it twice? Why improve Selectric IV typewriters while others develop notebook computers?
- It's OK if efficiency costs more; feebates can handle that. We should buy efficiency up to full avoided social cost, then do the bookkeeping to match up costs and benefits.
- Long-run fuel options look very different with high efficiency. Market-clearing levels of efficiency (vs. long-run fuel supplies) may imply U.S. transportation fuel needs nearer ~5-6 than today's 21½ q/y. That little could probably come sustainably from farm and forestry wastes, without special crops or fossil hydrocarbons; but at >10-15 q/y, no long-run fuel option makes much sense.
- Efficiency isn't enough. Even if we have clean, renewably fueled, ultrasafe, 150-mpg station-wagons, two billion Chinese (or 10 million Los Angelenos) driving them won't work: if we don't run out of fuel or air, 5%/y fleet growth soon runs us out of roads. Avoiding the "constraint du jour" requires rethinking transportation systems and policies from an end-use/least-cost perspective: the end-use is not mobility but access, and we need "negamile markets" where all solutions can compete. High technical efficiency is essential, but is only one step on a much longer path of redesigning transportation from scratch.

General Motors' "Ultralite" Concept Car

- conceived late April 1991
- road-tested mid-December 1991
- displayed at big Detroit auto show early January 1992
- 50-person, $4-6 million GM team
- 100-day construction time, >100 significant innovations
- curb weight 56% below average new U.S. car -- 1,400 lb (636 kg) including four airbags
- 6-piece carbon-fiber-composite body weighs 420 lb (191 kg)
- comfortable for four large adults with limited luggage
- interior space of Corsica, wheelbase nearly of Buick Park Avenue, exterior size of Miata -- wheels are at corners
- drag coefficient 0.19 (40% below average new U.S. car)
- accelerates 0-60 mi/h (0-97 km/h) in 7.8 seconds
- top speed 135 mi/h (218 km/h)
- EPA-rated efficiency twice that of average new U.S. car:
  - city 45 mi/US gal (5.22 l/100 km, 19.2 km/l)
  - highway 81 mi/US gal (2.90 l/100 km, 34.5 km/l)
  - composite 61 mi/US gal (3.85 l/100 km, 26.0 km/l)
- cruises at 50 mi/h at 100 mi/US gal on 4 hp (81 km/h at 2.35 l/100 km | 42.6 km/l on 3 kW) -- vs. Audi 100's 15 hp
- can cruise coast-to-coast on six fillings of its 5-US-gal (19-l) tank with a gallon of fuel (3.8 l) to spare
- 1.5-l, 2-stroke, 3-cylinder, in-line, direct-injection, stratified-charge, 111-hp (83-kW) engine in removable "pod"
- conventional automatic transmission (4-speed transaxle)
- should meet Ultra-Low Emission Vehicle standard
- simulations suggest excellent crashworthiness
- not yet optimized nor engineered for production

What Might Ultralight Cars Cost?

Carbon fiber costs ~$10-40/lb, vs. ~25-35¢/lb for sheet steel. But what matters is cost per <u>car</u>, not per <u>pound</u>:

- **A new GM process makes short fibers ~5-6x cheaper.**
- **Carbon-fiber composite's superior strength and stiffness allow >4x fewer pounds of it to be used than of steel.**
- **Of the cost of a typical steel car part, only ~15% buys steel; the other ~85% is for shaping and finishing. In contrast, the "net-shape" composite emerges from the mold virtually ready-to-use, in complex, sleek, beautiful shapes unattainable with practical metalforming tools.**
- **Composites' moldability into large, complex units can cut parts count by ~100x: the basic body can have not ~300-400 but only ~4-6 parts, cutting design, paperwork, tooling, transportation, and inventory costs.**
- **Those few parts can fit precisely together with almost no assembly labor and ~1/10th of normal assembly space.**
- **The epoxy molding dies cost half as much per copy as steel dies; are quickly made (under computer control) and amortized; hence support the very short product cycles that market nimbleness demands.**
- **Composite color-molding may be able to eliminate painting -- the costliest, most difficult part of automaking.**
- **Composites last practically forever -- they don't dent, scratch, blister, or rust -- so cars could last for enough decades to be heirlooms, then be recycled. The reduced maintenance dramatically cuts life-cycle cost.**
- **Composites' strength and bounciness makes cars safer.**

These features may make net-shape-materials cars cost about the same as steel cars, maybe less. Adding hybrid drive could yield radically simplified cars competitively made and delivered directly by a local plant and maintained at the owner's site. This PC-like "commoditization" would eliminate today's ~100% markup from factory gate to owner, accommodating even doubled production cost.