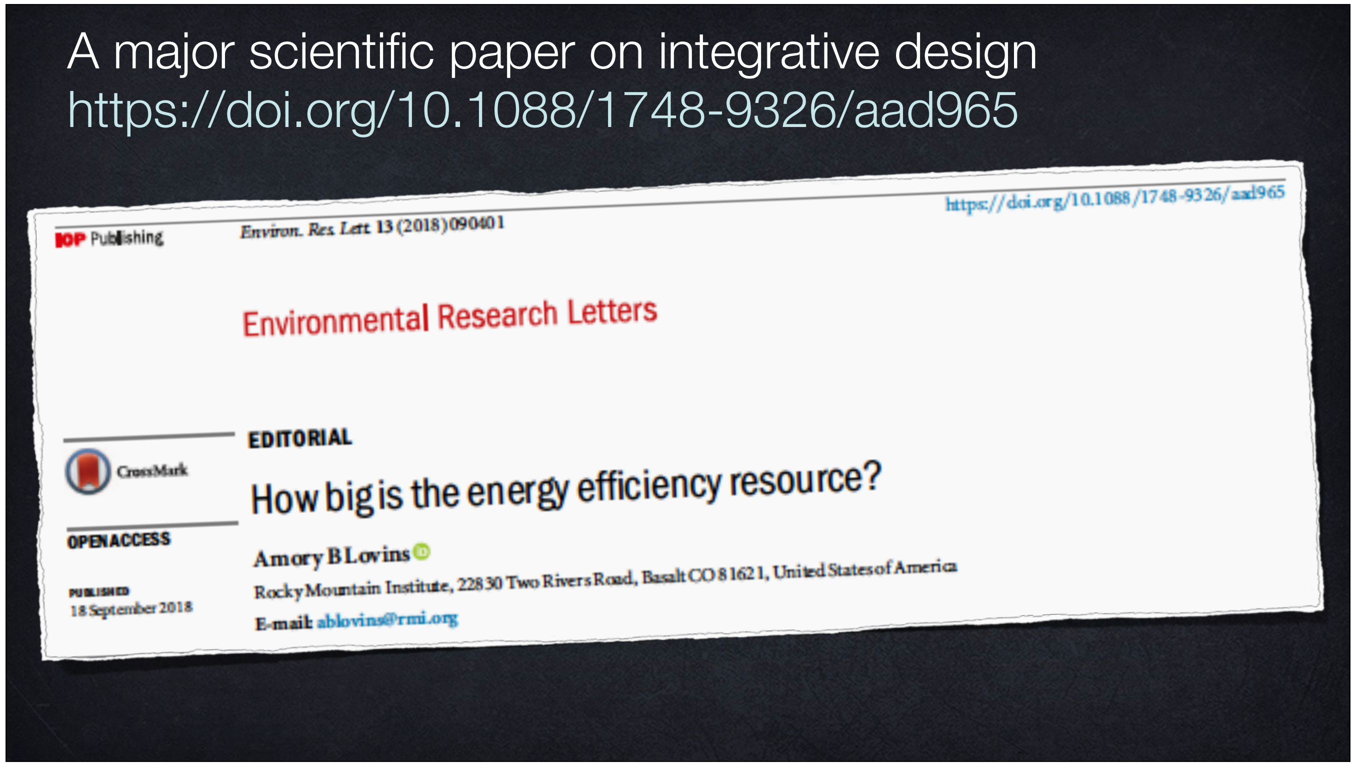
[target ~15m, rehearsal 21.5m, actual **TK**]

Thank you for inviting me. You'll get my slides and notes afterwards.
Since I first briefed this Committee in Irvine 29 years ago [9 Jul 1991], and under its commendable influence, our understanding of automotive efficiency has progressed enormously. Today I hope to help you accelerate further by suggesting that automobiles can cost-effectively become severalfold more efficient than officially believed, and at much lower cost, by optimizing whole-vehicle design. Such "integrative design" applies to most branches of engineering… *

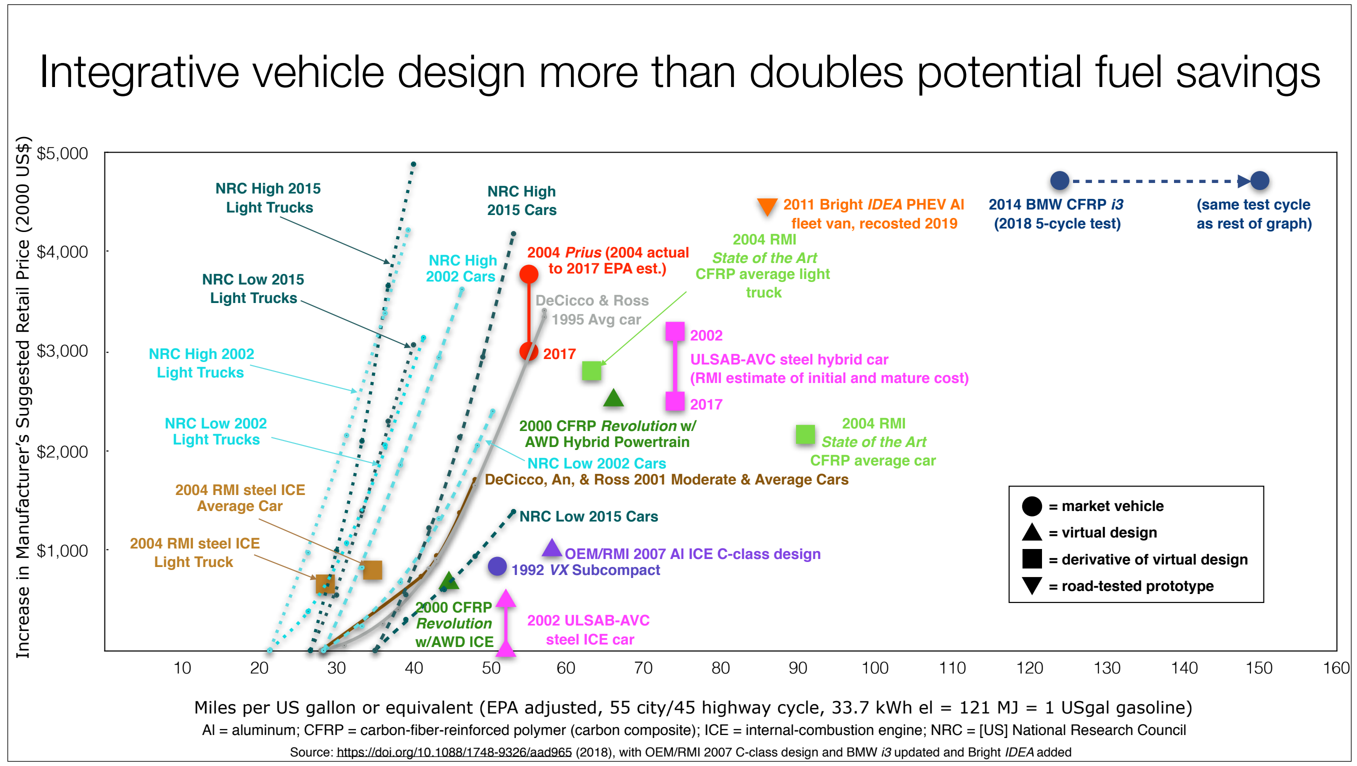


…and has been demonstrated in numerous buildings and factories and in some road, sea, and air vehicles. This September 2018 summary of evidence shows that bigger energy savings can cost *less* because they come not from adding *more or fancier* widgets but from using *fewer and simpler* widgets—more artfully chosen, combined, timed, and sequenced. My paper "Reframing Automotive Fuel Efficiency," now in peer review at SAE's *J-STEEP* (of which I'm also an Associate Editor), cites glimpses of such decreasing-cost curves in autobodies, but to see the full picture and power of integrative design, we must ask new design questions about the whole vehicle. *

Asking a different design question (OEM/RMI, 2007)

- Base case: high-volume C-class production platform, all req'ts futured to 2011
- Conditions: no compromise in volume, safety, performance; conventional light-metals techniques only; all technologies legal and in supply chain by 2010–11
- Finding: a large group of solutions could raise mpg by 60% (CO_2 –38%, –40% lifecycle) at reasonable incremental mfg cost (just into four figures), with ≤2-y retail payback @ $3/gal (not counting lower maint. cost or potentially higher resale value)
  - Over 10 y, OEM cost could be zero net of expected CAFE + $10/t$CO_2$ credits
  - Robust marketing and business case; fatter margins; same or better safety
  - *Halved engine displacement helped pay for fuel savings*; 0–60-mph time –14%
  - *Platform fitness:* m_c – 31%, C_d –31% (first 19% cost <$70), r_0 –24% (~free)
- OEM found same methodology could achieve similar fuel economy gains across other platforms in its fleet, with even larger gains available from more-advanced powertrains that may be required in the future and that this approach enables

Here's an example that I was allowed 11 years later to say a little about at TRB. In 2007, a major OEM's research director and I co-led an intensive proprietary study driven from the top of the firm, asking its best analysts and excellent analytic tools a new design question: "How much lightweighting can we pay for by shrinking the powertrain to get the same acceleration?" Just with conventional ICE powertrain and aluminum-intensive construction, we got surprising answers. * The base vehicle was a MY2008 C-class in high-volume production, * with no compromised driver attributes, new technologies, or wishful thinking. * Many paths then yielded 60% higher mpg at a marginal gross manufacturing cost of $1,000 in year-2000 $, with retail payback <2 y. Without a hybrid powertrain, it beat *Prius* efficiency. The OEM's marginal cost could * plausibly be offset by CAFE and carbon credits. * Marketing and business cases were robust, including doubled OEM margins (and perhaps dealer margins). * Acceleration got 1/7 faster while engine displacement was halved, helping to pay for * cutting tractive load by about one-third. * These findings, applicable companywide, would become even more valuable if used to enable advanced powertrain sooner. / These results informed production intent, proved profoundly important for strategy, yet are inconsistent with common positions in today's CAFE debate. And the standard way of analyzing efficiency potential, using incremental supply curves summing individual efficiency technologies, *conceals* such results; they're revealed only by *whole-vehicle design.* *



To see this, let's construct an eyechart step by step, with marginal MSRP on the vertical axis and rated fuel efficiency on the horizontal axis. The canonical technology-by-technology analytic method yielded the * aqua NRC 2001 high and low supply curves of potential US light-truck and car efficiency ~15 years ahead, then their * dark-blue 2015 updates, catching up with * previously rejected independent analyses. But those assessments were soon overtaken by actual market platforms like these from * Honda, * Toyota (a hybrid), and BMW (an EV); by the major OEM's * light-metal gasoline-engine virtual design I just described; and by a Porsche Engineering ICE virtual design using * high-strength steel, or RMI's estimate for a hybrid variant. In 2004, my team adapted the * base vehicles in our *Winning the Oil Endgame* analysis, based on our * 2000 *Revolution* carbon-fiber SUV design, yielding these typical * light-truck and car values. And * here's a road-tested aluminum commercial fleet van from another RMI spinoff.

These 15 empirical data points show that traditional component-based analysis misses *the entire right-hand two-thirds or more of the design space:* highly integrative *whole-vehicle design can at least triple, and at lower cost, the fuel savings that policymakers now expect*. Conversely, analyzing auto efficiency by the part, not by the car, makes efficiency look severalfold smaller and costlier than whole-vehicle integrative design can achieve. So current efficiency standards are far more conservative than was thought, and electrification can be cheaper and faster than today's heavy platforms exploit. *

[Hypercar variants: A gasoline-engine version could save 58% of normal fuel use for 15¢/gal (2000 $), a gasoline-hybrid variant could save 72% for 56¢/gal, and a fuel-cell version with the costly stacks of 18 years ago could save 83% for $2.11/gal. NRC's 1991 report is labeled "1992" because a 1992 revision made slightly less conservative assumptions.

The 2002 ULSAB-AVC developed by 33 steel firms and Porsche Engineering was 2,200 lb., Taurus-class, 52 mpg, 5☆ safety, $9,538 production cost; its body-in-white was –52 kg and –$7.]

A competitive carbon-fiber electric car, 2013–

sglcarbon.com

2013 BMW *i3*, http://www.superstreetonline.com/features/news/epcp-1303-bmw-i3-concept-coupe/

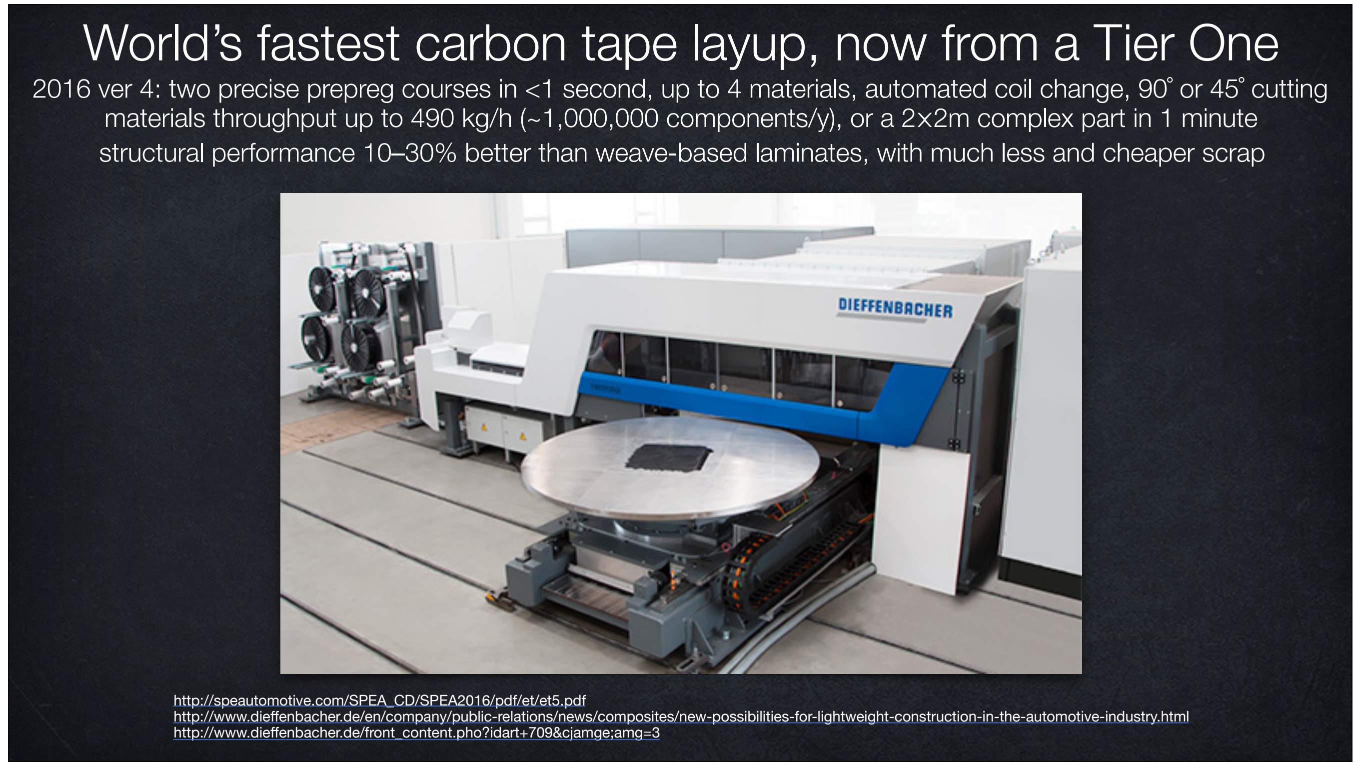
BMW MY2013's ~120–150-kg carbon-fiber-composite passenger cell; m_c 1,250 kg

https://www.autocar.co.uk/car-news/industry/bmw-set-make-more-extensive-use-carbon-fibre

BMW's sporty, 1250-kg, 4x-efficiency *i3* was reportedly profitable from the first unit: it…

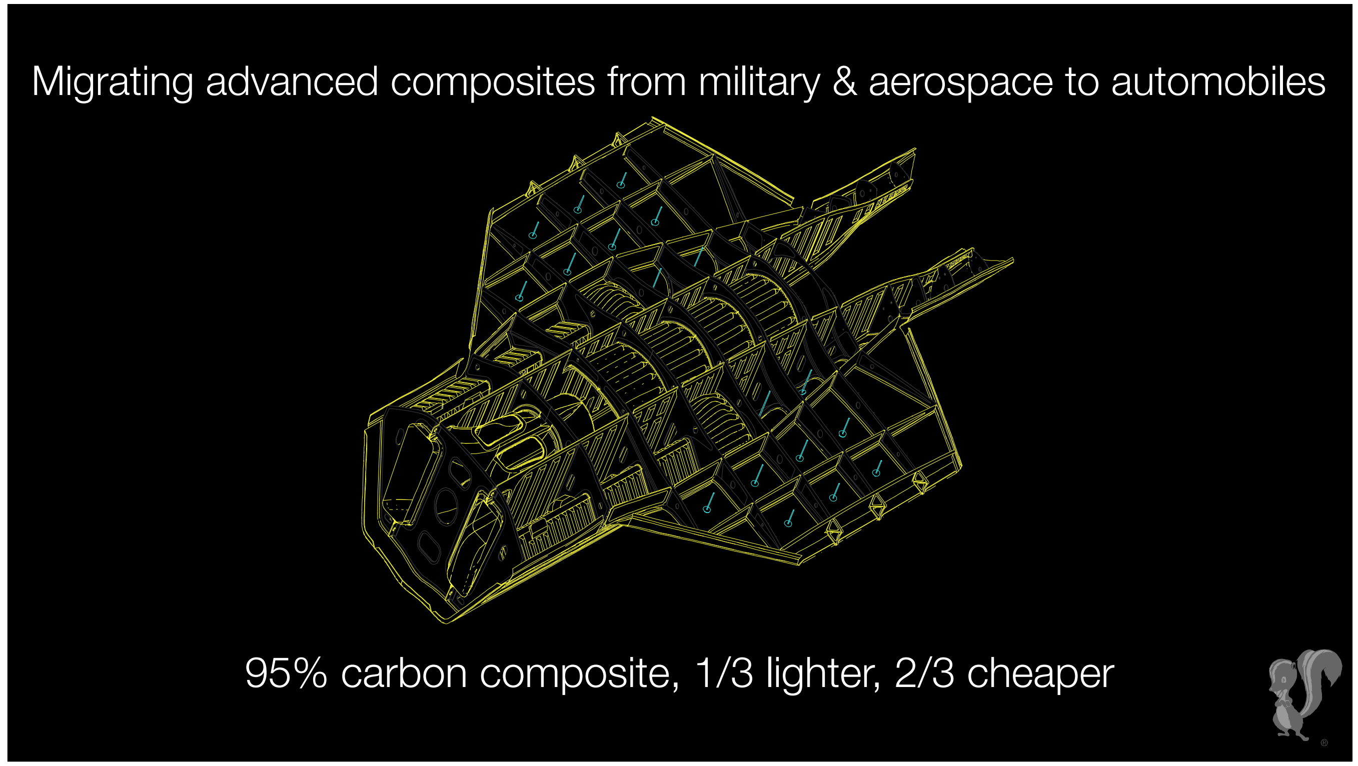
- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct mass saved (Detroit says <1.3–1.5)
- needs ~67% less capital, ~70% less water, ~50% less energy, space, time to make
- requires no conventional body shop or paint shop
- provides clean, quiet, superior working conditions
- delivers 1.9 L_{equiv}/100 km (124 mpge) on US 5-cycle test, 1.7 Ger., ~1.6 old US cycle
- provides exceptional visibility, agility, traction, crash safety, and halved turn radius

My *J-STEEP* paper documents from trade literature a striking case that I trust its design leader, Ulli Kranz, will kindly correct if needed. This * carbon-fiber electric car whose 2019 model I drive uses integrative design to tunnel through the cost barrier. Sandy Munro called it the "most significant vehicle since the [Ford] *Model T*" and "the most advanced vehicle on the planet." It reportedly * made money *from the first unit off the assembly line*. * Validating our 1990s claims, its carbon fiber is paid for by the batteries that its lightness saves (and fewer batteries mean faster recharging). Thus carbon fiber is costly per pound but not per *car*: this car pays for its ultralight materials by shrinking its powertrain. Its integrative design * compounds mass savings far more than usually assumed. Its * manufacturing is radically frugal, needing just a third the normal capital and water and half the normal energy, space, and time. * Making this car needs no conventional body or paint shop, and * is much better for workers. And the * quadrupled efficiency, without compromise, * brings driver advantages ranging from spacious packaging to exceptional visibility and traction control to halved turn radius. Please think of this as an archetype, because whatever exists is possible. *

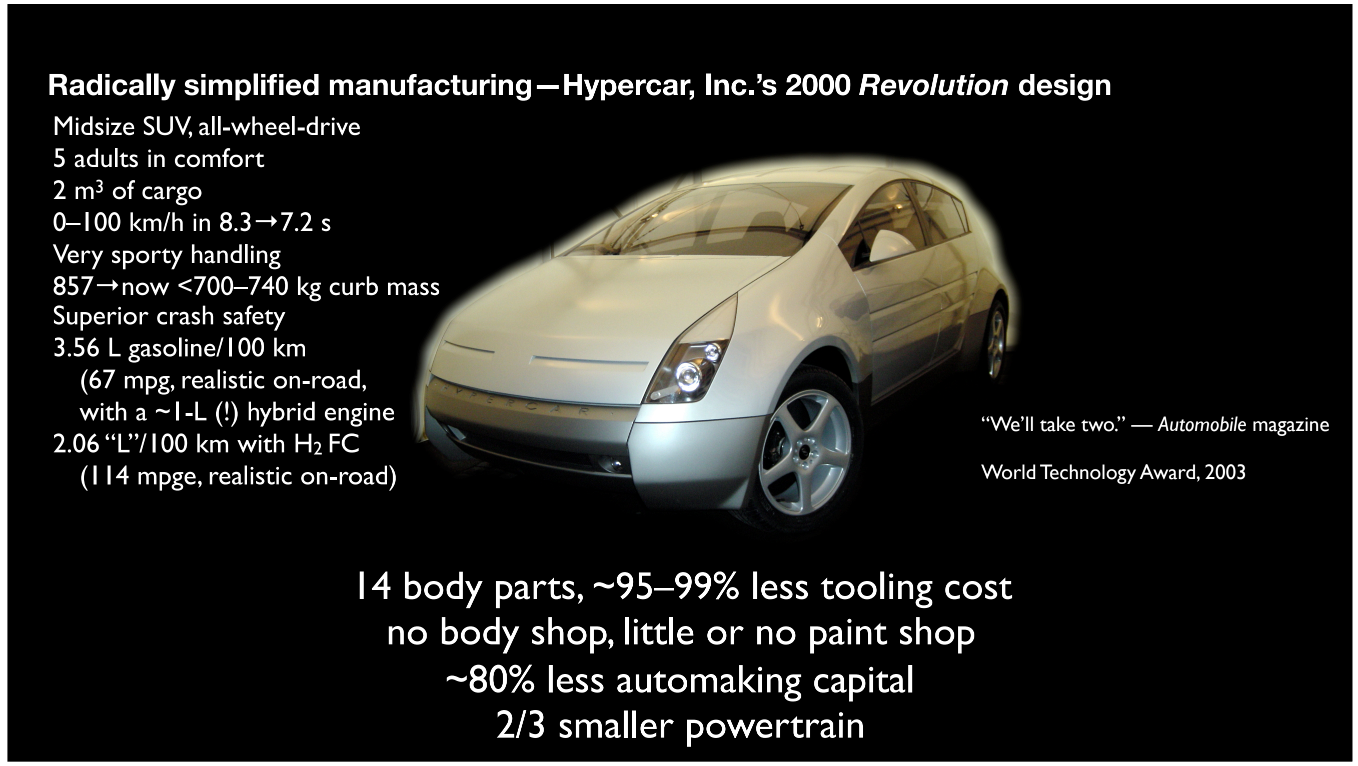


The *i3*’s carbon-composite passenger cell is beautifully made from woven carbon cloth using RTM—one of at least 17 competing manufacturing processes. Here’s another. Twelve years ago, our even faster and cheaper manufacturing technology made this carbon-fiber “carbon cap” *[ring “prop” like a bell]* in one minute. In 2013, our Fiberforge spinoff sold the process to a Tier One pressmaker. This 2016 version of the resulting machine can make a million components a year, or a complex, anisotropic, variable-thickness *2x2m* structural car part in one minute. It digitally lays up prepreg thermoplastic carbon-fiber tape, vacuum-consolidates, then thermoforms to net shape, yielding impressive properties *[ring sheets/bracket]*.

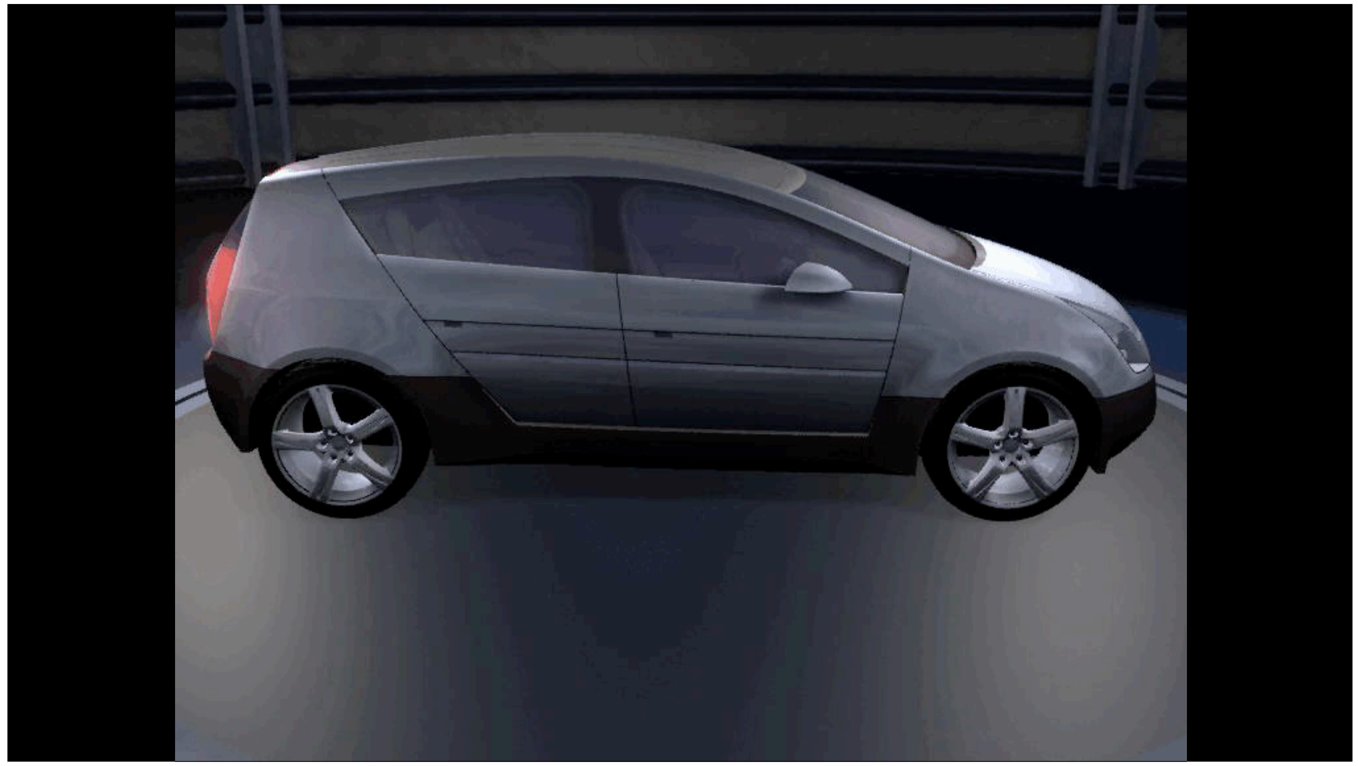
Making all U.S. autos this way could save more than a Saudi Arabia’s worth of oil for <$10 per saved barrel—and pay for electrification that gets autos completely off oil. And some newer materials and structures offer 1–3 orders of magnitude better properties than carbon-fiber composites. *



That worthy vision dates back to 1991, when my team began combining integrative design with advanced-composite structures. Nobody then thought carbon-fiber composites in automaking could achieve a thousandfold higher volume and lower cost than in aerospace. But I gained hope this gap might be bridgeable when Dave Taggart led for DARPA at the Lockheed-Martin Skunkworks * the design of a 95%-carbon advanced-tactical-fighter airframe that was * ⅓ lighter but ⅔ cheaper than the 72%-metal base design, because his clean-sheet design was optimally manufacturable from carbon. That activated the Joint Strike Fighter community's immune system, so Dave quit, and I soon hired him to lead in 2000 the complete virtual design with two Two Tier Ones of…



…a 53%-lighter carbon-fiber midsize SUV with an * airframe-inspired body—suspended from rings, not built up from a tub. Its body had just 14 parts, each made with one low-pressure dieset, saving ~95–99% of the tooling cost. Each part could be lifted in one or two hands with no hoist. The biggest part, on the side, I could briefly lift with one finger. * The parts snap precisely together for bonding, self-fixturing and detoleranced in two dimensions, eliminating the robotic body shop. Laying color in the mold can nearly eliminate the paint shop. There go the two hardest, costliest steps in automaking, * saving ~80% of capital. * That plus the two-thirds-smaller powertrain could pay for the carbon fiber, making the ultralighting approximately free, just as BMW did 13 years later. *



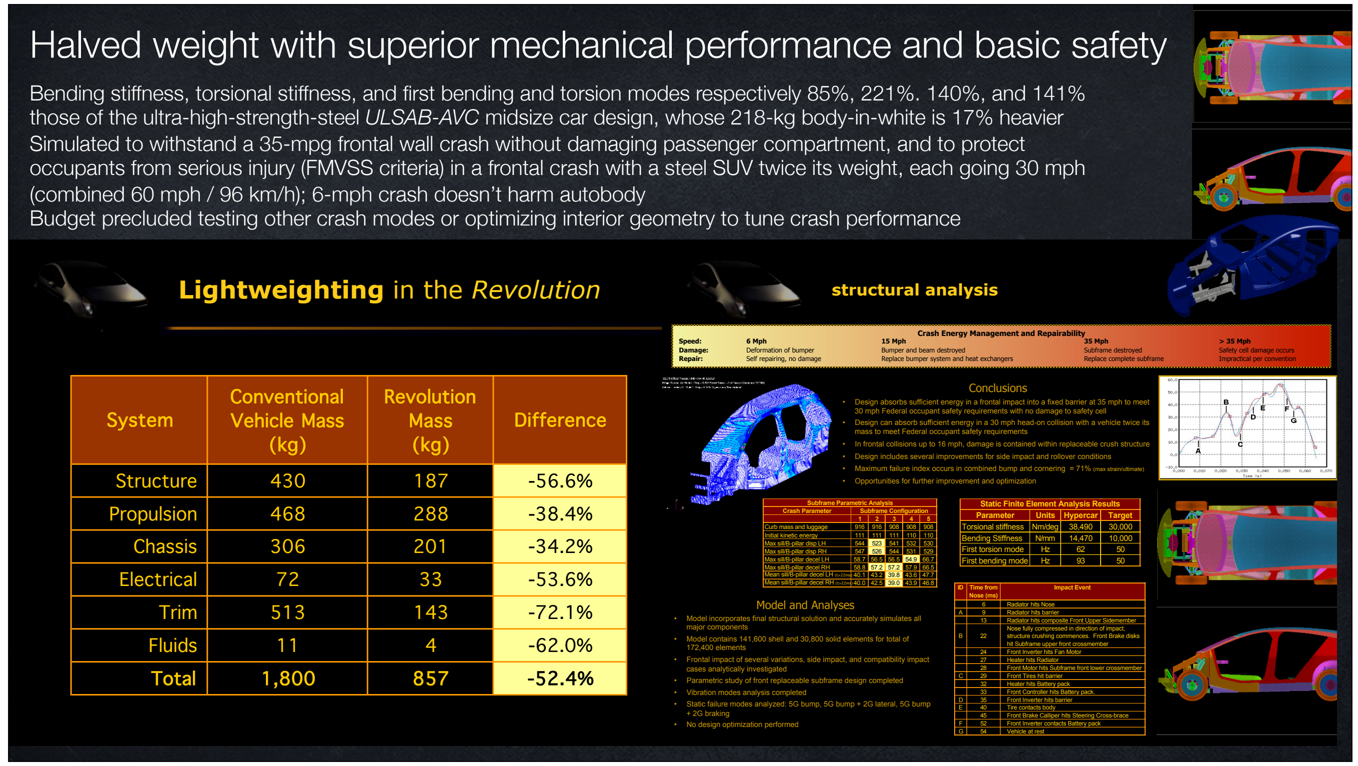
This active-outdoor-lifestyle crossover luxury hybrid SUV could carry 5 big adults in comfort plus up to 2 m³ of cargo, and haul a half-ton up a 44% grade. It could carry two adults and two standard kayaks inside if you fold down the right-side seats. It could accelerate 0–60 [mph] in 7.1 s with a ~*1-L* hybrid engine buffered by a 35-kW battery. Replacing the steering wheel and pedals with a joystick for either hand and either side enhanced safety.

[0–100 km/in 8.3 s: 2.06 L/100 km **(0–60 mph in 8.1 s, 114 mpg)** with fuel cell

0–100/7.2 s: 3.56 L/100 km **(0–60 mph in 7.1 s, 67 mpg)** with ~*1-L* gasoline hybrid]

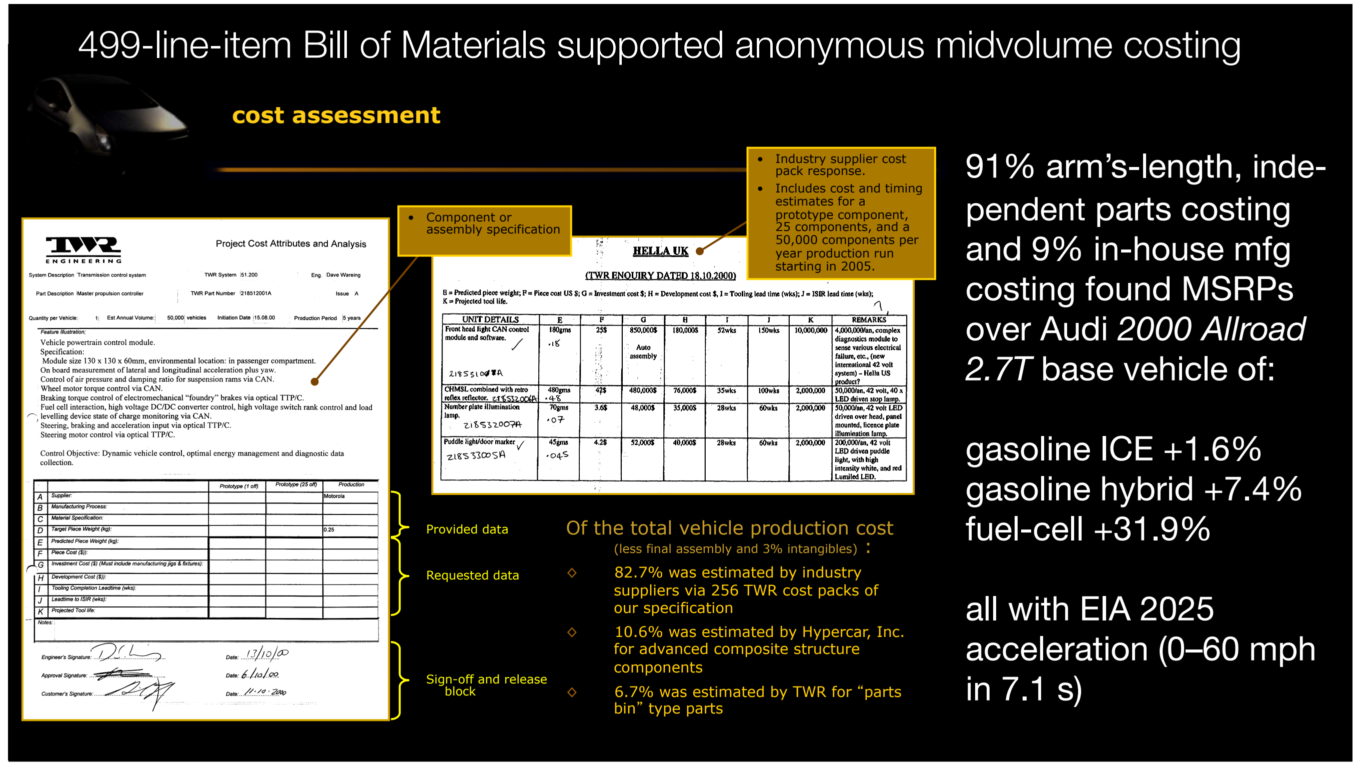
A computer with wheels, not a car with chips, this radically integrated and simplified design put nearly all functionality in updatable software—a pre-EV dream of Tesla IT architecture 20 years early. Way cool.

[Base vehicle was 2000 Audi *2.7T AllRoad with Tiptronic*.]



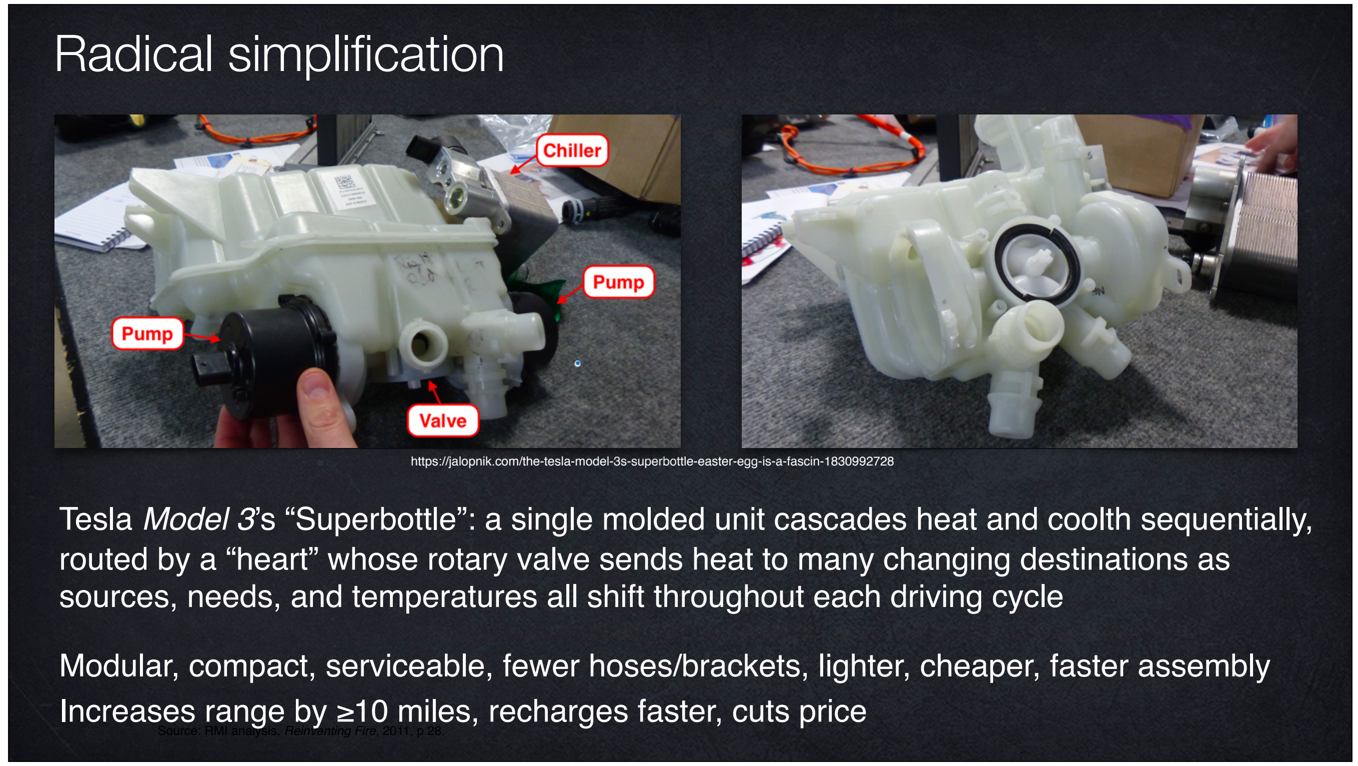
Our SUV's 57%-lighter carbon-fiber structure also yielded better-than-sports-sedan stiffness^ for the composite smart active suspension to react against, and it showed gratifying simulated basic crash safety. Today, the mass savings shown at the lower left would be at least 120–160 kg greater, rising from ½ to ⅔. *

^First torsion mode 62 Hz (target 50), first bending mode 93 Hz (target 50), bengin stiffness 38.5 kN-m/deg.



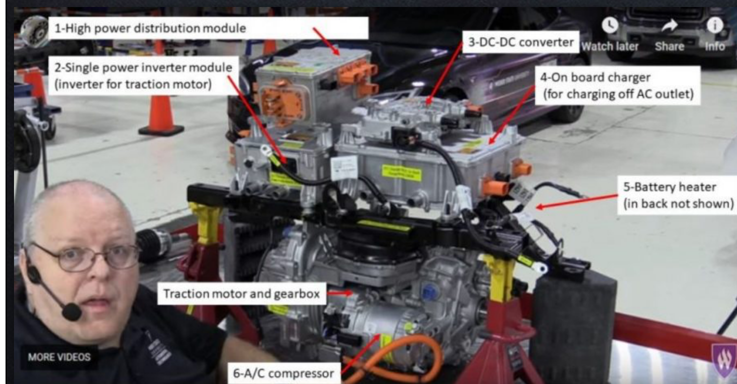
At 50k/y volume, using unnegotiated supply-chain first offers, our Tier One partners' detailed and 91% independent cost analysis found a $2,511 marginal MSRP (2000 $) for a ~2-y U.S. retail payback. Its Cost of Saved Energy in 2000 $ was 15¢/gal with an ICE and 56¢/gal with a scaled-down '04 *Prius* hybrid powertrain. *

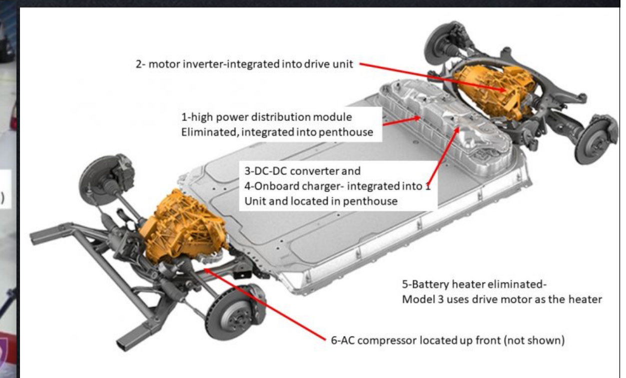
That design omitted many later lightweighting innovations like the in-wheel suspension of the *Edison2*, or today's >10 kW$_p$/kg hubmotors—without which this 2010 4-seater still got as light as 322 kg. *



Simpler, lighter, cheaper, better design rolls on. The Tesla *Model 3* replaces component-level heating and cooling systems or forests of hoses with a single molded plastic "heart" whose 4-way valve redirects thermal energy real-time from where it is to where it's needed, optimally sequencing and cascading temperatures. * The many benefits include at least 10 miles of extra range. *

Designing stuff out





https://insideevs.com/tesla-model-3-vs-chevy-bolt-high-voltage-components/, reporting Kohn Kelly (Weber University) analysis and video

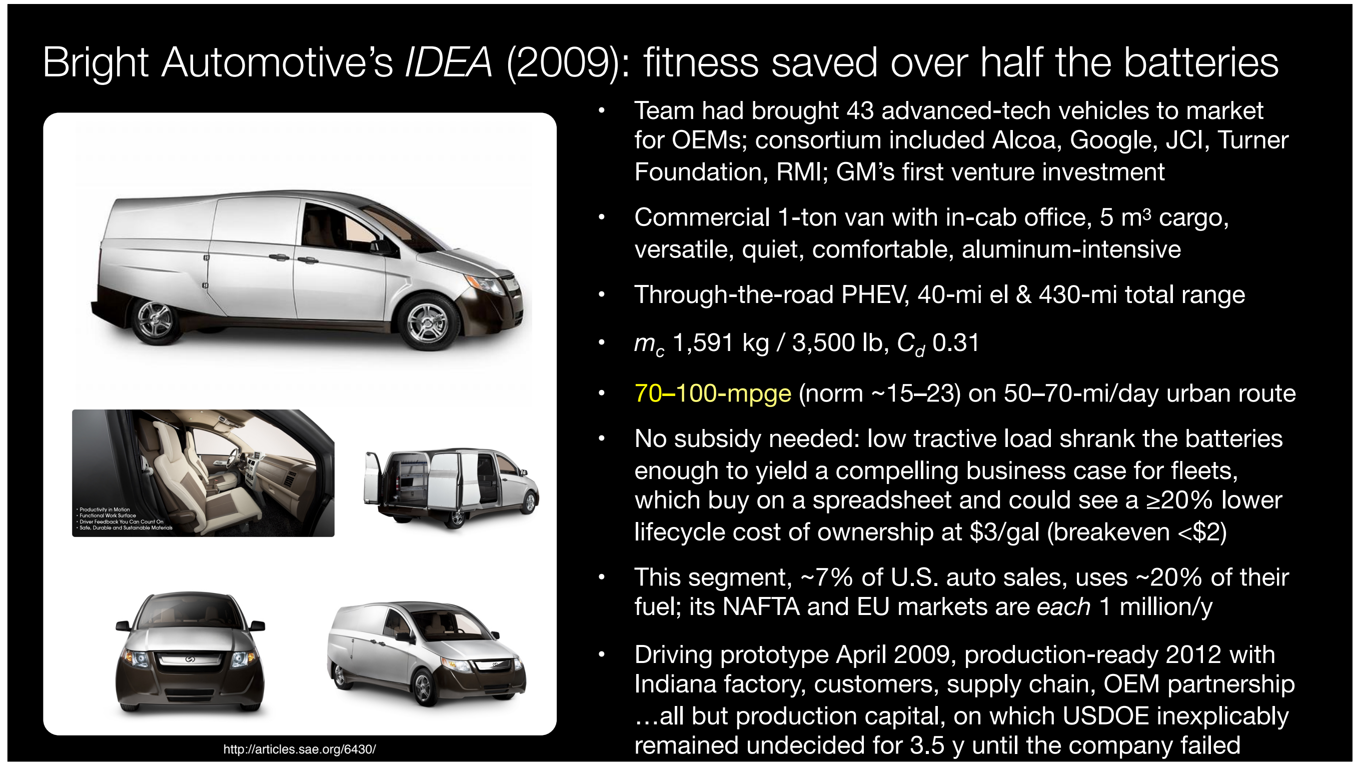
Chevrolet *Bolt*'s high-voltage system stuffs five modules into its small front compartment. *Tesla Model 3* eliminates two and combines the functions of two pairs into one component.

Modular, compact, serviceable, fewer wires & connectors, lighter, cheaper, faster assembly

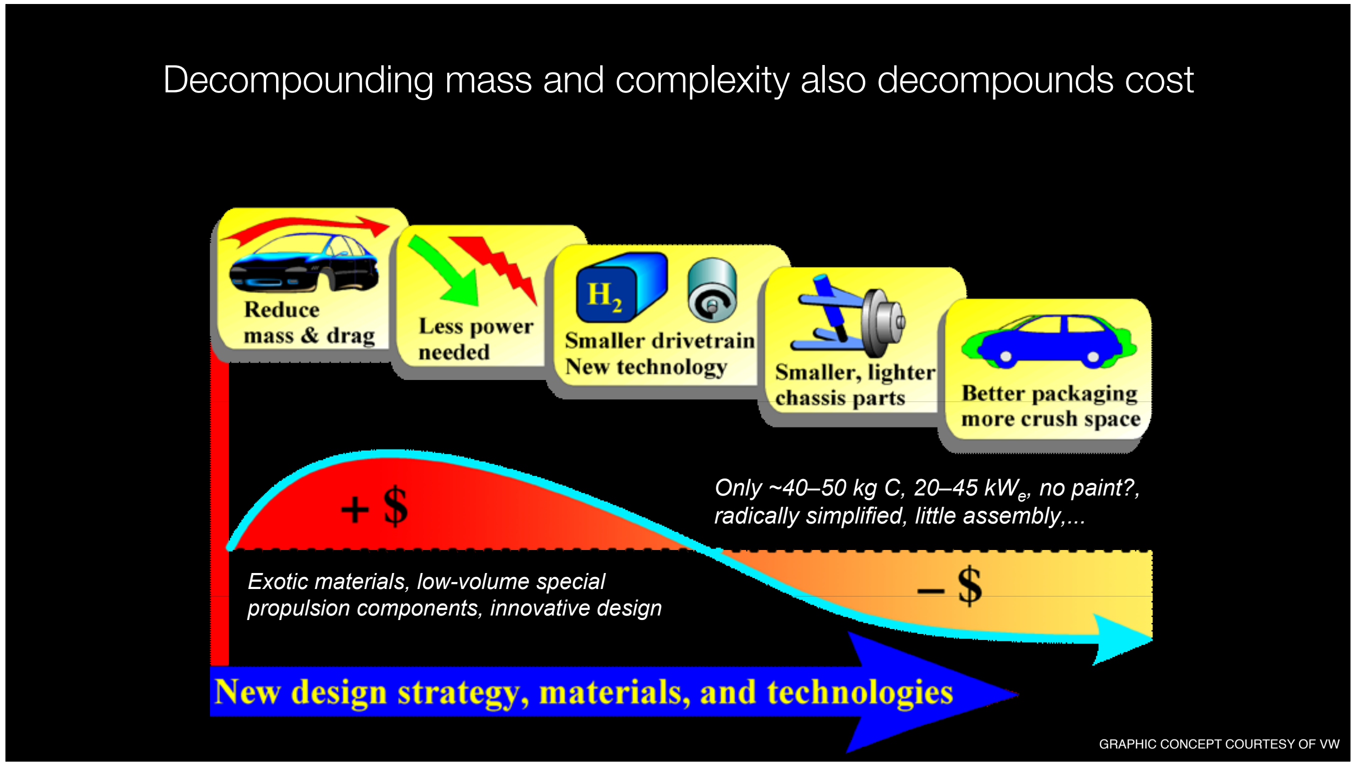
Increases range, recharges faster, cuts price

Source: RMI analysis, *Reinventing Fire*, 2011, p 28.

Likewise, of five separate power-related modules in the Chevrolet *Bolt* (stacked together in the left photo), Tesla's *Model 3* eliminates two and consolidates two more, radically simplifying the system to achieve * similar benefits. *



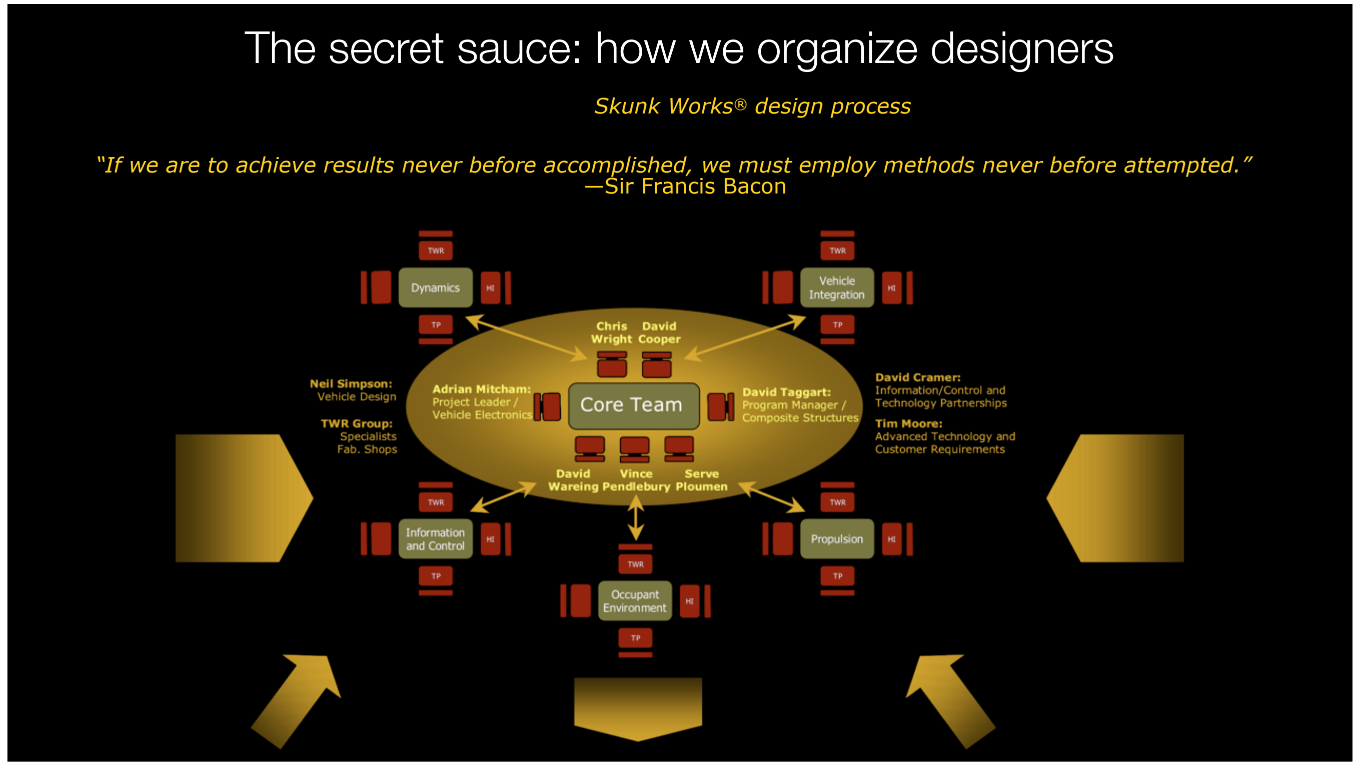
Integrative design can be powerful even with light metals. Eleven years ago, our * second car spinoff * designed an aluminum * PHEV fleet utility or delivery van that weighed * less with a ton of payload than its competitors weigh empty. That plus NASCAR aerodynamics saved most of the batteries and * ~80–85% of the energy, making a strong business case with * no subsidy for a plug-in hybrid offering * huge national fuel savings. * DOE killed the project, but an OEM bought the IP, and I understand some similar products now have production intent. *



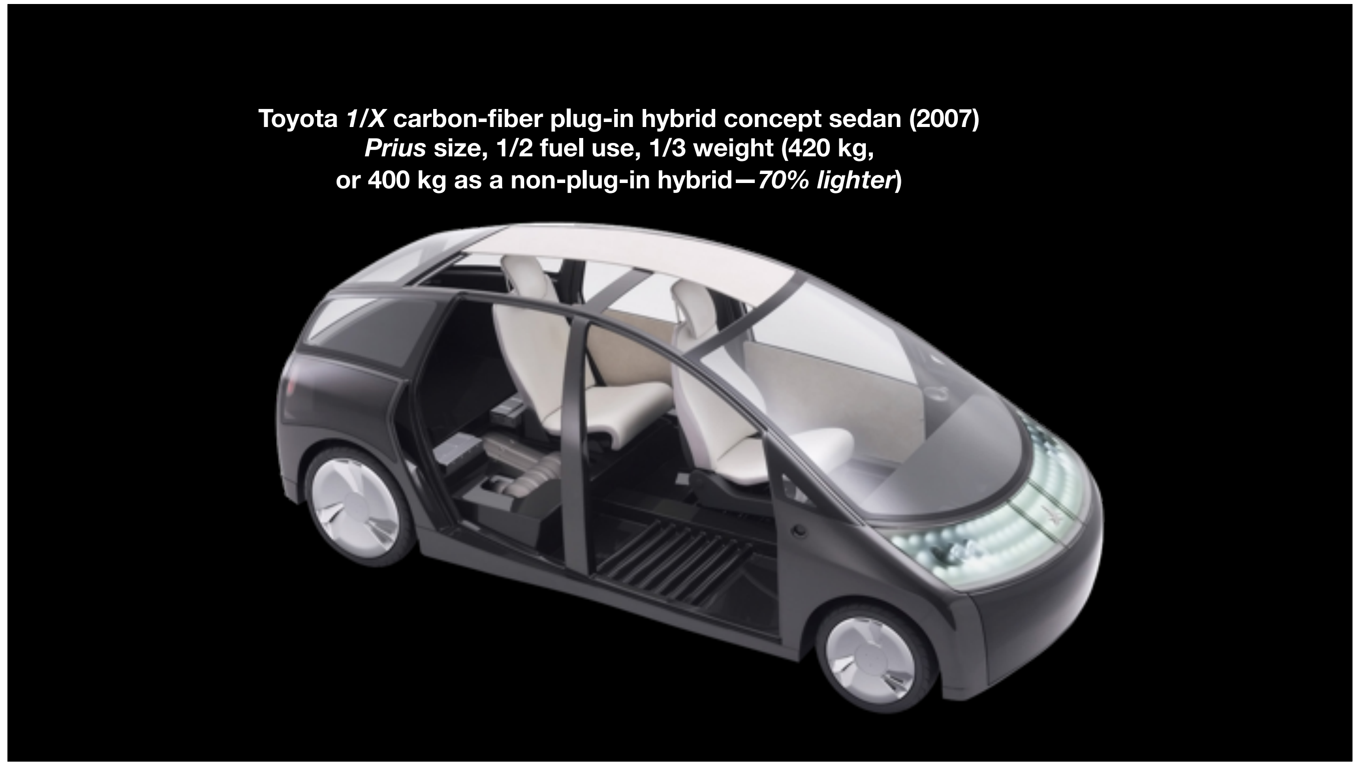
To save so much weight, you must go repeatedly around the “design spiral” [as it’s called in naval architecture] or “design cycle” [as it’s called in aerospace].

First you make the vehicle light and slippery, halving its tractive load and enabling smaller and more advanced powertrain and smaller, lighter chassis components. Those leave more packaging and crush space. Then you go around the spiral again, making components smaller as structural loads shrink, because the less weight you have, the less weight you need. This can also *eliminate* components: a good series hybrid doesn’t need transmission, clutch, flywheel, driveshaft, U-joints, axles, differentials, starter, or alternator! As those nine components disappear, they trigger a new recursion.

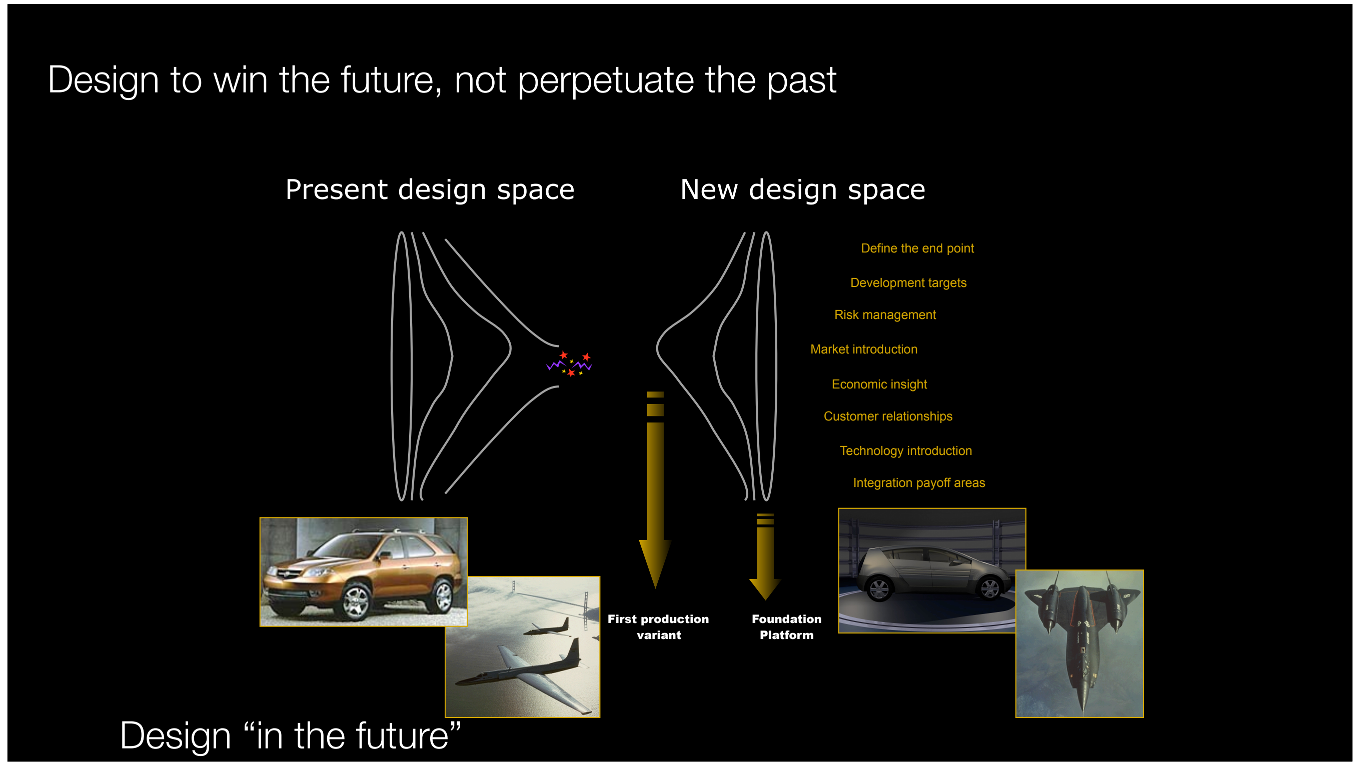
At first the special materials, powertrain, and design might seem too costly. But after many recursive cycles of mass decompounding and simplification, you need so little carbon fiber and powertrain that simplified manufacturing can bring total cost back to normal or even less. Thus incremental lightweighting raises cost as Tim said, while transformational whole-vehicle redesign lowers it again. Of course, that’s cost per *car*, the way we buy cars—not cost per part or per pound. *



Ultralighting also requires * organizing designers differently. Our SUV design process made * seven engineers, all around the same table, collectively responsible for dauntingly ambitious *whole-vehicle* requirements. Each engineer also owned one major vehicle system or function, but for those we deliberately wrote *no* requirements, because we didn’t want him to make his problem into her problem—we wanted to make the whole team design a highly integrated vehicle together. Two engineers weren’t comfortable without their very own requirements, so we replaced them in the first week or two, and then it went great and we got the intended result. Toyota asked us how we did it, we told them, and… *



…out came the carbon-fiber *1/X* concept car—as spacious as a *Prius* but with half its fuel use and *one-third* its mass, just [927 pounds] 420 kg…or 400 kg, a 70% mass saving, if it were a *Prius*-style non-plug-in hybrid. *



Such novel design processes flow from revolutionary design mentality. Dave Taggart learned at the Skunk Works to design in the future, not in the past. When the Soviets shot down * Francis Gary Powers’s U-2 spy plane in 1960, Kelly Johnson didn’t say, “I’m going to design a slightly better U-2”; he said, “I want to own the skies for decades, so * we’ll design a Blackbird [SR-71]; I don’t know how, but we’ll figure out.” And they did—in ~13 months.

Johnson understood that such an airplane was impossible within the conventional design context. He knew that design is * like a rubber band: if you try to stretch it too far from the conventional design space, you encounter more and more resistance, and eventually it breaks. But if you * jump to the new design space you aspire to, you can stretch the rubber band back to fit technologies not yet ripe, and then as they mature, the rubber band relaxes to where you want to be. Siloed cultures won’t get you there, and those cultural changes are the hardest part. *

NRC is gradually starting to recognize disruptive change

technology	NRC 2011–12	NRC 2015
hybrid-electric drive	79 models on U.S. market	ubiquitous reality, with plug-ins too
battery-electric cars	"small, limited-range" possible by 2016 (Tesla jumped the gun)	"a powerful method...likely to increase" more than forecast
fuel-cell cars	same barriers [mis]identified in 2004	ditto, so still unready for 2017–25
weight savings likely	most likely 10% over 5–10 y; ≤20% by 2016 for ≤$2,625	15% likely by 2025, >EPA: ≤20–25% (metals) for ~$1–2k, ≤25% (C-fiber bodies) for $2–4k
ultralighting	eventually with "exotic" materials, >50% "very expensive"; aluminum-intensive halved-weight bodies usually "cost prohibitive" at high volume	NHTSA's "safety-neutral weight savings" limit probably artifactual
carbon-fiber composites	only low-volume, high-performance niches for next 10 y; fiber cost is key; mfg is slow & hard	"emerging trend" but low volume for >10 y due to long production times...; higher insurance & repair costs
lightweighting text	3 pages, mainly metal	29 pages, including 4 updating safety
aero drag reduction	≤10% for ≤$68	≤20% for ~$100
powertrain:fitness text pp	2.8	262 (53 el.) / 57 = 4.6
"the entire spectrum in vehicle design"	2.2 in 2004 fleet's C_dA/m_c; ~0.7× tractive energy (industry has demonstrated ~0.1×!)	no further data

Let me conclude with five remarks about your current inquiry and forthcoming report. First, NRC's latest auto-efficiency studies, * in 2011 and 2015, * have gained * much * insight and * realism. [Among many commendable improvements, the 2015 report finds NHTSA's "safety-neutral weight savings" limit to be probably artifactual, and acknowledges rapid electrification. Its analysis of fuel savings, especially via powertrain (except fuel cells), is increasingly detailed, sophisticated, and modern. For the first time, it strongly recommends properly integrative vehicle modeling, agrees that saving weight saves lives as well as fuel (contrary to its 2001 majority finding), and begins to model credibly the important spiral of mass decompounding, especially for powertrain (6-22). It now accepts advanced composites as legitimate emerging competitors with potential safety advantages, and may become ready to consider their manufacturing advantages. It agrees in passing that lightweighting can shrink traction batteries (p 10) and turbochargers can valuably shrink engines (8-45, 8-48).] * The 2015 * report even fleetingly mentions that lightening autos can cut their cost (pp 6–10)—a crucial idea not followed up. * It remained outdated on composites, * but helpfully mentions (6-12) the 2009 Lotus lightweighting study that found 37% lighter could be just 3% costlier, meeting all current safety and performance standards, * though it omits the far more convincing FEV study. [It also mentions autonomous vehicles (6-47 – 6-50), though missing their strategic implications for speeding electrification.] [NRC's collisions with reality are becoming much milder, but some persist, as in carbon-fiber vehicles, and fuel-cell cars—still considered unready for another decade, though Honda has been leasing them since 2002 and, like Toyota, upped the ante in 2016.] * Disappointingly, these reports considered the "entire range of vehicle design" of tractive load, inferred from the 2004 fleet, *to span a range severalfold smaller than industry has already demonstrated*—consistent with my earlier eyechart showing all that blank design space on the right side. *

Encouraging foresight: *ask history* how low can we go

parameter	Lovins publications (NRC '91, ECEEE '93, VPATC#3 '95, SAE '95, ACEEE '95, IBEC '95, RMI '95, EVS '96, SAMPE '96,...)	modern empirical examples
curb mass m_c (kg) of carbon-fiber 4-seater	400 (advanced "Ultima")	2007 Toyota concept *1/X*: 420 plug-in hybrid, 400 ordinary hybrid; part-metal 1987 Renault concept *Vesta II*: 473; 1984 Citroën concept *ECO 2000*: 449
regenerative braking efficiency (% wheel-to-wheel)	70 (industry expectations in early 1990s were ≤20)	2004 *Prius:* 66; 2012 *Volt*: 70–73 (if ≥0.14 *g*); 2007 Tesla *S*: ~64–80
coefficient of rolling resistance r_0 (%)	0.5 ("Imagina")	2013 Michelin tires for VW *XL-1*: ≤0.5, probably ≤0.4
practical vehicles' coefficient of aerodynamic drag C_d	≤0.19	1991 GM *Ultralite,* 1987 Renault *Vesta II,* 1996 GM *EV1*: 0.19; 2013 VW *XL-1*: 0.189; 1983 Ford passive *Probe IV*: 0.152 (= *F-16*), 1985 active *Probe V*: 0.137
practical vehicles' C_dA (m^2)	0.27	2013 2-seat VW XL-1: 0.277 (A = 1.50 m^2); cf. 2007 Renault concept *Vesta II* 4-seater: A = 1.64 m^2; 1991 GM concept *Ultralight* 4-seater: A = 1.71 m^2
4-seater mpge	146 ("Gaia" with η-0.30 ICE, ~1990 EPA cycle)	2-seater 2013 VW *XL-1* (NEDC): 235 (diesel-only: ~120); 4-seater B-class 2014 Renault concept *Eolab:* ~235 and Audi concept *Crosslane*: 214; 4-seater 2015 BMW *i3* (EV): 124

Lovins sources: www.rmi.org/Knowledge-Center/Library/T91_20_AdvancedLightVehicleConcepts; www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/1993/Panel_5/p6_7/paper; www.rmi.org/Knowledge-Center/Library/1995-08_AdvancedUltralightHybrids; http://papers.sae.org/951906/; www.rmi.org/search-category/Transportation/Hypercars/sharepoint

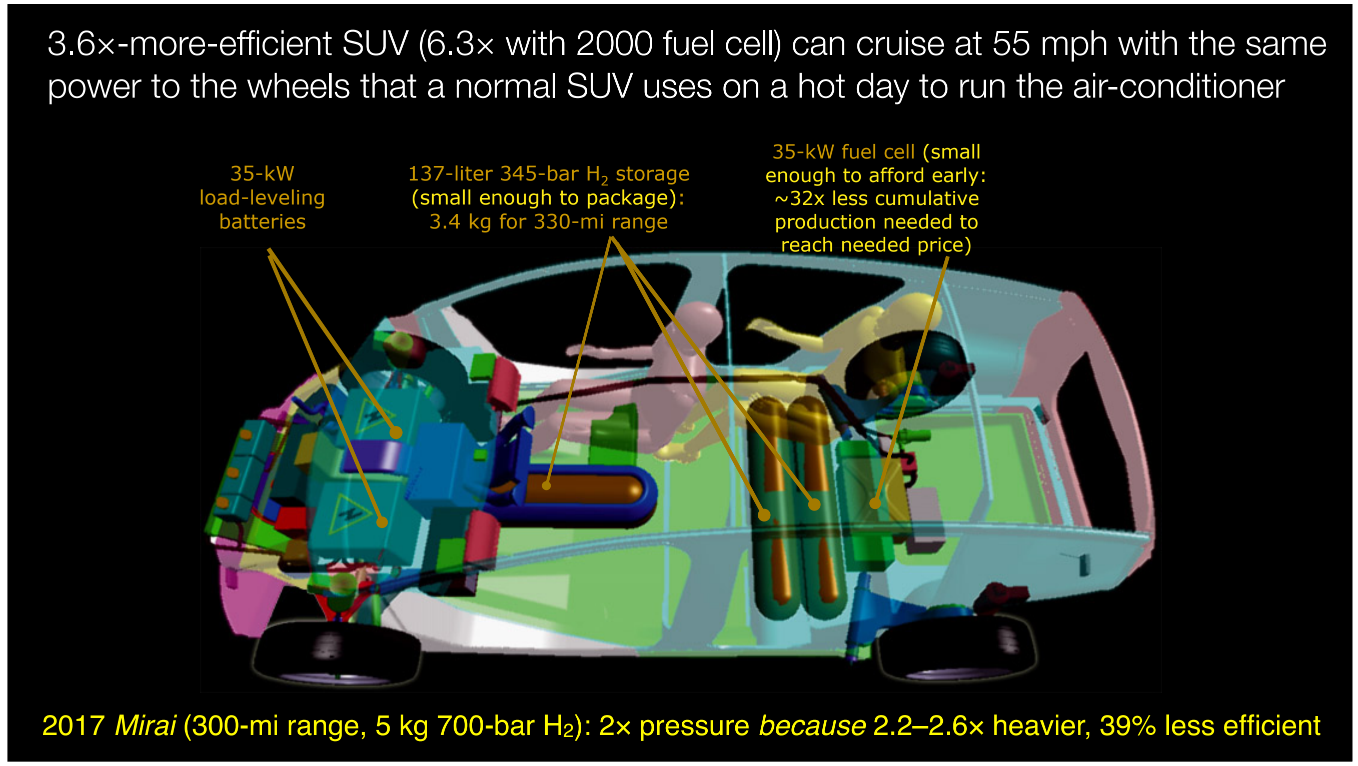
* Second, actual data can help you infer how low tractive load can go. My early-1990s analyses of critical platform parameters used historic concept-car and component data to infer what fuel economy production platforms should be able to achieve by about now. Those estimates were strongly criticized, but three decades later they're eerily close to market offerings. Such over-the-horizon radar signals are vital if you want to substitute accurate technological foresight for marketplace shocks, like the way Honda *VX* and Toyota *Prius* contradicted your predecessors' reports within weeks to months. *

[VW *XL1*: 795 kg due largely to heavy powertrain, 111 km/L gasoline; BMW *i3*: 1250 kg, efficiency 124 mpge pure-electric, or 2014 ReX EPA rated 117 mpge el-only, 39 gasoline-only]

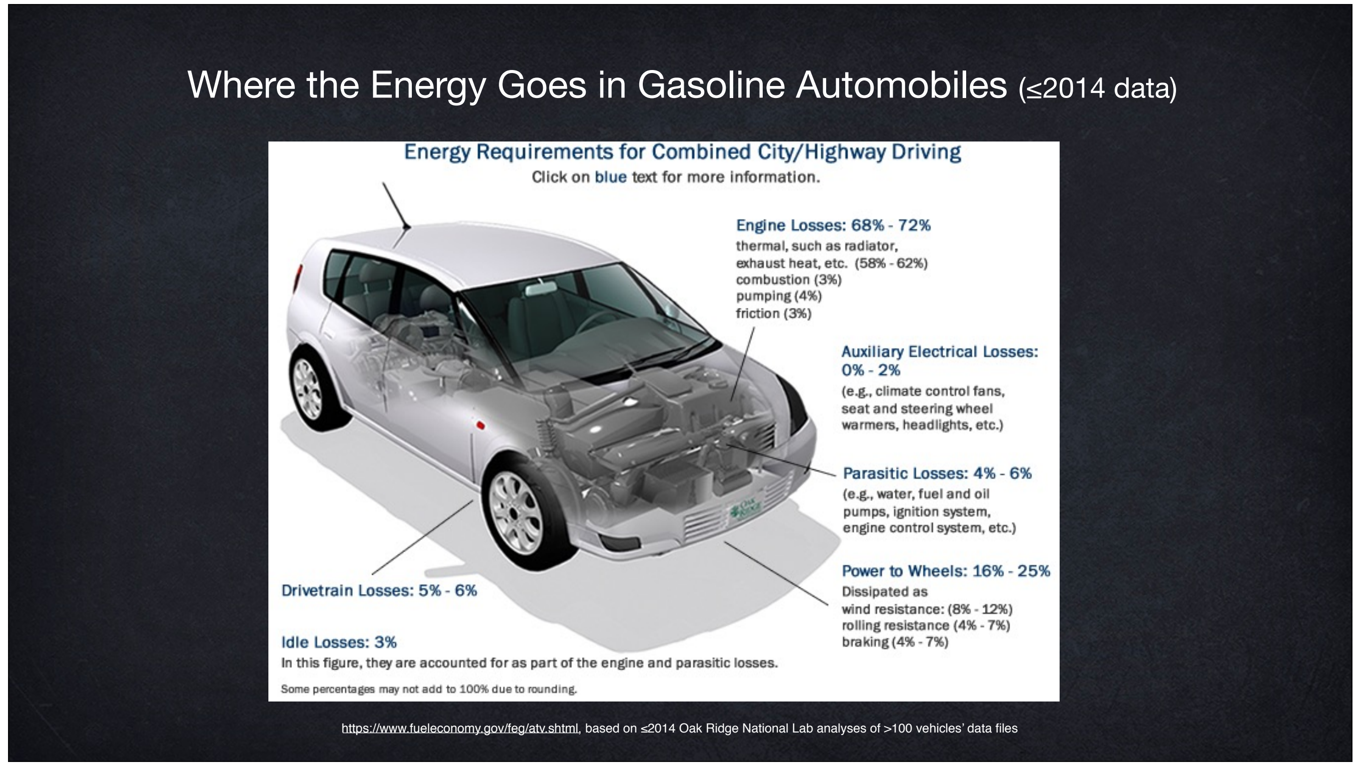
Ultralighting and electrification have both shared and differentiated (sometimes competitive) benefits

From ultralighting	*From electrification*
Getting off oil: avoid cost, price volatility, trade imbalance, depletion, insecurity, conflict, military costs	
Cleaner air: no oil-burning (uses optionally renewable electricity, H_2, or advanced biofuels), **public health**	
Climate protection: little or no CO_2 (depending on source of electricity or fuel), potential carbon credits	
Advanced composites' extreme durability (no rust or breakable spotwelds, limited fatigue and denting) **supports high-asset-utilization business models**	**More-reliable, ultra-low-maintenance powertrain, deeply coordinated with platform design that puts nearly all functionality in remotely updatable software,** reducing obsolescence risks and hence depreciation
Better stability and agility for avoiding accidents	Better traction control for avoiding accidents
Greatly increased acceleration but reduced noise, vibration, and harshness (NVH)	
Dramatically reduced manufacturing capital, space, time, labor, energy, water, waste, complexity, hence cost	
Shorter product cycles, lower breakeven volumes, and faster evolution boost profitability and competitive advantage for auto- and parts-makers, helping to speed and derisk further innovation	
Innovation and scaling cost and risk are shared and synergistic with other major industries (aerospace, windpower, polymers, military, electricity supply, smartphones, industrial drivesystems, software,…)	
Reduced debt, lead times, inflexibility, business risk, and potential exposure to global materials commodity cycles and politics (e.g. metal tariffs)	**Powerful synergies with electric grid and renewable generators can return valuable revenues**—worth, some practitioners claim, up to half the sticker price
Speeds deployment/effectiveness of renewable fuels & electricity, hence primary energy flexibility/optionality	
Increased national wealth, competitiveness, trade balance, development success, and energy security	

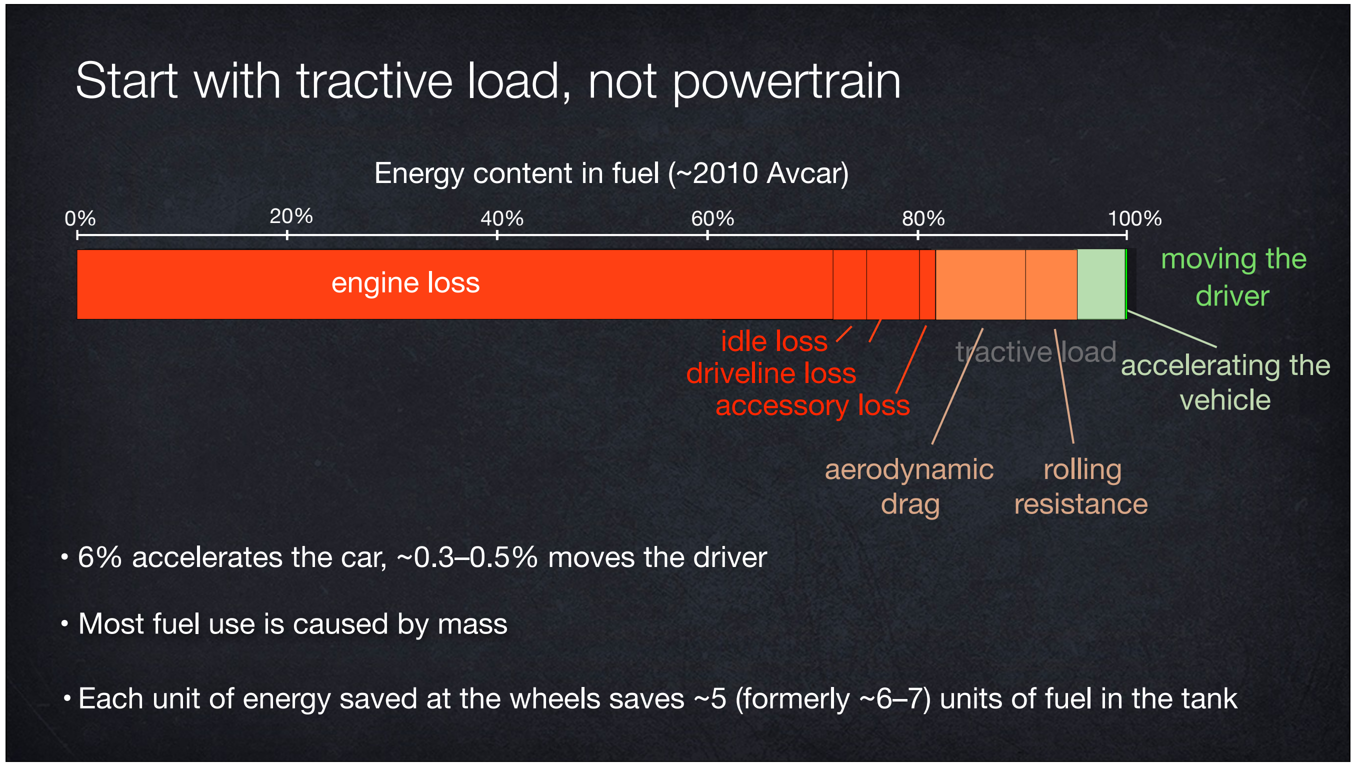
Third, you may well ask: If electrification outpaces ultralighting and captures most of the fuel-saving benefits first (the yellow line), why should we bother to ultralight too? Because these two strategies have *not just* that one big shared and competing benefit *but also* ~14 *other* benefits, some shared and many differentiated. We need *all* those combined benefits; they're not tradeoffs but complementary and often synergistic. So as ultralighting and electrification both accelerate in this exciting horse-race, it's smart to bet not on one specific horse but on the whole race, and to be sure you're racing horses, not oxen. *



Fourth, radical vehicle fitness enables advanced powertrain. In 2000, our carbon SUV design's ⅔ lower tractive load made its H_2 tanks ⅔ smaller for the same range, so 1990s 5-ksi (345-bar) cylindrical tanks packaged easily. We didn't need 10-ksi (700-bar) tanks like Toyota's two-ton *Mirai.* I'm in awe of *Mirai*'s doubled-power-density, 95%-cheaper-in-9-years [*vs* 2008 Highlander *FCV-adv*) fuel cell, but its stack and tanks could have been 2–3× smaller with an ultralight *1/X* than with *Mirai*'s heavy *Prius V* platform*.* Indeed, our SUV's fuel cell was 3× smaller, so you can pay 3× more per kW for it. At a standard 80% experience curve, you'd need ~32× less cumulative production volume to reach competitive cost, speeding the hydrogen transition by a decade or two [, using the integrative infrastructure solutions we described to the National Hydrogen Association in 1999]. Starting with platform fitness would thus reverse your Committee's longstanding critique of fuel cells, which may indeed lose to battery EVs but for the right reasons. *



Fifth and last, what's wrong with this DOE picture? Nothing…except that it's widely misinterpreted.
In a recent Avcar, and neglecting the small accessory loads, nearly four-fifths of the energy in combined city/highway driving is lost in the powertrain. OEMs traditionally focus mainly there because that's where the big losses are—much as Willie Sutton, when asked why he robbed banks, replied, "Because that's where the money is."
*



* But redrawing the data tells the opposite story. Of the roughly one-fifth of the Avcar's fuel energy that reaches the wheels and moves the car * against its tractive load, nearly half heats the * air; most of the rest heats * the tires and road. * Only about the last * 6% of the fuel energy accelerates the car and then heats the brakes when you stop. But 19/20ths of the mass you're accelerating is the heavy steel car, so just 1/20th of that 6%, or about * *0.3%*, of the fuel energy ultimately moves the driver—not very gratifying after one-and-a-third centuries of devoted engineering effort. And mass, by causing both inertial loads and and rolling resistance, * causes most of the tractive load. / Focusing mainly on powertrain efficiency is harder than reducing tractive load. It's also less rewarding, because saving one unit of energy in the powertrain saves only *one* unit of fuel in the tank—while * saving one unit of energy at the wheels avoids ~4 units lost in *getting* that energy to the wheels, leveraging ~5 units of energy saved at the tank. Thus we should *first* reduce tractive load, *then* improve powertrain—which shrinks for the same acceleration, saving even *more* mass *and* saving *capital* cost to help pay for the lightweighting! I therefore respectfully urge that your storytelling be reversed so it follows this logical design sequence—tractive load first, *then* powertrain and fuel.

I hope you'll feel that everything I've said here is obvious. As Marshall McLuhan said, "Only puny secrets need protection. Big discoveries are protected by public incredulity." Thank you for your good work and your kind attention. *